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Water Balances, Floods and Sediment Transport in the Hindu Kush-Himalayas

Data analyses, modelling and comparison of selected meso-scale catchments

Juerg Merz

University of Berne, Switzerland • Institute of Geography

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• MSWord 2000	word processing
• MSExcel 2000	tabulation of data, graphics and basic statistics
• SPSS 10.0	advanced statistics
• ArcView 3.2	mapping and GIS applications
• CorelDraw 9	graphics
• MSAccess 2000	data management
• HYMOS 4.03	data management and advanced hydrological analyses

Foreword

According to the first proposal, the research for this thesis should have been carried out entirely in the Yarsha Khola catchment area, comprising a field-based and in-depth process understanding of streamflow generation in a middle mountain catchment of the Hindu Kush-Himalayas. However, the political situation in Nepal did not allow extended field work, particularly after the incident at the Yarsha Khola field office on February 2, 1999. A second proposal was drafted one year into the work, detailing preparations for the first extended field season, due to begin in March 1999 with the onset of the pre-monsoon rains. This proposal aimed to review the existing database of the Jhikhu Khola catchment and attempted to synthesise information already collected. While field-based work in the Yarsha Khola catchment may have engendered a more proactive approach, with more chances to generate ’new knowledge‘, the reactive approach that was subsequently adopted for work in the Jhikku Khola catchment is probably more helpful in terms of understanding how far we have reached in the project over the years. The new knowledge in this study is the detailed interpretation of information and data from different surveys, measurement campaigns, and long-term data monitoring.

Juerg Merz
April 13, 2003

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Executive Summary

This study is embedded in the People and Resource Dynamics of Mountain Catchments in the Hindu Kush-Himalayas Project (PARDYP). PARDYP is a regional research-for- development project, working in natural resources and watershed management. The project includes five catchments of 20 to 110 km^2 across the Hindu Kush-Himalayan region, with sites in China, India, Pakistan, and two sites in Nepal.

The study examines the current situation of water resources in selected meso-scale catchments in both the biophysical and socioeconomic contexts. It focuses primarily on the Jhikhu Khola catchment (Kavrepalanchok district) in the middle mountains of Nepal, and compares the results with the Yarsha Khola catchment (Dolakha district), as well as with the PARDYP catchments in China, India, and Pakistan. It aims to contribute to increased understanding of water resources and water-related processes, such as soil erosion and land degradation, as well as contributing towards knowledge about integrated catchment development with minimised water-induced land degradation and minimised water resource degradation. The main components of the study are as follow:

- runoff generation and floods,
- sediment mobilisation and transport,
- water availability for domestic and agricultural purposes
- impact of future change on water resources and related processes, and
- synthesis and development of a framework for comparison of catchments in the region.

Research was based on the results of various surveys and mapping campaigns carried out in the catchments, and on detailed hydro-meteorological data collected according to the nested approach. This approach allowed the investigation of processes from the micro- to the meso-scale, that is, from plot to catchment level. It also determined the scale dependency of these processes.

To begin with, the inherent conditions of the catchments regarding flood generation, land degradation, and water scarcity from the perspectives of catchment characteristics, human settings, and processes were assessed. According to these criteria, the PARDYP Nepal catchments are in a fragile and vulnerable region. Water scarcity is caused mainly by the seasonality of water resources and their management. Precipitation is highly seasonal, with 75 to 80 % of the rainfall occurring during the monsoon season, and 10 to 15 % falling during the pre-monsoon season. The rest of the year is virtually dry. Evapotranspiration rates peak during the pre-monsoon season, making March to April the driest time of the year, as runoff also reaches its lowest point during this time. Water supply for domestic use is at a minimum during this time and many households face hardship fetching water. In terms of water quality concerns, the peak risk season is the early monsoon, with the highest microbiological and chemical contamination. Local water use for agriculture is, in general, well adapted to seasonality. Even so, farmers perceive there to be a water shortage since they are not able to grow any additional crops during this time. Farmers at the tail end of irrigation systems receive inadequate water supply even during the wet season. The time of highest risk for farmers is the time between the first pre-monsoon rains and the onset of the monsoon, as this is the time when maize is planted and the rice nurseries are prepared. Agriculture is also vulnerable in the winter season, when wheat and potatoes are grown. Rainfed crops can be damaged in dry conditions, and little rainfall might mean that one less crop can be planted on irrigated land. In addition, the growing number of farmers producing cash crops puts an additional stress on water resources. These issues suggest that in future the focus should be on improved management of irrigation systems, catchment-based management of water resources, appropriate technologies to reduce water demand and increase water availability during the dry season, and improved water quality management.

Floods are generated mainly in the monsoon season. In general, it is during this time that the most intense rainfall events with the highest intensities and volumes occur. It was shown that runoff generation on degraded areas as well as on grasslands contributes most to flood volumes, while

rainfed agricultural land only contributes marginally to flood behaviour. It is important to keep this in mind for the discussion on the impact of Himalayan farmers on downstream flooding. Cultivated land in general has a beneficial impact on flood generation, while degraded land and grassland increases the volume as well as the peaks. A cluster approach defined rainfall intensity and volume as the main determinants for flood generation. On degraded land and grassland, infiltration excess overland flow is expected to produce surface runoff; while, on agricultural land, it is largely saturation excess overland flow that is responsible for producing surface runoff. At the catchment level, processes similar to those on degraded land contribute to flood generation. In terms of the largest flood events, no particular pattern was observed, except that these events generally occur when rainfall throughout the catchment exceeds 25 mm, with a maximum of 30-minute rainfall intensities of >10 mm/h; or events in pocket areas of the catchment with more than 10 mm rainfall and more than 20 mm/h, 30-minute intensity. In addition, it was observed that land use had no impact on the largest events. In terms of flood protection and management, downstream planning and prohibition of river channel encroachment will yield better results than small-scale land-use changes in the upland catchments.

Soil loss was shown to be greatest on degraded land, followed by agricultural land, and grassland. A difference was observed between the seasons on the agricultural land in the Jhikhu Khola catchment, while in the Yarsha Khola catchment no difference was observed. Likewise, on grassland as well as on degraded land, no difference was observed between the seasons. From a total soil loss perspective, the current soil loss rates from the agricultural land are not of major concern as they balance the natural soil development. Surface erosion on degraded patches as well as gulling on these areas produce much higher loads and are of particular concern for downstream areas. The surface soil loss, in addition to the sediment produced in the streambed and the roads, adds up to sediment loads of medium to high magnitude.

Farmers themselves do not see surface erosion from their fields as a major issue. Soil conservation activities will only be successful if farmers see an additional benefit to soil conservation, such as increased fertility, increased income, or increased fodder availability. To reduce the sediment yield from the catchments, focus should be given to the streambanks, the road network, and the degraded areas.

The study also investigated the possible impacts of future changes on established and inherent conditions under different scenarios. To date, these include increasing population, global climate change, and marginalisation or extensification of the areas. It was shown that potential climate change might lead to lower water availability in the presently critical seasons, while increased rainfall may increase the magnitude and number of flood peaks. Population growth will lead to increased water demands for domestic purposes, while an intensification in the already highly intense farming systems is less likely, and food will have to be produced elsewhere, or more focus will have to be given to staple food production in the future. The land-use scenarios could not deliver conclusive answers, as the vegetation parameters were inadequate and need to be improved with the availability of the respective data. From a methodological perspective, the distributed model PREVAH (precipitation-runoff-evapotranspiration-hydrotope model) showed the best performance with potential improvement possibilities. The Tank model was the most user-friendly model tested. These models will have to receive further attention in terms of incorporation of rainfall intensity and calculation of evapotranspiration.

For the comparison of catchments in the region, an index approach for the assessment of the three susceptibilities is proposed. The Water Poverty Index (WPI), the Flood Generation Index (FGI), and the Water Induced Degradation Index (WDI) have shown good first results during the comparison of the PARDYP Nepal catchments and could be used to compare these catchments with those in Pakistan and India. The Jhikhu Khola catchment had a lower WPI than the Yarsha Khola catchment, mainly due to fewer water resources, less access, greater use, and more adverse effects on the environment, while in the Yarsha Khola catchment the capacity score was lower.

This study concludes that the most important considerations when developing water management decision-support systems are: location with reference to potential water sources, water use, and temporal distribution of water demand and availability.

Acronyms and Abbreviations

ADB	Asian Development Bank
ADR	altitude dependent regression
AET	actual evapotranspiration
API	antecedent precipitation index
BFI	base flow index
BSc	Bachelor of Science
CEAPRED	Centre for Environmental and Agricultural Policy Research, Extension and Development
CEC	cation exchange capacity
CEH	Centre for Ecology and Hydrology
CIAT	Centro Internacional de Agricultura Tropical (International Centre for Tropical Agriculture)
CR	criticality ratio
CV	coefficient of variation (= standard deviation/mean)
CWC	Central Water Commission
DDC	district development committee
DEM	digital elevation model
DHI	Danish Hydraulics Institute
DHM	Department of Hydrology and Meteorology
DSS	decision support system
DWSS	Department of Water Supply and Sewerage
EAWAG	Swiss Federal Institute of Environmental Science and Technology
ETH	Swiss Federal Technical High School
FAO	Food and Agricultural Organization of the United Nations
FGI	Flood Generation Index
FMIS	farmer managed irrigation systems
GBM	Ganges-Brahmaputra-Meghna basin
GBPIHED	G.B. Pant Institute for Himalayan Environment and Development
GCA	gross command area
GCM	global climate models
GEV	Gumbel extreme value distribution
GIS	geographic information systems
GLOF	glacial lake outburst flood
GRDC	Global Runoff Data Centre
HH	household
HKH	Hindu Kush-Himalayas
HMG	His Majesty's Government
HRU	hydrological response unit
HYREUETH	hydrological response unit – ETH
IAHS	International Association of Hydrological Sciences
ICIMOD	International Centre for Integrated Mountain Development
IDE	International Development Enterprises
IDF	intensity-duration-frequency
IDRC	International Development Research Centre
IDS	Institute of Development Studies
IDW	inverse distance weighting
IGCEDP	Indo-German Changar Eco Development Project
IIASA	International Institute for Applied Systems Analysis

IIDS	Institute for Integrated Development Studies
ILACO	International Land Development Consultants
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
JK	Jhikhu Khola catchment
KIB	Kunming Institute of Botany
KU	Kathmandu University
LRMP	Land Resource Mapping Project
masl	metres above (mean) sea level
MENRIS	Mountain Environment and Natural Resources Information System (ICIMOD)
MOPE	Ministry of Population and Environment
MRE	Mountain Risk Engineering Unit
MRM	Mountain Resources Management Project
MSc	Master of Science
NARC	Nepal Agricultural Research Council
NIH	National Institute of Hydrology
NPC	Nepal Planning Commission
NRs	Nepalese Rupee (1 US$ ~ 76 NRs; June 26, 2003)
NST	Nepal Standard Time (GMT + 5 3/4h)
OECD	Organisation for Economic Cooperation and Development
PAR	participatory action research
PARDYP	People and Resources Dynamics in Mountain Catchments of the Hindu Kush-Himalayas
PFI	Pakistan Forest Institute
PMP	probable maximum precipitation
PRA	participatory rural appraisal
PREVAH	precipitation-runoff-evapotranspiration-hydrotope model
RCM	regional climate models
RWSSSP	Rural Water Supply and Sanitation Support Programme
SDC	Swiss Agency for Development and Cooperation
SDR	sediment delivery ratio
SODIS	solar disinfection
SRI	system for rice intensification
TDR	time dependant reflectory
T&D	test and demonstration
TLU	tropical livestock unit
UBC	University of British Columbia
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFPA	United Nations Population Fund
UoB	University of Bern
VDC	village development committee
WECS	Water and Energy Commission Secretariat (Nepal)
WDI	Water Induced Degradation Index
WPI	Water Poverty Index
WMO	World Meteorological Organisation
WSSCC	Water Supply and Sanitation Collaborative Council
WWC	World Water Council
WWF	World Wildlife Fund for Nature
YK	Yarsha Khola catchment

Glossary

In this report the term catchment is used as a synonym for watershed, meaning the area drained by one particular river or stream. To indicate that the discussion is focusing on part of a catchment, the term ‘sub-catchment’ is used. Watershed is used as the term for catchment boundary or divide.

bari	rainfed agricultural land (Nepali)
bazaar	market (Nepali)
criticality ratio	ratio of average annual water withdrawal to water availability (Alcamo et al. 2000)
dry spell	a period of 15 days with no more than 1 mm of rain each day (Mosley and Pearson 1997)
hydrograph	graph of discharge as a function of time at a given station
hydrological response unit	catchment area unit with similar hydrological response
hyetograph	graph of rainfall as a function of time at a given station
Hymos	software for environmental data management distributed by Delft Hydraulics, the Netherlands
khet	irrigated agricultural land
khola	river, stream (Nepali)
kosi	river (Nepali)
kuwa	spring box (Nepali)
Landflucht	outmigration of people from rural to urban areas; urbanisation from the perspective of the rural areas
model calibration	process of appropriate parameter selection (Sorooshian and Gupta 1995)
model validation	process of parameter verification on a new dataset previously not used in the calibration procedure (Sorooshian and Gupta 1995)
rainy day	day with equal or more than 1 mm of rain per day
sanitation	use of sanitary means of excreta disposal using flush toilets or pit latrines (NPC 2000)

Symbols and Units

Units

In general SI units are used throughout this study.

Symbols

a	runoff coefficient
A	area
a, b, c	coefficients
AET	actual evapotranspiration
a_i	area of the hill slope per unit contour length that drains through point i
AI_{10}	erosivity based on 10-minute intensity
AI_{1030m}	erosivity based on 10- and 3-minute intensity
CD_i	cost-distance value of cell i
E	east
ET_0	reference evapotranspiration
H0	null hypotheses
HA	alternative hypotheses
I_{10max}	maximum 10-minute rainfall intensity during the event
I_{30max}	maximum 30-minute rainfall intensity during the event
I_{60max}	maximum 60-minute rainfall intensity during the event
I_{ave}	average rainfall intensity during the event
I_m	m-minute rainfall intensity
K_c	crop coefficient
n	number of observations
P	precipitation
p	probability
P_{25}	rainfall amount after 25 % of the event
P_{50}	rainfall amount after 50 % of the event
P_{75}	rainfall amount after 75 % of the event
Q_{max}	event peak flow
Q_{obs}	observed discharge
Q_{sim}	simulated discharge
Q_{start}	flow at the beginning of the event
Q_{tot}	total runoff, i.e. runoff between zero and hydrograph
R_i	relative contributing area
Sig.	significance level
ß	slope
T	return period
t	time/duration
t_P	rainfall event duration
t_Q	event duration
t_{rec}	time between peak and start of baseflow
t_{rise}	time between start of hydrograph rise and peak
U	test statistic for U-test Wilcoxon, Man and Whitney
w_i	weight
WT	water table
z	elevation
z	test value

Contents

All chapters are concluded with a brief synopsis targetted at development actors and policy-makers. The concluding remarks, including the outlook, should be relevant to all PARDYP clients.

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Chapter 1: Introduction

> ***"There is a water crisis today. But the crisis is not about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people — and the environment — suffer badly."***
>
> ***(World Water Vision)***[1]

Chapter 1 will introduce the background and the reasons for this study in the context of the PARDYP project and the water-related issues of the Hindu Kush-Himalayan region. The key issues discussed in this study are:

- **water availability**
- **flooding**
- **water-induced land degradation and sedimentation**

Current knowledge about these issues with particular focus on the HKH is presented. The status, relevant processes, their impact, and possible future scenarios are discussed before introducing the operational background and the structure of this study.

The Hindu Kush-Himalayas (HKH) are known for their beauty, their peaks — including Sagarmatha (Mt. Everest), the highest peak in the world — and their diversity in flora, fauna, and culture. However, these mountain ranges are also known for their environmental problems and their impact on the adjacent plains. Several studies have been carried out in the HKH searching for the reasons and causes of these issues. These studies fall into two schools of thought (Zurick and Karan 1999).

One school believes that human activity is the main cause of land degradation and environmental crisis in the region. The fragility and impending ecological crisis of this mountain ecosystem as a result of rapid population growth, along with increased firewood demand, deforestation, expansion to marginal lands, and increased landslides and soil erosion affecting downstream flood and sedimentation behaviour, was first mentioned by Eckholm (1976), and was later termed the 'Theory of Himalayan Environmental Degradation' by Ives and Messerli (1989). Although restricting the discussion to Nepal, this study was followed by a number of studies that came to the same conclusion. A compilation of many of these studies, including their major arguments, is given in Ives and Messerli (1989).

The second school argues that natural processes outweigh the importance of human impact. Ives and Messerli (1989), the main defenders of this school, provided the first synthesised analysis of the natural causes of land degradation to contradict the Theory of Himalayan Environmental Degradation. They argue that whereas serious environmental and human problems exist in the HKH, their impact on the downstream areas cannot be proven. Furthermore, in many instances, increased stability of the mountain slopes has occurred after human intervention and rapid reclamation and stabilisation of landslides. In general, the impact of human interventions is a question of scale (Ives and Messerli 1989; Lauterburg 1993). While the impacts of soil conservation methods are directly visible in a micro-scale catchment as they reduce soil loss rates, the impacts of these interventions are not detectable in the meso- to macro-scale catchments. This school of thought was supported by many follow-up studies (Bruijnzeel and Bremmer 1989; Hofer 1998a; Schreier and Wymann von Dach 1996).

Zurick and Karan (1999), not following either of these two schools, argue that in a region of great natural and cultural diversity such as the Himalayas, a generalisation is not valid and the application of a single environmental model must be rejected. In their view, the current

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[1] **Cosgrove and Rijsberman (2000)**

environmental conditions of the Himalayas, and therefore land degradation, has to be viewed as a product of natural and social forces. Increasing population growth and lack of governance and poverty are believed to be some of the main driving forces behind environmental degradation, besides the great natural potential for degradation in a high energy environment with steep topography, unstable geology, and short and intense rainfall periods (ICIMOD 2002a).

The above discussion focuses primarily on land degradation and the intertwined flood and sedimentation issues, both of which are related to water. In the context of water availability, the discussion centres on the importance of mountain waters and their proper management (Liniger et al. 1998). Mountains can be considered 'water towers' providing large portions of river flows in the plains. Bandyopadhyay et al. (1997) showed the global significance of mountain water resources. Viviroli (2001) demonstrated that mountains are 'humid islands' with increased specific yield, seasonal delay of discharge through storage of water in the form of ice and snow, and decreased seasonal discharge variability in comparison to their lowlands. Degradation of water resources in the mountains in terms of quantity and quality is therefore not only a threat to the people living in the mountain ranges, but also affects those in the adjacent plains. The HKH region is home to millions of people who rely on the water resources from the Indus and the Ganges-Brahmaputra-Meghna (GBM) rivers in the Indian subcontinent; the Mekong, Salween, and Indrawati rivers in South-east Asia; and the Yangtze and Yellow rivers in China. This region is projected as increasingly water-scarce in years to come (Rodda 2001). Causes of water resource degradation are population growth, increased water demand for intensive agriculture, industries and sanitation, and increasing water pollution (OECD 2001). At the local scale, mismanagement (Chalise and Sial 2000) and catchment degradation (Liniger et al. 1998) may also affect water availability. To what extent the impact of local catchment and land degradation affects water availability is still subject to discussion. The FAO (2002) showed that there is no visible effect of land-use change at the micro- and meso-scale to the macro-scale.

The impact of global climate change in years to come is unclear. A number of projections exist for the impact on hydrological parameters and water resources for this region, but no conclusive answers can be given at this stage (IPCC 1998). Not only climate change, but also population growth and potential conflicts between lower lying areas and mountain areas are scenarios that may affect mountain waters (Viviroli and Weingartner 2002).

In this context, water resources globally and in mountain areas such as the HKH face multiple challenges. The Ministerial Declaration of The Hague stated, “Business as usual is not an option”, in order to drive the point home that water security in the 21st century is an issue that needs to be taken seriously (World Water Forum 2000).

New management options and tools must be considered in order to ensure water availability for future generations and sustainable use to the satisfaction of both upstream and downstream parties. These options and tools must be based on a profound understanding of the current state of affairs and the relevant processes, rather than on myths. It is exactly this understanding that is is largely missing in the mountainous regions of the developing world. Mountainous regions globally are considered ‘the blackest of black boxes in the hydrological cycle’ (Klemes 1988; cited in Rodda 1994) with respect to data availability and understanding.

On the basis of the above introduction it can therefore be concluded that the depletion of natural resources such as forest, land, and water in the HKH is a serious concern at the micro- to meso-scale. Direct interventions on this scale may improve the conditions of the local residents both in terms of livelihoods and water security. The impact at the regional scale of such interventions, however, is questionable, mainly in terms of water availability, flood protection, and sedimentation. In terms of water quality, upstream-downstream linkages are visible with respect to heavy metals, pesticides, nutrients, and salinity (FAO 2002). A detailed understanding of the conditions and processes, however, is still missing for the mountainous regions of the HKH. This study will attempt to fill some of the gaps and contribute to a better understanding of the relevant processes in upland catchments in the foothills of the HKH, mainly through the integration of findings from the People and Resource Dynamics in Mountain Catchments of the Hindu Kush-Himalayas (PARDYP) project in this field to date, and through the synthesising of new knowledge.

1.1 THE KEY ISSUES IN THE HKH RELATED TO WATER

Water is Life — a perception shared by more than 60% of the residents in two catchments of the Nepal Himalayas. The same statement is used on many occasions and can be read in many publications. Simultaneously, water is destructive and a reason for great despair in many regions of the world. Too little and too much water are issues that are both prevalent in the HKH region on an annual basis during both the monsoon season and the dry season.

On the basis of an opinion poll conducted in July 2002 through the Internet, four key water-related issues were identified as being of utmost importance at the regional scale (see also Table 1.1):

- water availability for human purposes (agricultural, domestic, and industrial use) (see Section 1.1.1),
- flooding in the foothills and adjacent plains (see Section 1.1.2),
- water quality and pollution (see Section 1.1.1), and
- water-induced land degradation and sedimentation (see Section 1.1.3).

Table 1.1: **Key issues in the HKH related to water**[*]

Rank	Issue	No of responses [%]
1	Water scarcity	37.1
2	Floods	19.4
3	Water pollution	16.5
4	Erosion and sedimentation	13.5
5	Unequal access	8.2
6	Unproductive use of water resources	3.5
7	Biodiversity decline	1.2
8	Destruction of wetlands	0.6

(data source: own survey)

[*] The survey identified 170 issues from 49 respondents in 13 countries, including India, Nepal, China, the United Kingdom, and others. At the same time, 63 causes including water management, water institutions and policies, deforestation, and climatic constraints were mentioned.

Banskota et al. (2000) proposed the same issues as the key environmental issues related to water in the HKH region. The four key issues are discussed below in a global context with a focus on the HKH region. An attempt is made to provide an overview of the current status, the relevant processes, and the impact and future direction of each issue according to the literature available. Water quality and pollution are included in the section on water availability as they are often directly connected, and in the context of this study no particular emphasis is given to this key issue. Chalise (2000) provides a good overview of water resource management issues in the region, focusing on priority areas such as transboundary issues and data management.

1.1.1 Water availability

Adequate water resources for future generations are of great concern at the global scale. Water demand worldwide has increased six-fold over the past one hundred years, with approximately half of all available freshwater being used directly for human purposes (Cosgrove and Rijsberman 2000). Globally, about 38% of the population is living in countries where there is severe water stress (Alcamo et al. 2000). In the HKH, Pakistan and Afghanistan in particular are of concern as they have developed most of their available water resources. According to Shiklamonov’s (2000) classification, water availability in South Asia was catastrophically low in 1995 and shows a decreasing trend by 2025.

This global view also has a local dimension. Water availability was identified as the main issue for residents of the selected middle mountain catchments (Table 1.2). Adequate water availability for irrigation in particular is in short supply, closely followed by drinking water shortage. Increasingly, water pollution is becoming a concern in some catchments. Other studies in the HKH region have revealed similar issues. In Changar, located in Himachal Pradesh/India and part of the Indian Western Himalayas, there is an acute water scarcity, both for drinking as well as for irrigation (IGCEDP 2001). Negi and Joshi (2002) identified drinking water as a major problem in the Central Himalayan region. In the Sikkim Himalaya, Sharma et al. (1998) likewise postulated that the drying up of springs and drinking water scarcity are placing considerable stress on the local population. Singh and Pandey (1989) experienced water scarcity due to the drying up and decreasing yields of springs in the Kumaon Himalaya. They mainly held the degradation of the natural oak forests responsible for this process. Hill towns in Darjeeling and Shillong, the wettest corner of the Indian sub-continent, face water scarcity all year round according to Subba (2001). Bhaumik (2003) recently

Table 1.2: **Water-related key issues at the catchment scale, PARDYP catchments** (light grey cells indicate relation to water availability)[*]

Priority	Hilkot	Bhetagad	Jhikhu	Yarsha	Xizhuang
1	Water shortage for irrigation	Depletion of water resources	Irrigation water shortage	Irrigation water shortage	Water shortage during dry season
2	Water management	Inappropriate management of water resources	Drinking water shortage	Drinking water shortage	Too much water during wet season
3	Poor water quality and quantity for drinking	Soil and nutrient losses	Deteriorating water quality		Drinking water shortage
4		Water pollution	Topsoil loss and nutrient build-up		

(data source: own survey)

[*] These issues were identified by the PARDYP country teams through household surveys, focus group meetings, hydro-meteorological monitoring, and several years of work experience in their respective catchments; for location of the catchments refer to Figure 2.3 in Chapter 2.

reported this again. Similar issues are also reported by Grassroots (no date) for the Gharwal and Kumaon regions in India. Chalise et al. (1993) report the drying up of local groundwater resources, which are affected by changes in local land-use patterns. Due to these changes, women and children are forced to walk longer distances to collect water. They also report on cases from the Nepal middle mountains where men experience difficulty in finding a bride — a situation blamed on the drudgery the wife would face fetching water in these areas. Similar cases were also found in Bhaktapur, where a Newari folk song describes this situation (Prajapati Merz, pers. communication [translated from Newari]):

There are proposals (for marriage) coming from the upper part
and from the lower part (of Bhaktapur).
Wherever you send me, dear mother,
do not send me to the Tuthimala Tole.
There it is difficult to fetch water.

In the Xizhuang catchment, the biggest problem, as indicated by the respondents of a PARDYP survey, is access to irrigation water (35 villagers, 80%; Ma et al. 2002). Drinking water availability is only point wise an issue in certain villages and at selected drinking water supply schemes.
While the people of the HKH have learned to cope with the inherent seasonality in the past, new pressure from decreasing water availability may threaten the livelihoods of marginalised people. The root causes of this crisis can be attributed both to human as well as natural factors. Possible factors leading to water availability concerns are discussed below.

1.1.1.1 Status

For the purpose of assessing water resources at the national or global scale, various authors have defined renewable water availability. Alcamo et al. (2000) define it as fast surface runoff and groundwater recharge. In the UNEP (2001) study, renewable water availability is defined as total available surface water. Falkenmark (2000) introduced the blue and green water concept, blue water being groundwater recharge, surface, and river runoff available for exploitation, and green water being the moisture that would have evaporated before contributing to runoff. The green water is very important for biomass production in forests and grasslands. The focus of this research is based solely on blue water. Non-renewable groundwater and groundwater exploitation above the annual recharge are likewise not included in this discussion, as they are unsustainable and cause follow-up problems such as falling water tables, subsidence, and large-scale water scarcity, particularly for smallhold farmers (Postel 1999).

Worldwide, the renewable water availability is estimated at 40,000 km^3, with withdrawals of 2500 km^3 for irrigation, 750 km^3 for industrial use, and 350 km^3 for municipal (mainly domestic) use (Cosgrove and Rijsberman 2000).

The estimates of water availability for different countries in the HKH region vary greatly according to authors. In the case of Nepal, UNEP (2001) estimated the per capita water availability as 10,300 m^3/y for 1998. The World Bank (1998) estimated 7714 m^3/y per capita water availability for Nepal in 1996. Seckler et al. (1998) estimated the annual water resources for Nepal as 170 km^3/y. With a population of 19.3 million people, water availability was 8808 m^3/y per capita in 1990 (Seckler et al. 1998). Kayastha (2001) estimated a seasonal difference of 6100 m^3/y per capita, assuming 8800 m^3/y per capita in monsoon season and 2700 m^3/y per capita in the dry season. Within Nepal, the per capita availability drops to 1400 m^3/y in the Kathmandu Valley. Figures for other countries of the HKH are given in Table 1.3. Note that these values are for entire countries, not only for the mountainous areas.

Table 1.3: **Water availability in selected countries in the HKH**
(entire countries; source: Seckler et al. 1998)

Country	Population (1990)	Annual water resources	Per capita water availability	Total withdrawals	Per capita withdrawals m^3/y		
	Million	km^3/y	m^3/y	km^3/y	Dom.	Ind.	Irr.
Afghanistan	15.0	65.0	4333	25.6	102	34	1566
Bangladesh	108.1	2357.0	2180	23.8	7	2	211
Myanmar	41.8	1082.0	2588	4.2	7	3	91
Nepal	19.3	170.0	8808	2.9	6	2	143
Pakistan	121.9	418.3	3431	155.7	26	26	1226

Dom. Domestic use Ind. Industrial use Irr. Irrigation use

Nepal has the highest renewable per capita water availability in the list of countries above. This is mainly due to the fact that the entire country is within the boundary of the HKH region. Bhutan's per capita water availability of 120,405 m^3/y exceeds that of Nepal, according to a study by Subba (2001). In contrast, Pakistan, with a large part of the country in the plains and with the world's largest irrigation network, relies heavily on water resources from the Indus River originating in the HKH region (Liniger et al. 1998). Bangladesh's water availability, although located in the delta of the GBM, is reduced mainly due to the large population. Irrigation is, in all of the above countries, the largest user of renewable water resources. In Nepal, Bangladesh, and Myanmar, the withdrawals for both domestic and industrial use are small to negligible. Domestic withdrawals according to these figures are calculated to about 16 l person^{-1}day^{-1} in Nepal. Bangladesh and Myanmar show about 19 l person^{-1}day^{-1} and in Pakistan this corresponds to a daily withdrawal of about 71 l person^{-1}day^{-1}.

For the estimation of whether a country is water scarce or not, different approaches have been applied. Alcamo et al. (2000) used the criticality ratio (CR), which describes the ratio of average annual water withdrawals to water availability. On the basis of the 1995 data, Alcamo et al. (2000) determined that 49% of South Asia[2] is under severe water stress. In Southeast Asia[3] 6% of the area is currently under water stress, while in China+[4] presently 32% of the country is facing severe water stress. Applying the same method to the above data from Table 1.3 shows that Afghanistan and Pakistan are currently under moderate water stress, while the remaining countries are well below the threshold of water stress (Table 1.4).

Table 1.4: **Criticality ratio for selected countries of the HKH**

Country	Annual water resources* km^3/y	Total withdrawals* km^3/y	Criticality ratio CR %
Afghanistan	65.0	25.6	39
Bangladesh	2357.0	23.8	1
Myanmar	1082.0	4.2	1
Nepal	170.0	2.9	2
Pakistan	418.3	155.7	37

* data source: Seckler et al. (1998)

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[2] South Asia here includes Bangladesh, India, Nepal, Pakistan, and Sri Lanka (Alcamo et al. 2000).

[3] Southeast Asia here includes Bhutan, Brunei, Cambodia, East Timor, Indonesia, South Korea, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan (Alcamo et al. 2000).

[4] China includes China, Hong Kong, North Korea, Laos, Macao, Mongolia, Vietnam (Alcamo et al. 2000).

According to Gleick (2000), the estimated per capita water use for all countries of the HKH for the year 2000 was below 100 l person^{-1}day^{-1}. Note that these figures are for the entire country, including the plain areas and large cities. It can, however, be assumed that the figures for the HKH are below the given values. This assumption is strengthened by the fact that the minimum was estimated for Bhutan with 10 l person^{-1}day^{-1} followed by Nepal with 12 l person^{-1}day^{-1}, when both countries have most of their territory in mountainous areas. Bangladesh follows with 14 l person^{-1}day^{-1}, Myanmar with 15 l person^{-1}day^{-1}, Afghanistan with 28 l person^{-1}day^{-1}, India with 31 l person^{-1}day^{-1}, Pakistan with 55 l person^{-1}day^{-1}, and finally China with 59 l person^{-1}day^{-1}. Note the differences between the figures on the basis of Table 1.3, which in general show the same order of magnitude except in the case of Afghanistan.

It is not only the quantity of water that determines water availability. In many cases, deteriorated water quality also reduces water availability. A large part of the world's population still has no access to safe and affordable drinking water (Cosgrove and Rijsberman 2000). In Nepal, 78.1% of the rural population had access to a water supply in 2000 (NPC 2000). The national average was 79.9 with 92.3% water supply coverage in the urban centres of Nepal. However, none of the screened surveys reported on the water quality of the supply schemes. Water supply coverage of the other countries in the region is as follows (WSSCC 2000; in brackets the percentage for rural areas): Afghanistan 13% (11%), Bangladesh 97% (97%), Bhutan 62% (60%), China 75% (66%), India 88% (86%), Myanmar 68% (66%), and Pakistan 88% (84%).

In Nepal, the water supplied by the different water suppliers, including the Government's Water Supply and Sewerage Corporation, is mostly unsafe (IIDS 2001). The main pollutants are of microbiological origin and other organic pollutants. This is certainly true in the case of Kathmandu, but also for most other major settlements. Even groundwater supply in the Kathmandu Valley is highly contaminated with nitrates, ammonia, and faecal coliforms (UNEP 2001).

1.1.1.2 Processes

The main driving forces for water availability issues globally are population growth and increased water demand for intensive agriculture, industries, and sanitation. Availability has also been influenced by increasing contamination of water (OECD 2001). The domestic use of water is crucial, but represents only a small part of the total global water demand. As mentioned earlier, water use has increased six-fold, but world population has only tripled (Cosgrove and Rijsberman 2000). This indicates the increased per capita demand for water, which is attributed to the increased demand of water for industries, which is about twice as much as for domestic use (Cosgrove and Rijsberman 2000). Industrial use of water is mostly for cooling in the production of electricity; and for intensive agriculture where the irrigation of higher-yielding varieties results in increased water demand. Shiklamonov (2000) determined a global increase of 492% for industrial use from 1940 to 1995. In the same period, municipal and agricultural use increased by 484 and 179%, respectively. This adds up to a total increase of 248%.

In the context of the HKH, Chalise and Sial (2000) discuss a number of factors, including increasing demand for water due to population growth, modern lifestyles which demand greater amounts of water, and increasing livestock numbers for dairy farming and meat production. They also attribute the crisis to the collapse of local institutions for water management, which are not able to meet the demand of present day needs. This collapse is a direct effect of the loss of local knowledge about local water resources' management, as reported in Agarwal and Narain (1997), and the impact of external interventions.

Water quality and pollution of watercourses are an increasing concern in the region due to the uncontrolled disposal of human and animal waste. Nepal's situation of sanitation (use of sanitary means of excreta disposal by means of flush toilets or pit latrines; NPC 2000) is very poor with sanitation coverage of just 23% for rural areas, 73% for urban areas and a national average of 29% (NPC 2000). The progress of sanitation in the last decade is particularly frightening with a progress of just 9% (NPC 2000). Afghanistan has the lowest sanitation coverage with only 12% of the population having access to adequate sanitation. Worldwide, only 60% of the population had access to adequate sanitation in 2000. Other countries in the region have the following sanitation coverage as shown in Table 1.5.

In selected areas, over use and indiscriminate use of pesticides and mineral fertilisers adds to the problem. According to Kraemer et al. (2001), Asia's surface waters have faced the most rapid growth in eutrophication due to fertilisers. The same authors argue that the high sediment loads, which are a major source of pollution, are another reason for concern in the region. In recent years, arsenic pollution has become a significant problem in Bangladesh and West Bengal in India (Smedley et al. 2002). The primary cause for this is geological, but the change from using surface waters for domestic purposes to the use of shallow groundwater, as encouraged by the government and aid organisations, has had a negative impact. The natural factors attributed to uncertain water availability, which Chalise and Sial (2000) discuss, are mainly associated with the impact of climate change.

Table 1.5: **Sanitation coverage**

Bangladesh	53%	(44% rural areas)
Bhutan	69%	(70% rural areas)
China	38%	(24% rural areas)
India	31%	(14% rural areas)
Myanmar	46%	(39% rural areas)
Pakistan	61%	(42% rural areas)

(WSSCC 2000)

1.1.1.3 Impact and Future

The deterioration of water quality has a major impact on the health of consumers. At a global scale, 3.4 million people died in 1998 from water-related diseases, and 2.2 million from diarrhoeal diseases alone (WSSCC 1999). In Nepal, 16.2% of the children in a survey had diarrhoea during the two weeks prior to this survey conducted during the peak season for diarrhoea in April to May (NPC 2000).

Population growth is still continuing at a fast rate and no major change is foreseen. According to UNFPA (2001), population growth rates in the region range from a maximum of 3.7 in Afghanistan to a minimum of 0.7% in China (Figure 1.1) The population in 2050 in the South Central Asian region (countries below, excluding China) is estimated to be about 2.5 billion, with India being the most populous country in the world.

As a large part of the population in the region does not yet have access to adequate sanitation and safe water, a major increase in water demand for domestic purposes can be expected.

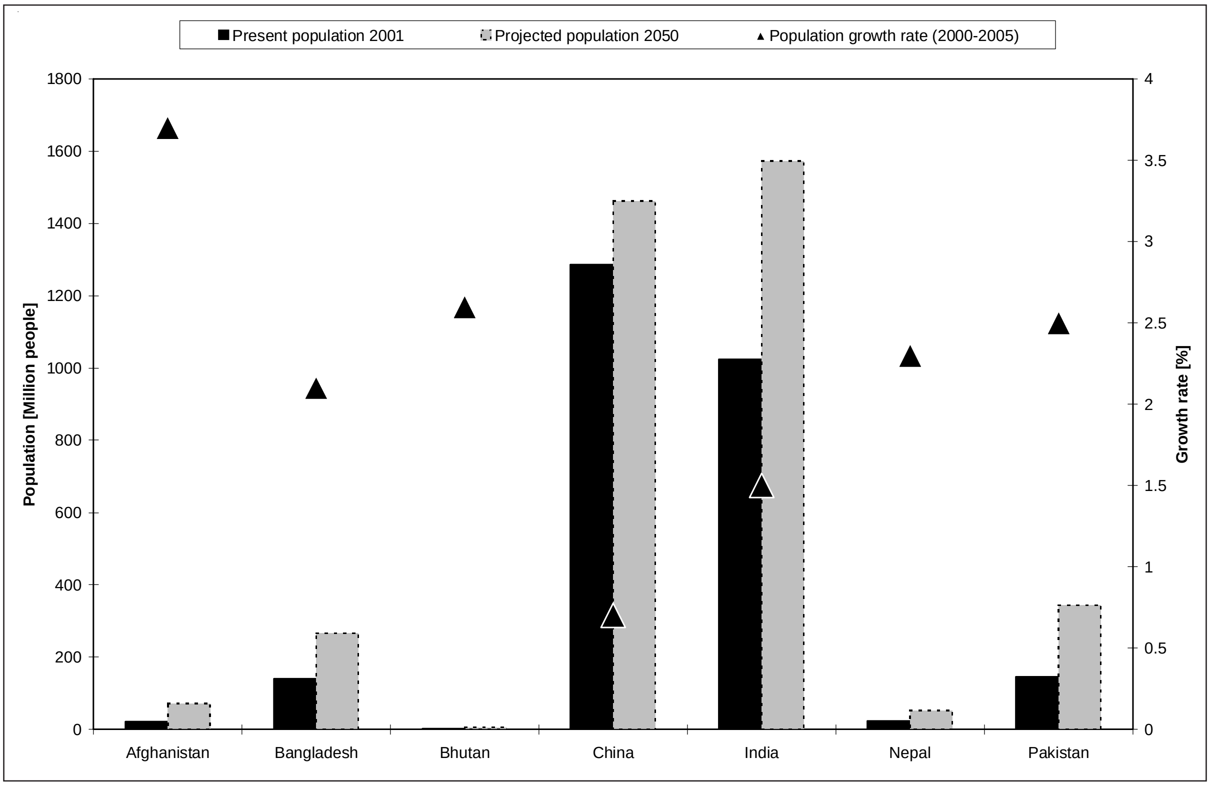

Figure 1.1: **Population development in the countries of the HKH**

(note: entire countries are included; data source: UNFPA 2001)

Gleick (2000) reviewed a number of projections published between 1967 and 1998. For the year 2025 the results ranged from 3625 km^3/y to 5500 km^3/y water withdrawal. He concluded that earlier studies mostly overestimated water withdrawals due to the selection of historical growth rates for projection. Increasingly, projection methods are becoming more sophisticated. He cautions that these projections should be used as possibilities, rather than as predictions, to make planners aware of the risks and benefits of certain policy implications.

Two of the later studies are the projections by Shiklamonov (2000) and Alcamo et al. (2000). On the basis of the 1995 data, Shiklamonov (2000) estimates the following increases by 2025:

- agricultural use +27% in withdrawal; +29% in consumption
- municipal use +77% in withdrawal; +49% in consumption
- industrial use +56% in withdrawal; +105% in consumption
- total water use +38% in withdrawal; +33% in consumption

Alcamo et al. (2000) noted that between 43 and 77% of the total population in South Asia[2] will face severe water stress by 2025 depending on different scenarios. In the case of China[4], 37 to 41%, and for Southeast Asia[3] between 33 and 46% will face water stress. Seckler et al. (1998) classified 116 countries into 5 groups according to the projected increase in total withdrawals for 1990 to 2025 and the percentage of the total withdrawals from the available water resources in 2025. This results in the following groups.

Group 1: water scarce countries; 8% of the population of the studied countries; these countries are mainly located in north Africa and west Asia; water scarcity major constraint on food production, human health, and environmental quality.
Group 2: 7% of the population of the countries studied; must develop more than twice the amount of water to meet reasonable future requirements.
Group 3: 16% of the population of the studied countries; must develop between 25% to 100% more of the current water resources for future needs.
Group 4: 16% of the population of the studied countries; must develop between 0 to 25% more of the current water resources for future needs.
Group 5: 12% of the population of the studied countries; no additional withdrawals required.

In the HKH region, Afghanistan and Pakistan belong to Group 1. Nepal and Myanmar were classified under Group 3 and Bangladesh under Group 4. India and China were not considered in this study due to their vast territory over a number of climatic zones and therefore their territory falls within multiple classes. Bhutan was likewise not included. These results suggest that major investments are required in the region to ensure adequate water supply for domestic and industrial demand and food production.

In addition, climate change may also have a major impact on water availability. Climate change could increase the rate of snowmelt and reduce the amount of snowfall due to shorter winters (IPCC 1998). This may have a major impact on downstream areas where rivers depend on the dry season flow from the upland areas, for example, 70% of the dry season flow in the Ganges is supplied from the catchments in Nepal (IPCC 1998). First examples of increases in anomalies, in this case droughts, are reported from the Western Himalayas and the Hindu Kush (Sial 2003). Any changes in the monsoon length or arrival may also be critical to soil moisture deficits in the region.

1.1.2 Flooding

Floods are not only the most frequently occurring natural disaster, they are also the most destructive natural disasters in terms of number of deaths, and are only overtaken by droughts in terms of affected people (Rodda 2001). In addition to drowning and direct injury, famine, and disease are often associated with flood disasters. It is important to note that floods only result in disasters if the natural flood hazard meets unsafe conditions such as low preparedness, a situation produced by a number of root causes and dynamic pressures (Blaikie et al. 1994).

1.1.2.1 Status

The HKH region has a long history of floods. Annually, tens of thousands of people are affected by medium to large flood events in the region. Floods are most destructive in terms of loss of life and financial loss in the plains adjacent to the mountain ranges. This is due not only to the force and magnitude of the flood, but also to the number of people and the values at risk.

In Bangladesh, globally the country worst affected by floods, flooding is an annual feature with 20% of the total area of the country being flooded every year (Hofer 1998a). Floods are very important for the Bangladeshi farmers and are considered to be a necessity for survival, as the agricultural calendar is highly adapted to the floods. Occasionally, catastrophic floods hit the country with return periods of 33 to 50 years (Miah 1988 cited in Hofer 1998a). Recent major flood events include the 1955, 1974, 1984, 1987, 1988, 1991, and 1993 floods (Hofer and Messerli 1997; Hofer 1998a).

According to Agarwal and Narain (1991), India is the most flood-affected country in the world after Bangladesh. The most flood-prone areas in India are the Ganges basin in Uttar Pradesh, Bihar, and West Bengal; and the Brahmaputra basin in Assam, followed by basins in Orissa (Agarwal and Narain 1991). Between 1953 and 1987 about 50,000 people died in floods in India and millions were displaced (CWC 1989; cited in Agarwal and Narain 1991).

Floods do occur in the inner Himalayan valleys. Agarwal and Narain (1991) and Subba (2001) present studies from the Gharwal-Kumaon Himalaya and the Eastern Himalaya in India where a number of destructive flood events occurred in the recent past. Recent disasters in Nepal include the 1981 flood in Lele, the 1993 flood of the Bagmati and Narayani, the 1998 Andhi Khola flood (Chalise and Khanal 2002), and the 2002 flood in the Kathmandu Valley. In the Lele flood, nearly all the agricultural land was damaged. Twenty-seven people died, more than 48 houses and seven water turbines were swept away. The 1993 flood disaster affected nearly 28,000 families in the middle mountains and 42,000 families in the lowlands. About 1000 people were killed during this event. The 1996 Larcha debris flow washed away roads, bridges, transmission lines, and 18 houses. Floods at a smaller scale with less disastrous, but still considerable, impact occur annually in a number of locations (Figure 1.2).

NEWS

Floods threaten villagers

Floods in India kill 94, make 2.5 million homeless

250 houses washed away

Floods swamp 30,000 in

Heavy rain plays havoc in cattle and crops

Floods destroy crops

Flood casualties rising

Floods affect Jyamire

Assam floods kill 35

Floods sweep awa over nine houses

Over 100 killed in India flood

Flood victims to be resettled

Flooded Bakraha amages embankment

NEWS

Thousands hit by floods

Girl swept away

Floods toll 123 in India

Floods block roads

Figure 1.2: **Headlines on flood issues from the region**

(source: all clips from The Kathmandu Post, Kantipur Publications, Nepal, on different dates)

Glacial lake outburst floods (GLOF) have occurred over the entire glaciated history of the Himalayas. The most recent events in Nepal documented in Mool et al. (2001a) are the 1985 Dudh Khosi GLOF, the 1991 Tamakhosi GLOF, and the 1998 Dudh Khosi GLOF. In 1985, an ice avalanche from Langmoche caused the Dig Tsho glacial lake to burst. The resulting flood wave destroyed the Namche hydropower plant, a number of bridges, and caused loss of life. Bhutan experienced the most recent GLOF in 1994, when the Lugge Tsho partially burst. The flood wave caused loss of life and property in the downstream areas (Mool et al. 2001b).

1.1.2.2 Processes

The reasons for flooding, both in the plains as well as in the foothills has been subject to extensive scientific and emotional discussions in the past. The basic causes of the flood hazard, however, are of a climatic and geomorphologic nature. The causes of major disasters in the Nepal Himalayas were extreme weather events with exceptionally high rainfall intensities at a small spatial scale, which one might call cloudbursts (Chalise and Khanal 2002). Incessant rainfall over a longer time period often triggers landslides, causing debris flows and the generation of landslide-dammed lakes, potentially posing a risk in case of dam failure (ICIMOD 2000). GLOFs have caused significant destruction over their immediate downstream areas across the HKH (Ives 1986; Mool et al. 2001a/2001b).

To understand the process of flood generation under different circumstances and conditions, runoff generation studies were, and are, being conducted extensively throughout the world (Pearce et al. 1986; Leibundgut et al. 2001). While the processes are widely accepted (Figure 1.3), the importance of the different mechanisms of flood generation in particular is still subject to scientific discussion.

Various studies have been conducted in New Zealand, with a particular focus on the Maimai catchment on South Island. Mosley (1982) described the importance of subsurface flow, previously believed to be of less importance in the generation of floods. He mainly held rapid throughflow through macropores responsible for this, as was later emphasised by Germann (1990). Pearce et al. (1986) favoured the theory of displacement of old water, or piston flow effect, to explain the rapid response through subsurface flow. Merz and Mosley (1998) show the impact of landsliding on the hydrological processes and runoff generation in the Tutira catchment of North Island, New Zealand. The impact is mainly due to an increase in potentially saturated areas, as well as loss of soil from impermeable areas, and therefore loss in soil water storage capacity.

In Europe, several studies have been undertaken with a focus on runoff generation. In the Brugga catchment in southern Germany, Uhlenbrook (1999) identified three main runoff components: direct runoff from saturated and impermeable areas, shallow groundwater flow with piston flow and groundwater ridging, and finally deep groundwater flow with matrix flow (see also Figure 1.3). First results from the Leissigen catchment near Bern in Switzerland show that, in the very wet areas, saturation overland flow seems to be important and, in the other areas, mainly matrix flow seems significant (Laemmli 2000). On the basis of rainfall simulation experiments, Scherrer (1997) showed the variability of runoff generating processes at different sites in Switzerland. However, Hortonian (or infiltration excess) overland flow at rainfall intensities of 50 mm/h to 100 mm/h occurred most often. Saturation overland flow only occurred in follow-up experiments. Lateral soil matrix flow and macropore flow were less important at the selected sites.

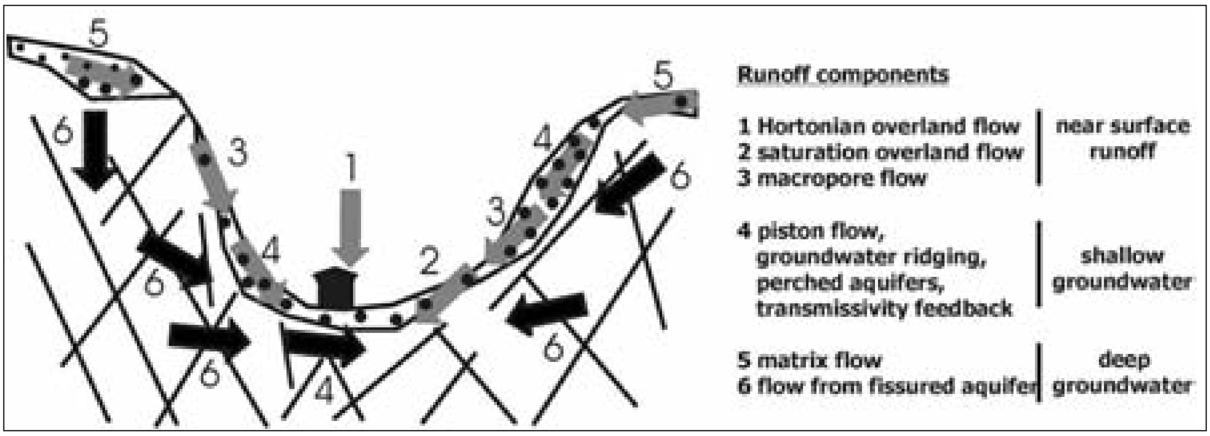

Figure 1.3: **Runoff generation (after Uhlenbrook and Leibundgut 2002)**

The number of investigations of runoff generation in the context of the HKH region, however, is limited. Collins et al. (1998a) report that, in the terraced land of the Middle Hills in Nepal, both infiltration excess and saturation overland flow contribute to runoff generation.

It is important to note that, although there is much information on runoff generation from Europe, America, and the Pacific, this information is only applicable to Asian conditions to a limited extent. In this context, it is mainly the impact of irrigation with prolonged saturation of large areas that should be mentioned. The time of extended saturation coincides with the time of highest rainfall input, the monsoon season, as well as the time with the most intense rainstorms. Saturation overland flow therefore is assumed to play a major role in the runoff generation process as also indicated by Collins et al. (1998b). The model shown in Figure 1.3 is therefore only applicable to the conditions prevailing in the Asian upland region to a limited extent. However, it shows schematically the different processes at different locations in a catchment.

In general, there is a popular feeling that human interventions in the upland areas of the HKH have aggravated floods in the plains; and this feeling can also be attributed to the Agricultural Development Bank (2003). Hofer (1998a) lists a number of causes cited in the literature for floods in Bangladesh. Most of the causes cited are of climatological and geomorphologic origin, both outside and inside Bangladesh, and are therefore not directly related to human activities. Deforestation in the Himalayas and land management practices of mountain farmers, however, top the list in terms of numbers of citations. However, this simplistic theory is heavily criticised by different authors referred to in Hofer (1998a). He proposes that:

- the rainfall in the Meghalaya hills and in Bangladesh itself is most relevant for flooding in Bangladesh;
- floods in Assam may be connected but, on the Indian Ganges plains, there is no obvious connection; and
- high baseflow may be imported, but flood peaks are home-made.

According to these theses, Himalayan farmers are not to be blamed for the floods in Bangladesh. In addition to this, Mirza and Dixit (1997) did not establish any conclusive trends of peak flood discharges at various stations on the Ganges, Brahmaputra, and Meghna rivers over the past decades. They concluded that there is no impact of human action on the mountains of their basins, nor is there any evidence of the impact of global climate change in terms of peak flows.

It is not only in the HKH where the role of forest cover with regard to flooding has been subject to discussion. There is little scientific evidence for the largest, most damaging flood events being caused by deforestation at the global scale (Calder 2000).

The most important factor in this discussion seems to be scale. While documentation of the effect of human intervention at the micro-scale is possible, the change in flood peaks and sediment load at a large scale is dominated by natural processes (Ives and Messerli 1989). Human intervention in the plains themselves becomes important, while the impact of the changes in the mountains becomes invisible. On the basis of a thorough literature review, FAO (2002) concluded that land-use impacts on hydrological parameters and sediment transport are inversely related to the spatial scale at which the impacts can be observed (Table 1.6). In contrast, the impact of land-use changes on water quality parameters may be relevant at the higher meso- and macro-scale.

Table 1.6: **Impact of land-use changes at different scales on various water-related parameters (FAO 2002)**

Impact	**Basin size [km^2]**						
	0.1	**1**	**10**	**100**	**1000**	**10,000**	**100,000**
Average flow	x	x	x	x	-	-	-
Peak flow	x	x	x	x	-	-	-
Base flow	x	x	x	x	-	-	-
Groundwater recharge	x	x	x	x	-	-	-
Sediment load	x	x	x	x	-	-	-
Nutrients	x	x	x	x	x	-	-
Organic matter	x	x	x	x	-	-	-
Pathogens	x	x	x	-	-	-	-
Salinity	x	x	x	x	x	x	x
Pesticides	x	x	x	x	x	x	x
Heavy metals	x	x	x	x	x	x	x
Thermal regime	x	x	-	-	-	-	-

Lauterburg (1993) notes that afforestation and soil conservation may be beneficial at the micro-scale, but that there is no impact at the upper meso- to macro-scale. A study of the impact of upstream catastrophic floods in Nepal has shown no more effect than the integration of this floodwater into the baseflow at the downstream location (Khanal et al. 1998). Hofer (1998a) gives several examples where upstream districts in India experience heavy flood events, without impacts in the downstream areas in Bangladesh.

In terms of people's vulnerability to flood disasters, it is important to remember that increased in-migration, intensified use, and urbanisation of flood zones and flood-prone areas have increased the number of people and values at risk (Blaikie et al. 1994). This was also shown in Switzerland where the damage potential increased exponentially after the Second World War (Weingartner 1999) due to land-use intensification and encroachment.

1.1.2.3 Impact and Future

The possible impact of climate change on flood behaviour in the region is uncertain and may have many facets (IPCC 1998). To date, no conclusive trends can be observed for precipitation in the Ganga basin (Mirza et al. 1998). Whetton et al. (1994; cited in IPCC 1998) predict increased frequency of heavy rainfall events. Wet season rainfall for the region is estimated to change by 0 to +10% by 2010. By 2070 an increase of +5 to +50% is estimated (Whetton 1994; cited in IPCC 1998). A change in monsoon duration, such as a prolonged wet season, may have a further impact on floods, as predicted by certain studies. Increasing temperature may also affect the occurrence of GLOFs (IPCC 1998). These authors report decreasing snowfall, deglaciation, and retreating glaciers in various parts of the HKH region; however, according to Mool et al. (2001a), it is premature to link these phenomena with the impact of climate change.

Population growth, further in-migration, urbanisation of flood areas, poverty, and inadequate planning may further increase the number of people and valuables at risk (Blaikie et al. 1994).

1.1.3 Water-induced land degradation and sedimentation

Soil erosion in the foothills of the HKH is considered a hot topic in land degradation research in the region (Scherr and Yadav 1996). This addresses mainly the issue of topsoil loss through surface erosion with a subsequent decline in the fertility of the land, which is a concern for agriculture and food security, and is believed to be one of the major ecological crises facing the HKH region today (Chalise et al. 1993). From the perspective of soil nutrient losses, nutrient leaching is however a more important mechanism (Gardner et al. 2000; Acharya et al. 2003). Mass wasting accounts for large parts of the sediment load in the rivers, but is only marginally responsible for soil fertility decline. In general, land degradation in this study is understood as the quantitative and qualitative loss of land resources (after Thapa and Weber 1995).

1.1.3.1 Status

Topsoil loss from water erosion is responsible for the degradation of 15.7% of the total land in South and Southeast Asia (Scherr 1999). Carson (1985) termed soil erosion the most serious resource problem in Nepal. Degradation of soils through erosion and fertility decline is, according to UNEP (2001), one of the key issues affecting the state of the environment of Nepal.

In terms of soil loss through surface erosion, some studies have been conducted in the region and rates of topsoil losses have been published in numerous publications. Some of these results are compiled in Appendix A1.1. In general, these results show degraded lands under different land management and use are most susceptible to soil erosion. Sal forests in different stages of degradation ranged from 3 t/ha to 10 t/ha soil loss per year, with this increasing according to the stage of degradation (Gerrard 2002). In terms of land use, forestland is least susceptible to soil erosion, followed by grassland, irrigated agricultural land, and finally rainfed agricultural land. In addition to land use, cover, and management, physical properties such as slope play a major role.

In the Likhu Khola catchment, sediment supply from mass wasting of approximately 7 t/ha*y was estimated for the 12.4 km^2 catchment in 1992 (Gardner and Jenkins 1995). Gerrard (2002) further detailed this information from the Likhu Khola catchment with 0.48 t/ha*y average soil loss from landsliding for irrigated terraces, 3.65 t/ha*y for rainfed terraces, 1.86 t/ha*y for grassland, 0.80 t/ha*y for forested land, and 23.95 t/ha*y for scrub and abandoned land. This study reports a total denudation rate due to landsliding of 5.55 t/ha*y.

The Himalayan rivers rank amongst the top rivers in terms of suspended sediment load (Meybeck and Ragu 1995; see also Figure 1.4). In terms of suspended sediment delivery, the rivers originating from the Central Himalayas such as the Karnali, Sethi Nadi, Tamur, Sun Khosi, Arun, and Marsyangdi show the highest figures, with values of more than 65 t/ha*y (Lauterburg 1993). In years with high intensity cloudburst in tributaries, such as from the Kulekhani catchment in Nepal during the 1993 event, sediment loads of 500 t/ha*y were reported (Galay 1995; cited in Schreier and Shah 1996). Over a time period of 13 years the sediment load was estimated to be approximately 53 t/ha*y. The western Himalayan rivers such as the Jhelum, Chenab, and Indus have low sediment delivery rates of below 15 t/ha*y. However, these rivers may have very high loads locally, as for example the rivers originating from the Karakorum draining into the upper Indus River. The Hunza and Gilgit rivers yield sediment above the global average, as shown in Figure 1.4. According to Lauterburg (1993), the rivers in the eastern Himalayas show likewise very low sediment loads. Merz et al. (2003a) reported a suspended sediment yield of 0.9 t/ha*y to 1.8 t/ha*y for the Wang Basin in Bhutan, the most important river for hydropower generation in the kingdom.

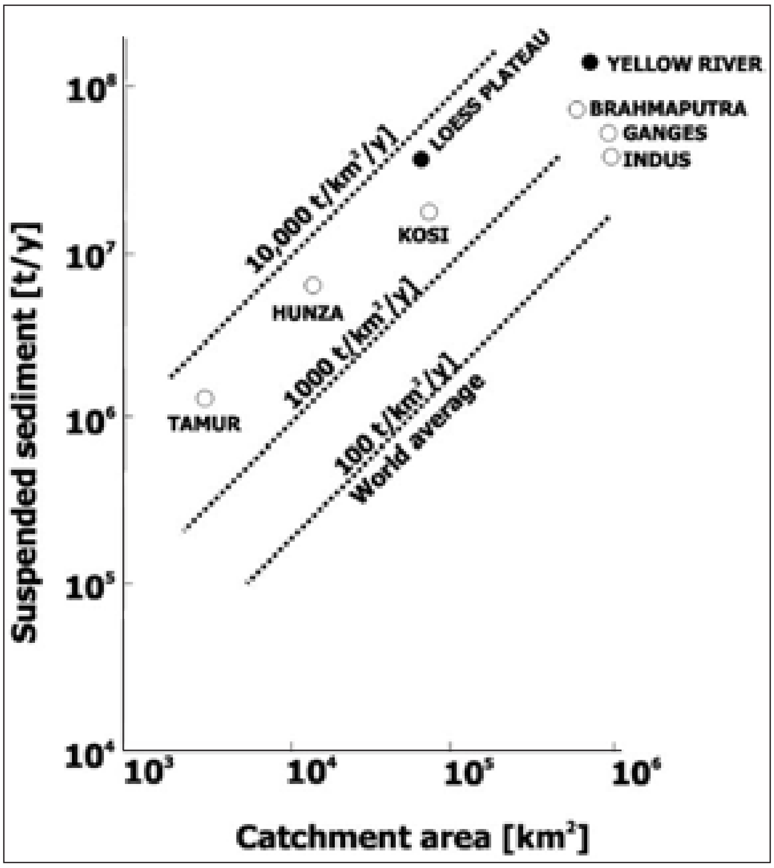

Figure 1.4: **The sediment load of selected South Asian rivers compared to the global average**
(Ferguson 1984 in Alford 1992)

1.1.3.2 Processes

Climatological extremes, such as the cloudburst of July 19 and 20, 1993 in the catchment draining into the Kulekhani reservoir, have a major impact, not only downstream in the reservoir (Sthapit et al. 1995) but also in the catchment itself, with numerous landslides and debris flows (Dhital et al. 1993). In general, the monsoon season rains have a major impact on sediment loads in the rivers. In the Wang Basin (3550 km^2) of Bhutan, the sediment load varies, on average, from approximately 15 t/day during the months of January to March in the dry season, up to 6000 t/day during August in the rainy season (Merz et al. 2003a). Maximum loads measured were 11,000 t/day.

Surface erosion is mainly influenced by the erosivity of the rainfall, the erodibility of the soils, topography, and land management practices (Carson 1985). The erosivity of rainfall measured with the erosivity index after Wischmeier peaks in the eastern Himalayas with EI30s of more than 1000 J*mm*m^{-2}*h^{-1} (Lauterburg 1993). The central Himalayas have EI30s of 500 J*mm*m^{-2}*h^{-1} to 800 J*mm*m^{-2}*h^{-1}. Erosivity decreases towards the west of the mountain range. However, from these figures it can be concluded that the Himalayas experience very intense erosivity as well as a high probability of catastrophic, high-intensity rains (Lauterburg 1993). Erodibility very much depends on soil characteristics. Carson (1985) identifies the red soils as being notorious for sheet and gully erosion. In terms of topography, the Himalayas contain some of the steepest relief in the world, and therefore are subject to increased erosion risk. In terms of crop cover and land management, the annual vegetation calendar is very important. Carson (1985) shows the vegetation cover in relation to the erosivity of rainfall (Figure 1.5).

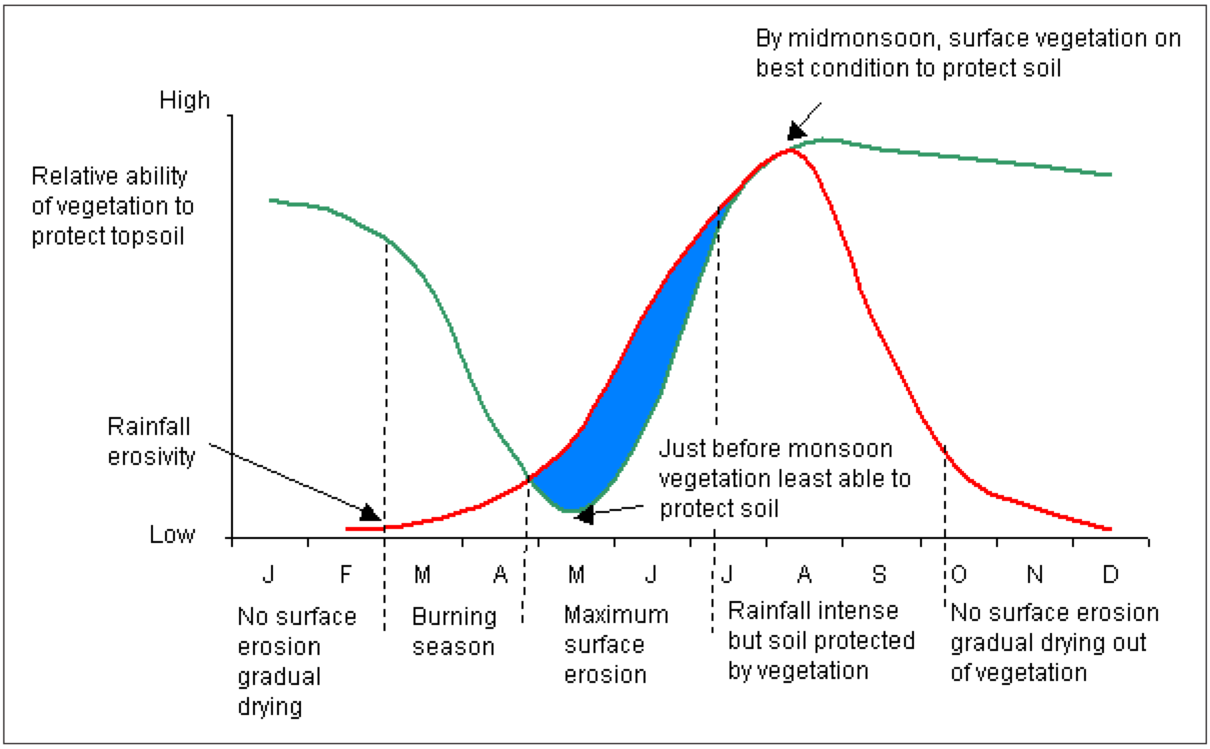

Figure 1.5: **Relationship between erosivity of rain and condition of surface vegetation throughout the year in the middle mountains of Nepal (Carson 1985)**

On the basis of this figure it can be concluded that the highest erosion risk occurs at times of low vegetation cover on agricultural land. This is supported by the findings of Carver and Schreier (1995), who have shown that the highest sediment concentrations are measured in the Jhikhu Khola during the pre-monsoon. Nakarmi et al. (2000) have further shown that in approximately 10 storms, more than 80% of the annual soil loss occurs from rainfed agricultural land. On grassland, 15 to 20 storms lead to the same percentage of soil loss.

Population is considered as the main push factor for degradation (Thapa and Weber 1995). An ever-increasing population has led to a reduction in landholding size which, for a family of five to six people, is currently below one hectare in Bhutan, the hill states of India, the mountain areas of Pakistan, and (except the Terai) large parts of Nepal (Thulachan 2001). Population density in 1991 was above 50 people per km^2 in most mountain parts of the HKH countries, peaking in Nepal with 126 people/km^2 (Sharma 1994). Since then, the population in all countries has increased (except in China, where the population is stagnant) aggravating the situation. In the Upper Pokhara Valley, agricultural expansion to steep and marginal lands used to be one of the strategies to supplement household crop production between 1957 and 1978 (Thapa and Weber 1995). Since then, this process has slowed down considerably with the remaining forest and shrub areas in steep and inaccessible areas. The same processes were documented for other parts of the HKH and were, amongst others, the reason for the implementation of the PARDYP project (ICIMOD 1996a).

Livestock are often blamed for land degradation, mainly due to overgrazing of forest and grasslands. In general, a decline in the number of cattle and sheep and an increase of buffaloes and goats have been observed throughout the HKH region in the last 20 years (Thulachan 2000). The change from cattle to buffaloes has had an especially positive impact on overgrazing. This is due to the fact that buffaloes are usually stall-fed and not grazed openly in the forests.

Deforestation and forest degradation were among the main issues in the 1970s and 1980s. Chalise et al. (1993) showed that 0.7% of the total forest area was deforested annually. Of the 613,000 ha deforested areas, only about half was replanted, and of this only half survived. The latest study on forest resources for the region shows that Nepal still loses approximately 78,000 ha of forest per year on the basis of 1990 and 2000 data, which accounts for about 1.8% of the total forest area of Nepal (FAO 2001a). This is the largest forest loss in the region in terms of national forest loss. Myanmar loses about 1.4% of its forest area annually (approximately 512,000 ha); the biggest forest losses in terms of area in the region. The reasons for this degradation of forest resources are stated as poverty and population pressure (FAO 2001a). Bhutan's forest area has remained roughly the same at 64.2% of the country's area. In Bangladesh, China, and India, forest cover has increased overall, due to plantations. To what extent this increase has occurred in the mountain areas of those countries is not described.

1.1.3.3 Impact and Future

In terms of soil fertility decline due to surface erosion, Nakarmi and Shah (2002), on the basis of figures from Brown et al. (1999), report that approximately 10% of the nitrogen losses on a rainfed agricultural terrace can be accounted for by surface erosion. One per cent of phosphate losses and approximately twenty per cent of calcium losses are lost through surface erosion. The areas most at risk in terms of fertility decline are the residual rainfed terraces, often owned by resource-poor farmers who do not have the capacity to improve their land (Gardner and Jenkins 1995). On the basis of soil formation processes, tolerable soil loss rates in the middle mountains of Nepal are estimated at 10 t/ha*y to 11 t/ha*y (Gardner and Jenkins 1995). This means that, with the exception of degraded lands and poorly managed agricultural land, there is no reason for concern at losing valuable soil resources. However, if terraces are poorly managed or land has reached a progressed stage of degradation this tolerable soil loss can be exceeded in the order of 20 times, and even up to 60 times (Laban 1978; see also Appendix A1.1).

In terms of impact on downstream infrastructure, Galay et al. (2001) show the impact of high sediment loads. These elevated loads often lead to the sedimentation of reservoirs as well as the aggradation of riverbeds. The 1993 storm in the Kulekhani catchment is only one example.

Future soil erosion rates and the subsequent impact on human life and infrastructure depend very much on future population growth, environmental policies regarding forests and land, and the impact of these policies on the respective resources. It is hoped that the current trend in policy towards increased community participation will support the increase in forest quality and to a certain extent the forest areas as well (FAO 2001a). Just how much precipitation alters as a result of climate change is uncertain (IPCC 1998).

1.1.4 Summary

The main issues related to water in the HKH region include water availability, floods, water quality, and land degradation caused by water. The current situation is rather bleak, with many areas of the HKH region already facing water shortages, flooding, and severe land degradation. The driving forces for all these key issues are population pressure, poverty, development status, inherent climatic conditions, bad governance of water resources, and, in future presumably, climate change and globalisation. The list of driving forces is not exhaustive, but should give an idea of the existing dynamics. The direct impact of these driving forces at the catchment scale and on larger basins is not yet fully understood. While certain forces may lead to decreasing water availability, which cause famine, thirst, and desertification, other forces may lead to increasing water masses and in extreme cases to more floods and land degradation. These processes may also increase the variability and frequency of events. Figure 1.6 shows this cause-effect chain in a very simplified form. It is important to remember the interdependency that is characteristic of water resources and the water use system (Moench 1999).

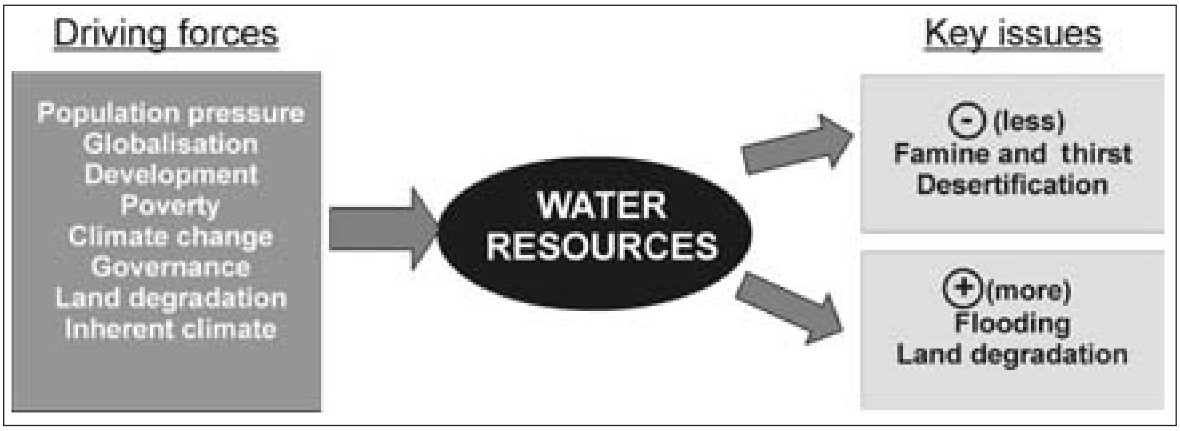

Figure 1.6: **Water resources in the future**

1.2 AIMS AND OBJECTIVES OF THIS STUDY

This study aims to contribute towards an improved understanding of the cause-effect chains in the HKH region that lead to flooding, water scarcity, and land degradation The discussion will mainly focus on the meso-scale with some deliberations at the regional level. The study tries to incorporate and synthesise information from different sources that influence water resource management. In this way it will contribute to the PARDYP project objective on water resources and to the overall goal of the project as documented by ICIMOD (1999).

The objectives of the study can be described as follow:

- to synthesise water-related information in order to reach an understanding of selected key issues related to water;
- to provide a methodology framework for the synthesis of a large amount of data and information to be considered for other project catchments, for comparison of catchments in the region, and potential up-scaling[5];
- to provide hydro-meteorological data and a number of basic analyses for further use in the project, such as diurnal temperature variation for agronomic trials, and rainfall frequency for water harvesting methods;
- to contribute towards the understanding of flood generation processes, the role of a catchment in flood generation downstream of the HKH middle mountains, and possible future threats;
- to contribute towards the understanding of water availability issues in a meso-scale catchment of the HKH;
- to contribute towards the understanding of land degradation through water and the relevant processes associated with this degradation; and
- to contribute towards an understanding of the dynamics of the above issues and their interaction.

Firstly, the study investigates the current status of the different key issues in each catchment and the processes leading to them (Figure 1.7). This is based on the assumption that each catchment has an inherent susceptibility to water scarcity, land degradation, and flood generation. In the second section, possible scenarios are explained and their impact on the catchments as well as on the processes discussed above are examined.

In this study, the term ‘susceptibility’ is understood according to the German word ’disposition’ as discussed in Kienholz (1990: cited in Weingartner 1999). It is the base condition of a catchment disposing it towards the generation of a certain process or reaction. In other words, it is the vulnerability of a catchment to floods, degradation, or water scarcity. This susceptibility is not only a function of the biophysical environment and land use, but is also a function of the people’s perceptions, needs, and ability to cope with the issue.

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[5] Up-scaling in this context is understood as the use of information and methodologies generated by the PARDYP project in other areas of the region, so that the project’s efforts reach a wider audience.

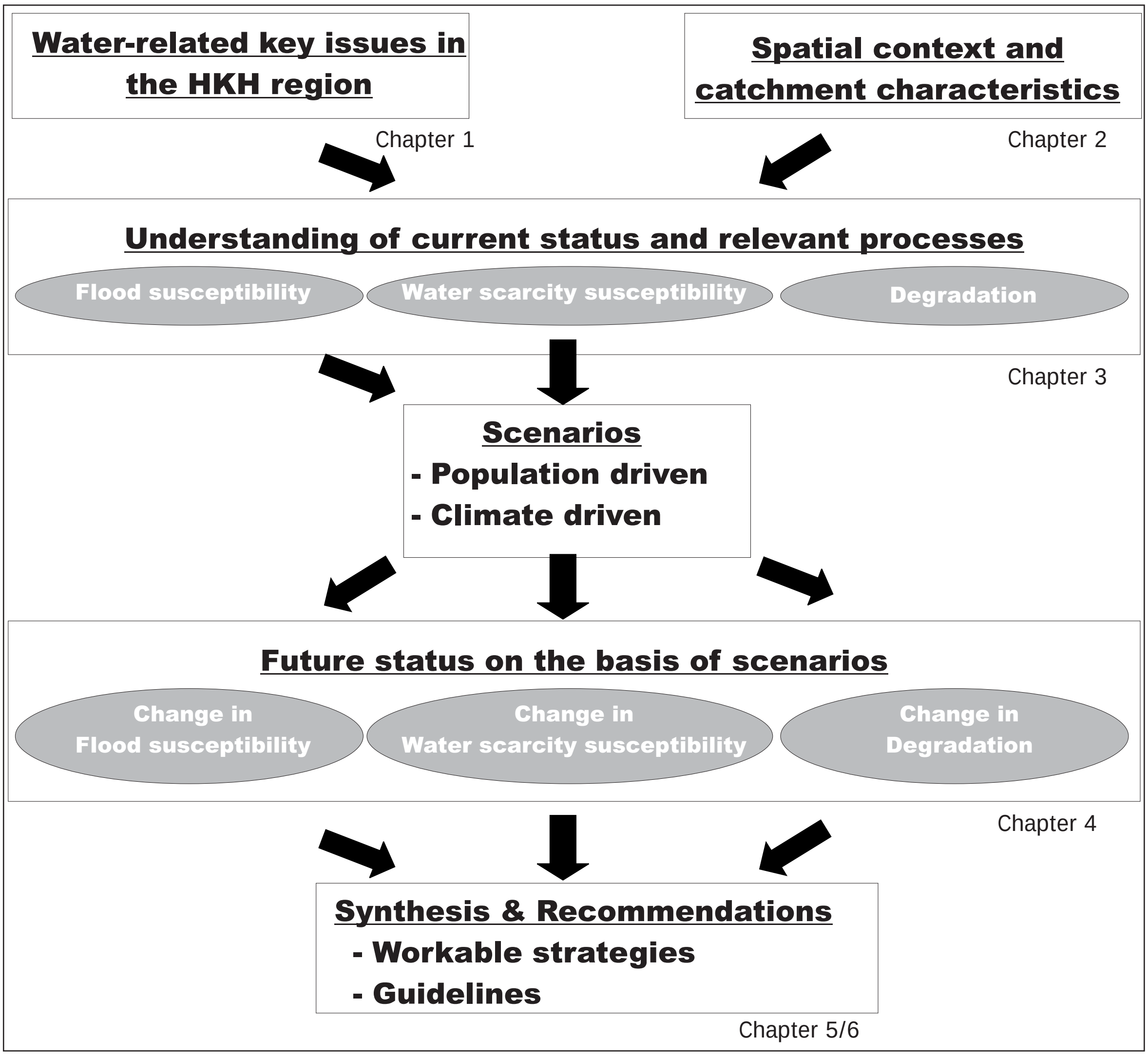

Figure 1.7: **Outline of the study**

Each susceptibility can be expressed as an index for the purpose of an objective catchment comparison and preliminary assessment of the conditions. It further helps in identifying potential areas for reduction in susceptibility. The indexes can also be used in other catchments of the area for a preliminary assessment of the situation. In this context, the Sustainable Livelihoods Approach (IDS 2000) provides a holistic framework to incorporate a wide range of views. This was then used to develop a proposed International Water Poverty Index (WPI) (Sullivan 2002; Lawrence et al. 2002; CEH 2002). The framework of the WPI has been adapted for this study to assess water scarcity. The two indexes related to flood generation and land degradation proposed in Chapter 5 are also adapted from this index to the specific requirements of these susceptibilities. For a more detailed discussion of the indexes and their indicators, please refer to Chapter 5.

The main research questions and hypothesis, which form the basis of this study, are as follow.

- Each catchment has an inherent flood, degradation, and water scarcity susceptibility on the basis of biophysical, socio-political, and economic variables.
  - What is the inherent flood, degradation, and water availability susceptibility of each catchment?
  - What biophysical and socioeconomic factors influence the different susceptibilities?

- Changes in these variables through superior driving forces have an impact on the different susceptibilities of the catchments.

  - What changes in driving forces could occur in the context of the middle mountains of the HKH?
  - What impact could these changes have on the different susceptibilities?

- The state of water resources in the catchments in terms of flood generation, land degradation, and water availability can be expressed as an index comparable to other catchments in the region.
  - What are the most appropriate indicators both in terms of sensitivity and in terms of measurability to form the backbone of these indexes?

1.3 OPERATIONAL BACKGROUND OF THE STUDY

This study was embedded in a long-term research-for-development project, the People and Resource Dynamics in Mountain Catchments of the Hindu Kush-Himalayas project (PARDYP). The project was initiated in order to provide an impetus for continuing a long-term monitoring programme that is essential for understanding the environmental dynamics and rates of change in catchments of the Hindu Kush-Himalayas.

The idea of PARDYP evolved over a period of seven years on the basis of three projects funded by the International Development Research Centre (IDRC), namely the Soil Fertility Project, the Mountain Resource Management (MRM) Project, and the Rehabilitation of Degraded Lands Project (more on the water and erosion component of all these projects can be found in the section on Water and Erosion Studies in PARDYP, below).

- **Soil Fertility Project**
  The Soil Fertility and Erosion in the Middle Mountains of Nepal Project (from 1989 to 1991) was an interdisciplinary project looking at resource use and related issues in a catchment. It was a collaborative research project between the University of British Columbia (UBC) and the Integrated Survey Section of the Topographical Survey Branch/Department of Survey, His Majesty's Government of Nepal.

- **Mountain Resource Management Project**
  The MRM project was implemented between 1992 and 1996 in the Jhikhu Khola catchment through the collaboration of UBC and ICIMOD. This project studied resource dynamics, concentrating on soil and water resources. Some achievements include the establishment of natural resources' baseline inventories, the setting up of an environmental monitoring programme, the documentation of land-use history over 50 years, and the rehabilitation of a degraded area.

- **Rehabilitation of Degraded Lands in Mountain Ecosystems Project**
  This project was conducted by research centres in four of ICIMOD's partner countries – Pakistan, Nepal, India, and China. It involved the rehabilitation of patches of degraded land and the screening of appropriate species and technologies for the revegetation of these barren slopes. Furthermore, the role of communities and individual landowners in the process of rehabilitation was better understood.

The evolving PARDYP project amalgamated the regional approach of the Rehabilitation project and the thematic thrust of the Soil Fertility and MRM projects.

1.3.1 The PARDYP Project

PARDYP is a regional research for development project in the field of integrated catchment and natural resource management. The first phase of the project began in October 1996 and ended in December 1999. A second phase lasted from January 2000 to December 2002. PARDYP is implemented in five catchments across the middle mountains of the HKH, with catchments in China, India, Nepal, and Pakistan. Overall coordination is provided by ICIMOD, while country activities are carried out by local country teams at the Kunming Institute of Botany (KIB) in China, the G.B. Pant Institute for Himalayan Environment and Development (GBPIHED) in India, ICIMOD in Nepal, and the Pakistan Forest Institute (PFI) in Pakistan, all along with their local partners. The project is supported by two international collaborators, UBC in the fields of resource management, soil fertility studies, and multimedia; and the Hydrology Group of the University of Bern/Switzerland (UoB) in the field of water and erosion studies. Funding for the project is received from the Swiss Agency for Development and Cooperation (SDC), IDRC, and in-kind contributions from all collaborating partners.

The project aims are the following:

- to build on the regional knowledge of resource dynamics in the middle mountains of the HKH;
- to help catchment residents, local groups, and line agencies to understand key issues in managing water, land, and forests;
- to improve natural resource management among farmers and communities through participatory action research, dissemination of knowledge and information, and demonstration and training;and
- to increase household and community benefits from farming and sustainable management of common resources through improved natural resource management.

In Phase 1 of the project, the overall goal was

> *"To further improve the understanding of the environmental and socioeconomic processes associated with the degradation and rehabilitation of mountain ecosystems, and to generate wider adoption and adaptation of proposed solutions by stakeholders in the HKH." (ICIMOD 1996a)*

The goal in Phase 2 then became:

> *"To contribute to balanced, sustainable, and equitable development of mountain communities and families in the HKH region." (ICIMOD 1999)*

The project includes the components 'community institutions', 'inequity and gender', 'economic potentials', 'water resources', 'common resources', 'on-farm resources', and 'implementation and management' (ICIMOD 1999). The project activities focus mainly on the generation and dissemination of information and knowledge and involve agronomic and horticultural initiatives, rehabilitation of degraded lands, forestry, socioeconomic and gender studies, participatory conservation activities, soil fertility considerations, and water and erosion studies.

In January 2003, a new phase was initiated in order to build on achievements to date and consolidate the databases as well as the findings. Furthermore, additional focus will be given to the regional nature of the project, fostering increased collaboration between the country teams and more regionally-based studies.

Further information on PARDYP is available on the web site: <http://www.pardyp.org/>. The project e-mail address is <pardyp@icimod.org.np>.

1.3.2 Water and erosion studies in PARDYP

The PARDYP project and its predecessors have carried out research related to water and erosion since 1989. Activities started in the Jhikhu Khola catchment in Nepal in 1989. Over time, the project has changed in terms of its objectives and main research interest. Below is a short description of the different phases and their focus on water and erosion studies.

1.3.2.1 Water and erosion studies in the soil fertility project

The aims of this project, as documented by Shah and Schreier (1991), were as follow (please note, only water and erosion related aims are listed):

- to map the basic topographic, geologic, geomorphologic, soils and land-use resources in a quantitative manner ;
- …
- to determine soil erosion and sedimentation rates from different land uses at three scales: catchment, sub-catchment, and plot studies;
- …

During the project, the first hydro-meteorological monitoring network was established in the Jhikhu Khola catchment. The use of Geographic Information Systems (GIS) was introduced to make the project a pioneer in this technology in Nepal. The project was able to initiate soil erosion research in the Jhikhu Khola and provide first ideas of possible erosion rates (Shah and Schreier 1991). However, the rates and sediment loadings identified were questionable, as high flow conditions were missed during the duration of the project. Upland and poor farmers were identified as the people most adversely affected by soil erosion, while downstream farmers owning irrigated land benefited from the fertile topsoil lost upstream. In terms of irrigation and water management, water availability was identified as key. Due to differing moisture conditions in different seasons, farmers are forced to adapt varying strategies during the monsoon, when drainage is critical, and during the dry season, when water has to be conserved.

While reviewing documentation and output it became evident that the main interest of this project was the question of soil erosion and sediment. Water was only of interest as an agent in sediment-related processes, only to a limited extent as a resource, and as a critical element in all natural resource interactions.

1.3.2.2 Water and erosion studies in MRM

The main aims of the MRM project as documented by Shah and Schreier (1995) were as follows (please note, only water and erosion related aims are given below):

- produce a detailed inventory of current climatic, soil, hydrological, land use, and socioeconomic conditions in the catchment;
- …
- identify major degradation processes such as soil erosion, sediment transport, and soil fertility decline, and determine rates of change in these processes under different land use practices;
- quantify stream flow and sediment dynamics and differentiate between naturally and human-induced processes and their effects on productivity and management in the catchment;
- identify successful land-use practices (traditional and introduced) that can be used to improve land use, productivity, and management in other parts of the middle mountains;
- …

The project's water and erosion studies were justified on the basis of the non-availability of scientific data and the scant understanding of hydrological processes in the middle mountains of the HKH region, endangered sustainability of the productive capacity through soil erosion, soil fertility decline, and irrigation issues.

The project was successful in:

- supplementing the basic resource surveys of the predecessor project and providing this information in digital format;
- setting up a detailed monitoring network and programme for climatic and hydrological parameters; and
- implementing small-scale community development projects in order to upgrade the infrastructure in the catchment.

In terms of water- and erosion-related findings, the project documented the critical time for soil loss during the pre-monsoon, where 60 to 80% of the annual soil and nutrient losses occurred during one or two major storms (Schreier et al. 1995). The concerns of farmers related to water shortages for both drinking and irrigation were documented and alternatives to flood irrigation were proposed. The interaction of upland rainfed agricultural land and lowland irrigated land in terms of nutrient and sediment dynamics was documented in Carver (1997), a very substantial PhD thesis on the topic of sediment dynamics and land management. During this project the use of CD-ROMS and multimedia was introduced.

This project, similar to its predecessor, was mainly interested in sediment dynamics and flood processes. Water as a resource was investigated in the context of irrigation efficiency and for household needs. No water balances were drawn up and the understanding of low flows was still missing.

1.3.2.3 Water and erosion studies in PARDYP Phase 1

The objective related to water and erosion studies in Phase 1 was:

> *"To generate relevant and representative information and technologies about water balance and sediment transport related to degradation on a catchment basis."*
> *(ICIMOD 1996a)*

The activities in this component involved the setting up of a hydro-meteorological and erosion research network in five catchments, an inventory of relevant resources in all catchments, the determination of water balances of different spatial and time scales, an investigation into sediment dynamics and water quality, and identification and testing of water management practices.

The project established a regional monitoring network in the fields of hydrology, meteorology, and erosion research, applying the same approaches and methods and using similar instruments (for reference see Hofer 1998b). Up until the end of the project, data analyses were still missing and no water balances and sediment related information were documented.

The focus of this project was regional and much effort was spent on setting up a regional network to contribute towards an understanding of key issues at the regional scale. The catchment scale along with local interventions and catchment specific activities were to a large extent neglected.

1.3.2.4 Water and erosion studies in PARDYP Phase 2

PARDYP Phase 2 was an extension of the earlier project with new activities, new organisation, and new objectives in the old framework. This phase lasted from 2000 to 2002.

The objective related to water and erosion studies in this phase was:

> *"To generate and exchange information on water as a resource and its role in land degradation, and to identify and test options to enhance water management decisions." (ICIMOD 1999)*

The activities in this phase included monitoring the research network and analysing data on water dynamics, water availability, sediment transport, and water quality. Several surveys were undertaken and water management at the local scale received much attention. The use of participatory rural appraisal methods (PRA) was intensified during the early stages of this phase.

Learning from Phase 1 of PARDYP, this project received more attention at the catchment scale at the cost of regional activities. Many questions targeted on-farm issues. At the regional scale, an analysis workshop to introduce HYMOS (a data management software) was held in March 2000. In 2002, the first steps in synthesising water- and erosion-related activities were taken. This involved a workshop (after intense preparation) attended by country team members working on water and erosion. The first ideas on this exercise are being published in Merz et al. (2003b) and the first output in the form of a CD-ROM is expected in mid 2004.

1.3.3 Summary

The scope of this study is the synthesis of a large amount of activities, resulting in a substantial body of data and information on key issues relating to water. In addition to contributing to an understanding of these issues, the study is also intended to provide an impetus for methodological development of integrated watershed management projects.

1.4 STRUCTURE OF THE REPORT

This report generally follows the outline presented in Figure 1.7. It is important to note that the methodologies applied in the study are discussed in the respective chapters.

Chapter 1 introduced the background to the study, including the reasons for concern and the urgent call for action. The study was introduced with its aims and objectives, and study's operational embedding within the PARDYP project described.

In Chapter 2, the report assesses the spatial context of the study and briefly discusses the selected catchments. The characteristics of the two catchments in Nepal are discussed in terms of catchment characteristics relevant for water scarcity susceptibility, flood susceptibility, and degradation susceptibility. The measurement networks in the selected catchments are briefly presented and the methods applied discussed.

The status in terms of different susceptibilities and the relevant processes leading to an increased or decreased susceptibility are discussed in Chapter 3. The main emphasis in this section is on the determination of relevant processes in the context of precipitation, evapotranspiration, discharge, and sediment mobilisation and transport. Water demand and supply in the catchments are presented. The resulting relationships and water balances are also presented.

Chapter 4 proposes four main scenarios, which may impact the relevant susceptibilities. After a detailed description of the scenarios, the possible impacts are presented by means of extrapolation and modelling techniques.

The information and findings from the preceding chapters are synthesised in Chapter 5 with the aim of presenting an overall view of the achievements of the study. The three indices, the Water Poverty Index, the Flood Generation Index, and the Water Induced Degradation Index are calculated for the two catchments in Nepal with a discussion of the different indicators, before a rapid assessment of these indexes is presented using data from the other PARDYP catchments.

The report ends with Chapter 6, where conclusions and recommendations for future research in the PARDYP catchments and in general are presented, keeping in mind the PARDYP project's various clients.

The appendices include relevant background information related to the text, such as statistical calculations and data tables (Appendix A), grey literature from the project, and the time series information used (Appendix B).

A number of boxes within the report refer to interesting experiences taking place during the PARDYP project, or interesting studies carried out in the PARDYP project with the involvement of the author, that are not directly the subject of this study.

SYNOPSIS 1: INTRODUCTION

In the fragile mountain environment of the HKH region, three main issues related to water were identified on the basis of an opinion poll and literature review:

- **water availability for human purposes including water quality,**
- **flooding in the foothills and adjacent plains, and**
- **water induced land degradation.**

For each of these issues, current understanding at the global scale and in other areas of the world is advanced. In the HKH region, however, data availability often does not allow detailed studies and process analyses into the issues of catchment management at the meso-scale. The main questions to be answered are related to scales, relevant processes, and the impact of future changes.

The study presented therefore aims to:

- **contribute towards improved understanding of key water-related issues in the region and the relevant processes at the meso-scale,**
- **develop a preliminary framework for catchment synthesis and comparison for questions related to these key issues, and**
- **initiate studies on improved understanding of water-related dynamics on the basis of foreseen and potential scenarios.**

Chapter 2: The Spatial Context of the Study

> ***"A land-use decision is also a water decision"***
>
> ***(Malin Falkenmark)***[1]

Chapter 2 presents the spatial context of the PARDYP study sites in the HKH region in terms of biophysical and socioeconomic parameters. The five PARDYP catchments and the reasons behind the selection of these catchments are briefly discussed.

The catchment characteristics are described on the basis of morphological, topographical, land-use, and socioeconomic considerations. Finally, the measurement networks and the data management procedures of the selected catchments are introduced. This section should help other projects involved in similar research work to learn from the mistakes and shortcomings of this approach.

The hydrological response of a catchment is primarily based on precipitation and catchment characteristics, including soils, land use/land cover, topography, and others. This relationship is often used to estimate hydrological parameters for ungauged catchments (Mosley 1981; Duester 1994; Weingartner 1999). In Nepal, this approach was used by WECS (1990) to determine methodologies for evaluating hydrologic characteristics, that is, design floods and design low flows of potential hydropower development on a reconnaissance and prefeasibility level. For the purpose of distributed modelling, catchment characteristics likewise play a vital role. In the context of people and resource dynamics as they are studied in the PARDYP project, the change of catchment characteristics on hydrological parameters through human interventions at the micro- to meso-scale is of interest.

In this respect, the catchment characteristics relevant for flooding, degradation, and water availability and changes observed in these characteristics during the study period or on the basis of historical data are discussed after a brief introduction of the larger HKH region. These characteristics were important in designing the measurement network in order to capture the relevance of different characteristics for different processes.

2.1 THE HINDU KUSH-HIMALAYAN (HKH) REGION

The HKH is the highest mountain range in the world and includes the world's highest mountains: Sagarmatha (Mt. Everest), K2, and other peaks of 8000 masl and over. The mountain range, extending about 2400 km from Afghanistan to China in east-west extension, and 250 to 300 km in width, includes parts or all of the mountain areas of Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan (ICIMOD 2002b). This includes, according to Wyss (1993), the mountain ranges in Balochistan, the Karakorum, the Hindu Kush, the Himalayas (defined as the mountain range separating India from Tibet and extending from the Indus Trench below Nanga Parbat to the Yarlungtsangpo-Brahmaputra gorge below Namche Barwa), the Hengduan mountain ranges, and a large part of the Qinghai-Xizang plateau.

2.1.1 Geology and soils

The Himalayas are geologically very young. The main uplift including the evolution of the Indo-Gangetic basin is dated to the late Tertiary/early Quaternary (~1.7-1.5 million) years before the present (Valdiya 1998). The geologic history of the Himalayas, however, began much earlier with the continental collision between the Indian subcontinent and Eurasia 40 to 60 million years ago and the subsequent subduction of the Indian subcontinent (Press and Siever 1986). This led to the

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[1] **Falkenmark (1999)**

overthrusting of slices of the old northern portion of India, stacked one on top of the other through compression, which continues today. Present-day earthquakes are attributed to this continuing drift of the Indian subcontinent at a rate of 56±4 mm/y (Valdiya 1998). This results in rapid uplift movements in different parts of the HKH. Rates documented vary according to region and geological domain. For the central part of Nepal, Jackson and Bilham (1994; cited in Valdyia 1998) report a little less than 8 mm/y for the Great Himalaya (for a definition of this, see below). Rates for the Lesser Himalaya (see below) are in the order of 23 mm/y. Denudation rates vary throughout the HKH depending on climate and geology. An overall average of 1mm was reported for the entire Himalaya in Ives and Messerli (1989) and a maxima of up to 5 mm was estimated for the eastern parts in the Nepal-Sikkim-Darjeeling Himalaya.

Geologically, the HKH can be divided into four domains: the Siwalik, the Lesser Himalaya, the Great Himalaya, and the Tethys domain (Valdiya 1998). The Siwalik or Outer Himalaya forms the southern delineation of the Himalayas and ranges from 250 to 800 masl. North of the Siwalik, separated by the Main Boundary Thrust, rise the ranges of the Lesser Himalaya, up to about 3500 masl, followed by the Great Himalaya, including the highest peaks of more than 8000 masl. The Lesser Himalaya are separated from the Great Himalaya by the Main Central Thrust. To the north, the Himalayas are delimited by the Tethys Domain following the Trans-Himadri Fault. The stratigraphies associated with the different domains are unconsolidated sedimentary rocks in the Siwalik, sedimentary and volcanic rocks covered by metamorphic and granitic rocks in the Lesser Himalaya, high-grade metamorphic rocks and gneissic granites in the Great Himalaya, and sedimentary rocks from the Tethys in the Tethys domain (Valdiya 1998).

In terms of soil resources, cambisols, leptosols, and acrisols dominate the region according to the World Soil Resources Map (FAO 1999). Cambisols frequently occur in mountain areas such as the Himalayan foothills due to the erosion and deposition cycles in these areas. These soils generally have good structured stability, high porosity, good water-holding capacity, and good drainage. They are moderately to highly fertile with an active soil fauna and therefore make good agricultural land. Leptosols, the most extensive soils in the world, are mostly found on the Tibetan plateau and high mountain, cold desert areas. They are a sign of eroding landscape or of climatic constraints that retard soil formation. These soils are very fragile, especially if cleared from their natural vegetation and exploited for agriculture. Acrisoils are mostly found in the eastern part of the HKH. These soils are very easily eroded, which imposes severe limitations on their potential for agriculture.

2.1.2 Topography and drainage

The topography of the Himalayas is unique. Over a distance of only (approximately) 170 km there is a relief from about 80 masl in the Gangetic plains to more than 7000 masl (Figure 2.1)

This suggests unprecedented gravitational forces along very steep slopes and steep river gradients, leading to high erosive potential and fast runoff generation mechanisms. A number of major rivers have their source in the HKH. The best-known rivers include (from west to east) the Indus, the Ganges, the Yarlungtsangpo-Brahmaputra, the Lancang-Mekong, the Yangtze, and the Huang rivers. These rivers are known for their flooding potential and their suspended sediment loads rank amongst the highest in the world (Meybeck and Ragu 1995). The mean discharge of these rivers is given in Table 2.1

There are two types of rivers present in this list. The Indus and the Huang He both have their origin in the Himalayas where most of their flow originates. During the course of flow they cross very dry areas where they have no tributaries. In the case of the Huang He, this is the semi-arid loess plateau, one of the most seriously eroded regions in the world. The Indus passes through the very dry areas of the Punjab and Sindh provinces of Pakistan. As a result, their specific discharge is very low. The other major rivers have specific discharges of between 14 and 22 $l/s*km^2$. This is a higher specific discharge than for European rivers. The Danube, for example, has a specific discharge of 8.8 $l/s*km^2$ (at Vadu-Oii-Hirsova) and the Rhine 14.3 $l/s*km^2$ (at Rees) (GRDC 1998). In general, Alford (1992) identified the altitudinal belt between 1500 and 3500 masl as the region in the Himalayas with the highest specific runoffs.

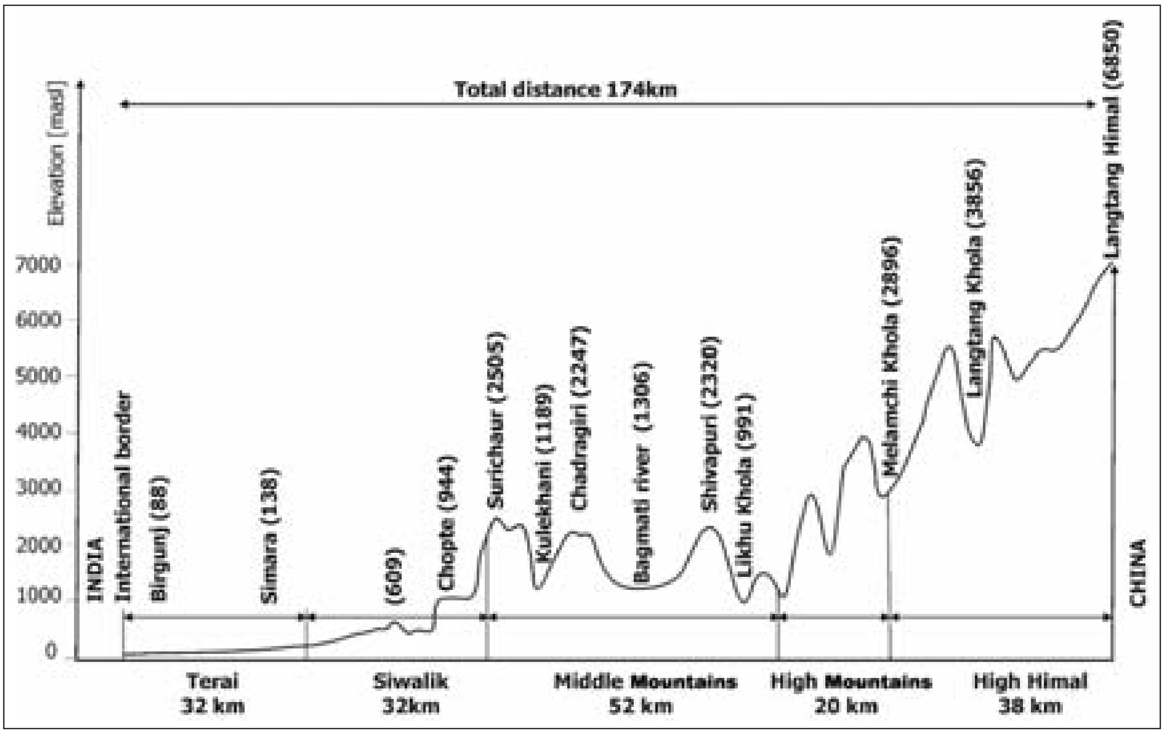

Figure 2.1: **Cross-section of the Himalayas in Central Nepal (from Chalise 1994)**

Table 2.1: **Discharge of the main rivers in the HKH**

(source: Liniger et al. 1998)

River	Basin area km^2	Mean discharge m^3/s	Mean specific discharge $l/s*km^2$
Indus	1,263,000	3850	3.0
Ganges	1,075,000	15,000	14.0
Yarlungtsangpo-Brahmaputra	940,000	20,000	21.3
Lancang-Mekong	795,000	15,900	20.0
Huang He (Yellow River)	445,000	1365	3.1
Yangtze	1,970,000	35,000	17.8
For comparison (data source: GRDC, 1998)			
Danube (Vadu-Oii-Hirsova)	709,100	6217	8.8
Rhine (Rees)	159,680	2280	14.3

2.1.3. Climate

Precipitation in the HKH shows an east-west and north-south variation at the macro-scale. The east-west variation is based on the dominance of different weather systems. Examples are given in Figure 2.2a,b,c,d, and e. In the western part of the HKH, air masses connected to the westerlies bring moisture during winter, leading to a winter peak in rainfall (Figure 2.2a). The eastern part is influenced by the southwest monsoon with a dominant maximum during summer (Figure 2.2c and 2.2e). The maximum rainfall in the area, and globally, is measured in Cherapunjee with an annual maxima of more than 10,000 mm (Figure 2.2d). Wyss (1993) determined the area of the Indian/ Pakistani border as the transition zone from one to two peaks. The example for two peaks is shown at the station in Peshawar (Figure 2.2b).

Monsoon rainfall is mainly of an orographic nature, which causes distinct variation of rainfall with elevation, and distinct differences between the southern rim of the HKH and the rain shadow areas

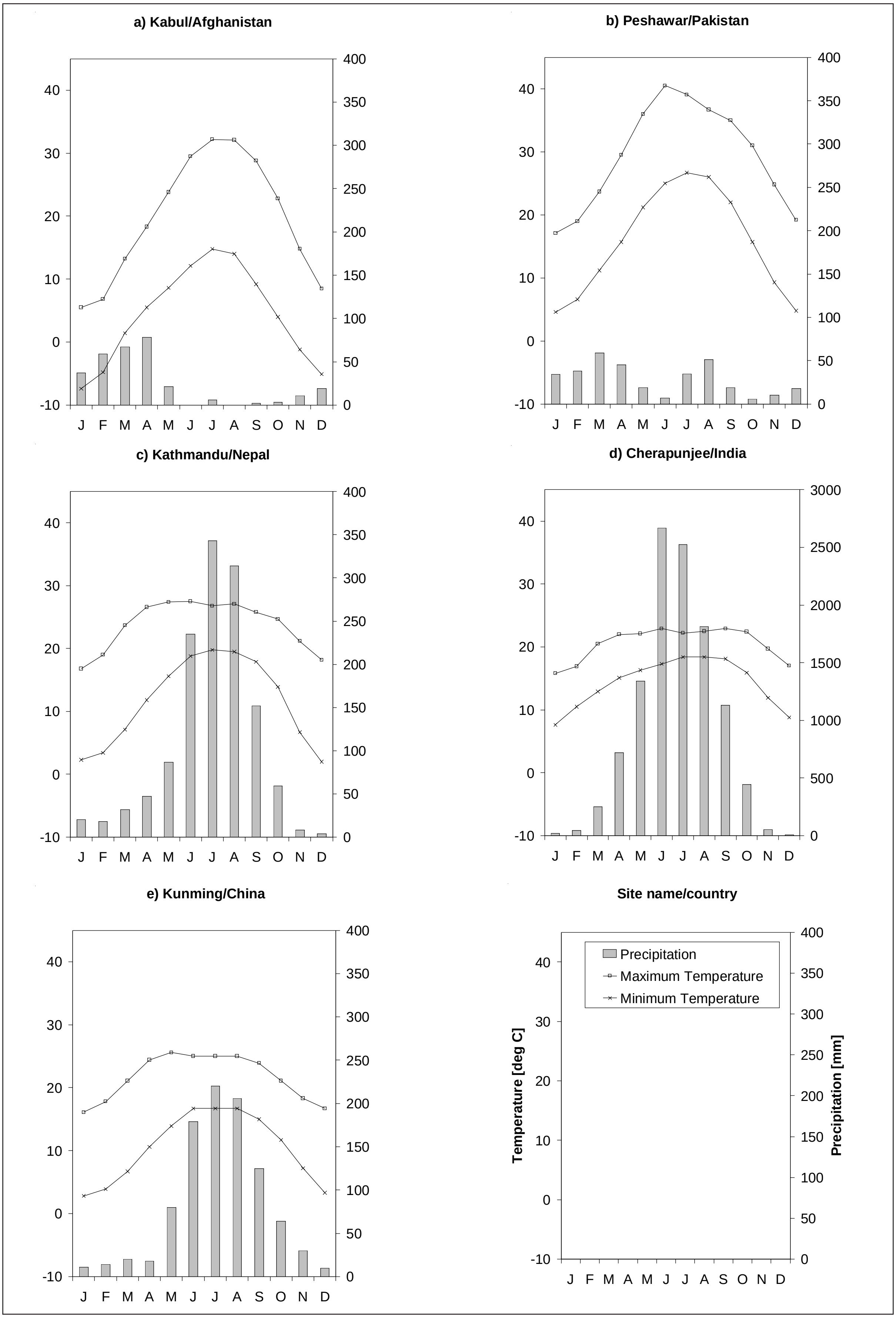

Figure 2.2: **Climatic diagram of five stations in a) the Hindu Kush, b) the Western Himalayas, c) the Central Himalayas, d) the Eastern Himalayas, and e) the Hengduan mountains**
(Data source: FAO 2001b; note: the precipitation axis in Cherapunjee is eight times higher)

of the Qinghai-Xizang plateau behind the main mountain range. Alford (1992) identified the lower and intermediate altitudes as the main source of precipitation, suggesting that there is an altitudinal trend up to about 3500 m after which rainfall again decreases.

At the meso-scale, climatic effects are driven mainly by local topographic characteristics such as ridges, slopes, valleys, and plateaux (Chalise 2001). In this context, the dry inner valleys and the luv-lee effect (i.e. more rain on the windward side than on the sheltered side of a mountain) have to be mentioned. According to Domroes (1978), the valley bottoms of the deep inner valleys in the high mountains get much less rainfall than the adjacent mountain slopes. This would suggest that the currently measured rainfall, which is mainly based on measurements in the valley bottom, is not representative for the area and major underestimates result from the use of these data. This was also shown by Flohn (1970; cited in Domroes 1978) and suspected by Baillie et al. (2002) for the Paro Valley in Bhutan. The luv-lee effect is best shown with the example of the rain gauges in Pokhara and Jomsom in Western Nepal. Pokhara receives about 3500 mm of rainfall annually, while Jomsom, only 60 km north of Pokhara but located behind the Annapurna Massif, gets only 270 mm of rainfall per annum (Domroes 1978).

The temperature regime according to Voeikov (1981; cited in Wyss 1993) varies from the tropical, with average annual temperatures of more than 24°C in the eastern part in Myanmar and Bangladesh, to alpine in the area of the Qinghai-Xizang plateau and the high mountain peaks, with annual average temperatures below 3°C. Most of the areas on the southern rim of the HKH are sub-tropical, with annual average temperatures of 18 to 24°C followed by small bands of warm-temperate and cool-temperature climates.

Potential evapotranspiration (PET) in the region reaches a maximum in the border area between India and Pakistan and shows a general decreasing trend from west to east and from south to north with increasing altitude (Wyss 1993). PET in the foot slopes of the HKH reaches about 1250 mm per year.

2.1.4 Vegetation and land use/cover

The vegetation cover of the HKH was first described in its east-west extension and its altitudinal variation by Schweinfurth (1957). In general, a variation of species along the Himalayan arc can be observed as well as an extreme vertical zonation. From east to west, vegetation becomes sparse with tropical rain forest in Assam, to sub-tropical, thorn-steppe in the Punjab (Gurung 2002). The forests of the humid regions of the eastern Himalayas are composed of broad-leaved species, while the forests of the central Himalayas are made up of oak and coniferous trees. The western part is home to mainly coniferous species (Gurung 2002).

Land use in the HKH varies from east to west and according to elevation. In the west of the Himalayas, in Balochistan, desert prevails, followed by shrubland in the remaining part of Pakistan. The middle mountains of the HKH are mainly under cropland. North of the main cropping areas at higher altitudes there are extensive pasture areas. In the east of the HKH, large forest areas cover significant parts of Yunnan province and the parts of Myanmar falling within the boundaries of the HKH. In northeast India and parts of Myanmar mostly shifting cultivation is being practised.

The prevailing farming systems are rice-wheat; integrating irrigated rice, wheat, vegetables, and livestock on the southern boundary of the HKH and the inner valleys of the middle mountains; followed by highland mixed farming systems incorporating a range of cereals, legumes, tubers, fodder, and livestock (Dixon et al. 2001). Large areas of Afghanistan and Balochistan are pastoral and sparsely farmed. On the upper slopes of the Himalayan ranges above 3000 m farming depends on potatoes and buckwheat, as well as cattle and yak.

In the HKH, over 80% of the population depends either on full- or part-time farming for their livelihood (Thulachan 2001). Most of the farm households in the HKH there are engaged in subsistence farming and produce mostly grain. This grain production has remained stable over the last 10 to 15 years according to Thulachan (2001). However, with an increase in population, the per capita grain availability is decreasing. In addition, the expansion of agricultural land does not seem to have major prospects. A promising development according to Jodha (1997) and Thulachan (2001) is the increments in high- value cash crop production, such as fruit, vegetables, and medicinal plants. However, there is concern about declining yields of these crops in the region.

2.1.5 Population distribution and livestock

Population is believed to be one of the important driving forces for environmental degradation, as shown in Chapter 1. The foothills of the HKH in particular are under heavy population pressure with population densities of 75 to 500 people/km^2 and more than 5000 people/km^2 in the Kathmandu Valley in Nepal and the upper Indus plains in Pakistan. The high mountain areas and the Qinghai-Xizang plateau are very sparsely populated.

The carrying capacity of the land varies with altitude, since all-year-round cultivation as practised in the foothills of the Central Himalayas can support more people than high altitude farming with only one crop per year. The land's carrying capacity further varies from east to west with shifting cultivation, which is mainly practised in the Eastern Himalayas, since land under shifting cultivation has a lower carrying capacity than that under permanent cultivation in the central Himalayas (Lal 1990). In the Western Himalayas, the cropping season lasts only six to eight months, forcing people to migrate or trade for further income. Pudasaini (1997) estimated the carrying capacity for Nepal only on the basis of food production. On the basis of this estimation, the carrying capacity in the hills and mountains has already been reached and the carrying capacity of the entire country is about to be exhausted.

Population growth in the region is still rapid. Maximum population growth rates as estimated by UNFPA (2001) for the period 2000 to 2005 are expected to be as follow: Afghanistan at 3.7, Bhutan following at 2.6, Pakistan at 2.5, Nepal at 2.3, and Bangladesh at 2.1. Other countries in the region have growth rates of 0.7 (China), 1.5 (India), and 1.2 (Myanmar).

It is important to mention that most of the countries in the region belong to the poorest countries in the world. China (Human Development Index rank: 87), India (115), and Myanmar (118) are classified in the medium human development group (UNDP 2001). However, their mountainous regions are believed to be below the national average. The other countries belong to the low human development group: Pakistan (127), Nepal (129), Bhutan (130), and Bangladesh (132). Afghanistan is not listed in the report, but it is believed to be in the group of low human development due to the long period of war.

Poverty is regarded as another main factor in the degradation of natural resources, mainly due to the lack of alternatives, which forces the poor to use natural resources intensively (Papola 2002).

Livestock are an integral part of the farming systems of the HKH. The most common livestock species are cattle, buffaloes, goats, sheep, and yak at higher elevations. The pressure from livestock on land resources is high and is one of the highest in the case of Nepal (Thulachan and Neupane 1999). Generally, there is a decreasing trend in the cattle and sheep population across the HKH and an increasing trend in the buffalo and goat population, which shows the shift in the economic importance of the respective species for farm households in the HKH (Thulachan 2001). Buffaloes are important for milk production, which has increased in importance across the region. In the case of the Jhikhu Khola catchment in Nepal, the same trend has been observed along with a shift from free grazing to stall-fed animals during the wet season (Brown 2000a).

2.1.6 Synthesis of the above information for study site selection

A number of regionalisation approaches discussed in Ives and Messerli (1989) have been suggested for the HKH on the basis of the above information. More recent regionalisation approaches include the Global Agro-ecological Zones' methodology by FAO and IIASA (FAO/IIASA 2002) at the global scale and the on-going project on Methodologies for Assessing Sustainable Agricultural Systems in the HKH region by ICIMOD (ICIMOD 2002c) at the regional scale of the HKH.

For the purpose of this study, with the aim of understanding the human impact on natural resources in general and on land degradation in particular (PARDYP Phase 1 aim), the geological domains as suggested by Valdyia (1998) were central. The physiographic regions of Nepal as defined by Carson et al. (1986) provided a first step to relate the geologic domains to other parameters and then to scale up to the region. They are primarily based on geological delineation and include physiography, geomorphology, and soils information. The regions are (Carson et al. 1986 including comments on land use and elevation from Zonneveld et al. 1986: in brackets the classification according to Valdiya 1998) as follow.

- **Terai [not included] elevation 60-330 masl**
  The Terai includes the recent and post-Pleistocene alluvial plains adjacent to the mountainous areas and is not part of the HKH. Soils in this region are predominantly loamy textured, slightly acid, and stone free. A high percentage of the Terai is cultivated land and the remaining is made up of mainly large stands of sal (*Shorea robusta*) forests.

- **Siwaliks [Siwalik] elevation 200 -1500 masl**
  The geology of the Siwaliks is weakly consolidated and consists mainly of Tertiary and Quaternary mudstones, siltstones, sandstones, and conglomerates. In addition to the weak geology, the steep slopes tend to be responsible for severe surface erosion despite good forest cover. The extent of agricultural land is very limited. Textures of soils are directly related to the underlying bedrock geology with medium textured soils on siltstones and coarse textured soils with boulders on conglomerates.

- **Middle Mountains [Lesser Himalaya] elevation 800 - 2400 masl**
  The geology of the Middle Mountains consists of phyllites, schists, and quartzites of probably Cambrian to Precambrian age and granites and limestones of different ages. The phyllites are often deeply weathered, whereas the schists are more competent and therefore resist weathering. Soils on these rocks are well developed and moderately fine textured in the case of phyllites, and coarse textured for underlying schists. Soils on quartzites are shallow, strongly acidic, and coarse textured. Areas of quartzites are often associated with pine forest. In general, the Middle Mountains are intensively cultivated.

- **High Mountains [Great Himalaya] elevation 2200 - 4000 masl**
  Generally, the geology of the High Mountains is high grade metamorphic. Soils tend to be shallow due to the increased competence of rocks and a less suitable climate for weathering. They also tend to be stony. Agricultural land is limited and supports only about one crop per year. Forests in this region are usually made up of different coniferous species.

- **High Himal [Great Himalaya] elevation >4000 masl**
  Physical weathering is the predominant process in this region, which consists of gneisses, schists, limestones, and shales of different ages. The only land use in this region is grazing.

The Thetys domain was not included in the Land Resource Mapping Project (LRMP) classification due to the negligible area of this zone within the boundary of Nepal and low significance for agricultural production.

For the assessment of human impact, population distribution and population density in particular were very important. High population pressure mainly exists in the foothills of the HKH region. This includes the middle and high mountains of Nepal (Zonneveld et al. 1986) on the southern rim of the HKH region and on the eastern rim adjacent to the Hengduan mountains. The remaining areas are sparsely populated.

2.2 THE FIVE PARDYP CATCHMENTS

On the basis of the simple classification approach as explained above, five catchments were selected in the middle and high mountains of the HKH to carry out PARDYP activities. All catchments meet scientific criteria that stress the similarity of the catchments, as follows:

- elevation ranges between 700 and 3000 masl;
- the predominant land use is agriculture, both irrigated as well as rainfed;
- mixed highland cropping system with rice and maize-wheat based cropping systems on irrigated, rainfed land respectively;
- population density is more than 75 people/km^2, therefore a lot of pressure is placed on natural resources;
- catchment size is of 10 to 100 km^2, which corresponds to the lower meso-scale according to the hydrological scales presented in Becker (1986; cited in Nemec 1993); and
- each catchment should be representative of a larger area with local factors being represented in sub-catchments of the size 0.1 to 5 km^2; and these sub-catchments should be as homogenous as possible.

On the basis of the elevation criteria (between 700 and 3000 masl) and precipitation criteria of 800 to 2500 mm precipitation per annum, Tashi and Rotmans (2003) report that 11% of the entire HKH region fits into the scientific criteria listed above.

In order to account for the differences within the east-west extension, mainly due to climatic parameters, the catchments were spread along the Himalayan arc from Pakistan to China. To study the altitudinal variation within the foothills, a catchment each from a lower and higher elevation were chosen in Nepal.

In addition to the scientific criteria, each catchment had to satisfy practical demands, including easy access by road, well-delineated catchments, a clear outlet with the possibility for constructing a hydrological station, the interest of local collaborating institutions, and others.

This selection process resulted in the selection of five PARDYP catchments, from west to east (see Figure 2.3):
- the Hilkot-Sharkul catchment, Manshera district, North Western Frontier Province, Pakistan
- the Bhetagad-Garur Ganga catchment, Bageshwor district, Uttaranchhal, India
- the Jhikhu Khola catchment, Kavrepalanchok district, Nepal
- the Yarsha Khola catchment, Dolakha district, Nepal
- the Xizhuang catchment, Baoshan prefecture, Yunnan Province, China

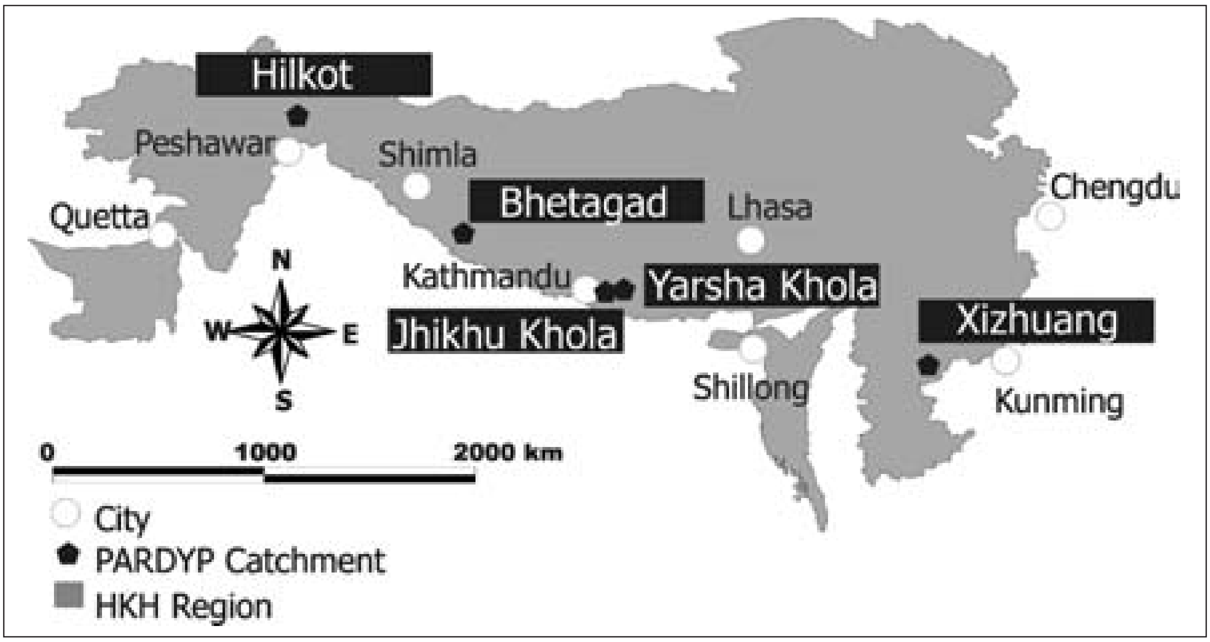

Figure 2.3: **The five PARDYP catchments in the middle mountains of the HKH**

The catchments are between 34 and 110 km^2 in area and elevation ranges from 800 to 3075 masl. Population density ranges from about 100 to 440 people/km^2. All catchments represent different river basins with the catchment in Pakistan finally draining into the Indus river basin, and the catchment in India and the two in Nepal contributing to the Ganges river basin. The Chinese catchment drains into the Lancang-Mekong river basin.

This study only incorporates full data and information from the catchments in Nepal. The time series available in the case of the Pakistan catchment are too short for meaningful analysis (1999-2000) and appropriate datasets from the Indian catchment up to date are not available. The data from the Chinese catchment were only made partly available. To assess the applicability of the proposed indexes, all catchments are included. While the catchments in Nepal are discussed in detail, the other catchments are assessed only in brief. In the following section, a short description of the catchments in Nepal with the main characteristics are presented in Table 2.2.

Table 2.2: **Brief overview of the PARDYP study sites in Nepal (PARDYP 1999)**

	Jhikhu Khola	**Yarsha Khola**
Area [ha]	11,141	5,338
Elevation range [masl]	790 - 2200	980 – 3,040
Population (year)	48,728 (1996)	20,620 (1996)
Population density [people/km^2]	437	386
Family size	6	5
Main staple crops	rice, maize, wheat, potato	rice, maize, millet, wheat
Main cash crops	potato, rice, tomato, vegetables	seed potato, garlic, fruit

2.2.1 Jhikhu Khola catchment, Nepal

The Jhikhu Khola catchment is situated approximately 45 km east of Kathmandu on the Arniko Highway. It covers 111.4km^2 with elevation ranging from 800 to 2200 masl. The catchment has a main valley with a large flat valley bottom of alluvial origin, where the major land use is irrigated agriculture. Short and steep slopes confine it on the southern and northern sides. Land use in these areas is mainly rainfed agriculture and forest. There are many pocket-like valleys on the flanks, which make the catchment very heterogeneous. The general aspect of the catchment is southeast, with the main valley extending from southeast to northwest. The Jhikhu Khola catchment is densely populated with 437 people/km^2 in 1996. Most of the agricultural production from the Jhikhu Khola, apart from the staple food, is sold to Kathmandu. This includes potatoes, tomatoes, and, increasingly, different types of vegetables. Agricultural production is very intense with substantial fertiliser and pesticide inputs.

2.2.2 Yarsha Khola catchment, Nepal

The Yarsha Khola catchment, at 53.4km^2, is located approximately 190 km east of Kathmandu on the Lamosangu-Jiri Road in Dolakha district. The elevation of the catchment ranges from 990 to 3030 masl. The general aspect of the catchment is southwest and the main valley extends from southwest to northeast. It consists of a south- and a north-facing slope with a small middle ridge between. An extensive flat valley bottom of alluvial origin is missing, and irrigated areas are limited, especially in comparison with the Jhikhu Khola catchment. Land use is dominated by rainfed agriculture and forest. The catchment is densely populated with 386 people/km^2 in 1996.

Good markets for seed potatoes and garlic, the two main cash crops in the area, are limited in the Yarsha Khola catchment.

2.2.3 Summary

In general, a strong altitudinal variation for most parameters can be observed. This leads to zones roughly parallel to the Himalayan arc, such as the physiographic zones discussed above in terms of geology, geomorphology, climate, vegetation, and land use. In addition, climate shows an east-west variation in terms of rainfall and humidity, influencing land use and vegetation. With the selection of one zone, the most populated zone in the HKH, the altitudinal variation is kept to a minimum. The east-west variation is studied with the spread of catchments from Pakistan in the west to China in the east.

The spatial context of the PARDYP catchments in the HKH shows that the region has

- high natural potential for erosion due to
  - present uplift rates of 2 to 7mm/y
  - unconsolidated geology
  - steep slopes and steep river gradients

- high potential of erosive forces due to
  - short and intense rainfall periods
  - high intensity rainfall events

- a high degree of human impact and pressure on natural resources due to
  - population pressure
  - poverty
  - land-use change
  - subsistence agriculture

- highly seasonal behaviour of water resources
  - long and extended dry season
  - short and intense rainy (monsoon) season

The PARDYP catchments are located in a vulnerable, resource poor, and mainly subsistence agriculture-based region. They generally range from 800 to 4000 masl, have a catchment area of 10 to 100 km^2, are predominantly cultivated, and have intense population pressure. In all catchments, the mixed highland cropping system is practised with rice on the irrigated land and maize on the rainfed land as the main monsoon season staple crops. Wheat is the main staple crop during the dry season.

2.3 PRESENT CATCHMENT CHARACTERISTICS

The comparison of catchment characteristics will establish a first fingerprint of the catchments under investigation in terms of hydrologically important characteristics and may explain similarities and/or differences in their hydrological behaviour at a later stage. Falkenmark (1999) stresses the importance of understanding the interactions between land and water, the land-water linkages. This is not only to understand the impact of human interventions, but also to avoid negative impacts such as floods, erosion, and environmental pollution.

This comparison is divided into morphometric, land use, other biophysical, population and socioeconomic characteristics. The potential impact on hydrological parameters is discussed at the end of the section. A general introduction to the catchments is given in the preceding section.

2.3.1 Data origin and quality

The variables discussed below were calculated on the basis of the GIS and map database from PARDYP. This includes the following maps:

- 1:20,000 topographical base map of the Jhikhu Khola catchment with 50 m contour interval (Integrated Survey Section 1989) (digital)
- 1:25,000 topographical base map of the Yarsha Khola catchment (compilation of four 1:25,000 maps of HMG (1996a-d) (digital)
- 1:20,000 land use map of the Jhikhu Khola catchment, 1996 (digital)
- 1:25,000 land use map of the Yarsha Khola catchment, 1996 (digital) (Shrestha 2000a)
- 1:20,000 geological map of the Jhikhu Khola catchment, 1996 (digital) (Nakarmi 2000a)
- 1:25,000 geological map of the Yarsha Khola catchment, 1998 (digital) (Nakarmi 2000a)
- 1:20,000 land systems map of the Jhikhu Khola catchment, 1990 (digital) (Maharjan 1991)
- 1:20,000 sediment source map of the Jhikhu Khola catchment, 2002 (digital) (MRE 2002)

All maps that are available in digital format can be found on the CD-ROM in Appendix B.7 as *.jpg files. The comparability of the maps and spatial datasets should also be mentioned. It is understood that, strictly, a comparison of maps of different scales cannot be made. For comparison's sake, however, it was deemed possible to compare the topographical and land-use information, as the scale difference is minimal. However, drainage parameters could not be compared between the catchments as the mapping procedures and the details for the drainage network were very different among the maps of the different catchments.

The agronomic information from the Jhikhu Khola and Yarsha Khola catchments is derived from a survey related to water demand and supply in the two catchments (Merz et al. 2002) if not stated otherwise. The information on water demand and supply in the two catchments is derived from the same survey.

2.3.2 Morphometric analysis and comparison

2.3.2.1 Importance and definition of morphometric parameters

Dyck (1980) proposed that morphometric parameters be structures into linear, areal, and topographical parameters. The investigated parameters are briefly discussed below.

The rivers themselves with their lengths and their distribution in the catchment are considered to be the **linear parameters** of a catchment. For this study, the parameters' total drainage length, the length of the main river, and stream order according to Strahler (e.g. Wilhelm 1993) were considered to be important.

The most important **areal parameter** is the area of the catchment. The area generally determines, together with precipitation, the discharge, which becomes greater as the catchment area increases (Wilhelm 1993). Exceptions are given in areas with karst or high percolation and evaporation rates (Baumgartner and Liebscher 1996). The specific discharge, on the other hand, is indirectly related to the catchment area and decreases with an increase in catchment area. Flood peaks decrease likewise with increasing drainage area due to increased retention of floodwaters in the areas adjacent to the riverbed. The peak is not only influenced by the increased retention, but also by increased concentration times leading to a flattening of the peak. Variability of discharge is the highest in small catchments where heavy rainfall may lead to a sharp increase in water level. This increase in level stops immediately after the end of the rain. In larger catchments this effect is averaged out. Drainage density, defined as the total length of all rivers in a catchment divided by the total area of the catchment (Wilhelm 1993), is an indicator of the geological and pedological conditions of the catchment. High infiltration and percolation and therefore increased groundwater flow lead to low drainage densities. According to Baumgartner and Liebscher (1996), the annual discharge is more evenly distributed in catchments of low drainage density. Karstic areas also usually show low drainage densities. In addition to the influence of the inherent conditions, the drainage density is influenced by the precipitation.

The shape of a catchment mainly influences the concentration time, that is, the time after which all parts of the catchment contribute to the flow at the catchment outlet, and therefore the flood generation in a catchment. The influence on mean flows and low flows is limited (Baumgartner and Liebscher 1996).

Topographically, elevation is important for the determination of evapotranspiration rates, soil moisture regime, and investigations into snow and ice cover — all of them important factors of the water balance and related to the temperature regime of a catchment. Vegetation is directly related to elevation and herewith interception. It also influences the flood behaviour, as certain elevation zones are often forest covered. Above the tree line, precipitation in the form of rainfall can often run off undisturbed. Furthermore, aspect plays a major role as this parameter is related to the microclimate, particularly with regard to radiation and temperature in particular.

Streamflow concentration is one of the sub-processes of a flood, which can be described with the help of catchment characteristics — topographical parameters in particular (Duester 1994). This parameter mainly describes the magnitude and the intensity of a flood event and depends on a number of variables. According to Duester (1994) there many variables that should influence the streamflow concentration are discussed in the literature. One of the characteristics most frequently associated with streamflow concentration is slope. Steep slopes often produce short hydrographs with high peaks. Additionally, the increasing mean slope of a catchment leads to a greater proportion of overland flow and therefore fast streamflow processes (Baumgartner and Liebscher 1996). Breinlinger (1995) identified parameters affecting the permeability of the ground (soil characteristics and land use/cover) and slope critical for flood generation.

Certain hydrological models are directly based on the prior analysis of the catchment topography, such as the TOPMODEL (Beven et al. 1995a) or THALES (Grayson et al. 1995). TOPMODEL is based on the Topoindex defined as follows (Quinn et al. 1991):

$$\mathbf{Topoindex = ln(a_i/tan\ ß_i)} \qquad \textbf{Equation 2.1}$$

where

a_i = area of the hillslope per unit contour length that drains through point i

$ß_i$ = slope [°]

The Topoindex represents the propensity of any point in the catchment to develop saturated conditions (Beven et al. 1995a). The index is high with long slopes, or upslope contour convergence, and low slope angles. For the calculation of the contributing area the index is expressed in a distribution function. In this study the Topoindex was calculated as described in Schulla and Jasper (1999).

Another index describing the topographic conditions but this time in relation to the drainage system is the concept of relative area contribution (Duester 1994). The concept of relative area contribution describes the probability of a particular area contributing to a flood event (Weingartner 1999). It is based on the assumption that the entire area of a catchment contributes to a flood. But each part of the area contributes to a different extent, depending on the distance from the channel and on the slope. The influence of the slope is calculated with the help of a coefficient (Duester 1994)

$$\mathbf{C_i = (90/ß_i)^{0.5}} \qquad \textbf{Equation 2.2}$$

where

C_i = coefficient [without dimension]

ß = slope [°]

The distance from the channel is calculated according to the least accumulative cost distance. This includes the geographic distance from the channel as well as the slope in this case. For this the cost distance function implemented in ArcView 3.1 was used with the channel network as input grid and the C^i coefficient grid as cost surface. The relative area contribution can then be determined as (Duester 1994)

$$\mathbf{R_i = 1/CD_i} \qquad \textbf{Equation 2.3}$$

where

R_i = relative contribution of cell i

CD_i = cost-distance value of cell i

Once streamflow generated on the slopes reaches the rivers, the process of open channel flow is initiated. This process is governed by the channel characteristics including channel slope, roughness, and width (Chow et al. 1988). The river elevation profile shows graphically the relationship between the length and the elevation and therefore overall steepness of the drainage system.

2.3.2.2 Area and shape

The two main catchments selected for this study and the remaining sites of the PARDYP project are in the range of 30 to 111 km^2 (Figure 2.4a). According to the hydrological scale classification of Becker (1986; cited in Nemec 1993), the catchments can be classified as small to large meso-scale catchments.

The project's monitoring and research network, which was set up according to the nested approach (Figure 2.15 (p.53) and Hofer 1998b), observes hydrological processes from 100 m^2 on the plot (micro scale) over approximately 100 ha in a sub-catchment (small meso-scale) to a catchment at about 100 km^2 (large meso-scale). For a visual comparison, the sub-catchments of the Jhikhu Khola catchment (which will be studied in further detail) are added to the figure (Figure 2.4b).

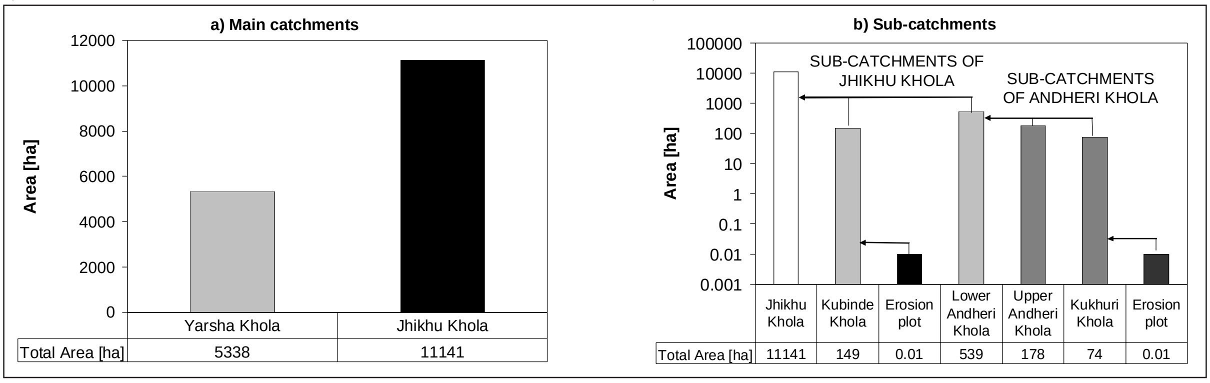

Figure 2.4: **Area of selected catchments: (a) Jhikhu Khola and Yarsha Khola catchments; (b) sub-catchments of Jhikhu Khola catchment**
(note: logarithmic scale in (b)

The Jhikhu Khola catchment is double the size of the Yarsha Khola catchment. The biggest sub-catchment in the Jhikhu Khola catchment is the lower Andheri Khola sub-catchment. including another two monitored sub-catchments of smaller size, the upper Andheri Khola and the Kukhuri Khola sub-catchments. The size of the Kubinde Khola sub-catchment is comparable to the upper Andheri Khola sub-catchment.

In terms of the shape of the catchment, the ratio between catchment width and elongation reveals that the Yarsha Khola catchment has a nearly balanced width/length relationship at a ratio of 0.8. The Jhikhu Khola catchment as well as its sub-catchments (with the exception of the Lower Andheri Khola) show a ratio of 0.5 to 0.6, which indicates that the catchment is twice as long as it is wide. The very long Lower Andheri Khola is three times longer than it is wide.

2.3.2.3 River length and drainage density

Note: Due to the use of maps of different origin with slightly different scales and different details in terms of drainage network mapping, this section can only be presented for the sub-catchments of the Jhikhu Khola catchment. These figures are all based on the same maps. The length of the main river is presented for all catchments: these values are, however, tentative.

The Jhikhu Khola catchment has a drainage network of 737 km (Table 2.3). This includes streams of the order 1 to 6 according to the method of Strahler. This calculates to a drainage density of 6.6 km/km^2 over the entire catchment area. The minimum drainage density is observed in the Upper Andheri Khola sub-catchment with a total drainage length of 12.2 km calculating to a drainage density of 6.9 km/km^2. The drainage density of the remaining catchments ranges from 7.5 km/km^2 in the Lower Andheri Khola sub-catchment to 7.9 km/km^2 in the Kubinde Khola sub-catchment.

Table 2.3: **River-related catchment characteristics**

Catchment name	Drainage length [km]	Drainage density [km km^2]	Length of the main river [m]
Jhikhu Khola	737.2	6.6	25,464
Kubinde Khola	11.7	7.9	2930
Lower Andheri Khola	40.3	7.5	7389
Upper Andheri Khola	12.2	6.9	2728
Kukhuri Khola	5.8	7.8	1449
Yarsha Khola	-	-	11,609

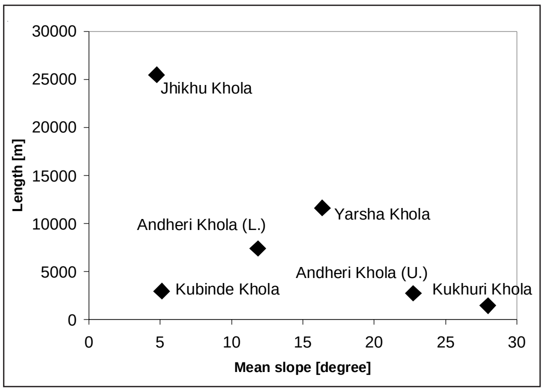

Figure 2.5: **Relationship between length of the mainstream and mean slope of the river**

The main river length determined in all catchments will be discussed in relation to the slopes of the catchment below and is shown in Figure 2.5.

2.3.2.4 Elevation

The two catchments are located in the Middle Mountains of the Himalayas. In general, they range from about 800 to 3100 masl. The elevation of the Jhikhu Khola catchment ranges from 790 to 2200 masl. The Yarsha Khola catchment has a relief of 2000 m (1000 to 3030 masl). The distribution of elevation classes differs between the two catchments (Figure 2.6a). While the Yarsha Khola catchment shows a distribution of the elevation classes resembling a normal distribution, with a peak of between 1500 – 1750 masl, the distribution of the elevation classes in the Jhikhu Khola is positively skewed. This is due to the extended valley bottom, which can be found in other Middle Mountain valleys such as the Kathmandu Valley, the Pokhara Valley, Dhadingbesi, Tansen in Nepal, the Paro Valley in Bhutan or the Doon Valley in India.

A similar picture is shown by the sub-catchments of the Jhikhu Khola catchment (Figure 2.6b). The entire area of the Kubinde catchment is in the lowest class (750 -1000 masl). The lowest point of this catchment is the outlet at 850 masl. The other catchments show a bell-like distribution of altitudinal classes around 1000 to 1200 m in the case of Lower Andheri Khola catchment, and around 1250 to 1500 m in the case of Upper Andheri Khola and Kukhuri Khola catchments.

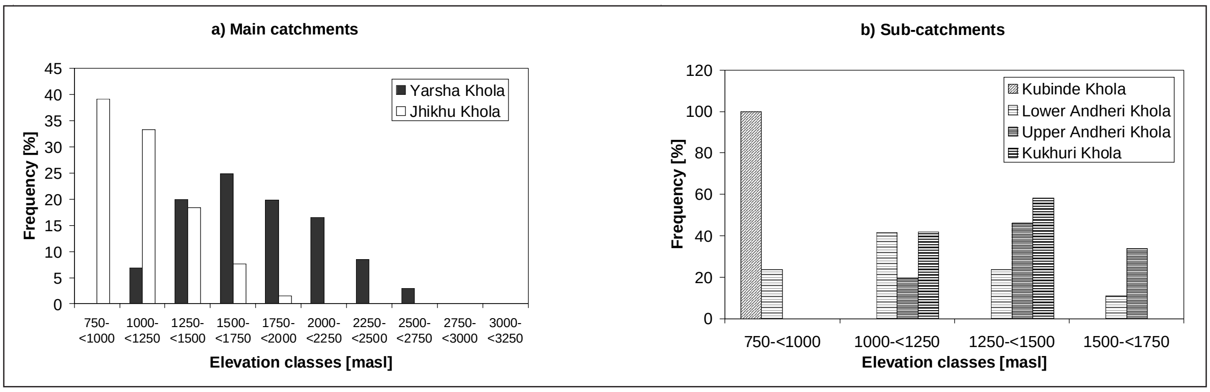

Figure 2.6: **Elevation distribution of (a) the main catchments, (b) the sub-catchments of the Jhikhu Khola catchment**

2.3.2.5 Slope

The mean slope of the main catchments varies from 17 degrees in the Jhikhu Khola catchment to 22 degrees in the Yarsha Khola catchment. This low mean slope value in the Jhikhu Khola catchment is mainly a result of the extended flat areas in the catchment. Nearly 40% of the catchment has a slope of below 5 degrees (Figure 2.7a). The remaining areas of this catchment are very steep and even steeper than the Yarsha Khola catchment. The slope distribution in the Yarsha Khola catchment peaks between 15-20 degrees.

The sub-catchments' mean slopes are 18 degrees (Lower Andheri Khola), 23 degrees (Upper Andheri Khola), 21 degrees (Kukhuri Khola), and 12 degrees (Kubinde Khola) with the distribution of slope peaking at 20 to 25 degrees in the case of the Kubinde Khola and degrees to 30 degrees in the remaining sub-catchments, respectively (Figure 2.7b). In order to express the relationship between steep slopes and flat areas of the catchments, a ratio of the slope classes 0 degrees to 5 to the sum of all slope classes from 15 degrees to >45 degrees was calculated. The selection of these classes is based on Breinlinger (1995) who identified the slope classes below 3 degrees and the classes above

15 degrees as most important for flood generation in addition to mean slope. The ratio is lowest for the Yarsha Khola catchment with 0.11. The Jhikhu Khola's flat valley shows a ratio of 0.70. The Kubinde Khola sub-catchment, in general very flat as shown above, has a ratio of 0.88, with the sub-catchments to the south having ratios between 0.32 and 0.57. These high values for the slope ratio in these catchments seem suspect as there is hardly any flat portion in reality and these values may be the result of an inaccurate contour map.

The difference in topography is also shown in Figure 2.5. The Yarsha Khola catchment shows a similar slope-river length relationship as the small and steep sub-catchments of the Jhikhu Khola catchment. The Kubinde Khola sub-catchment, on the other hand, is very similar to the Jhikhu Khola catchment in terms of slope, but is of course much smaller than the main catchment.

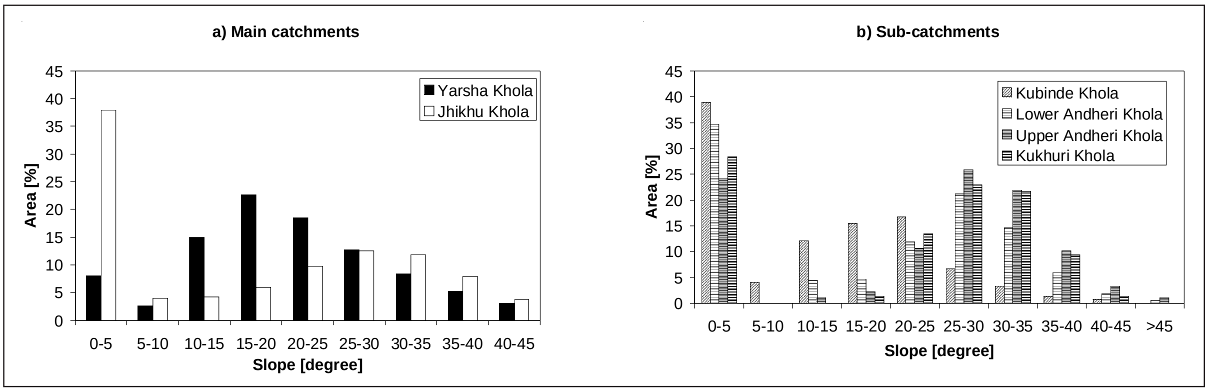

Figure 2.7: **Distribution of slope classes of (a) the main catchments and (b) the sub-catchments of the Jhikhu Khola catchment**

2.3.2.6 Aspect

The distribution of aspect classes in the two main catchments shows two different positions (Figure 2.8):

1) The Yarsha Khola catchment has an extended area facing towards north-northwest and south-southwest. The general orientation of the catchment is southwest.
2) The Jhikhu Khola has a general orientation towards the southeast with the main area of the catchment facing towards east-northeast. It is important to note the extended area of flat land, that is, areas without specific aspect. About 35% of the catchment is flat.

The overall orientation of the catchments is southeast for the Jhikhu Khola and southwest for the Yarsha Khola. The sub-catchments of the Jhikhu Khola show a general orientation towards the north (Lower Andheri Khola and Upper Andheri Khola), northwest (Kukhuri Khola), and southwest (Kubinde Khola).

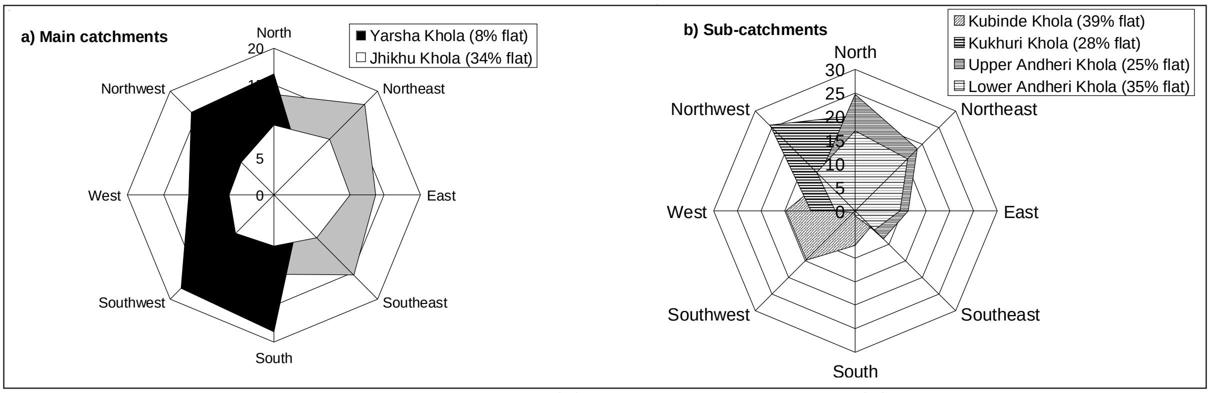

Figure 2.8: **Distribution of aspect classes in (a) main catchments and (b) sub-catchments**

2.3.2.7 Topoindex

The Topoindex is a measure of the likelihood of a cell in space contributing to runoff generation due to saturation. The analysis of the Topoindex in all catchments shows that the catchments all follow the same distribution, peaking at a Topoindex of 5 (Figure 2.9a) However, the Yarsha Khola catchment shows a higher percentage of low Topoindexes, indicating that this catchment is slower to saturate than the Jhikhu Khola catchment. The Yarsha Khola catchment, with a mean Topoindex of 6.4, is followed by the Jhikhu Khola catchment with a Topoindex of 7.0.

Except for Kubinde Khola sub-catchment, the other sub-catchments of the Jhikhu Khola catchment show the same pattern (Figure 2.9b). The Kubinde Khola sub-catchment's distribution peaks at a Topoindex of 6, indicating that this catchment is the quickest to saturate due to its low topography and slope. The mean Topoindex shows the same, with a value of 7.4 in this sub-catchment. In the Lower Andheri Khola, the mean Topoindex is 6.6, in the Upper Andheri Khola and the Kukhuri Khola it is 6.2.

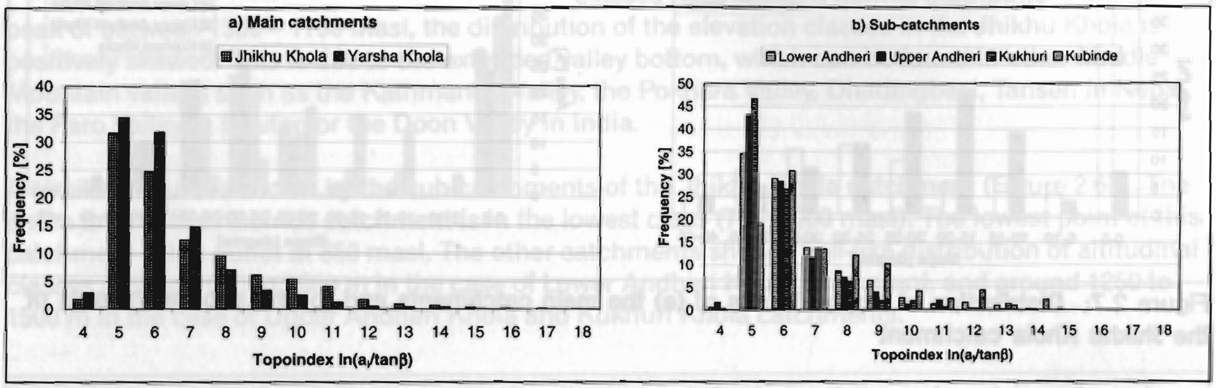

Figure 2.9: **Comparison of the distribution functions of ln (a/tanß) for a) the main catchments and b) the sub-catchments**

2.3.2.8 Relative contribution area

As in the case of the drainage network, the relative contribution area cannot be compared between different catchments unless the same data source or exactly the same data collection methodology has been applied for the drainage network. The reason for this is the strong dependence of the relative contribution area concept on the drainage network. However, a comparison of the sub-catchments in the Jhikhu Khola is presented below (Figure 2.10).

The Upper Andheri Khola sub-catchment at Site 7 shows the highest percentage of medium to large contributing areas, including the drainage system, closely followed by the Upper Andheri Khola sub-catchment and the Lower Andheri Khola catchment. Only about 37.5% of the Kubinde Khola sub-catchment is considered to contribute to a medium to large extent to runoff events. The average value per cell follows a similar pattern with 11.7 in the case of the Kukhuri Khola followed by the Upper Andheri Khola with 10.8. The lowest value is reported for the Kubinde Khola with 9.9 and the entire Jhikhu Khola catchment with 10.0.

It is important to note that the Topoindex and the relative contribution area are inversely related. As the relative contribution area is problematic in the case of different map sources with different details of the drainage network mapping, the Topoindex provides the same information and can be used exclusively.

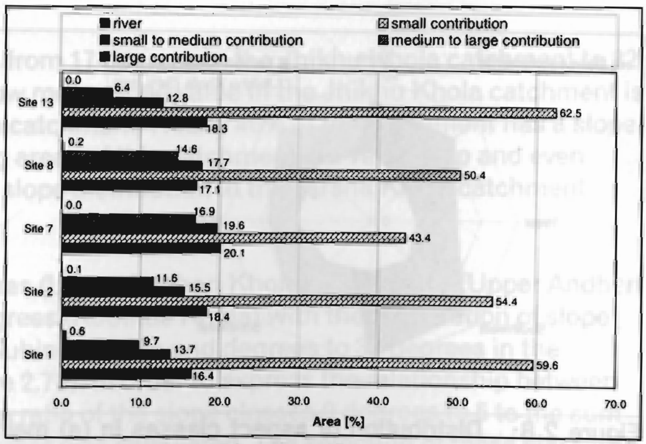

Figure 2.10: **Area of different relative contribution classes**

2.3.2.9 Summary

In summary, the catchments have the following characteristics (see also Table 2.4).

- The Jhikhu Khola catchment is the largest catchment generally oriented from northwest to southeast with very steep side slopes facing towards north and south and an extended flat valley bottom. It further shows the highest likelihood of saturation.
- The Yarsha Khola catchment covers the highest elevation range in a medium- sized catchment with general orientation from northeast to southwest. The topography is dominated by steep slopes, while flat areas are mostly not to be found. This is shown by a high mean slope and a low mean Topoindex.

The sub-catchments' characteristics can also be summarised as follows (see also Table 2.4).

- The biggest monitored sub-catchment, the Lower Andheri Khola sub-catchment, shows the largest elevation range, which is from the valley bottom to the catchment boundary with a general orientation towards the north. With a mean slope of 18 degrees it has similar overall slope conditions as the main catchment. The mean Topoindex shows medium propensity towards saturation.

Table 2.4: **Summary of morphometric catchment characteristics**

Catchment	Area	Elevation [m]				Slope	DD	Topo-index Mean*	Rel. area Mean
	$[km^2]$	Mean	Max	Min	Range	Mean			
Yarsha Khola	53.4	1775	3040	980	2060	22	-	6.4	-
Jhikhu Khola	111.4	1118	2200	790	1410	17	6.6	7.0	10.0
Lower Andheri K.	5.4	1182	1700	850	850	18	7.5	6.6	10.6
Upper Andheri K.	1.8	1408	1700	1070	630	23	6.9	6.2	11.7
Kukhuri Khola	0.7	1280	1500	1070	430	21	7.8	6.2	10.8
Kubinde Khola	1.5	908	1000	850	150	12	7.9	7.4	9.9

K. = Khola DD = drainage density Rel. area = relative contribution area

* The Topoindex was calculated on the basis of 50m*50m grid cells

- The two sub-catchments within the Lower Andheri Khola,viz., the Upper Andheri Khola and the Kukhuri Khola sub-catchments, are generally steep and show low inclination towards saturation. They can be characterised as typical upland catchments within the Jhikhu Khola catchment.
- The Kubinde Khola sub-catchment, on the south-facing slopes of the Jhikhu Khola catchment, shows a very low elevation range and low mean slope with high mean Topoindex.

The potential impact on water and erosion parameters can be described as follows.

- The Jhikhu Khola catchment has high erosive potential along the side slopes where steep slopes prevail. The flat valley bottom acts as a sediment depository and therefore a low sediment delivery is expected for the entire catchment. Similar observations are expected in terms of runoff generation with high potential for runoff along the foot slopes of the catchment, and high infiltration and percolation in the flat valley bottom leading to lowered flood peaks at the outlet of the catchment. In terms of water availability, morphometric characteristics have little influence, except that the flat valley bottom may act as major groundwater storage. This, however, is dependent on the geology of the catchment (see below). The low altitude of the catchment is expected to have an impact on the rainfall amount as well as the evapotranspiration rates.
- In the Yarsha Khola catchment, fast response to rainfall is expected due to its steep slopes as well as missing flood plains within the catchment. This is not only shown by the slopes, but also by a relatively low mean Topoindex. In addition to this, the balanced shape of the catchment may lead to a rapid concentration of floods. Sediment output as well as flooding is therefore expected to be high at the outlet of the catchment. In terms of water availability, the high mean elevation may reduce the evapotranspiration and have an effect on the rainfall amount.

The observed impact of the catchment characteristics is further described in Chapter 3, Section 3.5 (rainfall-runoff event analyses) and Section 3.6 (sediment transport and mobilisation) in particular.

2.3.3 Comparison of land use and land-use change

2.3.3.1 Importance of land use and land-use change

The importance of land use and land-use change on different aspects of the hydrological cycle, including water availability and flood behaviour, has been mentioned on many occasions and was discussed in Chapter 1. From Table 1.6 it is evident that forest plantations and deforestation as major land-use changes affect larger areas only a little. While these changes reflect themselves on micro- to lower meso-scale catchments, the effects on larger catchments are negligible. This is particularly true for all directly water-related parameters. Water quality and pollution-related parameters are found to show changes on all scales through the effect of land-use change. These are important considerations for up-scaling from micro and meso-scale information to macro-scale management.

Mean annual runoff and therewith overall availability of water is mainly influenced by altered vegetation cover and changing soil properties, which are both closely linked to land use and land management. Changing vegetation cover results in changing rates of evapotranspiration and interception. Altered soil properties mainly manifest themselves in terms of changed water-holding capacity and infiltration rates (Merz and Mosley 1998). The following changes were observed and reported in the literature (FAO 2002):

- in general, a change in land cover from low to high evapotranspiration rates decreases the annual mean flow;
- in general, a reduction in forest cover increases water yield; and
- exceptions to the rule are cloud forests and very old forests, which may consume less than newly-established forests.

Flow during the dry season depends largely on the base flow and the groundwater availability. Increased evapotranspiration rates through afforestation may lead to decreased base flows, as examples in Thailand have shown (FAO 2002). It was also shown that dry periods and droughts might not be substantially altered due to changes in forest cover (Brooks et al. 1991). Local observations by farmers from the Jhikhu Khola have shown that certain springs dried up after an afforestation programme in the area that planted Chir pine (*Pinus roxburghii*).

Peak flows are mainly a function of soil properties in addition to rainfall characteristics. With increased compaction of the soils through changes in land use or management, the infiltration capacity of the soil decreases and therefore increases the probability of runoff generation (Scherrer 1997). However, this effect diminishes with increasing event size (Merz et al. 2000a; Bruijnzeel 1990).

Sediment load is less influenced by land use, and more by land management (Calder 2000; Dangol et al. 2002). A poor quality forest with hardly any understorey yields more sediment than a well-maintained and well-managed piece of agricultural land. Dangol et al. (2002) showed that the biggest soil losses in a period of seven years occurred within ten days of weeding in terraced, rainfed agricultural land.

2.3.3.2 Current land use

The catchments of this study are all smaller or around 100 km^2, and therefore differences in hydrological parameters should be evident. The land use in the three main catchments is divided into classes, as follow.

- Irrigated agricultural land (level terraces; Zonneveld et al. (1986)

  In Nepal, this category is commonly known as ‘khet’, which can be defined as level terraces with a bund along the terrace riser (Figure 2.11). This land is irrigated by applying conventional flood and furrow irrigation.
- Rainfed agricultural land (sloping terraces; Zonneveld et al. (1986)

  The common name for this class is ‘bari’ in Nepal, which can be defined as sloping terraces without a bund along the riser (Figure 2.11). There is no provision for conventional irrigation on this land.

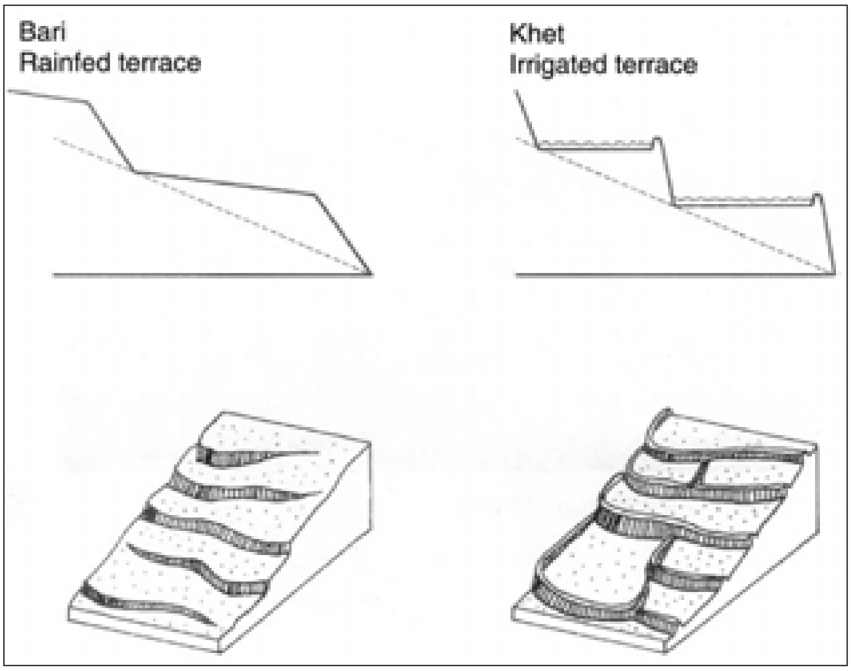

Figure 2.11: **Comparison of irrigated and rainfed agricultural terraces (from Ries 1994)**

- Forest land

  Zonneveld et al. (1986) defines a forest as an area with a crown density of more than 10% of the area.
- Grassland

  Zonneveld et al. (1986) defines grass lands as those areas mainly used for grazing, which lack sufficient shrub or tree cover to appear as forestland.
- Others

This class includes rock outcrops, settlements, roads, landslides/gullies/slips and water bodies.

It is evident that the two catchments from Nepal are heavily dependent on rainfed agricultural land, which accounts for up to 40% of the area of the two catchments (Figure 2.12). The total agricultural land accounts for more than 50% of the total area. Forested land contributes approximately 30% to the total area in the case of the Nepal catchments, while the amount of grazing land is very small.

As shown in the case of the catchments above, the sub-catchments of the Jhikhu Khola also differ mainly in terms of areas of forest and rainfed agricultural land (see also Figure 2.13). The two tributaries to the Andheri Khola, the Upper Andheri Khola, and the Kukhuri Khola have a high percentage of rainfed agricultural land (55 and 63% respectively). Their forest areas are about 20% of the total catchment area. In both sub-catchments there is hardly any irrigated land as both are

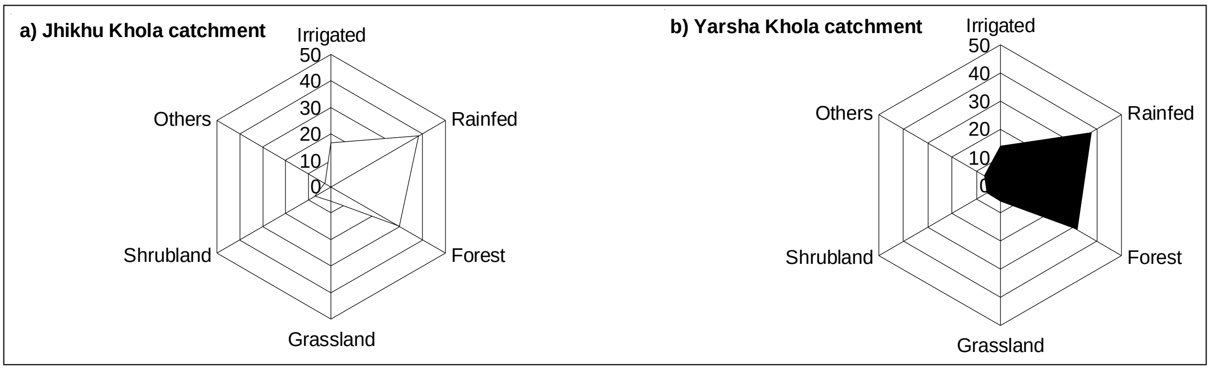

Figure 2.12: **Land use in a) the Jhikhu Khola catchment and b) the Yarsha Khola catchment**

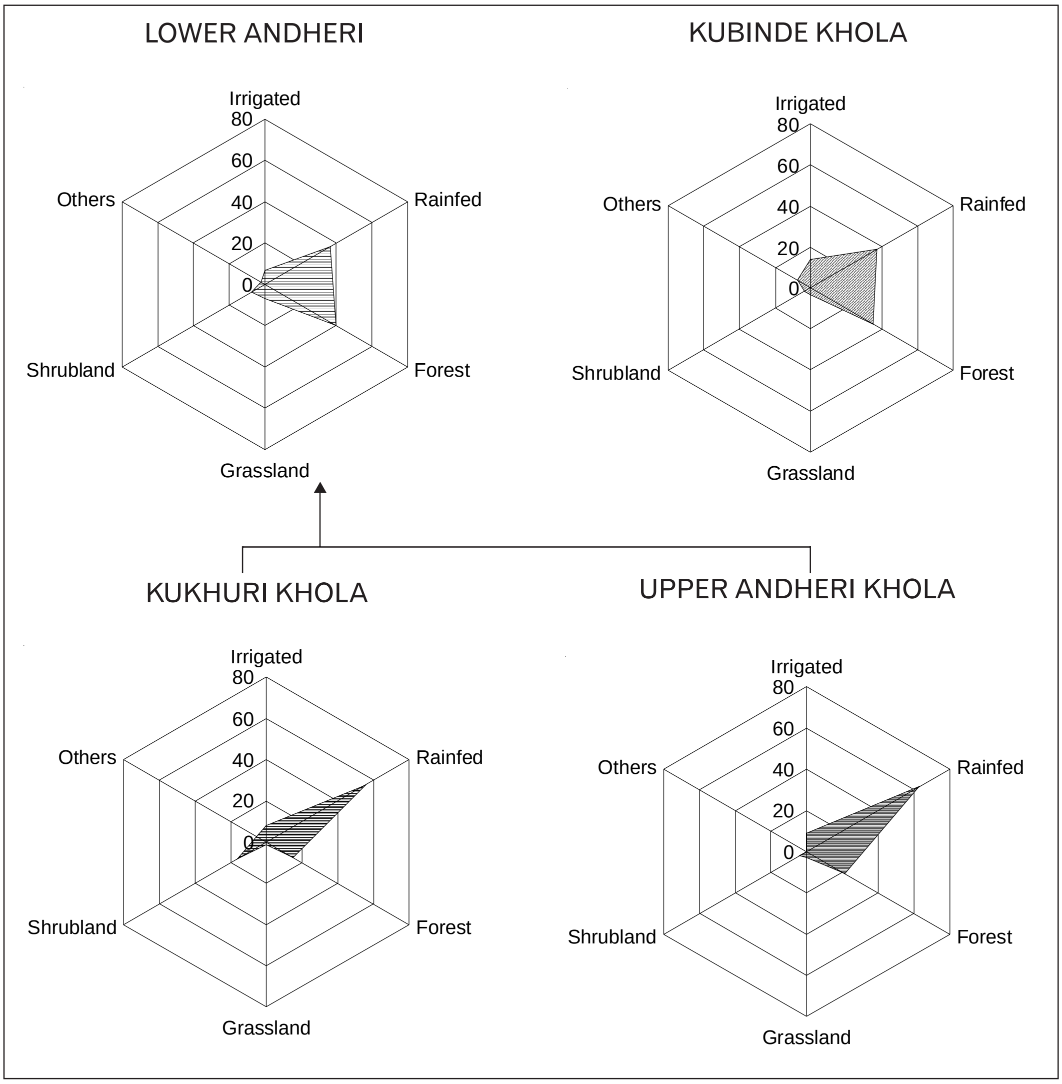

Figure 2.13: **Land use in the sub-catchments of the Jhikhu Khola catchment**

upland catchments with narrow valley bottoms, often only as broad as the river course. The Lower Andheri Khola and the Kubinde Khola sub-catchments are comparable in terms of land use, as in both cases rainfed agricultural and forest land contribute around 40% to the total area. The contribution of irrigated land is slightly higher in the case of the Kubinde sub-catchment (Table 2.5).

The most intensively cultivated catchments are the two headwater catchments of the Andheri Khola, where the area of the cultivated land is two to three times the uncultivated area (Table 2.6). The Lower Andheri Khola sub- catchment, on the other hand, is only sparsely cultivated in the lower stretches, shown with the ratio of 0.8.

Table 2.5: **Land-use related catchment characteristics**

Catchment name	Survey year	Scale	Total Area in ha	Irrigated land in%	Rainfed land in%	Forest in%	Grass-land in%	Others in%	Shrub-land in%
Jhikhu Khola	1996	1:20'000	11141	16.5	38.3	29.8	5.5	2.9	7.0
- Kubinde Khola	1996	1:20'000	149	14.1	37.6	34.9	3.4	7.4	3.4
- Lower Andheri Khola	1996	1:20'000	539	6.9	36.7	39.9	6.9	2.2	7.6
- Upper Andheri Khola	1996	1:20'000	178	9.0	62.9	21.3	2.8	0	3.9
- Kukhuri Khola	1996	1:20'000	74	8.1	55.4	14.9	1.4	5.4	16.2
Yarsha Khola	1996	1:25'000	5338	13.9	37.4	31.5	5.8	6.4	5.4

Table 2.6: **Ratio of cultivated / uncultivated and rainfed / irrigated land for all catchments**

Catchment name	Cultivated / uncultivated	Rainfed / irrigated
Jhikhu Khola	1.2	2.3
- Kubinde Khola	1.1	2.7
- Lower Andheri Khola	0.8	5.4
- Upper Andheri Khola	1.7	7.0
- Kukhuri Khola	2.6	6.8
Yarsha Khola	1.0	2.7

The project was initially started in 1990 due to the perceptions of extensive land degradation in the middle mountains of the HKH. Here, degraded lands are defined as areas with minimal vegetation cover on landslides, rilled and gullied surfaces, areas subject to frequent sheet erosion, and continuously eroding river banks (Shah et al. 2000). The comparison of the contribution of degraded areas to the total area of the study catchments and sub-catchments shows that the Kubinde Khola catchment displays the largest area of degraded land, about 12% of its catchment area. The Lower Andheri Khola catchment is about 10% degraded. These areas are mainly confined to the lower stretches of the sub-catchment, as the upper parts show only low degradation. The Kukhuri Khola has no degraded areas and the Upper Andheri Khola has only about 2% degraded areas. Approximately 5% of the entire Jhikhu Khola catchment has degraded lands according to the definition above.

Gullies and badlands, the most severe forms of land degradation, are not the only way in which the degradation of land resources manifests itself. Overuse of forest resources or afforestation with the wrong species can lead to degraded forests where there is no undergrowth. Overgrazing of grasslands can lead to decreasing vegetation cover and finally support sheet and rill erosion. These forms of degradation have not been considered in the above classification of degraded lands, but play a major role in the hydrological response of a catchment.

2.3.3.3 Land-use change and agricultural intensity

In rural catchments of the Hindu Kush-Himalayas, land-use change and agricultural intensity go hand in hand. Where agronomic intensity is decreasing, land use may change towards extensificiation and abandonment of agricultural fields. An increase in agronomic intensity is first manifested in the extension of irrigated land to all possible areas, followed by an extension of the rainfed areas to steep and marginal land. Finally, already developed fields are intensively cultivated with multiple crops and high fertiliser and pesticide application rates.

Land use changes in the Jhikhu Khola between 1947 and 1990 are well documented in Shrestha and Brown (1995). A period of deforestation between 1950 and 1960, when forests in Nepal were nationalised, was followed by an increase in forest cover through active afforestation programmes in the area. In the period 1947 to 1981 agricultural and shrubland increased at the cost of the forest land. This trend was followed between 1972 and 1990 by decreased grazing and decreasing shrub areas, and increasing areas of rainfed agriculture. The irrigated agricultural land remained stable throughout the entire period.

For the period between 1990 and 1996, Upadhyay (2001) showed that land use in the Jhikhu Khola catchment was stable. Only small changes in the magnitude of 1 - 2% occurred in all land-use types.

The trend of stabilising or even increasing forest area will most probably continue, as about a third of the forest in the catchment (11.8 km^2) is under the protection of the community forestry regulations, which does not allow clear felling. This includes the area of 36 of the total 39 community forest areas in the catchment in the year 2002 (Shrestha and Tuladhar 2002). Furthermore, some of the shrubland (0.9 km^2), grazing land (0.4 km^2), and rainfed agricultural areas (1.2 km^2) are also included in the community forest area, which suggests that they should remain stable or will be covered in forest in the future.

Land-use change in the Yarsha Khola catchment is documented in Shrestha (2000a). In the period between 1981 and 1996 the areas of rainfed agricultural land and shrub were observed to decrease. Forest cover increased from 21 to 31% of the total area. Grazing and other uses, amongst them settlements and infrastructure, likewise increased in area over this period. Although Shrestha

Table 2.7: **Current trends for land-use change**

Land use	Jhikhu Khola	Yarsha Khola
Irrigated agricultural land	stable	stable
Rainfed agricultural land	stable	decreasing
Forest	increasing	increasing
Grassland	decreasing	increasing

(2000a) stresses that the figures have to be considered with caution, the trend shows that forest land has gained at the cost of rainfed agricultural land and shrub. A comparison of the two catchments can be found in Table 2.7.

The two catchments differ largely in terms of access to markets, which is considered to be one of the major factors influencing agricultural intensity. The Jhikhu Khola catchment is only 45 km from Kathmandu, providing the farmers of the catchment with first class possibilities for selling their produce. Many farmers have started to grow cash crops such as potato, tomato, bitter gourd, chilli, and others in the catchment (Pujara and Khanal 2002). Cash crop production is closely related to increasing use of fertilisers and pesticides. The environmental risk of using large quantities of pesticide was closely studied by Herrmann and Schumann (2002) in the Jhikhu Khola catchment. Preliminary results of this study show that the actual environmental pollution through pesticide storage in the topsoil and its water bound transport is less than expected. However, health risks may still be present due to unsafe application practices and accumulation in the food chain.

The dynamics of agricultural intensity in the catchment can be shown by the historic changes of cropping intensity and changes in cropping patterns. According to Multidisciplinary Consultants (1988), the crops on irrigated land in Kavrepalanchowk district in the 1980s included rice, wheat, and potato. According to Shah (pers. comm.), during the late 1980s and early 1990s potatoes were grown in this district during the dry season on irrigated land, mainly in the area of Banepa, Panauti, and Dapcha Khola. Only a few farmers grew potatoes during the dry season in the Jhikhu Khola catchment. In addition, farmers often kept their land fallow in the dry season. A comparison of survey data from 1989 and 1999 has shown that the usual fallow periods, which were indicated by the farmers in 1989, have largely disappeared (Dangol et al., in prep). Rice and wheat dominated the cropping calendar in 1989. In 1999, the cropping diversified with a number of cash crops–including many farmers growing tomatoes, potatoes and different vegetables.

Yarsha Khola, on the other hand, is about 10 hours by bus from Kathmandu and therefore has only limited market access. Cash crop production is limited and includes mainly seed potatoes and garlic. Due to the elevation, the pest problem is not acute for these crops and pesticides are only used to a limited extent. In the Xizhuang catchment only one to two crops are grown on the irrigated land, with maize grown during the monsoon followed by wheat as a dry season crop. On the dry land, maize is grown and sometimes intercropped with soybean. Tea has, in many cases, taken over from maize on the dry land. It is the tea gardens which receive high pesticide doses. Otherwise pesticides are only used to a limited extent.

Livestock are an integral part of the farming systems in the middle mountains of the HKH (Dixon et al. 2001). The animal composition consists mainly of buffaloes, cattle, and goats (Table 2.8). In the Yarsha Khola, a number of families own ‘chauri’, a cross between yak and zebu cattle. Other animals, such as pigs, are only rarely found and are therefore not included in the calculations below. In order to compare the different animals and calculate stocking densities, tropical livestock units (TLU) were used as reported by Brown (1997). The stocking densities as reported by Brown (1997) show a similar magnitude with 3.8 TLU/ha cultivated land compared to 4.0 TLU/ha cultivated land in this study.

Brown (1997) notes that the maximum stocking densities in the Jhikhu Khola catchment belong to the highest in the world. According to FAO (1990; Thapa and Paudel 2000) Nepal’s stocking is about 7 TLU/ha cultivated land, a very high density compared to other countries in the Asia Pacific region. Kiff et al. (no date) compiled stocking densities of 2.9 to 5.8 TLU/ha on the basis of different studies from Nepal. The values from the two studied catchments, 4.0 in the Jhikhu Khola catchment and 5.8 TLU/ha cultivated land in the Yarsha Khola catchment, can therefore be assumed to be high in an overall context. However, Thapa and Paudel (2000) argue that carrying capacities based on cultivated land are not appropriate as livestock in the middle mountains of Nepal depend primarily

Table 2.8: **Livestock numbers and stocking density in the Jhikhu and Yarsha Khola catchments**

Animal	TLU* equivalents	Jhikhu Khola (8002HH)[2] No./HH#	TLU	Yarsha Khola (4362 HH) No./HH#	TLU
Buffalo	1.0	1.2	9602.4	1.1	4798.2
Bullock	1.0	0.8	6401.6	1.5	6543.0
Cow	0.8	0.9	5761.4	0.9	3140.6
Goat	0.1	3.5	2800.7	3.3	1439.5
Total			24,566.1		15,921.3
Stocking density entire catchment [TLU/ha]			2.2		3.0
Stocking density per cultivated land [TLU/ha]			4.0		5.8

* according to Brown (1997)
\# according to Merz et al. (2002)

on forest and, secondarily, on grasslands. They propose that stocking densities be determined on the basis of the entire catchment area. Using this approach, stocking densities of 2.2 in the Jhikhu Khola catchment and 3.0 in the Yarsha Khola catchment, respectively, are reported.

Table 2.9: **Agronomic intensity**

	Jhikhu Khola#	Yarsha Khola*
No. of crops on irrigated land	2-3 crops (up to 4)	2-3 crops
Productivity on irrigated land	high	low
No.of crops on rainfed land	1-2 crops (up to 3)	1-2 crops (up to 3)
Productivity on rainfed land	high	low
Fertilizer use	very high	medium
Pesticide use	very high	low
Livestock stocking density	high	high
Overall agricultural intensity	**very high**	**Medium**

\# Merz et al. (2002)
* Shrestha and Neupane (2002)

An overall assessment of agronomic intensity allows the view that the Jhikhu Khola is probably one of the most intensively cultivated catchments in the middle mountains of Nepal, and therefore shows much more of an extreme than a representative case (Table 2.9). This allows the studies in the catchment to venture into the possible future direction of other areas which are intensifying their agriculture. The Yarsha Khola catchment is of medium agricultural intensity, mainly due to its missing or limited cash crop production.

2.3.3.4 Summary

The two catchments in Nepal are dominated by agricultural land and large forest areas, which have been increasing in recent years. The large area of irrigated land in particular is noticeable, indicated by the low ratio of rainfed to irrigated land. Land use in general is stable with minor changes in forest and grassland in the Yarsha Khola catchment, observed mainly with the abandoning of rainfed agricultural land on the steepest slopes and in inaccessible locations (Table 2.10).

Table 2.10: **Summary of land-use related catchment characteristics**

	Jhikhu Khola	Yarsha Khola
Ratio cultivated/uncultivated	1.6	1.4
Ratio rainfed/irrigated	2.3	2.7
Land use change	stable	increasing forest and grassland
Livestock stocking density	high	high
Overall agricultural intensity	very high	medium

In general, and on the basis of a comparison with catchments from the Andes (Schreier et al. 2002), the catchments of the HKH region seem to be very intensively cultivated with multiple cropping and high inputs of both organic and inorganic fertilisers.

The land-use parameters and agricultural intensity are most likely to have a major impact on the water quality parameters in the catchments. But water quantity is also considered to be affected by

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[2] **Household**

the high percentage of irrigated land as well as cropping intensification and use of new varieties. For flood and sediment considerations, both the high degree of human intervention with respect to the high percentage of cultivated land as well as the considerable areas of degraded land may be of importance. Major land- use changes are not expected in Nepal, unless there are major policy decisions such as in China with reference to the Upland Conversion (Xu and Salas 2002) or economic driving forces that pressurise people to abandon or expand their cultivated areas.

2.3.4 Other biophysical characteristics and their comparison

Some of the other important biophysical characteristics of a catchment include its geology, the soils, and the landforms and geomorphologic setting (Baumgartner and Liebscher 1996). These characteristics are all closely interlinked. Geology's influence on the hydrological cycle is mainly evident in terms of water availability, water storage in aquifers, and release of the water during the dry season as baseflow. Porous and fractured rocks as well as quaternary formations in particular support water storage. This is closely linked with landforms, for example, an extended sediment deposition in a valley bottom is more likely to act as a major aquifer than the same sediment on a valley slope. Karstic areas, on the other hand, show very low water availability on the surface as most of the available water percolates into the shallow or deep groundwater, feeding often large and extensive karst aquifers and springs with large yields (Baumgartner and Liebscher 1996). An example for one of these good spring sources is the Tiger Cave spring in the Xizhuang catchment yielding about 200 l/min (Gao et al. in prep.).

The interrelationship between soils and water is important for runoff generation, land degradation, and water storage. For runoff generation, physical soil properties, such as texture and bulk density, are important for the determination of flow through the soil's column. Soil compaction with subsequent decrease in infiltration capacity may lead to an increase in peak flows (Scherrer 1997). The increase in terms of peak flows after land- use change towards lower infiltration capacity is expected to be largest in small events and smallest in large events (FAO 2002). The same was shown by Merz et al. (2000a) for the Yarsha Khola catchment in Nepal on the basis of 1998 data, where at a certain threshold land use did not matter for the generation of runoff at a plot scale, but all plots yielded high runoff volumes.

2.3.4.1 Geology

Nakarmi (2000a) elaborates on the geology of the Jhikhu and Yarsha Khola catchments. The Jhikhu Khola catchment area belongs to two domains, the Lower Kathmandu Complex and the Upper Nuwakot Complex, dissected by the Mahabarat Thrust. Lithologically, six formations–including meta-sandstone, schist and quartzite intercalation, mica schist, quartzite, marble, and garnetiferous mica schist– make up the Lower Kathmandu Complex. The Upper Nuwakot Complex consists of dark grey slate, intensively-folded green schist, grey phyllite, limestone, and dolomitic limestone. Hydrogeologically and for water availability considerations, the carbonate rocks (Shrestha 1999) and the alluvial valley fill are important (see also Section 3.4).

The Yarsha Khola catchment's geology consists of low- to medium-grade metamorphic rocks. The valley is basically formed by a syncline with graphitic schist and dark slate in the synclinical fold and mainly gneiss and phyllite along the flanks of the syncline. The black schist is underlain by a succession of talc, magnesite, and medium to thickly bedded quartzite. Green phyllite and chlorite schist underlay the quartzite bed, on the basis of which gneiss is found. This geological constellation does not show a particular constraint or benefit for water storage. In terms of water quality, however, the south- facing slopes tend to be more acidic as they are located on gneissic rocks. Water draining the talc and magnesite band exhibits very high electrical conductivity (Shrestha et al 2001).

2.3.4.2 Soils

The soils of the Jhikhu Khola were first described by Maharjan (1991) on the basis of a comprehensive soil survey. In general, the soils are of loamy texture and are moderately well to rapidly drained. Shah (1995) presents the indigenous soil classification in the catchment. A good relationship was found between this classification based on the vast knowledge and experience of the local farmers and selected land quality parameters. Since then, several publications have described the soil fertility issues and dynamics in this catchment. The issues include soil acidification (Schreier et al. 1995), nutrient losses, and dynamics — in particular phosphorous (Carver and Schreier 1995; Brown 1997; Brown and Schreier 2000; Von Westarp 2002). While the phosphorous levels used to be well below desirable levels (Schreier and Shah 2000), phosphorous is now in surplus in the very intensively-used fields due to increased fertiliser availability and inputs (Von Westarp 2002). Simultaneously, phosphate levels in groundwater as well as surface water is likewise elevated and is, in places, above guideline values (Merz et al. 2003c).

The soils of the Yarsha Khola catchment were described in Schreier and Shah (2000) with particular reference to soil fertility issues. It was found that the conditions in the Jhikhu Khola catchment were also represented in this catchment, that is, acidification and phosphorous dynamics. The latter issue was even more pronounced in the Yarsha Khola catchment, as there is only limited access to phosphorous fertiliser in this catchment as shown by Brown (2000b). The soils in the Yarsha Khola catchment tend to have adequate carbon content, particularly at the higher elevations.

According to Shah et al. (2000), red soils (Rhodustalfs; Carson et al. 1986) are particularly sensitive to degradation. Their chemical properties are inherently different, mainly dominated by iron and aluminium oxides, with kaolinite as the dominant clay mineral. The surface of these soils is often encrusted and their infiltration rates and permeability are low. This leads to a constant hazard of sheet, rill, and gully erosion on bare red soil surfaces (Carson et al. 1986).

Red soils are very common in the PARDYP catchments, making up more than a third of the area of the Jhikhu Khola catchment (Table 2.11). More than 3/4 of the area of the Kubinde Khola (a sub-catchment of the Jhikhu Khola) is covered by red soils.

Table 2.11: **Red and non-red soils in the catchments**

Catchment name	Red soil [ha]	Red soil [%]	Non-red soil [ha]	Non-red soil [%]	Ratio red / non-red
Jhikhu Khola	4132	37	7009	63	0.59
- Kubinde Khola	114	77	35	23	3.26
- Lower Andheri Khola	203	38	336	62	0.60
- Upper Andheri Khola	35	20	143	80	0.24
- Kukhuri Khola	17	23	57	77	0.30
Yarsha Khola	665	12	4673	88	0.14

In this sub-catchment, the area of red soils is higher than the area of non-red soils, which is shown with the ratio red/non-red soils. The Jhikhu Khola catchment displays a high ratio as well. The Yarsha Khola catchment has only very small patches of red soils, generally in the lower stretches of the catchment and on the middle ridge.

Additional information collected over time in the Jhikhu Khola catchment on biophysical characteristics includes landforms (Maharjan 1991) and sediment sources (MRE 2002). In the Yarsha Khola, Tschanz (2002) documented the geomorphologic processes on the south-facing slopes. This information is referred to and described in more detail in Section 3.6, dealing with sediment issues.

It should also be noted that the red soils represent the oldest and most weathered soils in Nepal, and they are usually not present above 1700 to 1900 m elevation due to climatic effects and more extensive degradation processes at higher elevations (steeper soils).

2.3.4.3 Summary

The main geological and soil characteristics of the two catchments are compiled in Table 2.12. The geology is dominated by rock formations favouring acidic soil conditions. This is in addition to the acidifying chemical fertilisers discussed above. The catchment of the Jhikhu Khola shows a very high percentage of red soils, which are generally very vulnerable to surface erosion and gullying.

Table 2.12: **Summary of biophysical catchment characteristics**

	Jhikhu Khola	Yarsha Khola
Dominant geology	mica schist and calcareous schist	gneiss and slate+graphitic schist
Dominant soils	well-drained soils of loamy texture; red soils in the lower part of the catchment	loamy textured soils
Ratio red/non-red soils	0.59	0.14
Soil fertility issues	soil acidification, phosphorous dynamics, low cation exchange capacity (CEC) and base saturation	soil acidification, phosphorous dynamics, low CEC and base saturation

The Yarsha Khola catchment has only some patches of red soil in the lower stretches of the catchment. The soil fertility issues are very similar in all three catchments, with soil acidification and phosphorous dynamics being the main problems.

The impact on the water resources from these biophysical characteristics was touched upon above. The low phosphorous levels in the soils in all catchments forces farmers to use high doses of fertiliser, which they often apply in excessive amounts (see Merz et al. 2002). While this is certainly true in the Jhikhu Khola, in the Yarsha Khola access to fertiliser is still limited but may be a major problem in the near future. Soil acidity may further lead to acidic water in the catchment.

In terms of water quantity, the existence of carbonate rocks and karst features may have an impact on increased water availability in terms of well-yielding springs and also in terms of dry surface conditions due to rapid percolation.

2.3.5 Population and socioeconomic characteristics and their comparison

High population density and increasing population growth are often held responsible for resource degradation in the HKH. As shown above, this is an issue in the middle mountains of the HKH region with population densities of 500 people/km^2. The catchments studied all have high population densities above 75 people/km^2. The Jhikhu Khola catchment has the highest density with 437 people/ km^2, followed by the Yarsha Khola catchment with 386 people/km^2. These densities are amongst the highest population densities in the region when compared with data from Sharma (1994). Population increase is rapid in the Nepal catchments. In the Jhikhu Khola catchment an annual population growth rate of about 3.5% was determined between 1947 and 1996 (Figure 2.14) and 3.1% during the period from 1990 to 1996. The last five to ten years in particular have experienced rapid population increase due to natural growth and immigration. Brown (2000a) documented a 1.8% growth rate per annum between 1972 and 1990 and 2.6% between 1990 and 1995 in the Bela-Bimsensthan sub-catchment of the Jhikhu Khola catchment. For the Yarsha Khola catchment the annual growth rate was 2.7% for the period from 1981 to 1996.

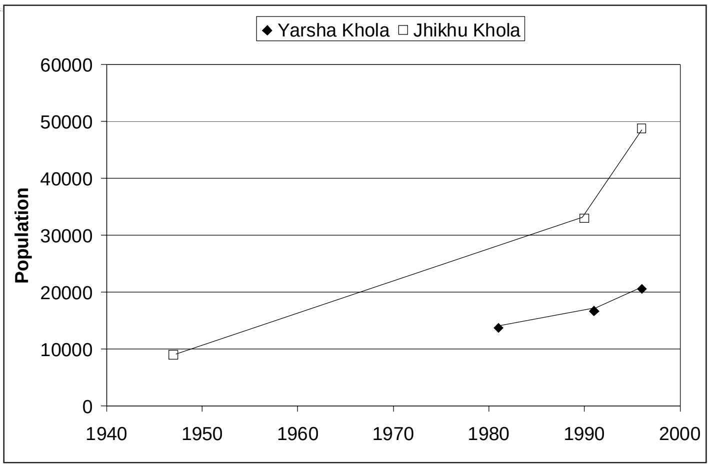

Figure 2.14: **Population dynamics in the Jhikhu Khola and Yarsha Khola catchments**
(data source: PARDYP)

The households in the Nepal catchments are quite large. In 2000 in the Jhikhu Khola catchment household size ranged from 2 to 27 with an average of 6.9 people per household (Merz et al. 2002). Shrestha and Neupane (2002) reported an average of 6.6 people per household for the Tinpiple sub-catchment in 1999. The household size in the Yarsha Khola catchment was 5.8 in 1999, ranging from 2 to 13 people per household (Merz et al. 2002).

The ethnic groups and castes represented in the Jhikhu Khola catchment are Brahmin, Chhetri, occupational groups (including Kami, Sarki, and Damai), Newar, Tamang, Danuwar, Magar, and Gurung. In the Yarsha Khola, Danuwar, Magar, and Gurung are replaced by Sherpas (Allen et al. 2000).

Land provides the major source of income for most rural households in the Nepal middle mountains. The social and economic status of a household therefore depends heavily on the amount of land, the type of land (rainfed vs. irrigated), the quality of land, and its accessibility. In general, land holdings in Nepal's middle mountains are small and fragmented. Yadav and Sharma (1996; cited in Thulachan 2001) reported an average parcel size of 0.2 ha with average holdings of 3.9 parcels or 0.78 ha per household in the high and middle mountains of Nepal. Approximately two-thirds of farm households have small land holdings of less than 0.05 ha and can be classified as marginal farmers. Less than a quarter of the households in these physiographic regions own 0.051 to 1 ha of agricultural land and 20% own more than 1 ha. Median land holding per household in the Bela-Bimsensthan sub-catchment was 0.92 ha during a survey of 85 households in 1994, with 53% of the households owning only 25% of the land or land holdings below 1 ha (Brown 2000a). Shrestha and Neupane (2002) report similar figures from a survey in 1999, with 52% of the households owning 22.5% of the land in the Tinpiple sub-catchment, another sub-catchment of the Jhikhu Khola catchment. In their study area more than 93.5% of the households (187 of 200) belonged to the group of marginal to small farmers with marginal farmers owning below 0.5 ha and small farmers between 0.5 to 1.5 ha land. Average land holding size was 0.60 ha (note the difference in classification of land holding sizes compared with Yadav and Sharma (1996), above.

In the Yarsha Khola catchment, Brown (2000b) reported a median land holding size of 0.8 ha per household in a survey of 150 households in 1998. Of these households, 67% owned 38% of the land and had holdings below 1 ha. A recent report by the Centre for Environmental and Agricultural Policy Research, Extension and Development (CEAPRED 2003) reports average land holding sizes of 0.94 ha/household in selected VDCs of the Kavrepalanchowk district, most of them in the Jhikhu Khola catchment.

Of the households taking part in various surveys, 21 to 50% reported that the land their farms did not yield enough for them to be self-sufficient (Shrestha and Brown 1995). In the Yarsha Khola catchment, 53% of the households were not able to fulfil their food demand from farming (Brown 2000b). CEAPRED (2003) indicates that only households with good access to irrigation water are self-sufficient in food. To keep up with demand, some household members are forced into off-farm employment, which together with the sale of agricultural products forms the main source of cash income for rural households in Nepal. The main off-farm activities reported by Shrestha and Brown (1995) were brick making, carpentry and masonry, shop/businesses, and farm labour. Lack of jobs and, in some cases, also landlessness forces many people in Nepal to migrate, mainly to urban centres, but also abroad (K.C. et al. 1998).

It can be summarised that, in the catchments of PARDYP Nepal, the population exerts significant pressure on the availability of natural resources, including water. The current population densities are amongst the highest in rural areas of the region (Table 2.13). Although agricultural production is very intense, in particular in the valley bottom of the Jhikhu Khola catchment, many households still do not produce enough food to reach self-sufficiency. This is mainly due to very small land holdings in these areas. Off-farm employment and often seasonal or even lifetime migration are solutions to lack of jobs in the rural areas as well as landlessness.

Table 2.13: **Summary of population and socioeconomic characteristics**

	Jhikhu Khola[*]	**Yarsha Khola**[**]
Total population (year)	48,728 (1996)	20,620 (1996)
Population density [people/km^2]	437	386
Growth rate [%] (period)	3.5 (1947-1996)	2.6 (1971-1996)

[*] Allen et al. (2000)

[**] Shrestha (2000)

2.3.6 Summary

The Yarsha and Jhikhu Khola catchments range from 50 to 110 km^2 in size. Due to their steep slopes, they have a high erosion and flood generation potential. While the Yarsha Khola catchment is expected to transmit the mobilised sediment and runoff through the outlet, the flat valley floor of the Jhikhu Khola catchment is expected to dampen the flood wave and act as a sediment depository.

Agriculture demands most water, with the majority of the area under irrigated or rainfed cultivation systems. Forest areas have the next biggest need for water. The forest areas have increased to a small degree in both catchments. Land-use changes, however, are believed to be stable. Both catchments have extensive red soil areas as well as large areas of degraded land. While the gullies and badlands are the most visible form of degraded land, a large part of the forests and grazing areas are also strongly degraded, visible through very poor vegetation cover and, often, low biodiversity. Agricultural areas are very intensively cultivated in the Jhikhu Khola catchment. A medium intensity of agricultural cultivation can be seen in the Yarsha Khola catchment

2.4 MEASUREMENT NETWORK AND DATA PREPARATION

Data availability for in-depth process studies has been the main limiting factor to improving the understanding of environmental issues in the HKH region. For this purpose, PARDYP has set up a research monitoring network across the HKH in five catchments. While this is by no means a representative sample of the entire region, it will provide an insight into the relevant processes leading to flooding, water availability constraints, and sediment mobilisation and transport at a high spatial and temporal resolution. The high resolution is achieved by means of automatic monitoring of temporal key parameters and detailed field surveys of spatial parameters. After an introduction of the basic principle of the measurement network design, the three steps from the field to the available data are discussed. This includes data collection, data management, and data dissemination.

2.4.1 The nested approach

This approach to measurement network design has its origin in the understanding that hydrological processes vary with scale, as, for example, described in Ives and Messerli (1989) and recently in FAO (2002). The idea of this network design is based on the investigation of processes and balances at different scales. For each scale, all input variables are determined by means of measurements, that is, at the plot scale rainfall is measured with a rain gauge, and runoff and soil loss are measured by means of the erosion plot method (see below for details). At the next larger scale, measurements are conducted by means of one or several representative rain gauges for the assessment of areal rainfall, by hydrological measurements at a hydrological station located at the outlet of a well-defined sub-catchment. The integral systems' response of the entire catchment is monitored at the outlet by means of hydrological and sediment measurements after establishing areal rainfall from a number of representative and well-distributed rain gauges. The approach is schematically described in Figure 2.15

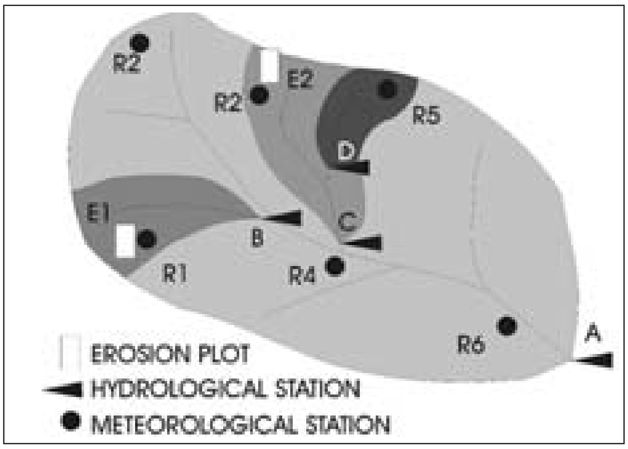

Figure 2.15: **The nested approach – a schematic explanation (abbreviations are explained in the text)**

Using the example in Figure 2.15, the response of the surface to a rainfall event measured at the raingauge R1 is investigated in the erosion plot E1 adjacent to the rain gauge. The response to the same event is then observed at the hydrological station of the sub-catchment B and finally at the outlet of the main catchment A. Relating the processes from the rain gauge, to the erosion plot, to the hydro stations at the sub-catchment and catchment levels allows one to draw conclusions about the processes involved. For this project the approximate size of the catchment scale was determined to be about 30 to 120 km^2 corresponding to the hydrological meso-scale. The catchments are believed to be representative of their environment or already showing the possible impacts of future processes in the region. The sub-catchments in the catchments are between 0.7 to 17 km^2. They either represent a specific part of the catchment, such as the north-facing slopes, or homogenous land use/land cover (as far as possible). The plot scale is of 100 m^2 representing dominant land use believed to be decisive in the runoff generation and sediment mobilisation process.

2.4.2 Data collection

The first step in the development of a database is data collection. For this purpose, PARDYP set up (as of July 15, 2002) a network of 19 hydrological stations, 31 meteorological stations, and 24 erosion plots in the China, India, Nepal, and Pakistan catchments. The stations in the Yarsha Khola were closed down in 2001 due to political instability in the area, and are therefore not counted. All networks are designed according to the nested approach (see above).

In general, automatic instruments are crosschecked with manual readings of the station readers wherever possible. This also helps in case of instrument failure due to battery or electronic problems. All stations are maintained by local employees, usually the owner of the land, a shopkeeper close by, or anybody else trustworthy and supported by the community. The readers get a monthly salary and annually receive two one-day training sessions, including a technical session, a discussion on operational problems, and a social event with lunch. This helps keep the readers up-to-date with their daily job, provides an atmosphere conducive to the discussion of problems and issues, and maintains a close link between the full-time project personnel and readers. In this respect the readers are an important part of the project and are valuable for other project activities as they are loyal to the project (Box 2.1).

Monthly record sheets are collected on the day of salary distribution. Automatic instruments are downloaded by the field staff, either in the field office if the readers can bring the loggers on salary distribution day, or in situ at the station using laptops and data shuttles or storage modules.

Box 2.1: **Hydro-meteorological readers as extensionists: an example from India**

PARDYP India has successfully used the services of their hydro-meteorological readers as extensionists of PARDYP activities. The readers, who draw a monthly salary and therefore enjoy a welcome cash-income from activities close to their homes, are loyal to the project. They are often in contact with project staff and therefore exposed to the new ideas the project tries to implement. In this context, the readers in India have all tested new ideas such as fish farming (Kothyari et al. 2003), poly tunnels, poly houses, and other on-farm technologies. From there, other farmers in the vicinity are exposed and can learn from the experiences of their peers with these appropriate technologies in a farmer-to-farmer exchange. Other PARDYP teams such as PARDYP Nepal are planning to follow the same approach in future.

2.4.2.1 The instruments and data collection methods

The selection of appropriate instruments and methods has a major impact on data quality. After a short description of the applied methods and instruments, a list of experiences with the selected methods will be shown.

Hydrological monitoring

Hydrological monitoring in the Jhikhu Khola and Yarsha Khola catchments in Nepal was carried out at hydrometric stations at the catchment outlet as well as in selected sub-catchments. At the stations, the water level was recorded using water-level recorders of the pressure transducer and floater types (see Table 2.14 for details). These automatic measurements were substantiated and compared with manual measurements from staff gauges twice a day (8:00 NST and 16:00 NST), with more frequent readings being taken during flood events. Discharge was measured on an irregular basis with the aim of obtaining discharge values for different water levels in order to generate a rating curve (that is, water level-discharge-relationship). For further detail on the rating curves, refer to Appendix A 3.1. Depending on the local site conditions, dilution methods (Uranin and salt tracers)

Table 2.14: **Hydrological data collection methods and instruments in JK & YK**

Instrument	Parameter	Type	Stations*	Remarks
Pressure transducer	Water level	Vega or Kern sensor logger: KERN FL-2	JK 1 YK 1	Digital, 5 min interval in monsoon, 15 min interval in dry season
		Pressure sensor logger: Smartreader 7	JK 2, 7, 8	Digital, 2 min interval
Floater	Water level	OTT R16	JK 13 YK 2, 5, 7	Analogue
Conductivity meter	Discharge	WTW LF 330	JK 7, 8 YK 5, 7	Used with momentary injection method and salt tracer (NaCl)
Current meter	Discharge	Price A, Gurley USA	JK 1, 2, 13	Used with wading rod or cable
Mariott bottle/ Spectrofluorimeter	Discharge	Swiss Hydrological Survey	YK 1, 2	Used with constant injection method and Uranin tracer
Sediment sampler	Sediment concentration	DH-48	JK 1	Used with suspension cable
		DH-76	JK 2, 7, 8, 13 YK 1, 2, 5, 7	Used with wading rod

* JK 1 = Jhikhu Khola catchment site 1 YK1 = Yarsha Khola catchment site 1

or current metering were applied to measure discharge. The applied methods are described in Merz (1998; salt dilution technique; Appendix B.3), Dongol et al. (1998; current metering; Appendix B.4) and Spreafico and Gees (1991; dilution method using Uranin tracer). Additionally, sediment samples were taken with DH-48 and DH-76 sediment samplers depending on the local site conditions, initially on a regular basis and only later above a certain flood threshold. This was due to high processing costs and the time-consuming tasks of sediment analysis (see more details in the section on erosion plot monitoring).

Meteorological monitoring

In general, a meteorological station in PARDYP Nepal consists of a tipping bucket rain gauge, a standard rain gauge as used by the DHM, and a thermistor in a Stevenson screen surrounded by a fence to keep animals out. The manual standard rain gauge is read once a day at 8:45 NST, the Department of Hydrology and Meteorology's (DHM) standard time for morning meteorological readings in Nepal. Refer to Table 2.15 for further details of the instruments used.

Table 2.15: **Meteorological data collection methods and instruments in JK & YK**

Instrument	Parameter	Instrument/Sensor Height	Stations	Remarks
Tipping bucket	Rainfall amount/ Rainfall intensity	1m above ground level	all sites	8" diameter 0.2 mm - 1.0539 mm buckets Event recording logger HOBO or Smart Reader 9
Ordinary rain gauge	Rainfall amount	1m above ground level	all sites	8" diameter
Thermistor (Temperature logger)	Air temperature	1.25 m – 1.50 m above ground level	all sites	In Stevenson screen
Thermistor (Temperature logger)	Soil temperature	20 cm below ground level	all sites	
Temperature probe	Air temperature	1.25 m – 1.50 m above ground level	YK 7	Connected to Campbell CR10X
Soil temperature probe	Soil temperature	10 cm, 20 cm, 50 cm below soil surface	YK 7	Connected to Campbell CR10X
Humidity probe	Relative humidity	1.25 m – 1.50 m above ground level	YK 7	Connected to Campbell CR10X
Anemometer/Wind vane	Wind speed/ wind direction	1.25 m – 1.50 m above ground level	YK 7	Connected to Campbell CR10X
Net radiometer	Net radiation	1.25 m – 1.50 m above ground level	YK 7	Connected to Campbell CR10X

Erosion plot monitoring

Plots to monitor erosion, with areas of about 100 m^2 per plot (note that the Bela plot in the Jhikhu Khola catchment is only about 65 m^2), were established on lands under different usages. The plots consist of a (usually) 20 m long by 5 m wide area delimited by metal sheets. Runoff and eroded material are collected in a gutter system, funnelling them to a first 200 l drum. To provide further storage, another drum is placed in sequence. This second drum has a 10-slot divider only allowing $^1/_{10}$ of the runoff into the last drum.

For detailed information about all the plots and their properties, refer to the section below. Runoff observations and sediment samples from these plots are taken by local observers. They are responsible for collecting representative samples by thoroughly agitating the drum content and filling 0.5 l leak-proof plastic sample bottles after major rainfall events. However, they visit the sites and make observations at 9:00 every day even if there is no rainfall, in order to ensure clean and empty drums.

The samples are accompanied with observation details, indicating data and time of recording, runoff height, and the drum number from which the sample originated. The sampled volume is measured and sediment is filtered and dried at 65 - 75°C in an electric oven at the PARDYP field lab. The water collected in all drums represents the runoff from the plot in the given rainstorm. The sediment derived from the sample is extrapolated to the content of the entire drum. The results from all drums are then summed up to determine the total soil loss from the plot.

All calculations are performed in an MSExcel macro developed by PARDYP, which creates a data entry sheet, then calculates and summarises the data. Runoff and soil loss are calculated per unit hectare. For additional information on the use of the macro and the method of erosion plots, refer to Nakarmi (2000b; Appendix B5).

Two BSc (Shrestha and Sharma 2000) and one MSc study (Voegeli 2002) were first experiences with surface flow collectors. These surface flow collectors are 1 m wide gutters located in large numbers on a hill slope. Tests with no delineation, with 1 m^2 plots and 2 m^2 plots were made. More details on this method can be found in the above theses.

Experiences with the applied methods

In general, the chosen instruments have proven successful, this includes OTT R 16 floaters, tipping buckets, thermistors, WTW conductivity meters, and HACH photometers. Operationally, discharge measurements were a major problem. Because of the security situation, night measurements (it is during the night that most events occur) could not be obtained. All sites have highly variable cross-sections making rating curve development a difficult task (see also Appendix A3.1). The approach of employing local observers has supported the data collection additionally during the political turmoil, when project staff were not allowed to visit the sites. Furthermore, the local observers proved to be very loyal and helpful in many other project activities.

2.4.2.2 Jhikhu Khola catchment

The development of a measurement network in the Jhikhu Khola catchment was initiated in 1989 by the Soil Fertility project of UBC and the Integrated Toposection of HMG Survey Department. This network was continuously upgraded and new stations were added to the network. On July 15, 2002, 5 hydrological plots (Table 2.16), 11 meteorological plots (Table 2.17), and 7 erosion plots (Table 2.18) were monitored with the instruments as described below and situated as shown in Figure 2.16.

2.4.2.3 Yarsha Khola catchment

The Yarsha Khola catchment activities were initiated in 1997 and had to be closed down due to political unrest in that area in 2001. At the time of closure, four hydrological stations (Table 2.19), eleven meteorological stations (Table 2.20), and four erosion plots (Table 2.21) were established (Figure 2.17).

Table 2.16: **Hydrological station network of the Jhikhu Khola catchment**

(July 15, 2002)

Site No	Site Name	Stream Name	Easting UTM	Northing UTM	Altitude [masl]	Catchment Area [ha]	Available Data	Start of Record
1	Main Hydro Station	Jhikhu Khola	369444.2	3053484.3	800	11141	WL, D, S	01/01/93
2	Lower Andheri Khola	Andheri Khola	365960.7	3055503.8	850	539	WL, D, S	01/01/93
7	Kukhuri Khola	Kukhuri Khola	363935.5	3054196.9	1075	74	WL, D, S	01/01/93
8	Upper Andheri Khola	Andheri Khola	363864.9	3054180.6	1075	178	WL, D, S	14/05/97
13	Kubinde Khola	Kubinde Khola	365527.3	3058502.7	830	149	WL, D, S	10/07/97

Available Data: WL = Water level; D = Discharge; S = Sediment concentration

Table 2.17: **Meteorological station network of the Jhikhu Khola catchment**

(July 15, 2002)

Site No	Site Name	Aspect	Easting UTM	Northing UTM	Altitude [masl]	Available Data	Start of Record	End of Record
3	Acharyatol-Baluwa	Flat	366556.6	3056431.6	830	RA, AT,ST	01/01/93	-
4	Baghkhor	NE	365074.5	3055689.8	940	RA, RI	25/04/97	-
6	Bela	NW	364207.0	3053631.6	1260	RA, RI, AT, ST	01/01/93	-
9	Dhulikhel	N	357515.6	3056403.3	1560	RA, AT	01/01/93	31/12/98
10	Bajrapare	SE	358619.3	3059374.7	1100	RA	01/07/97	-
12	Tamaghat	Flat	364014.1	3059221.7	865	RA, RI, AT, ST	01/01/97	-
14	Kubindegaun	SW	365535.5	3059647.8	880	RA, RI, AT	01/03/97	-
15	Bhimsensthan	Flat	367553.9	3057460.7	880	RA, RI, AT, ST	01/01/93	-
16	Bhetwalthok	SW	369056.2	3057419.3	1200	RA, RI, AT, ST	01/01/93	-
19	Kalikasthan	NE	359007.2	3055528.4	1700	RA, RI, AT, ST	01/01/98	-
20	Higher Chiuribot	NW	363661.1	3053412.7	1275	RA	01/01/00	-
21	Lower Chiuribot	NW	363765.0	3053991.7	1190	RA, RI	19/07/00	-

Available Data: RA = Rainfall amount ST = Soil temperature
RI = Rainfall intensity AT = Air temperature

Table 2.18: **Erosion plot network in the Jhikhu Khola catchment**

(July 15, 2002)

Site No.	Site name	Land use	Elevation [masl]	Aspect	Orientation	Plot size [m x m]	Area $[m^2]$	Slope [degree]
4	Baghkhor	Grassland	940	N	NE	19.8 x 5.03	99.6	11.5
6a	Bela	Rainfed terrace	1240	N	NW	13.61 x 4.54	61.8	24.7
6b	Bela	Rainfed terrace	1280	N	NW	20.43 x 4.97	101.6	18.0
14a	Kubindegaun	Degraded	880	S	SW	20.62 x 5.02	103.5	15.0
14b	Kubindegaun	Degraded (treated)	880	S	SW	19.88 x 5.03	100.0	16.2
16	Bhetwalthok	Rainfed terrace	1200	S	SW	12.64 x 7.66	96.82	6.7
17	Ghartithok	Rainfed terrace	1150	S	SW	19.01 x 5.02	95.43	9.2
20	Higher Chiuribot	Rainfed terrace (outward sloping)	1275	S	NW	20.16 x 4.96	100.0	24.5

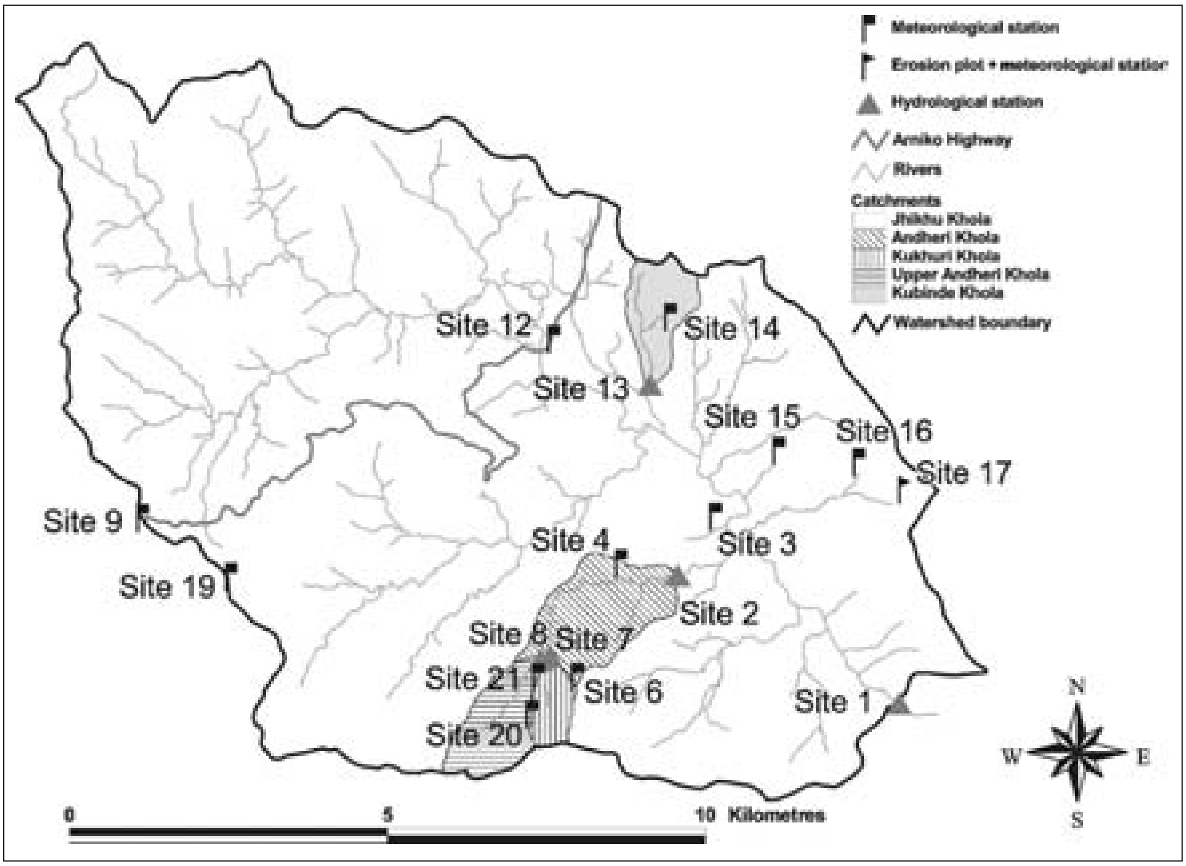

Figure 2.16: **Research monitoring network of the Jhikhu Khola catchment (July 15, 2002)**

Table 2.19: **Hydrological station network of the Yarsha Khola catchment**

Site No	Site Name	Stream Name	Easting UTM	Northing UTM	Altitude [masl]	Catchment Area [ha]	Available Data	Start of Record	End of Record
1	Main Hydro Station	Yarsha Khola	410597.9	3055928.5	990	5338	WL, D, S	15/05/97	25/06/01
2	Gopi Khola	L. Gopi Khola	410883.6	3055434.8	1040	1737	WL, D, S	17/05/97	25/06/01
5	Thulachaur	U. Khahare Khola	416903.0	3059409.6	2280	32	WL, D, S	27/06/97	25/06/01
7	Bagar	L. Khahare Khola	415838.0	3058148.1	1740	208	WL, D, S	24/06/97	25/06/01

Available Data: WL = Water level; S = Sediment concentration; D = Discharge

Table 2.20: **Meteorological station network of the Yarsha Khola catchment**

Site No	Site name	Aspect	Easting UTM	Northing UTM	Altitude [masl]	Available data	Start of record	End of record
1	Main Hydro Station	NW	410574.9	3055796.8	1005	RA, RI, AT, ST	01/06/97	27/06/01
3	Gairimudi	N	413165.8	3053855.4	1530	RA, RI, AT, ST	25/06/97	25/06/01
4	Yarsha Forest Site	NW	417474.5	3057291.2	1990	RA, RI, AT, ST	25/08/97	30/06/01
5	Thulachaur	S	417166.2	3059502.3	2300	RA, RI, AT, ST	23/06/97	27/06/01
6	Jyamire	S	416315.9	3058667.9	1950	RA, RI, AT, ST	01/06/97	26/06/01
7	Bagar (NARC)	SW	415703.9	3058154.4	1690	RA, RI, AT, ST, WS, WD, N, H	23/06/97	31/05/01
8 (old)	Nimkot	S	415011.6	3056921.6	1420	RA, RI, AT, ST	22/08/97	22/06/98
8 (new)	Lapse	S	414317.6	3057011.5	1420	RA, RI, AT, ST	04/07/98	25/06/01
9	Namdu	S	411365.6	3056816.6	1410	RA, RI, AT, ST	24/06/97	26/06/01
10	Thuloban	S	418720.4	3059978.4	2640	RA, RI, AT, ST	01/01/98	28/06/01
11	Mrige	N	415636.7	3055491.7	1610	RA, RI, AT, ST	01/06/98	25/06/01
12	Pokhari	N	414377.4	3051781.2	2260	RA, RI, AT	08/07/98	26/06/01

Available Data: RA = Rainfall amount; WS = Wind speed; RI = Rainfall intensity; WD = Wind direction;
AT = Air temperature; N = Net radiation; ST = Soil temperature; H = Relative humidity

Table 2.21: **Erosion plot network of the Yarsha Khola catchment**

Site No.	Site name	Land use	Elevation [masl]	As-pect	Orien-tation	Plot size [m x m]	Area [m^2]	Slope [degree]	Start of Records	End of Records
5	Thulachaur	Grass/shrub	2300	S	SW	20.2 x 5.0	100.4	19.1	04/06/97	24/06/01
6	Jyamire	Rainfed terrace	1950	S	S	20.1 x 5.0	99.9	17.0	03/06/97	23/06/01
9a	Namdu	Rainfed terrace	1410	S	S	20.1 x 5.1	101.8	17.5	04/06/97	23/06/01
9b	Namdu	Grass/fallow	1410	S	S	20.3 x 5.0	100.7	17.5	04/06/97	23/06/01

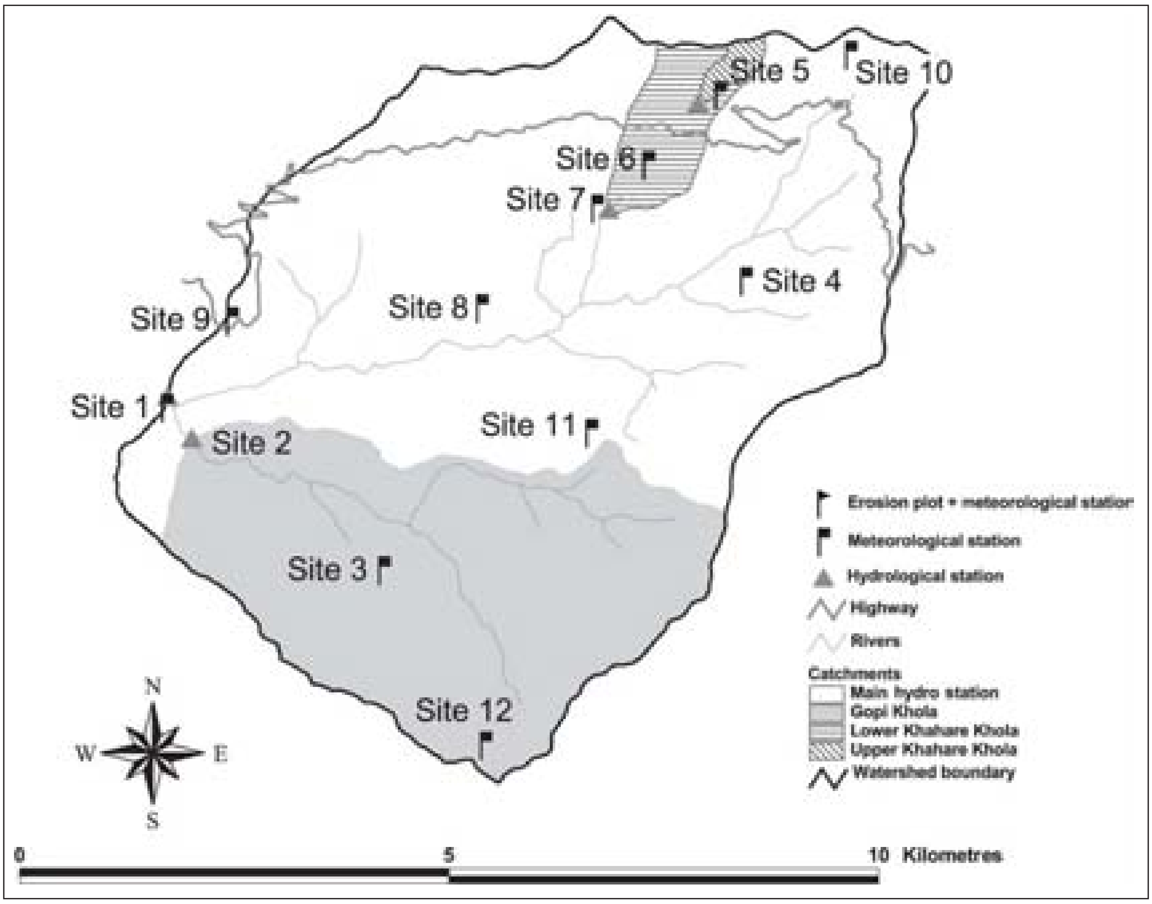

Figure 2.17: **Research monitoring network of the Yarsha Khola catchment**

2.4.3 Data management

All the data of the project is managed digitally. This means that all the data first has to be entered into digital form. All manual data, such as precipitation records, water levels, and discharge measurement results, are entered by field assistants and field hydro-meteorologists. The entered data and the data from the automatic stations are imported into HYMOS in original form and original time resolution by the project database manager. The HYMOS software developed by Delft Hydraulics in The Netherlands was introduced in 2000 at the beginning of Phase 2 with the aim of simplifying data exchange with the help of an identical data format.

In order to prevent any loss of data, the original files from the automatic recorders are kept and stored on digital media. The original recording sheets are filed and stored for later reference.

At least weekly, or whenever large amounts of data are imported, the database is backed-up on another project desktop computer and on two digital data carriers. The back-ups are kept in two different buildings to prevent data loss from fire or theft.
Data checking is a critical issue in hydro-meteorological data research. The data checking in PARDYP consists of four steps, as follow.

1. *Field check*
Upon receipt of the manual recording sheets, the readability, the plausibility of the numbers, and the digits are checked by the field assistants or the field hydro-meteorologists. In case anything is unclear, the reader can be asked for support immediately.

2. *Preliminary office check*
As soon as the data are entered into digital form, a graph is drawn for the identification of implausible values such as impossible extremes, breaks, steps, and the like.

3. *Consistency check*
When all the data are clean of outliers, the time series are checked for consistency by means of crosschecking where possible. The first check is done by comparing the same variables measured by different instruments (such as tipping bucket vs. ordinary rain gauge). A second check is performed between the same parameters of different stations.

4. *Homogeneity check*
For the homogeneity check, two methods were applied, that is, the visual double mass curve analysis (Dyck 1980) and the statistical U-test of Wilcoxon, Mann, and Whitney (Dyck 1980). The results of these analyses are presented in Appendices A3.2 to A3.5.

2.4.4 Data dissemination

At this stage, the data from PARDYP Nepal are published in the form of a yearbook in daily time series (ICIMOD 2002d; ICIMOD 2002e). The yearbook is published on a CD-ROM and is therefore very flexible. Any mistakes identified at a later stage can be eliminated for the next release of the yearbook. The yearbooks are usually updated annually. For the use of local line agencies, a summary yearbook in Nepali has been published (ICIMOD 2002f; ICIMOD 2002g).

Box 2.2: **Yearbooks**

Yearbooks are published by the government agencies collecting hydrological and meteorological data to enable access to data holdings by consultants, planners, researchers, and others who are interested. A yearbook consists primarily of checked, but still unanalysed, data. Often, simple overviews in the form of an annual graph and descriptive statistics are added.In PARDYP, the yearbook mainly aimed at two things:the publication of a yearbook forces the teams to check their datasets and compile them into readable form;andthe yearbooks can be exchanged between the different country teams.The yearbooks are by no means the final product, but act much more as a support for the data analyses at a later stage.

2.4.5 Data used for this study

This study primarily relies on data generated by the project itself. In general, daily data were used for all parameters. In the case of intensity analyses and event analyses, 10- min rainfall data and 30-min discharge were used. Appendices A3.6 (Jhikhu Khola catchment) and A3.7 (Yarsha Khola catchment) give an overview of the stations and data availability for all parameters. Secondary data and data from other sources substantiate the project's own data to put the study into the perspective of the larger area. Their sources are duly acknowledged. Unpublished data sets (received from the people who collected them) used in this study include the following.

- Godavari ICIMOD Test and Demonstration (T&D) site: meteorological data (received from Gopal Nakarmi/PARDYP Nepal)
- Dug well water levels in Shree Ram Pati and Dhuganabesi (received from Bhawani S. Dongol/ PARDYP Nepal and Monika Schaffner/PARDYP UoB)
- Community forestry areas in the Jhikhu Khola catchment (received from Bhuban Shrestha/ PARDYP Nepal)

In addition, the daily data from the PARDYP Nepal network used for this study can be found in ICIMOD (2002d) and ICIMOD (2002e).

2.4.6 Summary

PARDYP provides a unique database in the region in terms of temporal and spatial resolution. The rainfall and temperature parameters in particular are unique, providing insight into the high temporal resolution of these parameters. The discharge data are unique in their own sense, but are not uniformly of the quality one would wish. The sediment data from both the erosion plots as well as from the streams may support a number of studies into these important processes. The project team has done a lot within the framework of the project to improve data quality. However, mistakes cannot always be excluded.

In general, the measurement network is arranged in a nested approach, monitoring erosion plots, meteorological stations, and hydrological stations at different spatial levels. The set-up is such that a good spatial coverage is guaranteed and the most representative areas of the catchments are included in the measurement programme.

Data are available from 1993 to 2000 in the case of the Jhikhu Khola catchment and from 1997 to 2000 for the Yarsha Khola catchment. However, not all the sites cover the complete duration of the study period in the respective catchment. Data are continuously published in the form of a yearbook.

2.5 SUMMARY AND SYNTHESIS OF CHAPTER 2

This chapter was based on the assumption that biophysical and socioeconomic catchment characteristics influence water-related parameters, as was shown in many studies over time. A first fingerprint and assessment on whether a catchment is inherently conditioned to low water availability or is susceptible to flood generation and land degradation should therefore be possible just by looking at the catchments themselves without further monitoring of hydro-meteorological parameters. In Chapter 1, the key issues to be studied further were identified as water availability, flood generation, and land degradation induced by water. The ways in which catchment characteristics influence these key issues were highlighted throughout Chapter 2, and the main indicators will be discussed below according to each key issue after an overall summary of the chapter. The indicators will be taken up again in Chapter 5 to discuss an overall assessment, including the indicators identified from the remaining chapters along with the relevant processes.

2.5.1 Water availability

The key issue regarding water availability is governed by two base conditions:

a) the naturally available water resources in the catchment; and
b) the water demand in the catchment.

For a single household, both conditions have an impact on their water availability. If ample water is naturally available, the demand can be high and still adequate water is available. In the case of scarce water resources, a small water demand can lead to scarcity of water for the single household.

None of the above catchment characteristics indicates conclusively whether water can be assumed to be plentiful or scarce. Elevation could be used within physiographic regions, but, as Chyurlia (1984) and others showed, the relationship between elevation and rainfall changes over the boundary of different physiographic regions. While rainfall amount increases with altitude in the middle mountains, it decreases on the boundary of the Tibetan plateau. The elevation, however, plays a major role in the estimation of the snowline within the catchment (WECS 1990). The demand for water is largely governed by the catchment characteristics, mainly the areas of irrigated and rainfed cultivation. The forest areas are also believed to have a major impact on evaporation values. High population densities, particularly in the Nepal catchments, put a major stress on water quantity and quality. The current population growth rates of about 2.5 to 3% will aggravate these issues, with higher demand for increased food production and drinking water supplies.

The greater proportion and importance of agricultural land in the Jhikhu Khola catchment are accompanied by high overall agricultural intensity from the point of view of intensity, productivity, agrochemical inputs, and animal stocking density. The agricultural intensity in the Yarsha Khola catchment is of medium intensity. Agricultural intensity probably has a major impact on water resources in the catchments, in terms of both quality as well as quantity.

From a geology and soils point of view, soil acidification is a major issue for soil fertility in areas with non-limestone bedrock geology. In addition to this, phosphorous deficiency poses a risk. With the high fertiliser inputs mentioned above, phosphorous has recently become excessive in the Jhikhu Khola catchment. The same can be observed in the local drinking water supply.

A list of indicators relevant for water availability and based on catchment characteristics is presented in Table 5.1, Chapter 5 p. 291, this volume.

2.5.2 Flood generation

Duester (1994) presented a model for the estimation of extreme floods on the basis of catchment characteristics. The indicators proposed by him: elongation factor, sealed catchment area, mean slope, waste and grassland, and relative contributing areas, were partly adapted to the local conditions (Table 5.2) Chapter 5, p292, this volume. Any parameters based on the drainage network, such as the elongation factor and the relative contributing areas, should be avoided due to the large differences in mapping of this feature across the region. These indicators were therefore replaced by the Topoindex and the width/elongation ratio that basically presented the same information. The mean slope was substantiated with the slope ratio of the flat areas with the steep catchment areas. This was done to adjust for the topographic differences between the catchments with or without extended valley floors.

2.5.3 Land degradation

Degradation susceptibility is the basic condition of a catchment favouring water-caused degradation. In terms of sediment yield, Shen and Julien (1998) propose that the parameters of drainage density, catchment slope, and catchment area affect sediment yield the most. While the catchment slope and the area are incorporated, the drainage density had to be excluded due to the different details in stream network mapping in the two catchments and in comparison with other maps. Population and stocking density reportedly have a major impact on degradation and are, therefore, included, as well as a number of land-use/cover parameters. The high proportion of red soils makes the Jhikhu Khola catchment particularly vulnerable to surface erosion and land degradation. See Table 5.3, Chapter 5, p. 293, this volume for a complete list of the indicators.

Synopsis 2: Spatial context of the study

The PARDYP catchments are located in a region that is naturally very dynamic and fragile. From a development point of view, the region is very static, in certain cases even moving backwards. For water resource development this poses a major challenge as:

- **the vulnerabilities are high,**
- **the financial resources are low, and**
- **the number of dependents on subsistence agriculture is high,**

From a catchment characteristics' point of view, the catchments studied have high potential for flood generation and surface erosion. Water availability is not limited due to catchment characteristics per se. However, their combination with relevant processes could lead to water shortages.

Limited data availability is a major issue for improved understanding. Data of high spatial and high temporal resolution in particular are in short supply in addition to long time series' data. Efforts by PARDYP in this direction deserve support both from official institutions and the government as well as from the donor community.

Chapteer 3: Understanding the Current Status and Relevant Processes

"Mountains – a Hydrological Paradox or Paradise?"

(John C. Rodda)[1]

Understanding of the current status and relevant processes leading to the regional key issues as identified in Chapter 1 is limited in the mountainous region of the HKH. This is caused in particular by the absence of a long-term and high-resolution database as well as because the primary focus of research and development is concentrated in the plain areas. The main processes of interest in this study are precipitation, evaporation, discharge and runoff, sediment mobilisation and transport, and rainfall-runoff relationships. The perception of the people is assessed through participatory surveys. Finally, water balances are calculated and the water allocation is studied. The understanding of these conditions and the relevant processes may support the development of sound management and planning tools.

3.1 SPATIAL AND TEMPORAL DISTRIBUTION OF PRECIPITATION

This section firstly discusses rainfall during the study period from 1993 to 2000 in the Jhikhu Khola catchment, and from 1998 to 2000 in the Yarsha Khola catchment in the context of long-term data in order to put the study period into perspective. Temporal precipitation analyses, including the discussion of temporal variability and the temporal distribution of rainfall intensity are followed by a discussion of the spatial precipitation distribution in the catchments. Frequency analyses are carried out for monthly rainfall to establish the vulnerability of the current cropping systems to climatic variability. In addition, the theoretical frequencies of annual maximum rainfall events are calculated and put into the perspective of probable maximum precipitation. The Intensity-Duration-Frequency curves established for two sites in the Jhikhu Khola catchment are compared with the theoretical formula established for the middle mountains by Chyurlia (1984). The frequency analyses are only calculated for selected sites in the Jhikhu Khola catchment with adequate length of time series. Observed trends of different precipitation parameters conclude the analysis section before a brief comparison of the two catchments is presented.

For precipitation event analyses refer to Section 3.4 Rainfall-Runoff in this chapter

3.1.1 Precipitation in Nepal and the HKH

Precipitation in the HKH shows a distinct variation from east to west and south to north as was briefly shown in Chapter 2 and presented in Domroes (1978), according to whom a uniform climate cannot be expected, mainly due to the orographic complexity of the mountain range. In principal, two rainfall types can be observed (Domroes 1978), as follow.

1. The monsoon-type rainfall distribution can be seen, with two distinct seasons, a wet and a dry season each covering about half a year. This rainfall type is valid for all parts south of the high Himalaya with the exception of the Kashmir Himalaya.
2. The mixed monsoon-type rainfall is also observed. This is characterised by two rainfall maxima, the primary maximum during winter and spring, the secondary maximum during summer. The winter/spring maximum is due to the so-called 'Christmas rains' caused by weak westerlies in the Mediterranean area. The maximum during summer is due to the monsoonal depression in connection with the Bay of Bengal branch of the summer monsoon. The main regions of distribution for this rainfall type are those parts north of the High Himalaya and the west in the Kashmir Himalaya.

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[1] Rodda (1994)

These macroclimatic conditions are further broken up into numerous meso-climatic regions, for example, the phenomenon of dry mountain valleys or the luv and lee effect.

Nepal is primarily under the influence of the southwest monsoon (monsoon-type rainfall) with a distinct summer peak and a prolonged dry season from about October to May, except the areas of Nepal on the Tibetan plateau, which receive most of their annual rainfall during winter (January to March). This is due to synoptic-scale disturbances with origins in the Mediterranean region (Chyurlia 1984). The long-term mean precipitation in Nepal shows a decreasing trend from east to west with the highest annual precipitation of up to 5000 mm expected in the region of Pokhara in Kaski district (Chalise et al. 1996). The driest part of the country is the rainshadow area of Mustang on the Tibetan plateau with below 200 mm annual rainfall. The Jhikhu Khola and the Yarsha Khola catchments according to Chalise et al. (1996) receive about 1200 and 2200 mm respectively each year on a long-term basis.

The measurement period from 1993 to 2000 in the case of the Jhikhu Khola catchment was normal in the context of the long-term records. Statistically, using the U-test of Wilcoxon, Mann and Whitney after Sachs (1997), no difference between the long-term records of DHM at Panchkhal and Dhulikhel and the short-term records of the project at the same locations could be established (Table 3.1). In terms of the maximum and the minimum annual rainfall, the years of the study period were all within the range of the long-term records (Figure 3.1).

In the case of the Yarsha Khola, a comparison of long-term operational stations in Jiri, Charikot, and Melung with project stations show that the studied years from 1998 to 2000 were wetter than normal (Table 3.1). As there is no operational station within the Yarsha Khola catchment, adjacent stations of similar altitude were compared. In terms of annual maxima and minima the project period was within the range of the long-term records (Figure 3.1).

Table 3.1: **Test statistics for comparison of short-term with long-term records**

U-test Wilcoxon, Mann and Whitney (H0 is accepted if U1 and U2> z)	Critical value z, Sig. = 0.1	Test value	H0	HA
Jhikhu Khola				
Panchkhal (865 masl)	39	U1: 45 U2: 75	√	-
Dhulikhel (1560 masl)	80	U1: 142 U2: 116	√	-
Yarsha Khola				
Charikot (1940 masl) with Jyamire (1960 masl)	28	U1: 17 U2: 91	-	√
Jiri (2003 masl) with Jyamire (1960 masl)	22	U1: 16 U2: 71	-	√
Melung (1540 masl) with Gairimudi (1530 masl)	28	U1: 26 U2: 82	-	√

H0: PARDYP and DHM are from the same distribution √: not rejected
HA: PARDYP and DHM are from different distributions -: rejected
Source for long-term data: DHM (2000)

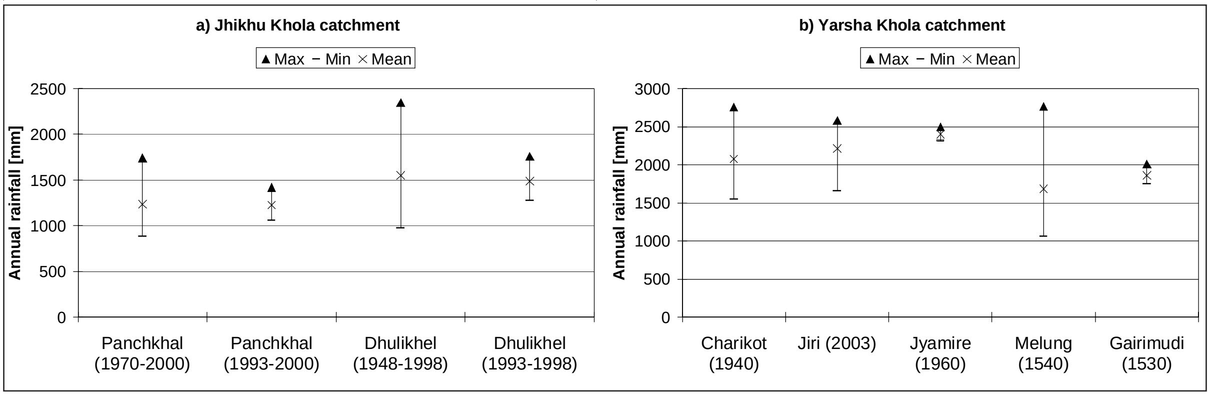


Figure 3.1: **Long- and short-term range of precipitation in a) the Jhikhu Khola catchment and b) the Yarsha Khola catchment**

(Source for long-term data: DHM 2000)

The results suggest the data are representative for conditions in the Jhikhu Khola catchment. The findings from the Yarsha Khola catchment have to be considered with caution as they represent wetter conditions than normal.

3.1.2 Definition of Seasons

The main seasons experienced on the Indian sub-continent are the southwest monsoon (June to September), the post-monsoon (October to November), winter (December to February), and the pre-monsoon (March to May). Nayava (1980) and Subramanya (1994) describe the four seasons for the case of Nepal as follows.

- *Southwest monsoon* (hereafter referred to as the monsoon)
  The southwest monsoon is the principal rainy season for large parts of the HKH. During this season 60 to 90% of the annual precipitation in Nepal occurs. The monsoon has its origin in the Indian Ocean and moves from there towards the Indian sub-continent. Nepal is mainly in the influence of the Bay of Bengal branch, setting in at Assam in India in early June and covering the north-eastern Indian states before moving towards Bihar and Uttar Pradesh in India and Nepal. The rainfall pattern is generally determined by the location of the monsoon trough, that is, the low-pressure region between the Bay of Bengal and Arabian Sea's monsoon branches. The weather during this season is usually cloudy with frequent spells of rainfall.

- *Post-monsoon*
  The post-monsoon is a transitional period where the subtropical westerly jet stream retreats from the north side of the Tibetan plateau to the southern side of the Nepal Himalayas. During this period, some isolated heavy rainfall events can be expected.

- *Winter*
  In winter, continental, dry, calm winds prevail from the west-northwest in western Nepal and from the east-northeast in eastern Nepal. Dry and clear weather prevails during this season. Westerly disturbances can cause moderate snowfall in the eastern parts of the country.

- *Pre-monsoon*
  Moderate to strong westerly winds prevail throughout Nepal, with scattered rainfall and a marked increase in temperature in March. Thunderstorms can become quite frequent, especially towards the end of this season.

The average duration of the monsoon in Kathmandu during the period from 1948 to 2000 and based on official onset and offset dates from DHM is 101 days, ranging from a minimum of 72 days to a maximum of 118 days. The earliest experienced onset of the monsoon for this period in Kathmandu was May 31, the latest onset was June 27. The normal onset for this period is June 12, coinciding with the normal onset as reported by Nayava (1980). The earliest offset of the monsoon was experienced on September 2 and the latest offset was on October 8. Normal offset for this period is September 20, one day earlier than the one reported by Nayava (1980). The monsoon onsets and offsets for Kathmandu are listed in Appendix A3.8. During the study, period monsoon duration ranged from 90 days in 1995 to 117 days in 1999. It is interesting to note that five monsoon seasons of the study period from 1993 to 2000 equalled or exceeded 110 days, which, since 1948, has only happened 11 times. During the study period, the onset of the monsoon was always close to the normal onset date ranging from May 31 (10 days before normal) to June 17 (7 days after normal). Offset ranged from September 2 (18 days before normal) to October 8 (18 days after normal).

For the seasonal calculations in the Jhikhu Khola and Yarsha Khola catchments, the monsoon was assumed to start one day earlier and end one day later than in Kathmandu, due to their position further to the east. The seasons for this study were defined as:

• pre-monsoon	March to onset of monsoon (March to May)
• monsoon	onset to offset of monsoon (June to September)
• post-monsoon	offset of monsoon to November (October and November)
• winter	December to February

For reasons of simplicity, in certain cases the season's definitions according to Hofer (1998b) given in brackets above were chosen. These cases are specially mentioned.

In both catchments, the majority of precipitation falls as rainfall. Chyurlia (1984) determined the snowline on the basis of different data for Nepal roughly as:

- 2430 masl in January on the basis of mean monthly minimum temperature;
- 5200 masl in July on the basis of mean monthly minimum temperature;
- 3460 masl in January on the basis of mean monthly temperature;and
- 6040 masl in July on the basis of mean monthly temperature.

During the project period the Jhikhu Khola catchment did not experience any snowfall. The uppermost parts of the Yarsha Khola experienced some snowfall in winter with annually two to three days of thin snow on the ground. Although the temperatures would have favoured snowfall, there was no precipitable moisture in the air during the cold months. In general, both catchments can therefore be assumed to be purely rainfed.

3.1.3 Temporal precipitation distribution

Temporal variability of precipitation is one of the main reasons for concern. Too much during the monsoon and too little during the dry season cause problems for the local residents and the entire region (Chalise and Sial 2000). Not only intra-annual variability but also inter-annual variability often causes havoc in the region, be it due to late onset of the monsoon and therefore adverse conditions for rice planting, or be it extraordinary events causing flooding and extensive erosion.

3.1.3.1 Jhikhu Khola

The long-term mean annual rainfall in the Jhikhu Khola catchment measured at Panchkhal in the period 1976 to 2000 was 1235 mm, according to data from DHM (2000). However, there was a large range between 882 to 1742 mm. The inter-annual variability over the entire period, measured with a coefficient of variation (C.V.) of 0.17, was statistically limited at this station. In terms of impact however, a range of 860 mm seems quite considerable. During the project period from 1993 to 2000, mean annual rainfall was 1226 mm with a maximum of 1418 mm and a minimum of 1055 mm (Table 3.2). The C.V. was only 0.09 during this time, showing statistically low inter-annual variability during the project period. The range between the minimum and maximum annual rainfall was 362.9 mm at this station between 1993 and 2000.

Table 3.2: **Statistics of annual rainfall in the Jhikhu Khola catchment**

	Period	Mean [mm]	Standard deviation	Max [mm]	Min [mm]	Range [mm]	C.V.
Site 3	1993-1996	1111	154	1291	942	349	0.14
Site 4	1998-2000	1177	178	1442	1069	373	0.15
Site 6	1993-2000	1249	149	1546	1045	501	0.12
Site 9	1993-1998	1487	155	1758	1273	485	0.10
Site 12	1993-2000	1226	108	1419	1056	363	0.09
Site 14	1998-2000	1289	137	1481	1188	293	0.11
Site 15	1993-2000	1071	104	1219	867	352	0.10
Site 16	1993-2000	1232	150	1464	949	515	0.12
Site 19	1998-2000	1688	236	1929	1456	473	0.14

Annual mean rainfall at the stations in the catchment ranged from 1071 mm at the Bhimsensthan station (Site 15) to 1688 mm at the highest station in Bhattindanda (Site 19) during the study period. The maximum was also observed at this station with 1929 mm in 1999. Inter-annual variability can be characterised by C.V.s ranging from 0.09 to 0.15 and absolute ranges of 294 to 515 mm at the different stations. For comparison, Chyurlia (1984) reported a C.V. of 0.22 with a mean of 1522 mm for Dhulikhel (no period given).

The wettest year during the measurement period on the basis of annual rainfall (Figure 3.2) was 1999, with 1419 mm at the main meteorological station. The main reason for this was an exceptional rainfall event from October 19 to 20, 1999 with 123 mm rainfall at the main meteorological station in

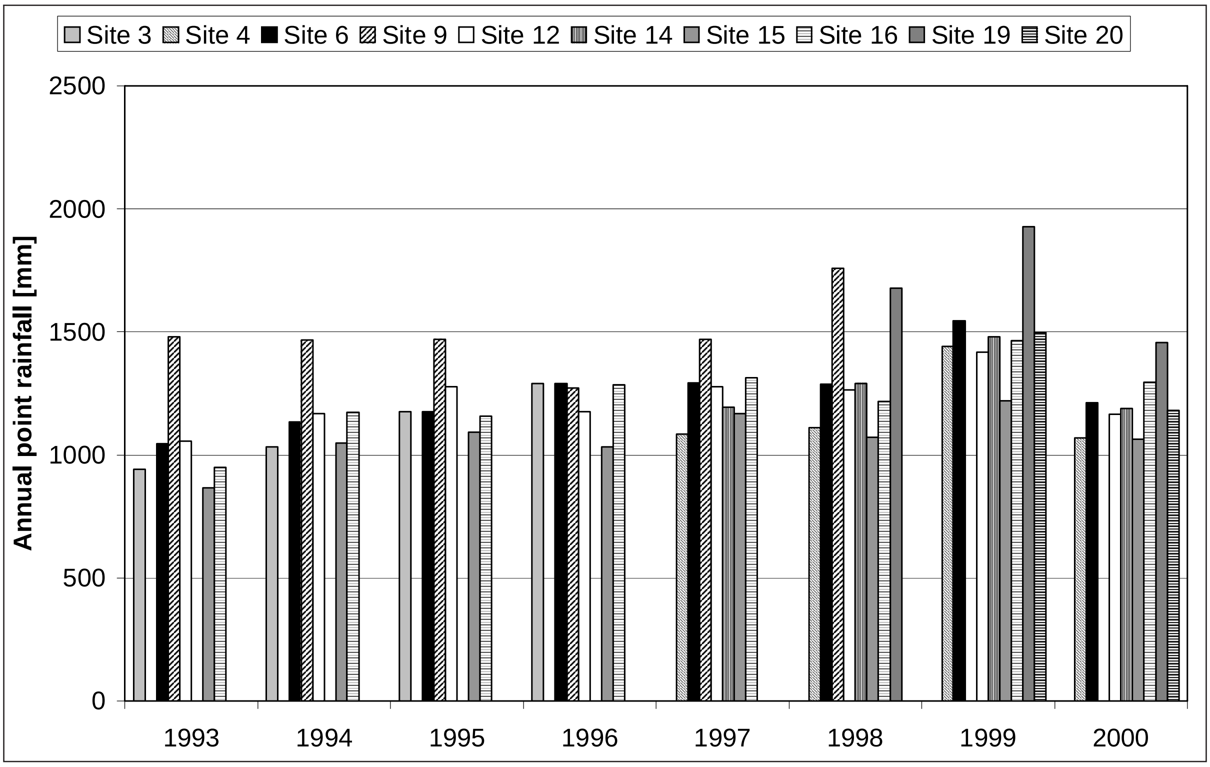


Figure 3.2: **Annual rainfall in the Jhikhu Khola at different stations**

the catchment. The lowest annual rainfall in this period was 1993, with 1056 mm at Site 12. Intra-annually, rainfall is highly seasonal. About 78% of the annual rainfall in the Jhikhu Khola catchment measured at Site 12 occurs during the monsoon season with the remainder occurring during the pre-monsoon season (14%), post-monsoon (5%), and winter (3%) (Table 3.3). Typically, 962 mm of rainfall is expected during the monsoon and 173 mm during the pre-monsoon. During the study period, 37 mm fell in winter and during the post-monsoon 67 mm of rain fell.

Table 3.3: **Seasonal rainfall in the Jhikhu Khola catchment, 1993-2000 (%)**

	Site 3	Site 4	Site 6	Site 9	Site 12	Site 14	Site 15	Site 16
Winter	4	2	4	4	3	2	4	3
Pre-monsoon	13	15	14	14	14	19	14	14
Monsoon	77	79	77	78	78	75	77	78
Post-monsoon	6	4	5	5	5	4	5	5

However, these percentages vary from year to year. The percentage for the monsoon varied from 69.8 to 84.9% at this site in the period from 1993 to 2000. This was mainly due to the high variability of rainfall during the seasons just before or after the monsoon. The percentage for the pre-monsoon ranged for the same station and period from 3.9 to 26.1%, and for the post-monsoon from 0.6 to 17.0%. During winter, the percentage varied from 0.0 to 6.8%. The other stations show a similar pattern for the same period.

The same can be shown by the monthly rainfall distribution (Figure 3.3). July is generally the wettest month with 27% of the annual precipitation, followed by August accounting for about 24% of the annual rainfall total. June accounts for approximately 19% of the annual rainfall. The additional 10% of rainfall during September adds up to the average monsoon rainfall as shown above. During the pre-monsoon, May is the rainiest month with about 8% of the total annual rainfall. The remaining 7 months together account for less than 5% of the annual rainfall. The driest months were November to February, each accounting for about 1% of total annual rainfall. This observed regime corresponds with a typical tropical monsoon climate with 2.5 to 5 months of dry season and a distinct summer peak (Mueller-Hohenstein 1981).

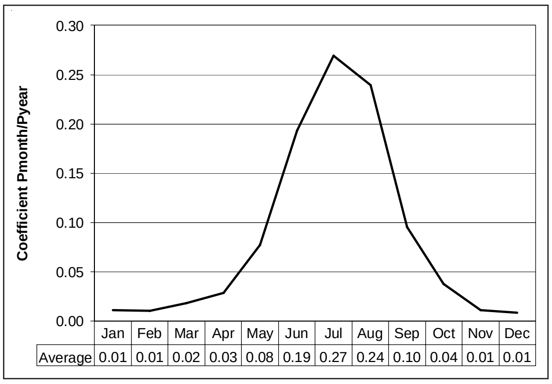


Figure 3.3: **Mean monthly rainfall distribution in the Jhikhu Khola catchment, period 1993 to 2000 (average of all sites)**

As mentioned above, this seasonal rainfall is highly variable over the years (Figure 3.4a). The lowest variability is shown by the monsoon season rainfall with a C.V. of approximately 0.2. The highest variabilities are shown in the case of the winter and post-monsoon rains, with C.V.s of approximately 0.9 and 1.1 respectively. The C.V. values for both winter and post-monsoon from the different stations in the catchment are highly scattered. In winter, the scatter is from 0.5 to 1.6, in the post-monsoon from 0.9 to 1.3, respectively. Pre-monsoon rainfall has a C.V. of about 0.5 and ranging from 0.3 to 0.8 at the different stations.

On a monthly basis, the months with the highest variabilities are December, November, October, and January, in this order (Figure 3.4b). The same result was observed by Chyurlia (1984) who reported C.V.s for Dhulikhel ranging from 0.32 in August to 1.81 in November and December. No period is given in this report. These months, along with February, are also the months with the lowest monthly rainfall amounts: at Site 12 about 10 to 20 mm on average in the period from 1993 to 2000. The scattering of the values from different sites is likewise the highest during these months.

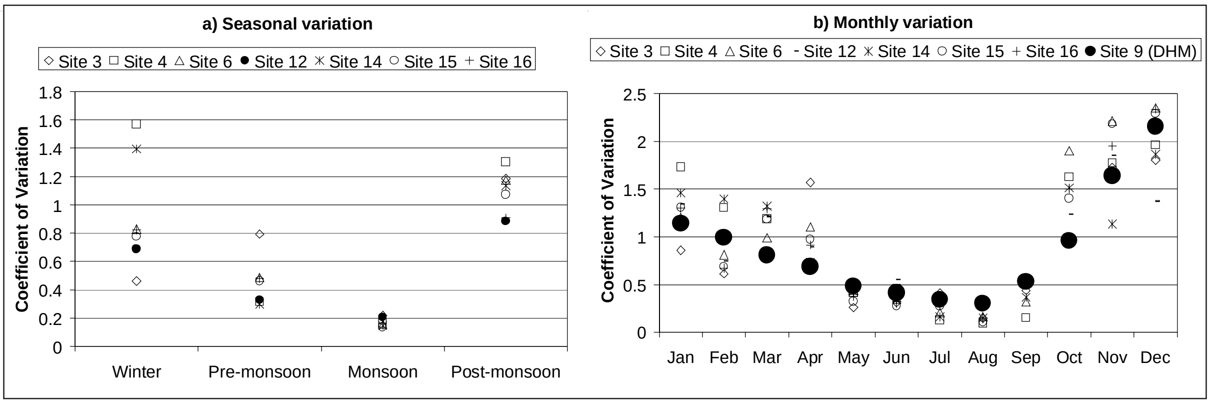


Figure 3.4: **Coefficient of variation for a) seasonal rainfall and b) monthly rainfall in the Jhikhu Khola catchment (period 1993 – 2000; values for Site 9 represent the period from 1948 - 1996)**

Annually, in the Jhikhu Khola catchment, 93 rainy days (days with equal or more than 1 mm of rain per day) are measured on average, ranging from 89 to 100 in the case of the site at Bhimsensthan (Site 15) for the period from1993 to 2000. At other sites for the same period, 103 (94-106; Site 6), 105 (93-117: Site 9), and 96 (89-100; Site 16) rainy days were measured. These rainy days mostly measure between 1 and 10 mm, according to the relative frequency distributions shown in Figure 3.5 between 10 and 20% per year or about 60% of all the rainy days. In terms of rainfall amount these days contribute about 21% to the total annual rainfall.

The empirical frequency distributions of daily rainfall are highly skewed to the left, showing that low magnitude rainfall is much more frequent than high magnitude rainfall. Days of more than 50 mm only accounted for 3% of the rainy days with a maximum of 141 mm measured at Site 6 on June 28, 1999. On the same date the other sites experienced maxima with 90.7 mm at Site 15 and 110.3 mm at Site 16. However, these events account for about 16% of the total annual rainfall. In 1999, this class even accounted for 34% of the total annual rainfall. These observed 24 h maxima are below the reported values of Chalise et al. (1996) according to which the 24 h maximum rainfall for this area is between 150 and 175 mm in 24 hours.

Comparing the short-term data of the project period with the long-term data set of Site 9 (Figure 3.5), it can be shown that the project period's daily rainfall distributions are within the long-term average. In the long-term data set both lower minima as well as higher maxima have been observed on the basis of annual frequency distribution of daily rainfall.

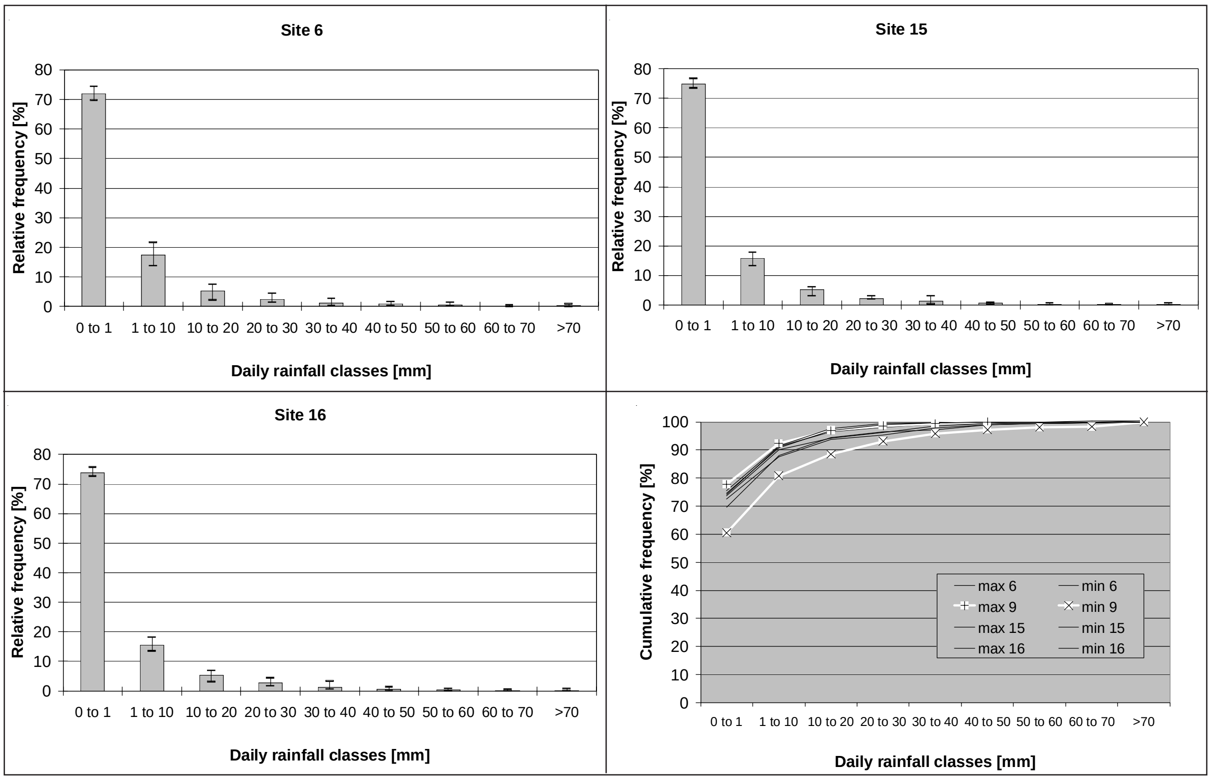


Figure 3.5: **Relative frequency distribution of daily rainfall at Sites 6, 15, 16 and comparison with long-term data set of Site 9**

Diurnal variation depends on the season. During the monsoon season, most of the rainfall occurs during the night half-day (6:00 PM – 6:00 AM). At Site 6, which is also representative for the other sites in the catchment, 60% of the annual rainfall from 1993 to 2000 occurred during the night in the monsoon season, in particular early in the morning between 12:00 and 6:00 AM (32%). During the other three seasons, the pre-monsoon, post-monsoon and during winter, rainfall occurred mostly during the afternoon between 12:00 and 6:00 PM (39.5 , 36.5 and 39.5%, respectively). Similar results were shown by Gardner and Jenkins (1995). The reason for this variation is the differences in rainfall generation. While during the monsoon season the rains are mainly of a frontal and orographic nature, during the reminder of the seasons the rains are due to the convection of moist air. In the pre-monsoon season these rains are mainly due to thunderstorms, formed by the heating up of the land surface and the subsequent rapidly rising air masses.

For water availability considerations, the number of days without rainfall are important. In this context days with rainfall of less than 1 mm are considered to be days without rainfall. This is mainly due to the fact that 1 mm rainfall does not contribute to runoff, but mostly and immediately evaporates from the soil surface. The number of days without rainfall ranged from 69 to 74% at Site 6 for the period 1993 to 2000. In general, days without rain make up 65 to 75% (230 to 275 days) of the year (Figure 3.5). While single or a few days without rainfall are usual, many consecutive days without rain may cause water stress in plants and trees. Mosley and Pearson (1997) defined a dry spell as “a period of 15 days with no more than 1 mm of rain each day”. In the period from 1998 to 2000 a total of 13 dry spells was recorded at Site 12, with one as long as 113 days (Figure 3.6a). The other sites had between 9 and 13 dry spells for the same period. The maximum length of a dry period was 141 days at Sites 15 and 16 during the winter and pre-monsoon 1999. This was also the time when the wheat harvest both in the Chinese catchment of Xizhuang and the two catchments in Nepal was very poor according to personal observations. Such dry spells usually occur during the dry season months of October to May.

During the period from 1993 to 2000, a total of 33 dry spells was recorded at Sites 6 and 16 (Figure 3.6b). The longest dry spell during that period was the same 141 days at Sites 15 and 16.

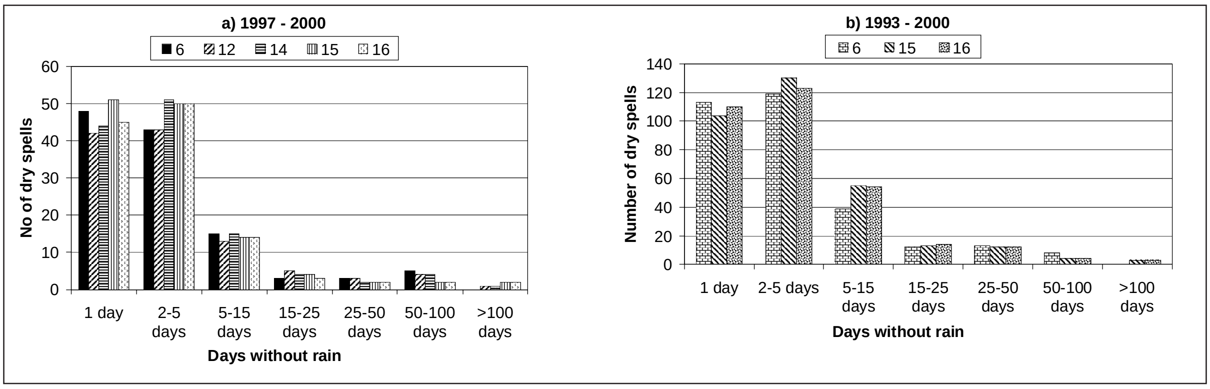


Figure 3.6: **Days with rain below 1 mm and dry spells in the Jhikhu Khola catchment a) short-time series 1997 – 2000; b) long-time series 1993 - 2000**

For flood and erosion considerations, the temporally high resolved intensity distributions are very important Figure 3.7a & b). On average, the highest 10-minute intensities on a daily basis occurred during the late pre-monsoon and early monsoon months of May, June, and July followed by the late monsoon months of August and September throughout the period from 1993 to 2000 (Figure 3.7b). These intensities measured about 50 to 80mm/h, that is, about 8.3 to 13.3 mm/10min. The maximum 10-minute intensity of 80 to 100 mm/h (13.3 to 16.7mm/10min) was usually measured during the same months (Figure 3.7a). However, isolated events in the late monsoon or in the post-monsoon season in the study period had very high intensity rainfalls.

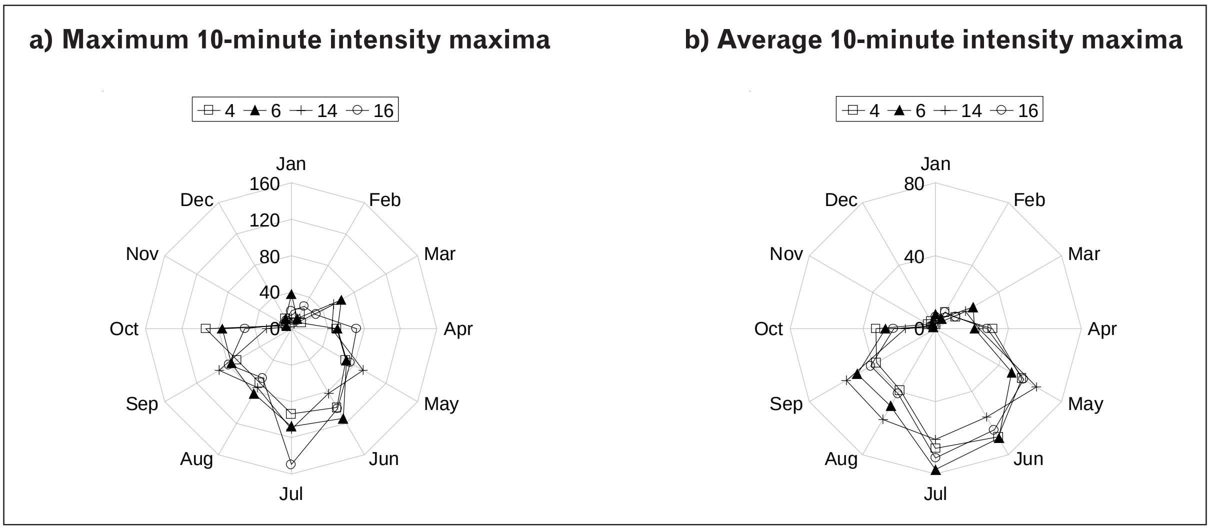


Figure 3.7: **Maximum (a) and mean (b) 10 min intensities at different stations in the Jhikhu Khola catchment [in mm/h]**

The highest measured 10-minute intensity in the Jhikhu Khola catchment was measured at Site 16, with 149.4 mm/h. For comparison, the greatest 8-minute intensity ever recorded was 126 mm/8min (945mm/h) in Fuessen, Bavaria/Germany, and the greatest 15-minute intensity was measured at Plumb Point (Jamaica) with 198 mm (792 mm/h) (WMO 1994). In the Leissigen catchment in the foothills of the Swiss Alps, the highest 10-minute rainfall intensity measured in the period from 1994 to 1997 was 93.6 mm/h (Wuethrich 1999). There is no 10-minute data available for comparison from Nepal.

The 30 and 60-minute intensities show similar distributions, with the highest measurements during the late pre-monsoon and early monsoon season. In the case of 30-minute intensities, the maximum is either measured in June or July with the higher intensities occurring, on average, during July. Maxima rainfall can reach 80 mm/h. For 60-minute maximum intensities, values of up to 50 to 60 mm/h were observed in the study period, usually occurring in July.

The erosivity of rainfall depends largely on rainfall amount, duration, intensity, drop size, and wind speed (Ries 1993). As it is difficult to measure drop size under field conditions, different authors have proposed a number of erosivity indices that are usually a combination of maximum rainfall intensity and rainfall amount. Ries (1993) discusses different erosivity indices and proposes the use of the AI_m-index according to Lal (1976), the reason being that this index is purely dependant on rainfall parameters without considering soil parameters or vegetation, as for example EI_{30} of Wischmeier and Smith (1978). The EI_{30} often underestimates the erosivity of a single large storm event. Furthermore, Ries (1993) proposes the use of the AI_{1030m} index, which incorporates the short-term intensity with a measure of the often longer duration of high intensities in storms of the monsoon areas.

For this study the AI_{10m} and the AI_{1030m} as proposed by Ries (1993) were calculated as follows and used for comparison:

$$\mathbf{AI_{10m} = \Sigma(\Sigma a i_m)} \qquad \textbf{Equation 3.1}$$

and

$$\mathbf{AI_{1030m} = AI_{10m} * I_{30}} \qquad \textbf{Equation 3.2}$$

where

a = amount of rainfall events 1 to n [mm]
I_m = maximum m-minute intensity [mm/h]
I_{30} = maximum 30-minute intensity [mm/h]

The temporal distribution of the erosivity indices shows that the highest rainfall erosivities have to be expected during the months of June to July (Figure 3.8). Interestingly, the erosivities calculated for the sites on the south-facing slope are considerably higher than the ones from the valley bottom and the north-facing slope.

In terms of rainfall amount, it was shown that events of less than 3 mm do not usually have the potential to mobilise soil (Carver 1997). As will be shown in Section 3.5 for runoff on the plot level, rainfall events of more than 2 mm may generate runoff. Over the duration of the entire year, about 90% of the rainfall may produce runoff (Table 3.4). Approximately 87% of rainfall on average may produce- sediment mobilisation over all stations. Seasonally, it can be observed that during the pre-monsoon and the monsoon season this annual average is achieved at all stations. During the post-monsoon and winter the percentage varies considerably between the different stations.

On the basis of the data and discussion above based on the period from 1993 to 2000, average conditions in the Jhikhu Khola catchment in terms of rainfall can be described as follow:

- annual rainfall [mm]: *1000 - 1700,*
- seasonal distribution (winter/pre-/monsoon/post-) [%]: *3:15:77:5,*
- monthly distribution (Jan – Dec) [%]: *1:1:2:3:8:19:27:24:10:4:1:1,*
- wettest month [mm]: *July with 27% of the annual rainfall,*

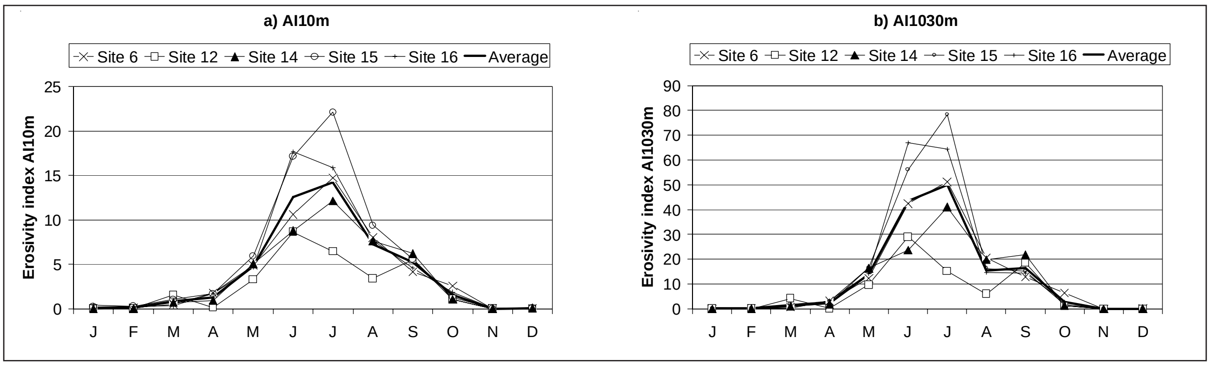


Figure 3.8: **Monthly erosivity in the Jhikhu Khola catchment a) AI_{10m} b) AI_{1030m}**

Table 3.4: **Precipitation with potential for runoff generation and sediment mobilisation, Jhikhu Khola catchment [in % from the total rainfall]**

	Runoff generation (> 2mm)					Sediment mobilisation (> 3mm)				
	Total	**Pre**	**Mon**	**Post**	**Winter**	**Total**	**Pre**	**Mon**	**Post**	**Winter**
Site 6	88	93	88	84	63	85	85	86	80	06
Site 12	92	86	90	93	13	89	84	88	60	12
Site 14	93	85	95	64	28	90	82	93	53	28
Site 15	91	89	94	74	65	87	83	91	67	61
Site 16	92	93	92	75	84	87	83	91	67	61

- driest month [mm]: *January, February, November, December with 1% each of the annual rainfall,*
- most variable months: *December, November, October,*
- most variable season: *post-monsoon season,*
- number of days without rain [No.]: *230 - 275 per annum,*
- number of rainy days [No.]: *89 - 117 per annum,*
- number of dry spells [No.]: *9 - 13 in the period 1998 to 2000,*
- month of highest erosivity: *July followed by June*, and
- total rainfall amount contributed by days with P > 50 mm [%]: *16 per annum.*

Extreme conditions both in terms of minimum as well as maximum rainfall can be described as below:

- maximum annual rainfall [mm]: *1200 - 2000,*
- minimum annual rainfall [mm]: *800 - 1500,*
- maximum seasonal distribution [%/season]: *4:19:79:6,*
- maximum seasonal distribution [%/season]: *2:13:75:4,*
- absolute daily maximum rainfall [mm]: *141 on 28/06/99 at Site 6,*
- longest dry spell [days]: *141 days at Sites 15 and 16,*
- highest 10-minute maximum intensity [mm/h]: *149.4,*
- highest 30-minute maximum intensity [mm/h]: *84.6,* and
- highest 60-minute maximum intensity [mm/h]: *58.0.*

3.1.3.2 Yarsha Khola catchment

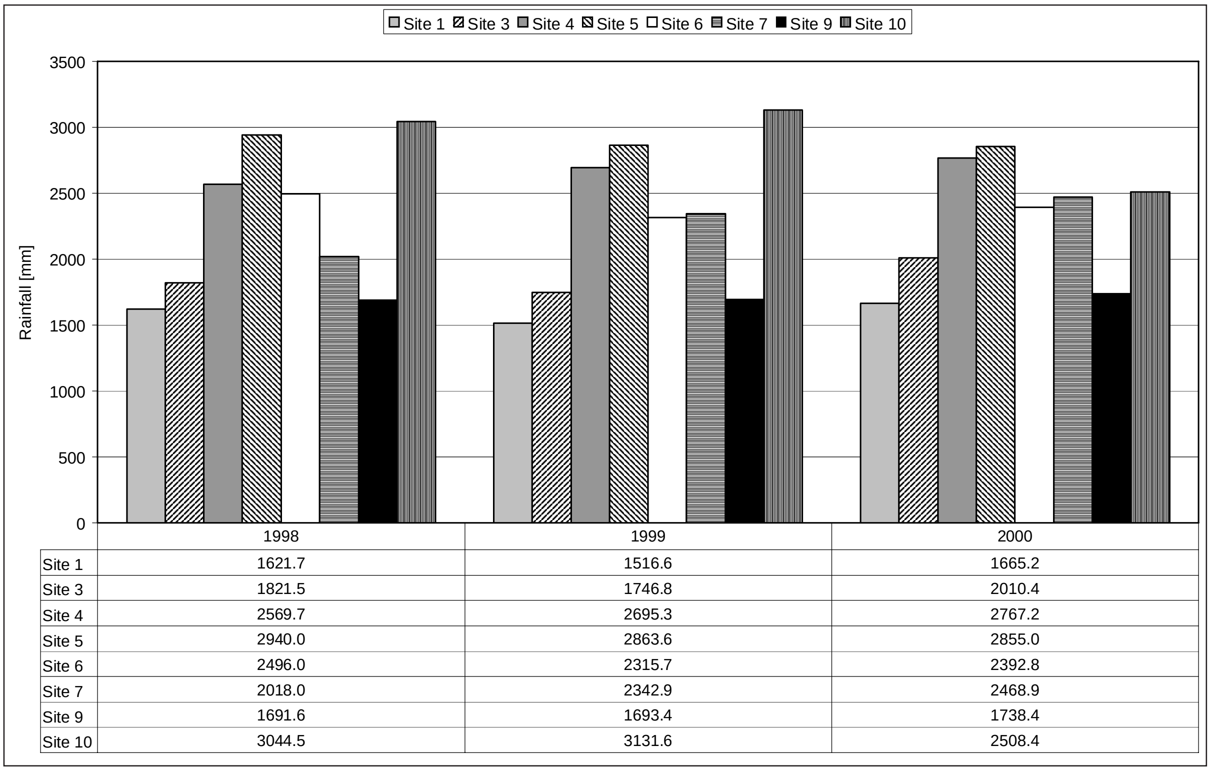
In the Yarsha Khola catchment only three complete years of data are available, from 1998 to 2000. The temporal variability, therefore, has to be looked at with caution, firstly due to the short data set, secondly due to the fact that the study period was wetter than normal (see above). The annual rainfall at the main meteorological station in Bagar (Site 7) varied from 2018 to 2468 mm during the three years (Table 3.5). The range at other sites is usually lower except at Site 10, where a range of 623 mm was measured during the project period. The C.V. (with caution) was, as expected, small and ranging from 0.02 to 0.12. A maximum of 3132 mm was observed at Site 10, the highest station in the catchment. The absolute minimum was recorded at Site 1, the lowest station.

Table 3.5: **Statistics of annual rainfall in the Yarsha Khola**

	Period	**Mean [mm]**	**Standard deviation**	**Max [mm]**	**Min [mm]**	**Range [mm]**	**C.V.**
Site 1	1998-2000	1601	76	1665	1517	148	0.05
Site 3	1998-2000	1860	136	2010	1747	263	0.07
Site 4	1998-2000	2677	100	2767	2570	197	0.04
Site 5	1998-2000	2886	47	2940	2855	85	0.02
Site 6	1998-2000	2402	91	2496	2316	180	0.04
Site 7	1998-2000	2277	233	2469	2018	451	0.10
Site 9	1998-2000	1708	27	1738	1692	46	0.02
Site 10	1998-2000	2894	338	3132	2508	624	0.12

For comparison with long-term data, Chyurlia (1984) calculated C.V.s of 0.13 with a mean of 2160 mm for Charikot, 0.10 with a mean of 2261 mm for Jiri, and 0.22 with a mean of 1816 mm for Melung (no period given). This indicates that the maximum C.V.s observed during the study period at selected sites correspond to the long-term results from sites nearby. However, at most sites the variability is greatly underestimated in the short-time period.

The three years are very similar in terms of rainfall at the different stations (Figure 3.9). It is therefore not possible to identify one year which was much wetter or much drier than others. The average of all stations over the three years differs only in millimetres. The average in 1998 was 2275.4 mm, in 1999 2288.2 mm, and in 2000 2300.8 mm. Although there is only a small difference in rainfall, the year 2000 can be considered the wettest year during the three-year study period. However, the absolute annual maximum was measured in 1999 with 3131.6 mm at Site 10. (The same can be shown on the basis of the areal rainfall for the different catchments [see Figure 3.23, p84]).



	1998	1999	2000
Site 1	1621.7	1516.6	1665.2
Site 3	1821.5	1746.8	2010.4
Site 4	2569.7	2695.3	2767.2
Site 5	2940.0	2863.6	2855.0
Site 6	2496.0	2315.7	2392.8
Site 7	2018.0	2342.9	2468.9
Site 9	1691.6	1693.4	1738.4
Site 10	3044.5	3131.6	2508.4

Figure 3.9: **Annual rainfall in the Yarsha Khola catchment at different stations**

Monsoon rainfall accounts, on average across all stations, for 78.6% of the annual total rainfall (Table 3.6) with a maximum of 81.7 and a minimum of 74.2%. The monsoon is followed by the pre-monsoon where 17% of the rain fell in the study period. The winter season accounts for 1.8 and the post-monsoon for 2.6% of annual rainfall. Expressed in mm at Site 7, the main meteorological station in the catchment, 1879.1 mm of rain fell on average during the monsoon periods of the three study years. During the pre-monsoon 329.6, in winter, 35.9 , and post-monsoon 55.5 mm of rain fell.

July was the wettest month during the study period, with about 30% of the total annual rainfall (Figure 3.10). August follows with 22% and June with 16%. During September 13% of the annual

Table 3.6: **Seasonal rainfall in the Yarsha Khola catchment, 1998 – 2000 [%]**

	Site 1	Site 3	Site 4	Site 5	Site 6	Site 7	Site 9	Site 10
Winter	2	2	2	2	2	2	2	1
Pre-monsoon	18	17	16	17	17	14	21	17
Monsoon	77	78	80	79	79	82	74	80
Post-monsoon	3	2	2	2	3	2	3	3

rainfall occurred, adding up to 81% of total annual rainfall falling during the monsoon months. May is the wettest month outside the monsoon season and accounts for 10% of the annual rainfall. The remaining months all contributed less then 5% each to the annual rainfall with the lowest rainfall amounts in November, January, and February, each with less than 1%.

The regime with a distinct monsoon peak in summer and about five months rather dry conditions shows the pattern of a tropical monsoon climate as shown by Mueller-Hohenstein (1981).

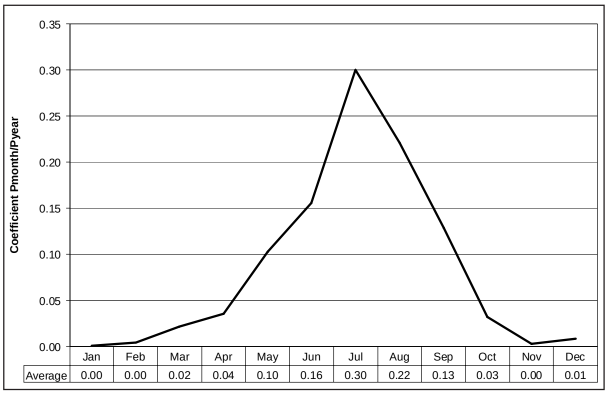


Figure 3.10: **Mean monthly distribution of rainfall in the Yarsha Khola catchment**

The distribution of daily rainfall amount is positively skewed with most daily measurements between 0 and 1 mm (Figure 3.11). In terms of rainy days, 1 to 10 mm is measured most often on about 45 to 50% of all rainy days. About 60 to 70% (or 219 to 256 days per annum) do not have any rain in the Yarsha Khola catchment. In terms of total rainfall these events account for approximately 15% of the total annual rainfall in the period from 1998 to 2000. Days with more than 50 mm rainfall contributed on average about 21% to the total annual rainfall. The absolute maximum of 97.8 mm was measured at Site 10 on 11/08/98. On the same date a maximum of 95.7 mm was measured at Site 5. The highest measurement in the project duration was in 1997 with 121.4 mm on 17/07/97. However, these measurements were not taken into consideration as the project had just begun and only an incomplete dataset is available for that year. Comparing the short-term data sets from the project period with the long-term data sets from the DHM monitoring stations in Charikot, it can be seen that the data of the project period is within range of the long-term observations. However, the maximum daily rainfall amounts ever measured probably did not occur during this period. According to Chalise et al. (1996) the maximum 24 h rainfall for this area was 250 to 300 mm. Variability of seasonal rainfall is highest during the winter and post-monsoon seasons with least

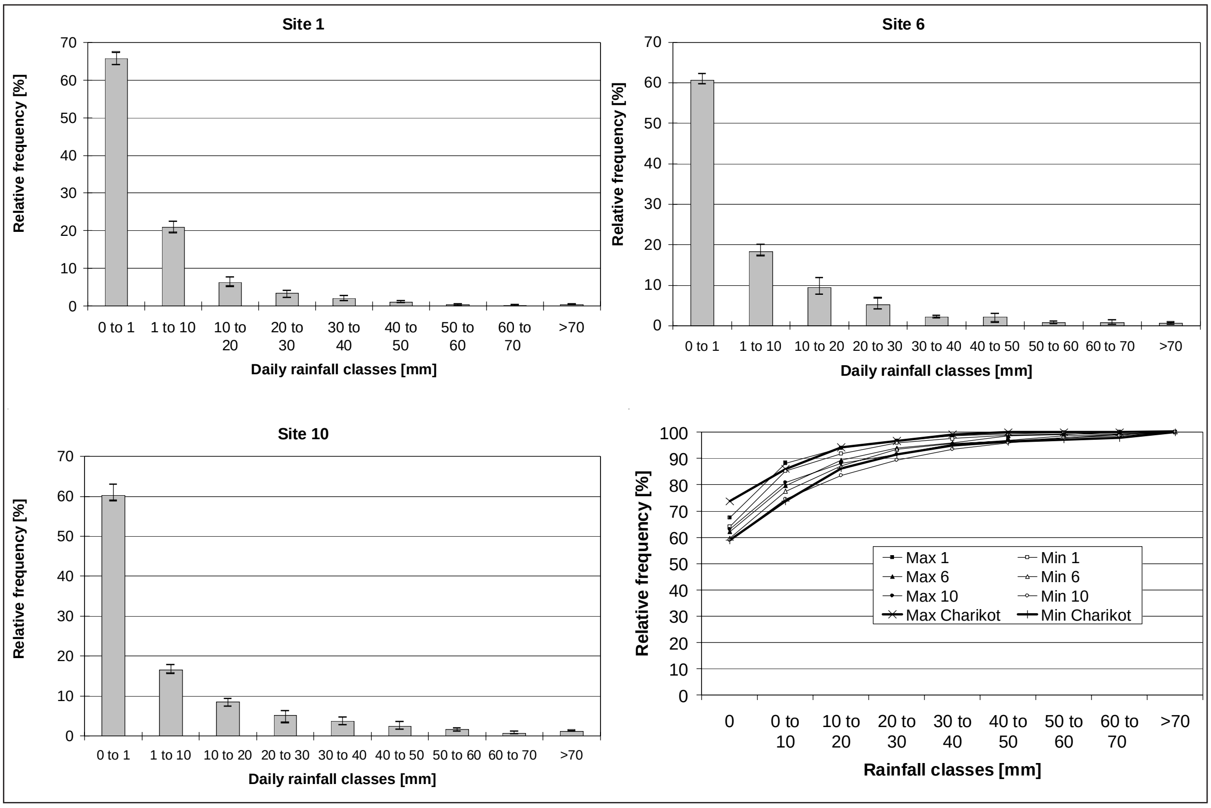


Figure 3.11: **Relative frequency distribution of daily rainfall in the Yarsha Khola catchment**

variation during the monsoon and pre-monsoon seasons (Figure 3.12a). The sites differ greatly, especially during the winter season. On the basis of monthly data, the months of November to March show the highest variabilities (Figure 3.12b). The monsoon months receive generally very similar amounts of rainfall between the different years. This shows that the time farmers are most vulnerable seems to be around maize planting, which is usually in April in the pre-monsoon season — but only if there is enough moisture available. During the project period, a very wet pre-monsoon as well as a very dry pre-monsoon were experienced in 1998 and 1999. Chyurlia (1984) showed a similar distribution of monthly C.V.s in Jiri, Charikot, and Melung with the highest values observed in the winter followed by the post-monsoon and pre-monsoon months.

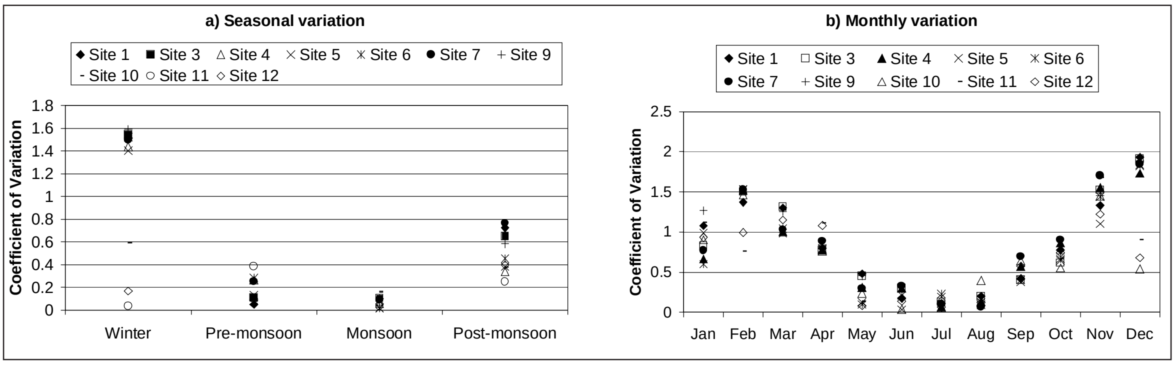


Figure 3.12: **Variability of a) seasonal and b) monthly rainfall in the Yarsha Khola catchment (period 1998-2000)**

A total of 8 to 11 dry spells were recorded at different sites in the period from 1998 to 2000 (Figure 3.13). The longest dry spell was measured at Site 3 with 134 days without more rain than 1 mm (or occasionally less). At Site 9, a dry spell of 127 days was observed. None of the other sites observed a dry spell longer than 100 days. Dry spells of up to 5 days are very common in this catchment.

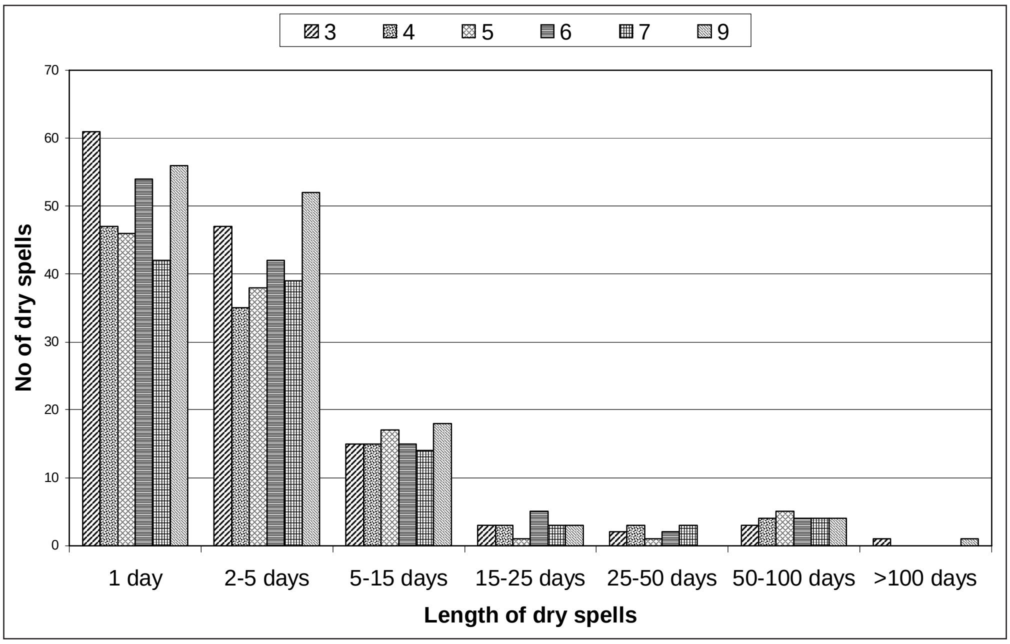


Figure 3.13: **Dry spells between 1998 and 2000 in the Yarsha Khola catchment**

During rainy days, rainfall intensity varies greatly. At most of the sites the maximum 10-minute intensity peaked in the month of May (Figure 3.14). However, the maximum 10-minute rainfall intensity measured in the study period was reached at Site 6 with a maximum of 175.2 mm/h in the month of June, with the next highest intensities in September. The very high intensities during September are the result of a major storm, which occurred in September 1999.

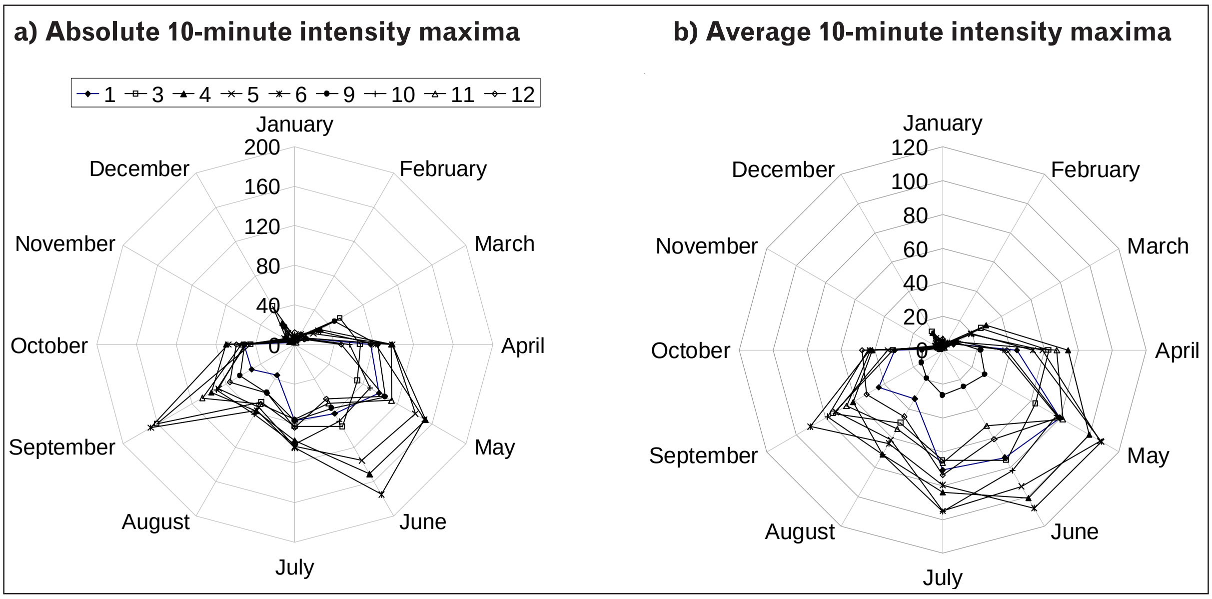


Figure 3.14: **Mean (a) and max (b) 10-minute rainfall intensity in the Yarsha Khola catchment [in mm/h]**

In the case of maximum 30 and 60-minute intensities, the same pattern was shown with an absolute 30-minute maximum of 119.6 mm/h and an absolute 60-minute maximum of 67.4 mm/h.

The erosivity of rainfall measured, as indicated in Figure 3.15, is highest in July, followed by June. The reason for the high erosivity calculated for the month of September is the same storm as indicated above. No distinct aspect difference in terms of erosivity can be determined in the case of the Yarsha Khola catchment. A relationship between erosivity and elevation is, however, indicated (further details in the next section).

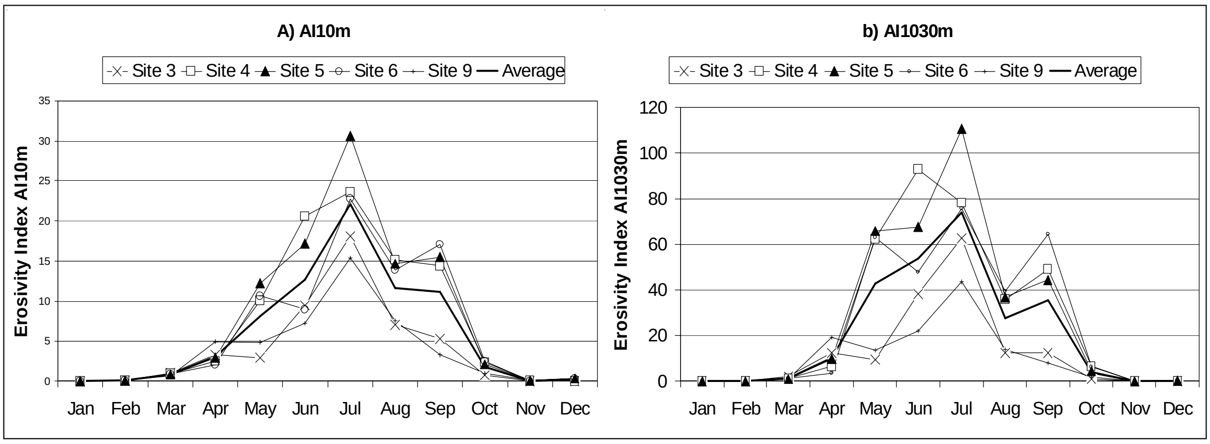


Figure 3.15: **Monthly erosivity indices in the Yarsha Khola catchment: a) AI_{10}, b) AI_{1030m}**

The part of the overall rainfall which has potential to generate runoff (events > 2 mm) and sediment mobilisation (events > 3 mm) is fairly high in the Yarsha Khola catchment. About 94% of the total annual rainfall has the potential to produce runoff (Table 3.7). This value is higher during the monsoon season. During winter this varies greatly between stations, with the percentage of rainfall having the potential to cause runoff ranging from 10 to 51%. Over the year, approximately 90% of total annual rainfall in the Yarsha Khola catchment has the potential to cause sediment mobilisation. During the monsoon itself about 90% of the rainfall has the potential to cause sediment mobilisation. This value drops to about 86% in the pre-monsoon, and 70 to 80% in the post-monsoon season. Again, during winter this figure varies widely from 8 to 50%.

Table 3.7: **Precipitation with potential for runoff generation and sediment mobilisation, Yarsha Khola catchment [in% from the total rainfall]**

	Runoff generation (> 2 mm)					Sediment mobilisation (> 3 mm)				
	Total	**Pre**	**Mon**	**Post**	**Winter**	**Total**	**Pre**	**Mon**	**Post**	**Winter**
Site 3	95	94	95	75	10	92	89	93	69	10
Site 4	94	93	96	92	20	92	91	94	86	11
Site 5	93	86	95	86	51	91	84	94	83	51
Site 6	88	89	89	88	47	86	86	88	86	8
Site 9	93	86	95	89	22	90	83	92	81	8

On the basis of the data and discussion above, based on the years 1998, 1999, and 2000, average conditions in the Yarsha Khola catchment in terms of rainfall can be described as follow:

- annual rainfall [mm]: *1600-2900,*
- seasonal distribution (winter/premonsoon/monsoon/postmonsoon) [%]: 2*:17:78:3,*
- monthly distribution (Jan – Dec) [%]:*0:0:2:4:10:16:30:22:13:3:0:1,*
- wettest month [mm]: *July with 30% of the annual rainfall,*
- driest month [mm]: *November, January, and February with less than 1% each of annual rainfall,*
- most variable months: *December, November, February, March, January,*
- most variable season: *winter and post-monsoon season,*
- number of dry spells [No.]: *8-11 in the period 1998 to 2000,*
- number of days without rain [No.]: *219-256 per annum,*
- month of highest erosivity: *July followed by June,*and
- total rainfall amount contributed by days with P > 50 mm [%]: *21 per annum.*

Extreme conditions in terms of both minimum as well as maximum can be described as below:

- maximum annual rainfall [mm]: *1600-3200,*
- minimum annual rainfall [mm]: *1500-2900,*
- maximum seasonal distribution [% /season]: *2:21:82:3,*
- maximum seasonal distribution [% /season]: *1:14:74:2,*
- absolute daily maximum rainfall [mm]: *97.8 on 11/08/98 at Site 10,*
- longest dry spell [days]: *134,*
- highest 10-minute maximum intensity [mm/h]: *175.2,*
- highest 30-minute maximum intensity [mm/h]: *119.6*, and
- highest 60-minute maximum intensity [mm/h]: *67.4.*

Again, it should be remembered that the conditions in the Yarsha Khola during the study period were wetter than normal compared with the long-term data sets from the DHM stations in Charikot, Jiri, and Melung.

3.1.4 Spatial precipitation distribution

Both catchments are within the influence of the monsoon rains and show high temporal variability within a year, as shown above. Spatial variations on this scale are mainly observed in terms of altitudinal variations and, to a lesser extent, according to aspect. Local climatic effects also play a major role, especially in the more heterogeneous Jhikhu Khola catchment. This was shown very clearly by Carver (1997) who monitored a dense 24-hour rain gauge system within the Bela-Bhimsensthan area. He showed that low rainfall events were highly variable, while events of more than 10 mm rainfall showed less variation. The relationship between elevation, aspect, and rainfall parameters are discussed below on an aggregated time series' bases. For a discussion of events refer to Section 3.4.

3.1.4.1 Jhikhu Khola catchment

The elevation-rainfall relationships in the Jhikhu Khola are not very clear, as the catchment is not homogeneous. On an annual basis, the lapse rates show, on average, a pattern of 444±167 mm increase in precipitation per 1000 m elevation (Figure 3.16). Amongst the seasonal relationships only the lapse rates for the monsoon show a similarly distinct pattern with 355±184 mm increase in precipitation per 1000 m elevation. The lapse rates in the pre-monsoon already vary greatly, but they still indicate a direct relationship. During the seasons with low rainfall (post-monsoon and winter) the relationships vary tremendously, and there are years where there is a negative relationship between rainfall and elevation, that is, there is more rainfall in the lower stations than in the upper stations. This is due to the very local storm cells during these seasons, which do not impact the entire catchment.

The maximum and minimum annual rainfall amounts over the entire period both show elevation dependency. While the maximum changes with a slope factor of 0.53 at an r^2 value of 0.73 show a very clear relationship with elevation, the minimum is related with a slope factor of 0.26 ($r^2 = 0.27$) to elevation, indicating that the linear relationship is not very strong nor very distinct.

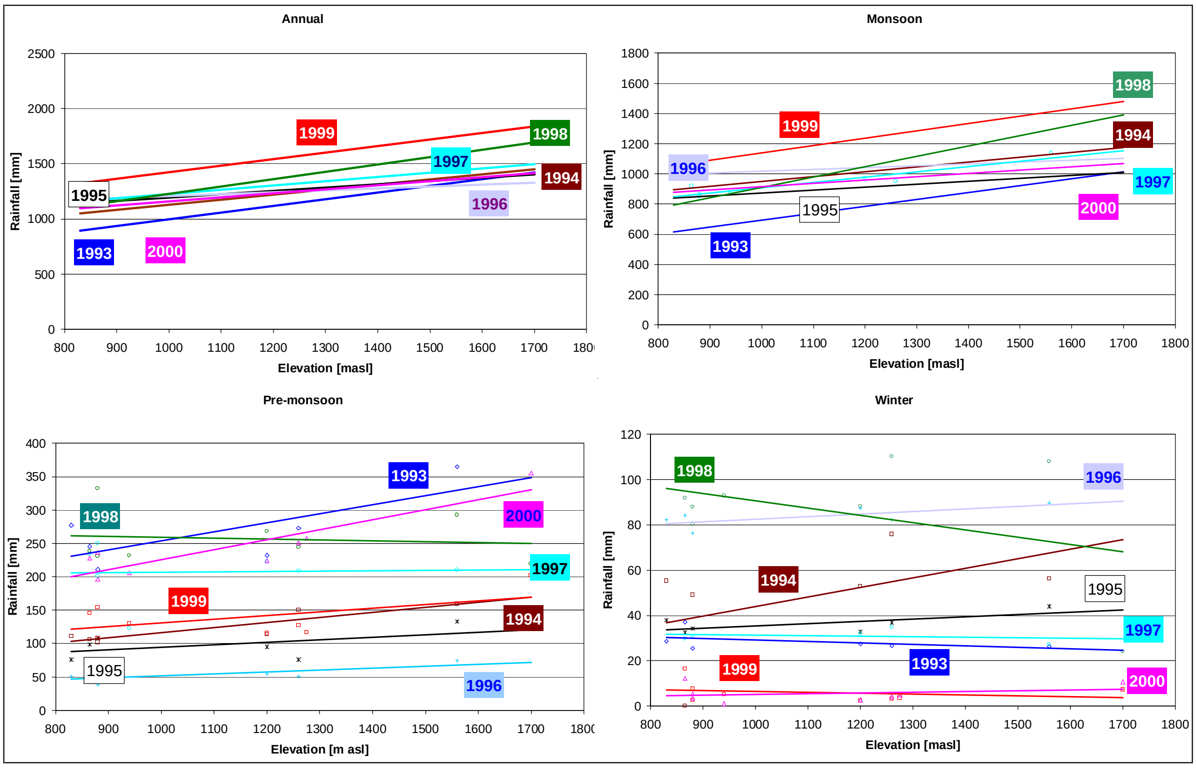


Figure 3.16: **Annual and seasonal elevation-rainfall amount relationships for the Jhikhu Khola catchment, 1993 to 2000** (for equations refer to Appendix A3.9).

The same can be shown for monthly rainfall, where no consistency in terms of lapse rates could be observed. In general, months with high rainfall — the monsoon months from June to September in particular — show clear and direct elevation-rainfall amount relationships. However, there are a number of exceptions to this rule, e.g., July 1997. In months with low rainfall, no regular pattern was observed. Local climatic effects are more important for daily rainfall. In addition, there are events that only partly affect the catchment, while other parts remain dry. Some of these events are discussed in Section 3.4.

There is a distinct relationship between the number of rainy days and elevation. The number of rainy days for the same period changed with elevation according to

rainy days per year [No.] = 0.0143*elevation [m] + 83.104 ($r^2 = 0.62$) Equation 3.3

No relationship with elevation can be observed for dry spells. The spatial distribution of dry spells is not related to either elevation or to aspect.

The annual isohyets for the calculation of areal rainfall were carried out using the ArcView spline interpolator. This interpolator was used rather than the inverse distance weighted (IDW) interpolator due to the shown influence of elevation on annual rainfall. Before interpolation a number of high-altitude stations were introduced and their annual rainfall calculated on the basis of the above lapse rates. The areal rainfall was calculated on the basis of the isohyet grids.

In general, the minimum rainfall in the catchment was observed in its northeastern part, the area of Shree Ram Pati-Kubinde-Bhimsensthan (Figure 3.17). This observation is also reflected in the areal precipitation calculated for the Kubinde sub-catchment (Figure 3.18). The highest rainfall input is normally calculated for the Upper Andheri Khola sub-catchment. Of the ungauged sub-catchments, it is the upper parts of the Jhikhu Khola — the Dhulikhel Khola and the Danphe Khola — which receive the highest rainfall input. Due to these upper zones in the western part of the Jhikhu Khola catchment, the entire catchment shows consistently high areal rainfall values, peaking in 1999 with 1628 mm.

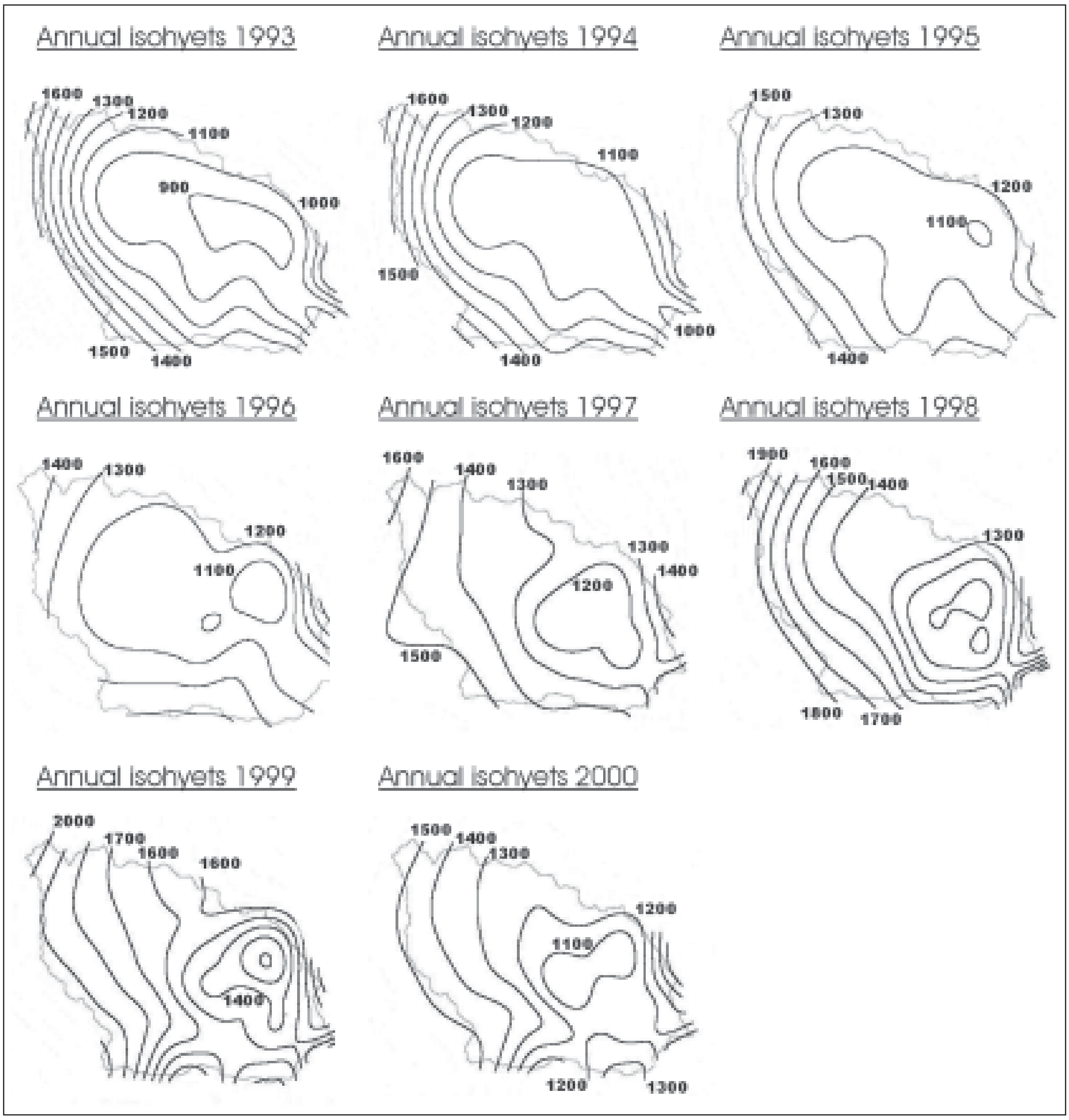
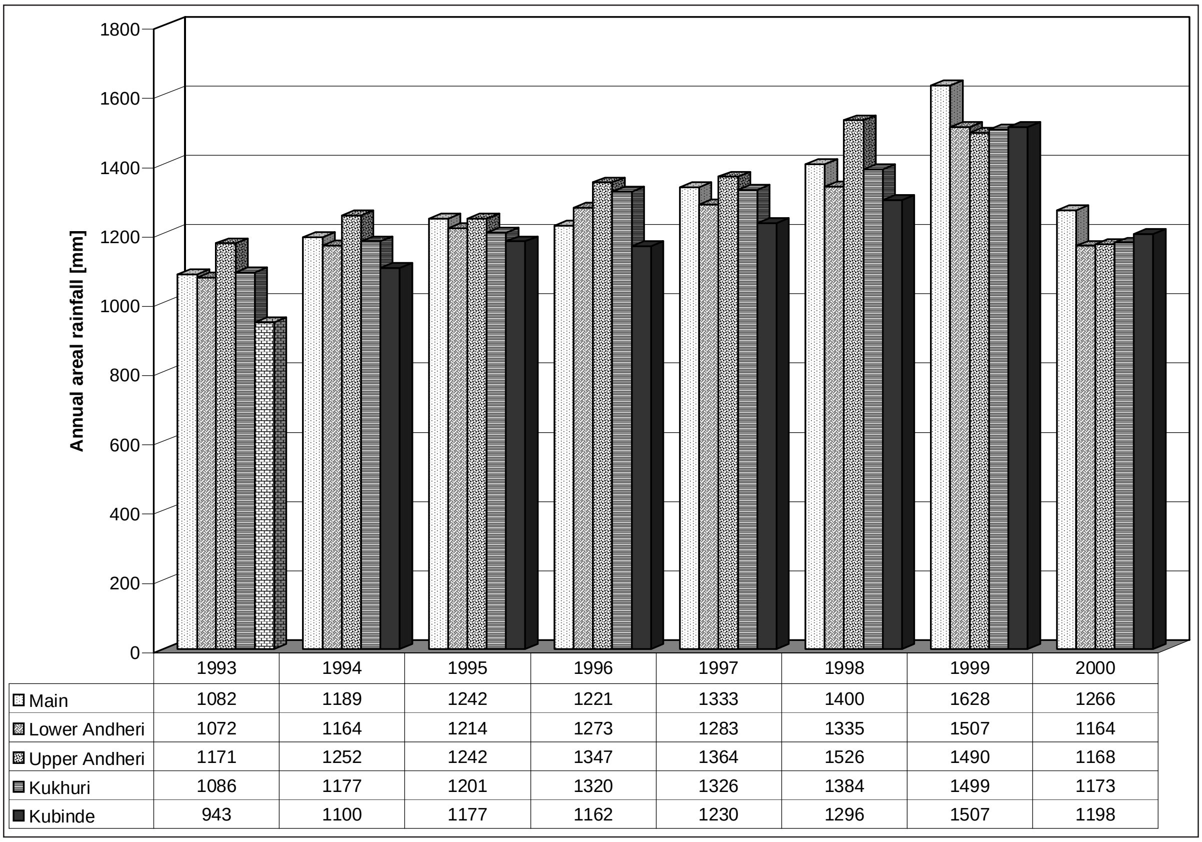


Figure 3.17: **Isohyets of annual rainfall in the Jhikhu Khola, 1993 to 2000**



	1993	1994	1995	1996	1997	1998	1999	2000
Main	1082	1189	1242	1221	1333	1400	1628	1266
Lower Andheri	1072	1164	1214	1273	1283	1335	1507	1164
Upper Andheri	1171	1252	1242	1347	1364	1526	1490	1168
Kukhuri	1086	1177	1201	1320	1326	1384	1499	1173
Kubinde	943	1100	1177	1162	1230	1296	1507	1198

Figure 3.18: **Areal rainfall of the Jhikhu Khola catchment and its sub-catchments, 1993 to 2000**

Despite it being commonly acknowledged that rainfall intensity decreases with increasing elevation (Carson 1985), this thesis is not borne out by the maximum intensity data of the Jhikhu Khola catchment where different trends were observed. While both the 10 and 60-minute maximum intensities usually follow an indirect relationship with elevation — or at least have no distinct positive or negative trend — in the Jhikhu Khola catchment they show a fairly strong direct relationship as well. In terms of erosivity, there was likewise no clear spatial dependence observed when taking into account all events at all sites in one year. However, if we take the 10, 50, or 100 biggest events in terms of AI_{10}, AI_{1030} or AI_{1060} of all stations, there is a clear relationship to altitude (Figure 3.19). The reason and justification for this approach is that only the largest events cause major destruction in terms of flooding and sediment losses. In terms of water availability, where low amounts of rainfall are also important, rainfall intensity and erosivity do not play a major role.

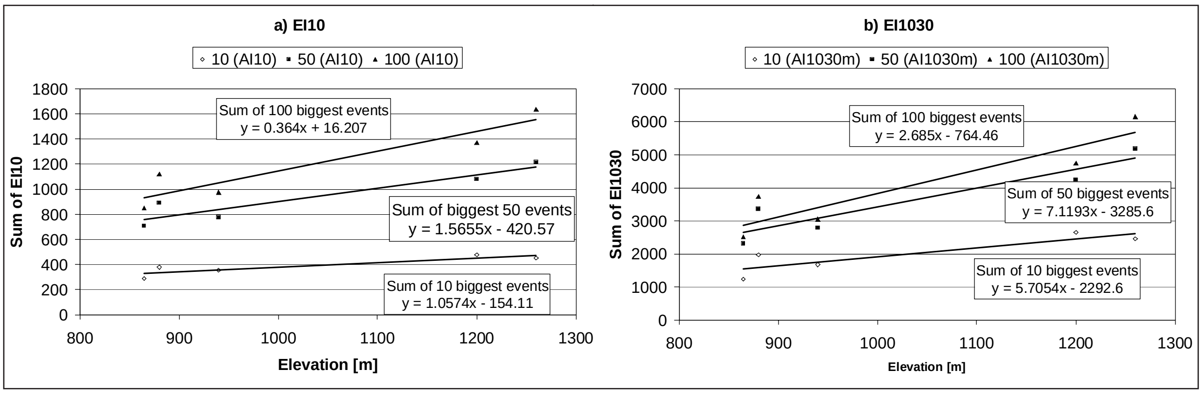


Figure 3.19: **AI_{10} (a) and AI_{1030} (b) (sorted according to size) in relation to elevation, Jhikhu Khola catchment**

Due to the limited station network for exact aspect comparisons, only rough estimates can be made at this stage. For this purpose Sites 3 (elevation 830 masl) and 15 (880 masl) were chosen to represent the lower foot slopes of the Jhikhu Khola catchment; Site 3 being north-facing and Site 15 south-facing. For the upper slopes, Sites 6 (1260 masl) for north-facing and 16 (1200 masl) for south-facing aspects were selected.

During the dry season months, no distinct difference between the north- and south-facing slopes can be observed; neither in terms of mean nor maximum rainfall. In some instances the rainfall on the north-facing slopes is higher, and sometimes it is the other way round. During the dry season, the minimum was consistently lower on the south-facing side, while during the monsoon season there was a difference between the upper and the lower slopes. While on the lower slopes the rainfall on the north-facing side was consistently higher for mean, maximum, and minimum rainfall, a similar relation could not be seen on the upper slopes. The mean rainfall tends to be higher on the north-facing side. No such relationship was observed for maximum and minimum rainfall.

Table 3.8: **Differences in mean, maximum, and minimum monthly rainfall due to aspect of stations on the upper and on lower slopes, Jhikhu Khola catchment**

	Upper slope			**Lower slope**		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**
January	**N>S**	**N>S**	S>N	N>S	N>S	S>N
February	S>N	N>S	S>N	S>N	**N>S**	S>N
March	S>N	S>N	S>N	N>S	**N>S**	S>N
April	N>S	N>S	S>N	**N>S**	**N>S**	S>N
May	**N>S**	**N>S**	S>N	**N>S**	S>N	N>S
June	S>N	S>N	S>N	**N>S**	N>S	**N>S**
July	N>S	S>N	N>S	**N>S**	**N>S**	**N>S**
August	**N>S**	N>S	S>N	**N>S**	**N>S**	**N>S**
September	**N>S**	S>N	N>S	**N>S**	**N>S**	**N>S**
October	S>N	N>S	S>N	S>N	**N>S**	S>N
November	N>S	**N>S**	S>N	S>N	S>N	S>N
December	**N>S**	**N>S**	S>N	N>S	N>S	S>N
Annual	**N>S**	**N>S**	N>S	**N>S**	**N>S**	N>S
N>S	**9**	**9**	**3**	**10**	**11**	**6**
S>N	**4**	**4**	**10**	**3**	**2**	**7**

The differences between the south-facing and the north-facing slopes can also be seen in Figure 3.17. While in the upper areas the rainfall amount does not seem to differ significantly, the lower areas tend to be drier on the south-facing foot slopes than on the north-facing foot slopes.

In summary, it can be said that in the Jhikhu Khola catchment:

- rainfall amount on an annual basis and during the monsoon and pre-monsoon season increases with elevation;
- rainfall amount on the basis of post-monsoon and winter seasons shows irregular behaviour;
- rainfall amount on the basis of monthly data does not show a distinct correlation with elevation;
- the maximum and the minimum annual rainfall observed over the entire period shows elevation dependence;
- the number of rainy days increases with elevation;
- the lower slopes on the south-facing slopes tend to be receive less rainfall than the lower slopes on the north-facing side of the catchment;
- no distinct difference in terms of aspect can be observed in the upper areas; and
- rainfall erosivity of larger events increases with elevation.

The relationships observed are presented in Figure 3.20 with the parameters standardised according to the values at 800 masl corresponding to 1. The erosivity parameters, AI_{10} and AI_{1030} , show the biggest change with increasing elevation at about 0.5 times the value at 800 masl per hundred metres change in elevation. The annual rainfall parameters double (approximately) over the entire relief of the catchment. The number of dry spells as well as the maximum intensity do not show any distinct relation to elevation.

3.1.4.2 Yarsha Khola catchment

In general, much stronger and clearer elevation-rainfall relationships are observed in the Yarsha Khola catchment. This is mainly due to the rather homogenous and bowl-shaped topography of the

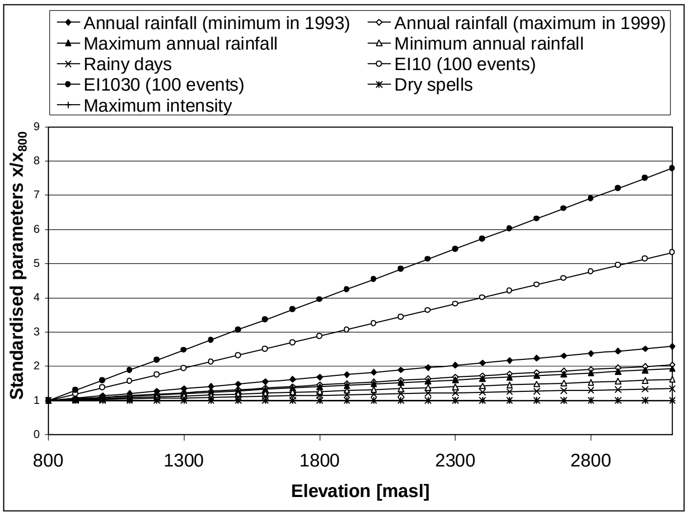


Figure 3.20: **Observed rainfall relationships with elevation**

catchment. The lapse rates in the Yarsha Khola catchment were, on average, 887±233 mm per 1000 m elevation on an annual basis for the year 1998 to 2000 (Figure 3.21). The monsoon lapse rates for the same period were 746±257 mm per 1000 m elevation. The pre-monsoon lapse rate in the case of the Yarsha Khola catchment and the given period likewise shows a distinct pattern with 114±34 mm per 1000 m.

The strong elevation-rainfall relationship in 1998 is due to large rainfalls in December 1997, which is part of winter 1998. The remaining years only show weak linear relations with elevation.

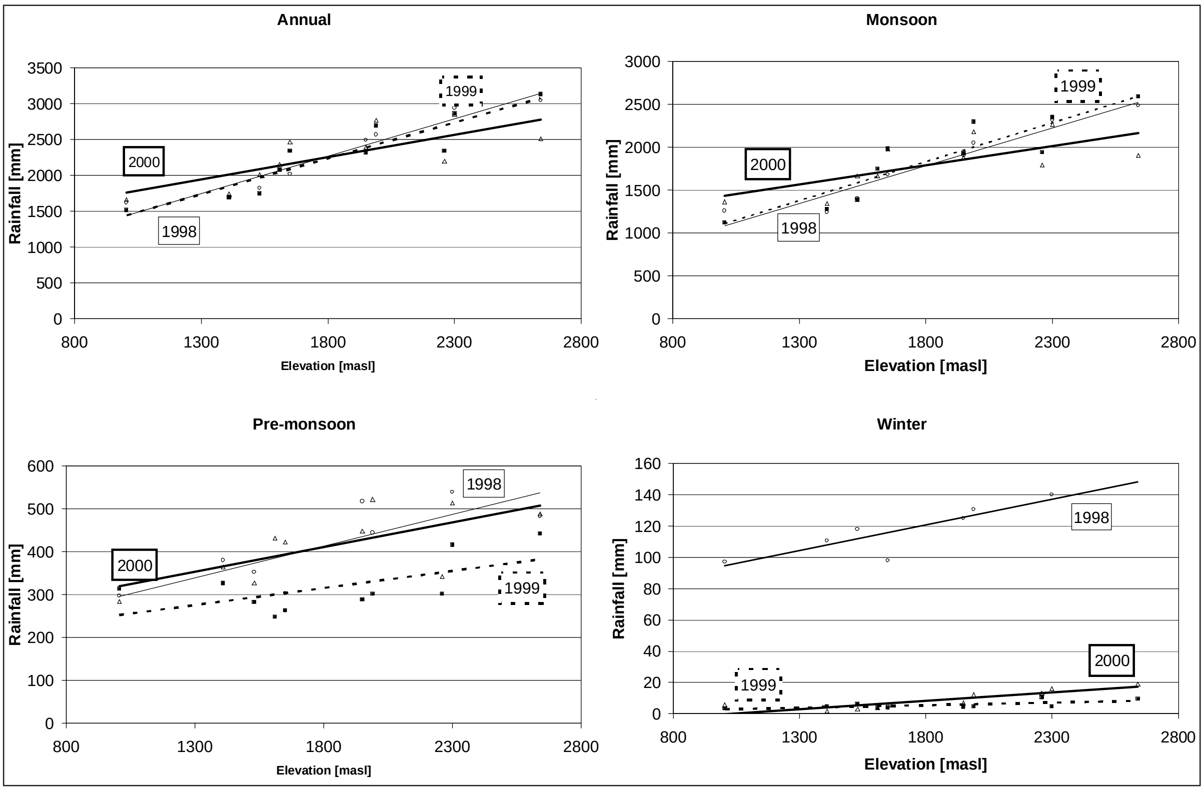


Figure 3.21: **Annual and seasonal elevation-rainfall amount relationships for the Yarsha Khola catchment, 1998 to 2000** (for equations refer to Appendix A3.9)

The maxima of annual rainfall measured at all sites show likewise a very strong relation with a slope factor of 1.0 and an r^2 of 0.91. The minima show a slightly weaker but still very strong relationship with a slope factor of 0.8 and r^2 of 0.80.

The lapse rate for the number of rainy days in relation to elevation can be expressed as follows:

Rainy days per year [No.] = 0.0147*elevation [m] + 112.2 (r^2 = 0.66) Equation 3.4

As in the Jhikhu Khola catchment, no relationship between the number of dry spells and elevation, nor dry spells and aspect could be established.

The annual isohyets calculated in the Yarsha Khola catchment range from 1500 to 3300 mm with a very steep gradient over a distance of only about 11 km from the outlet to the highest point in the catchment (Figure 3.22). It is important to note that there is no distinct difference visible between the north- and the south-facing slopes in the catchment. The isohyets follow roughly the contours on both sides of the catchment.

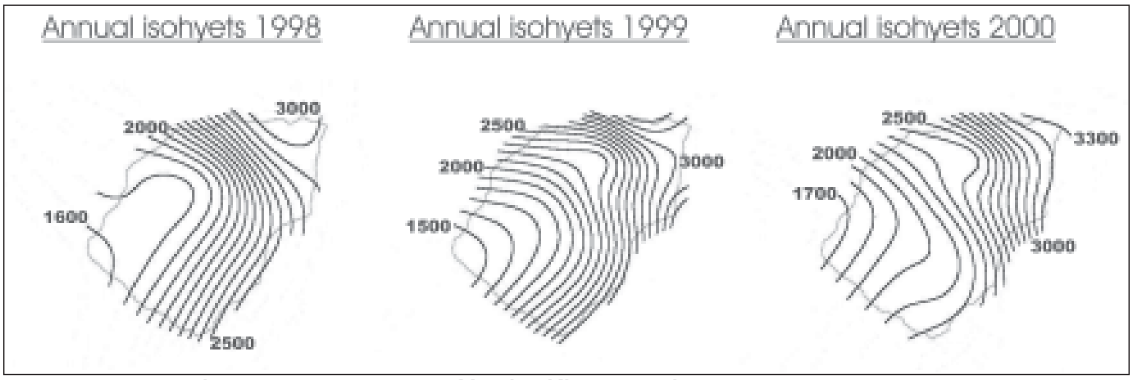


Figure 3.22: **Isohyets, 1998 to 2000, Yarsha Khola catchment**

The same results are evident if stations from both major aspects on the lower and the upper slopes of the catchment are compared (Table 3.9). Sites 3 and 9 are representative for the lower slopes on the south-facing and the north-facing side of the catchment, respectively. For the upper slopes, Sites 5 on the south-facing and Site10 on the north-facing slope are compared after adjusting for slight differences in elevation.

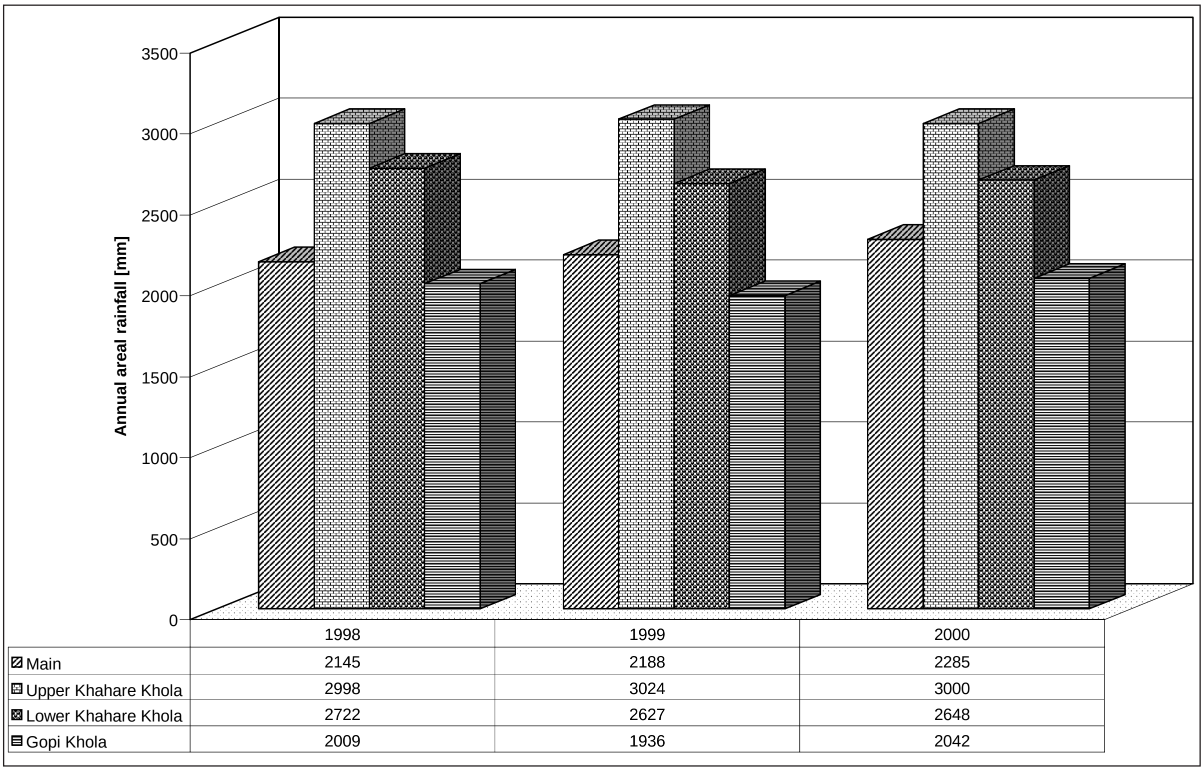
Table 3.9: **Differences in rainfall amount due to aspect**

	Upper slope						Lower slope					
	Site 5 (2300 masl)			Site 12 (2260 masl)			Site 9 (1410 masl)			Site 3 (1530 masl)		
	M	E	D	M	E	D	M	E	D	M	E	D
Jan	5.7	5.6	0.1	6.9	7.1	-0.1	1.5	1.6	-0.1	2.5	2.3	0.2
Feb	13.3	13.1	0.2	12.5	12.7	-0.2	10.1	11.0	-0.9	9.7	8.9	0.8
Mar	65.6	64.5	1.1	57.6	58.6	-1.0	44.2	48.0	-3.8	50.4	46.4	4.0
Apr	83.7	82.3	1.5	85.3	86.8	-1.5	88.2	95.7	-7.5	82.8	76.3	6.5
May	283.6	278.6	4.9	297.4	302.7	-5.3	199.2	216.2	-17.0	171.2	157.7	13.4
Jun	518.9	509.9	9.0	507.2	516.2	-9.0	235.2	255.2	-20.0	294.0	270.9	23.1
Jul	863.9	848.9	15.0	824.5	839.1	-14.6	534.9	580.5	-45.5	577.5	532.2	45.3
Aug	638.9	627.7	11.1	557.4	567.3	-9.9	371.3	402.9	-31.6	383.4	353.3	30.1
Sep	411.1	403.9	7.1	426.0	433.5	-7.5	168.0	182.2	-14.3	215.5	198.6	16.9
Oct	88.8	87.3	1.5	108.6	110.5	-1.9	49.3	53.4	-4.2	58.6	54.0	4.6
Nov	9.5	9.3	0.2	9.2	9.4	-0.2	6.9	7.5	-0.6	7.5	6.9	0.6
Dec	27.3	26.8	0.5	2.1	2.2	0.0	21.0	22.8	-1.8	23.0	21.2	1.8

M: measured E: estimated on the basis of rainfall from the other site D: difference

The three years were very similar in terms of areal precipitation (Figure 3.23). The Upper Khahare Khola sub-catchment usually shows the highest per area precipitation of about 3000 mm. The north-facing and lower elevation Gopi Khola sub-catchment contributes least to the overall areal precipitation of the entire catchment. This is less due to differences in general aspect (see also above), and much more due to the fact that the mean and maximum elevation of this sub-catchment are the lowest in the entire Yarsha Khola catchment.

Maximum rainfall intensity does not show any clear and distinct relationship with elevation. Most of the relationships are positive, but show very low regression coefficients. In addition, at a number of sites at higher elevations the intensities are lower than at lower elevation sites, and vice versa. This is true for all three intensity parameters calculated in this study, that is, 10, 30, and 60-minute maximum intensities.



	1998	1999	2000
▨ Main	2145	2188	2285
▦ Upper Khahare Khola	2998	3024	3000
▩ Lower Khahare Khola	2722	2627	2648
▤ Gopi Khola	2009	1936	2042

Figure 3.23: **Areal rainfall in the Yarsha Khola catchment and selected sub-catchments**

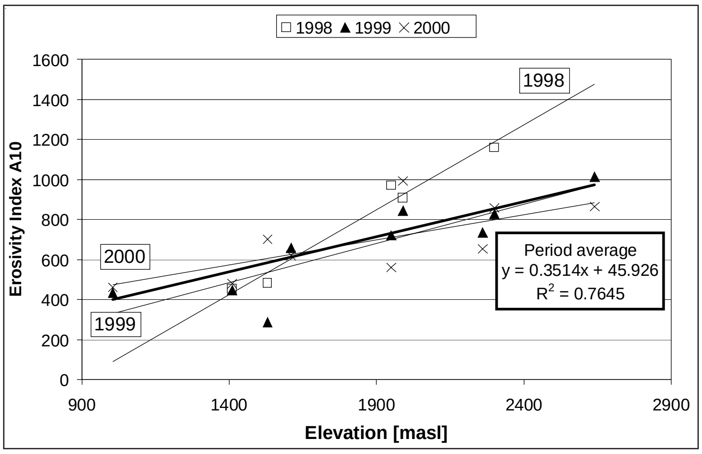


Figure 3.24: **Erosivity index AI_{10} in relation to altitude, Yarsha Khola catchment**

The erosivity index in the Yarsha Khola catchment has a direct relationship with elevation (Figure 3.24), unlike in the Jhikhu Khola where only the largest events show a relationship with altitude. In the Yarsha Khola the erosivity index has a clear relationship with altitude for all rainfall events. The year 1998 shows a slightly different picture than the remaining two years, with very high erosivities in the upper part of the catchment.

In summary, it can be said that in the Yarsha Khola catchment:

- rainfall amount on an annual basis and during the monsoon and pre-monsoon season increases with elevation;
- no trend can be observed in the remaining seasons mainly due to very low and erratic rainfalls;
- in case of a large event during these dry seasons a trend can also be observed;
- the number of rainy days increases with elevation; and
- rainfall erosivity increases with elevation.

The observed elevation-rainfall parameter relationships are compiled in Figure 3.25 showing a similar picture as in the Jhikhu Khola catchment. AI_{10} shows the biggest change with elevation followed by the annual rainfall parameters, which, as in the Jhikhu Khola catchment, nearly doubled over the entire relief of the catchment.

3.1.5 Frequency

For the estimation of future rainfall, it is important to review empirical rainfall distributions and the frequency of selected events. For different susceptibilities different rainfall parameters and their distribution are important. The distribution of dry spells and minimum rainfall amounts are of importance when estimating water scarcity, while high rainfall amounts and rainfall intensities must be understood when considering floods and soil erosion.

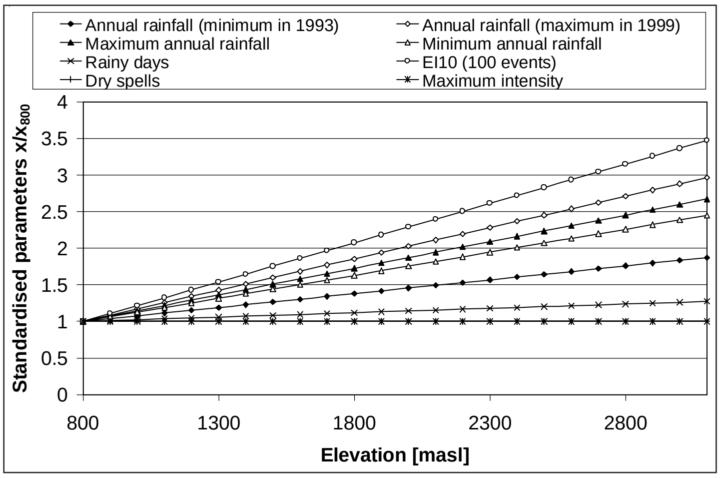


Figure 3.25: **Rainfall-elevation relationships in the Yarsha Khola catchment**

The project sites in the Jhikhu Khola catchment were only been installed in 1993 and there were just 8 years of data available at the end of the year 2000 at Sites 6, 15, and 16. Therefore, all frequency analyses are carried out only at these sites and then compared with the long-term data sets of Sites 9 and 12 monitored by DHM to assess their validity. In the Yarsha Khola catchment the longest record is 3 complete years, from 1998 to 2000. Frequency analyses have therefore not been calculated for this catchment, but for governmental sites close to the catchment where possible and applicable.

3.1.5.1 Frequency of selected monthly rainfall amounts

The empirical frequency distributions of monthly rainfall at sites in the Jhikhu Khola catchment show two patterns which, according to Gommes (1983), are typical for tropical countries with a distinct wet and dry season (Figure 3.26):

a) the positively skewed pattern in the dry season months (thin black and thick white lines);and
b) the pattern resembling a normal distribution in the monsoon months (thick black lines).

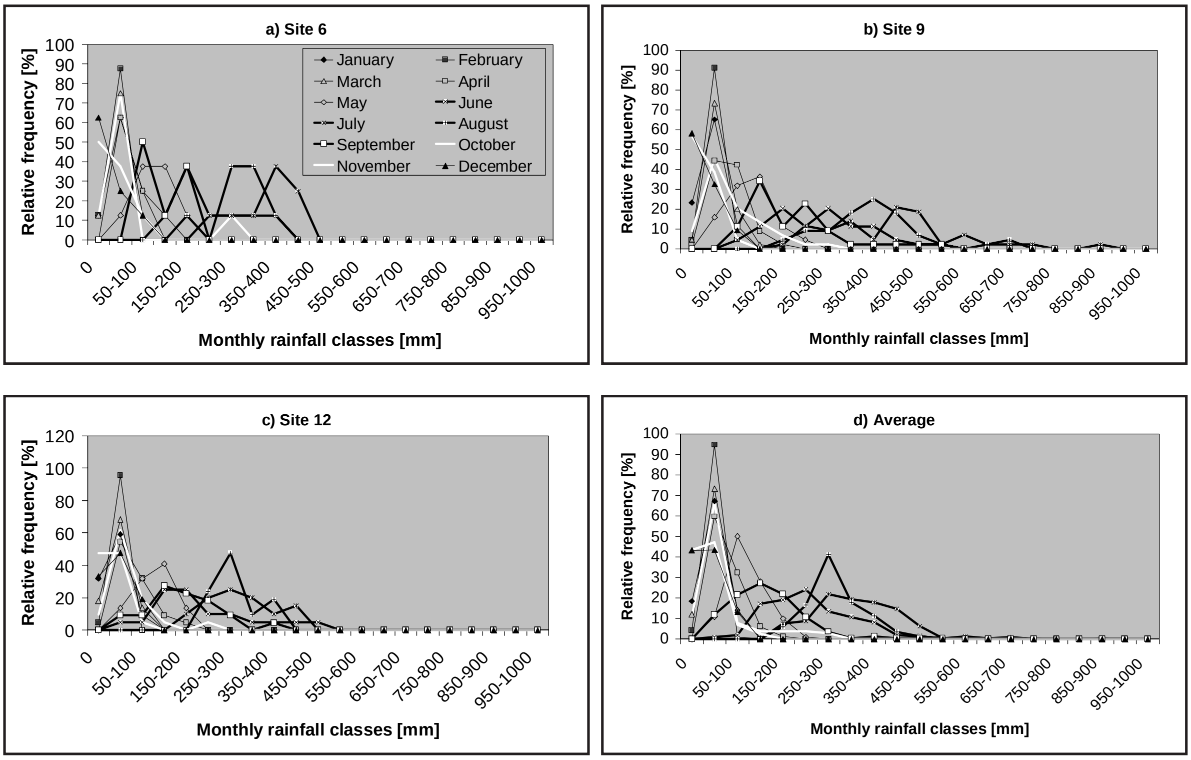


Figure 3.26: **Relative frequencies of monthly rainfall amount at Sites 6, 9, and 12 and average of these, Jhikhu Khola catchment** (data source for Sites 9 and 12: DHM 2000)

This pattern is seen in particular at Sites 9 and 12, where long-term data were used (b and c). The same was also clearly shown by averaging all the stations (d). At Site 6 (a), where only 8 years' data were available, the pattern is not as clear, but shows the same trend. Figure 3.26 and Table 3.10 show that at sites in the Jhikhu Khola catchment:

- in about 45% of the cases the months of November and December received no rainfall;
- in more than 75% of the cases the months of January, February, March, October, November and December received less than 50 mm rainfall;
- in about 60% of all cases the month of May received less than 100 mm rainfall;
- in about 60% of all cases the month of September had less than 150 mm rainfall;and
- July and August rainfall was never less than 150 mm and was most frequently between 250 and 300 mm.

Table 3.10: **Average monthly relative frequencies at all sites [%] (black = maximum)**

Month	0	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400	400-450	450-500	500-550	550-600	600-650	650-700	700-750	750-800	800-850	850-900	900-950
Jan	18.5	**67.3**	14.1																	
Feb	4.3	**94.8**	0.9																	
Mar	12.0	**73.3**	14.2	0.4																
Apr	0.4	**59.8**	32.3	6.1	1.4															
May		10.9	**50.2**	28.0	10.0	0.9														
Jun		1.0	1.9	17.3	19.1	**24.3**	13.6	10.8	8.3	1.9	1.5	0.5								
Jul					7.5	8.8	**21.9**	19.3	17.9	14.7	6.2	0.5	1.4	0.5	0.5	0.5			0.5	
Aug					5.9	16.6	**41.3**	18.0	11.3	3.6	1.4	0.5	0.0	0.5	0.9					
Sep		11.8	21.6	**27.3**	21.8	10.7	3.6	0.5	1.4	0.5	0.5	0.5								
Oct	11.2	**66.5**	7.9	3.7	3.9	3.9	3.0													
Nov	43.4	**47.3**	6.9	2.5																
Dec	43.3	**43.5**	13.2																	

Looking back at the study period, these results show that during a number of months the local farmers did not receive adequate water for the different development stages of their various crops. The most critical months in terms of water availability for different crops are given below. Note that water stress during any of the months below can cause a drastic decreases in yield (ILACO 1981; Doorenbos et al. 1979) (also refer to the agricultural calendar in Section 3.6, Figure 3.154).

- *April to June (onset of monsoon rains) for maize (rainfed)*

  The maize crop is sown any time after the first pre-monsoon showers, usually starting in the month of March/April. After germination, the young maize plants need adequate moisture for the early development stage of establishment (15 to 20 days). Flowering (after 40 to 65 days), where moisture stress can reduce yields, occurs in the early monsoon months and is therefore usually no problem. However, if the onset of the monsoon is late, yields can be reduced drastically.

- *October/November and February/March for wheat and barley (rainfed)*

  Wheat is sown in November, when the seed needs adequate soil moisture for germination and establishment. This soil moisture is usually provided by monsoon season rains, however, in case of early offset and no rains in September and October, germination rates can be reduced drastically. A critical time is February/March during ear formation and flowering, when wheat needs adequate moisture for good yield.

- *September and November for potatoes (rainfed)*

  Potatoes are sensitive to water deficit and the soil should be maintained with a relatively high moisture content. A potato crop needs about 100 mm of rainfall per month and even a short period of drought can cause decreased yields. For tuber formation and yield, adequate water is crucial in November, the middle part of the growing period.

For ripening and harvesting some crops need dry conditions . The months for two selected crops are given below (ILACO 1981; Doorenbos et al. 1979):

- *April for wheat and barley (rainfed)*
  For maturing and ripening in about April/May the wheat crop needs dry weather.

- *October/November for rice (irrigated)*
  After a long period where rice needs very moist conditions for its different development stages, which are usually met by both irrigation and rainfall, it then requires dry conditions during the ripening and harvesting for an even maturation and a low percentage of broken grains. This development stage is reached in about October.

For a preliminary analysis of farmers' vulnerability the following questions arise (the values are taken with reference to the calculated crop water requirements in Table 3.115). The answers are based on Figure 3.26 and Table 3.10.

1. How many times was rainfall less than 50 mm in the month of April or less than 100 mm in May, which may have caused decreasing yields in maize on rainfed land?
   - ❖ During the study period in 2/3 of the cases, rainfall was neither adequate in the month of April nor in May, and this presumably has an impact on maize yields.

2. How many times was rainfall less than 70 mm in the month of February or 50 mm in the month of March, which may have caused decreased yields in wheat and barley on rainfed land?
   - ❖ In most of the years rainfall was below 50 mm in the month of February and in 3/4 of the years it was less than 50 mm in the month of March, giving lower yields of wheat and barley crops.

3. How many times was rainfall less than 100 mm in the months of September to October each, which may have caused a decrease in potato yields on rainfed land?
   - ❖ In 1/3 of the years rainfall was below 100 mm in the month of September and in 3/4 it was below 100 mm in the month of October, resulting in lower potato yields.

4. How many times was rainfall more than 50 mm in the month of April or May, which potentially caused a decrease in wheat yields?
   - ❖ In 1/3 of the years rainfall was higher than 50 mm in the month of April, potentially causing damage to wheat yields. More than 90% of the years had more than 50 mm in May.

5. How many times was rainfall more than 50 mm in the month of October, which potentially caused a decrease in rice yields?
   - ❖ In 1/4 of the years rainfall was higher than 50 mm, potentially damaging the rice crop.

As shown in Figure 3.26, the monthly rainfall distribution in the dry season, especially the months with a high probability of having no rainfall at all, is strongly skewed. Chow et al. (1988) suggest the use of the Gamma function for the purpose of calculating the probabilities. However, this function is not appropriate for distributions where the lower end is bigger than 0. Gommes (1983) proposes the use of the incomplete Gamma function for this purpose. In this study, the Bernoulli equation of independent trials as discussed by Chyurlia (1984) and the formula corrected according to Sachs (1997) —

$$P_{(x,n)} = n!/[(x!*(n-x)!) * p^{x}*(1-p)^{(n-x)}] \quad \text{(Sachs 1997)} \qquad \textbf{Equation 3.5}$$

where

P = probability of x favourable events in n trials
p = probability of a single favourable outcome
x = number of years with a certain rainfall
n = number of total years

was applied to determine the probability of water stress or excess water during different stages of crop development. This would then show the vulnerability of the farmers who grow the respective crops in the catchment.

On the basis of Figure 3.27 and in answer to the questions above, the following can be noted: (numbering of response corresponds to numbering of questions, above).

1. The probability that in 6 out of 10 years rainfall is below 50 mm in April is 33% and there is a 25% probability that in half the years the rainfall in May is below 100 mm.
2. The probability that in all years rainfall in February is below 70 mm is 100%. For 9 out of 10 years, the rainfall is below 50 mm with a probability of 40%.
3. The probability that rainfall in September is below 100 mm in 1 out of 10 years is 40%. In October 10 out of 10 years are below 100 mm with a probability of 65%.
4. The probability that in 4 years out of 10 rainfall in April is higher than 50 mm is 25%. The probability that the rainfall in May is higher than 50 mm in 9 years out of 10 is 33%.
5. The probability that rainfall is higher than 50 mm in October in 2 out of 10 years is 30%.

From these analyses it is indicated that farmers are most vulnerable in terms of reduced water availability mainly in the post-monsoon and the early to late pre-monsoon season.

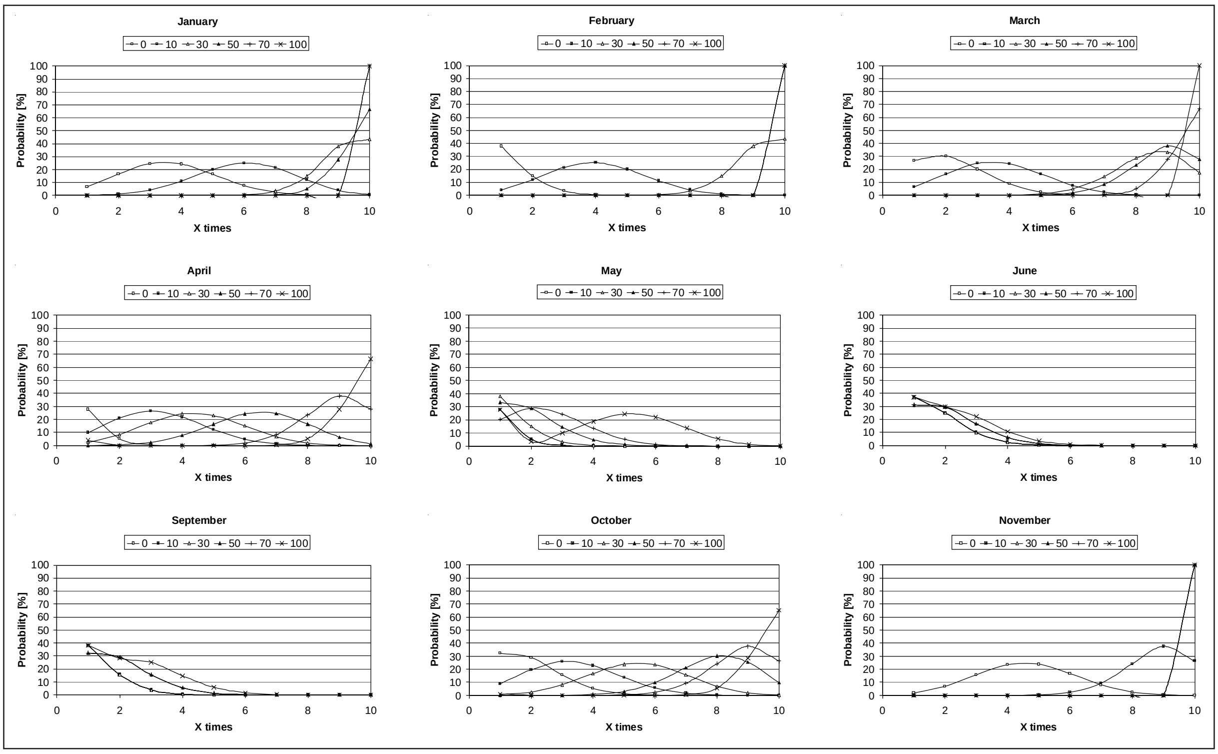


Figure 3.27: **Probabilities for monthly rainfall of different amounts in a 10-year period, Site 12 (1976 – 2000), Jhikhu Khola catchment**

3.1.5.2 Distribution of extreme rainfall values

For flood and degradation considerations the maximum rainfall is of most importance as these events cause the most damage (see also Sections 3.5 and 3.6). For the empirical assessment of return periods of extreme rainfall amounts, Chyurlia (1984) proposes using the Weibull equation for plotting positions, as this equation does not make any *a priori* assumption with regards to the type of distribution represented by the data. This equation is expressed as follows (Chyurlia 1984):

$$p = r/(n+1) \qquad \textbf{Equation 3.6}$$

where

p = probability
r = rank
n = number of observations

For frequency analyses of annual daily rainfall maxima, Chyurlia (1984) used Log-Pearson Type III and Gumbel Extreme Value (GEV) distributions. Using this approach he identified the maximum daily rainfall intensities of a 100-year return period as exceeding 400 mm in the mountainous regions of Nepal.

Different return periods can be calculated for the data of the Jhikhu Khola catchment (Figure 3.28a,b,c & d). The limiting factor in this case is the time series' duration. In general, a return period cannot be longer than double the length of the base time series. The longest return period therefore can be estimated for Site 9, where 43 years of data are available. On the basis of this data, rainfall with a 100-year return period (probability p = 0.01) can be estimated on 267 mm using the GEV for this location (Figure 3.28d). The result of the Log-Pearson Type III distribution, estimating a 100-year return period rainfall of 182 mm seems however to be more appropriate comparing the Weibull plotting positions with the theoretical distribution. The same can also be observed for the other sites, where the Log-Pearson Type III distribution generally shows a better fit with the Weibull plotting positions than the GEV. The maximum return period that can be estimated at Site 12 is 50 years (p = 0.02). The Log-Pearson Type III estimate for this return period is 146 mm (Figure 3.28b) with a considerably higher estimate by the GEV of 208 mm. For the same return period on the basis of data at Site 9, 135 mm is estimated applying Log-Pearson Type III, and 261 mm using GEV. On the basis of the project period of 8 years, a maximum of 20 years' return period can be estimated, as follows.

- Site 6 (8 years) GEV: 197 mm; Log-Pearson Type III: 136 mm
- Site 9 (43 years) GEV: 184 mm; Log-Pearson Type III: 143 mm
- Site 12 (25 years) GEV: 165 mm; Log-Pearson Type III: 125 mm
- Site 15 (8 years) GEV: 128 mm; Log-Pearson Type III: 93 mm

The empirical and theoretical frequency of events with different return periods (above) were established on the basis of observed years. In order to identify the biggest possible events, the probable maximum precipitation (PMP) defined as "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (Hansen et al. 1988) was calculated according to the method devised by Hershfield and described in WMO (1986).

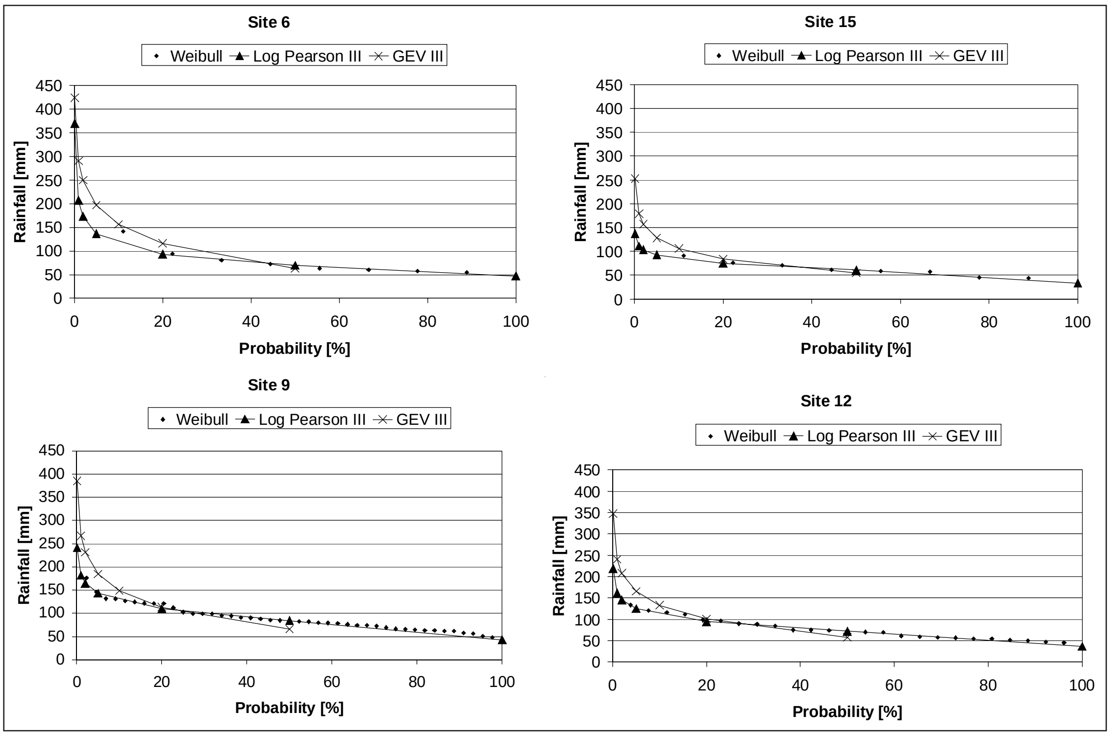


Figure 3.28: **Theoretical recurrence probabilities for daily maximum rainfall at Sites 6 (a) and 15 (b) compared with long-term data sets at Sites 12 (c) and 9 (d)**

Table 3.11: **PMP calculated according to Hershfield for different sites in the Jhikhu Khola catchment**

Site No.	Elevation [masl]	Point PMP (24 hrs) [mm]	Area PMP for 100km^2 (24 hrs) [mm]
Site 9	1560	537	521
Site 12	865	504	489
Nagarkot*	2150	336	326
Site 6	1260	441	428
Site 15	880	354	365
Site 16	1200	546	530

* Daily precipitation data for calculation from DHM (2000)

Table 3.12: **PMP calculated according to Hershfield for different sites near the Yarsha Khola catchment**

Site No.	Elevation [masl]	PMP (24 hrs) [mm]	Area PMP for 60km^2 (24 hrs) [mm]
Charikot	1940	893	875
Jiri	2003	426	417
Melung	1536	763	748

According to this method the maximum point PMP in the catchment was calculated for Site 9 in Dhulikhel with 537 mm in 24 hours (Table 3.11). This is 30 mm more than the point PMP determined for Site 12 in the valley bottom. On the basis of calculations for Nagarkot, which lies adjacent to the Jhikhu Khola catchment, the PMP was determined as 336 mm in 24 hours. Converting the point PMP to area PMP a reduction of about 20 mm was observed for an area of 100 km^2.

For the stations close to the Yarsha Khola catchment, much larger PMPs were determined in the case of Charikot, with 893 mm in 24 hours and 763 mm at the site in Melung (Table 3.12). In the case of Jiri, the determined PMP was only 426 mm in 24 hours.

Comparing these calculated values with the extreme one-day rainfall events observed in Nepal and an empirical relationship between PMP and elevation established for Western Nepal by Tahal Consulting Engineers (2002) (Figure 3.29), it is evident that the values in the Jhikhu Khola seem to be rather low. Comparing the values with the 100-year return periods determined above for Site 9 of 182 mm (Log-Pearson Type III) and 267 mm (GEV) they do seem justified. The values for the sites close to the Yarsha Khola are very high in comparison to the other values shown in the figure.

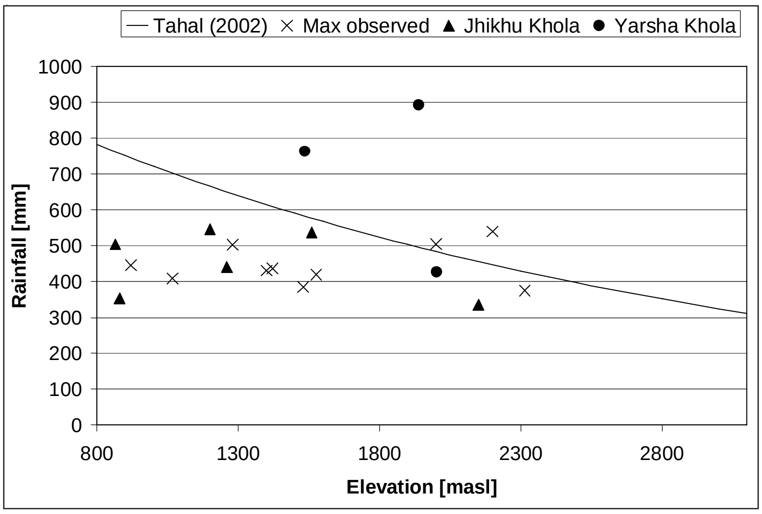


Figure 3.29: **Comparison of calculated PMP with extreme one-day events and empirical relationship between PMP and elevation by Tahal Consulting Engineers (2002)** (data source for maximum observed events: Thapa and Khanal 2002)

3.1.5.3 Intensity-duration-frequency relationships

For a number of applications in engineering as well as for the estimation of soil erosion and runoff generation vulnerability, knowledge on the frequency of certain rainfall intensities is desirable. However, the number of observation sites in Nepal with high temporal resolution rainfall measurements is limited. In addition to the sites in the Jhikhu Khola, some of which have been monitored since 1993, only short-term measurements have been conducted (such as Likhu Khola, Gardner and Jenkins 1995). Some of the high-resolution recording rain gauges are still monitored:

- ICIMOD established an automatic weather station in 1995 in its T&D site at Godavari;
- Kathmandu University has maintained an automatic weather station since 1999.

In the absence of the required data, Chyurlia (1984) estimated intensity-duration-frequency relationships for Nepal on the basis of an empirical relationship from monsoonal areas in West Africa. This work had shown that precipitation generally obeys a power function with a square root in the power index to duration. On the basis of investigations on the world record line of event rainfall (e.g., WMO 1994), the same authors concluded that precipitation intensity likewise follows a function with a power index to duration and therefore proposed:

$I = at^{-0.5}$ (Chyurlia 1984) **Equation 3.7**

where

I = precipitation intensity [mm/h]
a = constant
t = duration [h]

As the constant, 'a', is a function of the return period, 'T', measured in number of years Chyurlia (1984) replaced 'a' with the empirical relationship of maximum daily rainfall as a function of the return period. This yielded the empirical relationship for intensity-duration frequency for each physiographic region. Only the relationship valid for the middle mountains is given here:

$I = 23.5 * T^{0.18} * t^{-0.5}$ (Chyurlia 1984) **Equation 3.8**

This empirical approach on the basis of no high-resolution rainfall data was tested using the available rainfall intensity data sets with 2 min resolution from the Jhikhu Khola catchment. The intensity-duration-frequency diagrams (IDF) were prepared according to Chow et al. (1988), on the basis of which the design rainfall depth for a given return period 'T' is determined by

$p_{T,t} = p_{tmean} + K_T * p_{tstdev}$ (Chow et al. 1988) **Equation 3.9**

where

p = design precipitation depth [mm]
T = return period [years]
t = duration [h]
p_{mean} = mean precipitation of the rainfall depths of a specified duration t [mm]
K_T = frequency factor
p_{stdev} = standard deviation of the rainfall depths of a specified duration t [mm]

The frequency factor K_T is determined according to

$K_T = -(6^{0.5}/\eth) * [0.5772 + \ln(\ln(T/T-1))]$ (Chow et al. 1988) **Equation 3.10**

Due to the short time series of only 8 years, the maximum return period that can be determined on the basis of annual maxima series is 20 years. In general, they show a similar shape and similar values. For comparison of the IDF curves of the two sites, 6 and 15, the calculated values of each relationship are given below:

- for a return period of 8 years the 30-minute intensity was determined to be 69.2 mm/h at Site 6 and 68.5 mm/h at Site 15;
- for a return period of 8 years the 10-minute intensity was determined to be 103.9 mm/h at Site 6 and 106.0 mm/h at Site 15;and
- for a return period of 20 years the 30-minute intensity was determined to be 79.2 mm/h at Site 6 and 81.9 mm/h at Site 15 (see Figure 3.30).

Comparing the IDF curves established on the basis of data from sites in the Jhikhu Khola catchment with the theoretical relationship proposed by Chyurlia (1984) it is evident that the return periods of intensities for low duration rainfall, where no data were available in 1984, when Chyurlia developed his method, were underestimated (Figure 3.31). For example, the two-year return period for a 30-minute maximum intensity was determined to be 26 mm/h by the Chyurlia formula. On the basis of data from Site 15 the two-year return period rainfall was 49 mm/h and for Site 6 it was 52 mm/h. For longer time durations, the Chyurlia formula tends to overestimate the values at Site 15, for example for daily values the Chyurlia formula calculates 4.3 mm/h (= 103 mm/day), while the established IDF shows a value of 2.9 mm/h (= 70 mm/day). For Site 6 the Chyurlia formula seems to calculate appropriate values at longer duration.

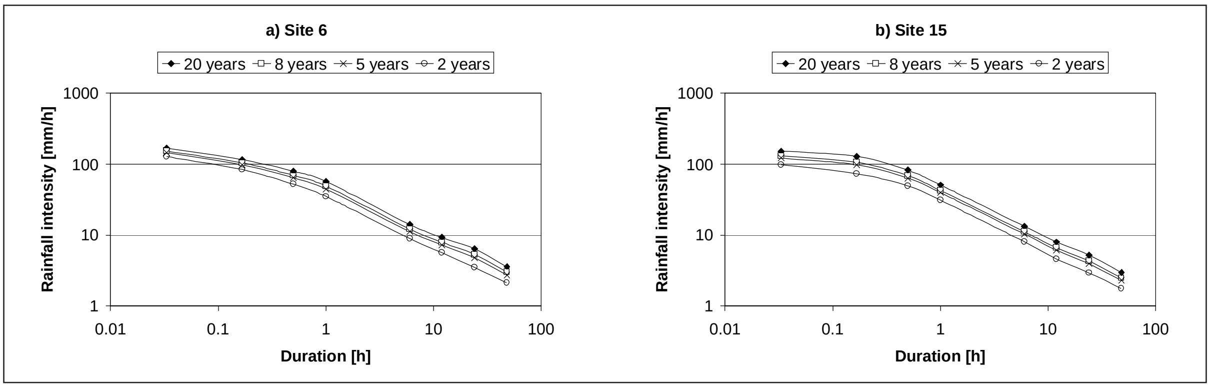


Figure 3.30: **IDF curve for Sites 6 and 15 in the Jhikhu Khola catchment**

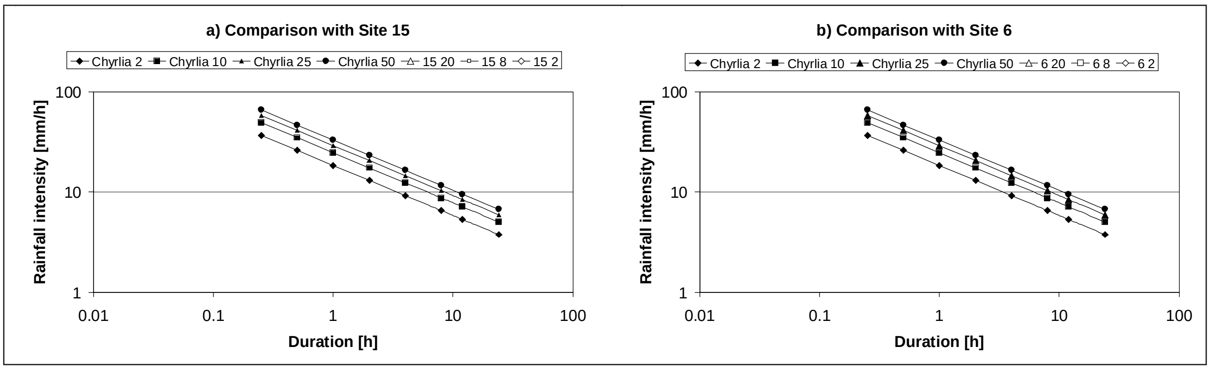


Figure 3.31: **Comparison of the IDF curves with the empirical IDF of Chyurlia (1984)**

3.1.5.4 Summary

The frequency analyses of rainfall in the Jhikhu Khola catchment above can be summarised as follows.

- 'No rainfall' occurs most often in November and December.
- The months of October to April generally have less than 50 mm.
- The pre-monsoon months are the months where farmers are at highest risk if there is inadequate water.
- The Log-Pearson Type III fits better with the empirical return periods than the GEV;
- Events of 20 years' statistical return period are estimated between 100 to 150 mm in the catchment.
- Long-term observations at Site 9 estimate approximately 180 mm for a rainfall event with a 100-year return period.
- The 100 km^2 PMP is estimated to be between about 300 and 600 mm for different sites according to the Hershfield method.
- In the Yarsha Khola catchment, the PMPs are estimated to be between 500 and 900 mm on the basis of long-term data close to the catchment.
- The 20-year return period maximum 10-minute rainfall intensity was estimated 116 mm/h for Site 6 and 153 mm/h for Site 15.
- The 20-year return period maximum 60-minute rainfall intensity was estimated as 57 mm/h for Site 6 and 51 mm/h for Site 15.
- The Chyurlia IDF formula seems to underestimate the short duration intensities by about 50%.

3.1.6 Trends for precipitation

Nepal's long-term data do not show an increasing trend of precipitation according to Shrestha et al. (2000), despite a number of climatic models predicting an increase in monsoon precipitation. The authors attribute this to the countering effects of increased atmospheric sulphate aerosols. Sharma (1997) came to a similar conclusion on the basis of his studies of the long-term precipitation data sets of Kathmandu and selected stations in the Koshi basin, where he was not able to establish any homogenous and significant trends.

Table 3.13: **Mann-Kendall test statistics for trend of mean annual rainfall in the Jhikhu Khola catchment** (data source: DHM 2000)

Station	Period	Critical value*	Test value	Result
Annual mean				
Site 9	1948 - 1996 (N= 36)	1.96 (Sig.=0.05)	1.3605	H0 is rejected
Site 12	1976 - 2000 (N= 23)	1.96 (Sig.=0.05)	0.1585	H0 is rejected
Annual daily maximum				
Site 9	1948 - 1996 (N= 36)	1.96 (Sig.=0.05)	0.1884	H0 is rejected
Site 12	1976 - 2000 (N= 23)	1.96 (Sig.=0.05)	0.4465	H0 is rejected

* according to Salas (1992)
Test: H0 is accepted if the test value is bigger than the critical value[1]
H0: there is a significant trend
HA: there is no significant trend

As the long-term annual precipitation of Panchkhal and Dhulikhel is not distributed normally (see Appendix A3.10), the non-parametric test according to Mann-Kendall was used to test the existing time series for trends. According to Salas (1992), although the test is mostly used for sample sizes of more than 40, it can also be applied for samples as small as 10. On the basis of the long-term data available for the Jhikhu Khola catchment, no significant trend can be established for annual precipitation amount at the confidence level of 5% (Table 3.13). The same can be concluded for the case of annual absolute maximum, where no trend was observed over the measurement period.

The short-term time series from the study period are distributed normally (Appendix A3.11) and therefore a parametric method to test for trends can be applied. For this purpose, the test for linear regression according to Sachs (1997) was selected. Unlike for the long-term data series, for the short-term data series of eight years, all selected stations show a linear trend (Table 3.14).

Table 3.14: **Linear trend test statistics for annual mean in the Jhikhu Khola catchment**

Station	Period	Critical value*	Test value	Result
Site 6	1993 - 2000 (N= 8)	0.707 (Sig.=0.05)	1.378	H0 is not rejected
Site 12	1993 - 2000 (N= 8)	0.707 (Sig.=0.05)	0.814	H0 is not rejected
Site 15	1993 - 2000 (N= 8)	0.707 (Sig.=0.05)	1.123	H0 is not rejected
Site 16	1993 - 2000 (N= 8)	0.707 (Sig.=0.05)	2.017	H0 is not rejected

* according to Sachs (1997)
Test: H0 is accepted if the test value is bigger than or equals the critical value
H0: there is a significant trend HA: there is no significant trend

There are no long-term data available for the Yarsha Khola catchment, so the three adjacent stations from the DHM network, Charikot, Jiri, and Melung, were used for the assessment of trends. As the data of some of the sites are not distributed normally (Appendix A3.12), the Mann-Kendall test for trends was used for all three stations. On the basis of these datasets no homogenous and significant trend can be established (Table 3.15). At the site in Charikot a negative trend was established over the period from 1961 to 1996. However, at the two other sites, no significant trend could be established. The same is true for the annual daily maximum where statistically no trend could be observed over the measurement period.

Table 3.15: **Mann-Kendall test statistics for trends around the Yarsha Khola catchment** (data source: DHM 2000)

Station	Period	Critical value*	Test value	Result
Annual mean				
Charikot	1961 – 1996 (N= 36)	1.96 (Sig.=0.05)	2.3564	H0 is not rejected
Jiri	1962 – 1996 (N= 29)	1.96 (Sig.=0.05)	0.8816	H0 is rejected
Melung	1961 – 1996 (N= 36)	1.96 (Sig.=0.05)	1.5119	H0 is rejected
Annual daily maximum				
Charikot	1961 – 1996 (N= 36)	1.96 (Sig.=0.05)	0.1046	H0 is rejected
Jiri	1962 – 1996 (N= 29)	1.96 (Sig.=0.05)	0.7747	H0 is rejected
Melung	1961 – 1996 (N= 36)	1.96 (Sig.=0.05)	0.5993	H0 is rejected

* according to Sachs (1997)
Test: H0 is accepted if test value is bigger than critical value
H0: There is a significant trend HA: There is no significant trend

The study period in the Yarsha Khola from 1998 to 2000 is, at only three years, too short to assess trends.

In summary, it can be said that no trend was observed over the long-term period. In recent years over the duration of the study in the Jhikhu Khola catchment, an increasing trend was observed.

3.1.7 Summary and impact of rainfall on water-related susceptibilities

The comparison with the long-term data showed that the project period in the Jhikhu Khola catchment from 1993 to 2000 was average in terms of precipitation. In the Yarsha Khola catchment, the project period from 1998 to 2000 was wetter than average. It also showed that, although there was a trend observed in the short-term data of the project period, no trend was detected in the long-term data.

There is a distinct difference in rainfall behaviour, mainly rainfall amount, between the Yarsha Khola and the Jhikhu Khola catchments. The main reason for this is the higher mean elevation of the Yarsha Khola catchment, which is about 650 m higher than the mean elevation of the Jhikhu Khola catchment. Annual rainfall in the Yarsha Khola catchment is about double that of the Jhikhu Khola. While the amount differs between the catchments, the distribution is very similar, showing that the wettest month is July and the driest months are November to February. The Jhikhu Khola catchment also displays drier conditions than the Yarsha Khola catchment in terms of number of days without rain and number of dry spells. In terms of events, the Yarsha Khola catchment shows higher rainfall intensities, although the largest event measured in the study period was observed in the Jhikhu Khola catchment.

Temporal variability is mainly expressed by a distinct seasonal behaviour with most of the rainfall (about 75% to 80%) occurring in the monsoon season. An additional 10 to 15% of the annual rainfall occurs during the pre-monsoon season. The remainder of the year is nearly dry, with occasionally some exceptionally heavy events during the post-monsoon season. The highest variability of rainfall can be seen during the dry season, the months of November to January in particular.

The lowest amounts of rainfall on average were observed in November to January. Annually, about 3 to 4 dry spells, that is, periods of 15 or more days with no more than 1 mm rainfall, can be seen. The longest dry spells observed during the study period from 1993 to 2000 were approximately 110 to 140 days in the Jhikhu Khola catchment, and between 1998 to 2000, about 130 days in the Yarsha Khola catchment. For farmers the most critical period for an additional crop is the pre-monsoon season. In case there is adequate water availability for irrigation, an additional crop, such as tomato or maize, is grown (also see Section 3.6). Rainfed land lies fallow during this period. The highest vulnerability farmers experience is in terms of maize planting in the pre-monsoon, rice transplanting in the early monsoon, and the post-monsoon for yield formation of wheat, barley, and potato.

The maximum intensities are observed late in the pre-monsoon and early in the monsoon seasons. The highest 10-minute intensities that were observed during the study period were about 150 mm/h in the case of the Jhikhu Khola catchment and about 175 mm/h in the Yarsha Khola catchment. This high-resolution rainfall data set with this duration is unique in Nepal and could be used for the establishment of intensity-frequency-duration relations. They were established for two sites in the Jhikhu Khola catchment and showed that the theoretical relation proposed by Chyurlia (1984) largely underestimates the short-time interval intensities for given return periods by about half. The 20-year return period daily rainfall varies from site to site, ranging from about 125 to 200 mm. The PMP was estimated at about 500 to 700 mm in the Yarsha Khola catchment and about 300 to 500 mm in the Jhikhu Khola catchment, depending on the site.

Spatially, a number of rainfall parameters show a good relation with elevation, for example, annual rainfall amount, maximum rainfall amount, erosivity, and number of rainy days. Rainfall intensity, however, did not show any significant relation with elevation. In general, it can be said that the longer the duration, the wetter the conditions; which leads to a better relationship with elevation. This means that annual rainfall shows a better relation than seasonal rainfall, which shows a better relation than monthly rainfall.

Water availability is mainly dependent on the rainfall amount of different temporal aggregation as well as the frequency of no or low rainfall. In addition, the duration and number of dry spells is important for water availability considerations. The indicators, which have an impact on the water resource availability and are used for the calculation of an index, are compiled in Table 5.1.

In terms of flood generation, the most important indicators for flood hazards are related to precipitation amount and intensity (Table 5.2, Chapter 5, p. 292, this volume). This includes maximum rainfall amount, intensity, rainfall events with a high return period, and the PMP. Roughly the same indicators, with the addition of rainfall erosivity, are used for the Water Induced Degradation Index (Table 5.3,Chapter 5, p. 293, this volume).

3.2 EVAPOTRANSPIRATION – AN IMPORTANT WATER LOSS IN THE CATCHMENTS

Potential evapotranspiration was calculated using a temperature-based method on the basis of the data available. After a discussion of the temperature, wind, radiation, and humidity parameters for the Jhikhu Khola and Yarsha Khola catchments, the results of the potential evapotranspiration calculations are presented and discussed on the basis of temporal and spatial distribution. Finally, actual evapotranspiration is determined for the calculation of water balances.

3.2.1 Evapotranspiration in Nepal and the HKH

Evapotranspiration in the HKH is discussed briefly in Chapter 2 on the basis of Wyss' study (1993). To summarise, mean potential evapotranspiration in the region ranges from about 1000 mm in the high areas of the Tibetan plateau to about 2000 mm in the Tharr Desert. In general, a decreasing gradient from south to north and from east to west can be seen.

In Nepal, Lambert and Chitrakar (1989) showed a decreasing trend for potential evapotranspiration with increasing elevation (Figure 3.32). For western Nepal, Tahal Consulting Engineers (2002) likewise determined an overall decrease in potential evapotranspiration across the country. However, during the coldest month, January, the upper areas seem to have higher potential evapotranspiration. This is believed to be due to the higher wind factor in these areas. The evaporation rates are highest immediately before the onset of monsoon when saturation deficits in the air are highest (Chyurlia 1984 and Figure 3.32). During this time, potential evapotranspiration rates in the Terai are considerably higher than in the mountains (Tahal Consulting Engineers 2002).

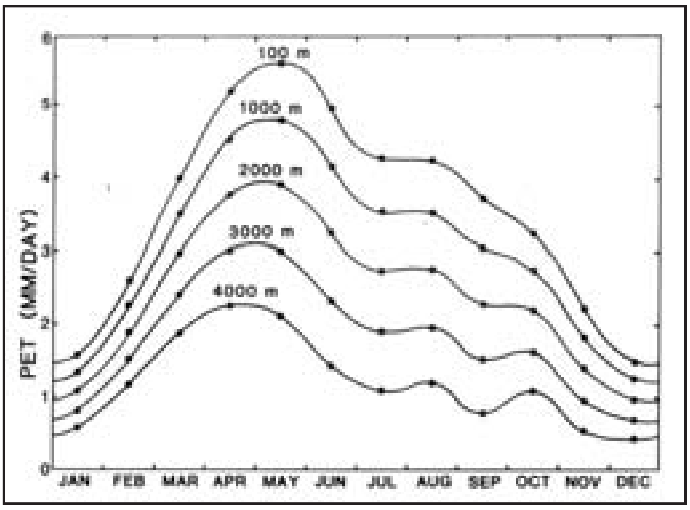


Figure 3.32: **Seasonal trends in potential evapotranspiration at selected elevations of Nepal** (from Lambert and Chitrakar 1989)

3.2.2 Calculation of reference evapotranspiration

There is a range of methods which can be used to compute potential evapotranspiration. Selecting the appropriate method largely depends on the availability of data for different climatological parameters such as radiation, sunshine hours, cloud cover, and others. Following the decision support system in Shuttleworth (1993) and the data locally available for the Jhikhu and Yarsha Khola catchments, a temperature-based method was used for these calculations. In this context the FAO Penman-Monteith method with limited climatic data as proposed by FAO (1998) was selected.

The FAO Penman-Monteith method calculates reference evapotranspiration ET_0 or potential evapotranspiration on the basis of the following.

- The aerodynamic and surface characteristics of a reference surface, that is, “a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sm^{-1}, and an albedo of 0.23” (FAO 1998). This reference crop closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water.
- The FAO Penman-Monteith Equation (for example, FAO 1998). This equation requires location parameters of the station such as elevation above sea level, and latitude. It also needs input data of radiation, air temperature, wind speed, and humidity on a daily basis for daily calculations. For the selected catchments only daily air temperature is available. Other missing climatic data were estimated from short-term measurements in the catchment, from data of stations close by or on the basis of the estimation approaches from FAO (1998). The estimated parameters are validated on the basis of measured data sets in the two catchments, from the Godavari T&D site of ICIMOD, or on the basis of the literature.

The quality of the evaporation data collected from the agro-climatological stations of DHM is very questionable and full of gaps. Due to this reason no comparison was made.

3.2.2.1 Air temperature

Air temperature is the main parameter used for the reference evapotranspiration calculations in this study. Temperature was measured at different locations throughout the catchments, as shown in Section 2.4, using automatic temperature loggers in both the Jhikhu Khola and Yarsha Khola catchments recording hourly temperature values.

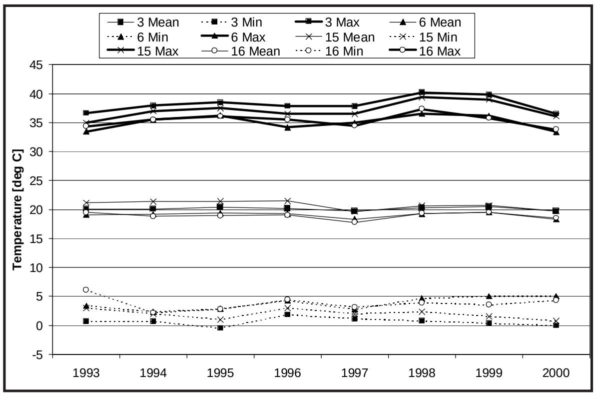


Figure 3.33: **Annual mean-minimum-maximum temperatures at different stations in the Jhikhu Khola catchment**

In the Jhikhu Khola catchment no trends were observed over the project period from 1993 to 2000, neither for minimum nor maximum, nor for mean temperatures (Figure 3.33). Mean annual temperatures in this period were about 18 to 20°C at the selected sites. The minimum annual temperatures measured at the same sites ranged from -0.5 to 5°C. Maximum temperatures reached up to 40°C with a lowest value of 33°C.

Intra-annually, there is a temperature variation between average temperatures of 11.3°C in January to 26.2°C in June measured at Site 12 (Figure 3.34a). The data of the main meteorological station in the Jhikhu Khola catchment are only for the period from 1998 to

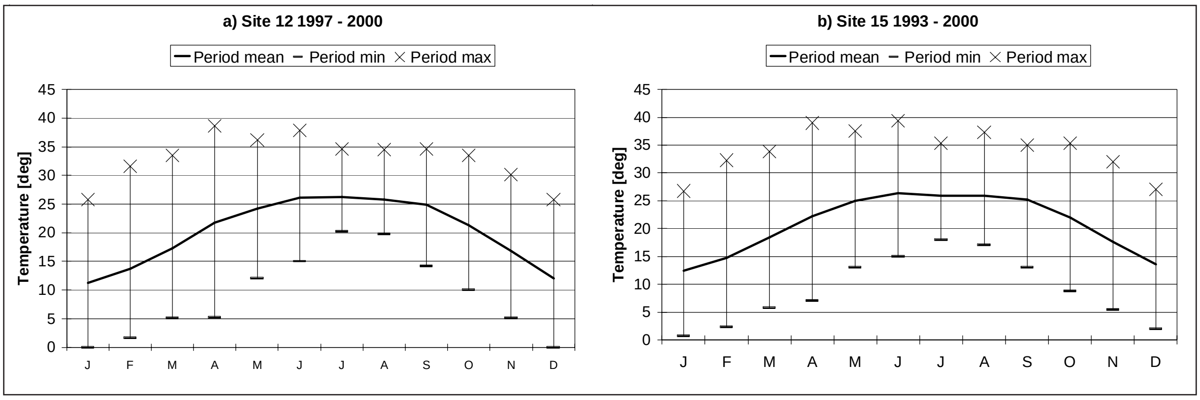


Figure 3.34: **Annual temperature variation: a) Site 12, period ‘97-2000 b) Site 15, period ‘93 -2000**

2000. At Site 15 with data from 1993 to 2000, a variation of from 12.3°C in January to 26.3°C in June was observed (Figure 3.34b). The absolute minima are observed in both cases in the month of January, with values around 0°C. The highest values are observed in the months of April to June. Seasonally, the highest maximum temperatures are measured in the pre-monsoon, although the highest average temperatures are usually observed in the monsoon season. This is mainly due to the increased cloud cover during the rainy season. In the pre-monsoon season this cloud cover often breaks up and allows full sunshine and heating up of the air.

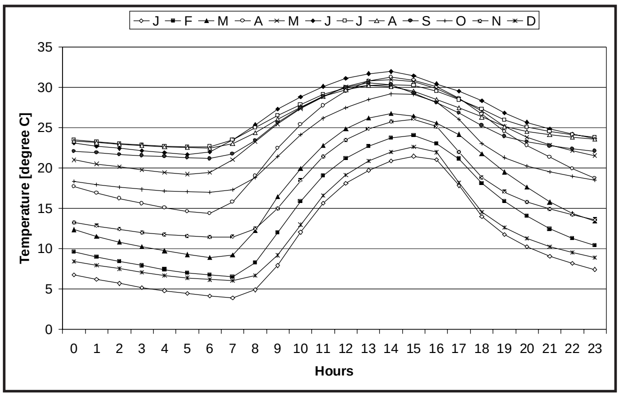


Figure 3.35: **Diurnal temperature variation in different months, Site 12, Jhikhu Khola catchment**

Diurnal variation is very important for agronomic considerations. Rice yields are increased if temperature varies about 10°C between night and day, while large differences between night and day temperatures improve tuber formation in potato crops (ILACO 1981). The diurnal variation differs according to the month. At Site 12 and in the coldest month of January, the minimum average temperatures of 4°C were observed at 7 AM (Figure 3.35). The maximum average temperature in the same month was recorded at 3 PM at about 22°C.

In the hottest month, June, the temperature varied from 22°C at 5 AM to 32°C at 2 PM. The July and August temperatures, when rice is being cultivated, differ about 7 C to 8°C between night and day. The November temperature, decisive for potato yields, varied about 14°C between minimum and maximum temperatures.

Elevation is the main influencing factor on temperature, together with geographical location and aspect. About 99% of the variation in temperature can be explained by elevation and geographical location, and 90% by elevation alone (Khanal et al. 1998). Dobremez (1976; Khanal et al. 1998) observed a lapse rate of -0.52°C/100 m. In this study, the observed average lapse rate for the period from 1993-2000 was -0.51°C/100 m on the basis of annual data (Table 3.16). The lapse rates vary seasonally with mean changes of -0.43°C/100 m during the pre-monsoon and -0.65°C/100 m during

Table 3.16: **Temperature lapse rates in the Jhikhu Khola catchment: for mean (maximum, minimum) temperatures [°C/100 m]**

	Annual	Pre-monsoon	Monsoon	Post-monsoon	Winter
1993	-0.631 (-0.84, -0.31)	-0.47 (-0.96, -0.03)	-0.71 (-0.86, -0.82)	-0.80 (-1.08, -0.35)	-0.56 (-1.25, -0.23)
1994	-0.60 (-0.85, -0.33)	-0.57 (-0.95, -0.07)	-0.73 (-0.82, -0.71)	-0.61 (-1.13, -0.03)	-0.48 (-1.17, -0.16)
1995	-0.58 (-0.55, 0.10)	-0.50 (-0.76, 0.13)	-0.64 (-0.71, -0.61)	-0.62 (-1.39, -0.06)	-0.47 (-1.13, 0.04)
1996	-0.56 (-0.73, -0.07)	-0.41 (-0.88, -0.11)	-0.61 (-0.80, -0.35)	-0.64 (-1.09, -0.20)	-0.62 (-1.13, -0.12)
1997	-0.54 (-0.73, -0.06)	-0.51 (-0.71, -0.17)	-0.55 (-0.72, -0.32)	-0.56 (-1.21, -0.09)	-0.59 (-1.02, 0.08)
1998	-0.44 (-0.66, 0.09)	-0.40 (-0.82, -0.13)	-0.56 (-0.85, -0.453)	-0.43 (-1.18, -0.16)	-0.38 (-1.16, 0.01)
1999	-0.27 (0.85, 1.01)	-0.23 (-0.75, 0.59)	-0.68 (-0.89, -0.40)	-0.19 (-0.73, 0.39)	0.24 (-0.64, 0.95)
2000	-0.42 (-0.80, 1.11)	-0.36 (-0.83, 0.37)	-0.74 (-0.93, -0.42)	-0.34 (-1.01, 0.53)	-0.08 (-0.81, 1.01)
Mean	-0.51 (-0.75, 0.19)	-0.43 (-0.83, 0.07)	-0.65 (-0.82, -0.51)	-0.52 (-1.11, 0.01)	-0.37 (-1.04, 0.20)
Max	-0.27 (-0.55, 1.11)	-0.23 (-0.71, 0.59)	-0.55 (-0.71, -0.32)	-0.19 (-0.73, 0.53)	0.24 (-0.64, 1.01)
Min	-0.63 (-0.85, -0.33)	-0.57 (-0.96, -0.17)	-0.74 (-0.93, -0.82)	-0.80 (-1.01, -0.35)	-0.62 (-1.25, -0.23)

the monsoon itself. The lowest temperature changes can be seen during the winter season with a mean lapse rate of -0.37°C/100 m.

The minimum temperatures and maximum temperatures change at very unsystematic lapse rates. Mainly the minimum temperatures are directly affected by inversion during the colder season, from December to February in particular.

Aspect only shows a difference in temperature for the sites on the lower slopes, in this case the comparison of Site 3 at 830 masl on the north-facing slope and Site 15 at 880 masl on the south-facing slope. Mean and minimum temperatures at Site 15 are always 1 to 2°C higher than at Site 3 (note that these differences are after adjusting for the elevation difference of 50 m by means of a calculated lapse rate; see below). The maximum temperatures, on the other hand, are approximately 1 to 2°C higher at Site 3. At the sites higher up the slope, in this case Sites 6 on the north-facing slope at 1260 masl and Site 16 on the south-facing slope at 1200 masl, no systematic difference was observed.

The mean temperature does not seem to be as influenced by aspect as the minimum and maximum temperatures on the lower foot slopes of the Jhikhu Khola catchment (Figure 3.36). In the first four years, mean temperature at Site 3 was lower than at Site 15; during the remaining years, however, no distinct difference was observed. The minimum temperature, however, is generally lower on the north-facing foot slope at Site 3 and the maximum temperature vice versa, that is, higher at Site 15 on the south-facing slope. On the upper slope at Sites 6 on the north-facing slope and Site 16 on the south-facing slope, no systematic difference was seen.

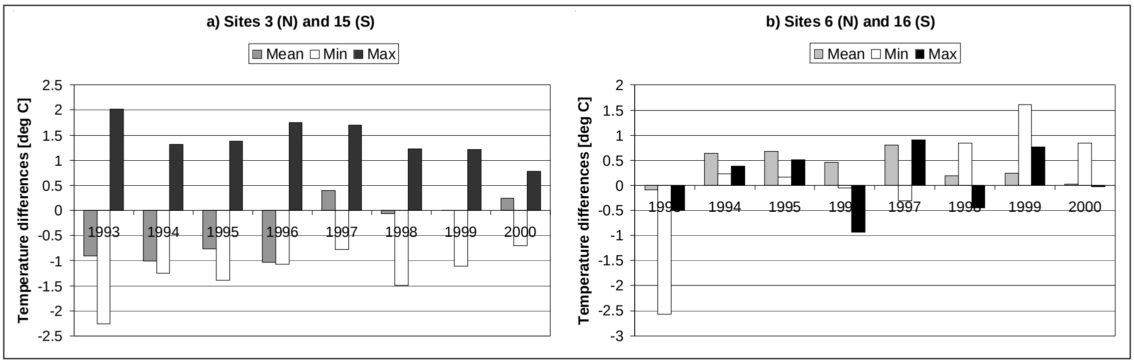


Figure 3.36: **Temperature differences according to aspect at different elevation zones (note: adjusted for elevation differences) a) lower slopes b) upper slopes**

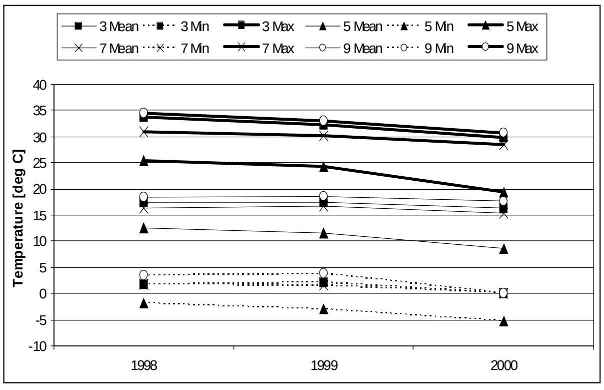


Figure 3.37: **Annual mean-minimum-maximum temperatures at different stations in the Yarsha Khola catchment**

In the Yarsha Khola catchment, temperature decreased over the project period (Figure 3.37). However, trends cannot be calculated due to the short time period of only three years. The average temperature ranged between 15°C and 17°C at Site 7, the main meteorological station. The maximum temperature ranged from 28 to 31°C, while the minimum temperatures observed during this period were between -2 and 2°C. At the highest station (Site 5), average temperature was about 10°C. The minimum temperature at this site reached a low of -5.2°C. The highest maximum temperature was measured at the lowest station, Site 1, at 35.2°C.

The lowest average temperatures of about 8°C at Site 7 were measured in January (Figure 3.38). The highest average temperatures were observed in the month of June. Maximum temperatures were observed in the same month with a first peak in April. Seasonally, the highest temperatures were observed in the monsoon season closely followed by the pre-monsoon season. The lowest temperatures were observed in the month of January.

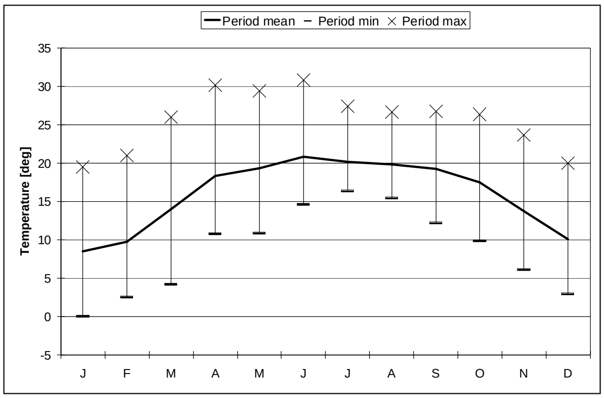


Figure 3.38: **Annual temperature variation at Site 7 of Yarsha Khola, period 1998 - 2000**

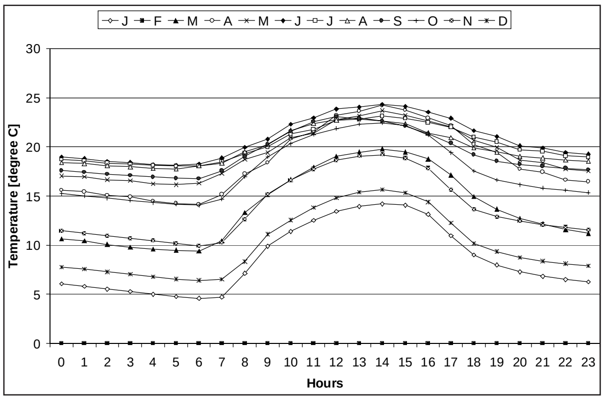


Figure 3.39: **Diurnal temperature variation, Site 7, Yarsha Khola catchment**

In the Yarsha Khola catchment at Site 7 in Bagar, diurnal variation varied, on average, from about 10°C in January (4.5°C at 6 AM to 14°C at 2 PM) to about 6°C in June (18°C at 5 AM to 24°C at 2 PM) (Figure 3.39).

The average lapse rates for annual mean temperatures during the period from 1998 to 2000 were -0.65°C/100 m (Table 3.17). The maximum temperatures changed at the rate of -0.89°C, the minimum temperatures at -0.46°C/100 m. In the Yarsha Khola catchment the seasonal difference is negligible. The lapse rate during winter is slightly lower, at about -0.58°C/100 m, whereas in the other seasons the lapse rate is about -0.66°C/100 m.

In summary, it is evident that:

- no trend in either mean, minimum, or maximum temperature could be established;
- January is generally the coldest and June the hottest month in both catchments;
- there is a lower temperature variation during the monsoon months than during the reminder of the year;
- diurnal variations are higher in winter;
- there is a good relationship between elevation and mean temperature;
- there is no distinct relationship between elevation and minimum or maximum temperature;
- there is a difference in temperature according to aspect on the lower slopes; and
- differences between sites on the north- and south-facing upper slopes are negligible and unsystematic.

Table 3.17: **Temperature lapse rates in the Yarsha Khola catchment: for mean (maximum, minimum) temperatures [°C/100 m]**

	Annual	**Pre-monsoon**	**Monsoon**	**Post-monsoon**	**Winter**
1998	-0.64 (-1.03, -0.57)	-0.66 (-0.97, -0.49)	-0.65 (-0.85, -0.50)	-0.64 (-0.80, -0.73)	-0.61 (-0.96, -0.58)
1999	-0.61 (-0.74, -0.53)	-0.66 (-0.79, -0.54)	-0.62 (-0.73, -0.53)	-0.59 (-0.66, -0.48)	-0.49 (-0.60, -0.47)
2000	-0.70 (-0.89, -0.30)	-0.73 (-0.88, -0.55)	-0.72 (-0.88, -0.57)	-0.70 (-0.79, -0.61)	-0.65 (-0.68, -0.42)
Mean	-0.65 (-0.89, -0.46)	-0.68 (-0.88, -0.53)	-0.66 (-0.82, -0.54)	-0.65 (-0.75, -0.61)	-0.58 (-0.75, -0.48)
Max	-0.61 (-0.74, -0.30)	-0.66 (-0.79, -0.49)	-0.62 (-0.73, -0.50)	-0.59 (-0.66, -0.48)	-0.49 (-0.60, -0.42)
Min	-0.70 (-1.03, -0.57)	-0.73 (-0.97, -0.55)	-0.72 (-0.88, -0.57)	-0.70 (-0.80, -0.73)	-0.65 (-0.96, -0.58)

3.2.2.2 Wind speed

Wind speed in both catchments was only measured at one location, and in the case of the Jhikhu Khola catchment only during two incomplete years. Therefore the wind speed data used for the calculation were estimated from these incomplete datasets. Figure 3.40 (a& b) shows the distribution of daily wind speed from the two catchments. In the Jhikhu Khola catchment most of the days have a daily wind speed of 0.5 to 1 m/s. The average wind speed is 0.7 m/s. In the Yarsha

Khola catchment the most frequent wind speed is likewise 0.5 to 1 m/s, with a mean wind speed of 0.99 m/s. This mean wind speed measured at 1.7 m was then transformed into a mean wind speed at 2 m of 1.02 according to the formula described in FAO (1998). For further calculations, therefore, the daily wind speed was assumed to be 0.7 m/s in the Jhikhu Khola catchment and 1.0 m/s in the Yarsha Khola catchment, respectively.

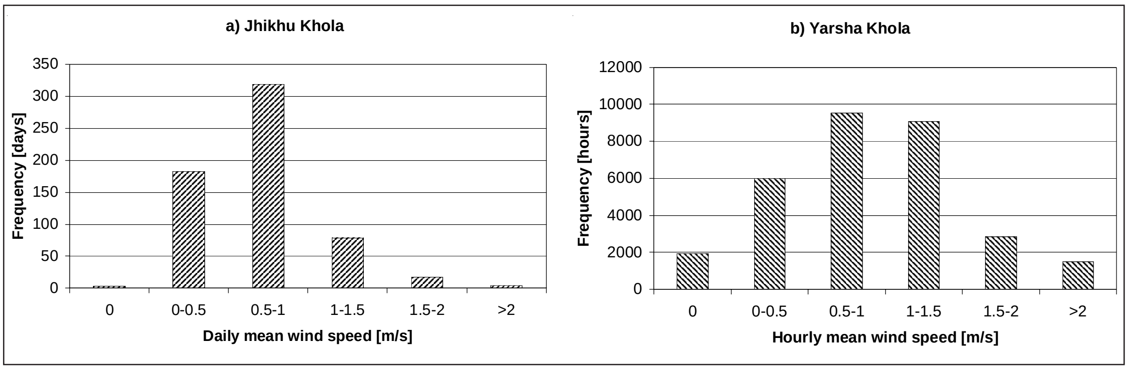


Figure 3.40: **Wind speed in the Jhikhu (a) and Yarsha Khola (b) catchments (note that in the Jhikhu Khola the daily mean is given and in the Yarsha Khola the hourly mean is given)**

These values correspond to the reported values by Baidya (2001), presented in the form of a map. According to this map, mean annual wind speed at 20 m for the area of the Jhikhu Khola catchment has to be estimated between 0.5 and 1.0 m/s. The calculated value for Panchkhal adjusted for 10 m above ground is 0.9 m/s. In the Yarsha Khola catchment the values would have to be estimated between 1.0 and 1.5 m/s. The calculated value for 10 m above ground is 1.3 m/s.

3.2.2.3 Relative humidity

Relative humidity is monitored at only one site in each catchment. However, the spatial variability of this parameter is too high and cannot be estimated from this single location. Therefore the FAO (1998) method was used to determine relative humidity from the maximum and minimum temperatures measured at each site. FAO 's method (1998) assumes that the dew point temperature is close to the minimum daily temperature and therefore uses this value for the estimation of the actual vapour pressure.

The results of this calculation show big differences from the measured values, as shown in Figure 3.41. It is mainly during the dry season that relative humidity is largely overestimated. During the monsoon season the estimation is very close, within 10% relative difference to the measured values. During the dry season the differences may be up to 60%. In absolute terms, the relative humidity is overestimated by between 15 and 20% during the months of May and April. The most obvious explanation for this is the fog during the cold months.

However, for the final reference evapotranspiration calculations, humidity is not directly used but actual vapour pressure (e_a) estimated on the basis of the assumption that T_{dew} is approximately T_{min}. The error resulting due to this assumption is a maximum of ±0.2 mm difference in daily reference evapotranspiration, which totals approximately 6 mm per month at most.

3.2.2.4 Radiation

Radiation is, like relative humidity, estimated from the observed temperature data according to the Hargreaves' radiation formula presented in FAO (1998). The formula is based on the principle that the maximum and the minimum air temperatures are related to the degree of cloud cover at a given location. The cloud cover itself is an important factor in the amount of radiation that reaches the earth's surface. The minimum and maximum temperatures can therefore be used as indicators for radiation.

Figure 3.42 shows a comparison of the $ET_{0,}$ calculated using the measured radiation data and the estimated radiation data at Site 7 in the Yarsha Khola catchment and at the meteorological station

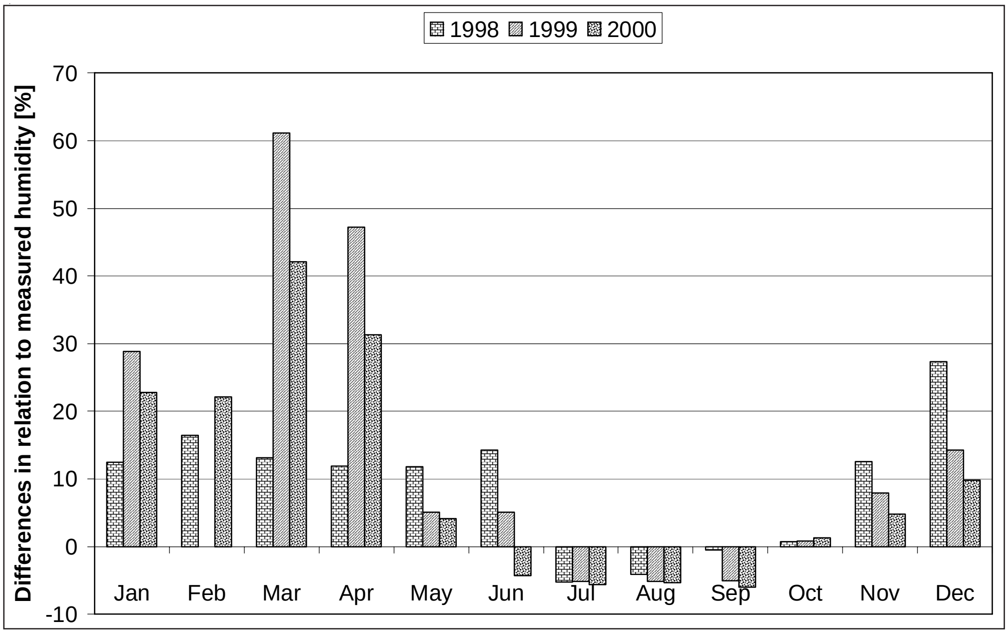


Figure 3.41: **Comparison of measured with calculated humidity, Site 7 Yarsha Khola**

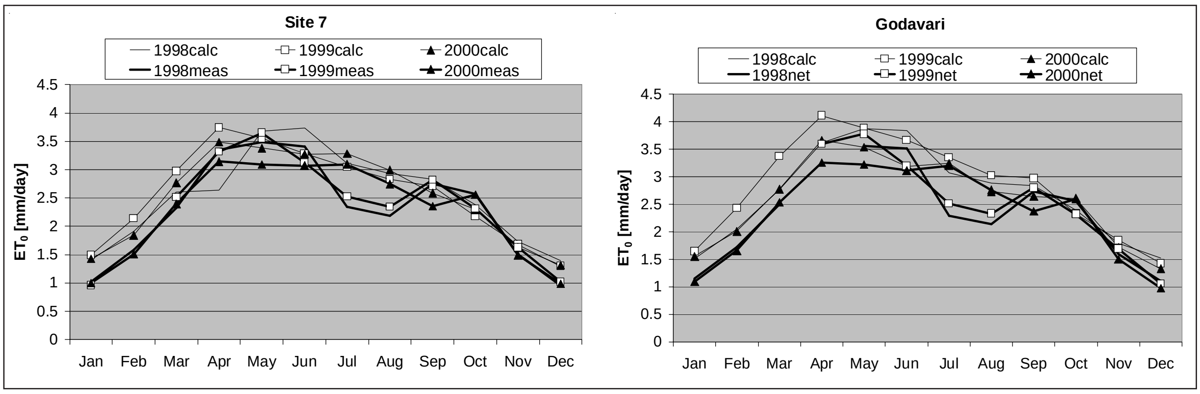


Figure 3.42: **Comparison of ET_0 determined by measured net radiation and calculated net radiation at Site 7 in Yarsha Khola catchment and Godavari T&D**

at the ICIMOD T&D site in Godavari. In general, a good fit can be observed, with the exception of the dry season where the potential evapotranspiration rates based on the estimated data generally overestimate ET_0 by a maximum 0.5 mm. This results in an error of about 15 mm during those months. Altogether, over the period of one year, an average error of 7 mm per month can be estimated between the ET_0 calculated on the basis of measured data and on the basis of estimated data. In Godavari, the error is bigger due to a higher difference during the pre-monsoon season months.

3.2.2.5 Results of the reference evapotranspiration calculation

On the basis of the measured and estimated data as discussed above, mean daily reference evapotranspiration rates were calculated (see Table 3.18). The values in the Jhikhu Khola catchment range from 1.7 mm/day at different sites, in both January and December, up to about 5 mm/day in the month of May. In the Yarsha Khola catchment the minimum daily ET_0 was calculated to be between 1.0 and 1.5 mm/day. The maximum is reached in the months of April and May with values ranging from 3 to 5 mm/day, depending on the location of the station.

The results from this study were compared with the results of other studies of Lambert and Chitrakar (1989), MacDonald & Partners (1990), and Tahal Consulting Engineers (2002) for validation (Figure 3.43). The calculated values correspond well throughout the range with the values reported by Lambert and Chitrakar (1989). The calculated values are slightly lower compared to the values

Table 3.18: **Mean daily ET_0 for different sites in the Jhikhu and Yarsha Khola catchments [mm/day]**

Month	Jhikhu Khola					Yarsha Khola					
	Site 3	**Site 6**	**Site 12**	**Site 15**	**Site 16**	**Site 1**	**Site 3**	**Site 5**	**Site 7**	**Site 9**	**Site 10**
January	1.9	1.7	2.0	1.9	1.7	2.0	1.8	1.3	1.6	1.7	1.4
February	2.7	2.4	2.7	2.6	2.3	2.6	2.3	1.8	2.1	2.3	1.8
March	3.8	3.3	3.7	3.6	3.2	3.8	3.1	2.4	3.0	3.2	2.6
April	4.8	4.2	4.7	4.6	4.1	4.7	3.9	3.1	3.7	4.0	3.2
May	5.1	4.5	4.9	4.9	4.5	4.4	3.9	3.0	3.7	3.9	2.8
June	4.8	4.2	4.8	4.6	4.2	4.4	3.8	2.7	3.6	3.7	2.7
July	4.5	4.2	4.3	4.4	3.9	3.8	3.8	2.5	3.2	3.4	2.4
August	4.3	3.9	4.0	4.2	3.8	3.5	3.5	2.4	3.0	3.2	2.2
September	3.8	3.5	3.7	3.8	3.4	3.3	3.1	2.2	2.9	2.9	2.1
October	3.3	3.0	3.2	3.3	3.0	3.0	2.6	2.0	2.5	2.6	2.0
November	2.4	2.1	2.3	2.4	2.2	2.2	2.0	1.5	1.9	2.0	1.6
December	1.9	1.7	1.8	1.9	1.7	1.9	1.6	1.2	1.5	1.6	1.3
Annual	**3.6**	**3.2**	**3.5**	**3.5**	**3.2**	**3.3**	**3.0**	**2.2**	**2.7**	**2.9**	**2.2**

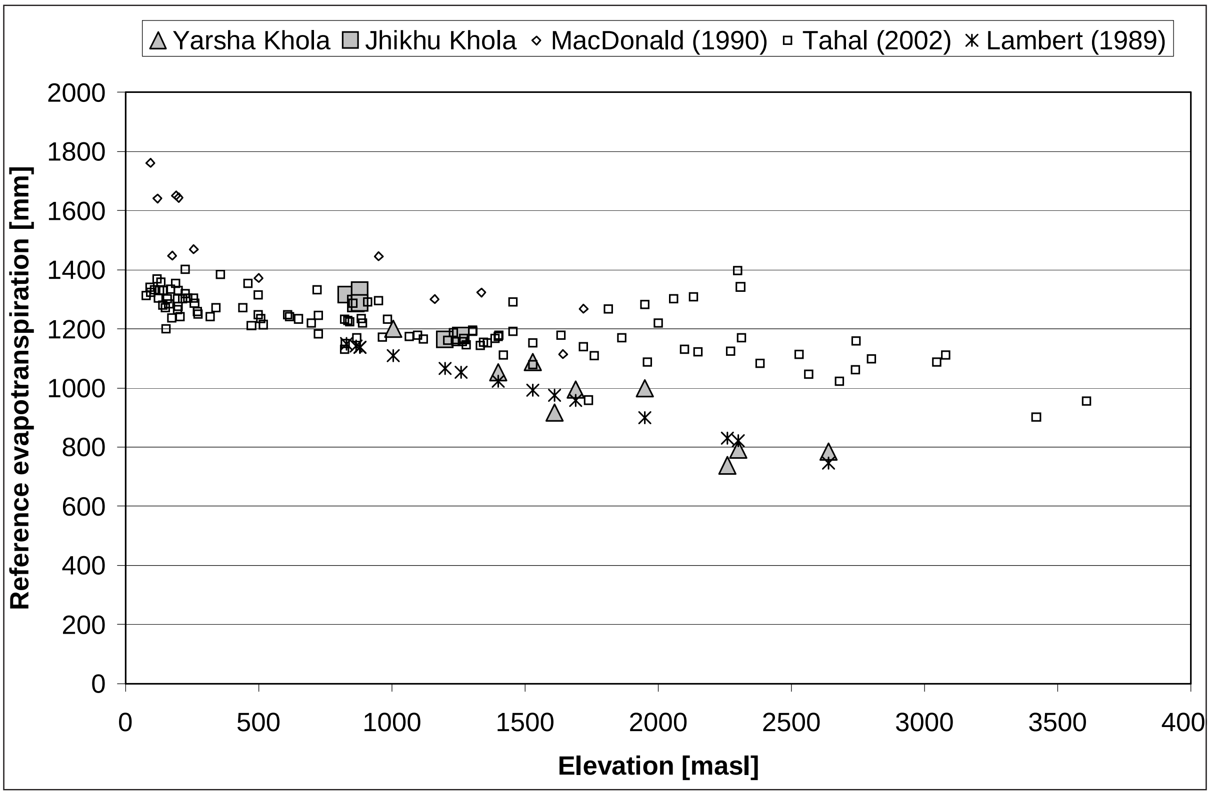


Figure 3.43: **Annual reference evapotranspiration data of the Jhikhu and Yarsha Khola catchments compared with calculations of other authors**

reported by MacDonald & Partners (1990). MacDonald (1990) used the method as proposed by FAO (1977), which, according to FAO (1998), was reportedly found to frequently overestimate ET_0. A considerable difference can be seen in comparison to values reported by Tahal Consulting Engineers (2002), where a wide divergence in the values of sites higher than 1500 masl is evident.

It has to be noted that the given values of Tahal Consulting Engineers (2002) are all from Western Nepal, that is, west of Kathmandu. There is a considerable difference in terms of sunshine duration between the western and the eastern parts of the country. The months of April, May, and June in particular differ widely in terms of mean daily sunshine (Chalise et al. 1996). These are incidentally the months with the highest reference evapotranspiration rates (see above) and could therefore explain the differences between the two calculations. In general, the above-calculated values are plausible.

3.2.3 Temporal distribution

As shown above, the daily reference evapotranspiration rates are highest just before the onset of the monsoon during the pre-monsoon season months of April, May, and June. The same can be shown with the temporal distribution of monthly reference evapotranspiration rates, which peak in May in the Jhikhu Khola and in April and May in the Yarsha Khola catchment (Figure 3.44). The peak in April was also observed in the long-term monthly distribution of potential evapotranspiration calculated on the basis of pan evaporation in Jiri (Merz et al. 2000b).

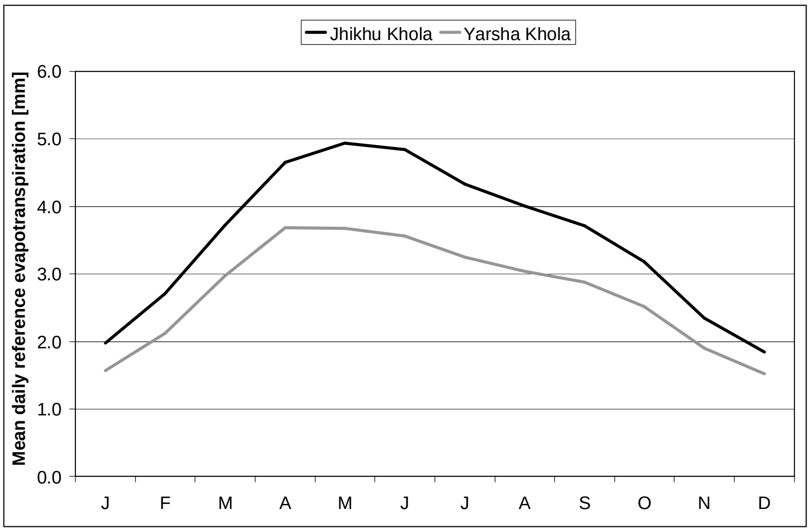


Figure 3.44: **Mean daily reference evapotranspiration at the main stations of both catchments**

This distribution is worth keeping in mind in terms of agricultural water demands (see also Section 3.6). It is during this time that maize is broadcasted on the rainfed agricultural land and the rice seedbed is prepared. While the latter depends on irrigation water, the former depends solely on rainfall and soil moisture. Usually, farmers plant maize after the first pre-monsoon rains. If these rains are isolated storms, the soil moisture depletes rapidly and the freshly germinated maize plants are subject to considerable water stress.

3.2.4 Spatial distribution

Depending on the spatial distribution of the different parameters relevant for reference evapotranspiration calculations (temperature in particular) ET_0 decreases with altitude in the selected catchments (Table 3.19). The ET_0 lapse rates varied between about 18 mm and 42 mm per 100 m decrease in elevation during the study period from 1993 to 2000 in the Jhikhu Khola catchment. In the Yarsha Khola catchment, it varied from 25 to 30 mm per 100 m in decrease elevation in the period from 1998 to 2000. On average, the reference evapotranspiration is estimated to change at about 28 to 32 mm per 100 mm elevation difference.

Table 3.19: **Annual lapse rates for ET_0 [mm/100m]**

	1993	1994	1995	1996	1997	1998	1999	2000	Average
Jhikhu Khola	-26.7	-31.0	-33.1	-33.7	-36.0	-42.1	-17.8	-31.6	-31.5
Yarsha Khola	-	-	-	-	-	-28.3	-25.3	-29.4	-27.7

The isopleths shown in Figure 3.45 indicate that the highest reference evapotranspiration rates have to be expected in the valley bottom of the Jhikhu Khola catchment, the area of Shree Ram Pati in the central to southeast corner of the catchment in particular. The highest annual ET_0 rates observed in the project period were between 1400 and 1500 mm. The minimum rates were seen in the area of Tinghare, the highest area in the catchment.

In the Yarsha Khola catchment (Figure 3.46) the highest reference evapotranspiration of 1300 mm was estimated at the outlet of the catchment at about 1000 masl gradually decreasing towards the highest point at Hanumante, where ET_0 of about 700 to 800 mm was estimated for the project period.

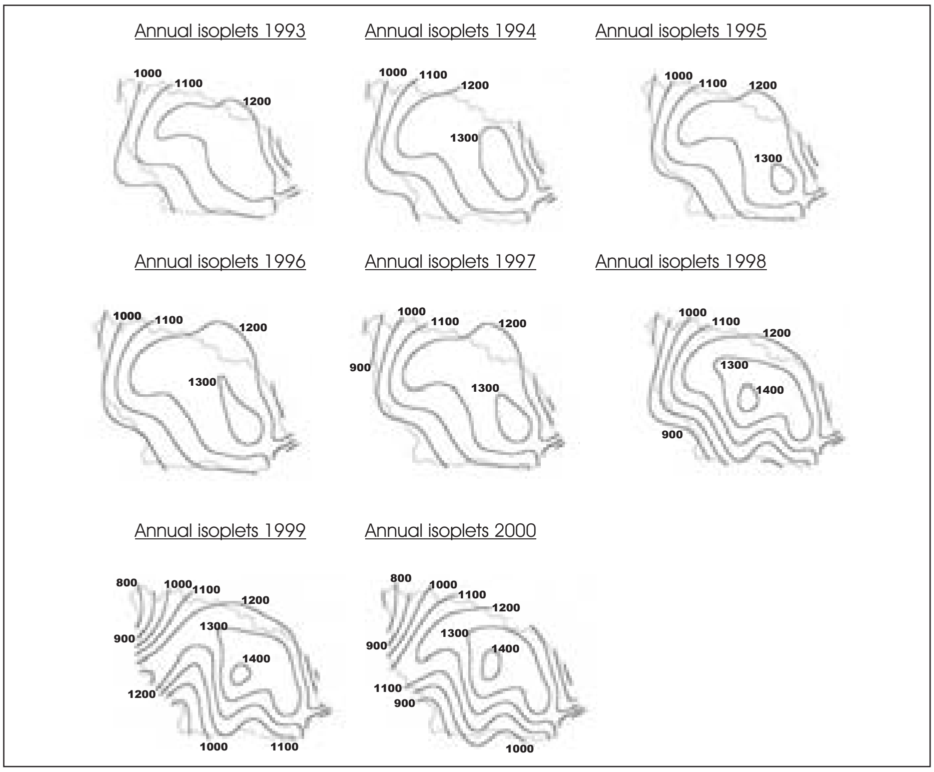


Figure 3.45: **Isopleths of ET_0 in the Jhikhu Khola catchment for 1993 to 2000**

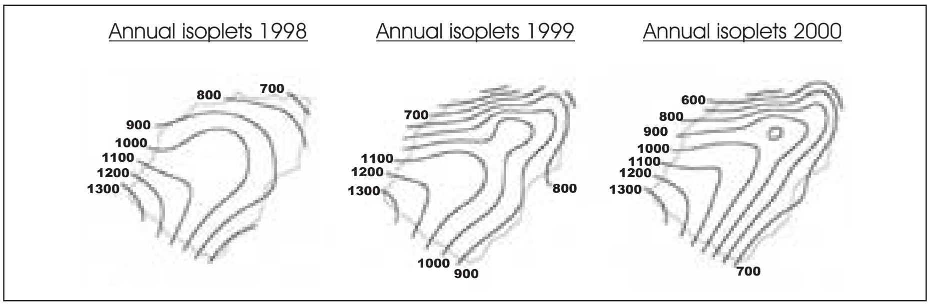


Figure 3.46: **Isopleths of ET_0 in the Yarsha Khola catchment for 1998 to 2000**

3.2.5 Conversion of reference to actual evapotranspiration

The reference evapotranspiration is, by definition, the evapotranspiration of a grass crop with defined parameters (FAO 1998). The conversion of this evapotranspiration to the actual to-be-expected evapotranspiration — usually called actual evapotranspiration or AET — can be calculated using different methods (for example, Thornthwaite and Mather 1955; FAO 1998). In this study, the crop coefficient approach, as discussed by FAO (1998), was used, according to which the reference evapotranspiration ET_0 is multiplied with a crop specific coefficient K_c as shown in Equation 3.11 (FAO 1998).

$$AET = K_c * ET_0 \qquad \textbf{Equation 3.11}$$

where

AET = actual evapotranspiration [mm]
K_c = crop coefficient
ET_0 = reference evapotranspiration [mm]

The crop coefficients used are listed in Appendix A2.1. On the basis of these crop coefficients and a number of assumptions shown below, an average crop coefficient over the entire year according to the cropping calendars (in Figure 3.154) and land use was estimated as shown in Table 3.20.

The rationale of the coefficients is as follows.

- The reference crop is green grass with a good cover of 10 cm length and ample water supply (→ $K_c = 1$).
- On the cultivated land there are (brief) periods of fallow and initial crop development stages with low K_c values, which reduce the overall K_c.
- In the Yarsha Khola catchment only two crops are grown on the irrigated land, therefore K_c is lower than in the Jhikhu Khola catchment.
- There are only limited times of fallow on the irrigated land in the Jhikhu Khola, which is the reason for a higher K_c on irrigated land than on rainfed land in this catchment.
- The forests in the Jhikhu Khola are of sub-tropical vegetation (mainly) and therefore more adjusted to reduce transpiration. In addition many forests have no understorey.
- The shrub in the Jhikhu Khola catchment is generally of bad quality, which reduces the K_c in comparison with the Yarsha Khola catchment.

Table 3.20: **Average crop coefficient K_c for different land uses**

	Jhikhu Khola	Yarsha Khola
Irrigated land	0.80	0.70
Rainfed land	0.70	0.70
Forest	0.80	0.90
Grazing land	0.50	0.80
Shrub	0.60	0.90
Other	1.05	1.05

It is important to note that these coefficients are very arbitrary and mainly based on assumptions. Further work on this issue is crucial in order to fully understand evapotranspiration losses. First steps towards this have already been taken by establishing a catchment-wide measurement network for relative humidity at an hourly time interval. In addition, crop water requirements should be further studied and phenological characteristics of the major crops documented (see Chapter 6).

On the basis of the available database AET was estimated as shown in Table 3.21 for the Jhikhu Khola catchment and in Table 3.22 for the Yarsha Khola catchment. The AET varies from sub-catchment to sub-catchment according to location and mean elevation. The highest AET values are estimated in the Kubinde Khola catchment with the entire sub-catchment area below 1000 masl. Values of areal AET in this sub-catchment ranged from 917 to 1011 mm per annum for the project period. The lowest AET values were estimated in the Upper Andheri Khola sub-catchment, with a mean elevation of 1408 masl. Here, AET values ranged from 793 to 831 mm per annum. For the entire Jhikhu Khola catchment values of 850 to 886 mm per annum were estimated.

Table 3.21: **Areal AET in the Jhikhu Khola catchment for the period from 1993 to 2000 calculated by FAO (1998) and Thornthwaite and Mather (1955) (T&M) [mm]**

Sub-catchment	1993		1994		1995		1996		1997		1998		1999		2000	
	FAO	T&M	FAO	T&M	FAO	T&M	FAO	T&M	FAO	T&M	FAO	T&M	FAO	T&M	FAO	T&M
Main	850	826	886	786	854	776	873	738	859	851	884	909	878	804	869	836
Lower Andheri	851	892	892	870	863	855	876	830	866	923	864	973	874	882	855	906
Upper Andheri	804	885	831	846	794	824	810	817	793	903	823	946	828	862	809	890
Kukhuri	820	884	861	846	835	823	841	816	831	902	801	946	812	848	791	874
Kubinde	917	912	990	924	917	927	979	863	958	973	995	1036	1003	947	1011	996

Table 3.22: **Areal AET in the Yarsha Khola catchment for the period from 1998 to 2000 calculated by FAO (1998) and Thornthwaite and Mather (1955) (T&M) [mm]**

Sub-catchment	1998		1999		2000	
	FAO	T&M	FAO	T&M	FAO	T&M
Main	778	845	790	677	732	715
Upper Khahare Khola	694	762	657	611	592	638
Lower Khahare Khola	690	807	698	690	645	723
Gopi Khola	809	937	840	818	759	811

These values roughly correspond with the values calculated according to Thornthwaite and Mather (1955). The biggest variations can be seen between the values of the two methods in the entire Jhikhu Khola catchment. The variation in this catchment ranged from 25 to 150 mm. In the Kubinde Khola catchment, values from both methods correspond.

In the Yarsha Khola catchment AET values were estimated at about 730 to 790 mm per annum in the period from 1998 to 2000. The highest values are estimated for the Gopi Khola sub-catchment, mainly due to the lowest mean elevation of all sub-catchments in the Yarsha Khola catchment.

3.2.6 Summary

Evapotranspiration was calculated applying the FAO-Penman-Monteith method with the proposed equations for estimation of missing climatological data other than minimum and maximum temperature. Actual evapotranspiration was determined using the crop coefficient approach.

The evapotranspiration analyses can be summarised as follows:
- annual reference evapotranspiration rates at different sites in the Jhikhu Khola range from 800 to 1400 mm per annum;
- annual reference evapotranspiration rates at different sites in the Yarsha Khola range from 600 to 1300 mm per annum;
- actual evapotranspiration accounts for about 800 to 900 mm per annum in the Jhikhu Khola and 600 to 800 mm per annum in the Yarsha Khola catchment; and
- the evapotranspiration showed a good regression with elevation.

In general, it has to be noted that although the values calculated above seem to be plausible in comparison with measured data and data from other studies, evapotranspiration remains an area where much more work is required to reach conclusive answers. In order to improve the quality of the evapotranspiration data, additional measurements are necessary at all sites. The measurement of relative humidity in particular is necessary and possible, and has already been initiated in the Jhikhu Khola catchment. In addition, the actual water demand of the different plants in the catchment (both natural as well as cultivated) is not known. This may have a major impact on the accuracy of the evapotranspiration calculations.

In terms of indicators for the indexes, only the Water Poverty Index is relevant for the parameter evapotranspiration (proposed indicators are compiled in Table 5.1, Chapter 5, p. 291, this volume). For flood generation and land degradation, evapotranspiration plays only a minor role in connection with the antecedent moisture. However, this changes frequently and constantly and can not be used, therefore, as an indicator for the two indexes.

3.3 RUNOFF AND DISCHARGE

This section describes runoff on three different spatial scales — from the study plots, sub-catchments, and catchments. After a comparative analysis of the plot scale runoff, the temporal and spatial variability of runoff in the catchments and sub-catchments are discussed. The low flows are sustained over the entire dry season by the groundwater and soil water storage in the catchments. Groundwater information is presented from the well monitoring network in the Jhikhu Khola catchment. The section ends with some frequency considerations and concludes with a summary of the main findings.

For discharge event analyses refer to Section 3.4, Rainfall-Runoff, in this chapter.

There is often confusion over the use of the words ‘runoff’ and ‘discharge’ and in many cases they are used interchangeably. Runoff is understood in this study as the water leaving a delineated catchment as surface flow and expressed as a volume (usually mm). Discharge is the rate of flow of a river at a particular moment in time and usually related to its volume and its velocity, for example, m^3/s or l/s (Whittow 1984).

3.3.1 Rivers in Nepal and the HKH

The Hindu Kush-Himalayas and the Tibetan plateau are the largest storehouse of freshwater in the lower latitudes. Not only nearly one hundred and fifty million people in the mountains depend on the freshwater from these mountain ranges, these ranges also supply water to nearly five hundred million people in the adjacent plains and downstream basins. Mighty rivers such as the Indus, the Ganges, the Yarlung-Tsangpo, the Brahmaputra, the Nu-Salween, the Yangtze, the Yellow River, the Mekong and others have their origin in these mountains. Some of them, such as the Huang He or the Indus, are the lifeline for the lower areas, providing water for human consumption and irrigation. They also contain the largest mass of ice and snow outside the earth's polar regions (Chalise 2000).

Nepal has four major river systems draining the country (Figure 3.47). These are the Saptakosi in the east, the Sapta Gandaki in central Nepal, the Karnali in the west, and the Mahakali in the far west of the country (Sharma 1977). Both the Jhikhu Khola and the Yarsha Khola catchments are part of the Saptakosi system, first draining into the Sunkosi, which forms the Saptakosi after the confluence with the Tamur and Arun rivers. The Saptakosi is a tributary of the Ganges. The diverse basin characteristics and differences in human activities combine to generate a spatially and temporally dynamic mosaic of river flows across the physiographic regions of Nepal (Kansakar et al. 2002). However, the flow of these rivers is mainly characterised by a distinct peak in either July to September, July to August, or August depending on the length of the monsoon rains. The sizes of the flow peaks closely correspond to the average basin rainfall amount. Baseflow of the major rivers is characterised by the snow and glacier cover in its highest headwaters.

The Jhikhu Khola and Yarsha Khola are both rainfed rivers. Their regime is therefore characterised by high flows during the monsoon season, receding rapidly to a dry season flow with a minimum in May depending solely on the soil and groundwater storage within their catchment area (for more detail see below).

In the following paragraphs the runoff from three different spatial units will be discussed. Firstly, runoff from the erosion plots will be presented as a first approach to understanding the flow response to rainfall, followed by the runoff from the sub- and the entire catchments, which includes the storage component. For detailed analyses on the rainfall-runoff response during rainfall events refer to Section 3.4.

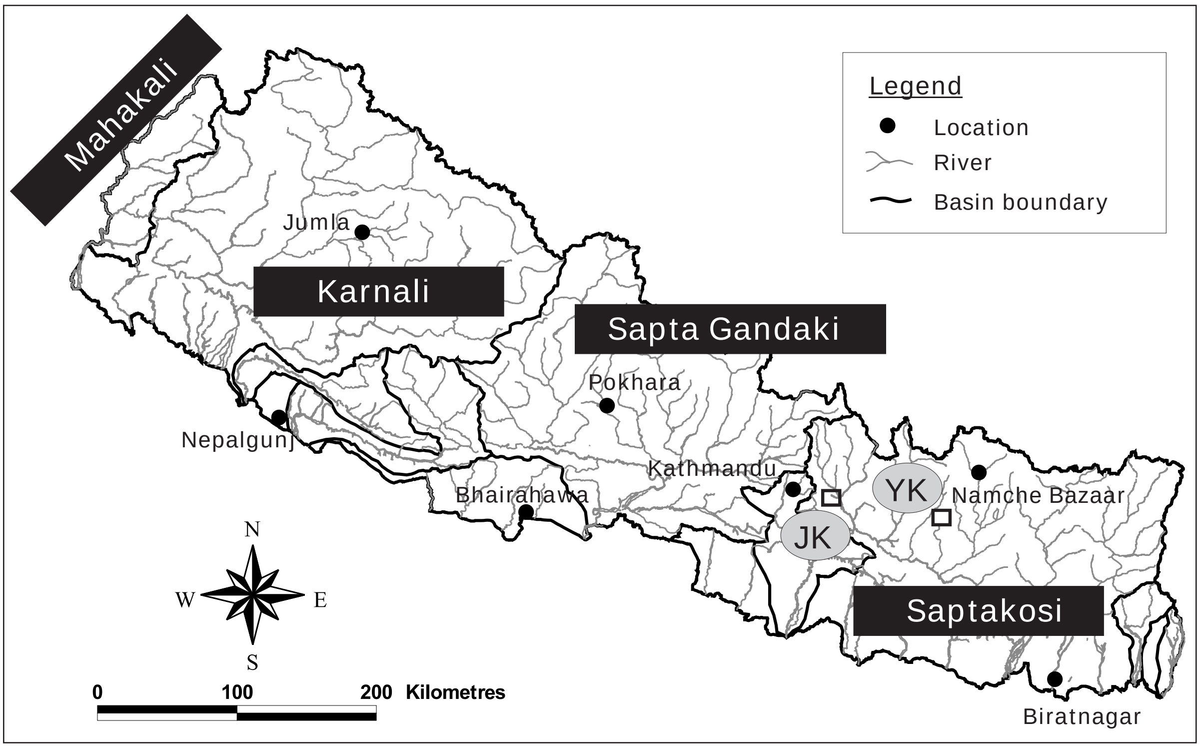


Figure 3.47: **Four major river basins in Nepal (data source: MENRIS/ICIMOD)**

3.3.2 Runoff at the plot scale

Surface runoff is one of several streamflow generation processes discussed in Chapter 1 and illustrated in Figure 1.3. Two different surface runoff types can be expected, Hortonian overland flow and saturation overland flow. Hortonian overland flow is generated when rainfall intensity exceeds infiltration capacity and is usually associated with impermeable soils, little vegetation, and high soil compaction (Anderson and Burt 1990). Saturation overland flow is mostly expected on shallow soils with moderate hydraulic conductivity and on flat land.

The PARDYP project established erosion plots with different land use to monitor surface runoff. For the analysis below, four erosion plots in the Jhikhu Khola catchment and four plots in the Yarsha Khola catchment were selected on the basis of data availability.

The plots were compared in terms of annual and seasonal response to the respective rainfall conditions at each site in order to understand the magnitude of difference between land under various uses and in different locations.

3.3.2.1 Runoff analyses in the Jhikhu Khola catchment

The four erosion plots included in the analyses for the Jhikhu Khola catchment include two plots on degraded land, Sites 4a and 14a; and two sites on rainfed agricultural terraces, Sites 6a and 16a. In Table 3.23, below, annual runoff from all the plots is compiled.

At a first glance, it is evident that the annual runoff between the degraded and the agricultural plots varies tremendously. The average runoff on the degraded plots is about 20 times more than the runoff from the agricultural plots. Rainfall at the sites differs only slightly by about 100 mm. In addition, it is not only the plots with the highest rainfall that produce the highest runoff, but often vice versa. This is also shown with the average runoff coefficients of 1 and 3% on agricultural land and 34 to 40% on degraded land. Inter-annual runoff variation is very small and is comparable to the variation of rainfall.

Table 3.23: **Annual runoff at the plots in the Jhikhu Khola catchment (in mm; in brackets: annual rainfall)**

Year	Plot 4a (d/11.5)	Plot 6a (r/20.4)	Plot 14a (d/14.0)	Plot 16a (r/6.7)
1993		23*(1045)		5* (949)
1994		17 (1136)		31 (1173)
1995		17 (1176)		15 (1157)
1996		26 (1291)		52 (1287)
1997	458* (1084)	35 (1294)	296* (1195)	33 (1313)
1998	445 (1111)	33 (1288)	449 (1292)	20 (1217)
1999	519 (1442)	35 (1546)	476 (1481)	13 (1464)
2000	497 (1069)	36 (1213)	416 (1188)	5 (1296)
Average**	**487 (1207)**	**28 (1278)**	**447 (1320)**	**24 (1272)**
Average 98-00	**487 (1207)**	**35 (1349)**	**447 (1320)**	**13 (1326)**
Average runoff coefficient [%] 98-00	**0.40**	**0.03**	**0.34**	**0.01**

d= degraded, r = rainfed agriculture

* This figure should not be used for calculations as this represents the data of the first year where the soil in the plot was disturbed during its setting up.

** This average is calculated excluding the first year's runoff.

Seasonally, it can be seen that most of the runoff occurs during the monsoon season on all plots. About 80% of the annual runoff occurred in this season on the degraded plots (Figure 3.48). This shows the direct relationship between rainfall and runoff. As shown in Section 3.1, about 78% of the annual rainfall is expected during the monsoon season. On the agricultural terraces on the other hand, although most of the runoff (about 60%) likewise occurs during the monsoon season, about 30% of the annual runoff occurs during the pre-monsoon season. This shows a significantly higher portion of runoff during the pre-monsoon season where about 14% of the annual rainfall occurs at all selected sites. The pattern of the plots of the same land use is congruent, which shows that there is a high probability that most of the differences between the plots can be explained by differing land use and management.

On the basis of monthly data, distinct differences can be confirmed (Figure 3.49). The maximum average monthly runoff was observed in July on the degraded plots — incidentally the month with the highest monthly precipitation (see Section 3.1). The months with the next highest runoff were

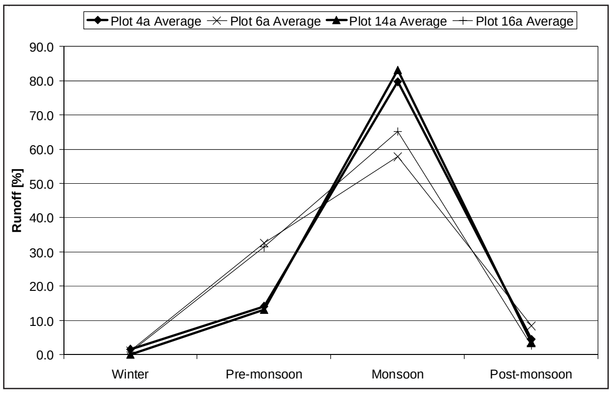


Figure 3.48: **Seasonal runoff from erosion plots under different land use from 1998 to 2000**

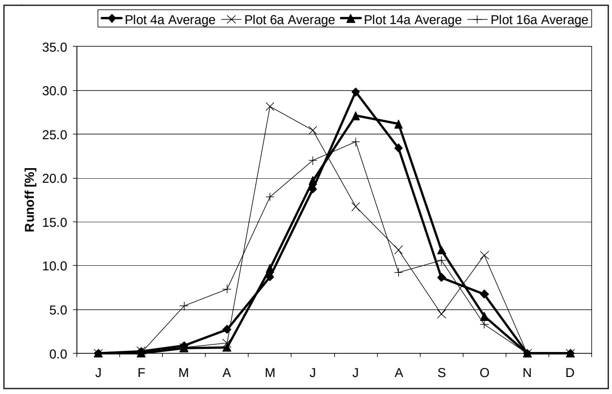


Figure 3.49: **Monthly runoff from erosion plots on different land use, 1998 to 2000**

August and June, indicating that the mid- to late-monsoon season is particularly prone to runoff generation on the degraded plots. On the agricultural plots the maximum mean monthly runoff was seen in the late pre-monsoon season and the early monsoon season months. At Site 6a the maximum mean monthly runoff was recorded in May, followed by June and July. At Site 16 the maximum runoff was observed in July, followed by June, then May.

In the study of Gardner et al. (2000), who monitored agricultural plots in western Nepal, runoff usually peaked in the months of June, July, or August. Relating rainfall with runoff, monthly runoff coefficients of the type monthly runoff/monthly rainfall are determined (Figure 3.50a). While the mean monthly runoff coefficients on degraded plots reach their maximum of 40 to 50% in the main monsoon season months of June, July, and August; on the agricultural land the maximum mean of 6% on Plot 6 and 3% on Plot 16 were observed in May and June respectively, during the late pre-monsoon and early monsoon season. The mean runoff coefficients on the agricultural sites were consistently observed to be below 5%, which corresponds with the findings of Gardner et al. (2000). On the agricultural plots in that study, runoff consistently represented only up to 10% of the rainfall. Infiltration in these plots is very high and 50 to 80% of the annual rainfall infiltrated to a depth below the root zone (>40 cm) on all the monitored plots. They identified distinct differences between the pre-monsoon and the monsoon seasons. In the pre-monsoon season about 30% of the rainfall infiltrated to depth with the remainder wetting the surface soil layer. In the monsoon season, 60 to 80% infiltrated and soil saturation was attained most of the time.

The maximum runoff coefficients on degraded plots were observed throughout the rainy season from April to September (Figure 3.50b). In addition to this, at Site 4 a maximum of the same magnitude was also observed in April. On the rainfed agricultural land on the other hand, the maxima are confined to the late pre-monsoon to early monsoon season with one exception in October. This was due to the exceptional event mentioned several times above.

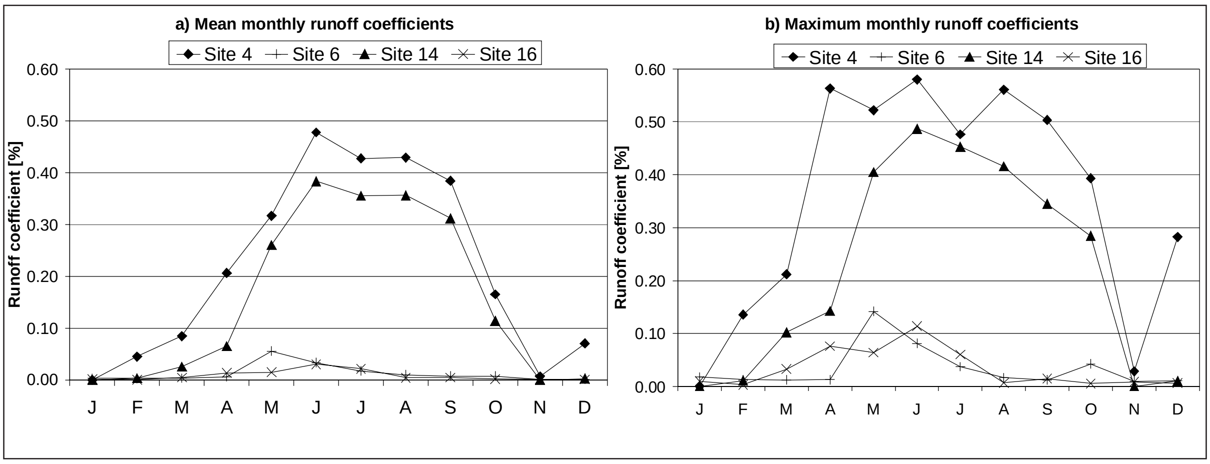


Figure 3.50: **Monthly runoff coefficients on erosion plots: a) mean b) maximum**

On the degraded land approximately 20 to 25 of all the runoff events produce 75% of the annual runoff (Figure 3.51). This differs from the number of events producing the same amount of annual runoff on agricultural land. On these plots about 10 to 15 events cause 75% of the annual runoff. The number of events producing the same amount of annual runoff differs slightly from year to year, for example, on Plot 6a in 1998, 11 events produced 75% of the annual runoff, while in 1999 it was 13 events and in 2000, 14 events. On Plot 16a, 75% of the annual runoff was generated by 9 events in 1998, 10 events in 1999, and 11 events in 2000; resulting in an overall average of 10 events per annum producing about 75% of the annual runoff. On Plot 4a, 21 events were responsible for 75% of the annual runoff in 1998, 22 events in 1999, and 19 events in 2000, respectively. Plot 14a shows a similar behaviour to Plot 4a, with 23 events in 1998, 20 events in 1999, and 17 events in 2000; producing 75% of the annual runoff. On the basis of these results, it can be said that in terms of runoff generation the importance of single, large events is more important on rainfed agricultural land than on degraded land.

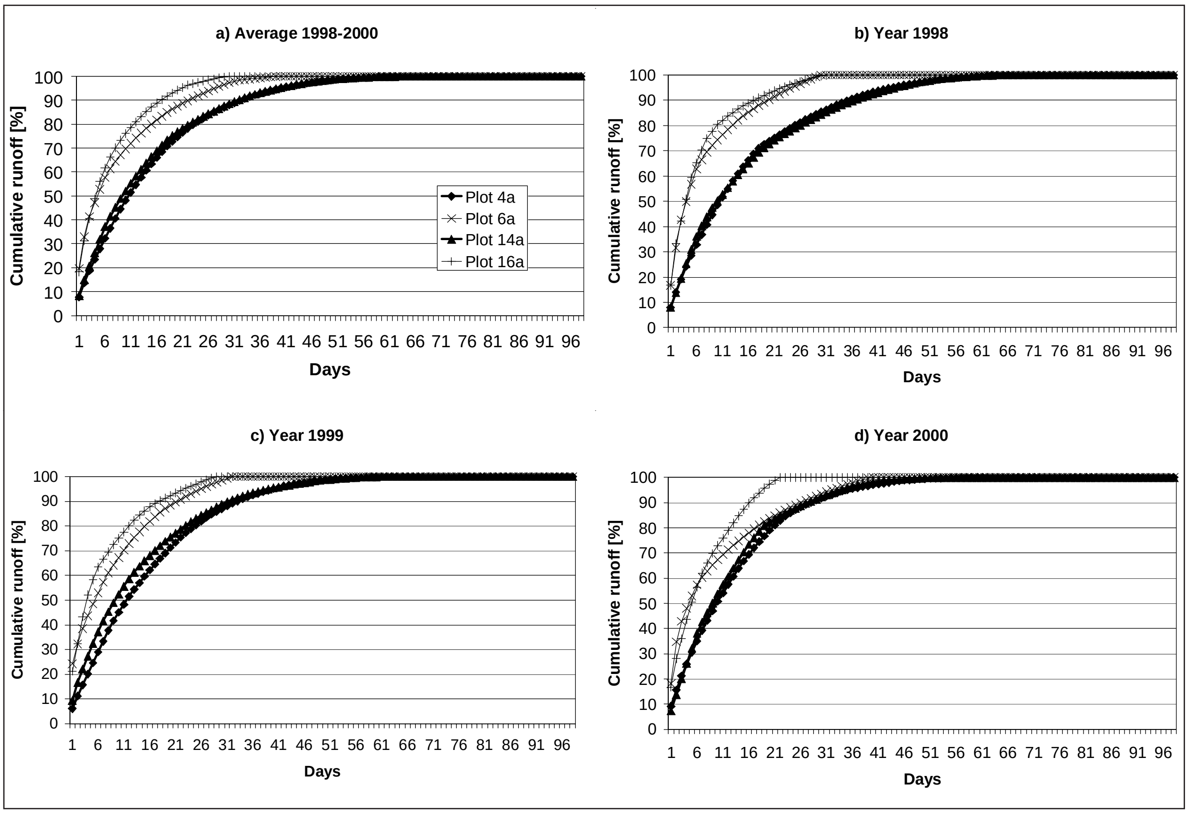


Figure 3.51: **Cumulative runoff for all plots in the Jhikhu Khola catchment**

The above analyses can be summarised as follow:

- there is a distinct difference in runoff from agricultural and from degraded land with degraded land experiencing runoff some 20 times greater than agricultural land;
- the percentage of runoff amount on degraded land during the different seasons roughly corresponds to the seasonal rainfall pattern;
- on agricultural land, runoff during the pre-monsoon season is more important than runoff in the same season on degraded land;
- runoff coefficients vary greatly between degraded and agricultural land;
- runoff coefficients peak at about 0.40 throughout the wet season on degraded land;and
- on agricultural land the peak is in the late pre-monsoon or early monsoon season.

3.3.2.2 Runoff analyses in the Yarsha Khola catchment

In the Yarsha Khola catchment the selected plots included two plots on rainfed agricultural terraces, Sites 6a and 9a; and two plots on grazing land, Plots 5a and 9b. These plots were all on similar slopes and on the south-facing part of the catchment (Table 3.24). The plots, however, differ in terms of elevation, which has a considerable impact on the rainfall amount as well as on the erosivity of the rainfall (see Section 3.1). For this reason, two approaches were selected:

a) to compare the annual runoff coefficients between plots;and
b) to compare Plots 9a and 9b located 20 m apart from each other.

Table 3.24: **Annual runoff [mm] (in brackets the annual rainfall in mm at the plot and the annual runoff coefficient)**

Year	Plot 5a (g/19.1)	Plot 6a (r/17.0)	Plot 9a (r/17.5)	Plot 9b (g/17.5)
1998	673 (2940/0.23)	250 (2496/0.10)	108 (1692/0.06)	276 (1692/0.16)
1999	468 (2864/0.16)	232 (2316/0.10)	240 (1693/0.14)	376 (1693/0.22)
2000	704 (2855/0.25)	239 (2393/0.10)	258 (1738/0.15)	473 (1738/0.27)
Average	**615 (2886/0.21)**	**240 (2402/0.10)**	**202 (1708/0.12)**	**375 (1708/0.22)**

g = grazing, r = rainfed agriculture

Both approaches show that rainfed agricultural land produces considerably less runoff than grazing land. Plot 5a, with the highest rainfall inputs, produces on average about 615 mm runoff annually, which corresponds to a mean annual runoff coefficient of 21%. The other grazing land, Plot 9b, in a lower rainfall regime with about 1100 mm less rainfall per annum, shows a similar runoff coefficient of 22% and a mean annual runoff of 375 mm. Comparing this runoff coefficient with that of the adjacent plot 9a, it is evident that plot 9a only accounts for about half the runoff with the same rainfall and a mean annual runoff of 202 mm. This ratio runoff at Plot 9a to runoff at Plot 9b varies from 40 to 65%. Plot 6a, about 500m higher than Plot 9a and with 700 mm more rainfall per annum, shows a similar annual runoff coefficient of 10% with a runoff coefficient at Plot 9a of 12%.

Seasonally, there is no distinct difference observed between the different land uses (Figure 3.52a). Average seasonal runoff varies from 75 to 90% on all the plots during the monsoon season with the observed minimum at Site 9a and the observed maximum at Site 6a. During the pre-monsoon season, 10 to 20% of the runoff occurs on all the plots with the maximum observed on Plot 6a.

On the basis of the monthly runoff data (Figure 3.52b) it can be shown that the maxima in all plots was observed in the month of July, the wettest month of the season, followed by August and September or June. However, there was no distinct difference observed between the plots in terms of runoff volume. At Site 9a May seems to have played an important role during the study period. In terms of mean monthly runoff coefficients, the grazing plots show generally higher values throughout the year (Figure 3.53a). The mean coefficients tend to peak in the rainy season any time between May and September. No seasonal pattern between pre-monsoon and monsoon and differences between grazing and rainfed agricultural land could be observed. The same can be said for the maximum runoff coefficients observed during the study period (Figure 3.53b).

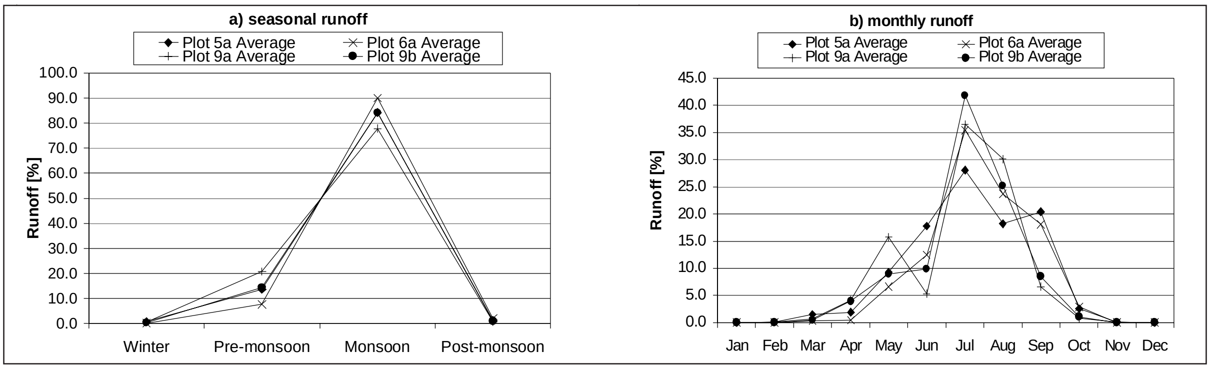


Figure 3.52: **Seasonal a) and monthly b) runoff from erosion plots on different land use 1998-2000**

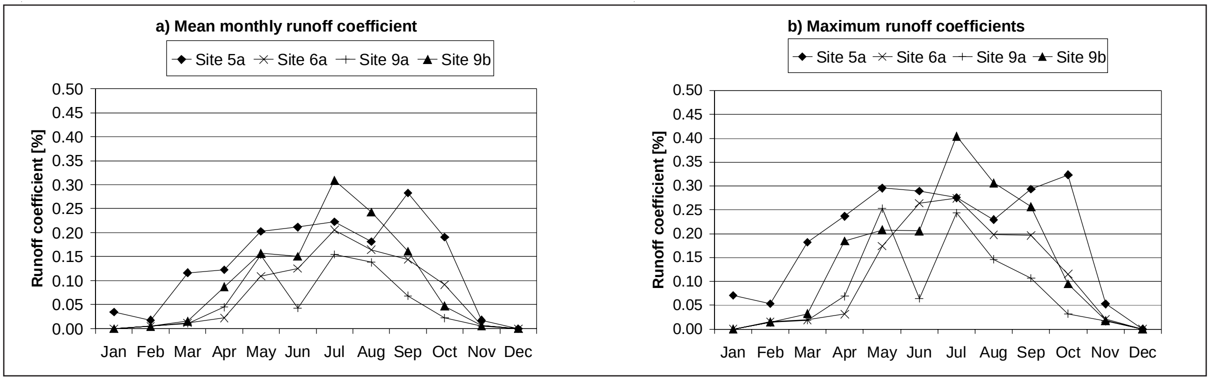


Figure 3.53: **Monthly runoff coefficients on erosion plots from the Yarsha Khola catchment: a) monthly mean, b) monthly maximum**

There is no distinct difference visible in terms of cumulative runoff on the different plots in the Yarsha Khola catchment (Figure 3.54). Approximately 20 events produce 75% of the annual runoff in this catchment, varying from 19 events on Plot 9a, 21 events on Plots 6a and 9b, to an average of 28 events on Plot 5a. The number of events responsible for 75% of the annual runoff differs slightly between the years. On Plot 5a the plot where the largest number of events produced 75% of the annual runoff, 1998 had 28 events, 1999 saw 26 events, and 2000 had 30 events. On the other grassland plot (9b) 21 events caused the same percentage of runoff in 1998, 21 in 1999, and 22 in 2000. On the adjacent plot (9a), 21 events were responsible for 75% of the annual runoff in 1998, 18 events in 1999, and 18 events in 2000, totalling an average of 19 events over the study period and the lowest number of events amongst the four plots. On Plot 6a, rainfed agricultural land, 17 events caused 75% of the annual runoff in 1998, 25 events in 1999, and 22 events in 2000.

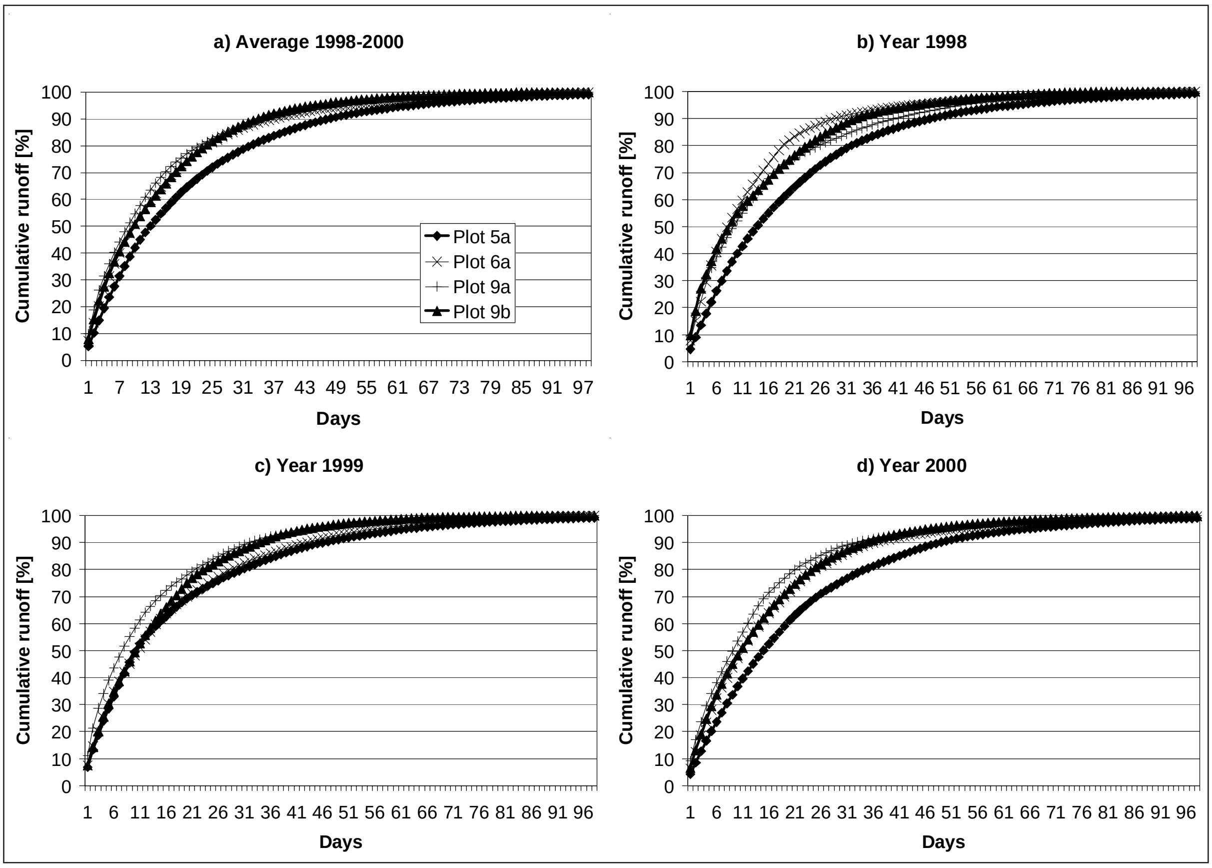


Figure 3.54: **Cumulative runoff, Yarsha Khola catchment**

In summary, it can be said that:

- there is no distinct difference between seasons in terms of runoff from grazing and agricultural land;
- runoff on grazing land is about double the runoff on agricultural land;
- average runoff coefficients on grazing land are about 20 to 25%;
- average runoff coefficients on agricultural land are about 10 to 15%; and
- the peak runoff coefficients tend to be later in the wet season on all plots.

It has to be noted that the results above are from plot studies and therefore run-on is controlled. However, Gardner et al. (2000) identified sites with run-on from fields above as the most critical sites for soil erosion and therefore causing severe land management problems.

3.3.3 Discharge in the rivers of the catchments and the sub-catchments

In addition to the surface runoff from the plots and the slopes as far as it reached the drainage network, further processes contribute to the generation of basin runoff. This includes different subsurface flow processes and contributions by groundwater (see Figure 1.3). Below, the flow measured at the hydrological stations is examined after a brief discussion of the data origin and quality.

3.3.3.1 Measurement and calculation of discharge

As described in Section 2.4, discharge at five sites in the Jhikhu Khola catchment and four sites in the Yarsha Khola catchment was measured indirectly with the help of a rating curve. In the same section the difficulties related to the generation of a rating curve were discussed (more detail can be found in Appendix A3.1). Overall, it can be said that:

- the data quality of low flows is inadequate due to instable and low flow insensitive cross-sections;and
- the data quality of high flows has to be considered inadequate due to missing measurements for the establishment of that range of the rating curves.

As identified above, the stability of the cross-sections and the measurement of high as well as very low flows compromises the accuracy of the rating curves and therefore the discharge data. For future analyses Merz (2002; Appendix B.6) suggested the following:

- stabilising the cross-sections on either side as well as on the bottom with artificial cross-sections;and
- constructing defined structures such as flumes and various weirs and compounds, mainly to cater for the low flow sensitivity and the infrastructural problems associated with night measurements.

Due to the inaccuracies of the data in this range of the rating curves:

- the annual runoff values, which are heavily dependent on accurate low flow measurements, of Sites 8 and 13 in the Jhikhu Khola catchment had to be discarded;and caution is advised with low flows and very high flows.

3.3.3.2 Temporal variability at the main hydrological stations

In both catchments, the Jhikhu Khola and the Yarsha Khola catchments, the integral systems response to rainfall is monitored at the outlet with a main hydrological station (also see Section 2.4). Below the hydrological data of these two sites are discussed in relation to temporal variability of flow.

The mean discharge at the main station at the outlet of the Jhikhu Khola catchment was 1.45 m^3/s in the period from 1993 to 2000 (Table 3.25). It ranged from 1.12 m^3/s in 1994 to 1.79 m^3/s in 1996. In this period the daily maximum discharge was observed to be about 30 m^3/s, and the minimum was below 10 l/s during the same time. However, these extreme values have to be considered with caution due to the insecurities related to the stage-discharge relationship (see above). However, there are no long-term data sets available at this site for validation of the results.

Table 3.25: **Annual principal discharge figures for Site 1, Jhikhu Khola catchment**

	1993	1994	1995	1996	1997	1998	1999	2000
Mean discharge [m^3/s]	1.198	1.118	1.440	1.788	1.143	1.675	1.578	1.660
Max discharge [m^3/s]	19.671	12.428	32.966	30.804	29.033	19.890	20.258	14.989
Min discharge [m^3/s]	0.005	0.005	0.004	0.115	0.022	0.000	0.002	0.001
Mean specific yield [$m^3/s*km^2$]	0.011	0.010	0.013	0.016	0.010	0.015	0.014	0.015
Annual runoff [mm]	339	317	408	506	324	474	447	470

The annual mean specific yields range from 0.010 to 0.016 $m^3/s*km^2$. These values are very low and show a considerable human impact on the streamflow conditions in the catchment. For comparison, the Rosi Khola in a catchment south and adjacent to the Jhikhu Khola and with an area of 87 km^2 the specific yield was recorded to be 0.030 $m^3/s*km^2$ (Alford 1992). The reason for the higher specific yield in this catchment is that water is used extensively for irrigation and for the domestic supply of the small townships of Banepa and Panauti, and it is located in a higher rainfall regime. The catchment extends up to 2943 masl at its highest point and receives much more rainfall than the Jhikhu Khola catchment, having a peak elevation of 2200 masl.

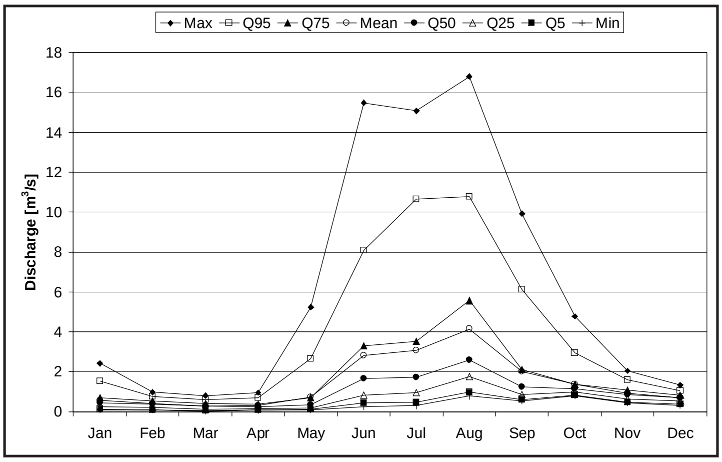


Figure 3.55: **Comprehensive runoff regime at Site 1, Jhikhu Khola catchment**

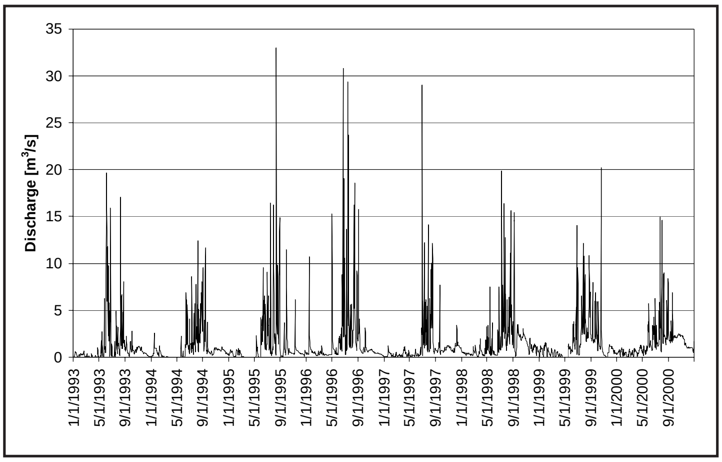


Figure 3.56: **Daily discharge at Site 1 of the Jhikhu Khola catchment**

Seasonality is evident from the average runoff regime, including the major percentiles and the extreme values (Figure 3.55). The highest mean and median flows were observed during the month of August followed by July and June. In comparison with the monthly distribution of rainfall (Figure 3.3) this maximum is delayed by one month. The absolute minimum flows occur in the month of March closely followed by April, February, and May, indicating the driest time of the year in terms of discharge in the river system completely fed by groundwater (see below). With increasing pre-monsoon showers in May, the flow starts to pick up and rapidly increases to maximum flows in the monsoon season. After reaching the maximum flows in this season, the flows decline, reaching dry season flows in November, with September and October usually showing intermittent flow amounts.

The daily discharge shows the distinct dry season/ wet season pattern which can also be observed in Figure 3.56, above. The largest events usually occur during the wet season with only very few and small peaks during the dry season. These dry season events usually occur during the early dry season, the post-monsoon season (such as the event on October 19/20 1999) or during the late dry season. These events could already be classified as wet season events, as they occur in the often long and extended pre-monsoon showers that continue up to the onset of the monsoon rains (also see Section 3.1). Occasionally, large events happen during the dry season, such as occurred on January 15-16, 1996, but only rarely.

The monthly flows are generally variable in the catchment (Figure 3.57). The lowest variabilities were observed in the monsoon season, the months of August and July in particular. The February flows also have low variability as they were consistently low throughout the measurement period. Generally, the pre-monsoon flows in March, April, and May show the highest variabilities as they can be very low if there are late, weak pre-monsoon rains. They can also be high if intense pre-monsoon events and extended showers occur, as they do at this time of the year.

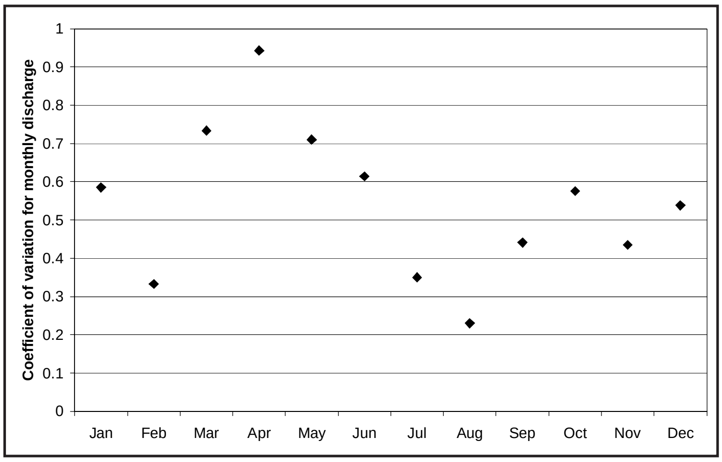


Figure 3.57: **Temporal variability on the basis of monthly data, Site 1, Jhikhu Khola catchment**

The highest flow at Site 1 during the year is, on average, 16 times higher than the mean annual flow. With respect to the minimum flow, the highest daily discharge was approximately1500 times bigger on average throughout the study period and the mean flow was 83 times bigger than the lowest annual flow.

Data monitoring started in the Yarsha Khola catchment in 1997, and complete annual data are available from 1998 to 2000. In this period the mean discharge was observed to range from 1.9 to 2.9 m^3/s (Table 3.26). The maximum discharge in the same period ranged from 11.6 to 14.3 m^3/s. The observed minima were below 100 l/s in 1998 and about 250 l/s in the remaining years. The same reservations about the quality of the extreme values have to be made here as in the case of Jhikhu Khola catchment.

Table 3.26: **Annual principal discharge figures for Site 1, Yarsha Khola catchment**

	1998	**1999**	**2000**
Mean discharge [m^3/s]	1.930	2.056	2.862
Max discharge [m^3/s]	11.637	12.978	14.265
Min discharge [m^3/s]	0.086	0.280	0.256
Mean specific yield [$m^3/s*km^2$]	0.036	0.039	0.054
Annual runoff [mm]	1140.3	1214.7	1690.6

The mean specific yield was considerably higher in this catchment, ranging up to 0.05 $m^3/s*km^2$ in 2000. In 1998 and 1999, the measured specific yield was 0.04 $m^3/s*km^2$. This matches with the values observed in the Rosi Khola of similar size and similar elevation, but where there is much more human interference.

The absolute minimum flows in this catchment were observed in the month of May (Figure 3.58). However, where there are strong pre-monsoon rains or early onset of the monsoon events, the minima are observed in the month of April and February, with the smallest range of flows over the study period. The flows are consistently low from December onwards up to the onset of the new rainy season. The maxima are observed in July and August followed by September and June, with October and November showing intermittent flows. The flows observed during the month of August range from 4 to 12

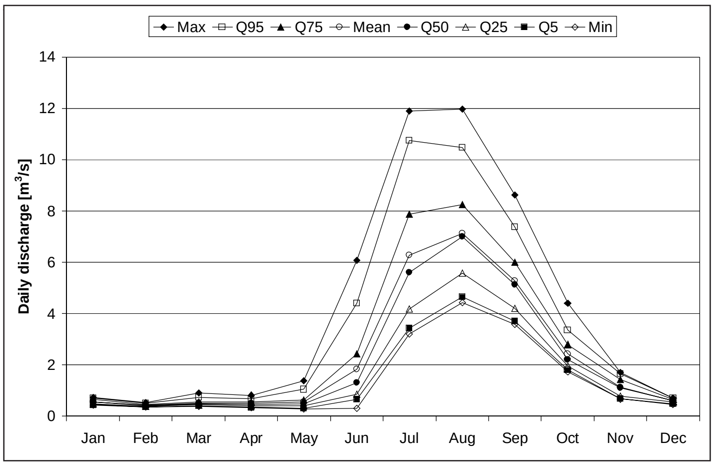


Figure 3.58: **Comprehensive runoff regime at Site 1, Yarsha Khola catchment**

m³/s. As mentioned above, the smallest range in terms of minimum flows is shown in February, with values of 0.36 to 0.52 m³/s.

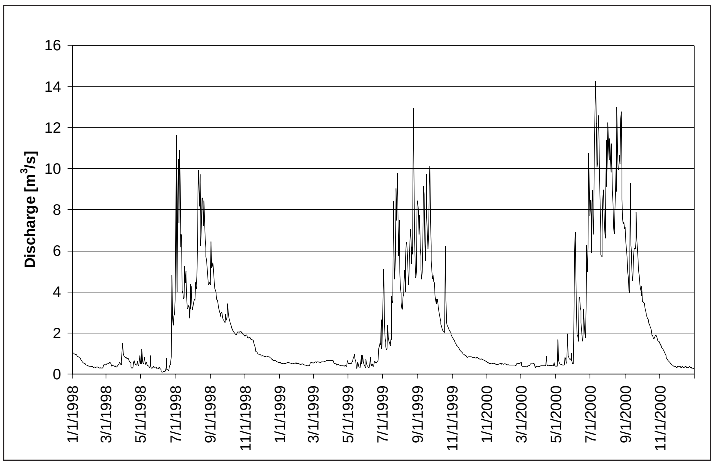


Figure 3.59: **Daily discharge at Site 1, Yarsha Khola catchment**

No dry season events of mentionable size were observed during the study period in the Yarsha Khola catchment (Figure 3.59). The earliest sizable events were observed in early June and the latest events in late October. It is important to note that the base flow during the monsoon season was consistently high in all three years compared to the Jhikhu Khola catchment, where baseflows were quite low even during the monsoon season.

Variability was not assessed for the Yarsha Khola catchment as only three years' worth of data were available and a variability analyses would not make any sense. The intra-annual variability can, however, be shown with the ratio between the highest, lowest, and mean flows at the outlet of the catchment. The highest flows are, on average, about 6 times bigger than the mean flows. With respect to the lowest flows at the outlet, the highest flows are approximately 64 times bigger on average. The lowest flows on average only show about 1/10 of the mean flow.

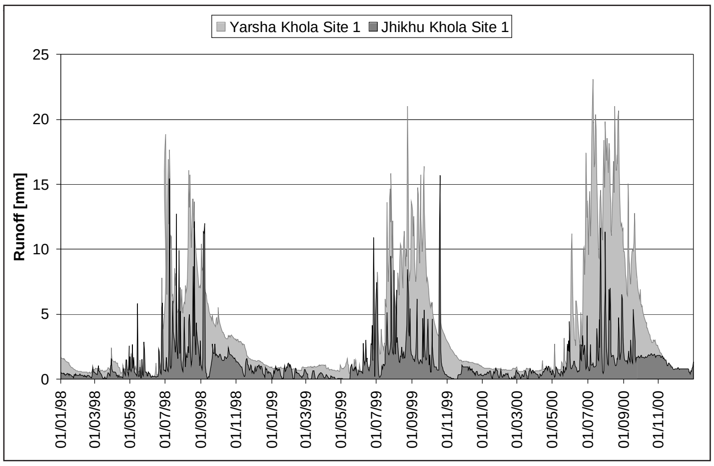


Figure 3.60: **Comparison of daily runoff at Sites 1 of Yarsha and Jhikhu Khola catchments**

A comparison of the daily runoff at the hydrological stations located at the outlet of the Yarsha and Jhikhu Khola catchments (Figure 3.60) shows that the Yarsha Khola generally carries more water per unit area than the Jhikhu Khola. The baseflow in particular is higher in the latter catchment (this will be discussed in further detail below).

The analyses from above can be summarised as follows:

- distinct wet season/dry season regime with the lowest flows in the pre-monsoon season (March/April) and the highest flows in July/August;
- mean specific yields of about 12 l/s*km² in the Jhikhu Khola catchment and 40l/s*km² in the Yarsha Khola catchment;
- the annual runoff ranging from 300 to 500 mm during the period from 1993 to 2000 in the Jhikhu Khola catchment and from 1200 to 1600 mm in the Yarsha Khola catchment for the period 1998 to 2000;and
- highest flow variabilities observed in the pre-monsoon season flows.

3.3.3.3 Spatial variability

Discharge often varies spatially to a considerable degree. This is mainly due to different catchment size, different rainfall patterns, and different catchment characteristics. Below, the flow of Site 1 in both catchments is compared with the flow from selected sub-catchments where the data allow. It is important to note that the following analyses were carried out for two catchments in the middle mountains between 800 and 3000 masl of Eastern Nepal and are, therefore, only strictly applicable for the two catchments studied. For the applicability of these relationships in other areas their validity has to be tested first.

The area of the catchment is the most obvious parameter to be used for the prediction of flow parameters, assuming that the larger the catchment the larger the flow. This, however, only yields a limited regression with annual mean flow (Figure 3.61a). The regression with average maximum daily discharge over the study period on the other hand shows a very strong relationship (Figure 3.61b). This suggests that in the middle mountains of Nepal a catchment's area could be used for the prediction of large events.

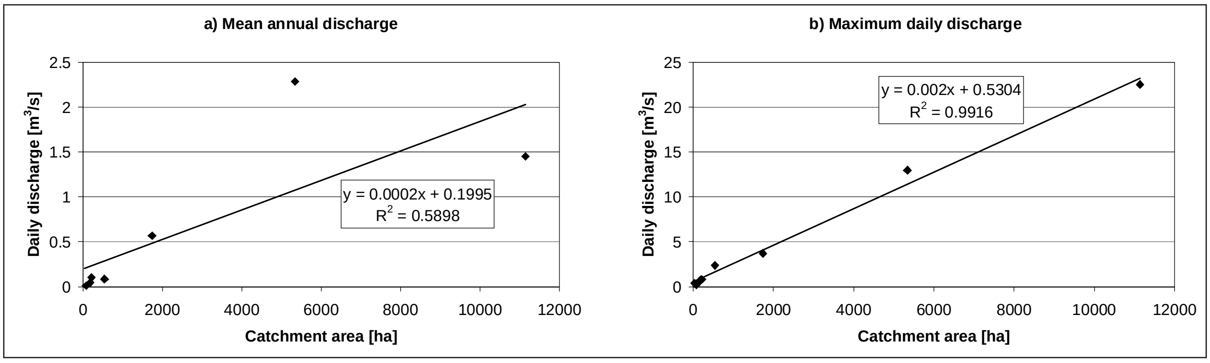


Figure 3.61: **Relationships between (a) catchment area and average mean annual daily discharge; or (b) average maximum annual daily discharge**

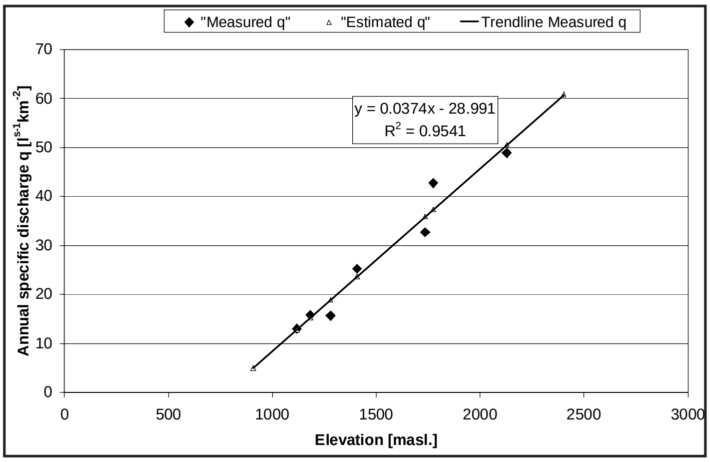


Figure 3.62: **Annual specific yields of different sub-catchments in the Jhikhu Khola and Yarsha Khola catchments**

The specific discharge expressed in $ls^{-1}km^{-2}$ adjusts the streamflow for the catchment area and allows the comparison of different catchments. As Alford (1992) notes, the specific discharge varies with the mean altitude of the catchments. It tends to increase with elevation from sea level up to about 3200 masl in the case of the Sapta Koshi basin. In catchments with mean altitudes higher than 3200 masl, the specific discharge tends to decrease again with increasing elevation. For the Jhikhu Khola catchment and the Yarsha Khola catchment and their sub-catchments this proves to be true, as shown in Figure 3.62. The relationship between mean catchment elevation and specific discharge in the case of the Jhikhu and Yarsha Khola catchments was determined to be

$q = 0.0374\, z - 28.991$ **Equation 3.12**

where

q = specific yield [$m^3/s*km^2$]
z = elevation [masl]

This equation had a very good fit shown by a regression coefficient r^2 of 0.95. The determination of this relationship excluded the data from Site 13, which, as mentioned above, has very doubtful low flows. By means of this equation, a specific yield, q, can be estimated for this site to be used in Section 3.7 on water balances. None of the other relationships between percentage of different land use and specific discharge, or mean catchment slope and specific discharge, produced any significant regressions. This suggests that the elevation of the catchment is the most important factor in determining the specific discharge in the catchment. As shown in Section 3.1, the annual rainfall is closely related to the elevation and this relationship between elevation and specific discharge is therefore well explained.

As shown in Section 3.1, most of the rainfall in the Jhikhu Khola catchment is expected during the monsoon season from June to September. During this time, 75 to 80% of the annual rainfall occurs. As the Jhikhu Khola is completely rainfed and no snow is observed in the catchment, the discharge follows the same pattern as rainfall (also shown in Figure 3.55). The sub-catchments in the Jhikhu Khola likewise follow this seasonal pattern. It is, however, important to note that there is a difference in terms of monthly peak flow between the different catchments. In the Jhikhu Khola catchment the small upland catchment of the Kukhuri Khola displays its peak in July, while at Sites 1 and 2 the peak is in August (Figure 3.63a). In the Yarsha Khola catchment this difference cannot be observed as all catchments show their peak flows in the month of August, one month after the peak rainfall in the catchments (Figure 3.63b).

The spatial variability can be summarised as follows:

- the maximum daily discharge shows a significant regression with catchment area;
- annual specific discharge varies with elevation according to the relation, $q = 0.0374 z - 28.991$; and
- no particular spatial difference can be observed in the flow regime of the two catchments and their sub-catchments.

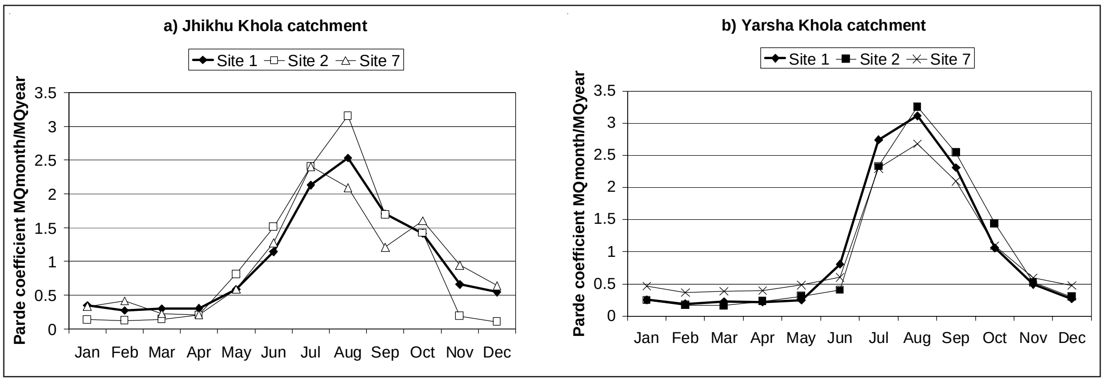


Figure 3.63: **Hydrological regime in the Jhikhu Khola catchment (a) and the Yarsha Khola catchment (b) (period 1998 to 2000)**

3.3.3.4 Low flows and storage

While the flow during the monsoon season is governed by rainfall distribution, the flow in the post-monsoon and winter season — and often to a large extent also in the pre-monsoon season — is dependent on the emptying of the storages in the catchment. These storages and their capacities are important for potential water availability assessment in particular. Some of the best storage systems are glaciers and snow as well as lakes (natural and man-made) delaying flow by a year or even years in the case of glaciers (Table 3.27). None of the catchments studied contain any of these and therefore rely solely on groundwater and soil water storage for the low and dry season flows. In general, these storage systems are believed to have capacities of up to one year. Kansakar (2001) mentions three main types of geological settings where groundwater can be expected in the hills of Nepal:

Table 3.27: **Storage of different water bodies**

(after Schaedler 1990; Nemec 1993)

Time Storages	min	hours	days	weeks	months	year	years
Soil water in upper zone	XXXX	XXXX	XXXX	XXXX	XX		
Soil water in lower zone		XXXX	XXXX	XXXX	XXXX		
Groundwater			XXXX	XXXX	XXXX	XXXX	
Snow cover		XX	XXXX	XXXX	XXXX	X	
Glacier						XXXX	XXXX
Lakes			XXXX	XXXX	XXXX	XX	
Reservoirs (man-made)		XX	XXXX	XXXX	XXXX	X	

- thick unconsolidated fluvial, glacial, and lacustrine sedimentary deposits in river and tectonic valleys;
- thick weathering mantles with coarse debris over bedrock;and
- fractured bedrock.

The main valley of the Jhikhu Khola catchment is filled with alluvial deposits, forming a potential aquifer of the first type (see also section on geology in Chapter 2). Adhikari et al. (2003) showed that spring yield closely correlated with rock type in the eastern part of the Jhikhu Khola catchment, showing a potential aquifer of the third type. Seventy-five per cent of the high yields were related to carbonate rocks such as limestone, dolomite, and marble beds. These were observed to be highly fractured and contained interconnected holes and fissures. In contrast, metamorphic rocks, such as phyllite, schist, quartzite, and gneiss, showed moderate to low discharge. The highest yields were further observed in the base of the syncline fold in the Jhikhu calcareous beds.

In the Yarsha Khola, both massive sedimentary deposits and thick weathering mantles are to a large extent missing. Subsurface water feeding base flow therefore mainly hails from potential aquifers in the fractured bedrock and from soil water storage.

In general, the Yarsha Khola catchment shows a higher storage capacity than the Jhikhu Khola catchment. This was shown by Dongol (2003) with the base flow index (BFI). The period BFI for 1998 to 2000 for the Jhikhu Khola catchment was 0.36. For the same period in the Yarsha Khola catchment the BFI was 0.46, showing a higher proportion of the annual runoff sustained by baseflow. In order to assess the storage capacities, the flow recession curves after the monsoon rains were determined at Site 1 in both catchments (Figure 3.64). The fit in the Yarsha Khola catchment of a logarithmic curve with base e is very good with r^2 of 0.93 in the dry season 1998/1999, and 0.95 in the dry season 1999/2000. Following the curve to the point of intercept with the x- axis, a storage capacity of about 310 days (304 days in 1998/1999, 321 days in 1999/2000) was determined. In the Jhikhu Khola catchment the fit was not as good: it was especially poor in 1999 after a drop of the hydrograph (probably a measurement error) after a very large event at that site. The storage capacity was determined at 299 days in 1998/1999 and 305 days in 1999/2000, with an average of about 300 days.

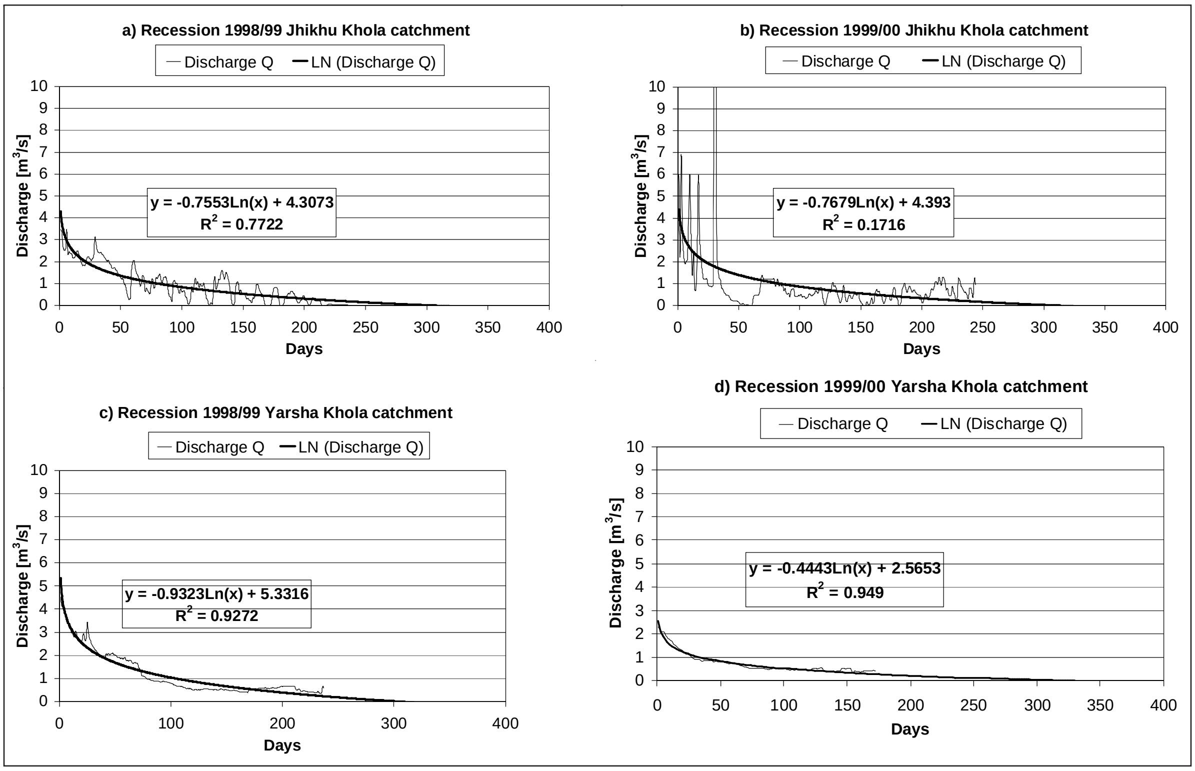


Figure 3.64: **Flow recession curves in the Jhikhu Khola: a) dry season 1998/1999, b) dry season 1999/2000; and the Yarsha Khola c) dry season 1998/1999, d) dry season 1999/2000.**

For a first assessment of the groundwater in the Jhikhu Khola catchment, PARDYP is monitoring dug wells constructed by local residents. The monitoring programme is presented in Dongol et al. (2003) and Schaffner (2003). It includes microbiological, physical, and chemical quality parameters on a seasonal basis during the first year, as well as on-going monthly measurements of water level. The quality parameters are discussed in the above-mentioned publications. In total, 43 wells are monitored at present in Tamaghat (wells W1-3), Shree Ram Pati (W4-14), and in the Dhunganabesi area (W15-38) of the Jhikhu Khola catchment (see Figure 3.65). Of these 43 wells, 25 could be used for water table analyses as they had adequate data to identify at least one recession period and one recharge period.

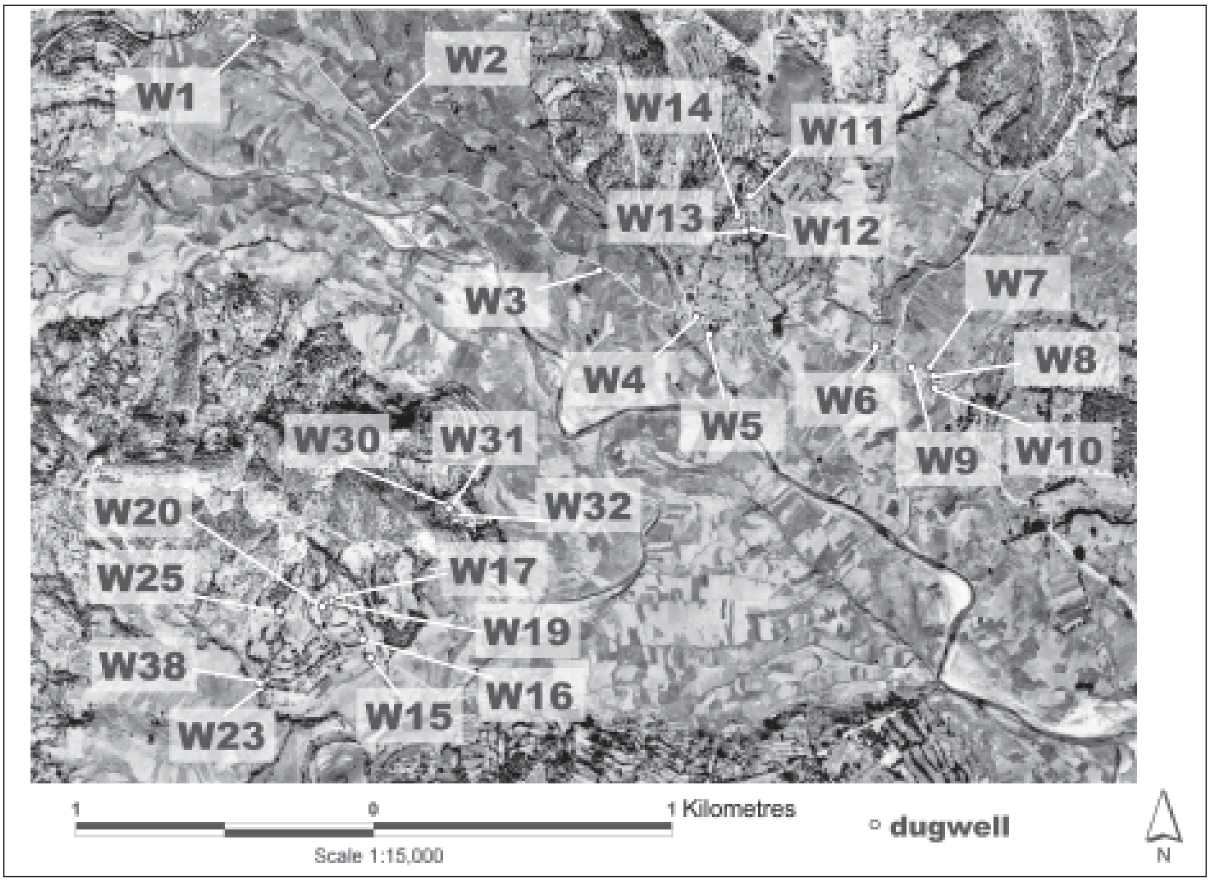


Figure 3.65: **Location of the monitored dug wells in the Jhikhu Khola catchment**

The depth of the water table, measured from the soil surface at the wellhead shows very different patterns in different wells (Figure 3.66). In most of the wells, a clear seasonal pattern is visible with a recharge period of one to four months (usually around May to August) and a recession period lasting from August to April or May. This pattern is very clearly visible in wells W11 to 14 (Figure 3.66c). In these wells the largest differences between the maximum water level in the monsoon season and the minimum water level in the pre-monsoon season were observed (see also Figure 3.67). This is due to their location on top of an accordant ridge. The recharge of these wells is very fast: usually the maximum water level is reached within one to two months. Recession of the water table obeys an exponential decay function of the form

$$WT = a*e^{-bt} \qquad \textbf{Equation 3.13}$$

where

WT = water table [m]
t = time [days]
a,b = coefficients

W13 shows the best example of a recession up to a plateau of about 10 m depth. Other wells, such as W3, never reach this plateau before the recharge of the early monsoon season sets in again.

Other wells, such as wells W38, 23, or 6 only show a slight seasonal pattern and very low differences between high water table and low water table. The last mentioned wells are all located adjacent to a stream, thereby benefiting from direct recharge of river flow. Neither a distinct recharge nor recession period is visible in these wells.

The rainfall amount of 2001 and 2002 varied considerably with 1109.8 mm in 2001 and 1656.6mm in 2002, as measured at Site 12 in Panchkhal (Figure 3.66f). This difference is also visible in many wells, with a higher water table during the peak recharge period in 2002 than in 2001. This is particularly visible in wells 11 to 14. However, in others, such as wells 1 to 5, this could not be observed.

The fast recharge of the wells above, in addition to the importance of river water for the recharge of certain wells, has to be considered in terms of water pollution considerations. As Dongol et al. (2003) have shown, wells 11 to 14, with very fast recharge times and located in the vicinity of human settlements with sanitation facilities and livestock stables, show the highest nitrate contamination. Phosphate levels were generally higher in the agricultural areas of the catchment, although all wells exceeded the guideline values in all seasons.

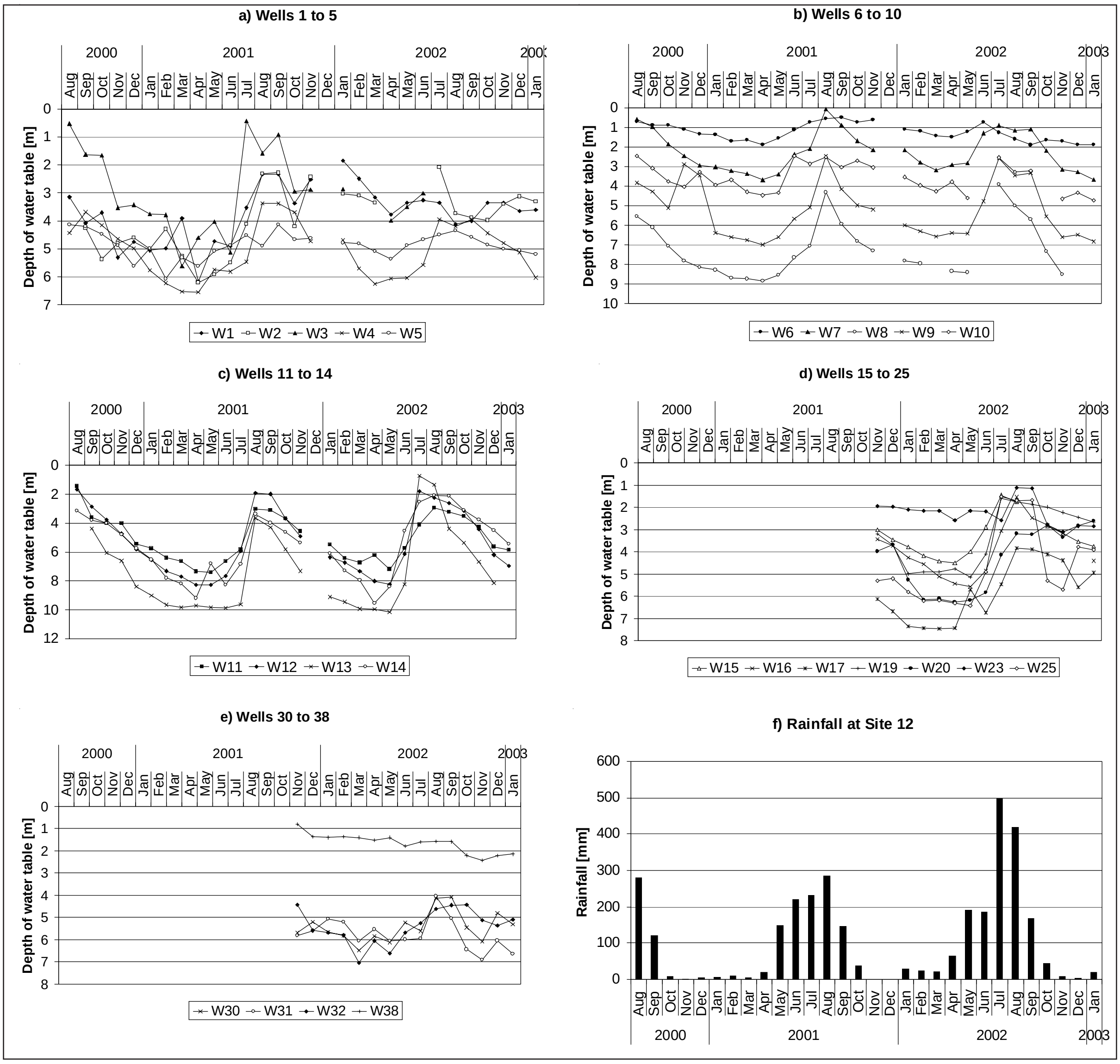


Figure 3.66: **Depth of the water table at selected well (a – e) and rainfall at Site 12 (f)**

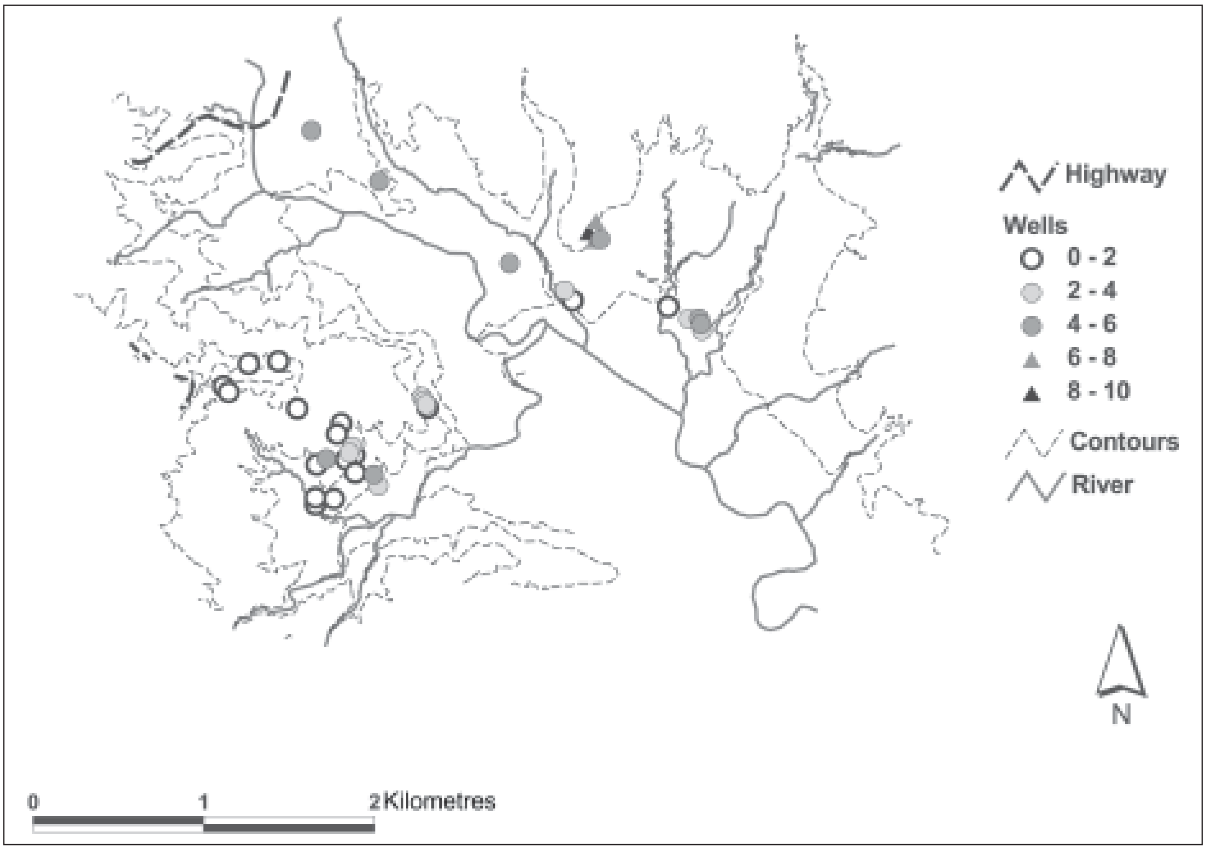


Figure 3.67: **Variation in depth of the water table in selected wells**

In summary it can be noted that:

- both catchments have soil and groundwater storage only;
- the storage can provide water for about 300 days in the Jhikhu Khola and 320 days for the Yarsha Khola catchment before it runs completely empty;
- the shallow groundwater is most reliable in river depressions and foot slopes;and
- the highest variations in shallow groundwater are observed on ridges.

3.3.3.5 Probabilities of exceedance and deficit

For flood- and water-caused land degradation the probability of the occurrence of high flows $Q_{x(exc)}$ is of particular interest. For low flow considerations and water availability analyses it is the probability of occurrence for low flows $Q_{x(def)}$. As shown above, it is these values that are most likely affected by inadequate discharge measurements. However, by using the major percentiles for this analysis a quite stable result can be expected as the most likely errors are in the extreme values.

As shown above, only the 20 to 30 biggest events generate a large part of the annual runoff on the erosion plots (Figures 3.51 and 3.54). In terms of days, this corresponds to 5 to 10% of the year. Assuming that the events on the erosion plots are also representative for the floods at the catchment scale (this will be further investigated in Section 3.4), it can be said that only 5 to 10% of the annual events seriously affect flood behaviour in the catchment. For this reason, the $Q_{5(exc)}$ and the $Q_{10(exc)}$ identified from the duration curves shown in Figure 3.68 were used for further analyses of flood behaviour in the catchments. In terms of low flows $Q_{25(def)}$ was determined.

At Site 1 a, $Q_{95(exc)}$ was determined as nearly 6 m^3/s. This corresponds to 53 $l/s*km^2$. At Site 2, $Q_{95(exc)}$ was determined as 0.41 m^3/s or 76 $l/s*km^2$, which was the highest value in relation to the catchment area amongst the sub-catchments of the Jhikhu Khola catchment. In terms of low flows, the highest values were observed at Site 8 with 0.02 m^3/s or 11.2 $l/s*km^2$ for $Q_{25(def)}$. The lowest values were observed at Site 2 with 0.003 m^3/s or 0.6$l/s*km^2$. This underlines the flashy nature of the stream at Site 2 (Table 3.28).

At the outlet of the Yarsha Khola catchment, a $Q_{25(def)}$ of 0.49 m^3/s or 9.2 $l/s*km^2$ was determined (Table 3.29). This in comparison to a value of 2.4 $l/s*km^2$ in the Jhikhu Khola catchment, which shows that the Yarsha Khola has a better and more sustained baseflow throughout the year, as is also evident above in the low flow section. $Q_{95(exc)}$ displays a value of 8.55 m^3/s or 160.2 $l/s*km^2$ compared with 53.1 $l/s*km^2$. This shows both the impact of the steep overall topography in the Yarsha Khola catchment as well as the high rainfall regime here. The duration curve for Site 1 in Yarsha Khola is given in Figure 3.69.

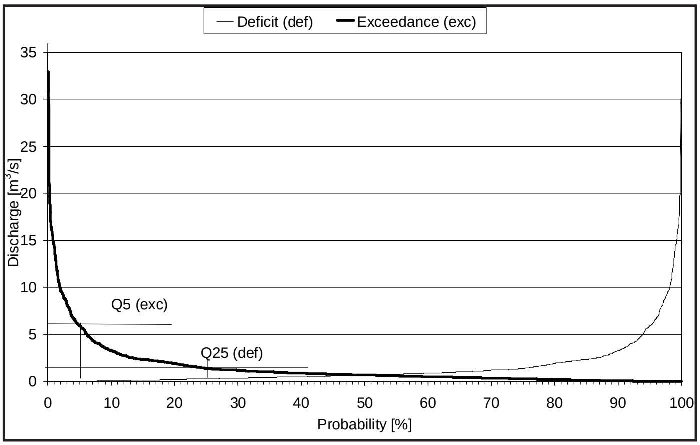


Figure 3.68: **Duration curve for Site 1 in the Jhikhu Khola catchment**

Table 3.28: **Critical values of deficit and exceedance, Site 1 Jhikhu Khola catchment (nr = not reliable)**

Parameter	Site 1		Site 2		Site 7		Site 8	
	m^3/s	$l/s*km^2$	m^3/s	$l/s*km^2$	m^3/s	$l/s*km^2$	m^3/s	$l/s*km^2$
$Q_{90(exc)}/Q_{10(def)}$	0.06	0.5	nr	nr	nr	nr	nr	nr
$Q_{75(exc)}/Q_{25(def)}$	0.27	2.4	0.003	0.6	0.002	2.7	0.02	11.2
$Q_{50(exc)}/Q_{50(def)}$	0.68	6.1	0.02	3.7	0.006	8.1	0.03	16.9
$Q_{25(exc)}/Q_{75(def)}$	1.37	12.3	0.05	9.3	0.01	13.5	0.04	22.5
$Q_{10(exc)}/Q_{90(def)}$	3.27	29.4	0.19	35.3	0.03	40.1	0.08	44.9
$Q_{5(exc)}/Q_{95(def)}$	5.92	53.1	0.41	76.1	0.04	54.1	0.12	67.4

For theoretical design flow estimation of daily discharge, Shakya (2001) proposes the use of the Pearson Type III distribution. Chyurlia (1984) used the Log-Pearson Type III and the GEV III to estimate extreme events. He finally recommended the GEV distribution as this provided the best fit for the three highest-ranking events.

In this study only eight years of daily discharge data were available by the end of 2000 and the three proposed distributions were calculated for the maximum discharge at Site 1 (Figure 3.70). Therefore the maximum theoretical event that can be estimated with reasonable confidence is the event with a 20-year return period. On the basis of this data, the Log Pearson Type III distribution shows the best fit (Table 3.30). This is confirmed both by analysing the residuals for all cases as well as for the highest ranked cases.

Table 3.29: **Critical values of deficit and exceedance at Site 1, Yarsha Khola catchment [m^3/s]**

Parameter	m^3/s	$l/s*km^2$	Parameter	m^3/s	$l/s*km^2$
$Q_{5(def)}$	0.30	5.6	$Q_{25(exc)}$	3.53	66.1
$Q_{10(def)}$	0.36	6.7	$Q_{10(exc)}$	6.44	120.6
$Q_{25(def)}$	0.49	9.2	$Q_{5(exc)}$	8.55	160.2
$Q_{50(exc)}/Q_{50(def)}$				0.94	17.6

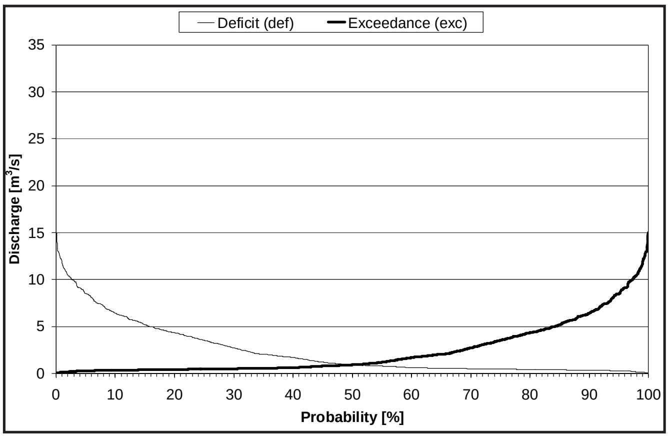
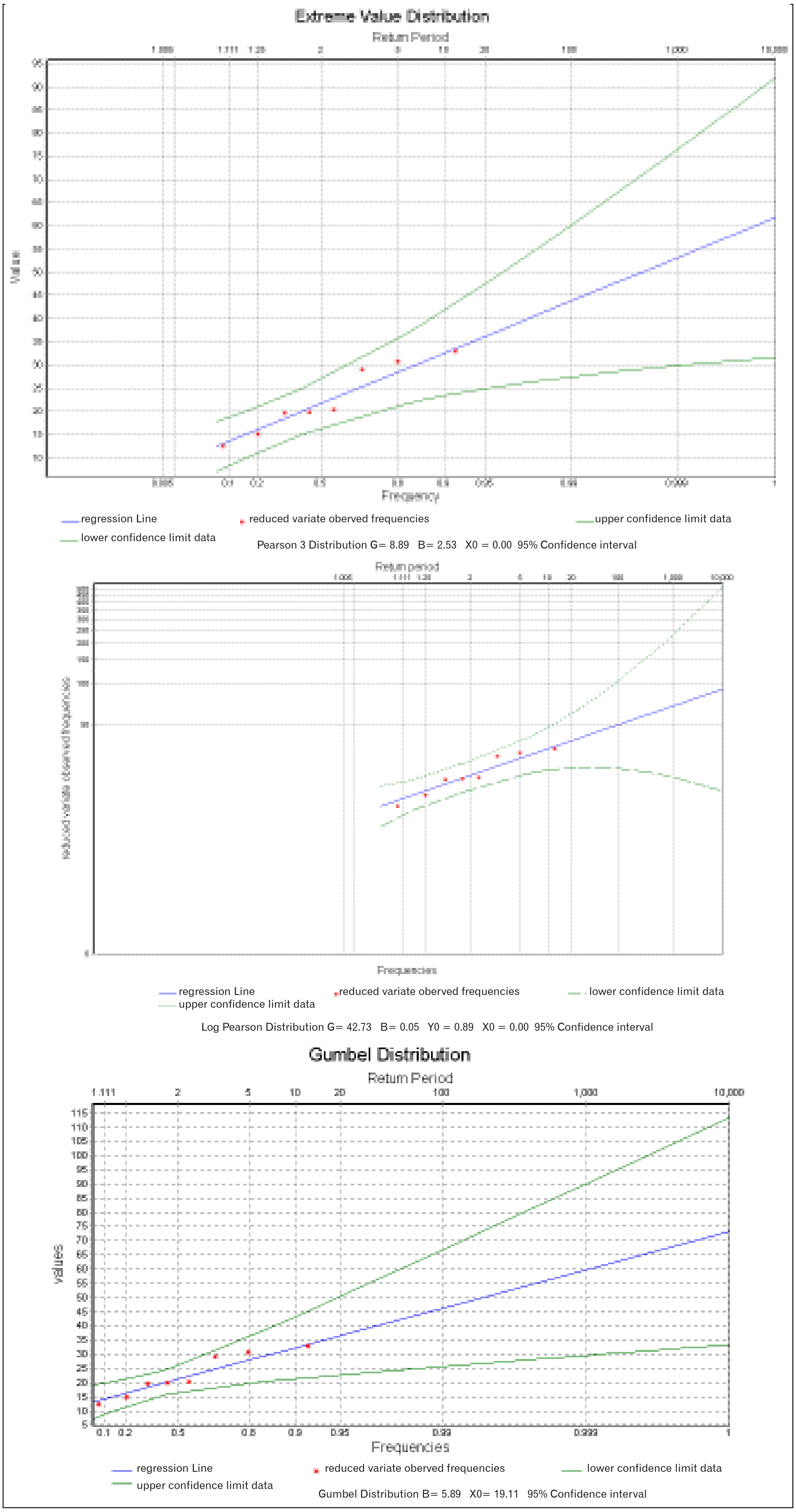


Figure 3.69: **Duration curve for Site 1 in the Yarsha Khola catchment**

The difference between the estimated design flows calculated on the basis of the three different distributions is small. The estimated value for the 25-year flood applying the Log-Pearson Type III distribution is 39.492 m^3/s. The flow for the same return period estimated with the GEV is 37.933 m^3/s, and with the Pearson Type III distribution 37.290 m^3/s. The 95% confidence interval is slightly bigger in the case of the Log-Pearson Type III



Pearson 3 Distribution G= 8.89 B= 2.53 X0 = 0.00 95% Confidence interval

Log Pearson Distribution G= 42.73 B= 0.05 Y0 = 0.89 X0 = 0.00 95% Confidence interval

Gumbel Distribution B= 5.89 X0= 19.11 95% Confidence interval

Figure 3.70: **Theoretical and empirical design flows for Site 1 in the Jhikhu Khola**

Table 3.30: **Comparison of theoretical design flows on the basis of different distributions, Site 1, Jhikhu Khola catchment (all flow values in m^3/s)**

	Pearson Type III			Log-Pearson Type III			GEV		
	Estimated value	95% confidence interval Lower	Upper	Estimated value	5% confidence interval Lower	Upper	Estimated value	5% confidence interval Lower	Upper
2	21.667	16.558	26.776	21.015	16.369	26.979	21.265	16.462	26.067
5	28.490	21.287	35.692	28.082	21.007	37.541	27.936	19.848	36.023
10	32.558	23.324	41.793	33.001	23.029	47.291	32.353	21.429	43.276
25	37.290	25.254	49.325	39.492	24.103	64.707	37.933	23.204	52.662
Average residuals									
All values	0.078			0.068			0.071		
Top 3 ranks	0.105			0.076			0.078		

distribution, with a range from 24.103 to 64.707 m^3/s. For the other two distributions the upper confidence limit is about 10 m^3/s less.

A comparison of the design flows calculated above with the estimation method as proposed by WECS (1990) showed that the WECS method in general overestimates the maximum daily flows for any return period. While the return periods for a 2-year flood above was estimated at about 20 m^3/s, the WECS method calculates about 75 m^3/s. For a 100-year flood the three distributions above estimate flows between 45 and 100 m^3/s, while the WECS method estimated for the same 223 m^3/s. In WECS (1990) it was shown that the method often overestimates the design flows for smaller catchments. It also must be noted that that report cautions and recommends the use of the method only for pre-feasibility studies.

3.3.3.6 Trend in flow characteristics

Precipitation showed an increasing trend in the study period from 1993 to 2000, which may just be part of a cycle, or may even indicate the start of an increase in annual precipitation. On the basis of the long-term data at Sites 9 and 12, no trend could be established for these sites (for a more detailed discussion see Section 3.1).

The flow data in the Jhikhu Khola show a number of different trends, whereas with the increase in precipitation an increase in flow would be expected as a result. This is observed in the case of mean annual discharge and mean specific discharge (Table 3.31), which both show an increasing trend on the basis of the Mann-Kendall test for trends. This test was chosen because the values proved to be abnormally distributed on the basis of a Kolgomorov-Smirnov test for normality. In the case of annual minimum flow, a decrease was observed over the study period. However, $Q_{5(def)}$ shows no trend and $Q_{25(def)}$ shows an increasing trend. In addition to this, the differences at the lowest flows between 1993 and 2000 are only in the order of one to two litres. The maximum annual flows do not show any trend over the study period.

Table 3.31: **Mann-Kendall test statistics for trend of flow parameters at Site 1 in the Jhikhu Khola catchment (period from 1993 to 2000)**

Station	N	Critical value*	Test value	Result
Site 1 MQ	8	0.707 (α=0.05)	1.113	H0 is not rejected (positive trend)
Site 1 Mq	8	0.707 (α=0.05)	1.113	H0 is not rejected (positive trend)
Site 1 HQ	8	0.707 (α=0.05)	0.371	H0 is rejected
Site 1 LQ	8	0.707 (α=0.05)	1.361	H0 is not rejected (negative trend)
Site 1 Q25	8	0.707 (α=0.05)	2.103	H0 is not rejected (positive trend)
Site 1 Q5	8	0.707 (α=0.05)	0.619	H0 is rejected

* according to Sachs (1997)
Test: H0 is accepted if the test value is bigger than the critical value
H0: there is a significant trend
HA: there is no significant trend

The same pattern can be shown for monthly discharge, where either increasing or no trends were observed over the study period. These results of the trend analyses are in stark contrast to the observations by PARDYP staff, who have carried out field work over the last 15 years in the Jhikhu Khola catchment. Bhuban Shrestha presents his observations on the flows in the Jhikhu Khola:

> *"... in the early nineties there was always water, about 2 feet deep near the Baluwapati and 2.5 to 3 feet near the main station, even during the dry season in April and May. I remember those hot and humid days in the dry season when I went to download data from the automated logger at the main station. I used to cross the Jhikhu Khola near Baluwapati and the main station got my trousers wet up to the knee. Now times have changed completely; over the last decade the water flow has changed drastically.*
>
> *Now during the dry season my trousers do not get wet at all when crossing the Jhikhu Khola near Baluwapati and the main station. There is hardly any water and one can see ants marching along the river bed...."* (from Merz et al. 2002)

This difference between the staff observations and the flow data in the Jhikhu Khola needs further investigation. It is, however, acknowledged that the low flow data are the most difficult data to obtain, as already discussed above. Mistakes in the dataset for these values cannot be excluded. For this purpose, the sites have to be improved mainly for low flow sensitivity (see also Merz 2002 or Appendix B.6). This includes the replacement of pressure transducers, which are not sensitive at low flows, with floaters.

3.3.4 Summary and Synthesis

The runoff regime shows a distinct wet season/dry season regime with the lowest flows occurring in the pre-monsoon season (March/April), and the highest flows in July/August. This roughly coincides with the start of the wet season and the peak of the wet season. The mean specific yields in the catchments are very low, indicating high human impact on the water resources. The specific discharge in the two catchments and their sub-catchments showed a good regression with elevation, indicating the overriding importance of precipitation. On an annual basis, the runoff ranges from 300 to 500 mm during the period from 1993 to 2000 in the Jhikhu Khola catchment and from 1200 to 1600 mm in the Yarsha Khola catchment for the period from 1998 to 2000.

It is important to note that the maximum daily discharge shows a significant regression with catchment area, which is testimony to its importance for the flood generation index. The flood with a return period of 25 years at the outlet of the Jhikhu Khola catchment was determined at about 40 m^3/s with a confidence interval ranging from about 20 to 60 m^3/s.

In terms of low flow, the storage within the catchment is important. In both catchments only soil and groundwater storage are observed. Long-term storage supplying continuous flow for the dry season delayed from the monsoon rainfall would provide water for about 300 days in the Jhikhu Khola and 320 days in the Yarsha Khola catchment before it ran completely empty. The recently developed shallow groundwater shows the highest reliability in river depressions, river tars, and foot slopes, while it is very variable on ridges. It was also shown that the Yarsha Khola catchment generally has more sustained baseflow and higher runoff values than the Jhikhu Khola catchment. This is both due to the higher rainfall observed in the Yarsha Khola catchment and the lower pressure placed on water resources by agriculture. This pressure, particularly in the last 10 years, has been observed by PARDYP staff who have worked in the Jhikhu Khola catchment since the late 1980s. However, this cannot be supported with the runoff data due to the low flow insensitivity of the hydrological stations.

Regarding indices, it is mainly the principal values of runoff as well as selected values from the duration curve that are are important. In terms of the water availability index, it is mainly the low flows and the low flow parameters that are decisive (see Table 5.1). For floods and high flows, it is the discharge at the upper end of the duration curve that needs attention.

3.4 RAINFALL-RUNOFF RELATIONSHIPS AND EVENT ANALYSES

This section presents detailed event analyses at the level of precipitation, erosion plot, and hydrological data and their combinations. It mainly focuses on the parameters important for runoff generation and sediment mobilisation. In each section the respective events are statistically and qualitatively described. This is followed by a discussion of the interrelationship between the parameters as well as a discussion of the causes for these conditions. This section ends on a synthesis of the event parameters in relation to catchment characteristics and a discussion of the largest events in each catchment.

On the basis of the annual areal data for the Jhikhu Khola catchment, about 32% of the precipitation became runoff, ranging from 25 to 40% between 1993 and 2000. In the Yarsha Khola catchment about 62% of precipitation became runoff in the period from 1998 to 2000 ranging from 53 to 74%. In comparison with other catchments in Nepal, the runoff percentage is very low in the Jhikhu Khola (Figure 3.71). The Yarsha Khola catchment is more in line with other catchments in terms of rainfall and runoff pattern. It is important to mention that the rivers marked with 'A' are rivers with high contributions from glacial melt as well as with a significant portion of their area on the Tibetan plateau. This includes rivers such as the Arun, the Bhotekosi, the Kali Gandaki, and the Karnali. For comparison with the Jhikhu Khola and the Yarsha Khola, the Rosi Khola (B) and the Sun Koshi (C) are particularly interesting. These two rivers show rainfall-runoff ratios similar to those of the Jhikhu Khola and Yarsha Khola catchments. The reason for the very low percentage of runoff in the Jhikhu Khola catchment is also believed to be because of the high degree of agricultural water used for irrigation in the catchment (see Section 3.7 for more detail).

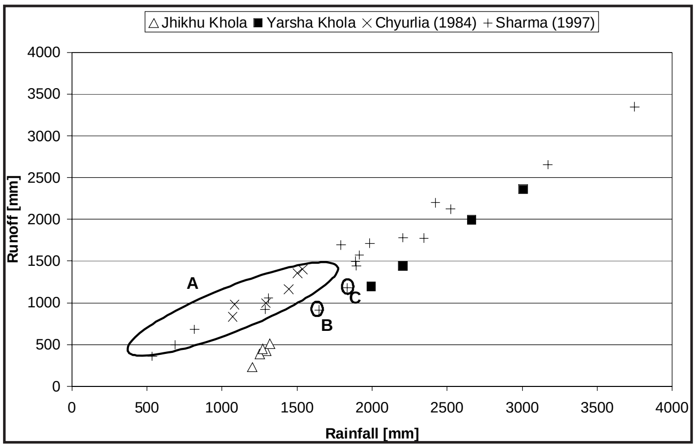


Figure 3.71: **Average annual rainfall versus average annual runoff from different sub-catchments in the Jhikhu Khola and Yarsha Khola catchments in comparison with other catchments**

In the following the rainfall-runoff relationships are discussed in detail on the basis of single events at the meteorological sites, at the hydrological sites, and at the erosion plot sites.

3.4.1 Event analyses

Event analyses have been conducted in many studies, particularly with the aim of investigating runoff generation processes (for example, Mosley 1979; Naef et al. 1986; Merz 1997; Wuethrich 1999; Laemmli 2000; Voegeli 2002). In general, these studies comprise

- rainfall event separation;
- hydrograph separation;
- identification of typical events of different magnitudes; and
- statistical observations.

In the case of this study, the event analyses were carried out to answer the questions on when and under what conditions runoff occurs, as well as under what conditions floods are generated. The event analyses here were carried out separately at different levels in the Jhikhu Khola and Yarsha Khola catchments, and each for different purposes (see below and Table 3.32):

precipitation event analyses —> investigation of runoff triggering mechanisms
erosion plot event analyses —> investigation of surface runoff generation
discharge event analyses —> investigation of runoff concentration
different combined event analyses —> investigation of runoff routing

Table 3.32: **Structure of the chapter on event analyses**

	Precipitation	Erosion plot	Discharge
Precipitation	JK 3.4.3/ YK 3.4.6		
Erosion plot	JK 3.4.4/	YK 3.4.7	
Discharge		JK 3.4.5/ YK 3.4.8	
Synthesis		3.4.9-3.4.10	

The results are finally summarised for each catchment before they are compared across the catchments in relation to catchment characteristics and with respect to the largest events in the catchments during the study period.

As mentioned in Section 2.4, the measurement network was set up according to the nested approach. This resulted in the station hierarchy as shown in Figure 3.72. From this figure, it is evident that plot-sub-catchment-catchment analyses cannot be conducted for all the sites. For this purpose only two options were given in the case of the Jhikhu Khola catchment, one including Sites 6 and 7 and the other including Sites 14 and 13. In the Yarsha Khola catchment this included likewise two complete ’nests‘, one with Sites 5 and 7, the other with Sites 6 and 7.

For precipitation analyses, all sites with adequate data were used in both catchments. In the case of erosion plots in the Jhikhu Khola catchment, the sites (which are part of a nest as shown above and in Figure 3.72) were included as well as an additional plot on degraded land and one on rainfed agricultural land. In the Yarsha Khola catchment all plots were included in the analyses, that is, the ’nested’ plots 5a and 6a as well as the two plots at Site 9.

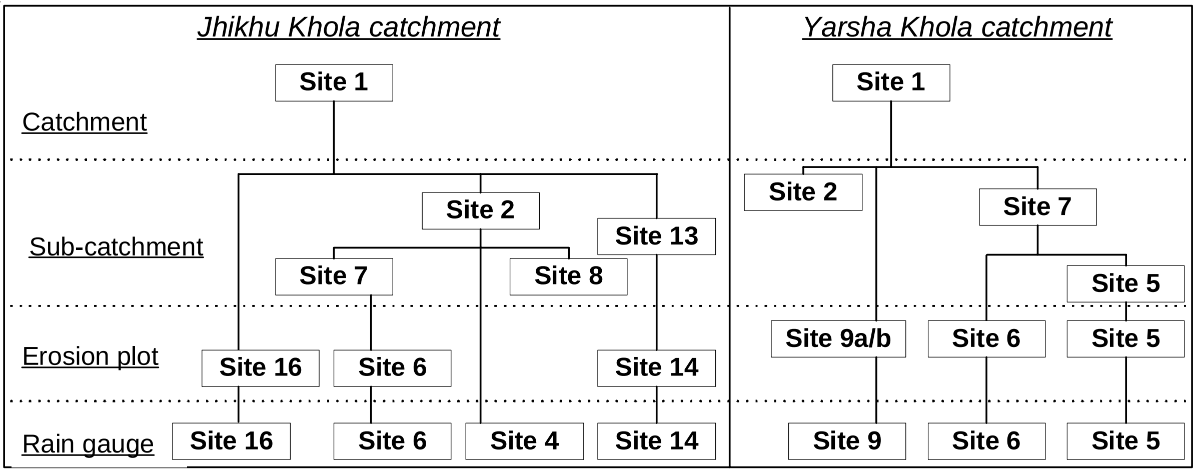


Figure 3.72: **Site hierarchy for event analyses (for a map of the measurement networks see Figures 2.16 (Jhikhu Khola) and 2.17 (Yarsha Khola)**

3.4.2 Event definition and parameters

Carver (1997) defined a storm event on the basis of the storm separation time $S_{min,}$ (that is, the time between two distinct rainfall events without any rain) and a minimum precipitation amount P_{min}. For the Jhikhu Khola catchment and the years 1993 to 1995, he proposed to define an event with $P_{min} = 3$ mm and $S_{min} = 120$ min. P_{min} was given as 3 mm because storms below 3 mm are unimportant for sediment generation. The figure of 120 min is derived from the investigation of the numbers of events with different S_{min}. A major change in N could be observed between $S_{min} = 60$ min and $S_{min} = 120$ min.

In terms of S_{min} the same could be shown for the data from 1993 to 2000, and therefore this value was adapted. In terms of P_{min} it was shown that the value of 3 mm is not appropriate for studying runoff generation. While on degraded plots events with as little as 2 mm rain can produce runoff and sediment, on cultivated plots runoff generation only starts at more than 5 mm rainfall.

For this study the following values were selected for rainfall event separation:

P_{min} = 2 mm
S_{min} = 120 min

A rainfall event can be characterised with a variety of parameters. A selection of parameters as proposed by Mosley (1979), Merz (1997), and Wuethrich (1999) and used in the following sections is given below and in Figure 3.73.

• P_{tot}	[mm]	rainfall amount during the event
• t_P	[s]	rainfall event duration
• I_{10max}	[mm/h]	maximum 10-min rainfall intensity during the event
• I_{30max}	[mm/h]	maximum 30-min rainfall intensity during the event
• I_{60max}	[mm/h]	maximum 60-min rainfall intensity during the event
• I_{ave}	[mm/h]	average rainfall intensity during the event
• P_{25}	[%]	rainfall amount after 25% of the event duration in% of total rainfall
• P_{50}	[%]	rainfall amount after 50% of the event duration in% of total rainfall
• P_{75}	%]	rainfall amount after 75% of the event duration in% of total rainfall

The above parameters show the following: (Wuethrich 1999)

• the shape of the hyetograph	(P_{25}, P_{50}, P_{75});
• the intensity of the event	(I_{ave}, I_{10max}, I_{30max}, I_{60max});
• the duration and magnitude of the event	(P_{tot}, t_P).

An event on the erosion plot is considered when the reader has taken a sample from at least the first drum. This means that runoff was generated on the plot with or without mobilising sediment. Usually a minimum of 5 cm depth of water has to be observed in the collection drum to facilitate proper sampling. Events that produced lower runoff were discarded.

Hydrologically, an event is defined as a flow peak on the hydrograph differing from the baseflow due to rainfall, snow, and glacial melt; or the surge of a GLOF, the break of a landslide dammed lake, or a human intervention. The peaks from GLOFs or breached dams show very rapid rising limbs (for example ICIMOD 2000; Mool et al. 2001a and b). The rising limb of peaks caused by rainfall depends

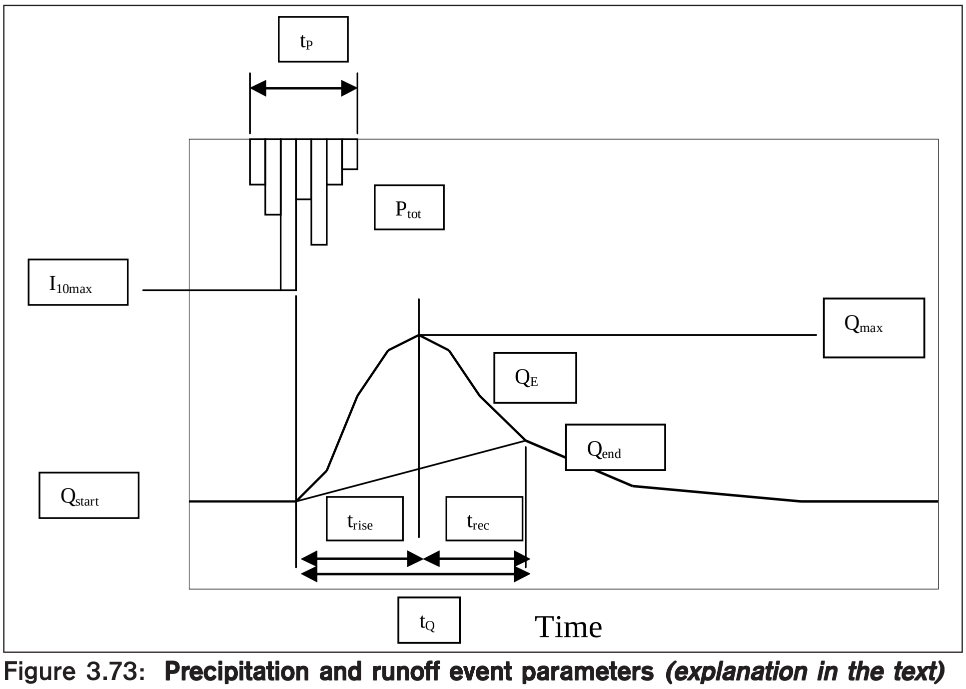


Figure 3.73: **Precipitation and runoff event parameters *(explanation in the text)***

on the rainfall characteristics. Snow and glacial melt only cause very slow rises in the hydrograph. In the following, only hydrological events caused by rainfall are discussed as there is no snow or glacier in the PARDYP catchments. Large landslide dams have not been observed in the last ten years.

Similar to the rainfall event analyses, discharge events can also be analysed. Before starting with event analysis, the event flow has to be separated from the base flow. Base flow separation in this study was carried out using the straight-line method (Chow et al. 1988). A discharge event can be characterised with the parameters proposed by Mosley (1979), Merz (1997), and Wuethrich (1999), and these are as follows.

• Q_E	[mm]	event runoff, i.e., runoff between baseflow separation line and hydrograph
• Q_{Emax}	[mm]	peak event runoff
• Q_B	[mm]	base runoff, i.e. runoff between zero and baseflow separation line
• Q_{tot}	[mm]	total runoff, i.e. runoff between zero and hydrograph
• Q_{max}	[m³/s]	event peak flow
• Q_{start}	[m³/s]	flow at the beginning of the event
• Q_{end}	[m³/s]	flow at the end of the event
• Q_E / Q_{tot}		event based runoff vs. total runoff
• t_Q	[s]	event duration
• t_{rise}	[s]	duration of rising limb, i.e. time between start of hydrograph rise and peak
• t_{rec}	[s]	duration of recession limb, i.e. time between peak and start of baseflow
• α		runoff coefficient, i.e. event runoff/event rainfall

For the estimation of moisture conditions before the onset of the event antecedent, precipitation indices were calculated. AP_x as proposed in Wuethrich (1999) are the short-term indices indicating the expected moisture conditions of the few days prior to the event. The indices API_x (Merz 1997) give an indication of the long-term moisture conditions:

• AP_1	[mm]	rainfall 1 day before the event
• AP_2	[mm]	rainfall 2 days before the event
• AP_3	[mm]	rainfall 3 days before the event
• AP_4	[mm]	rainfall 4 days before the event
• AP_5	[mm]	rainfall 5 days before the event
• API_1	[mm/d]	sum of rainfall 1 day before the event divided by 1
• API_7	[mm/d]	sum of rainfall 7 days before the event divided by 7
• API_{10}	[mm/d]	sum of rainfall 10 days before the event divided by 10
• API_{14}	[mm/d]	sum of rainfall 14 days before the event divided by 14
• API_{30}	[mm/d]	sum of rainfall 30 days before the event divided by 30

(AP_1 and API_1 show the same information and give the same result).

The above discharge event parameters can be grouped as follows (adapted from Wuethrich 1999):

• Duration and amount	(t_Q, t_{rise}, t_{rec}, Q_{tot}, Q_E, α);
• Intensity	(Q_{max}, Q_{Emax});
• Pre-event moisture conditions	(AP_x, API_x, Q_{start}, Q_B).

3.4.3 Precipitation event analyses in the Jhikhu Khola catchment

3.4.3.1 Description of the precipitation events

In the Jhikhu Khola catchment, seven sites were instrumented with an automatic rain gauge for more than three years any time between 1993 and 2000. The number of events therefore varies considerably according to the number of observation years and missing data. Table 3.33 presents the summary of all sites and events. Most events were observed at Site 6, where data are available from 1993. This is followed by Site 15, where data are likewise available from 1992. Site 16, which has data available from 1992 was excluded from the following analyses as there were too many gaps in the automatic rain gauge data (519 days), for the rainy season in particular.

Table 3.33: **Events at selected sites (in brackets: no of missing days)**

Site	Period	Pre-monsoon	Monsoon	Post-monsoon	Winter	Total
3	1993-1996	38 (0)	270 (0)	20 (5)	14 (0)	342 (5)
4	1997-2000	80 (2)	270 (63)	11 (33)	12 (1)	373 (99)
6	1993-2000	150 (10)	511 (141)	35 (21)	34 (22)	730 (194)
12	1998-2000	55 (26)	181 (40)	9 (0)	4 (0)	249 (66)
14	1997-2000	75 (45)	247 (23)	10 (0)	7 (1)	339 (69)
15	1993-2000	130 (4)	453 (94)	27 (5)	27 (9)	637 (112)
16	1993-2000	113 (115)	299 (367)	25 (36)	26 (1)	463 (519)

Annually, there are on average approximately 86 events with 73% of the events occurring during the monsoon followed by 20% of the total events in the pre-monsoon season. It is therefore not surprising that during the observation period most of the events were observed during the monsoon season followed by the next largest number of events in the pre-monsoon season. About 10 to 30 events at each site were also observed during the post-monsoon season. The events during the winter season in the study period numbered about 5 to 30. The minimum number of events — 249 — was observed at Site 12 during a two-year study period from 1998 to 2000. The maximum number of events on an annual basis of 114 events was measured at Sites 4 and 6 in 1998. According to rainfall amount the most frequently occurring events are the 2 to 5 mm events, which account for more than 30 and up to 45% of all events (Figure 3.74). Due to this strongly left-skewed distribution of events, the analyses below are all based on the median values of the distribution as proposed by Helsel and Hirsch (1992), as the mean does not seem to be appropriate for this purpose due to the strong maximum outliers. The same skew is true for other parameters, that is, events of low rainfall intensity are much more frequent than a few events with exceptionally high rainfall intensities.

Note: The event data in the following analyses is for different years and different period length, influencing the number of events per site. As shown above in Section 3.1, the rainfall during the study years is not exceptional. It can therefore be assumed that all the events show situations representative for the area and that the median and the other statistical values show representative conditions.

The events above 25 mm, probably the most important events in terms of sediment mobilisation and runoff generation, numbered between 30 and 70 depending on the site; or between 9 and 15% of all the events. As mentioned above, each event can be described with a number of parameters. Table 3.34 just shows the median values for all sites and all rainfall event parameters calculated in this study. To show the range of the most important parameters, refer to Figure 3.75, which shows the quartiles for rainfall amount P_{tot} and maximum 10 min rainfall intensity I_{10max}.

The median of the rainfall amount ranged, depending on the site, from 5 to 8 mm with durations of 1 to 3 hours. The 75% quartile for rainfall amount reached a maximum of approximately 15 mm with a 25% quartile of about 4 mm. Fifty per cent of the events in the Jhikhu Khola catchment are therefore within the range of about 4 to 15 mm and are classed as minor events. I_{10max} ranged in general from a 25% quartile of about 1 mm/10 min (= 6 mm/h) to about 4 mm/10 min (= 24 mm/h). The observed median was at all sites around 2 mm/10 min (= 12 mm/h). In terms of hyetograph shape parameters there seems to be a difference between the sites on the north-facing slopes (Sites 3, 4, and 6) and the sites on the south-facing slope or the valley bottom (Sites 12, 14, and 15). The P_{25} values showed that in more than 50% of the events more than a quarter of the event rainfall amount — in certain cases nearly half the rainfall amount (for example, Sites 4 and 6) — occurs in the first quarter of the event duration (which may have an impact on the intensity during this time). On the south-facing slopes about 30 to 35% of the rainfall amount occurs in the first quarter. Another 30 to 35% of the rainfall occurs in the second quarter at these sites, with 20 to 25% of the rainfall in the third quarter

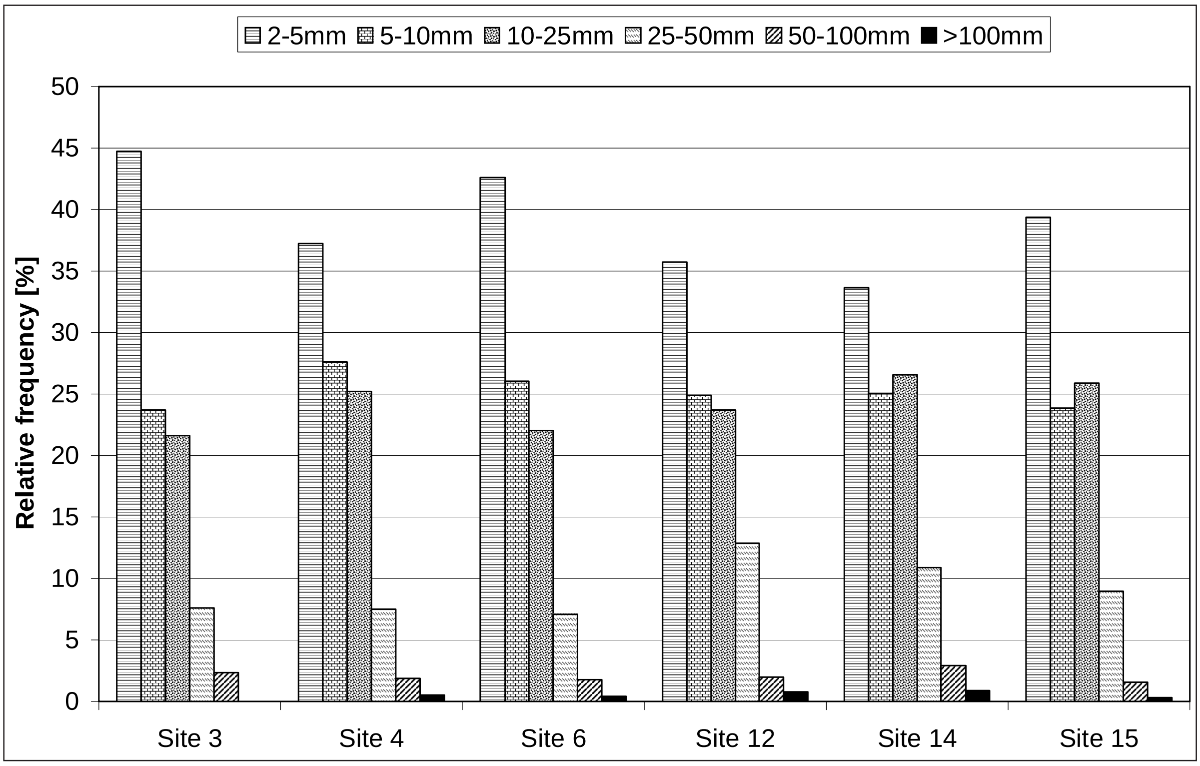


Figure 3.74: **Relative frequency of events of different rainfall amounts**

Table 3.34: **Median of different event parameters considering all events**

Site (N)	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10min]	I_{30max} [mm/30min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
3 (342)	5.2	90	4.2	2.1	3.1	4.2	40.0	50.0	74.2
4 (372)	6.3	91	4.5	2.1	3.1	4.2	42.9	53.3	75.0
6 (729)	6.3	80	5.1	2.1	3.2	4.2	45.5	50.0	72.7
12 (249)	7.4	172	2.9	2.0	3.4	4.8	33.9	65.9	88.2
14 (337)	8.0	182	3.1	2.2	3.7	5.0	34.5	67.1	89.5
15 (637)	6.9	186	2.5	1.8	3.4	4.3	35.0	66.4	88.9

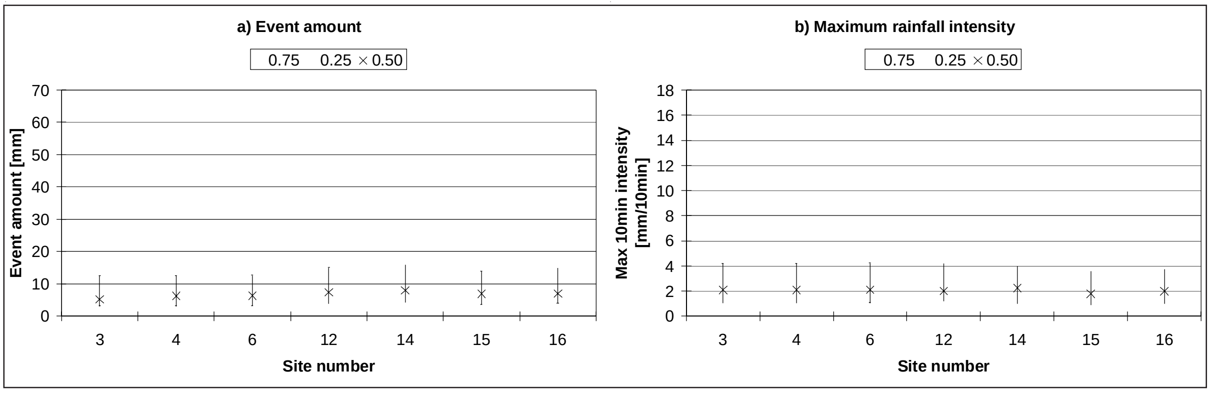


Figure 3.75: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution for all events at all sites**

and about 12% of the rainfall in the last quarter of the event. At the north-facing sites the second quarter is rainfall poor and the two last quarters receive proportional amounts of rainfall with respect to time.

The typical event in the Jhikhu Khola catchment therefore has the following properties:

- about **5 mm to 8 mm** rainfall amount;
- from about **1 to 3 hours** duration;
- from about **2 mm/h to 5 mm/h** average intensity with 10-minute maximum intensities of **2 mm/10 min**, 30-minute intensities of **3.5 mm/30 min** and 60-minute intensities of **4.5 mm/60 min**;
- about **35%- 40%** of rain falls in the first quarter of the event, **50% - 70%** in the first half, and 70**%- 90%** in the first three quarters of the event.

Large events are more important for runoff generation and sediment mobilisation as they are responsible for most of the soil loss (Nakarmi et al. 2000; Voegeli 2002) as well as for the largest flood events (Merz et al. 2000a). Carver (1997) showed that serious sediment output from the catchments occurred at a threshold of 30 mm P_{tot} and I_{10max} of 50 mm/h. He therefore defined major events as events with rainfall amounts higher than 30 mm and maximum 10-minute intensities of more than, or equal to, 50 mm/h. He excluded events with large rainfall amounts but minor to medium rainfall intensity from the class of major events. This is, as he has shown, certainly correct for sediment considerations. However, for flooding the definition of major events is believed to be different. While short and intense storms can lead to sharp peaks, long and persistent rainfall of low intensity can produce large flood volumes with minor peaks (for example Wuethrich 1999 or following sections). Therefore rainfall intensity was left out of event classification at this preliminary stage of event description and will be further discussed later in the section. A large event in the following is therefore understood as an event of $P_{tot} > 30$ mm. Medium events are of 10 to 30 mm rainfall amount and minor events are designated as $P_{tot} < 10$ mm. The limits are adopted from Carver (1997).

The statistics of the large events for all sites are shown in Table 3.35 and Figure 3.76. It should be noted that the range has decreased considerably between the different sites in comparison to the statistics shown for all events. However, there is still high variation for all parameters at the different sites.

Table 3.35: **Median for selected rainfall parameters of large events**

Site (N)	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10min]	I_{30max} [mm/30min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
3 (19)	40.7	464	5.1	5.2	9.4	14.6	39.0	58.8	84.6
4 (22)	41.7	387	6.7	7.3	13.6	20.9	35.3	59.4	90.1
6 (51)	39.0	356	6.5	6.3	13.7	20.0	34.5	67.5	85.7
12 27)	39.8	523	4.7	5.4	11.8	16.2	22.8	57.0	88.3
14 (31)	43.6	474	5.5	6.0	11.0	16.7	23.4	66.4	89.8
15 (46)	41.0	477	5.5	7.3	13.4	19.9	23.8	63.7	89.6

The median of these large events ranged from 40 to 45 mm in the case of P_{tot}. The 25% quartile of about 32 to 35 mm and the 75% quartile of about 50 to 60 mm show that 50% of the large rainfall events are between 30 and 60 mm. In terms of I_{10max} half the large events are between 3 and 12 mm/ 10 min (= 18 to 72 mm/h). The same difference of shape parameters between the north- and the south-facing sites is shown for large events, where the first quarter of the event from the north-facing sites accounts for more than a third of the total amount, whereas on the south-facing slope less than a quarter of the rainfall occurs during this quarter. The remaining quarters are similar.

A typical large event in the Jhikhu Khola catchment therefore has the following qualities:

- rainfall is about **40 mm** in quantity;
- is from about **6 to 8 hours** in duration;
- is, on average, about **4 to 7 mm/h** in intensity, with 10- minute maximum intensities of about **5-7 mm/10 min**;

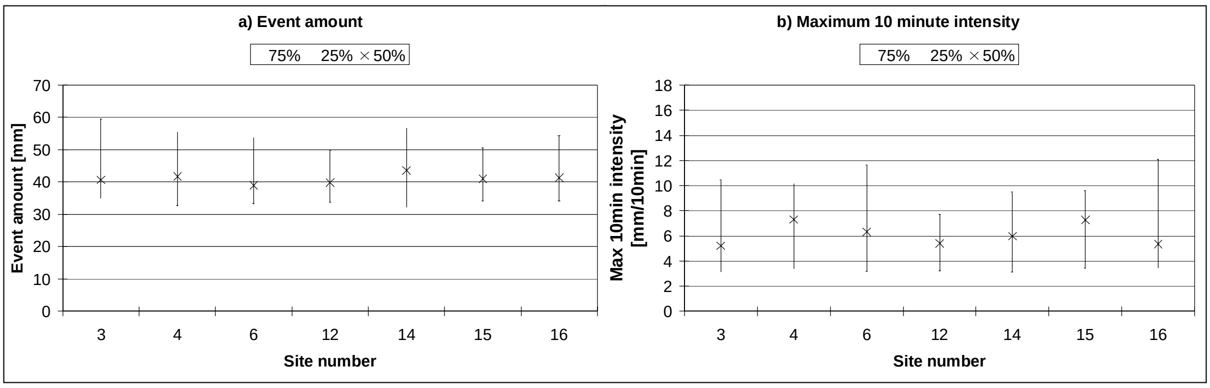


Figure 3.76: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution of large events at all sites**

- has 30 minute intensities of about **10-15 mm/30 min;** and 60 minute intensities of about **15-20 mm/60 min**; and
- has about **20-40%** of rain falling in the first quarter of the event, **55-60%** in the first half, and **85-90%** in the first three quarters of the event.

As shown above in Table 3.33 most rainfall events occur during the pre-monsoon and monsoon seasons. This is also the case for the medium- and large-sized rainfall events, in particular the large events that mostly occur during the monsoon season (see Figure 3.77). However, the largest events of the year often occurred in the post-monsoon season during the study period. In general, these values roughly match with Carver's (1997) classification, according to which 76.8% of the events were minor, 19.7% were intermediate, and 3.5% were major. Classified only on the basis of rainfall amount, 63.5% were minor events, 28.6% were medium events, and 7.8% were large events. The difference hails from the inclusion of rainfall intensity in Carver's classification, which underestimates the number of large and medium events for flood generation.

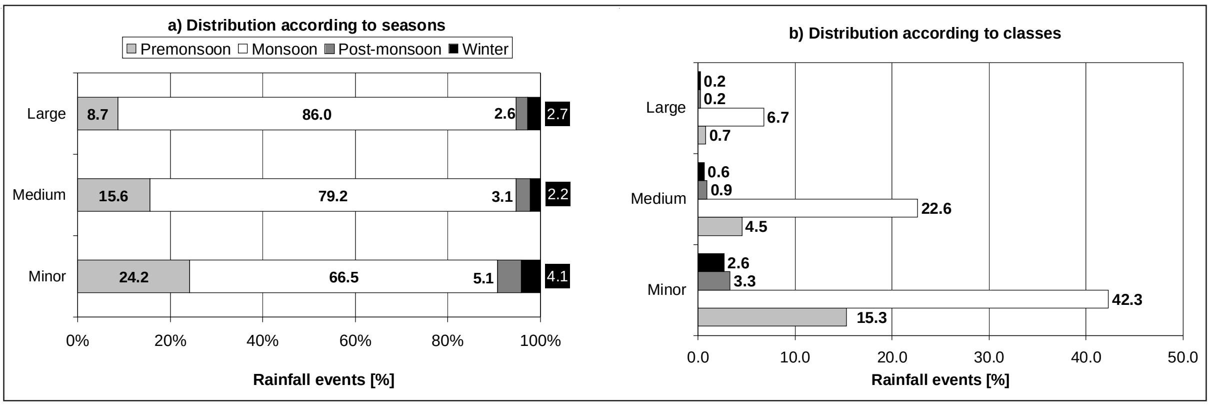


Figure 3.77: **Rainfall events classified according to rainfall amount (thresholds from Carver 1997)**

Large pre-monsoon and monsoon events differ on the basis of the calculated statistics (Table 3.36). While the rainfall amount tends to be lower during a large pre-monsoon event, the intensities — both maximum and average — tend to be higher (see also Figure 3.78). Pre-monsoon storms tend to be shorter than the storms in the monsoon season. Interestingly, at most sites the event rainfall is concentrated to one quarter of the event duration during pre-monsoon events. At Sites 3, 4, and 6 it is during the first quarter of the event duration. At Sites 12 and 15 it is during the third quarter of the event. During monsoon season events the rain is more evenly spread throughout the event duration. The number of pre-monsoon events is limited, in general only one to five events were observed in the study period.

The typical large event in the pre-monsoon in the Jhikhu Khola catchment therefore has these qualities:

Table 3.36: **Rainfall event parameters (median) for large pre-monsoon and monsoon events**

Site* (N)	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10 min]	I_{30max} [mm/30 min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
3PM (1)	30.2	56	32.4	15.6	22.9	30.2	51.7	72.4	93.1
M (17)	40.7	464	5.1	5.2	9.4	14.6	33.3	58.8	81.8
4PM (2)	41.7	259	10.2	8.9	17.2	23.5	52.7	61.6	75.5
M (18)	39.6	387	6.7	7.8	14.1	20.9	35.3	62.7	90.2
6PM (2)	37.9	317	7.3	9.0	16.3	19.0	51.2	78.1	93.2
M (46)	39.5	347	6.5	7.4	14.8	20.6	34.3	66.3	85.1
12PM (3)	39.8	315	9.0	8.0	20.4	28.2	25.7	43.5	92.5
M (23)	37.0	523	4.2	5.4	11.8	16.2	19.5	58.5	88.3
14PM (5)	37.8	318	10.7	10.0	17.7	22.4	34.5	67.1	98.4
M (28)	43.6	493	4.5	5.4	9.2	13.9	23.0	69.0	90.1
15PM (2)	36.4	203	10.7	10.3	18.8	27.3	12.7	36.4	81.6
M (42)	42.2	477	5.5	7.3	13.6	20.7	29.2	72.0	91.0

* In the pre-monsoon only one to five events were observed and therefore no further statistics were calculated.

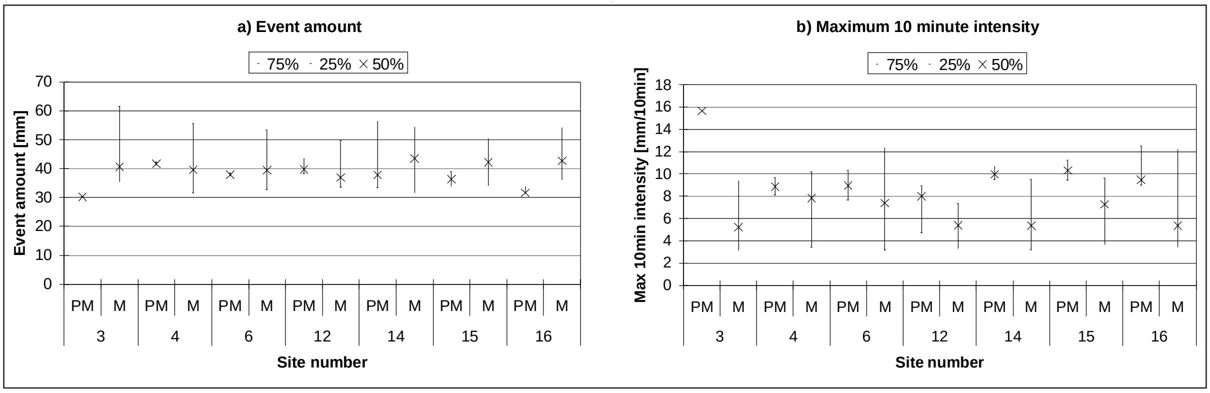


Figure 3.78: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution for large pre-monsoon and monsoon events at all sites**

- rainfall is about **35 mm** in quantity;
- rainfall is of about **4 hours** duration;
- average intensity is from about **13 mm/h**, with 10 minute maximum intensities of about **10 mm/10 min**; 30 minute intensities of about **19 mm/30 min;** and 60 minute intensities of about **26 mm/60 min**;
- about **10 - 50%** of rain falls in the first quarter of the event: **50% - 80%** in the first half, and **75 - 90%** in the first three quarters of the event.

The typical large event in the monsoon in the Jhikhu Khola catchment has these qualities:

- rainfall is about **40 mm** rainfall in quantity;
- rainfall is of about **8 hours** duration;
- average intensity is from about **6 mm/h,** with 10 minute maximum intensities of about **6 mm/10min**; 30 minute intensities of about **12 mm/30 min;** and 60 minute intensities of about **18 mm/60 min;**
- about **10 – 35%** of rain falls in the first quarter of the event, **60 - 70%** in the first half, and **80 - 90%** in the first three quarters of the event.

The ten largest events at all stations show a median rainfall amount of about 60 mm ranging from a 25% quartile of about 55 mm up to maximum 75% quartiles of 100 mm (Figure 3.79 and Table 3.37). The maximum intensities (median) are very low and show only values of 4 to 7 mm/10 min (=24 mm/h to 42 mm/h). The 75% quartile can reach more than 10 mm/10 min (66 mm/h) in the case of Sites 4 and 14.

Table 3.37: **Rainfall event parameters (median) for the ten largest events**

Site		P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10 min]	I_{30max} [mm/30 min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
3	Median	59.5	705	4.5	3.7	8.9	13.0	20.4	55.6	82.5
	75% quartile	62.3	957	6.5	7.6	18.8	27.9	54.2	66.9	86.5
4	Median	60.0	493	8.4	6.3	13.6	21.9	36.0	59.4	89.1
	75% quartile	70.4	772	11.8	11.2	24.8	35.7	43.8	74.7	90.9
6	Median	66.4	1032	5.6	4.2	8.4	13.2	27.3	53.0	81.9
	75% quartile	98.8	1466	6.2	5.3	11.9	20.8	39.2	58.3	85.0
12	Median	51.4	494	5.8	7.0	14.0	18.0	22.4	50.6	88.5
	75% quartile	63.1	830	7.4	7.9	16.7	20.8	36.3	68.5	94.0
14	Median	60.5	451	8.1	7.7	16.8	23.5	21.2	56.8	88.2
	75% quartile	94.1	1390	9.5	10.4	24.3	36.9	33.5	69.3	93.8
15	Median	62.2	622	5.7	6.7	16.6	22.3	22.1	59.0	89.1
	75% quartile	93.2	1538	8.5	9.4	21.7	33.4	53.3	75.5	91.6

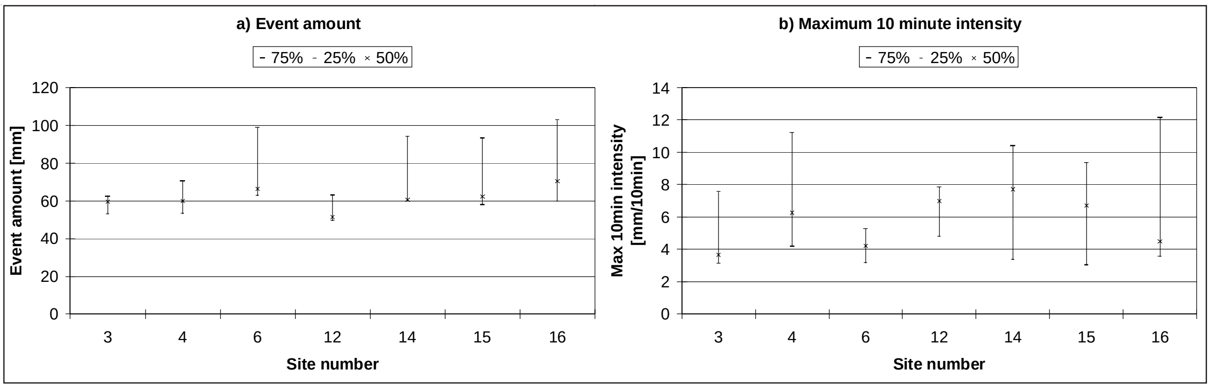


Figure 3.79: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution for the 10 largest events at all sites**

3.4.3.2 Relationships between the different precipitation parameters

In order to review the full content of information of a rainfall event, many event parameters were calculated. This is accepting that many parameters are closely related and show similar characteristics of the events. For further analyses the parameters with the highest information content had to be established. This was done by means of correlation and factor analyses. As the event parameters are not normally distributed (see Kolmogorov-Smirnov test results for normality in Appendix A3.13), the non-parametric correlation analysis according to Spearman was used to show the correlations between the different rainfall parameters. Table 3.38 shows the summary of the correlation analyses from Sites 3, 4, 6, 14, and 15. This table shows the correlation coefficients of Site 6 and number of significant correlations at all sites in brackets. The maximum that can be reached is five, corresponding to five sites. The detailed correlation tables are appended in Appendix A3.14.

Table 3.38: **Correlations at Site 6 with number of sites with significant correlations at all sites in brackets (maximum = 5; detailed correlation matrices in Appendix A3.14)**

	P_{tot}	t_P	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}
P_{tot}	1.00(5)	0.67(5)	0.10(5)	0.67(5)	0.82(5)	0.90(5)	-0.29(5)	0.22(4)	0.72(5)
t_P		1.00(5)	-0.64(5)	(2)	0.20(3)	0.34(5)	-0.32(5)	(1)	0.35(5)
I_{ave}			1.00(5)	0.62(5)	0.54(5)	0.43(5)	0.14(3)	0.21(5)	0.21(5)
I_{10max}				1.00(5)	0.91(5)	0.84(5)	(2)	0.35(5)	0.59(5)
I_{30max}					1.00(5)	0.96(5)	(1)	0.35(5)	0.68(5)
I_{60max}						1.00(5)	-0.16(3)	0.31(5)	0.72(5)
P_{25}							1.00(5)	0.58(5)	(2)
P_{50}								1.00(5)	0.60(5)
P_{75}									1.00(5)

A rather strong correlation of P_{tot} with most parameters is evident at all sites except I_{ave} and the shape parameters. The different maximum intensity parameters I_{10max}, $I_{30max,}$ and I_{60max} in particular show a strong linear relation with P_{tot} at all sites. The correlation of the shape parameters P_{25}, $P_{50,}$ and P_{75} is only limited, which shows that the rainfall amount is not influenced by these parameters or vice versa. In fact, certain events show very strong rainfall in the early stages, others at late stages or throughout the event that shows a large rainfall amount. In the section above, where the events were described, the hypothesis was formulated that in case over proportional amounts of rainfall occur in any particular quarter of the event duration, the intensity would be higher. This cannot be shown on the basis of the correlation between the shape parameters and the intensity parameters. The event duration t_p is only strongly related to the event amount P_{tot} in a linear way. The remaining correlations are weak. As expected, the interrelation between the intensity parameters are strong.

The strong correlation between the intensity parameters and P_{tot} suggest that the rainfall intensity parameters, which are very important for the streamflow generation and sediment mobilisation assessment (see also sections below and Section 3.5), could be estimated rather well from the daily rainfall data if the intensity data are not available. This assumption was tested on the basis of the data from Sites 4 and 14 (Figure 3.80). The best fit is observed for daily rainfall with I_{60max} showing a regression coefficient of 0.85 and 0.91 at Sites 4 and 14, respectively. It is also the regression with I_{60max} that is comparable in both catchments. For the regression between daily rainfall and I_{30max} the regression coefficient is 0.88 and 0.76 at Sites 14 and 4 respectively, indicating a slightly lower fit than I_{60max}. For I_{10max} the regression coefficients were 0.55 at Site 4 and 0.77 at Site 14.

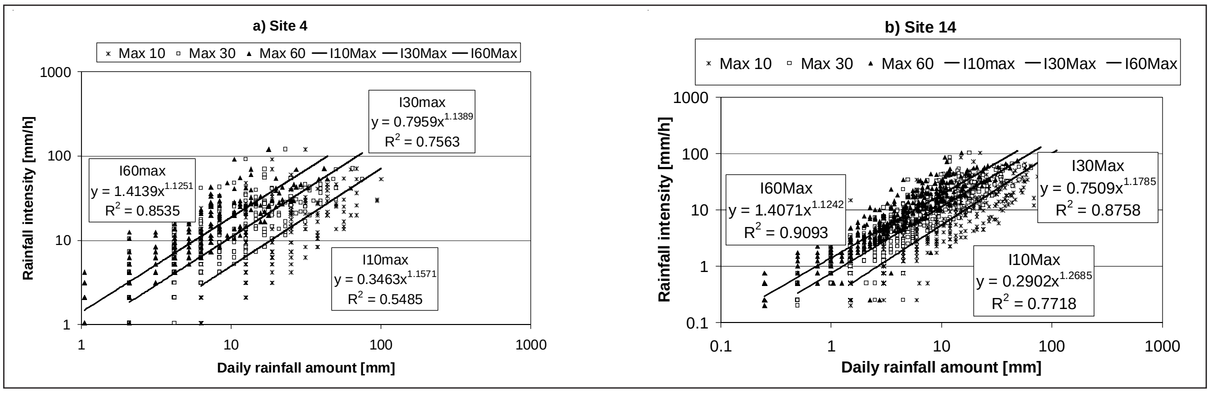


Figure 3.80: **Daily rainfall in relation to I_{10max}, I_{30max} and I_{60max} for Sites 4 and 14, Jhikhu Khola catchment**

This fact cannot be used to estimate I_{xmax} data from daily rainfall measurements where no intensity measurements are available. However, for missing days due to instrument failure, for the intensity estimation and for back logging of intensity at a rain gauge site upgraded with a recording gauge, it could be used.

Different parameters show very similar aspects of the hyetographs, for example, the four intensity parameters I_{ave} and I_{xmax}. In order to identify the key variables of precipitation on the basis of the different rainfall parameters, multivariate statistics were applied. Wuethrich (1999) suggested the use of factor analyses as discussed in StatSoft (1999). For this purpose, the parameters were firstly standardised and transformed to z-scores with mean 0 and standard deviation 1. The reason for this transformation are the different scales of the various parameters going into the analyses, e.g., P_{25} in % (0.00 to 1.00), t_p in minutes (>1).

The factor extraction was carried out on the basis of the principal components approach, as discussed in StatSoft (1999). The extracted factors, i.e., the factors with eigen values of at least 1 (and herewith explain at least their own variance) are rotated using the varimax method (StatSoft 1999). The results of these analyses suggest the following grouping with the following key parameters (🔑) (see also Table 3.39):

Table 3.39: **Key variables (🔑) for precipitation, Jhikhu Khola catchment**

Site	P_{tot}	t_P	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}
3	2	(🔑)2	1	(🔑)1	1	1	2	(🔑)2	2
4	2	(🔑)2	1	1	(🔑)1	1	3	(🔑)3	3
6	2	(🔑)2	1/2	1	(🔑)1	1	3	(🔑)3	3
12	3	(🔑)3	1	(🔑)1	1	1	2	(🔑)2	2
14	3	(🔑)3	1	1	(🔑)1	1	2	(🔑)2	2
15	1/2	(🔑)2	1	1	(🔑)1	1	2	(🔑)3	3

Three factors:
- I_{ave}, I_{10max}, I_{30max} (🔑), I_{60max}
- P_{25}, P_{50} (🔑), P_{75}
- P_{tot}, t_P (🔑)

For comparison and support of the identified groups, roughly the same grouping with the same key parameters was seen at the Fulwasser station in the Leissigen catchment in Switzerland (Wuethrich 1999). The above grouping can also be supported with a hierarchical cluster analysis on the basis of the variables as shown in Figure 3.81. The dendrogramme shows the hierarchical pattern of proximity between the different variables. It shows that variables 5 and 6 (I_{30max} and I_{60max}) have the closest distance followed by I_{10max} and later I_{ave}. This intensity group is joined by a group of the amount P_{tot} and duration t_P and only later by the shape parameters P_{50}, $P_{75,}$ and P_{25}.

The precipitation events were classified according to P_{tot} and the thresholds proposed by Carver (1997). This classification was based on the observations of major storm events with a particular focus on sediment issues as well as on the plot experiments. The classification presented here is based on the k-means cluster analysis (SPSS 1999). For this purpose the key variables for precipitation I_{30max}, $t_{P,}$ and P_{50} were used in the clustering process. In addition, on the basis of the dendrogramme presented in Figure 3.81 and the strong correlation of this parameter with most other parameters, the variable P_{tot} was added.

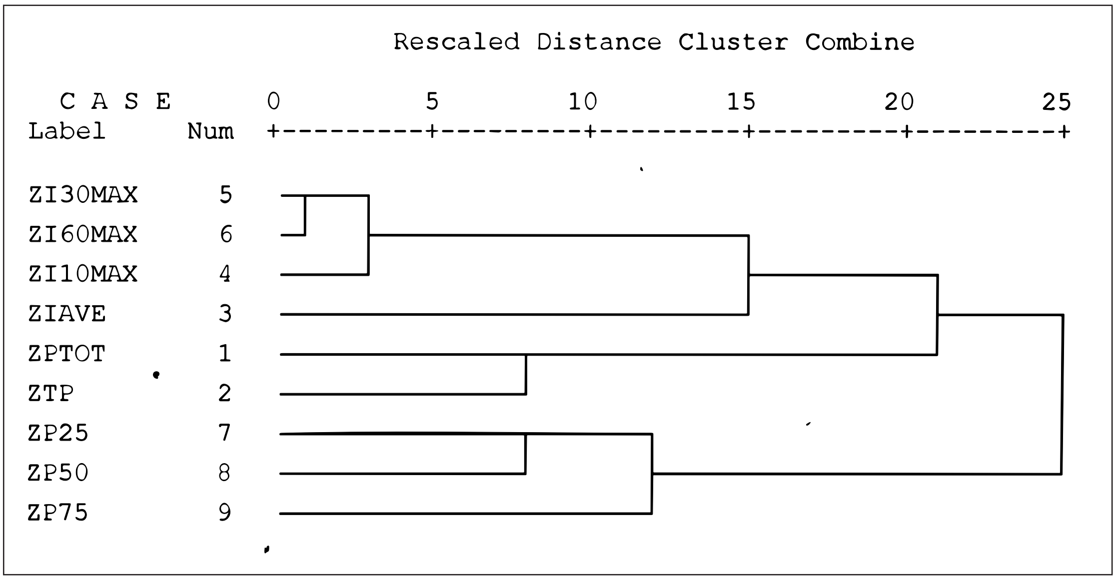


Figure 3.81: **Dendrogramme of rainfall variables, Site 14, Jhikhu Khola catchment**

The number of clusters has to be defined in advance in the case of the k-means cluster analysis. Four clusters were identified as appropriate. Three clusters lump the lower clusters together into a main lower cluster, a medium cluster, and a cluster of the very large events. Four clusters do not change anything in the large events, but divide the lower cluster into an additional cluster. Five clusters results in the break down of the largest event cluster, producing two very small clusters with only two to three cases in each.

On the basis of four predefined clusters, the cluster centres as shown in Table 3.40 were identified. The centres roughly show classes with gradients from low to high rainfall amount, intensity, and duration.

The events, which formed the basis of these cluster centres, were all attributed to one cluster centre. The range of the parameters is given in Table 3.41.

Table 3.40: **Cluster centres of different parameters at different sites**

	Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Site 3	P_{tot} [mm]	5.0	16.7	43.1	56.8
	t_P [min]	88	201	263	1028
	I_{30max} [mm/30 min]	2.8	7.9	25.7	6.8
	P_{50} [%]	9.1	28.0	24.5	4.0
Site 4	P_{tot} [mm]	5.5	22.6	23.4	145.0
	t_P [min]	93	140	424	1493
	I_{30max} [mm/30 min]	3.1	14.3	5.6	9.9
	P_{50} [%]	11.7	36.6	10.6	14.8
Site 6	P_{tot} [mm]	4.8	19.4	24.2	113.4
	t_P [min]	75	340	151	1480
	I_{30max} [mm/30 min]	3.1	5.4	15.1	7.4
	P_{50} [%]	15.0	0.6	32.0	14.4
Site 12	P_{tot} [mm]	6.4	25.0	31.6	126.4
	t_P [min]	159	617	247	1711
	I_{30max} [mm/30 min]	3.8	5.1	17.8	9.2
	P_{50} [%]	22.9	22.5	28.0	13.8
Site 14	P_{tot} [mm]	7.0	27.3	32.5	118.9
	t_P [min]	167	621	251	1815
	I_{30max} [mm/30 min]	3.8	6.4	17.9	7.3
	P_{50} [%]	22.9	14.6	37.3	17.7
Site 15	P_{tot} [mm]	6.2	21.2	30.2	74.7
	t_P [min]	170	601	252	1661
	I_{30max} [mm/30 min]	3.4	4.9	16.9	5.7
	P_{50} [%]	24.1	20.2	28.4	23.4

Table 3.41: **Final clusters for rainfall event classification, Jhikhu Khola catchment**

Variable	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	Min	Max	Min	Max	Min	Max	Min	Max
P_{tot} [mm]	2.1	9.6	9.4	32.5	12.8	45.4	52.1	164.4
t_P [min]	22	250	98	728	46	421	795	1931
I_{30max} [mm/30 min]	1.8	5.4	2.7	10.4	9.4	28.7	4.7	10.7
P_{50} [%]	40.0	82.6	29.7	80.6	43.3	91.3	36.6	62.2

These clusters can be described in words as follows.

Cluster 1: Minor
Low amount – short duration – low maximum intensity rainfall event with most rainfall amount in the first half of the event.

Cluster 2: Medium
Low to medium amount – medium duration – medium intensity rainfall event with rainfall occurring throughout the event.

Cluster 3: High intensity
Medium amount – medium duration – high intensity rainfall event with most rainfall occurring in the first half of the event.

Cluster 4: Large
High amount – long duration – medium intensity rainfall events with most rainfall in the second half of the event.

On average over all sites and all events, it was noted that most of the events belong to cluster 1, the minor events (71.9%; Figure 3.82a). Of these events, 49.9% occur during the monsoon season and 16.1% during the pre-monsoon season. Another 14.2% of the events during the monsoon season belong to cluster 2, accounting overall for 16.2% of the events. Cluster 3 contains 10.9% of the events, while cluster 4, the exceptional events, only account for 1% of all events.

Seasonally, it is noted that the post-monsoon and winter seasons account for an over- proportional share of events belonging to cluster 4 (Figure 3.82b). During the post-monsoon in particular, a number of exceptional storms occurred. During the pre-monsoon season the share of minor events as well as the high intensity events is higher in comparison with the other clusters.

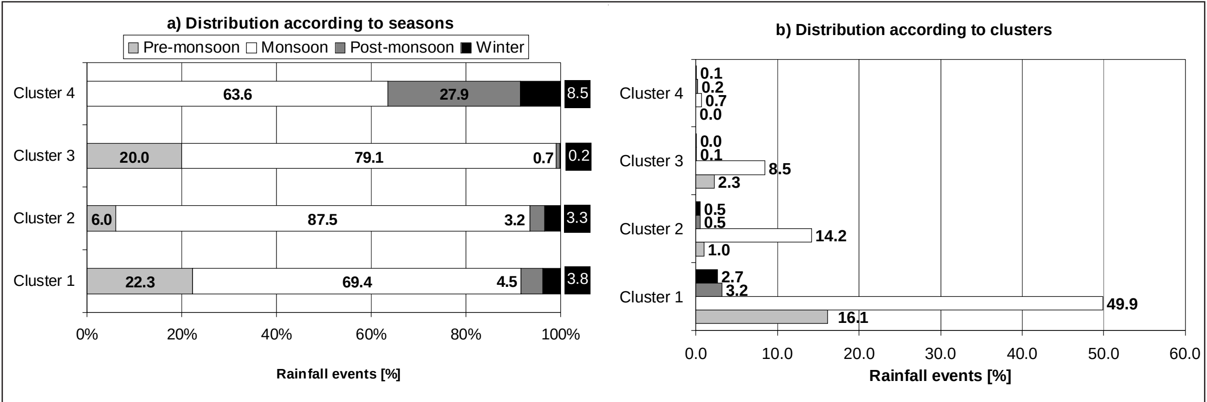


Figure 3.82: **Rainfall events' distribution according to the different seasons and clusters**

Comparing the classifications on the basis of rainfall amount only, according to Carver (1997) and on the basis of cluster analysis (see Figure 3.77ab and Figure 3.82ab) it can be observed that the cluster analysis-based classification puts more emphasis on the events with high intensities and high rainfall amount, which in theory are the most destructive events. It takes into account the difference between the high intensity-medium duration events, which are particularly important during the pre-monsoon season, as well as the exceptional events with long duration and high rainfall amounts, but only medium intensities. The latter drop out of Carver's classification, as they are not decisive for sediment mobilisation. For the remaining classes, Carver's classification and the cluster analysis-based classification are generally very close with similar thresholds of 10 mm rainfall amount for intermediate/medium events and 30 mm for major/large events.

The rainfall-runoff analyses on the erosion plots and the sub-catchments in the following sections are based on the cluster analysis-based classification shown in Table 3.41. In terms of annual and seasonal frequencies of the different clusters, refer to Table 3.42. This table shows that on average over the entire catchment about 61 minor events should be expected a year. Medium events number about 14, while the high intensity events number about nine. These high intensity events mainly occur during the monsoon season, with about six to ten events. During the pre-monsoon season, two to three of these events have to be expected. Large events only occur exceptionally with about one each year occurring either in the monsoon or post-monsoon season. According to Carver's classification (1997), 2.8 major storms have to be expected, 1.0 storm during the pre-monsoon season, and 1.8 storms during the monsoon season. However, this also includes some of the large, high intensity storms.

Table 3.42: **Annual frequencies of different events classified according to clusters**

	Pre-monsoon				Monsoon				Post-monsoon				Winter			
Cluster	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Site 3	7.8	1.5	0.3	0.0	43.8	20.0	2.5	1.3	4.0	0.8	0.0	0.0	3.3	0.3	0.0	0.3
Site 4	15.0	1.0	2.8	0.0	43.5	10.8	10.8	0.3	2.3	0.3	0.0	0.3	2.5	0.3	0.0	0.0
Site 6	14.0	1.6	2.3	0.0	41.1	11.4	10.3	0.4	3.4	0.5	0.4	0.1	2.9	0.9	0.1	0.1
Site 12	15.0	0.3	3.0	0.0	42.3	11.7	6.0	0.3	2.3	0.3	0.0	0.3	1.0	0.3	0.0	0.0
Site 14	16.0	0.3	2.3	0.0	43.5	11.0	6.5	0.5	2.0	0.3	0.0	0.3	1.3	0.5	0.0	0.0
Site 15	14.5	0.5	1.3	0.0	40.5	8.0	7.5	0.6	2.6	0.5	0.1	0.1	2.9	0.4	0.0	0.1
Catchment	13.7	0.9	2.0	0.0	42.5	12.1	7.3	0.6	2.8	0.4	0.1	0.2	2.3	0.4	0.0	0.1

3.4.3.3 Summary

- Annually, about 86 events occur, of which approximately 73% occur in the monsoon season and 20% in the pre-monsoon season.
- The event distribution is strongly left skewed with the events between 2 to 5 mm being most frequent.
- During an average rainfall event, about 5 to 8 mm rainfall is observed during one to three hours and with a maximum 10-minute intensity of 12 mm/h.

- During average large events, about 40 mm rainfall is observed during 6 to 8 hours and with a maximum 10-minute intensity of 30 to 42 mm/h.
- The pre-monsoon events show higher maximum intensities, shorter duration, and less rainfall than the events during the monsoon season.
- The total event rainfall volume P_{tot} is strongly correlated with most other rainfall event parameters.
- The rainfall event duration t_P, the maximum 30-minute intensity I_{30max}, and the rainfall that occurred in the first half of the event P_{50} are the key variables in a rainfall event.
- The maximum intensities can be estimated on the basis of daily rainfall with r^2 values of more than 0.85 in the case of I_{60max}.
- Four clusters can be identified on the basis of P_{tot}, t_P, I_{30max}, and P_{50}:
  - ❖ **Cluster 1 – minor events.** Low amount – short duration – low maximum intensity rainfall event with most rainfall amount in the first half of the event.
  - ❖ **Cluster 2 – medium events.** Low to medium amount – medium duration – medium intensity rainfall event with rainfall occurring throughout the event.
  - ❖ **Cluster 3 – high intensity events.** Medium amount – medium duration – high intensity rainfall event with most rainfall occurring in the first half of the event.
  - ❖ **Cluster 4 – large events.** High amount – long duration – medium intensity rainfall events with most rainfall in the second half of the event.
- Annually about nine high intensity events and one large event occurred.
- Out of these, seven high intensity events occurred during the monsoon season and two to three during the pre-monsoon season.
- Large events generally occurred during the monsoon season or the post-monsoon season.

3.4.4 Runoff event analyses from the erosion plots in the Jhikhu Khola catchment

In the following only runoff from the erosion plots will be discussed. The analysis of the sediment data will be discussed in the next section, Section 3.5, on sediment mobilisation and dynamics. At this point it is important to note that, strictly speaking, a comparison of the plots is not possible due to differences between them, including slope, soil type, rainfall at the site, and land management. However, the main purpose of the comparison below is to identify the orders of magnitude and to identify processes common for their areas. Later in this section the differences between the plots are further discussed.

Note: The land use of each plot is mentioned in all figures and tables below with 'd' for degraded land and 'a' for agricultural land.

3.4.4.1 Description of the runoff events

From the eight erosion plots in the Jhikhu Khola catchment, data from Sites 4, 6, 14, and 16 were used. Sites 4 and 14 represent degraded land on red soils, and Sites 6 and 16 sloping rainfed agricultural land. Degraded land on red soils is prevalent in the lower areas of the catchment up to 1200 masl. In these foot slope areas, the slopes are generally gentle. The sloping agricultural lands of the upper areas, for which the two plots 6 and 16 are representative, are generally steeper. Degraded lands, in the sense of the degraded areas for which Plots 4 and 14 are representative, are widely missing in this altitudinal belt above 1200 to 1900 masl.

About 55 runoff events are observed on the degraded plots annually. Most of these events occur during the monsoon season, about 4/5 of all events (Table 3.43). This is followed by the number of events in the pre-monsoon season, about 1/5 of all events per year. On the rainfed agricultural plots, only about 20 to 30 events were observed annually, with most events occurring in the monsoon season. During the monsoon season about twice as many events can be observed on the degraded plots than on the plots on rainfed agricultural land. The same approximate factor applies for the pre-monsoon season.

Table 3.43: **Erosion plot events in the Jhikhu Khola catchment**

	Site 4 (d)				Site 6 (a)				Site 14 (d)				Site 16 (a)			
	Pre	Mon	Post	Win	Pre	Mon	Post	Win	Pre	Mon	Post	Win	Pre	Mon	Post	Win
1993*					0	13	0	0					6	4	1	0
1994					5	14	0	2					1	31	0	1
1995					4	20	3	2					2	1	1	0
1996					1	19	1	0					0	27	2	1
1997*	11	43	3	4	4	24	0	1	9	33	1	1	6	20	0	2
1998	12	48	2	1	8	22	1	1	10	42	1	1	4	17	0	1
1999	6	54	2	0	3	28	1	0	9	54	1	0	2	8	1	0
2000	15	26	0	0	9	25	0	0	14	45	0	0	no rainfall data			

Pre: pre-monsoon Mon: monsoon Post: post-monsoon Win: winter

* 1993 in the case of Sites 6 and 16, and 1997 in the case of Sites 4 and 14 are the initial years and therefore are only of limited use. This is due to the disturbed soil conditions just after installation of the plots.

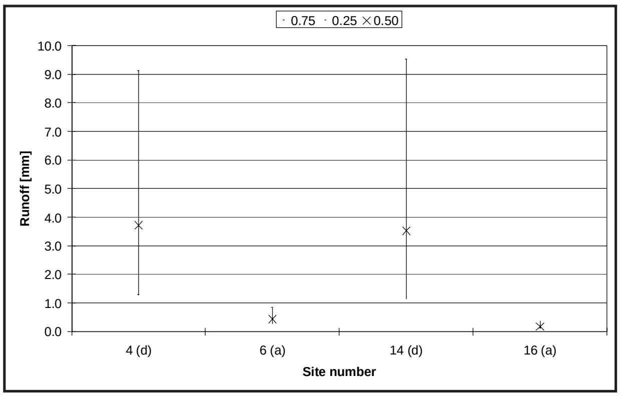


Figure 3.83: **Event parameters (first, second, and third quartile) for runoff distribution of all events on the erosion plots in the Jhikhu Khola catchment**

According to the evidence presented above and the results in the next section on sediment dynamics, it is clear that the plots on the degraded land and the plots on the agricultural land behave differently. The same can be shown on the basis of the runoff event analyses. The median runoff of all measured events at Sites 4 and 14 is, at 40 m^3/ha (= 4 mm), about 8 times higher than on the agricultural plots at Sites 6 and 16, where only about 2 to 5 m^3/ha (= 0.2 to 0.5 mm) runoff were measured (Figure 3.83). The values on degraded land range from a 25% quartile of about 1 mm up to a 75% quartile of 9.5 mm. On the agricultural land the statistical values are consistently below 1 mm.

The median rainfall parameters corresponding to these runoff events are of medium size, that is, between 10 and 30 mm rainfall (Table 3.44). Again, the plots of different land use differ slightly, with the median rainfall amount of the events on agricultural land being slightly higher than on the degraded land, that is, lower rainfall leads to more runoff and to earlier runoff than on agricultural land. This was also shown with the establishment of lower thresholds for runoff generation on degraded plots (see Figure 3.89 later in this section). Comparing the runoff coefficients a from the degraded plots and the agricultural plots, it can be shown that degraded plots are more susceptible to runoff generation than the agricultural plots. A median 31% of the rainfall from the degraded plots runs off, while on agricultural land this value is only about 1 to 3%. In terms of the other parameters, there is no distinct visible difference. A slight difference is observed between the intensity parameters from the different plots, that is the I_{60max} on the degraded plots tends to be slightly lower than on the agricultural land.

The events differ largely between the seasons. While runoff events on the plots during the post-monsoon and winter are seldom (Table 3.43), about ten events on degraded plots and five events on

Table 3.44: **Medians of all runoff events on the erosion plots, Jhikhu Khola catchment**

	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10 min]	I_{30max} [mm/30 min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]	α
4(d)	3.7	10.4	138	4.6	2.1	4.2	6.3	33.3	60.0	80.0	30.9
6(a)	0.4	14.8	166	5.8	3.2	6.3	8.4	40.0	63.6	83.3	2.7
14(d)	3.5	11.0	214	3.5	3.0	5.0	6.7	34.5	70.6	90.9	31.2
16(a)	0.2	19.4	270	4.1	3.7	7.7	10.5	29.6	67.4	91.7	0.9

agricultural plots occur during the pre-monsoon season. Most of the events occur during the monsoon season. While on the degraded plots the runoff volume largely follows the rainfall distribution (more rainfall occurring during the monsoon season, therefore more runoff occurring during the same season, Table 3.45); on agricultural plots runoff is higher during the pre-monsoon season or is the same as during the monsoon season, although more rainfall occurred. The same can be shown with the runoff coefficient a, an overall and summarised measure of infiltration and storage processes (Scherrer 1997). On degraded plots the runoff coefficients during the pre-monsoon season tend to be smaller than during the monsoon season (also see Figure 3.84). On agricultural plots it tends to be just the other way around, that is, higher coefficients during the pre-monsoon season. This is particularly interesting as the intensity parameters only differ slightly between the seasons. However, the pre-monsoon events tend to be more intense according to the I_{xmax} parameters. The range of runoff coefficients is rather high, ranging from 10 to 40% on degraded land during the pre-monsoon season and about 20 to 50% during the monsoon season. On agricultural land, runoff coefficients of only up to roughly 10% are observed.

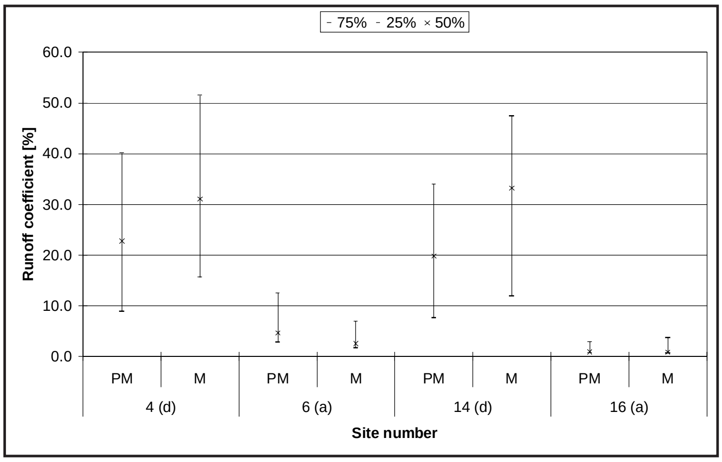


Figure 3.84: **Quartiles of the runoff coefficient distribution of the runoff events on the erosion plots of the Jhikhu Khola catchment**

Table 3.45: **Median all PM and M events**

	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10 min]	I_{30max} [mm/30 min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]	α
4(d) PM	1.9	7.3	120	4.7	3.1	4.2	5.2	41.4	54.4	78.9	4.7
M	4.3	11.5	154	4.5	3.1	4.2	6.3	33.3	62.5	83.3	31.1
6(a) PM	0.6	10.5	72	7.5	4.2	7.4	9.0	42.9	66.7	85.6	6.9
M	0.4	15.8	190	5.4	3.2	6.3	8.4	40.0	60.9	83.3	2.5
14(d) PM	2.3	9.7	130	5.6	4.0	6.2	6.9	46.4	76.0	93.8	7.1
M	3.7	11.1	249	3.3	2.7	4.9	6.7	33.3	70.6	90.5	33.2
16(a) PM	0.2	17.4	170	5.0	5.5	9.2	11.5	30.4	74.0	94.9	13.4
M	0.2	19.7	313	3.8	3.9	7.7	10.0	28.5	67.5	91.5	0.9

This seasonal pattern can also be shown in a runoff coefficient time series with data from Plot 6 representing the agricultural land and Plot 14 for degraded land (Figure 3.85). While there is no obvious seasonal pattern visible in the case of data from Plot 14, there is a clearly visible higher contribution of pre-monsoon (May and early June) and early monsoon events (late June and early July) in the case of Plot 6. Fourteen events had a runoff coefficient of higher than 10% in the pre-monsoon season. In addition, 11 events in the early monsoon exceeded 10%. Only 9 events exceeding 10% were observed in the late monsoon. The same pattern was observed in the other two plots, Plots 4 (like Plot 14) and 16 (like Plot 6).

Of all the rainfall events during a year, only some generate runoff on the plots. Most of these runoff events however are minor events with only small amounts of runoff. Only the largest events can be considered important (Figure 3.86). At Sites 4 and 14, the degraded lands, about 10 events produce 50% of the total annual runoff. Twenty events produce about 75% and 30 to 35 events produce about 90% of the total annual runoff. On the rainfed agricultural land, (Sites 6 and 16) only 5 events produce 50% and 10 to 15 events produce 75% of the total annual runoff. At Sites 16, 15 to 20 events produce 90% of the total annual runoff. At Site 6 the same is achieved by 20 to 30 events. The importance of selected large storms is even higher in the case of soil loss (see Section 3.5).

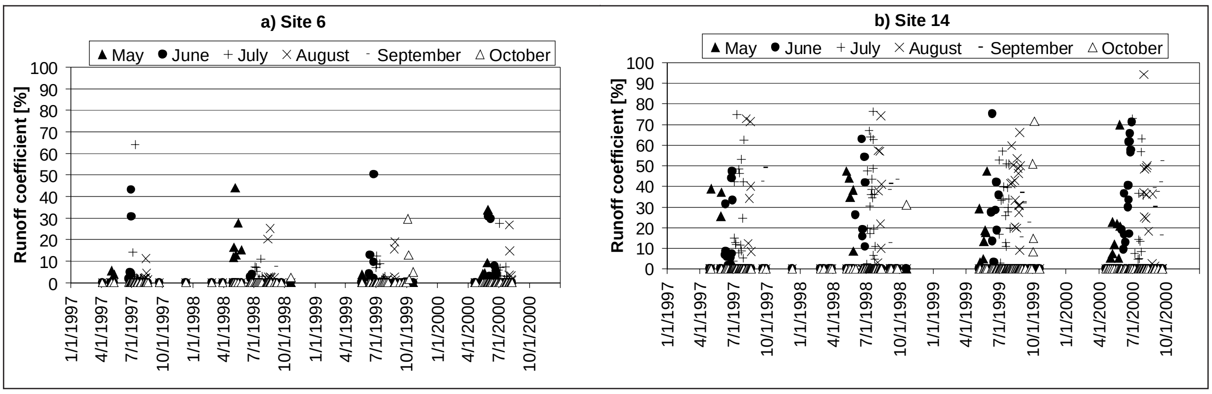


Figure 3.85: **Monthly distribution of runoff coefficients on Plot 6 (agricultural land) and Plot 14 (degraded land)**

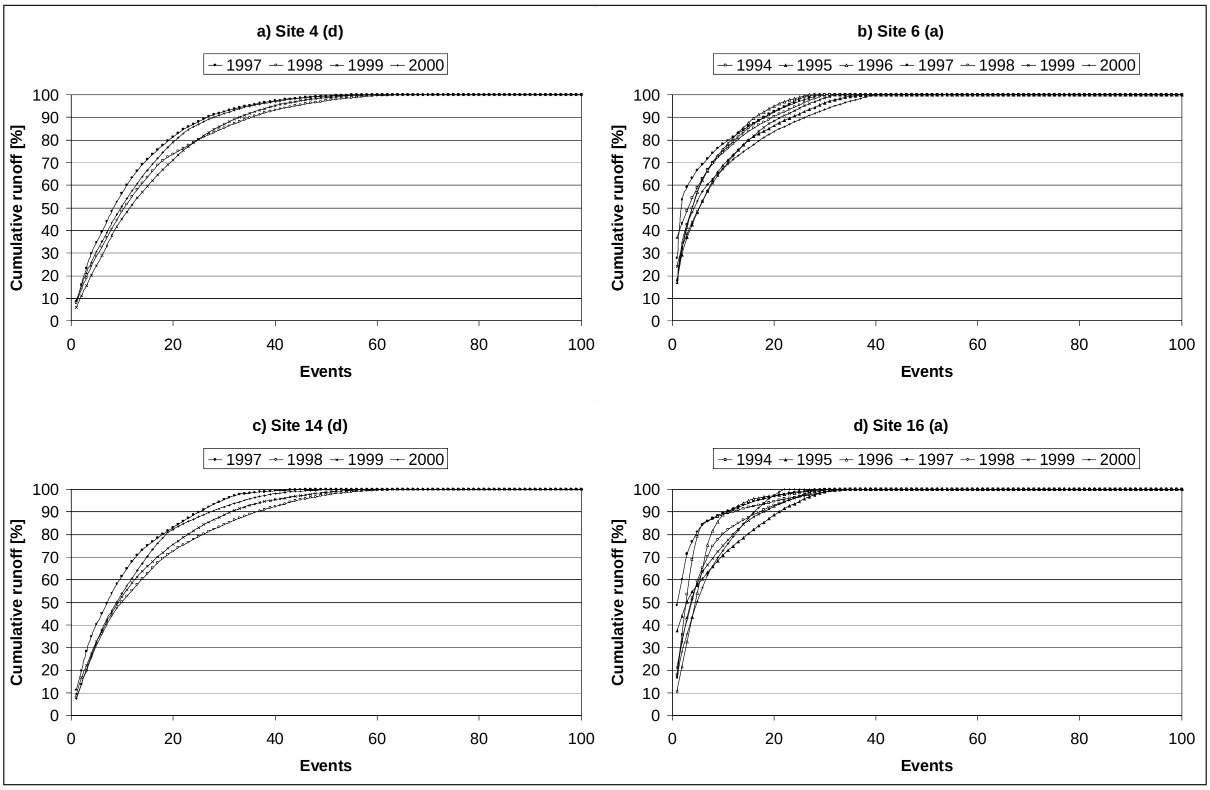


Figure 3.86: **Annual cumulative curves for runoff on all erosion plots, Jhikhu Khola 38**

The ten largest runoff events on the erosion plots of the Jhikhu Khola catchment show a similar picture to that described above for all events and for seasonal breakdown. There is a distinct difference between the events on the agricultural plots and the plots on the degraded land (Table 3.46 and Figure 3.87). The events on degraded lands show median values of about 25 mm runoff during the largest events. On the agricultural land the largest events only record about 6 mm runoff. A difference is also observed in terms of the runoff coefficient α. On the degraded plots 40 to 50% of rainfall results in runoff on average, while on the agricultural land only medians of 16.2% at Site 16 and 32.3% at Site 6 were observed.

The above descriptions can be summarised as follows:

- the runoff behaviour on the degraded plots differs strongly from the runoff behaviour on the agricultural plots;
- there is a clear seasonal pattern on the agricultural plots;
- no seasonal pattern was observed on the degraded plots;

Table 3.46: **Median of the largest 10 runoff events, Jhikhu Khola catchment**

	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10 min]	I_{30max} [mm/30 min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]	α
4(d)	23.0	42.8	215	10.9	10.4	24.5	26.1	47.0	60.3	90.2	50.9
6(a)	6.0	18.4	74	11.2	5.8	9.5	12.6	50.0	71.9	85.8	32.3
14(d)	25.1	41.8	286	8.7	8.0	15.3	21.7	32.5	76.4	93.5	43.1
16(a)	5.6	35.7	242	6.6	9.7	16.2	21.3	53.0	92.0	96.6	16.2

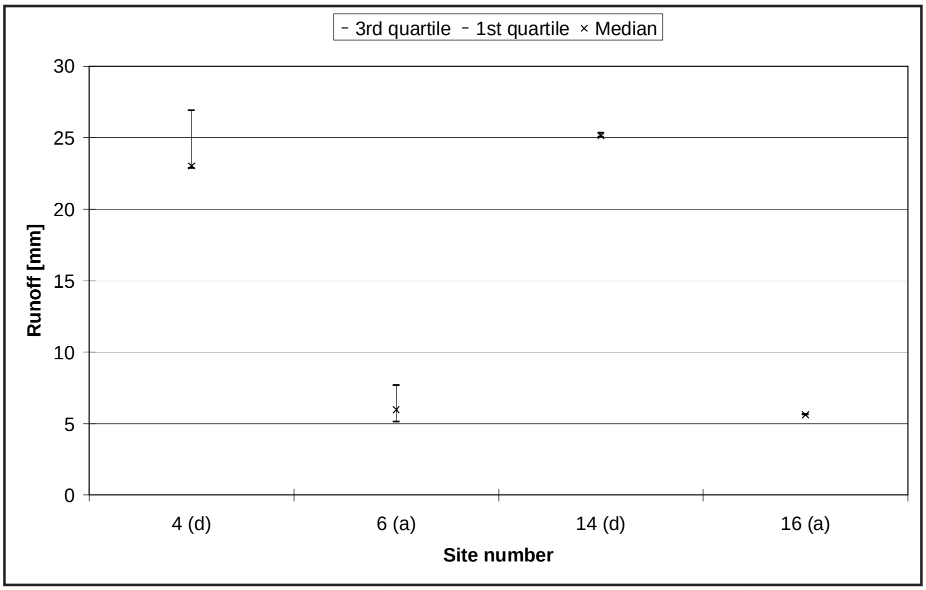


Figure 3.87: **Event parameters (first, second and third quartile) for runoff distribution of the ten largest runoff events on the erosion plots in the Jhikhu Khola catchment**

- an average event on a degraded plot produces about 3 to 4 mm runoff, while on a rainfed agricultural plot it only produces 0 to 0.5 mm;
- the ten largest events on a degraded plot produce on average about 2 to 25 mm runoff, while on a rainfed agricultural plot these only produce 5 to 6 mm;and
- of annual runoff, 75% is produced during about 20 events on the degraded plots, while on rainfed agricultural plots only 10 to 15 produce the same percentage of runoff.

3.4.4.2 Causes for the runoff conditions described

Surface runoff at the plot scale is caused by a number of factors. Collins et al. (1998a) show that both infiltration excess and saturation excess processes contribute to runoff generation in the middle mountains of Nepal. Kandel et al. (2002) therefore use a surface runoff model, which incorporates both processes after accounting for the canopy interception losses. In this respect, vegetation parameters, a number of soil parameters including hydraulic conductivity, infiltration capacity, and soil moisture are equally important as rainfall characteristics. In the following, the runoff data from the erosion plots are studied in an attempt to shed more light on the causes of runoff generation on the plots.

Rainfall parameters

The comparison of the plots as described above assumed similar conditions over time, that is, over the number of events a difference of rainfall between the sites would be averaged. In order to compare events, which probably have similar rainfall conditions, five events were identified and selected for detailed investigations (Figure 3.88; the number of five events is random). These events showed a difference in rainfall amount of a maximum of 7 mm between the lowest rainfall and the highest rainfall. The rainfall intensities differed by a maximum of 4 mm in one case, in the event of August 5 1997; by 3 mm in the event of July 17 1997; and only in the order of 1 mm during the

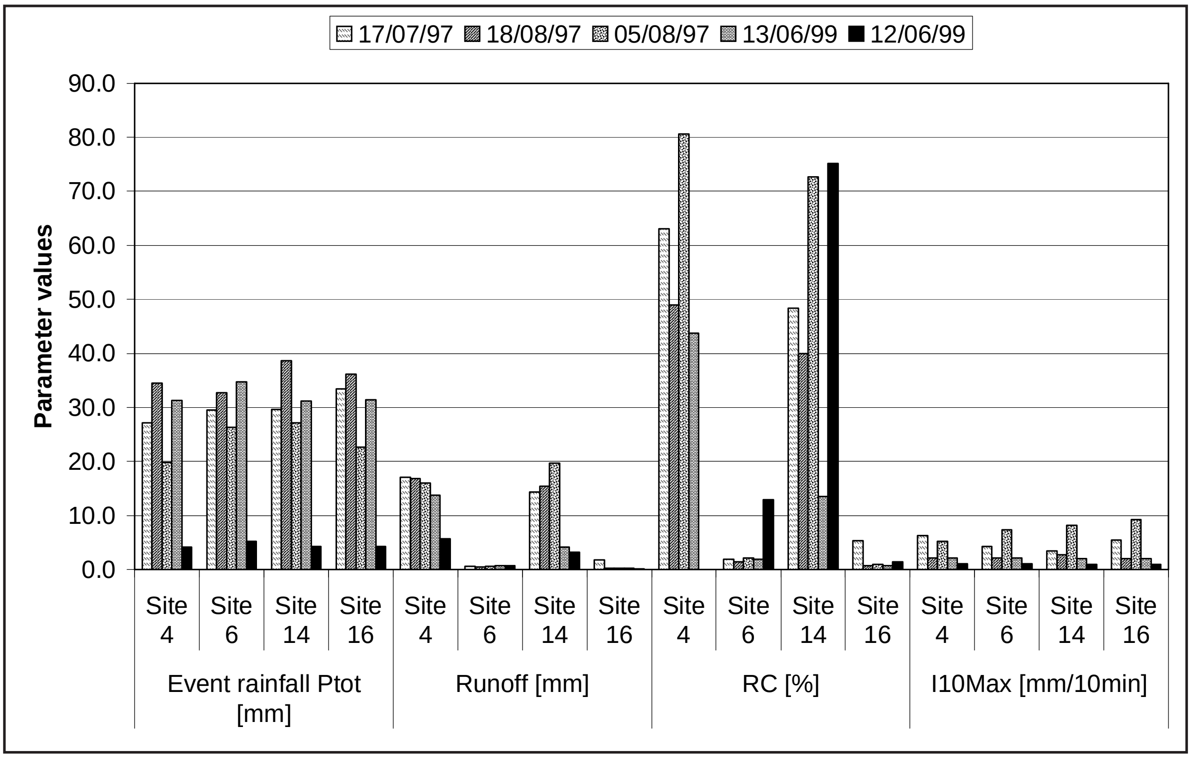


Figure 3.88: **Five runoff events measured at all sites with similar rainfall conditions**

remaining events. The reason why the two events with the larger differences were included is that otherwise only events of small intensities would have been included.

From the data of these five events, the same can be shown as above, that the degraded plots generally produce more runoff in the order of one magnitude. The differences between the two land uses are also observed with the runoff coefficients. While the degraded land shows runoff coefficients ranging from 10 to 70%, on the agricultural land α generally shows values below 5%. That the differences are due to location or rainfall parameters can be excluded, since these are more due to the plot's characteristics. Below, rainfall parameters are discussed in relation to the runoff of the plots. The differences in plot characteristics will be discussed later in this section.

There is no argument that the triggering mechanism for surface runoff is rainfall. However, the question regarding what parameter leads to lower or higher runoff remains and will be discussed here. The Spearman correlation coefficients (the erosion plot data are not distributed normally; Appendix A3.15) presented in Table 3.47 show that there is a distinct difference between the plots on agricultural land (grey shaded) and the plots on degraded land. The runoff amounts from the degraded plots show a strong correlation with the rainfall amount P_{tot} as well as the intensity parameters, I_{60Max} in particular. The runoff amounts on the rainfed agricultural land however show only poor relations with the rainfall amount as well as with the intensity parameters. This suggests that other factors, such as land management and cropping, are more important for the estimation of runoff generation on these plots. On all four plots the antecedent precipitation shows mostly significant, but only weak correlation with the runoff amounts on the plots. The rainfall 24 hours prior to the event expressed with both the API_1 and AP_1 shows the highest correlation coefficients, ranging from 0.20 to 0.43. On Plot 16, however, no significant correlation between runoff and these two parameters was observed. The shape of the event hyetograph shows no or only very weak correlation and can therefore be assumed to have no influence on the runoff generation.

The significant correlations between rainfall amount and runoff can also be shown with Figure 3.89, which shows the seasonally disaggregated data from four erosion plots on a daily basis. Runoff rates on degraded plots are generally higher with the highest events at well over 10 mm.

Table 3.47: **Correlation coefficients for plot runoff – Summary of the four erosion plots in the Jhikhu Khola catchment (grey shaded: agricultural plots)**

Site	P_{tot}	t_P	α	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_1	AP_2	AP_3	AP_4	AP_5
4 (d)	0.82	0.31	0.82	0.38	0.62	0.72	0.81		0.26	0.51	0.20				0.15	0.20	0.22	0.21	0.24	0.21
6 (a)	0.37		0.56	0.23	0.36	0.38	0.39			0.18	0.32	0.35	0.32	0.27		0.32	0.35	0.35	0.36	0.38
14 (d)	0.67	0.24	0.74	0.42	0.63	0.71	0.74			0.19	0.43	0.22	0.20	0.16	0.16	0.43	0.43	0.32	0.27	0.26
16 (a)	0.51		0.70	0.39	0.49	0.51	0.53					0.21	0.20	0.23	0.20			0.21	0.17	0.18

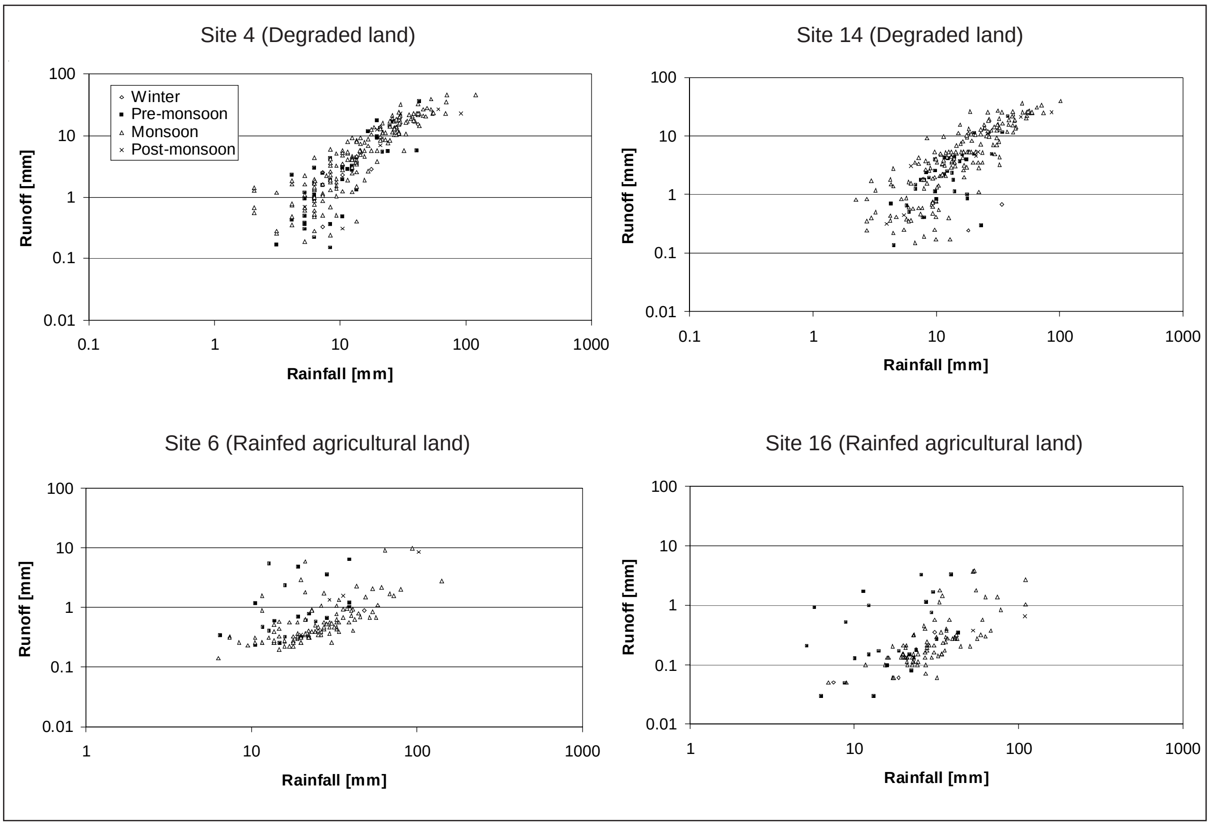


Figure 3.89: **Daily rainfall versus daily runoff on degraded plots (Sites 4 and 14) and on rainfed agricultural land (Sites 6 and 16). Note: graphs are in log-log scale**

On agricultural land, the highest measured rates were between 8 and 10 mm. The thresholds where rainfall produces runoff are lower on degraded land than on rainfed agricultural land. These thresholds are estimated as 2 mm rainfall on degraded sites and 5 mm on rainfed agricultural land. While seasonality does not seem to have any effect on degraded sites, on rainfed agricultural plots pre-monsoon rainfall events seem to yield higher runoff rates than events in the remainder of the year.

In Section 3.4.3, rainfall events were classified into four clusters according to event rainfall amount, maximum 30-minute intensity, rainfall event duration, and shape parameter P_{50}. Comparing the runoff events from the erosion plots with these rainfall event clusters, it is evident that cluster 3 event rainfall events, that is, high intensity events, are most responsible for runoff generation on the degraded plots (Figure 3.90). This is followed by cluster 2 events. The large-amount-long-duration events (cluster 4) are only marginally responsible for runoff generation and are often in the same range as the runoff generated by cluster 1 events.

On the agricultural plots the picture presented is different between the two plots at Sites 6 and 16. While at Plot 6 there is a clear dominance and role of cluster 4 events responsible for runoff generation, at Site 6 both cluster 3 and 4 events show similar impact. In both cases, events of clusters 1 and 2 do not show much impact. A possible explanation for this difference between the plots is the importance of different runoff generating mechanisms on the land under different uses.

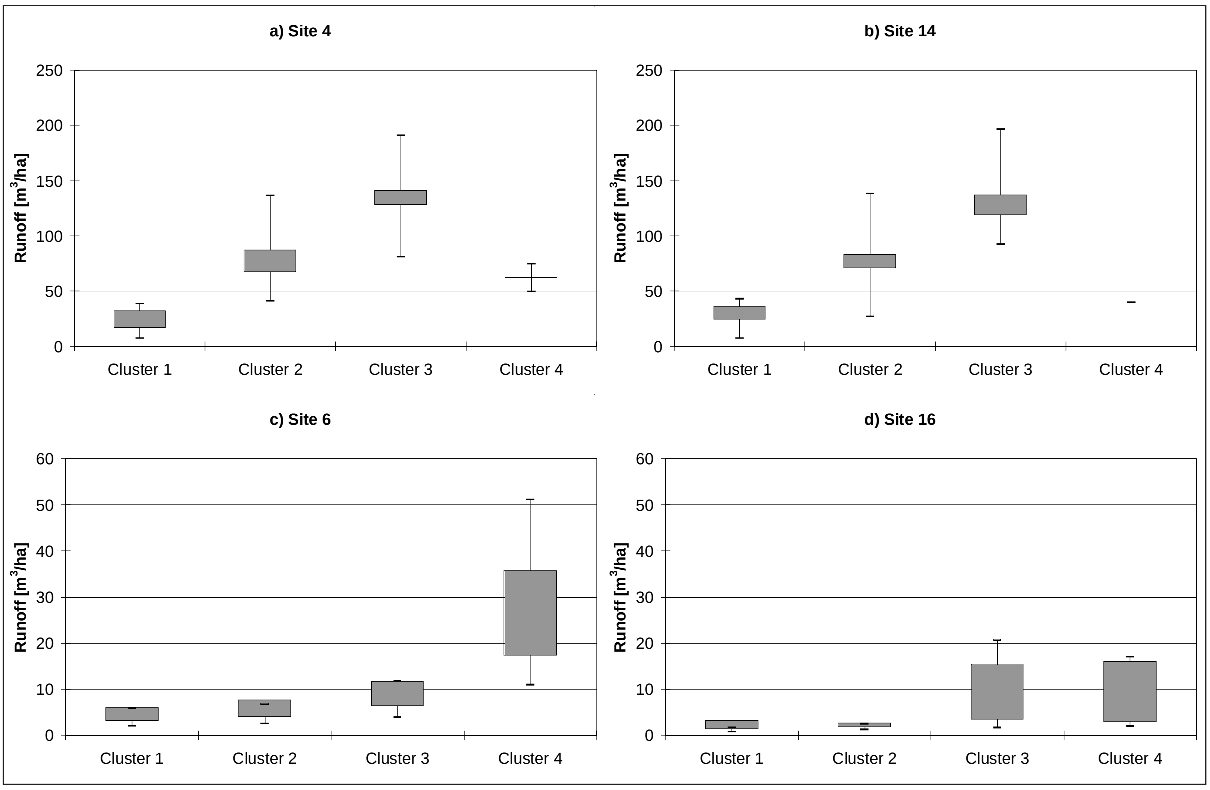


Figure 3.90: **Relationship between runoff and the rainfall clusters**

While on degraded land it is mainly infiltration excess overland flow that contributes to the runoff, on agricultural land saturation excess overland flow gains importance. However, this depends on the plot characteristics and different agricultural plots can show a different picture.

<u>Plot characteristics</u>

Scherrer (1997) has shown that to explain the size of a runoff reaction to a precipitation event, soil parameters solely describing the soil matrix such as bulk density, and textural classes are not useful. The same can be shown on the basis of the textural composition of the studied plots (Table 3.48). None of the tabled parameters could be established as the main reason for high or low infiltration rates. The infiltration rates are assumed to be more dependent on parameters describing the structure of the soils, such as the permeability and surface crust. This phenomenon of the surface crust, often called surface seal, seems to be particularly important in preventing infiltration on the degraded plots. The impact of a crust on infiltration is described in detail in Hillel (1998). In summary, a crust can reduce infiltration even it is very thin or the underlying soil is very permeable. On both degraded plots a surface seal can be observed, while a crust of this sort cannot form on the agricultural land.

Preferred pathways, the type of clay, as well as organic matter content (which improves the soil structure) further influence infiltration rates. In addition, the infiltration rates given in Table 3.48 were measured using the ring-infiltrometer method (e.g., Chow et al. 1988). This method, however, is acknowledged to overestimate the infiltration capacity of a soil due to a standing water head, which is physically very different from a rainfall event (Dunne and Leopold 1978). Furthermore, infiltration is spatially very variable and can change in an order of magnitude at small spatial intervals (Merz

Table 3.48: **Plot and soil characteristics** (source: Singh 2001)

Site	Slope [degree]	Textural composition			Textural class	Infiltration rate [cm/h]
		Sand%	Clay%	Silt%		
4 (d)	11.5	43.3	23.9	32.8	loam	3.2±1.2
6 (a)	24.7	33.3	25.9	40.8	loam	9.7±3.8
14 (d)	15.0	49.3	17.9	32.8	loam	15.5±4.3
16 (a)	6.7	49.9	31.9	18.2	sandy clay loam	6.9±3.3

1997). This was taken into account during the measurement of the infiltration rates by conducting three measurements at three different sites in the plot. Shrestha (1999) made several measurements on different bedrock and on land under different use in the eastern part of the Jhikhu Khola catchment, but could not establish any valid relationship to be used for runoff generation assessment.

Trials to use the erosion plot results to identify the infiltration rates did not produce the same results as given in the table above. For this analysis, only events with event rainfall amounts of more than 5 mm, event durations of less than 60 minutes, and average intensities of a minimum of 10 mm/h were used to calculate the infiltration rate over the duration of the entire event. This resulted in infiltration rates of about 10 mm/h for degraded land and about 20 mm/h for rainfed agricultural land (Table 3.49).

Table 3.49: **Infiltration rates calculated from rainfall events $t_P < 60 min$, $I_{ave} > 10$ mm/h and $P_{tot} > 5$ mm [all values in mm/h]**

Site	Count	Mean	Median	75% quartile	25% quartile
4 (d)	20	10.2	8.4	14.6	5.6
6 (a)	28	24.7	20.4	30.4	15.3
14 (d)	11	12.4	9.8	16.6	7.0
16 (a)	8	22.1	17.2	26.4	11.1

While these values differ considerably when compared with the values given in Table 3.48, they correspond quite well with the values given in Hillel (1998). The steady infiltration rates for loams are given as 5 to 10 mm/h and for clayey soils 1 to 5mm/h. The reason for higher infiltration rates on the rainfed agricultural land is assumed to be due to the land management and the continuous breaking up of the surface. This basically suggests that this 'natural sprinkler' approach yields more feasible results than the ring infiltrometer approach.

Land management

Table 3.50: **Example of farmer's activities on the Plot 16a in 1998**

Month	Day	Activities
April	13	Adding compost
April	27	Harvesting wheat
May	28	Ploughing and sowing maize
June	22	Applying fertilizer
July	1	Preparing bed for millet
September	7	Transplanting tomatoes in the upper plot
October	26	Harvesting maize, stalks and grass
November	18	Ploughing and wheat broadcasting

The seasonality shown above on the agricultural plots cannot only be explained by the changing vegetation cover, but also by field preparation and land management. While there is no human influence on the degraded plots at present, except activities related to this research such as soil samples and infiltration measurements, on the agricultural plots a considerable impact has to be expected from land management and crop production. An example of a calendar of the farmer's activities on the erosion plots on agricultural land is given in Table 3.50. The fields are prepared and the maize is sown after the first pre-monsoon rains at the end of April to the end of May. This is followed by hoeing after about one month and a second time after two months in certain plots and in certain years. In July, the field can be prepared for millet transplantation. Harvesting of maize begins in August and can last up to September. Grasses are cut any time during the year on the basis of need and availability. If there is adequate moisture, wheat is broadcast in November, for which the field first has to be ploughed.

Out of these activities, ploughing and hoeing are considered to have an impact on plot characteristics, mainly by breaking up the soil surface. Theoretically, this can lead to increased infiltration and therefore decreased runoff generation, as well as making soil particles available for mobilisation as their natural aggregates are broken up. On the other hand, decreased runoff also theoretically means less soil loss (see Section 3.5 for details on soil losses).

To shed some light on this issue and to test the hypothesis that farmers' interventions, such as ploughing and hoeing, decrease runoff, data from the two plots 6a and 16a were screened for events close to before and after the farmers' intervention with more than 10 m^3/ha runoff and:

- similar rainfall amounts and maximum rainfall intensity to show a difference between before and after the farmer's intervention;
- similar rainfall amount and higher intensity in the event after the farmer's intervention to show that the hypothesis can be assumed to be correct;or
- similar rainfall amount and higher intensity in the event before the farmer's intervention to show that the hypothesis does not hold.

On the agricultural plots in the Jhikhu Khola, a constellation which allows the drawing of some preliminary conclusions only occurred once (Figure 3.91). On June 18, 1995, a 35.8 mm rainfall event caused 28.3 m^3/ha (= 2.8 mm) runoff. The maximum hourly rainfall intensity observed during this event was 14.8 mm/h. Seven days later, the farmer hoed the plot. Another 8 days later, a 40.0 mm rainfall event with an I_{60max} of 30.6 mm/h caused only 8.8 m^3/ha (= 0.9 mm) of runoff.

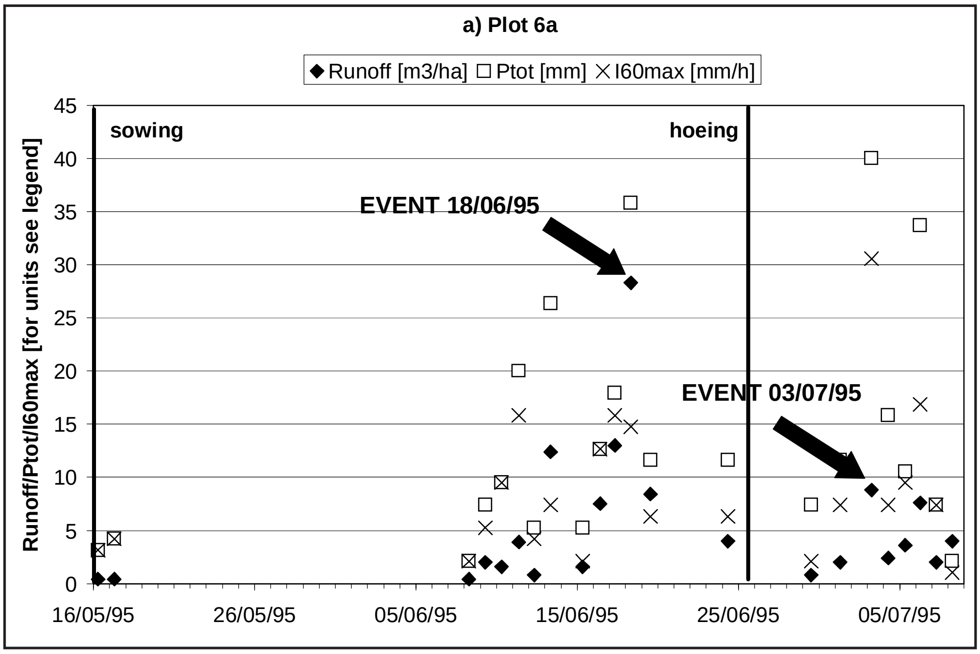


Figure 3.91: **Impact of land management on runoff generation**

Overall, the runoff seems to have decreased after the intervention with most values below 0.5 mm runoff, and only 2 events out of a total of 6 events (33%) above 0.5 mm runoff after the intervention. This is in contrast to the events before the intervention with 5 out of 12 events (42%) above 0.5 mm.

The difference between before and after the intervention is clear, however, the data could not show the opposite. For strong conclusions this is not enough and therefore has to be considered with caution.

In summary it can be said, that:

- total rainfall volume and the maximum intensities, I_{60max} in particular, show the highest correlations with runoff;
- on degraded plots a rainfall event volume threshold of 2 mm was observed for runoff generation;
- on rainfed agricultural land the threshold was 5 mm;
- infiltration excess overland flow is the dominant surface runoff generation process on degraded land;
- saturation excess overland flow is the dominant surface runoff generation process on rainfed agricultural land;
- there is a clear impact of seasonal as well as weed vegetation on the agricultural plots;
- infiltration on rainfed agricultural land exceeds the infiltration rates on degraded land mainly due to a surface seal on the latter; and
- the impact of land management is likely, but only proven on the basis of one case.

3.4.4.3 Runoff prediction and input for modelling

Surface runoff is an important parameter both for hydrological models as well as for erosion models. As shown above, precipitation amount, intensity, and to a certain extent the pre-event conditions play a major role in the generation of this flow parameter. This assumption seems to certainly be valid for the degraded plots. On the agricultural plots the vegetation cover was crucial.

For a first proximate, a multi-linear regression was calculated using the three independent parameters P_{tot}, API_1, and I_{60max}. These parameters were selected on the basis of the factor analysis above. As shown above, these variables are not normally distributed, therefore a multiple regression can only be performed after a transformation of the data (SPSS 1999). In this case, the data were lognormal transformed with base e. The resulting coefficients are tabulated in Table 3.51. It is immediately clear that the multiple regression only yields acceptable results for the two degraded plots (Figure 3.92), while the results for the two agricultural plots are not satisfactory. It therefore seems that using only precipitation parameters to explain the runoff on the plots is not sufficient and the inclusion of a vegetation parameter, such as canopy interception, is crucial to further improving the result.

Table 3.51: **Coefficients for multiple regression $y = a+b*P_{tot}+c*I_{60max}+d*API_1$**

Site	a (coefficient)	b (P_{tot})	c (I_{60max})	d (API_1)	r^2*
4 (d)	-0.183	0.700	0.778	0.201	0.564
6 (a)	-0.072	0.056	0.334	0.305	0.199
14 (d)	0.333	0.165	0.989	0.275	0.473
16 (a)	-1.415	0.106	0.918	-0.027	0.183

* r^2 between the observed and the estimated values

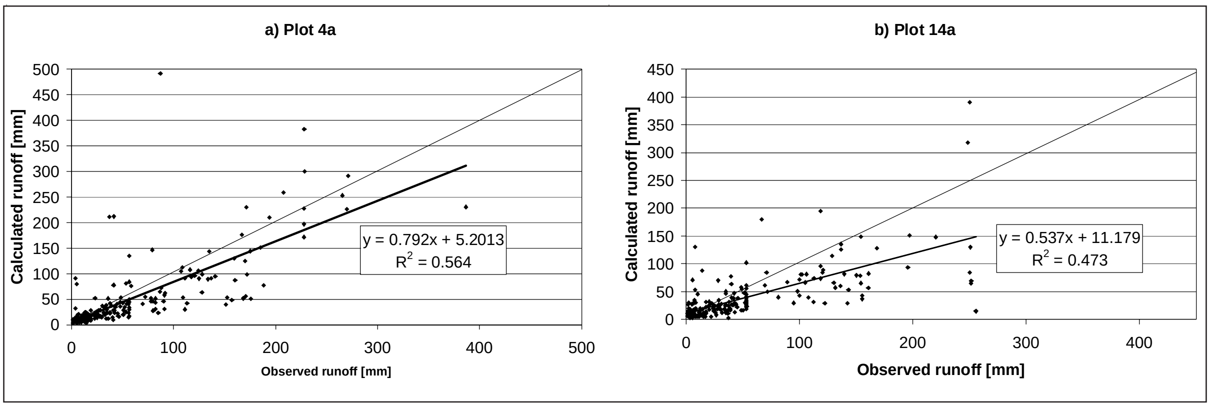


Figure 3.92: **Multiple regressions for Plots 4a and 14a on degraded land**

It was also shown that the importance of the two main surface runoff-generating mechanisms might differ between the plots (see Figure 3.90). While on the degraded plots, infiltration-excess runoff is more important (and can be, to a large extent, explained by rainfall parameters and the infiltration capacity of the soil) saturation-excess overland flow depends, in addition to the precipitation parameters, on other factors such as the permeability of the soils and soil depth.

In this context it seems appropriate that Kandel et al. (2002) have selected a surface model that represents the processes precipitation, canopy interception, infiltration, evapotranspiration, and deep percolation to account for both infiltration and saturation excess overland flow.

3.4.4.4 Summary

The surface runoff event analyses on the erosion plots can be summarised as follows:

- degraded lands are more prone to runoff generation than rainfed agricultural land;
- degraded lands yield higher runoff rates than rainfed agricultural lands;
- degraded lands do not show seasonal effects, while agricultural land shows a clear seasonality;
- rainfed agricultural lands are more prone to high rates of direct runoff during the pre-monsoon than during the remainder of the year;
- only a few large rainfall events cause a large portion of the annual runoff on the erosion plots;

- event rainfall volume and maximum 60-minute intensity are the key variables in terms of runoff generation;
- infiltration excess flow is the key process in terms of runoff generation on the degraded land;and
- saturation excess overland flow is the key process in terms of runoff generation on the rainfed agricultural land.

3.4.5 Hydrological event analyses in the Jhikhu Khola catchment

After a general description of the hydrological events at all sites in the catchment, more detailed event analyses are conducted for the four sub-catchments in the Jhikhu Khola catchment. The main reason is the clear attribution of rainfall events to the resulting hydrographs at the outlet of each sub-catchment. For the entire Jhikhu Khola catchment this is difficult as the entire upper and north-western part is not monitored, neither hydrologically nor meteorologically. The relevance of different land use and other catchment characteristics is discussed after the detailed event analyses of the Yarsha Khola catchment together with the data from that catchment. Finally some special events are discussed in detail.

Note: **The site numbers used in this section refer to the site numbers in Figure 2.16.**

3.4.5.1 Description of the hydrological events

All in all, 655 hydrological events could be clearly identified and used for further analyses (Table 3.52). It is important to stress at this point that these are not all the events that occurred in the sub-catchments, but only the events that could be clearly identified. Some hydrological events had to be excluded later from the analyses, as the corresponding rainfall was missing or incomplete. The number of events at Site 1 is less. This is due to the overlay of hydrographs with their origin from other and ungauged parts of the catchment, which often produces a very complex and unclear event. Only events that could be clearly separated from the rest of the hydrograph are included in these 95 events. The number of events at Sites 7, 8, and 13 is very similar, however at Site 7 these events were observed in a three-year period, while at the other sites the 127 and 128 events respectively were observed in a four-year period from 1997 to 2000.

Table 3.52: **Events at all sites in the Jhikhu Khola catchment (in brackets: events where rainfall was missing)**

Site	Period	Pre-monsoon	Monsoon	Post-Monsoon	Winter	Total
1	1997-2000	16	78	1	0	95
2	1997-2000	35	135	4	0	174
7	1997-1999	15	111 (5)	2	3	131 (5)
8	1997-2000	21	104 (1)	2	0	127 (1)
13	1997-2000	16 (1)	106 (3)	5 (1)	1	128 (5)

It is clear that most of the events occur during the rainy season, mostly in the monsoon season from June to September. Only about 15 to 20% of the events occur during the pre-monsoon season. In winter, only a few events occurred which were observed at the hydrological stations. During the post-monsoon season a number of heavy events were recorded, such as the event on October 19 to 21, 1999.

In general, the largest events are observed at the outlet of the Jhikhu Khola catchment (Table 3.53). These events also show the longest duration and longest rising and receding limbs. The rising limbs in the sub-catchments are very short and in the order of 30 to 60 minutes. Event duration in the sub-catchments ranges from 2 to 6 hours, with the shortest events observed at Site 8. Q_{start} and Q_{end} are both very dependant on the base flows and therefore differ widely due to different catchment sizes. Q_B is adjusted for catchment size and can therefore be directly compared. The values range from 0.6 mm in the two upland sub-catchments of Sites 7 and 8, with negligible baseflows throughout the dry season and only little baseflow during the monsoon season. The total event flow was observed to be lowest at Sites 7 and 8, likewise the maximum event runoff was observed at these sites. The peak runoff rates expressed in mm are observed at Sites 1, 2, and 13. The ratio Q_E/Q_{tot} shows that about 50 to 65% of the total runoff originates from the rainfall of the event.

Table 3.53: **Median of all parameters for hydrological events, Jhikhu Khola**

Site	t_O [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1	630	1.944	3.404	2.7	0.9	1.7	0.3	19.909	0.65	120	510
2	360	0.117	0.301	2.6	1.0	1.5	0.4	1.464	0.64	60	270
7	270	0.013	0.033	1.8	0.6	1.1	0.3	0.175	0.65	60	180
8	120	0.054	0.152	1.1	0.6	0.5	0.2	0.313	0.41	60	60
13	180	-	-	2.6	-	1.4	0.4	0.430	0.53	30	120

The biggest ranges in event runoff are observed at Sites 1 and 2 (Figure 3.93a) with the highest median of 1.7 mm observed at Site 1. This is followed by Site 2 with a median of 1.5 mm. The lowest range as well as the lowest median is observed at Site 8 with 0.5 mm. In terms of peak event runoff, a different picture is presented (Figure 3.93b). The highest peak event runoffs were observed at Site 2 in terms of range as well as in terms of median. The median peak event runoff at this site is 0.4 mm. At Site 1 the median is 0.3 mm.

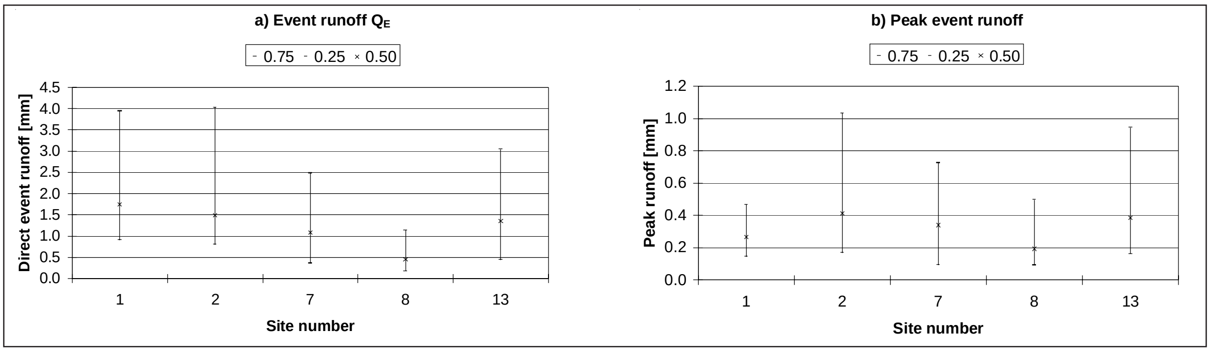


Figure 3.93: **Event runoff (a) and peak event runoff (b) at different sites in the Jhikhu Khola catchment**

There is a distinct difference between the events of the pre-monsoon and the monsoon season (Table 3.54 and Figure 3.94). The events during the pre-monsoon season are based on lower baseflows, as shown with the variables Q_{start} and Q_B. The same can also be shown by the ratio between Q_E and Q_{tot}, which is generally higher in the pre-monsoon season. This suggests that during the pre-monsoon season the event runoff is more important than during the monsoon season. However, the monsoon season events tend to be of bigger magnitude, shown with Q_{tot}, $Q_{E,}$ and Q_{Emax}. No distinct differences can be observed in terms of timing on the basis of event duration, the rising, or the receding limb of the hydrographs.

Table 3.54: **Median of pre-monsoon and monsoon hydrological events, Jhikhu Khola**

Site	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1 PM	525	0.754	1.998	1.7	0.4	1.2	0.2	15.958	0.74	120	450
M	705	2.163	3.745	3.4	1.0	2.02	0.3	20.589	0.63	120	540
2 PM	360	0.05	0.203	1.5	0.5	0.94	0.2	0.739	0.68	60	300
M	360	0.147	0.396	3.2	1.2	1.96	0.4	1.62	0.64	90	270
7 PM	210	0.002	0.008	0.6	0.1	0.44	0.3	0.113	0.76	60	150
M	270	0.015	0.035	2.1	0.6	1.24	0.4	0.186	0.65	60	180
8 PM	120	0.038	0.111	0.8	0.4	0.24	0.2	0.279	0.34	60	60
M	120	0.062	0.165	1.1	0.7	0.5	0.2	0.3135	0.41	60	60
13 PM	240	0.06	0.116	2.6	1.1	1.4	0.4	0.395	0.60	90	165
M	165	0.076	0.15	2.7	1.0	1.38	0.4	0.483	0.51	30	120

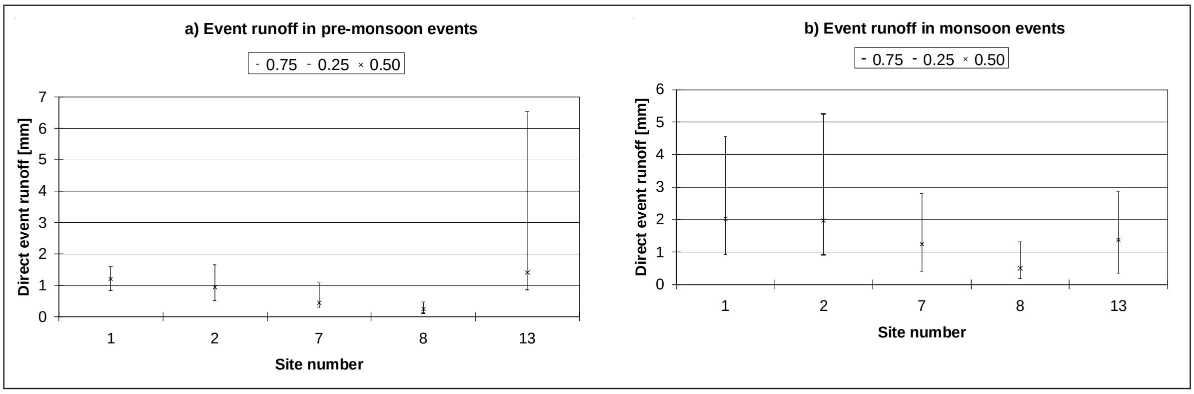


Figure 3.94: **Event runoff of pre-monsoon events (a) and monsoon events (b) at all sites in the Jhikhu Khola catchment**

The median values for the largest 10 events at all sites are compiled in Table 3.55 (see also Figure 3.95). Adjusted to the catchment area, the highest events are observed at Site 2 with median values for Q_E of 13.9 mm and Q_{Emax} of 4.6 mm.

At all stations, the median Q_E/Q_{tot}-ratio was about 80%, that is, 80% of the event was caused by the rainfall and about 20% was due to baseflow in the stream.

Table 3.55: **Median of maximum ten hydrological events, Jhikhu Khola**

Site	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1	1200	2.831	2.895	11.7	2.3	9.4	1.0	64.815	0.84	225	870
2	480	0.290	1.020	16.5	3.1	13.9	4.6	14.088	0.79	60	420
7	345	0.015	0.054	8.1	1.3	7.5	2.6	1.124	0.87	60	285
8	135	0.141	0.675	6.8	2.1	5.9	2.2	2.804	0.66	60	90
13	180	0.068	0.551	11.5	2.3	7.9	4.1	3.578	0.83	30	135

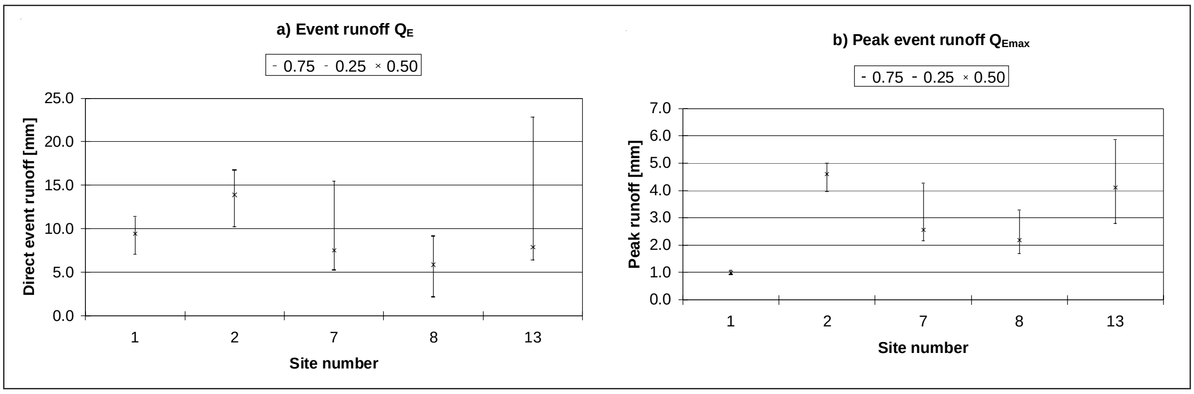


Figure 3.95: **Event runoff (a) and peak event runoff (b) during the ten largest events at each site, Jhikhu Khola catchment**

The duration of the rising limb expressed with t_{rise} shows similar durations for all events, with no distinct difference being observed between the largest events and all the events. This is with the exception of Site 1, where the rising limb of large events is about two hours longer. The same can be observed for the entire event duration t_Q. Except for Site 1, the event durations of large events do not differ considerably from the event durations of al events.

3.4.5.2 Relationships between the different hydrological event parameters

Several parameters calculated for this study have similar information content. The parameters t_Q, t_{rise} and t_{rec} are duration parameters, while Q_B, Q_E, Q_{Emax}, Q_{tot} and Q_{max} represent amount and intensity parameters. Q_{start} and Q_{end} are based on baseflow and represent pre-event conditions. Most of the parameters are therefore significantly correlated with the other parameters according to the Spearman correlation coefficients in Table 3.56. This table is a summary table of all hydrological stations. The detailed correlation tables for each site can be found in Appendix A3.17. This is with the exception of t_{rise}, the rising limb of the hydrograph, which is only strongly correlated with t_Q. The other correlations are only weak. t_{rec} is generally significantly correlated but like $t_{rise,}$ only strongly with t_Q. The strongest correlations are observed between parameters Q_{tot}, Q_E, $Q_{Emax,}$ and Q_{max}.

Table 3.56: **Correlation coefficients at Site 2 and number of significant correlations at all four sub-catchments, Jhikhu Khola (maximum = 4; Appendix A3-16)**

	t_Q	Q_{start}	Q_{end}	Q_{tot}	Q_B	Q_E	Q_{Emax}	Q_{max}	Q_E / Q_{tot}	t_{rise}	t_{rec}
t_Q	1.00(4)	(0)	(1)	0.48(4)	0.38(4)	0.50(4)	0.23(3)	0.20(3)	0.37(3)	0.68(4)	0.92(4)
Q_{start}		1.00(4)	0.76(4)	0.43(4)	0.73(4)	0.24(2)	0.22(3)	0.33(3)	-0.47(3)	(0)	-0.17(1)
Q_{end}			1.00(4)	0.76(4)	0.88(4)	0.62(4)	0.63(4)	0.73(4)	(2)	(0)	(1)
Q_{tot}				1.00(4)	0.88(4)	0.96(4)	0.86(4)	0.90(4)	0.43(4)	0.28(3)	0.47(4)
Q_B					1.00(4)	0.74(4)	0.61(4)	0.70(4)	(2)	0.33(4)	0.31(4)
Q_E						1.00(4)	0.93(4)	0.92(4)	0.63(4)	0.23(3)	0.53(4)
Q_{Emax}							1.00(4)	0.98(4)	0.68(4)	(0)	0.33(3)
Q_{max}								1.00(4)	0.57(4)	(0)	0.27(3)
Q_{tot} / Q_E									1.00(4)	(2)	0.49(4)
T_{rise}										1.00(4)	0.40(4)
T_{rec}											1.00(4)

In order to identify the key parameters of the above parameter set, factor analyses using the principle components approach for the factor extraction and the varimax method for rotation of the factors (StatSoft 1999), was conducted, resulting in the following groupings and key parameters (🔑) (see also Table 3.57):

- Q_{Emax} (🔑), Q_{max}, (Q_{tot})
- t_Q (🔑), t_{rise}, $t_{rec,}$, (Q_{tot})
- Q_{start} (🔑), Q_{end}

Table 3.57: **Results of the factor analyses for hydrological parameters of all events, Jhikhu Khola**

Site	t_Q [min]	Q_{start} $[m^3/s]$	Q_{end} $[m^3/s]$	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} $[m^3/s]$	T_{rise} [min]	T_{rec} [min]
2	(🔑)1	(🔑)3	3	1	3	1	(🔑)2	2	1	1
7	(🔑)1	(🔑)3	3	1	1	1	(🔑)2	2	1	1
8	(🔑)2	1	1	1	1	1	1	(🔑)1	2	2
13	(🔑)2	(🔑)3	1	1	2	1	(🔑)1	1	2	2

The Sites 2, 7, and 13 generally show the same results in terms of key parameters. However, different results were obtained for parameters Q_{tot}, $Q_{B,}$ and Q_E. While Q_{tot} was lumped into the duration parameters group in the case of Sites 2 and 7, it belonged to the amount and intensity parameters group for Sites 8 and 13. Q_B was part of group pre-condition at Site 2, duration at Site 7, pre-condition and amount at Site 8, and duration at Site 13. Q_E belonged to group duration at Sites 2 and 7 and to group amount and intensity at Sites 8 and 13.

The dendrogramme shown in Figure 3.96 roughly supports the grouping presented above. It shows that the intensity parameters Q_{Emax} and Q_{max} have the smallest distance simultaneously with the amount parameters Q_{tot} and Q_E. The grouping on the basis of the dendrogramme suggests three to four groups with the intensity parameters, the amount parameters, the duration parameters, and finally the pre-conditions' parameters in case of four groups and lumping the duration and amount parameters into one group in the case of three groups.

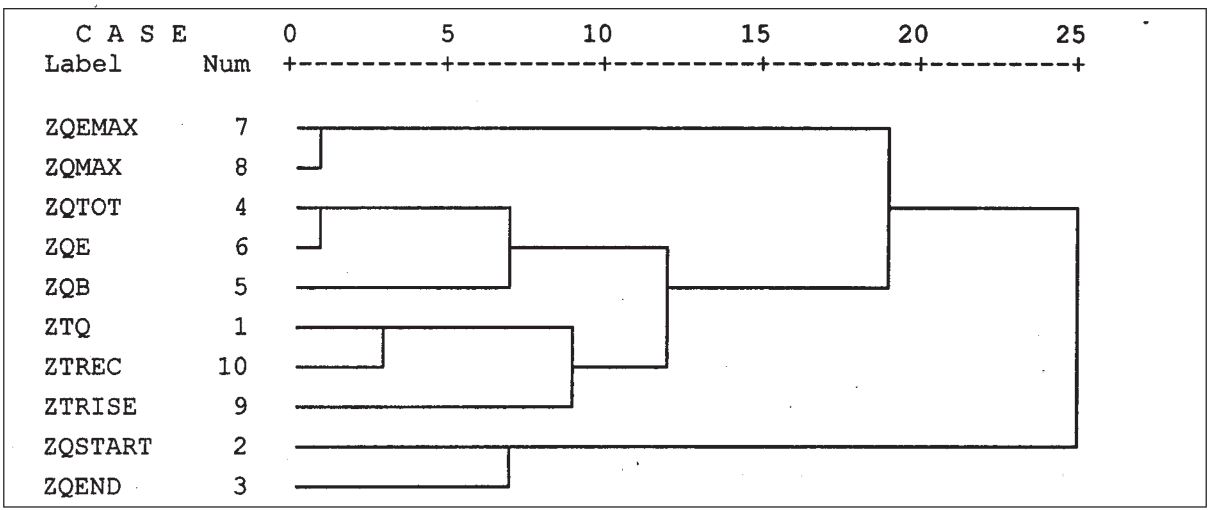


Figure 3.96: **Dendrogramme for hydrological event parameters at Site 2, Jhikhu Khola catchment**

On the basis of the result from the factor analyses, hydrological event parameter clusters were identified using the k-means cluster approach (SPSS 1999). For this analysis, the following variables were used: Q_{Emax}, t_Q, Q_{start}, and Q_{tot}. Several trials with different cluster numbers showed that 3 clusters gave the best results. This is also shown in the dendrogramme above in Figure 3.96. However, the cluster sizes differ widely. Most of the events belong to cluster 1, where about 90 to 95% of all the events were located, that is, 87% of the events at Site 2, 96% at Site 7, 96% at Site 8, and 90% of all events at Site 13 (Table 3.58). The final clusters are given in Table 3.59.

These clusters can be described as follows:
Cluster 1: Minor
short to medium duration – small runoff volume – small peak
Cluster 2: Large peak
short to medium duration – medium to large runoff volume – large peak
Cluster 3: Large volume
long duration – large runoff volume – small peak

Table 3.58: **Discharge event parameter clusters**

		Site 2	Site 7	Site 8	Site 13
Cluster 1	**Count**	152	122	121	111
	t_Q [min]	386	302	177	200
	Q_{start} [m^3/s]	0.190	0.019	0.073	0.080
	Q_{tot} [mm]	3.3	2.3	2.0	2.8
	Q_{Emax} [mm]	0.5	0.5	0.4	0.6
Cluster 2	**Count**	19	2	2	2
	t_Q [min]	565	255	450	75
	Q_{start} [m^3/s]	0.233	0.014	0.658	0.125
	Q_{tot} [mm]	16.2	13.4	28.5	34.0
	Q_{Emax} [mm]	3.8	9.0	2.7	23.3
Cluster 3	**Count**	3	2	3	10
	t_Q [min]	1920	1935	2600	840
	Q_{start} [m^3/s]	0.208	0.020	0.055	0.079
	Q_{tot} [mm]	54.3	37.6	16.5	16.8
	Q_{Emax} [mm]	2.5	2.0	0.3	2.0

Table 3.59: **Final clusters**

Site		Q_{tot} [mm]			Q_{Emax} [mm]		
		Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
Site 2	75% quartile	5.1	18.7	51.1	0.7	4.6	2.7
	25% quartile	1.2	10.7	49.4	0.1	2.6	2.6
	median	2.5	13.4	50.2	0.3	3.3	2.7
Site 6	75% quartile	3.2	16.3	37.8	0.7	10.9	2.3
	25% quartile	0.6	10.5	37.3	0.1	7.0	1.7
	median	1.7	13.4	37.6	0.3	9.0	2.0
Site 8	75% quartile	1.8	35.3	21.7	0.5	3.0	0.3
	25% quartile	0.6	21.7	12.5	0.1	2.5	0.2
	median	1.0	28.5	18.8	0.2	2.7	0.2
Site 13	75% quartile	3.5	35.0	23.4	0.9	26.7	2.1
	25% quartile	1.0	33.0	11.1	0.1	20.0	0.9
	median	1.9	34.0	15.5	0.3	23.3	1.2

3.4.5.3 Reasons for these events

In the following analyses, the current situation of conditions and reasons for flood events in the Jhikhu Khola catchment are assessed. Whether these conditions have changed or not over time cannot be assessed with the current dataset. There was insufficient change in terms of land use over the study period of eight years (see also Chapter 2) , neither was there any dramatic change in terms of urbanisation or increased degradation. The main change that occurred in the catchment during the study period was agricultural intensification. This change is not believed to have an impact on the flood pattern in the catchment. It is, however, suggested that similar analysis be conducted on the bases of longer time series or time series in a later phase of this project or a follow-up project. Changes in flood generation at the process level could then be detected. The major reasons for flood generation therefore are believed to be antecedent moisture conditions, rainfall characteristics, surface flow generation, and catchment characteristics. The first three reasons are discussed in detail below. The impact of catchment characteristics is discussed in combination with the results from the Yarsha Khola catchment at the end of this chapter.

Antecedent moisture conditions

Antecedent moisture conditions expressed with the precipitation prior to the event of different duration only shows very limited correlation with most parameters (Table 3.60) .

Table 3.60: **Correlation coefficients of hydrological parameters with respect to antecedent precipitation conditions at Site 2 and number of significant correlations in brackets, Jhikhu Khola catchment (maximum = 4; detailed matrices in Appendix A3-18)**

	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_1	AP_2	AP_3	AP_4	AP_5
t_Q	(1)	(0)	(0)	(1)	(1)	(1)	(1)	(0)	(0)	(0)
Q_{start}	0.26(3)	0.46(4)	0.49(3)	0.52(3)	0.53(3)	0.26(4)	0.31(4)	0.40(4)	0.45(4)	0.45(4)
Q_{end}	0.41(4)	0.49(4)	0.51(4)	0.55(4)	0.53(3)	0.41(4)	0.43(4)	0.45(4)	0.49(4)	0.51(4)
Q_{tot}	0.37(4)	0.41(4)	0.46(4)	0.48(4)	0.44(3)	0.37(4)	0.37(4)	0.38(4)	0.42(4)	0.44(4)
Q_B	0.37(4)	0.50(4)	0.55(4)	0.58(4)	0.57(3)	0.37(4)	0.39(4)	0.44(4)	0.50(4)	0.52(4)
Q_E	0.34(4)	0.32(3)	0.39(4)	0.38(4)	0.34(2)	0.34(4)	0.33(4)	0.31(4)	0.34(3)	0.37(3)
Q_{Emax}	0.36(4)	0.32(3)	0.38(3)	0.37(3)	0.32(1)	0.36(4)	0.36(4)	0.31(4)	0.32(3)	0.35(3)
Q_{max}	0.41(4)	0.38(4)	0.44(3)	0.43(3)	0.37(1)	0.41(4)	0.41(4)	0.37(4)	0.39(4)	0.42(3)
Q_E / Q_{tot}	(2)	(0)	(0)	(0)	(1)	(2)	(1)	(0)	(0)	(0)
T_{rise}	(1)	(0)	(0)	(0)	0.16(1)	(1)	(0)	(0)	(0)	(0)
T_{rec}	(1)	(0)	(1)	(1)	(1)	(1)	(1)	(0)	(0)	(0)
α	0.18(3)	0.34(3)	0.39(3)	0.41(3)	0.36(1)	0.18(3)	0.24(3)	0.23(2)	0.26(2)	0.30(2)

The highest correlations are observed for the pre-condition parameters Q_{start} and Q_{end} and the baseflow parameter Q_B. The amount and intensity parameters are only weakly correlated and show the highest correlations with the very short-term indexes API_1/AP_1 and AP_2. The duration parameters do not show any significant correlations at most sites, resulting in a very low summarised coefficient as shown in Table 3.60. Of the long-term antecedent precipitation indexes, API_{14} shows in general the highest correlations with all parameters. Not all the ten indices are necessary, as they all present similar information. In a factor analysis, the most informative parameters were identified as key parameters (Table 3.61). Basically two groups could be identified. One group describes the recent precipitation conditions of the few days before the event. This group includes the parameters AP_1 to AP_5 as well as API_1. The key parameter in this group is AP_1 or API_1, respectively. The other group includes the parameters API_7 to $API_{30,}$ with API_{14} being the key parameter. For further investigations, the calculation of the two parameters API_1 and API_{14} would be sufficient to get adequate information on the short-term and the long-term antecedent rainfall conditions.

Table 3.61: **Results of the factor analyses for antecedent precipitation characteristics, Jhikhu Khola**

Sites	API_1*	API_7	API_{10}	API_{14}	API_{30}	AP_1*	AP_2	AP_3	AP_4	AP_5
6_2	(🗝)1	2	2	(🗝)2	2	(🗝)1	1	1	1	1
6_7	(🗝)1	2	2	(🗝)2	2	(🗝)1	1	1	1	1
6_8	(🗝)1	2	2	(🗝)2	2	(🗝)1	1	1	1	1
14_13	(🗝)1	2	2	(🗝)2	2	(🗝)1	1	1	1	1

* API_1 and AP_1 represent the same information content: rainfall 24 hours before the event start

Comparing these two indexes API_1 and API_{14} with the hydrological event clusters, it is evident, that cluster 1 events generally show only low antecedent precipitation values for both indexes (Figure 3.97). For API_{14} there is however no difference observed between the antecedent precipitation values of cluster 1 and 2 events. There is likewise no difference observed between the APIs of cluster 1 and 3 at Sites 8 and 13. Cluster 2 events tend to show medium values for API1. The largest API values are observed in both cases for the large events of cluster 3, suggesting that the characteristic large flow volume over a period of time mainly occurs during wet conditions. Cloud breaks and intense storms with high rainfall intensities however depend less on these wet preconditions.

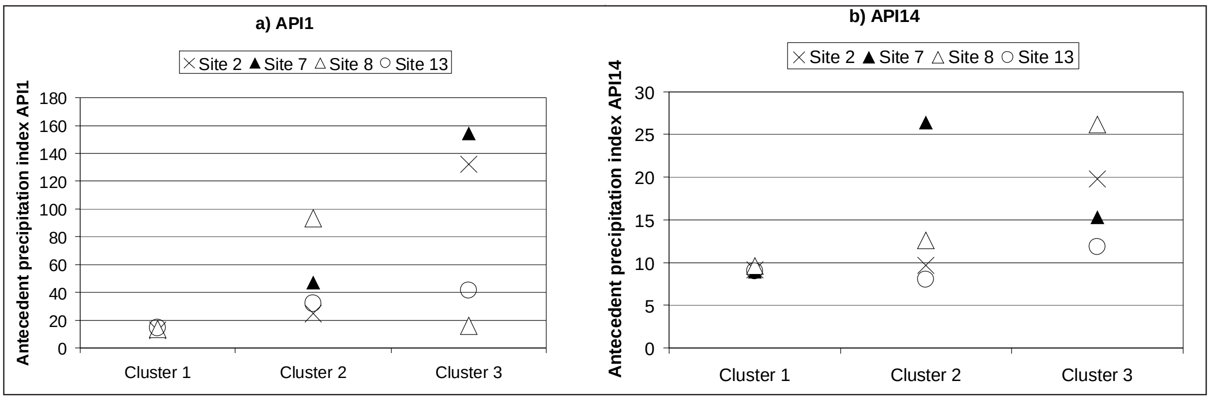


Figure 3.97: **Antecedent precipitation in comparison with discharge clusters**

Event rainfall characteristics

Rainfall is the main trigger for flood events in the Jhikhu Khola catchment. Whether the magnitude of the event, the volume of the event, or the intensity of the event depends on different rainfall characteristics has to be analytically established.

The correlation matrix presented in Table 3.62 between hydrological event characteristics and parameters describing rainfall events shows that:

Table 3.62: **Correlation of discharge event with rainfall event parameters at Site 2 and number of significant correlations at all sites, Jhikhu Khola catchment (maximum = 4; for detailed matrices in Appendix A3-19)**

	t_Q	Q_{start}	Q_{end}	Q_{tot}	Q_B	Q_E	Q_{Emax}	Q_{max}	Q_E / Q_{tot}	t_{rise}	t_{rec}	α
P_{tot}	0.51(4)	(1)	0.39(4)	0.72(4)	0.54(4)	0.76(4)	0.66(4)	0.65(4)	0.51(4)	0.32(4)	0.49(4)	0.30(3)
t_P	0.47(4)	0.27(4)	0.32(4)	0.47(4)	0.54(4)	0.40(3)	0.21(2)	0.25(3)	(1)	0.52(4)	0.35(4)	(0)
I_{ave}	-0.15(3)	-0.30(2)	(0)	(2)	-0.20(2)	0.16(3)	0.33(4)	0.25(4)	0.50(4)	-0.34(3)	(0)	0.20(3)
I_{10max}	(1)	-0.19(2)	(2)	0.33(4)	(0)	0.44(4)	0.56(4)	0.50(4)	0.60(4)	-0.24(2)	0.18(2)	0.25(3)
I_{30max}	(0)	-0.15(2)	0.20(3)	0.44(4)	0.16(3)	0.56(4)	0.65(4)	0.59(4)	0.64(4)	-0.18(2)	0.24(2)	0.30(3)
I_{60max}	0.21(2)	(1)	0.27(3)	0.55(4)	0.27(3)	0.65(4)	0.71(4)	0.66(4)	0.65(4)	(1)	0.31(3)	0.34(3)
P_{25}	-0.20(2)	-0.19(1)	-0.20(1)	-0.24(2)	-0.29(3)	-0.20(2)	(0)	-0.17(1)	(0)	-0.21(1)	(1)	(0)
P_{50}	-0.16(3)	-0.15(1)	(0)	(0)	-0.17(1)	(0)	(1)	(1)	0.16(2)	-0.21(3)	(1)	(0)
P_{75}	(1)	(0)	(0)	0.18(2)	(0)	0.27(3)	0.34(3)	0.28(3)	0.38(3)	-0.16(1)	(1)	(1)

- the duration parameters t_Q, t_{rise} and t_{rec} are only strongly correlated to the rainfall duration;
- the pre-condition parameters Q_{start} and Q_{end} show often significant, but generally weak correlations;
- the amount parameters Q_{tot} and Q_E show high and significant correlation with P_{tot}— other correlations are mostly significant, but weak;
- the intensity parameters Q_{Emax} and Q_{max} show high correlations with P_{tot} and the rainfall intensity parameters, I_{60max} in particular, with I_{ave} only showing weak correlations;
- the ratio Q_E/Q_{tot} shows high correlations with the maximum intensity parameters I_{10max}, I_{30max} and I_{60max};and
- the runoff coefficient α shows only weak correlations with all rainfall parameters.

Above, in Section 3.4.3, the rainfall events in the catchment were grouped into four clusters on the basis of rainfall amount, rainfall intensity, and rainfall duration. A comparison of the two main parameters of interest, the event runoff Q_E and the peak event runoff Q_{Emax} with rainfall clusters, shows that at all sites the event runoff Q_E tends to be highly dependent on high rainfall amount (Figure 3.98). Q_E of more than 10 mm is exclusively produced by events belonging to cluster 4.

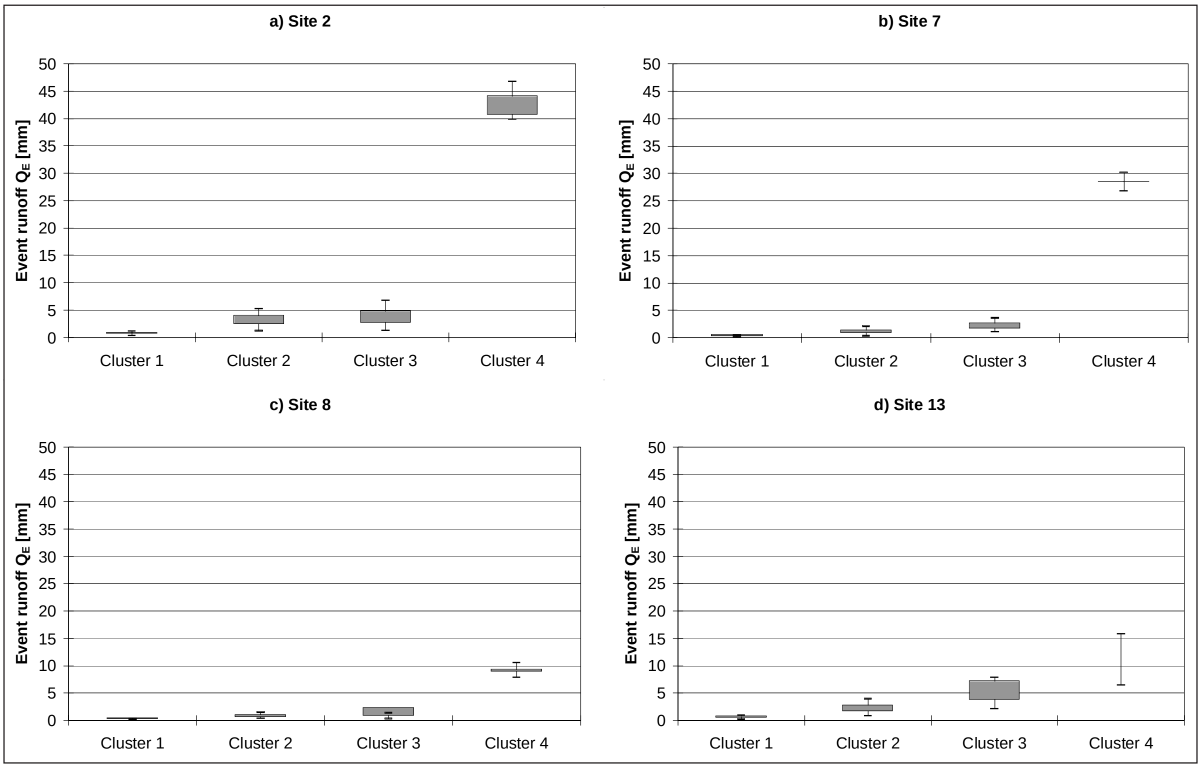


Figure 3.98: **Event runoff Q_E with rainfall clusters at different sites in the Jhikhu Khola catchment**

The peak event runoff Q_{Emax} presents a slightly different picture (Figure 3.99). This parameter is both dependent on the rainfall amount shown with the generally high values for cluster 4 events and rainfall intensity shown by the high values for cluster 3 events. At Site 13 (Figure 3.99d) the cluster 3 events even tend to produce higher Q_{Emax} than the cluster 4 events. This would support the hypotheses that degraded land displays mainly infiltration excess overland flows, as the sub-catchment 13 is highly degraded and gullied (see also Chapter 2).

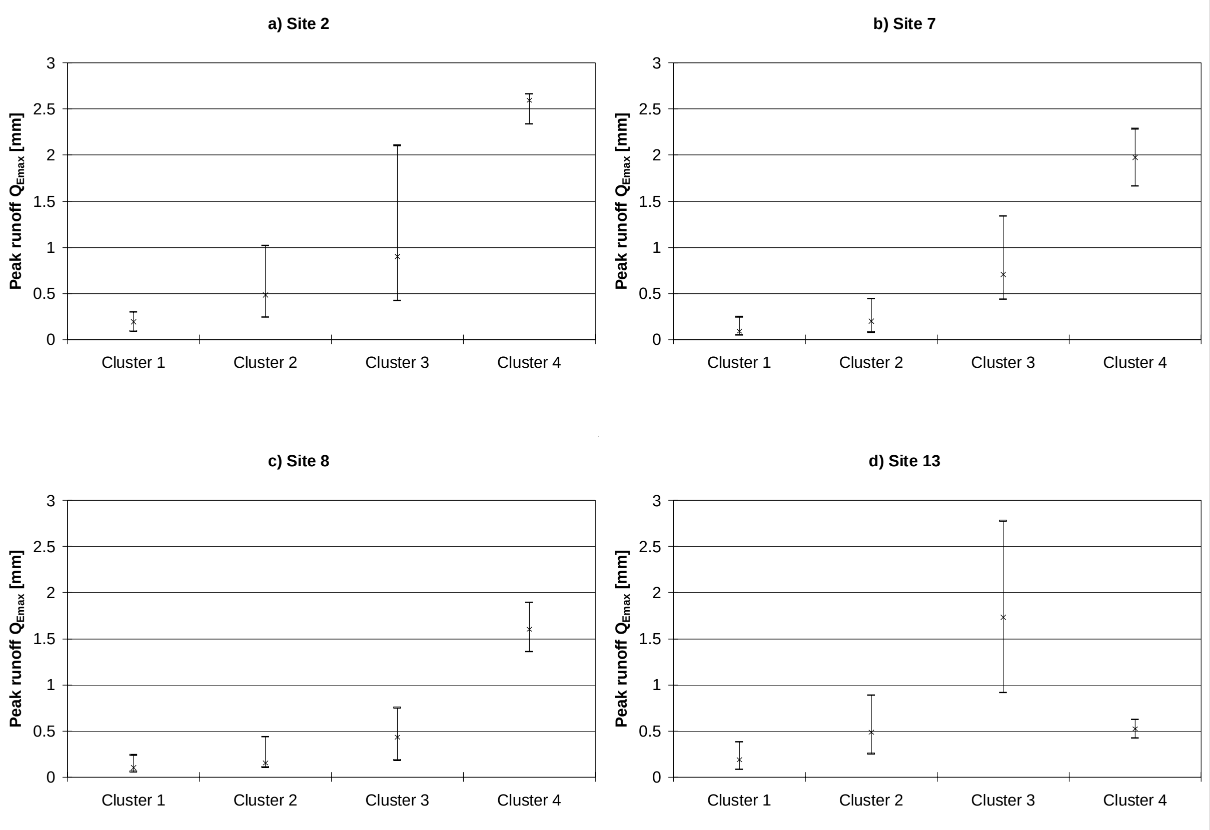


Figure 3.99: **Peak event runoff Q_{Emax} with rainfall clusters at different sites in the Jhikhu Khola catchment**

Comparing the clusters generated on the basis of the rainfall data with the clusters generated with the discharge data, significant correlations can be observed in most sub-catchments (Table 3.63). These correlations, although they are significant at the 0.01 level, are rather weak, with Pearson correlation coefficients between 0.32 and 0.43. The correlation between the rainfall data of Site 6 and the discharge data of Site 8 is not significant. This suggests that Site 6 cannot be used for data analysis with respect to Site 8. In terms of meteorological site development in the catchment, it is proposed that another meteorological site be set up in the catchment of the Upper Andheri Khola, e.g., upgrading Site 20, which at present only includes a standard rain gauge.

Table 3.63: **Pearson and Spearman correlation coefficients between clusters of different origin (in column correlation coefficient: Pearson/Spearman)**

Meteorological station	Hydrological station	Correlation coefficient	Significance
Site 6	Site 2	0.430/0.381	YES (0.01)
Site 6	Site 7	0.328/0.268	YES (0.01)
Site 6	Site 8	0.067/0.105	NO
Site 14	Site 13	0.323/0.363	YES (0.01)

Surface runoff

Surface runoff generation mechanisms were often considered to be a major reason for a flood. For a long time it was considered the only mechanism in flood generation (Horton 1933; Betson 1964). This was however corrected by many authors, who highlighted the importance of subsurface flow in the generation of floods (e.g. Mosley 1979, Pearce et al. 1986).

To assess the role of surface runoff in the Jhikhu Khola sub-catchments and catchments, the relationship between the erosion plot runoff and the runoff at the sub-catchment outlet was determined. The runoff between the agricultural plot at Site 6 showed only a very weak correlation with the sub-catchment event runoff (Figure 3.100a). The relationship between the degraded plot at Site 14 with the sub-catchment runoff at Site 13 on the other hand showed quite a good relationship to a regression coefficient of 0.51.

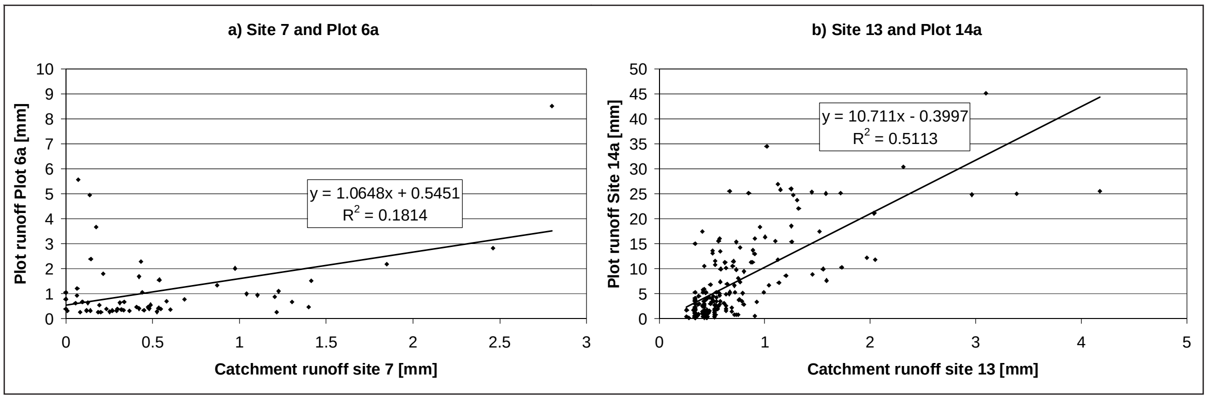


Figure 3.100: **Relationships between erosion plot runoff and sub-catchment runoff (note: difference in scale between a and b)**

A similar analysis was performed on the runoff data of Site 1 in relation to the runoff on all the four plots. Firstly, the temporal distribution of the plot runoff was compared to the runoff at the catchment outlet (Figure 3.101a and b). These graphs show that the runoff on the agricultural plots cannot be accountable for the runoff at the catchment outlet. The runoff on the degraded land on the other hand could provide a considerable input to the floods downstream.

Figure 3.101c and d, showing the relationships between the runoff on the plots and the runoff at the catchment outlet, indicates the same as the figures above. Figure 3.101c only shows a weak correlation with the runoff at Site 1 with a regression coefficient of 0.0053 and 0.0252 for Sites 16 and

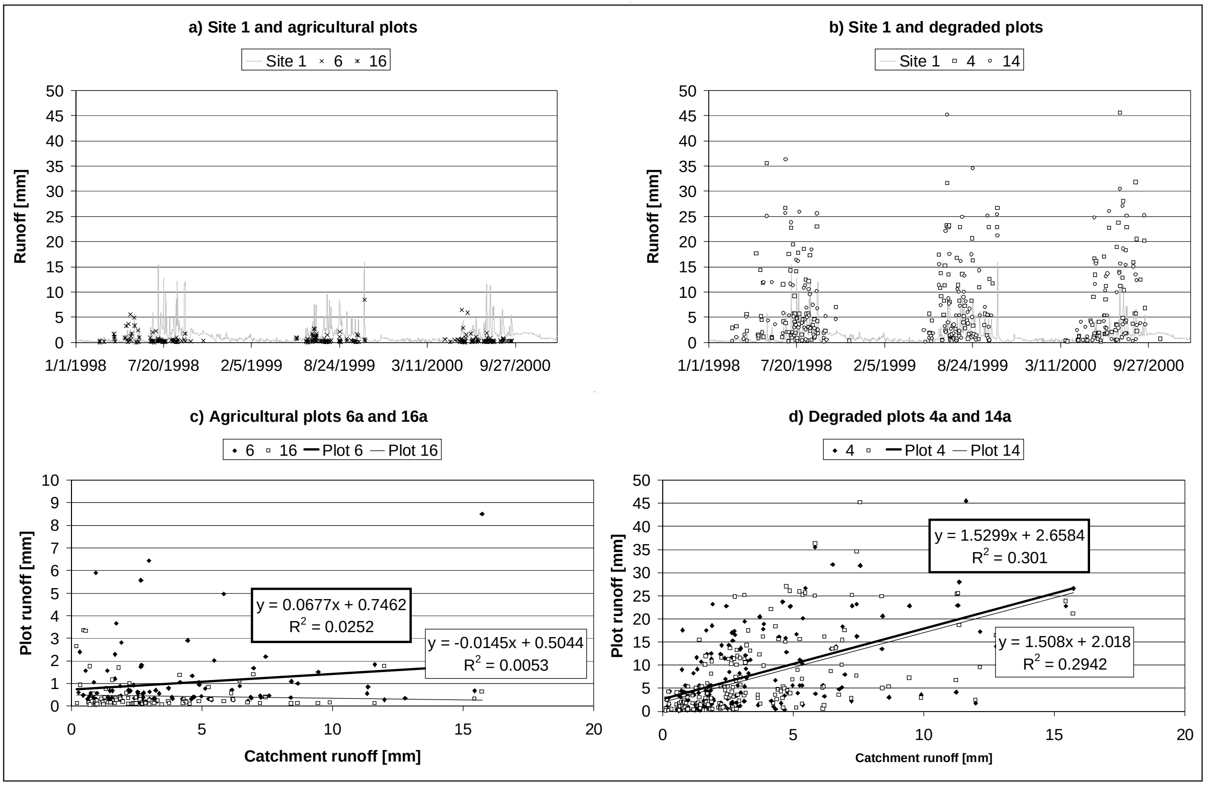


Figure 3.101: **Relationships between erosion plot runoff and catchment runoff at Site 1 (note: difference in scale between c and d)**

6, respectively. The relationships between the degraded plots and the outlet runoff show a much stronger regression, with regression coefficients of 0.30 and 0.29 at Sites 4 and 14, respectively. These results suggest that the degraded areas, or areas showing a similar response to these areas, contribute considerably to the catchment runoff. The agricultural areas, on the other hand, seem to play only an insignificant role in the generation of a flood.

Table 3.64 shows the correlation coefficients according to Spearman for the runoff at the erosion plots at Sites 6 and 14 with the event parameters at the respective catchment outlets at Sites 7 and 13. In the case of Sites 6-7 only a weak correlation was observed for the amount and intensity parameters of the hydrological events. The duration and baseflow parameters do no show any significant correlation. At Sites 14-13 both the amount as well as the intensity hydrological event parameters show a rather strong correlation. This supports the suggestions above, according to which the degraded plots are a main source area for catchment runoff or they show similar conditions to the actual source areas.

Table 3.64: **Correlation coefficients for runoff from the plots with event parameters at the sub-catchment outlet**

Sites*	t_Q	Q_{start}	Q_{end}	Q_{tot}	Q_B	Q_E	Q_{Emax}	Q_{max}	Q_{tot}/Q_E	T_{rise}	T_{rec}
6-7				0.30		0.33	0.33	0.32	0.29		
14-13	0.25		0.47	0.54	0.41	0.56	0.57	0.57	0.53		0.24

* Plot number – hydrological station number

3.4.5.4 Summary

The hydrological event analyses in the Jhikhu Khola catchment can be summarised as follows.

- An average hydrological event in the Jhikhu Khola has a total event runoff of about 1.5 to 3 mm and a peak event runoff of 0.2 to 0.4 mm. The event runoff accounts for about 40 to 60% of the total event runoff. The events further show very fast rising limbs of about 1 hour.
- The largest events at all sites show more than 5 mm total runoff, of which about 65 to 90% can be accounted for as direct event runoff. The rising limb is about 1 hour with the exception of Site 1, where the rising limb lasts about 3 to 4 hours.
- Pre-monsoon events are based relatively more on event runoff than monsoon events.
- Most events occur during the monsoon season.
- The strongest correlations between hydrological event parameters are observed for Q_{tot}, Q_E, $Q_{Emax,}$ and Q_{max}.
- The key variables for hydrological events are t_Q, $Q_{Emax,}$ and Q_{start}.
- Three clusters can be identified on the basis of the key variables and Q_{tot} with the following descriptions.
  - ❖ **Cluster 1 - minor:** short to medium duration – small runoff volume – small peak
  - ❖ **Cluster 2 - large peak:** short to medium duration – medium to large runoff volume – large peak
  - ❖ **Cluster 3 - large volume:** long duration – large runoff volume – small peak

- The APIs generally show a weak correlation with the hydrological event parameters. Nevertheless, API_1 increases with clusters showing the highest API_1 values for cluster 3 of the hydrological events. No distinct pattern is observed for API_{14}.
- Rainfall volume shows a significant and strong correlation with the amount and intensity parameters of a hydrological event.
- The maximum rainfall parameters show strong significant correlation to the intensity parameters of a hydrological event.
- The event runoff Q_E depends largely on rainfall volume shown with high Q_E values for rainfall cluster 4.
- The peak event runoff Q_{Emax} depends largely on rainfall volume and rainfall intensity shown with high values of Q_{Emax} for rainfall clusters 3 and 4.

- Surface runoff on the degraded plots is rather strongly correlated with the runoff at the sub-catchment outlets.
- Surface runoff on the agricultural plots is only weakly correlated with the runoff at the sub-catchment outlets.

3.4.6 Precipitation event analyses in the Yarsha Khola catchment

3.4.6.1 Description of the rainfall events

During the three complete years from 1998 to 2000, where meteorological monitoring was carried out in the Yarsha Khola catchment, 472 rainfall events were identified at Site 5 at an altitude of 2300 masl. (Table 3.65). At Site 6, 1960 masl, 410 events were identified during the same study period. At the lowest site with three years' data available, Site 9 at 1420 masl, 368 events were identified. Most of the events — 73 to 74% of total events — occurred during the monsoon season. In the pre-monsoon season about 21 to 23% of all events occurred. The remaining events occurred during the post-monsoon season (3%) and in winter (1%).

Table 3.65: **Events at selected sites (in brackets: no of missing days)**

Site	Period	Pre-monsoon	Monsoon	Post-monsoon	Winter	Total
5	1998 - 2000	106 (0)	346 (15)	14 (0)	6 (0)	472 (15)
6	1998 - 2000	88 (37)	305 (0)	12 (0)	5 (0)	410 (37)
9	1998 - 2000	85 (3)	269 (0)	11 (0)	3 (0)	368 (3)

Annually, about 120 to 160 events occur on average at the three sites, with about 30 events in the pre-monsoon season, 90 to 120 events in the monsoon season, about 5 events in the post-monsoon season, and 1 to 2 events in winter. This corresponds to about 22, 74 , 3 and 1% in all seasons, respectively. However, it has to be noted that the study period was wetter than normal as shown in Section 3.1 and a considerable difference could be observed in a drier year.

Most of the events during the study period were between 2 and 25 mm (Figure 3.102), with no distinct difference in frequency between the three classes 2-5 mm, 5 -10mm and 10 -25 mm. Of the total events, 25 to 30% belonged to each of these classes. At Site 9, events between 2 and 5 mm occurred slightly more often and accounted for about 35% of all events. At both Sites 6 and 9, events between 5 and 10 mm were observed less frequently than events between 2 and 5 mm, or 10 and 25 mm.

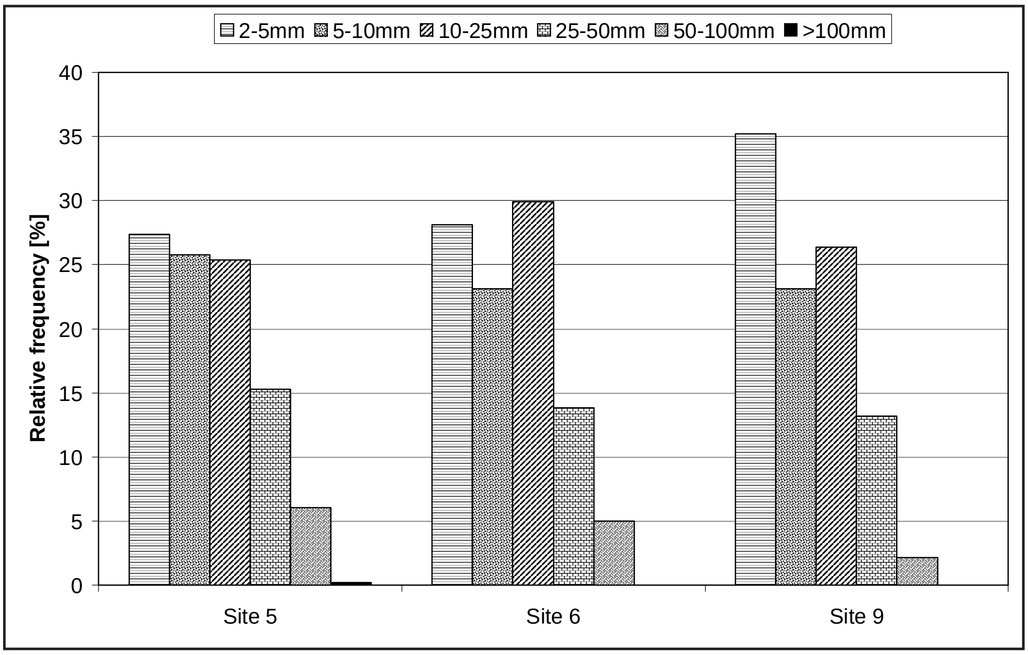


Figure 3.102: **Relative frequency of rainfall events in the Yarsha Khola catchment**

A brief characterisation of all the events in the Yarsha Khola catchment shows that their rainfall amount generally tends to be around 9 mm, event duration is typically about 3 to 4 hours, and the average intensities are about 3 mm/h (Table 3.66). Maximum intensities are around 2.5 mm/10 min (=15 mm/h) for the 10-minute maximum intensity, 4 mm/30min (=8 mm/h) for the 30-minute maximum intensity, and 5 to 6 mm/h for the 60-minute maximum intensity. The distribution of rainfall during an event shows that, on average, 30% of the total event rainfall falls during the first 25% of the event duration. Another third occurs in the second quarter and about 20 to 25% occurs in the third quarter of the event duration.

Table 3.66: **Median of different event parameters considering all events**

Site	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10min]	I_{30max} [mm/30min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
5 (497)	9.2	221	3.0	2.6	4.4	5.9	29.4	62.7	86.7
6 (441)	9.6	234	2.8	2.6	4.2	5.6	31.3	62.4	87.9
9 (371)	8.2	193	2.8	2.2	3.8	4.8	34.0	62.5	86.7

Event rainfall amount in the Yarsha Khola ranged at all selected sites between a 25% quartile of 4 to 5 mm to a 75% quartile of 17.3 at Site 9 and about 21 mm at Sites 5 and 6 (Figure 3.103a). The maximum rainfall intensity for 10 minutes ranged from about 1.5 mm/10 min to about 4 to 5mm/10 min, which corresponds to 9 mm/h to 24 to 30 mm/h (Figure 3.103b).

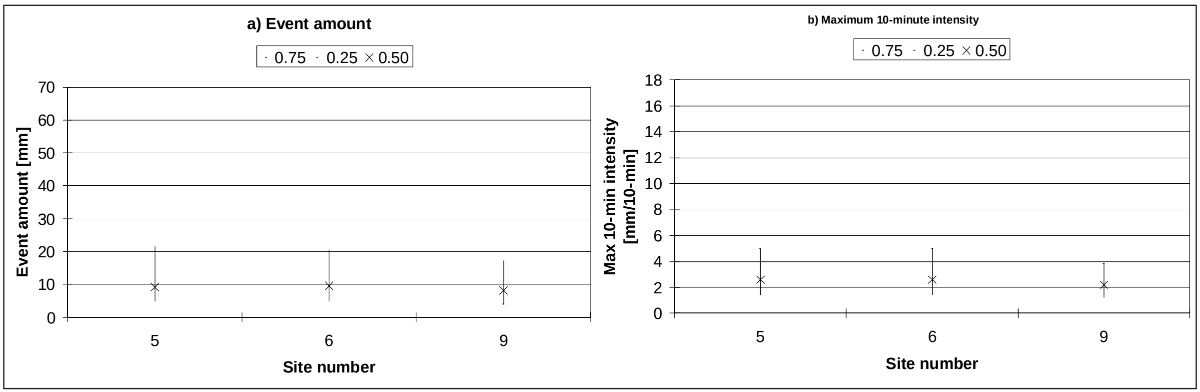


Figure 3.103: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution for all events at selected sites**

The typical event in the Yarsha Khola catchment therefore has the following characteristics.

- Rainfall is about **9 mm** in quantity;
- The event is from about **3 to 4 hours** in duration;
- It has about **3 mm/h** average intensity, with 10-minute maximum intensities of **2.5 mm/10 min**; 30-minute intensities of **4 mm/30 min**; and 60 -minute intensities of **5 to 6 mm/60 min**.
- The first quarter of the event sees about **30%** of the rainfall, while **30%** falls in the second quarter, **20 to 25%** in the third quarter, and **15 to 20%** in the last quarter.

Large events, defined as events with rainfall amounts of more than 30 mm, show a median value of about 40 to 45 mm at all sites, with a median of 37 mm at Site 9 at a lower altitude (Table 3.67). The P_{tot} values ranged up to 60 mm at Sites 5 and 6 as indicated by the 75% quartile. At Site 9, the 75% quartile was nearly 50 mm during the study period from 1998 to 2000. Typically, the events last about 8 to 10 hours and have an average intensity of about 5 mm/h. The maximum intensities observed at the three sites were about 6 to 7 mm/10 min for I_{10max}, 12 to 15 mm/30 min for I_{30max}, and 18 to 20 mm/h for I_{60max} on average. The 10-minute maximum intensities ranged from 4 to 10 mm/10 min, which corresponds to 24 to 60 mm/h (Figure 3.104b). The distribution of rainfall over the duration of the event is similar to the distribution as shown for all events above in Figure 3.103. On average, about 30% of the rainfall occurs in the first quarter of the event. In the second quarter another 30% is expected, with about 30% in the third quarter, and approximately 10% of the total rainfall in the last quarter.

Table 3.67: **Median for selected rainfall parameters of large events**

Site	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
5 (82)	44.9	548	5.1	7.0	14.7	19.9	30.1	63.4	90.5
6 (63)	43.6	616	4.6	7.0	14.2	19.6	29.9	68.1	93.0
9 (45)	37.4	497	5.6	5.8	12.6	18.2	28.0	53.0	91.3

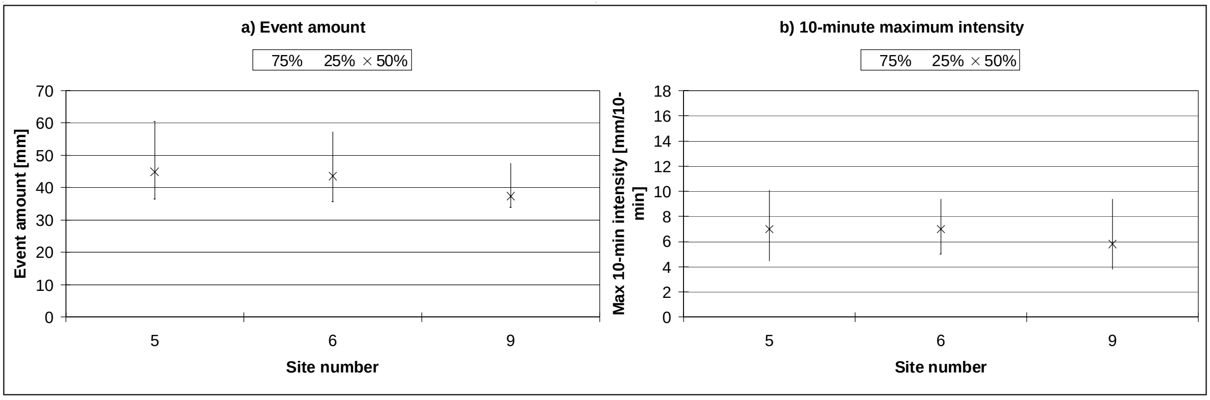


Figure 3.104: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution of large events at selected sites**

The typical large event in the Yarsha Khola catchment can therefore be characterised as follows:

- rainfall of about **40 to 45 mm** in quantity;
- about **8 to 10 hours** in duration;
- with **5 mm/h** average intensity, with 10-minute maximum intensities of **6 to 7 mm/10min**; 30-minute intensities of **13 to 15 mm/30min;** and 60-minute intensities of **18 to 20 mm/60min**.;
- having about **30%** of rain falling in the first quarter of the event, **30%** in the second quarter, **30%** in the third quarter and **10%** in the last quarter.

As shown above, most of the events occur during the monsoon period followed by the pre-monsoon season. For this reason, the large events occurring during these two seasons are compared in Table 3.68. There is no distinct difference visible between the two seasons events in terms of event rainfall amount P_{tot}. In general, a median of 38 mm to 45 mm was observed at the three sites corresponding to the values determined for all events above in Table 3.66. The range of the event amount does not show any distinct difference between the two seasons (Figure 3.105a). The pre-monsoon events tend to be of shorter duration than the large events in the monsoon season, which additionally causes a slight difference in average intensity and higher values for this parameter in the case of the pre-monsoon events. A distinct difference is observed in terms of maximum intensity parameters. While the pre-monsoon events have a median of 10 to 12 mm/10 min in the case of I_{10max}, the monsoon events only show a median value of 5 to 7 mm/10 min. This corresponds to median values of 60 to 72 mm/h in the case of pre-monsoon events and 30 to 42 mm/h in the case of monsoon events. (This difference was also observed with the ranges of this parameter presented in Figure 3.105b.) The pre-monsoon event's 75% quartile reaches up to 20 mm/10 min or 120 mm/h at Site 6 during the pre-monsoon season.

Table 3.68: **Rainfall event parameters (median) for large pre-monsoon and monsoon events**

Site	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
5PM (11)	45.6	340	6.5	10.8	20.2	25.0	31.1	64.0	94.0
M (69)	44.2	589	5.0	7.0	14.6	19.6	30.1	64.9	90.7
6PM (8)	40.1	256	10.4	12.1	22.3	28.0	58.1	90.7	96.9
M (52)	43.9	621	4.5	6.7	14.1	19.1	29.2	60.9	92.5
9PM (8)	38.5	349	6.6	9.6	20.6	27.6	71.7	77.6	93.5
M (35)	36.8	526	5.5	5.2	12.2	17.2	23.4	51.3	91.1

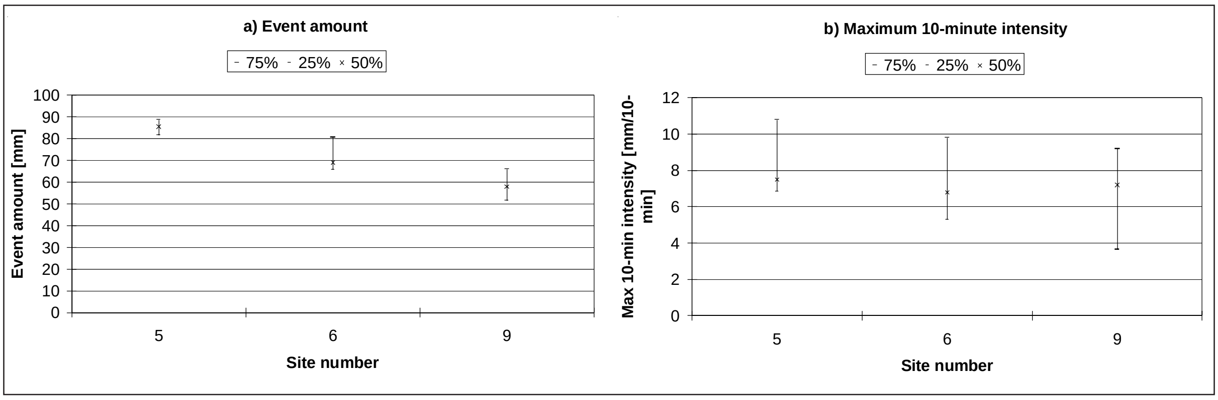


Figure 3.105: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10 min] distribution for large pre-monsoon and monsoon events at selected sites**

At Site 5, values of more than 15 mm/10 min or 90 mm/h were observed in the pre-monsoon seasons of the study period. The I_{10max} values at Site 9 reached a 75% quartile of about 13 mm/10 min or 78 mm/h. During the same study period, large monsoon events only showed median values for I10max of between 5 and 6 mm/10 min (=30 mm/h to 36 mm/h; Figure 3.105b). The highest 75% quartile during the monsoon season was observed with 9.8 mm/10 min at Site 5, corresponding to 58.8 mm/h.

The typical large pre-monsoon event in the Yarsha Khola catchment therefore has the following characteristics:

- rainfall is about **38 to 45 mm** in quantity;
- the events is about **4 to 6 hours** in duration;
- average intensity is about **6 to 10 mm/h,** with 10-minute maximum intensities of **10 to 12 mm/10min**; 30-minute intensities of **20 to 22 mm/30 min**; and 60-minute intensities of **25 to 30 mm/60 min.**
- There is no distinct pattern of rainfall distribution over the event period.

The typical large monsoon event in the Yarsha Khola catchment can be described as follows:

- experiencing rainfall of about **38 to 45 mm** in quantity.
- about **9 to 10 hours in** duration;
- about **4 to -6 mm/h** average intensity, with 10-minute maximum intensities of **5 to 7 mm/10 min**; 30-minute intensities of **12 to15 mm/30 min;** and 60-minute intensities of **17 to 20 mm/60 min.**;
- having **30%** of rain falling in the first quarter of the event, **30%** in the second, **30%** in the third quarter, and **10%** in the last quarter.

The parameters for the ten largest rainfall events observed at the three meteorological sites are presented in Table 3.69 and Figure 3.106. The largest events are observed at Site 5, the highest site at 2300 masl, with a median event amount of 85.5 mm followed by Site 6 with a median event amount of 69 and 57.9 mm at Site 9. At Site 5 the largest 10 events had a 25 to 75% quartile range of 80 to 90 mm. At Site 6, this range was from 65 to 80 mm and at Site 9 it was 50 to 70 mm. The duration of the largest events is between 11 and 13 hours. I_{ave} is similar at all sites with about 5.5 mm/h. Median I_{10max} varied only slightly between the three sites, ranging from 6.8 mm/10 min at Site 6 to 7.5 mm/10 min at Site 5. The range from the 25 to the 75% quartile was from 7 to 11 mm/10 min at Site 5. The range at Site 6 was 5 to 10 mm/10 min, and at Site 9 from 4 to 9 mm/10 min. I_{30max} ranged from 13 to

Table 3.69: **Rainfall event parameters (median) for 10 largest events in the Yarsha Khola catchment**

Site	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	P_{25} [%]	P_{50} [%]	P_{75} [%]
5	85.5	881	5.4	7.5	17.9	27.7	31.6	69.7	87.2
6	69.0	785	5.4	6.8	13.5	20.3	26.9	59.8	87.9
9	57.9	667	5.7	7.2	17.8	23.2	23.9	59.3	91.0

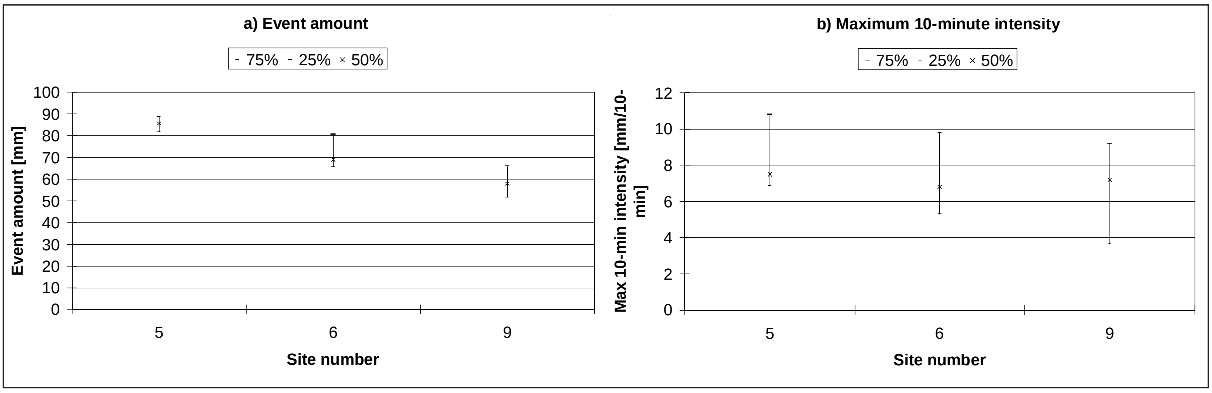


Figure 3.106: **1st (25%), 2nd (50%) and 3rd (75%) quartiles for event amount [in mm] and maximum 10-min intensity [mm/10-min] distribution for the 10 largest events at selected sites**

18 mm/30 min, with the lowest intensities again observed at Site 6. For I_{60max} the medians ranged from 20 to 28mm/h and the lowest values were observed at Site 6. The distribution of rainfall does not differ greatly between the sites, and in comparison with all events, large events, or large monsoon events. About 25 to 30% of the total event rainfall occurs in the first quarter. The second quarter sees about another 30% of the total rainfall and in the third quarter about 20% was observed.

3.4.6.2 Relationship between the different precipitation parameters

The event rainfall amount P_{tot} is strongly correlated with the maximum intensity parameters I_{10max}, $I_{30max,}$ and I_{60max} (Table 3.70). The maximum intensity parameters are further significantly and strongly correlated amongst themselves. The remaining parameters are only weakly or insignificantly correlated. The shape parameters P_{25}, $P_{50,}$ and P_{75} in particular show only very weak correlations with the other parameters.

Table 3.70: **Rainfall event parameter correlation analysis for Site 6 and number of significant correlations for all sites in brackets (detailed correlation matrices in Appendix A.3.21; maximum = 3)**

	P_{tot}	t_P	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}
P_{tot}	1.00(3)	0.62(3)	0.40(3)	0.72(3)	0.82(3)	0.89(3)	(2)	(0)	0.28(3)
t_P		1.00(3)	-0.41(3)	(1)	0.18(3)	0.28(3)	-0.15(3)	-0.12(2)	(0)
I_{ave}			1.00(3)	0.74(3)	0.72(3)	0.67(3)	0.12(2)	0.24(3)	0.34(3)
I_{10max}				1.00(3)	0.96(3)	0.90(3)	0.10(2)	0.26(3)	0.43(3)
I_{30max}					1.00(3)	0.97(3)	(0)	0.22(3)	0.43(3)
I_{60max}						1.00(3)	(0)	0.18(3)	0.41(3)
P_{25}							1.00(3)	0.73(3)	0.35(3)
P_{50}								1.00(3)	0.63(3)
P_{75}									1.00(3)

The factor analyses in this catchment using the principal component approach for extraction of the factors and the varimax method for rotation (StatSoft 1999), result in the following grouping and key variables (see also Table 3.71):

- P_{tot}, I_{ave}, I_{10max}, I_{30max} (🔑), I_{60max}
- t_P (🔑)
- P_{25}, P_{50} (🔑), P_{75}

Roughly the same grouping resulted as in the Jhikhu Khola catchment, with the exception of P_{tot}, which belongs here to the intensity parameters and in the Jhikhu Khola catchment it formed a group with the event duration t_P. The key variables are the same as in the Jhikhu Khola catchment.

Table 3.71: **Key variables (⊶) for precipitation, Yarsha Khola catchment**

	P_{tot}	t_P	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}
3	1	(⊶)3	3	1	(⊶)1	1	2	(⊶)2	2
4	1	(⊶)3	1	1	(⊶)1	1	2	(⊶)2	2
6	1	(⊶)3	1	1	(⊶)1	1	3	(⊶)3	3

On the basis of the factor analysis above, and the result of the correlation analysis which showed that the event rainfall amount, P_{tot} , showed the strongest correlations, the four variables P_{tot}, t_P, $I_{30max,}$ and P_{50} were used for the cluster analysis applying the k-means' cluster approach. As in the Jhikhu Khola catchment, several trials showed that four clusters gave the best results. Table 3.72 shows the cluster centres for the different clusters and the different variables as identified through the k-means' cluster approach.

On the basis of these cluster centres and the cluster identification for each case, the final clusters were determined as shown in Table 3.73. These clusters can be described as follows.

Cluster 1: Minor
Low amount – short duration – low maximum intensity rainfall event
Cluster 2: Medium
Low to medium amount – short to medium duration – medium intensity rainfall event
Cluster 3: High intensity
Medium to high amount – medium duration – high intensity rainfall event
Cluster 4: Large
High amount – long duration – medium intensity rainfall event

Table 3.72: **Cluster centres of different parameters at different sites, Yarsha Khola catchment**

Site	Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
5	P_{tot}	6.6	23.8	50.9	60.4
	t_P	171	479	366	1035
	I_{30max}	3.8	9.0	24.1	10.8
	P_{50}	56.3	59.4	73.9	53.9
6	P_{tot}	6.2	16.5	33.4	52.4
	t_P	187	195	685	291
	I_{30max}	3.2	8.9	7.8	28.1
	P_{50}	53.8	81.7	53.8	82.0
9	P_{tot}	6.6	23.8	26.4	54.0
	t_P	176	701	237	646
	I_{30max}	3.4	5.1	14.1	15.4
	P_{50}	60.8	47.2	66.0	61.1

The distribution of rainfall events is given in Figure 3.107 (a&b). Most events belong to cluster 1, about 66.3% of all events (Figure 3.107b). Of all events, 18.5% belong to cluster 2, 11.3% to cluster 3, and the remaining 3.8% to cluster 4. Seasonally, there is no distinct difference visible between the occurrence of different clusters (Figure 3.107a). Cluster 3 events during the pre-monsoon, accounting for overall 2.1 and for 19. 6% of the cluster 3 events, seem to occur slightly more frequently than expected. There is a clear decrease in events from clusters 1, 2, 3, to 4 during the monsoon season; accounting for overall 45.7 , 15.1 , 8.8 and 3.0%, respectively. This decrease cannot be observed with the same clarity for pre-monsoon events, which were overall 16.3% events as part of cluster 1, 2.3% part of cluster 2, 2.1% part of cluster 3, and 0.5% part of cluster 4.

Table 3.73: **Final clusters for rainfall events, Yarsha Khola catchment**

	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	Min	Max	Min	Max	Min	Max	Min	Max
P_{tot}	3.2	10.1	12.0	30.4	20.0	69.8	26.7	69.2
t_P	77	308	80.0	760.0	147.3	507.3	586.5	1121.0
I_{30max}	1.8	5.0	3.0	13.6	10.7	44.4	5.1	19.4
P_{50}	20.0	79.5	6.9	92.3	20.2	94.6	10.1	68.8

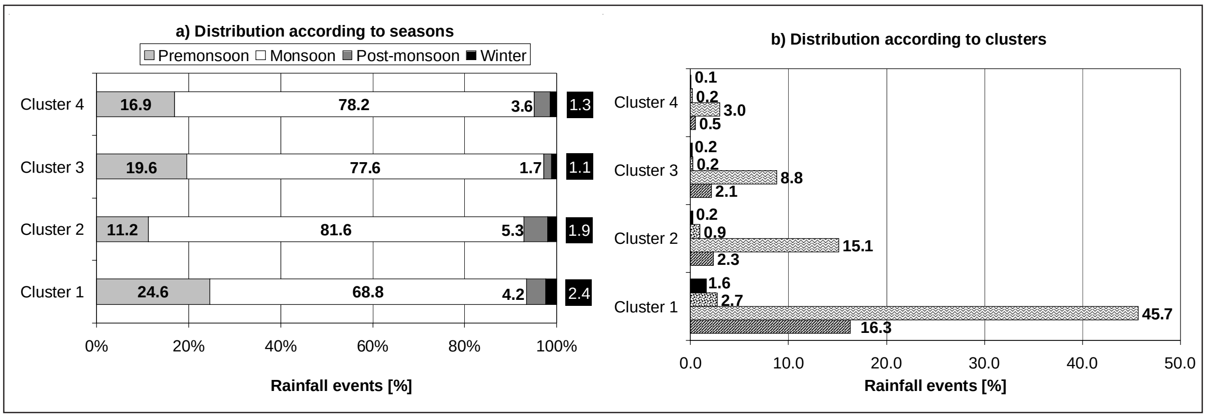


Figure 3.107: **Distribution of rainfall events according to the different seasons and clusters**

On the basis of these observed frequencies, annually about 120 to 160 events can be observed in the Yarsha Khola catchment on the basis of the data from the three selected sites (see above). These events occur in the following seasons and belong to the following clusters (for details see Table 3.74):

Table 3.74: **Annual frequencies of events of different clusters**

	Pre-monsoon				Monsoon				Post-monsoon				Winter			
Cluster	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Site 5	28.7	4.0	2.3	0.3	65.3	35.0	7.7	7.3	4.3	0.3	0.0	0.3	1.3	0.3	0.0	0.0
Site 6	20.7	6.3	1.0	1.0	63.7	18.0	2.0	18.0	1.7	1.7	0.0	0.7	1.3	0.0	0.0	0.3
Site 9	21.7	0.3	5.3	0.7	62.7	12.0	11.0	4.0	2.3	0.7	0.3	0.3	0.7	0.3	0.0	0.0
Catchment	23.7	3.6	2.9	0.7	63.9	21.7	6.9	9.8	2.8	0.9	0.1	0.4	1.1	0.2	0.0	0.1

- about 31 events occur in the pre-monsoon season of which about 3 events are of the high-intensity type and 1 event is large;
- about 102 events occur in the monsoon season with about 10 large events and 7 high-intensity events on average;and
- during the post-monsoon only 4 events occurred and during the winter only 1 event occurred. These events are generally minor or medium with the exceptional large or high-intensity event.

3.4.6.3 Summary

The rainfall event analyses in the Yarsha Khola catchment can be summarised as follows.

- Annually about 120 to 160 rainfall events are observed, depending on the location in the catchment.
- Most events are between 2 and 15 mm rainfall volume with no distinct differences in terms of occurrence in the three rainfall event classes 2 to 5 mm, 5 to 10 mm, and 10 to 25 mm.
- An average event in the Yarsha Khola catchment has about 9 mm rainfall amount in 3 to 4 hours and a maximum 10-minute intensity of 15 mm/h.
- A typical large event in the catchment has 40 to 45 mm rainfall amount in 8 to 10 hours and a maximum 10-minute intensity of 36 to 42mm/h.
- The key variables for rainfall are event duration t_P, 30-minute maximum intensity $I_{30max,}$ and the rainfall that occurred in the first half of the event P_{50}.
- Four clusters were identified on the basis of P_{tot}, t_P, I_{30max} and P_{50}:
    - **Cluster 1 - Minor:** Low amount – short duration – low maximum intensity rainfall event.
    - **Cluster 2 - Medium:** Low to medium amount – short to medium duration – medium intensity rainfall event.
    - **Cluster 3 - High intensity**: Medium to high amount – medium duration – high intensity rainfall event.
    - **Cluster 4 - Large:** High amount – long duration – medium intensity rainfall events.

- Annually, about 10 high-intensity events are observed on average in the catchment, with 3 such events in the pre-monsoon season and 7 events in the monsoon season.
- Annually, about 11 large events are observed on average in the catchment with about 1 event in the pre-monsoon season, 10 events in the monsoon season, and occasionally an event in the post-monsoon or winter seasons.

3.4.7 Runoff event analyses from the erosion plots in the Yarsha Khola catchment

Note: The land use of each plot is mentioned in all figures and tables below with 'g' for grass land and 'a' for agricultural land.

3.4.7.1 Description of runoff events

In the Yarsha Khola catchment, four plots were monitored during the study period from 1997 to 2000. This included two plots on rainfed agricultural land, Plots 6 and 9a, and two plots on grassland, Plots 5 and 9b. For further details on the plots refer to Section 2.3. The first year of the study period had to be excluded from the analyses of the erosion plot results as this year was incomplete and the observations started on different dates at different plots. For the period from1998 to 2000 about 70 events were observed annually at the two plots at Site 9, Plots 9a and 9b (Table 3.75). The lowest number of events was observed at Site 6, with an average of about 60 events per year. At Site 5, the plot at the highest elevation in the catchment, about 80 events were observed annually.

Table 3.75: **Events on the erosion plots**

	Site 5 (g)				Site 6 (a)				Site 9a (a)				Site 9b (g)			
	Pre	Mon	Post	Win	Pre	Mon	Post	Win	Pre	Mon	Post	Win	Pre	Mon	Post	Win
1997*		7	1	4		10	2	4				2				1
1998	23	61	3	1	12	49	2	1	17	45	2	1	21	45	2	1
1999	13	55	1	1	6	47	2	0	9	55	2	0	9	56	2	0
2000	18	61	3	1	17	39	3	0	21	55	2	0	22	55	2	0

* Incomplete year as plots were established in 1997

Most of the runoff events can be observed during the monsoon season, with on average, about 74% events on all plots. This accounts for about 45 to 60 events depending on the plot. During the pre-monsoon season, about 22% of the total events occur. During the post-monsoon and winter seasons only about 3 and 1% of all the events per annum occur. At this point one should bear in mind that the precipitation at the different sites varied considerably (see also Section 3.1). For a direct comparison, Plots 9a and 9b can be used. The two plots 5 and 6 should not be used for direct comparison, but for support of the findings at the Plots 9a and 9b.

In general, the grassland plots tend to yield more runoff than the agricultural plots (Figure 3.108). Runoff on Plot 9b showed about double the median than the adjacent Plot 9a on agricultural land. The range as shown with the 75% quartile on this plot extends up to 5 mm runoff, while on Plot 9a this quartile is about 2.5 mm.

The largest median is shown by Plot 5a with 1.3 mm (see also Table 3.76), followed by Plot 9b. For direct comparison of all the plots, the runoff coefficient a allows an important observation. The highest a are observed on the two grassland plots, about double of the agricultural plots. The remaining parameters, including the rainfall totals, the event durations, and the maximum infiltration parameters, are all comparable between the different sites. The median duration is about 4 hours and the average intensities measured about 3mm/h.

As shown above, most of the runoff events occur in the rainy seasons of the pre-monsoon and monsoon. A comparison of the medians for the two seasons separately shows:

- monsoon runoff tends to be higher on all plots;
- the runoff coefficients tend to be higher in the monsoon season with the exception of Site 5, where the pre-monsoon a is higher than the monsoon alpha (the same is shown in Figure 3.109);

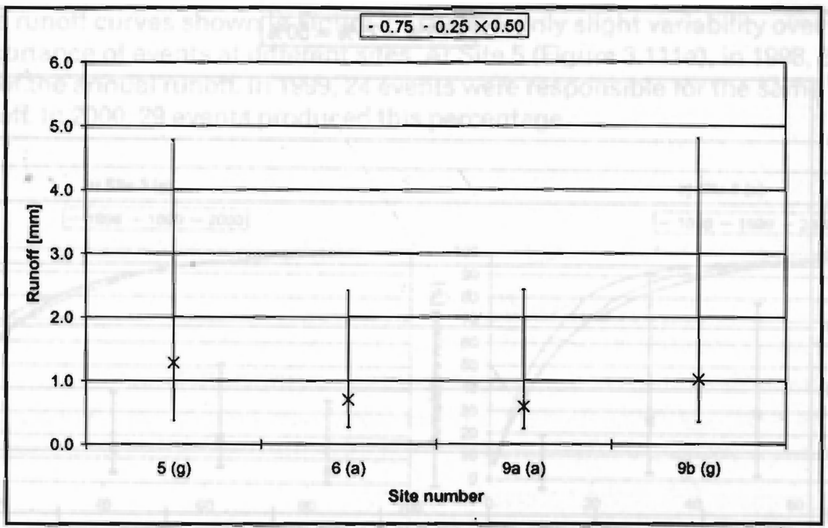


Figure 3.108: Event parameters (1st, 2nd & 3rd quartile) for runoff distribution of all events on the erosion plots in the Yarsha Khola catchment

Table 3.76: **Medians of all runoff events on the erosion plots in the Yarsha Khola catchment**

Site	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	α
5 (g)	1.3	12.4	256	3.2	3.4	5.8	7.4	9.8
6 (a)	0.7	13.4	274	2.9	3.0	5.2	7.0	5.7
9a (a)	0.6	10.6	220	3.2	2.8	5.0	6.4	5.2
9b (g)	1.0	10.3	212	3.2	2.8	4.8	6.4	11.5

- the rainfall events causing runoff in the pre-monsoon season tend to be shorter than in the monsoon season and are much smaller in terms of rainfall amount;
- the average intensities of the rainfall events causing runoff tend to be higher in the pre-monsoon season than in the monsoon season; and
- no particular pattern is observed in the case of the maximum intensity parameters.

The runoff coefficients, as shown above with the median, tend to be higher during the monsoon season (Table 3.77). The same is true for the range of a (Figure 3.109). Plot 9b shows the highest range from 6.4 to 29.5%, followed by Plot 5 with 3.3 to 19.4%. The two plots on agricultural land show a range of 2.2 to 16.2% and 3.6 to 11.9% at Sites 6 and 9a respectively. During the pre-monsoon season at Plot 5, a 25% quartile runoff coefficient of 3.1% was observed, and on the upper end a 75% quartile of 17.0%. The ranges between the 25 and 75% quartiles on Plots 9a and 9b are similar, with 3.3 to 9.6% and 2.4 to 9.0%, respectively.

Table 3.77: **Medians of pre-monsoon and monsoon runoff events on the erosion plots in the Yarsha Khola catchment**

	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	α
5 (g) PM	0.9	8.7	134	4.4	2.8	4.5	6.5	8.1
M	1.6	15.8	329	3.0	3.8	6.8	8.7	7.5
6 (a) PM	0.3	12.6	145	5.2	3.8	6.8	9.0	3.0
M	0.9	14.8	322	2.7	2.6	4.6	6.8	5.8
9a (a) PM	0.3	10.0	178	4.4	3.6	5.0	6.8	3.3
M	0.6	11.2	251	3.0	2.8	5.0	6.4	6.0
9b (g) PM	0.4	9.5	157	4.6	3.5	5.0	6.6	5.0
M	1.7	10.9	249	3.0	2.7	4.7	6.2	14.1

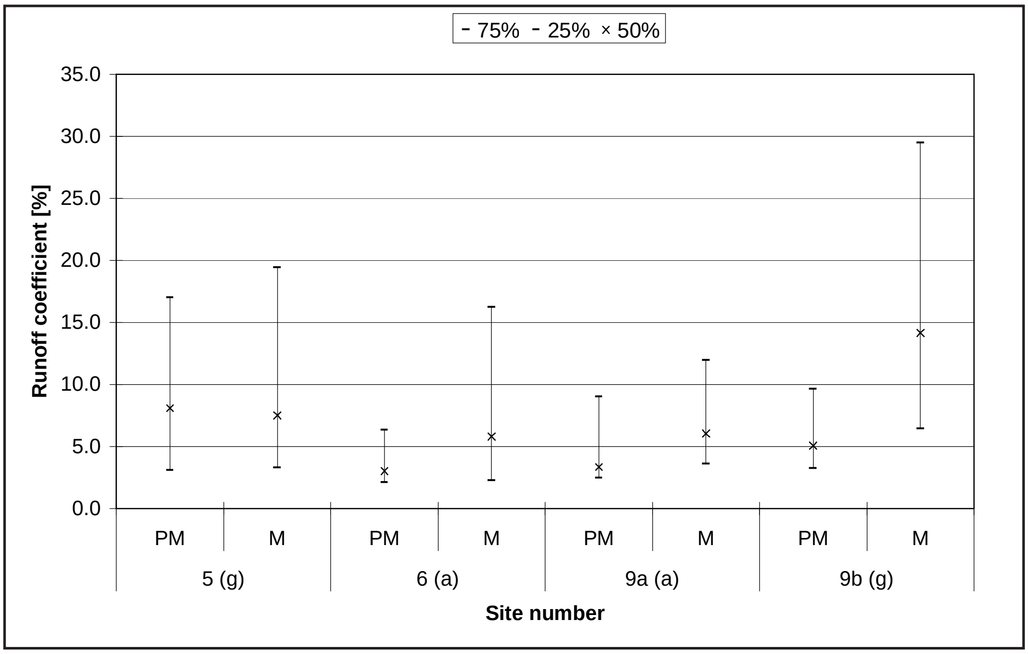


Figure 3.109: **Quartiles of the runoff coefficient distribution of the runoff events on the erosion plots of the Yarsha Khola catchment**

The runoff coefficients do not show any particular difference in terms of temporal distribution between the plots (Figure 3.109). There is a slight difference in terms of pre-monsoon events. They differ slightly, however, in terms of magnitude, with runoff coefficients on grassland being generally bigger than the coefficients on agricultural land. The monthly distribution of runoff coefficients on all plots in the Yarsha Khola catchment is given in Figure 3.110.

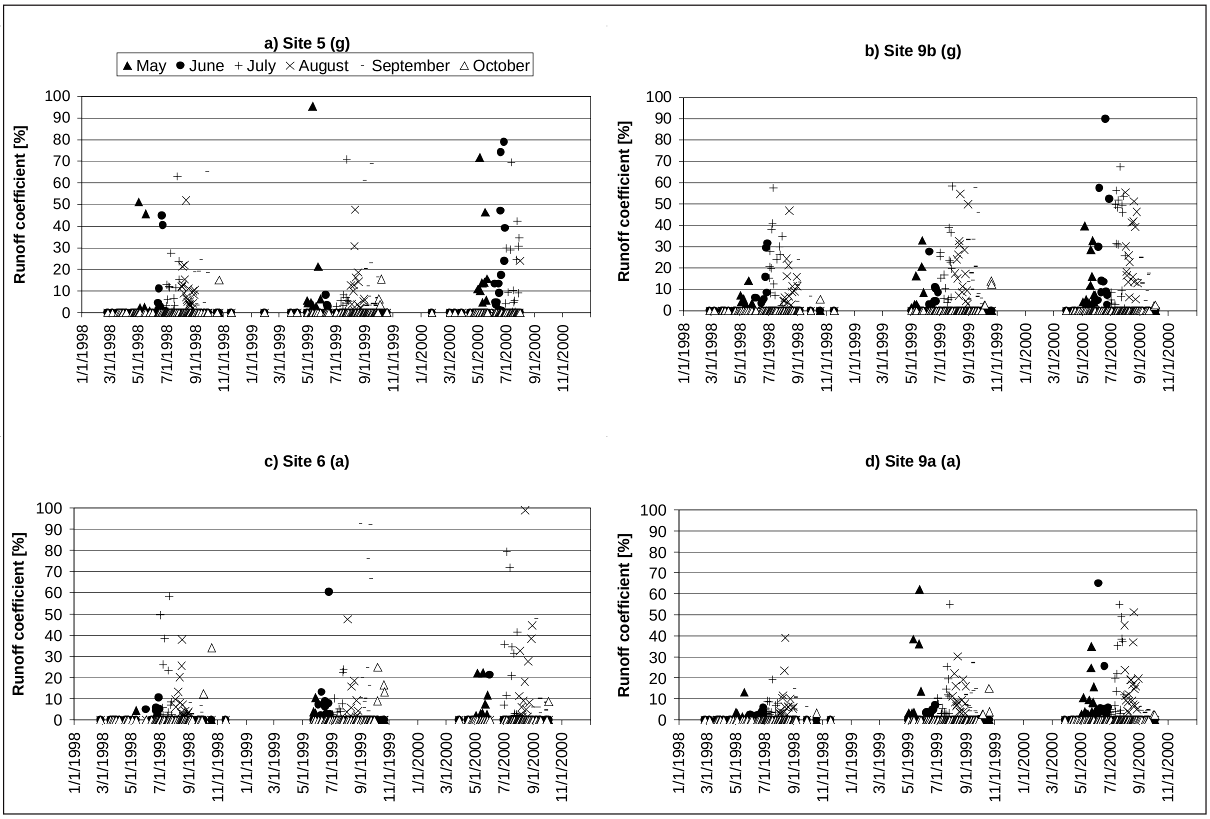


Figure 3.110: **Monthly distribution of runoff coefficients on all plots in the Yarsha Khola catchment**

The cumulative runoff curves shown in Figure 3.111 show only slight variability over the study period in terms of importance of events at different sites. At Site 5 (Figure 3.111a), in 1998, 27 events produced 75% of the annual runoff. In 1999, 24 events were responsible for the same percentage of the annual runoff. In 2000, 29 events produced this percentage.

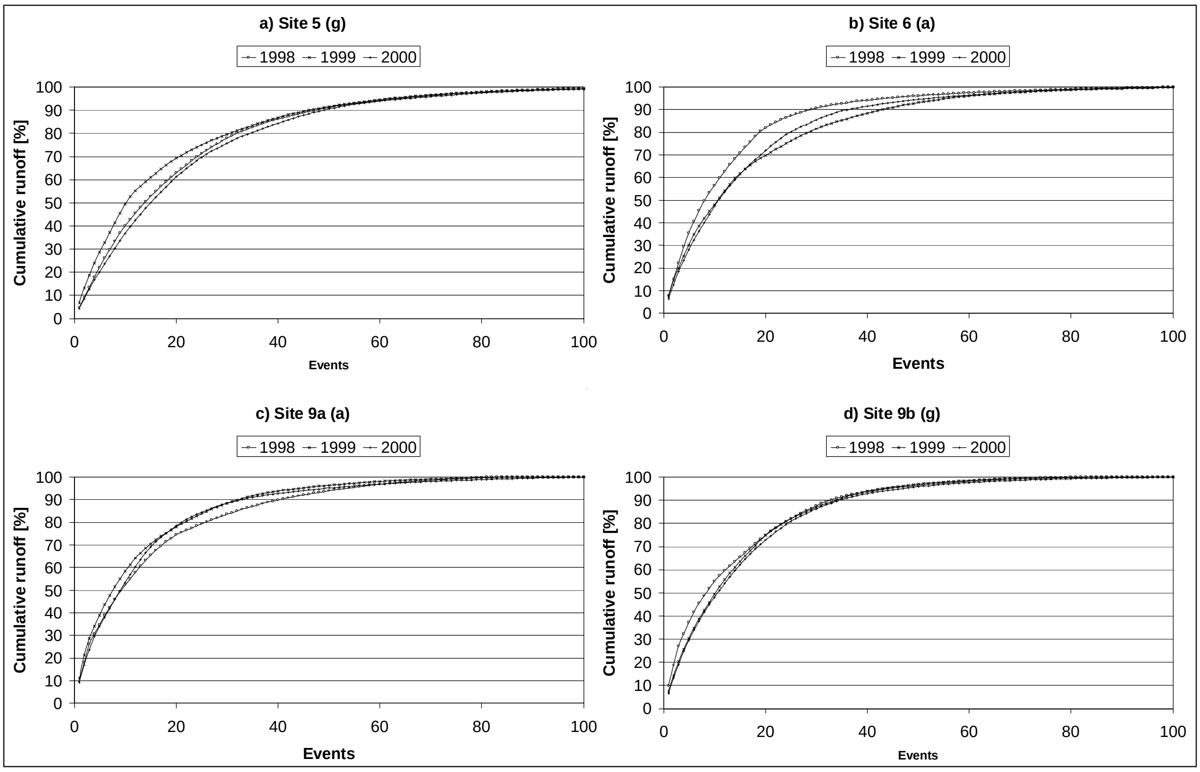


Figure 3.111: **Annual cumulative runoff curves for all erosion plots, Yarsha Khola catchment**

On average, 27 events therefore produce 75% of the annual runoff at this site. At Site 9b, the other grassland plot, an average of 21 events produce this percentage of the annual runoff. The two agricultural plots show a similar number of events, with about 19 events on Plot 9b and 21 events on Plot 6. About 10 events produce 50% of the annual runoff on all plots .

The ten largest events at each plot can be characterised as follows on the basis of their median (Table 3.78):

- runoff varies distinctly between the grassland and the agricultural plots, with 25 to 30 mm runoff on the grassland plots and 12 to 16 mm on the rainfed agricultural plots;
- the runoff coefficients are higher on the grassland plots with 50 to 65%, than on the agricultural plots which have runoff coefficients of 35 to 45%;
- the rainfall parameters vary slightly from plot to plot, for example, the rainfall intensities were higher on Plot 9b than on the other plots and event duration was about 3 to 4 hours at Sites 5 and 6, and about 6 to 7 hours at Sites 9a and b. Rainfall amount ranged from 30 to 50 mm with the lower values at the higher sites rather than at the lower sites.

Table 3.78: **Median of the 10 largest runoff events, Yarsha Khola catchment**

Site	RO [mm]	P_{tot} [mm]	t_P [min]	I_{ave} [mm/h]	I_{10max} [mm/10-min]	I_{30max} [mm/30-min]	I_{60max} [mm/h]	α
5 (g)	29.6	38.5	232	5.9	7.9	15.0	18.0	65.9
6 (a)	15.9	32.9	182	7.1	6.8	14.0	18.7	43.6
9a (a)	11.8	42.4	380	6.5	6.5	15.4	20.3	37.3
9b (g)	26.2	51.3	430	6.3	9.8	20.5	28.7	53.0

The difference between the grassland plots and the agricultural plots can also be shown with Figure 3.112. The plots 9a and 9b show a distinct difference between the runoff volumes of the ten largest events, even though they are located adjacent to each other. On Plot 9a, the agricultural plot, the median runoff is 11.8 mm, ranging from a 25% quartile of 10.8 mm to a 75% quartile of 19.3 mm. The grassland Plot 9b shows a median of 26.1 mm with a range from 23.5 to 28.0 mm for the 25 and 75% quartile respectively. This observation can be supported with the results of Plots 5 and 6. Plot 5, with a very small range between the 25 and the 75% quartile of only 2.2 mm shows a median of 29.6 mm, comparable to Site 9b. At Site 6, a median of 15.9 mm is observed and a range of 13.5 to 20.7 mm. In summary it can be noted that:

- 60 to 80 surface runoff events occurred annually on the plots in the catchment;
- grassland produces generally more runoff than agricultural land;
- grassland generally shows higher runoff coefficients than agricultural land;
- monsoon events tend to produce higher runoff amounts than pre-monsoon events;
- no distinct seasonal difference can be observed between the plots on grass and agricultural land;
- 20 to 30 events produce 75% of the annual runoff;and
- the maximum events on the erosion plots produce on average 25 to 30 mm runoff on the grassland plots and 10 to 20mm on the agricultural plots.

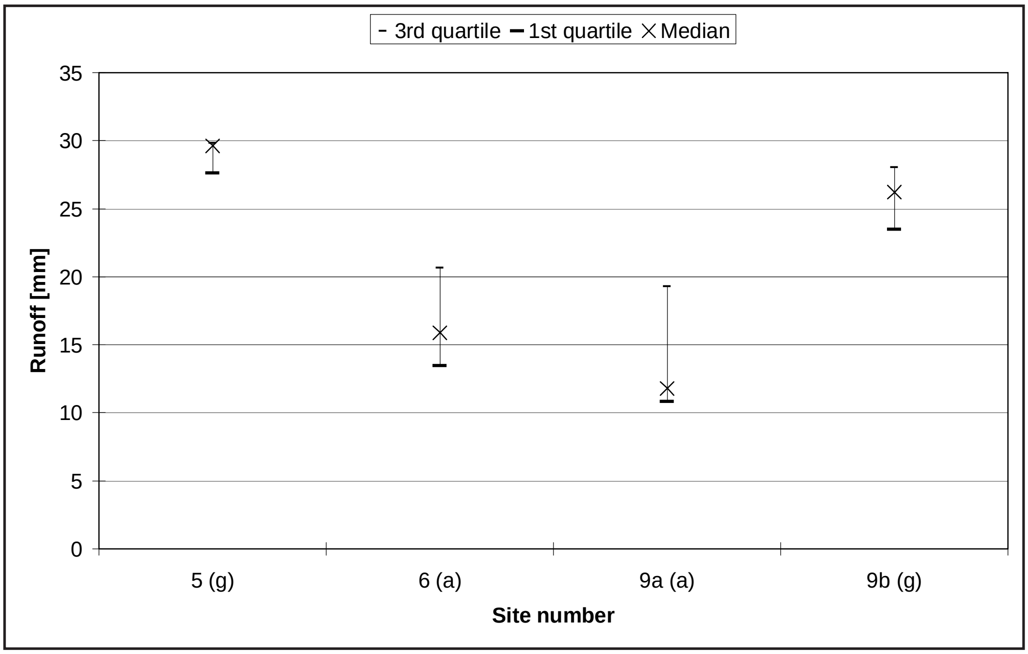


Figure 3.112: **Event parameters (1st, 2nd and 3rd quartile) for runoff distribution of the 10 largest runoff events on the erosion plots in the Yarsha Khola catchment**

3.4.7.2 Causes of the described runoff conditions

No distinct seasonality was observed in the data of the plots in the Yarsha Khola catchment as was found in the data set from the Jhikhu Khola catchment, presented above. The main factors for runoff generation seem to be based on rainfall. This can also be shown with the correlation matrix according to Spearman, as the data are not distributed normally (Appendix A3.22) (Table 3.79). Runoff tends to be strongly correlated with event rainfall amount P_{tot} as well as the maximum intensity parameters I_{10max}, $I_{30max,}$ and I_{60max}. Out of these intensity parameters, I_{60max} shows the highest correlations. However I_{30max} tends to be in a similar order of magnitude. The event duration does not show any strong correlations with runoff, although they are consistently significant. The hyetograph shape parameters do not show, or only show weak correlations with runoff. The antecedent precipitation of 24 hours prior to the event seems to have a good correlation, particularly with the two plots at Site 9. For the other two plots, this correlation is likewise weak. The remaining parameters describing antecedent precipitation are all weaker than AP_1 or API_1.

Table 3.79: **Correlation coefficients for runoff – summary of the four erosion plots in the Yarsha Khola catchment** (grey shaded: agricultural plots)

Site	P_{tot}	t_P	α	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_1	AP_2	AP_3	AP_4	AP_5
5 (g)	0.57	0.33	0.80	0.23	0.42	0.50	0.54				0.33					0.33	0.29	0.19	0.16	
6 (a)	0.55	0.34	0.74	0.22	0.39	0.45	0.49		0.18		0.31	0.31	0.25	0.26	0.20	0.31	0.32	0.34	0.33	0.32
9a (a)	0.82	0.42	0.78	0.38	0.56	0.67	0.73				0.49	0.36	0.31	0.30	0.28	0.49	0.46	0.39	0.38	0.39
9b (g)	0.85	0.39	0.89	0.43	0.61	0.74	0.79				0.54	0.38	0.33	0.35	0.29	0.54	0.52	0.46	0.42	0.41

Above, in the precipitation event analyses for this catchment, four rainfall clusters were identified. A comparison of these clusters with the runoff of the four erosion plots shows a distinct pattern on three of the four plots (Figure 3.113). At Site 5, cluster 3 events generate the highest runoff amounts, suggesting that on this plot infiltration excess overland flow is the most important process for runoff generation. At Sites 9a and 9b , the runoff increases with the clusters and therefore cluster 4 events can be seen as responsible for the largest runoff events. This shows a greater importance of saturation overland flow on these plots. At Site 6, cluster 2, 3, and 4 events generate very similar runoff responses.

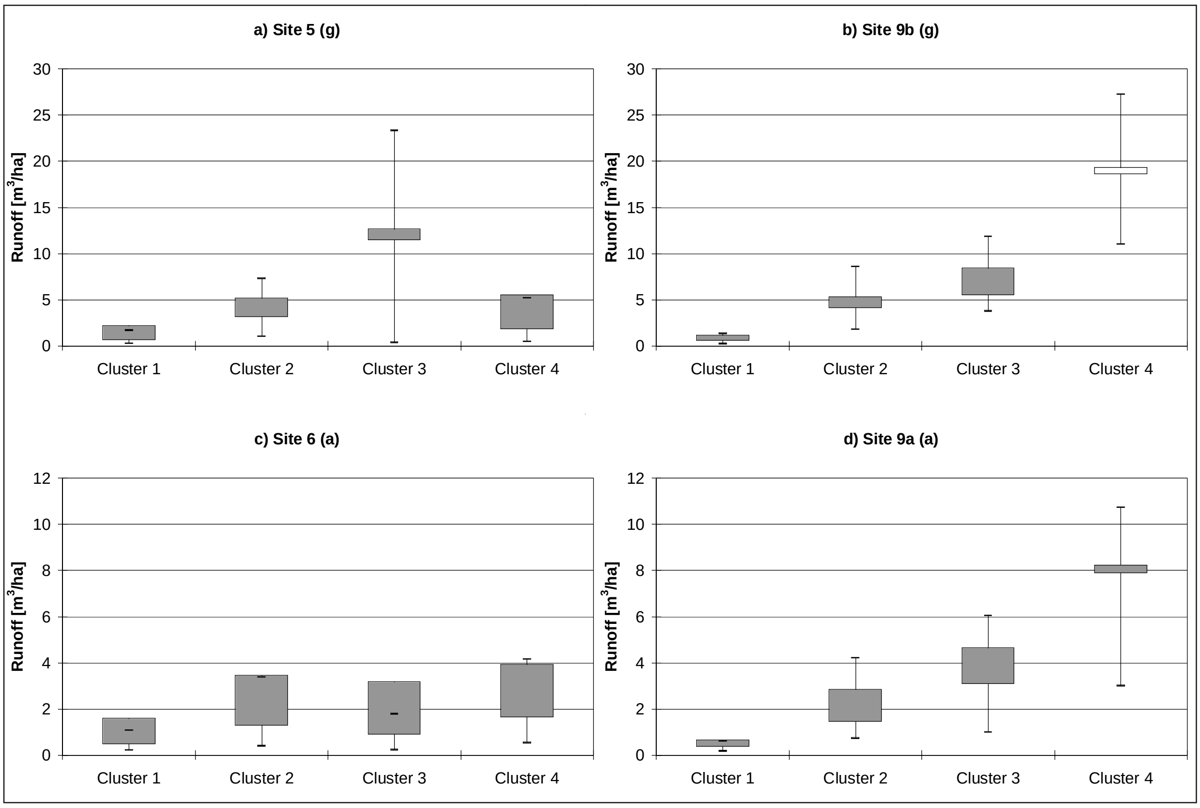


Figure 3.113: **Relationship between runoff from the erosion plots and the rainfall clusters, Yarsha Khola catchment**

As shown above, the results support the idea that saturation excess overland flow is of greater importance on the agricultural land than infiltration excess overland flow. This corresponds to the results from the Jhikhu Khola catchment. On grassland, both infiltration excess and saturation excess overland flows are observed, as shown with the results from the two plots 5 and 9b.

So far, the main differences discussed in terms of plot characteristics are land use. The plots further differ in terms of infiltration rates (Table 3.80). The slopes are very similar and vary within only two degrees. Generally, the soil is a sandy loam with the exception of Site 9a where a loam underlies the plot. As already discussed in the erosion plot event analyses, the infiltration rates shown in Singh (2001) based on ring infiltrometer measurements are used to discuss infiltration measurements based on a 'natural infiltrometer' approach (Table 3.81).

Table 3.80: **Plot and soil characteristics**

Site	Slope [degree]	Textural composition			Textural class	Infiltration rate [cm/h]
		Sand %	Clay%	Silt%		
5 (g)	19.1	63.3	5.9	30.8	sandy loam	3.1
6 (a)	17	67.3	15.9	16.8	sandy loam	16.7
9a (a)	17.5	43.3	23.9	32.8	loam	16.4
9b (g)	17.5	61.9	19.9	18.8	sandy loam	10.8

(source: Singh 2001)

Table 3.81: **Infiltration rates calculated from rainfall events t_P<60min, I_{ave} > 10 mm/h and P_{tot} > 5 mm [all values in mm/h]**

Site	Count	Mean	Median	75% quartile	25% quartile
5 (g)	5	6.1	6.6	9.3	4.2
6 (a)	7	22.1	21.3	26.0	18.9
9a (a)	7	15.4	12.7	18.8	10.9
9b (g)	7	14.4	11.8	18.0	9.5

The infiltration rates calculated on the basis of the erosion plot rainfall-runoff data differ in the order of one magnitude from the ring infiltrometer tests, but show the same pattern with the lowest rates observed at Plot 5, followed by the rates of Plot 9b and Plot 9a, and finally the rates of Plot 6 showing the highest infiltration rates. The infiltration rates in Table 3.81 correspond well with the infiltration rates reported by Hillel (1998). For loams he reports 5 to 10mm/h and for sandy soils 10 to 20mm/h.

3.4.7.3 Summary

The surface runoff event analyses for the data from the erosion plots in the Yarsha Khola catchment can be summarised as follows.

- Annually, 60 to 80 surface runoff events were observed on the four plots.
- Runoff on the grassland plot is generally higher. This is also true for the runoff coefficient.
- The runoff coefficients tend to be higher during the monsoon season than in the pre-monsoon season.
- No distinct temporal variability between the monsoon and the pre-monsoon season is observed in terms of runoff generation on the four plots.
- About 20 to 30 events produce 75% of the annual runoff.
- A comparison of the rainfall clusters with the surface runoff on the plots shows that cluster 3 and 4 events are generally responsible for the surface flow on the plots. While on the agricultural plots saturation excess overland flow prevails, on the grassland both processes are observed.

3.4.8 Hydrological event analyses in the Yarsha Khola catchment

In the Yarsha Khola catchment, four sites were monitored during the study period from 1998 to 2000. One site was located at the outlet of the catchment, one at the outlet of the predominantly north-facing slopes, and two sites in the Khahare Khola sub-catchment in the upland of the south-facing slopes (also see Section 2.4). Below, the hydrological events are described for these four sites and the interrelationships between the different parameters established. Finally, the triggering mechanisms for the events are determined. The relevance of different land use and other catchment characteristics is discussed after this section together with the data from the Jhikhu Khola catchment.

Note: The site numbers used in this section refer to the site numbers in Figure 2.17

3.4.8.1 Description of the hydrological events

For the identification of the hydrological events, the same rule applies as in the Jhikhu Khola catchment. Only the events that could be clearly identified including a clear start and a clear receding limb were used for the analysis below. This resulted in 111 events at the outlet of the catchment at Site 1, 172 events at Site 2 at the outlet of the Gopi Khola sub-catchment, and 116 events at Site 5 in Thulachaur (Table 3.82). Only 46 events could be clearly identified at Site 7. This is due to a lot of background noise and frequent entangling of the floater rope. The results of this site are therefore only indicative and should be considered with caution as these events mainly represent the larger events.

Table 3.82: **Events at all sites in the Yarsha Khola catchment**

Site	Period	Pre-monsoon	Monsoon	Post-monsoon	Winter	Total
1	1998-2000	33	77	1	0	111
2	1998-2000	18	140	7	7	172
5	1998-2000	8	108	0	0	116
(7)	1998-2000	7	38	1	0	46

The majority of the events were observed during the monsoon season followed by the pre-monsoon season. Only very few events were observed during the dry half of the year in the post-monsoon and winter seasons. The events based on the median values of the different parameters differ largely at the different sites and only a few commonalities can be established (Table 3.83). In general, these events last on average between two to three hours at the sub-catchment level and about five to six hours at the catchment outlet. In terms of rising limb $t_{rise,}$ the four sites are very similar with about one to one-and-a-half hours. The receding limb lasts from one to three hours at the sub-catchment sites and four hours at Site 1. The event magnitude expressed with parameters such as Q_{tot}, $Q_{E,}$ and Q_{Emax} tended to be smallest at Site 2, followed by Site 1 and finally the two sites in the Khahare Khola. This suggests the event magnitude per unit area decreases with catchment area (this will be discussed in the next section). As expected, the peak discharge was observed at Site 1.

Table 3.83: **Median of all parameters for hydrological events, Yarsha Khola**

	t_O [min]	Q_{start} [m³/s]	Q_{end} [m³/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m³/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1	330	2.569	4.329	1.9	1.4	0.6	0.2	7.420	0.37	90	240
2	195	1.023	1.640	1.3	1.1	0.2	0.1	2.424	0.16	90	90
5	120	0.068	0.080	3.7	2.2	0.9	0.5	0.176	0.29	60	60
(7)	210	0.226	0.309	4.5	1.9	2.4	0.9	1.398	0.57	60	150

As mentioned above, the highest median event runoffs are observed at the upland sites in the Khahare Khola sub-catchment. The same is observed with the quartile ranges shown in Figure 3.114. At Site 5, the event runoff ranges from a 25% quartile of 0.3 mm to a 75% quartile of 4.0 mm (Figure 3.114a). At Site 1, a range of about 1mm from 0.3 to 1.5 mm was observed. The smallest range is observed at Site 2, with a 25% quartile of 0.1 and a 75% quartile of 0.4.

The peak event runoff Q_{Emax} shown in Figure 3.114b shows the same pattern, with the highest ranges in the upland catchments at Site 5 and 7 and the lowest ranges at Site 2. As most of the events were observed during the two seasons of pre-monsoon and monsoon, their respective events are compared below (Table 3.84 and Figure 3.115). In general, the events during the pre-monsoon season are longer than during the monsoon season. Their total runoff on the other hand is smaller during this season, which is mainly a function of the lower baseflows as indicated by the parameter Q_{start}, $Q_{end,}$ and Q_B. At Site 5, the total runoff Q_{tot} is on average higher during the pre-monsoon season.

The importance of event runoff in comparison with baseflow during the pre-monsoon season is also highlighted by the ratio of Q_E and Q_{tot}. This ratio tends to be higher during the pre-monsoon season, indicating that mainly event runoff from the immediate rainfall event is responsible for this hydrological event. During the monsoon season, baseflow plays a more important role than during

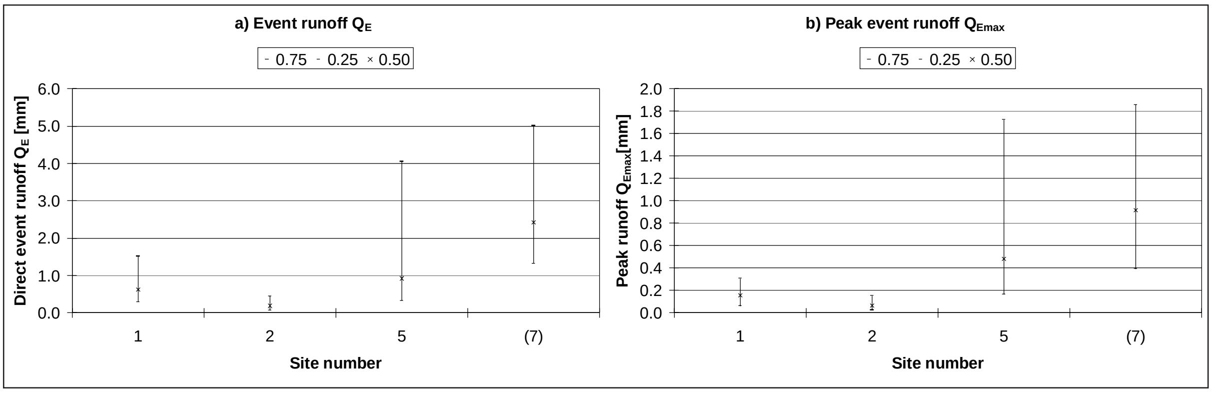


Figure 3.114: **Event runoff (a) and peak event runoff (b) at different sites in the Yarsha Khola catchment**

Table 3.84: **Median of pre-monsoon and monsoon hydrological events, Yarsha Khola**

	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1 PM	330	0.493	0.825	0.6	0.3	0.3	0.0	2.206	0.47	90	240
M	300	4.026	5.661	3.1	2.1	0.9	0.2	11.039	0.35	120	210
2 PM	240	0.134	0.261	0.3	0.2	0.1	0.0	0.381	0.21	90	60
M	180	1.307	1.983	1.4	1.2	0.2	0.1	2.613	0.16	90	90
5 PM	195	0.032	0.039	6.1	2.0	4.1	1.5	0.307	0.69	90	105
M	120	0.068	0.080	3.6	2.3	0.9	0.5	0.176	0.27	60	60
(7) PM	210	0.038	0.086	3.6	0.5	3.2	0.7	0.891	0.79	30	180
M	210	0.228	0.323	5.4	2.2	2.3	1.0	1.488	0.54	60	150

the pre-monsoon season. The rising limb tends to be similar in both seasons, while the receding limb tends to be shorter during the monsoon season.

In terms of event runoff Q_E during the two seasons, it is mainly Site 5 that showed a bigger range during the pre-monsoon season than during the monsoon season (Figure 3.115), which could be explained by the small size of the catchment (most of which is located at high elevations above 2500 masl) and the resulting fast response to intense storms during this season.

The ten largest events at each site are compared in Table 3.85 and Figure 3.116. The median duration of these events is very similar at Sites 2 and 7, at about 4 hours. At Site 1 one of these largest events lasted on average about 10 hours, at Site 5 it lasted about 2 hours. The peak of these events is, on average, reached after about 1 to 2 hours at the sub-catchment outlets of 2 and 7. The reaction time

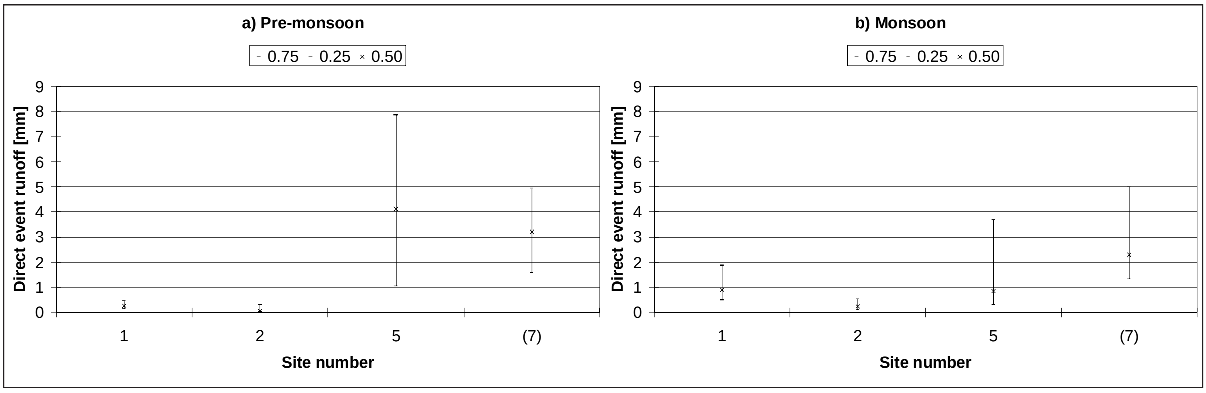


Figure 3.115: **Event runoff of pre-monsoon events (a), and monsoon events (b) at all sites in the Yarsha Khola catchment**

at Site 5 is very fast and the peak is reached after only 30 minutes. At Site 1 the rising limb lasts for about 3 hours. The receding limb differs likewise between the catchment and the sub-catchment outlets with t_{rec} values of one to three hours for the sub-catchments and about six hours at the catchment outlet.

Table 3.85: **Median of 10 maximum hydrological events, Yarsha Khola**

Site	t_Q [min]	Q_{start} [m³/s]	Q_{end} [m³/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m³/s]	Q_E / Q_{tot}	t_{rise} [min]	t_{rec} [min]
1	585	5.478	9.280	10.8	5.0	5.3	0.7	28.641	0.48	195	375
2	240	1.304	5.074	5.4	3.2	3.0	0.6	9.793	0.41	120	120
5	105	0.080	0.130	28.9	2.3	24.3	14.9	2.733	0.90	30	60
7	255	0.218	0.402	15.5	3.5	10.7	3.5	4.387	0.82	75	180

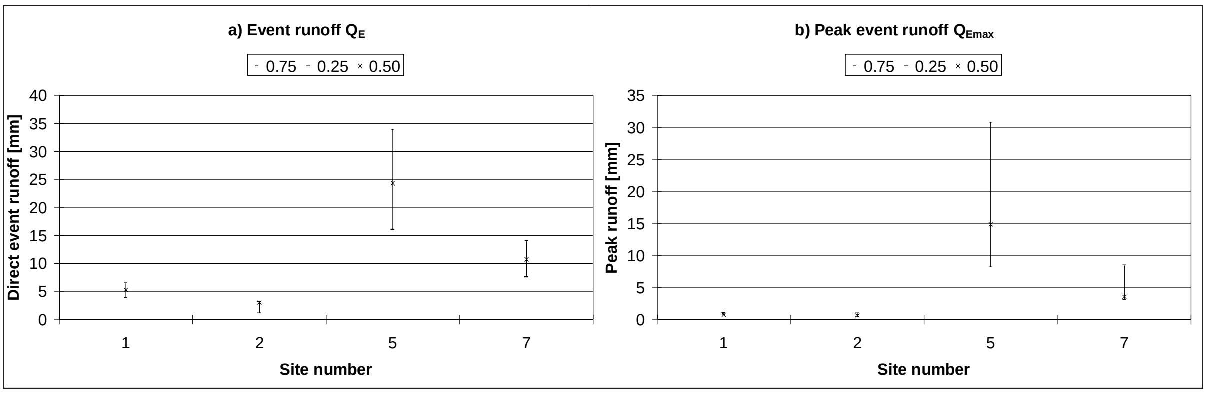


Figure 3.116: **Event runoff (a) and peak event runoff (b) during the 10 largest events at each site, Yarsha Khola catchment**

The Q_E/Q_{tot} ratio is about 40 to 50% of Sites 1 and 2. At Sites 5 and 7, more than 80% of the runoff of one of these large events is direct event runoff, showing the rather low importance of baseflow at these sites during large events.

In terms of event magnitude, Site 5 shows the highest per unit runoff values as also shown in Figure 3.116. The median total event runoff at this site was nearly 30 mm, which is double the runoff from Site 7, triple the runoff from Site 1 and 6 times more than at Site 2. Site 2 shows the lowest total event runoffs, with 5.4 mm on average. Due to the greater importance of direct runoff at this site, the direct runoff is then also more than double the Q_E of Site 7 and five times more than at Site 1. The Q_E values at Site 5 range from about 15 to 35 mm per event. The range at Site 7 is considerably lower with about 5 to 15 mm. At Sites 1 and 2, the range is from 4 to 6 mm and 1 to 3 mm respectively. The peak discharges for these ten largest events were observed at the catchment outlet with about 30 m^3/s. At Site 2, the observed peak discharges are about 10 m^3/s, at Site 7, 5 m^3/s, and at Site 5, 3 m^3/s. These values correspond to peak event runoffs of 8 to 30 mm at Site 5, 4 to 8 mm at Site 7, and about 1 mm at Sites 1 and 2.

3.4.8.2 Relationship between the different hydrological event parameters

To reduce the number of parameters and in order to identify the parameters with the highest information content, a factor analysis was performed on the data. However, prior to this analysis it has to be ensured that the parameters are sufficiently correlated. According to the correlation coefficients of Spearman (data are not distributed normally; Appendix A3.23), the duration parameters t_Q, $t_{rise,}$ and t_{rec} are strongly and significantly correlated (Table 3.86). The same is true for the parameters describing the event's magnitude. However, there is only a weak correlation between the magnitude and the duration parameters.

Table 3.86: **Correlation coefficients at site 7 and number of significant correlation in brackets, Yarsha Khola** (max. = 3; detailed tables in Appendix A3-24)

	t_Q	Q_{start}	Q_{end}	Q_{tot}	Q_B	Q_E	Q_{Emax}	Q_{max}	Q_E / Q_{tot}	t_{rise}	t_{rec}
t_Q	1.00(3)	(0)	(0)	0.31(3)	0.41(3)	0.31(3)	(0)	(0)	(0)	0.65(3)	0.84(3)
Q_{start}		1.00(3)	0.85(3)	0.34(2)	0.62(3)	(1)	(1)	0.36(3)	-0.38(2)	(1)	-0.37(2)
Q_{end}			1.00(3)	0.59(3)	0.78(3)	0.42(3)	0.52(3)	0.62(3)	(1)	(0)	(1)
Q_{tot}				1.00(3)	0.73(3)	0.94(3)	0.89(3)	0.92(3)	0.43(3)	0.48(3)	(2)
Q_B					1.00(3)	0.52(3)	0.46(3)	0.54(2)	(0)	0.56(3)	(2)
Q_E						1.00(3)	0.94(3)	0.92(3)	0.68(3)	0.46(1)	(2)
Q_{Emax}							1.00(3)	0.98(3)	0.65(3)	0.33(1)	(0)
Q_{max}								1.00(3)	0.55(3)	0.32(1)	(0)
Q_{tot} / Q_E									1.00(3)	(0)	(1)
T_{rise}										1.00(3)	(1)
T_{rec}											1.00(3)

The resulting factor analysis, using the principal component method for extraction and the varimax method for rotation of the factors, resulted in the grouping of these duration parameters with the key variable $t_{Q,}$ and the magnitude parameters with key variables Q_{tot}, $Q_{E,}$ or Q_{Emax} (Table 3.87). A third group was identified with parameters describing the pre-event history and the baseflow. The key variable in this group is Q_{start}.

Table 3.87: **Results of the factor analyses for hydrological parameters of all events, Yarsha Khola**

Site	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	T_{rise} [min]	T_{rec} [min]
2	2(🔑)	3(🔑)	1	1(🔑)	1	1	1	1	2	2
5	2(🔑)	3	3(🔑)	1	2	1(🔑)	1	1	2	2
7	2(🔑)	3(🔑)	3	1	3	1	1(🔑)	1	2	2

On the basis of the results from the above factor analysis and the correlation matrix in Table 3.86, the parameters t_Q, Q_{start}, $Q_{tot,}$ and Q_{Emax} were used for cluster analyses according to the k-means clustering method. Several trials showed that three clusters were most appropriate. The results of the analysis with the cluster centres for all sites and all clusters are presented in Table 3.88. These clusters can be described as follows.

Cluster 1: Minor
short duration – small runoff volume – small peak
Cluster 2: Large peak
medium duration – medium to large runoff volume – small peak
Cluster 3: Large runoff
short to long duration – large runoff volume – large peak

Table 3.88: **Centres of discharge event parameter clusters, Yarsha Khola catchment**

		Site 2	Site 5	Site 7
Cluster 1	Count	136	99	5
	t_Q [min]	186	126	168
	Q_{start} [m^3/s]	1.063	0.069	0.653
	Q_{tot} [mm]	1.1	5.1	7.5
	Q_{Emax} [mm]	0.1	1.5	1.3
Cluster 2	Count	34	13	37
	t_Q [min]	478	492	270
	Q_{start} [m^3/s]	1.391	0.059	0.179
	Q_{tot} [mm]	4.4	10.7	5.1
	Q_{Emax} [mm]	0.3	0.7	1.1
Cluster 3	Count	1	3	4
	t_Q [min]	510	90	330
	Q_{start} [m^3/s]	0.817	0.084	0.200
	Q_{tot} [mm]	18.7	51.0	23.7
	Q_{Emax} [mm]	2.3	31.9	9.6

Final clusters for discharge events, Yarsha Khola catchment, are given in Table 3.89.

Table 3.89: **Final clusters for discharge events, Yarsha Khola catchment**

		Q_{tot} [mm]			Q_{Emax} [mm]		
		Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 1**	**Cluster 2**	**Cluster 3**
Site 2	75% quartile	1.1	4.4	18.7	0.1	0.3	2.3
	25% quartile	1.6	5.0	18.7	0.1	0.4	2.3
	median	0.5	3.1	18.7	0.0	0.1	2.3
Site 5	75% quartile	5.1	10.7	51.0	1.5	0.7	31.9
	25% quartile	5.8	12.3	59.0	1.5	1.1	36.5
	median	2.3	5.5	36.3	0.2	0.1	28.1
Site 7	75% quartile	7.5	5.1	23.7	1.3	1.1	9.6
	25% quartile	6.9	6.4	29.5	1.3	1.5	11.2
	median	4.2	2.6	16.3	0.9	0.3	8.4

3.4.8.3 *Reasons for these events*

The results below are based only on the analysis of the data in the Khahare Khola sub-catchment, that is, the sub-catchments at Sites 5 and 7. The reason for the exclusion of Site 2 is the often doubtful rainfall information of high temporal resolution. Before the rainfall event parameters are discussed, some words on the antecedent moisture conditions.

Antecedent moisture conditions

The antecedent moisture conditions here are expressed in terms of antecedent precipitation due to the otherwise missing soil moisture information. In general, only a weak correlation can be established between the different discharge event parameters and the different APIs (Table 3.90). The event duration as well as the two parameters describing the hydrograph t_{rise} and t_{rec} do not show any correlation with the antecedent precipitation conditions, as could probably have been expected. The strongest correlations are observed between the APIs and the parameters describing the in-stream history of the event, i.e., the parameters Q_{start} and Q_{end}. These parameters additionally show the highest correlations with the long term APIs, for example, API14 and API_{30} describing the rainfall 14 and 30 days before the event. The short-term APIs tend to show significant, but very weak correlations with the magnitude parameters as well.

As in the Jhikhu Khola catchment, API_1 (AP_1 respectively) was identified as the key variable for the short-term antecedent precipitation conditions (Table 3.91). In the case of the Yarsha Khola catchment, however, the short-term group only included AP_1 to AP_3. In the Jhikhu Khola catchment, AP_4 and AP_5 were also part of this group. Here, AP_4 and AP_5 are part of the parameters describing long-term antecedent precipitation conditions with the key variable API_{14}.

Table 3.90: **Correlation coefficients of hydrological parameters with respect to antecedent precipitation conditions at Site 7 and number of significant correlations in brackets (maximum = 2; Appendix A3-25).**

	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_1	AP_2	AP_3	AP_4	AP_5
t_Q	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Q_{start}	0.32(1)	0.56(2)	0.45(2)	0.58(2)	0.72(2)	0.32(1)	(0)	0.35(2)	0.43(2)	0.45(2)
Q_{end}	0.31(2)	0.67(2)	0.59(2)	0.69(2)	0.73(2)	0.31(2)	(0)	0.37(2)	0.52(2)	0.54(2)
Q_{tot}	(1)	0.33(2)	(1)	0.32(2)	0.37(1)	(1)	(1)	(1)	(1)	(1)
Q_B	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
Q_E	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(1)	(0)	(1)
Q_{Emax}	(0)	(0)	(0)	(0)	(0)	(0)	(1)	(1)	(1)	(1)
Q_{max}	(0)	0.34(2)	(1)	0.33(2)	0.38(1)	(0)	(1)	(1)	(1)	(1)
Q_E / Q_{tot}	(0)	(0)	(0)	(0)	-0.38(2)	(0)	(0)	(0)	(0)	(0)
T_{rise}	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
T_{rec}	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
α	(0)	0.46(2)	0.35(2)	0.45(2)	0.57(1)	(0)	(0)	0.37(1)	0.46(1)	0.48(1)

Table 3.91: **Results of the factor analyses for antecedent precipitation characteristics, Yarsha Khola**

Site	**API_1***	**API_7**	**API_{10}**	**API_{14}**	**API_{30}**	**AP_1***	**AP_2**	**AP_3**	**AP_4**	**AP_5**
5_5	(🔑)1	2	2	(🔑)2	2	(🔑)1	1	1	2	2
5_7	(🔑)1	2	2	(🔑)2	2	(🔑)1	1	2	2	2

* API_1 and AP_1 represent the same information content: rainfall 24 hours before start of the event

The two key APIs were compared with the discharge clusters showing that for the short term, APIs (API_1) there is a trend of higher API values in higher clusters (Figure 3.117a). This suggests that there is a certain relationship between the moisture conditions in the catchment and the size of the event, although no particularly strong correlation could be observed with the magnitude parameters above in Table 3.90. No particular relationship could be observed in the case of the API_{14} (Figure 3.117b).

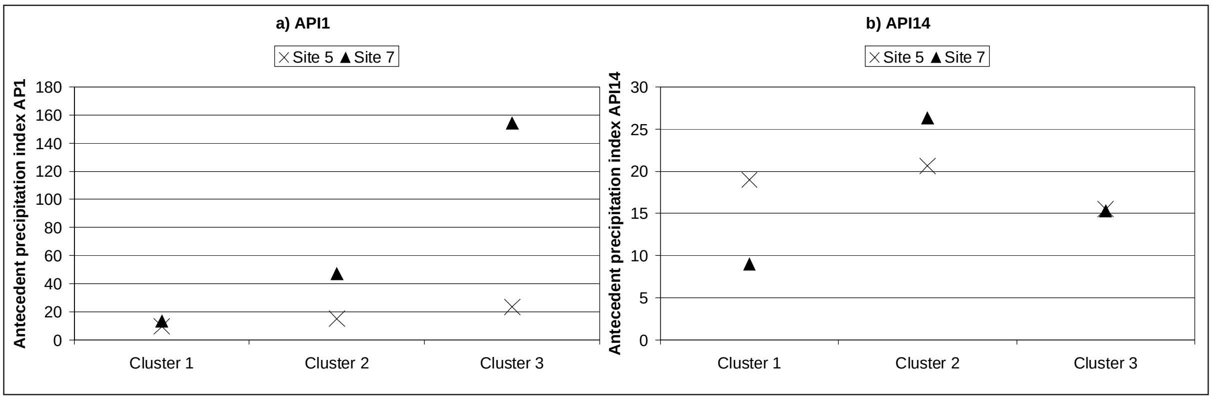


Figure 3.117: **Antecedent precipitation in comparison with discharge clusters**

Event rainfall characteristics

The main triggering mechanism for the discharge events in the Yarsha Khola catchment is rainfall. To what extent the discharge parameters are correlated with the rainfall parameters is shown in Table 3.92.

The highest correlations with rainfall parameters are observed by discharge event parameters describing the amount and intensity, e.g., the magnitude parameters. Generally P_{tot} shows high correlation with Q_{tot}, Q_E, Q_{Emax}, and Q_{max}. t_P shows high correlation with the baseflow Q_B, which is understood as Q_B and increases the longer the event lasts. The intensity parameters show the highest correlations with the Q_E/Q_{tot} ratio. The correlations with the amount parameters are also rather strong. The hyetograph shape parameters P_{25}, P_{50}, and P_{75} show no or only very weak

Table 3.92: **Correlation of discharge event with rainfall event parameters at Site 7 and number of significant correlations at both sites (maximum = 2; for detailed matrices refer to Appendix A3-26)**

	t_Q	**Q_{start}**	**Q_{end}**	**Q_{tot}**	**Q_B**	**Q_E**	**Q_{Emax}**	**Q_{max}**	**Q_E/Q_{tot}**	**t_{rise}**	**t_{rec}**	**α**
P_{tot}	0.33(1)	(0)	(1)	0.62(2)	0.30(2)	0.68(2)	0.57(2)	0.53(2)	0.56(1)	0.46(1)	(0)	(1)
t_P	0.30(2)	0.37(2)	0.47(2)	0.41(2)	0.63(2)	(1)	(1)	(1)	(0)	0.41(2)	(0)	(1)
I_{ave}	(0)	-0.56(2)	-0.36(2)	(0)	(1)	0.38(1)	0.35(1)	(0)	0.72(1)	(0)	(0)	-0.33(1)
I_{10max}	(0)	-0.47(1)	(0)	0.37(2)	(0)	0.52(2)	0.47(2)	0.42(2)	0.74(2)	(0)	(0)	(0)
I_{30max}	(0)	-0.42(1)	(0)	0.41(2)	(0)	0.57(2)	0.52(2)	0.47(2)	0.78(2)	(0)	(0)	(0)
I_{60max}	(0)	-0.37(1)	(0)	0.48(2)	(0)	0.63(2)	0.56(2)	0.50(2)	0.78(2)	(0)	(0)	(1)
P_{25}	(0)	(0)	(1)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
P_{50}	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)	(0)
P_{75}	(0)	-0.48(1)	-0.33(1)	(0)	(0)	(0)	(0)	(0)	0.45(1)	(0)	(0)	(0)

correlation with discharge event parameters. The two hydrograph shape parameters t_{rise} and t_{rec} likewise do not show any strong correlation.

Comparing the two discharge event magnitude parameters Q_E and Q_{Emax} with the rainfall clusters established in Section 3.4.6, it is clear that the cluster 3 events, i.e., high intensity events with medium to high rainfall amount, produce the largest events in the two sub-catchments of the Yarsha Khola catchment. Events with high amount, but low intensity, i.e., cluster 4 events, do not tend to produce events in the same magnitude (Figures 3.118 and 119).

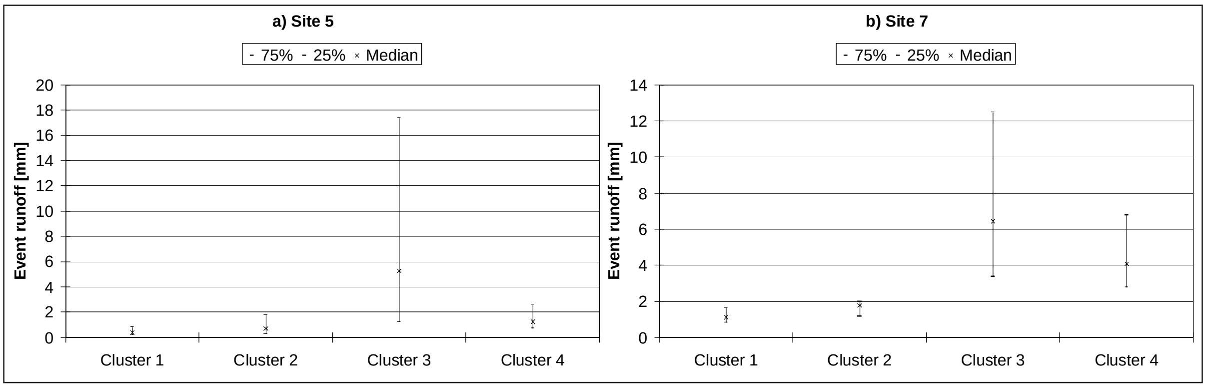


Figure 3.118: **Event runoff Q_E with rainfall clusters at Sites 5 and 7 in the Yarsha Khola catchment**

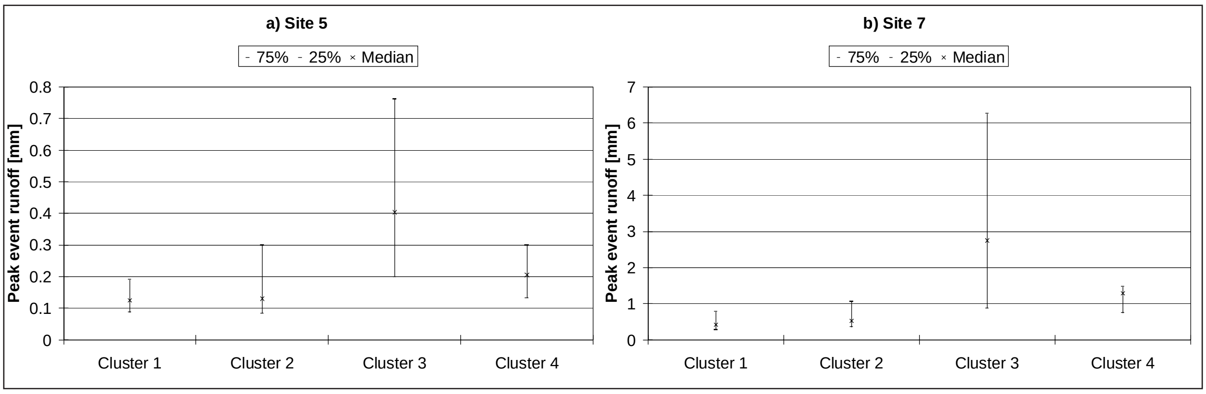


Figure 3.119: **Peak event runoff Q_{Emax} with rainfall clusters at Sites 5 and 7 in the Yarsha Khola catchment**

3.4.8.4 Summary

The hydrological event analysis in the Yarsha Khola catchment can be summarised as follows.

- The largest events on the basis of unit area are observed from the sub-catchment on the south-facing slopes.
- The events show a total event runoff of 1.5 to 4 mm with the minimum observed at the outlet of the north-facing sub-catchment.
- The median peak event runoff ranges from 0.1 mm at the Gopi Khola sub-catchment to 0.9 mm at the Lower Khahare Khola sub-catchment.
- During the monsoon season, baseflow plays a more important role in flood generation than in the pre-monsoon season.
- In the small sub-catchments, the majority of event runoff during large events hails from direct event runoff, while at the outlet of the catchment as well as at the outlet of the Gopi Khola catchment baseflow is still more important.
- The key variables for discharge events are t_Q, $Q_{start,}$ and one of the magnitude parameters, Q_{tot}, $Q_{E,}$ or Q_{Emax}.
- Three clusters were determined on the basis of the key variables and $Q_{tot.}$

  - **Cluster 1 - minor:** short duration – small runoff volume – small peak
  - **Cluster 2 - large peak:** medium duration – medium to large runoff volume – small peak
  - **Cluster 3 - large runoff:** short to long duration – large runoff volume – large peak

- The APIs show only weak correlation with the hydrological event parameters. Nevertheless, there is an increase in API_1 with cluster number showing the highest API values for cluster 3. No relationship can be observed with API_{14}.
- A high correlation is observed between the rainfall amount and intensity parameters and the hydrological amount and intensity parameters. This is also shown by comparing the rainfall clusters with the Q_E and Q_{Emax} values. In general, cluster 3 events produce the largest discharge events in the catchment, followed by cluster 4 rainfall events.

3.4.9 Synthesis

In the sections above, the hydrological parameters were related to the rainfall and erosion plot event parameters. This basically showed that rainfall amount and rainfall intensity are the main hydro-meteorological parameters of interest. Both runoff at the plot scale as well as at the sub-catchment scale is directly correlated with these two parameters. In both catchments, rainfall events were grouped into four clusters, which showed very good relations with the runoff behaviour at both scales. The clusters of the two catchments are compared in Table 3.93. In general, the two systems coincide rather well and show similar minima and maxima rainfall volumes and rainfall intensities for most of the clusters. Cluster 1 in both catchments is of 2 to 10 mm rainfall volume and about 2 to 5 mm/30 min (=4 to 10 mm/h). Rainfall volumes of cluster 2 range from about 10 to 30 mm with maximum 30-minute rainfall intensities of 3 to 15 mm/30min (6 to 30 mm/h). The most important clusters for flood generation, clusters 3 and 4, differ slightly — mainly due to the small number of events at this magnitude and therefore the more random setting of minima and maxima. While in the Jhikhu Khola catchment cluster 3 occupies the middle segment of rainfall volume and the top segment of rainfall intensity, in the Yarsha Khola catchment the rainfall volumes of clusters 3 and 4 show the same limits. They differ however in terms of maximum intensities and show here similar lower limits as the Jhikhu Khola catchment and slightly elevated maxima.

Table 3.93: **Rainfall clusters of the Jhikhu Khola and Yarsha Khola catchments**

Variable	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	Min	Max	Min	Max	Min	Max	Min	Max
Jhikhu Khola catchment								
P_{tot} [mm]	2.1	9.6	9.4	32.5	12.8	45.4	52.1	164.4
t_P [min]	22	250	98	728	46	421	795	1931
I_{30max} [mm/30 min]	1.8	5.4	2.7	10.4	9.4	28.7	4.7	10.7
P_{50} [%]	40.0	82.6	29.7	80.6	43.3	91.3	36.6	62.2
Yarsha Khola catchment								
P_{tot} [mm]	3.2	10.1	12.0	30.4	20.0	69.8	26.7	69.2
t_P [min]	77	308	80.0	760.0	147.3	507.3	586.5	1121.0
I_{30max} [mm/30 min]	1.8	5.0	3.0	13.6	10.7	44.4	5.1	19.4
P_{50} [%]	20.0	79.5	6.9	92.3	20.2	94.6	10.1	68.8

Antecedent precipitation and herewith an approximation of antecedent moisture conditions only has a limited influence on the runoff behaviour at the sub-catchment scale. This further showed that land use at the plot scale was decisive in terms of runoff generation, as the land use had an impact on the soil characteristics as well as on the vegetation cover. In order to extend the spatial dimension and determine the impact of land use and other catchment characteristics, the hydrological parameters are put into relation with a number of selected characteristics.

3.4.9.1 The relevance of different catchment characteristics on hydrological event parameters

In Chapter 2, several catchment characteristics were identified, which on the basis of literature or process understanding may have an impact on the hydrological behaviour of the catchment during flood events. In order to verify these assumptions in Chapter 2, selected characteristics were tested for their impact on the hydrological event parameters in meso-scale catchments of the middle mountains in Nepal. The hydrological event characteristics included in these analyses were:

- the median runoff coefficient α [%];
- the median total event runoff Q_{tot} [mm];
- the median direct event runoff Q_E [mm];and
- the median peak event runoff Q_{Emax} [mm].

Q_{max}, although probably the most important parameter in terms of flooding, was excluded in this comparative analysis as it is directly correlated to catchment area. It was replaced by Q_{Emax}, which accounts for the different catchment areas and can therefore be directly compared amongst catchments of different sizes.

These characteristics were always tested both for the median of all events as well as for the median of the ten largest events at each hydrological measurement site. As the variables are not normally distributed, linear regression cannot be used to determine a linear relation between the parameters. For this purpose the Spearman correlation coefficient was used instead. Some plots with linear regression lines are presented to help visualise the relationships.

Note: It is important to note that the relationships discussed are tentative and have to be confirmed with larger samples, e.g., in comparison with the PARDYP catchments in China, India, and Pakistan or other meso-scale catchments in the region. This is particularly necessary since the correlation between the two parameters does not yet explain their causal correlation. Sachs (1997) uses the example of the strongly positive correlation between the number of storks and the number of newborns, which obviously is a spurious correlation and does not show any functional relation.

Morphometric and topographic characteristics

The areal morphometric characteristics that were tested included the catchment area, the width/ elongation ratio, and the drainage density (only for the Jhikhu Khola catchment and its sub-catchments). The topographic characteristics that were included were the mean Topoindex, the mean relative contributing area (only Jhikhu Khola and sub-catchments), the mean slope, and the ratio between areas below a 5-degree slope and the areas of more than a 15-degree slope. Elevation was not included in this analysis as the influence of elevation is largely included in the rainfall characteristics (see Section 3.1). Table 3.94 presents the Spearman correlation coefficients for these catchment characteristics in relation to the selected discharge event parameters. Generally, the correlations are weak and/or insignificant. However, a number of correlations can be observed. These include for the median of all events:

- drainage density and α with an r of 1 and a correlation significant at the 0.0% level;
- drainage density and Q_{Emax} with an r of 0.90 and a correlation significant at 0.04% level;and
- Topoindex and Q_{tot} with an r of 0.93 and a correlation significant at 0.01% level.

In addition to these significant and strong correlations, the Topoindex shows a rather strong correlation at the significance level of 0.15% with Q_E and the relative contributing area with Q_{tot}.

In Figure 3.120 the significant and strong relationships mentioned above are visualised. It is important to note that these relationships are only for the sub-catchments of the Jhikhu Khola, as drainage density could not be calculated for the Yarsha Khola due to differently detailed mapping of the drainage network in the two catchments. The relationship between the Topoindex and the Q_{tot} additionally includes the value from the Yarsha Khola catchment.

Table 3.94: **Spearman correlation coefficients r for morphometric and topographic catchment characteristics in relation to hydrological event characteristics**

Parameters		Median of all events				Median of 10 largest events		
		α	Q_{tot}	Q_{Emax}	Q_E	Q_{tot}	Q_{Emax}	Q_E
Catchment area	r	0.14	-0.08	-0.52	0.08	0.42	-0.08	0.25
	Sig.	0.79	0.83	0.15	0.83	0.27	0.83	0.52
Width/elongation	r	-0.32	0.32	-0.62	-0.09	-0.09	**-0.74*****	-0.50
	Sig.	0.68	0.53	0.19	0.87	0.89	**0.10**	0.31
Mean slope	r	-0.12	-0.23	-0.03	-0.30	-0.25	-0.20	-0.25
	Sig.	0.83	0.56	0.93	0.44	0.53	0.60	0.51
Topoindex	r	0.74	**0.93***	0.44	0.73***	**0.75****	0.23	0.58
	Sig.	0.26	**0.01**	0.39	0.10	**0.08**	0.66	0.23
RCA	r	-0.60	-0.80***	-0.30	-0.60	-0.50	-0.10	-0.50
	Sig.	0.40	0.10	0.62	0.29	0.39	0.87	0.39
Slope ratio	r	-0.49	-0.17	-0.15	0.23	0.38	0.50	0.43
	Sig.	0.33	0.67	0.70	0.55	0.31	0.17	0.24
Drainage density	r	**1.00***	-0.10	**0.90***	0.00	0.40	**1.00***	0.40
	Sig.	**0.00**	0.87	**0.04**	1.00	0.51	**0.00**	0.51

r = correlation coefficient according to Spearman, Sig.= significance level

* Correlation is significant at the 0.05% level (Sig.<0.05%)

** Correlation is significant at the 0.1% level (Sig.<0.1%)

*** Correlation is significant at the 0.15% level (Sig.<0.15%)

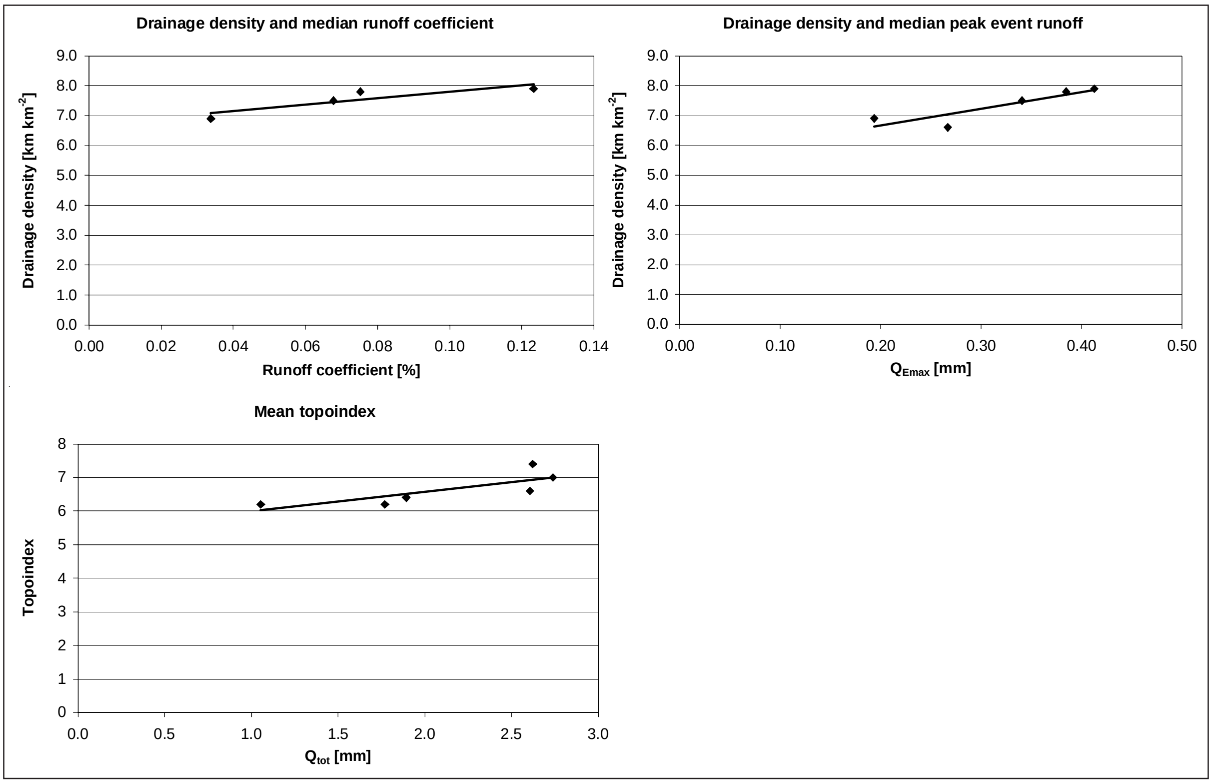


Figure 3.120: **Linear relationships between selected morphometric and topographic catchment characteristics and hydrological event parameters**

For the median of the ten largest discharge events at all sites drainage density again shows a high and significant correlation with Q_{Emax} and the Topoindex with Q_{tot}. An additional significant and strong correlation is observed between the ratio of catchment width and catchment elongation in relation to Q_{Emax}.

For the assessment of the catchment's susceptibility to floods, the use of the Topoindex is therefore proposed. The width/elongation ratio can also be used. Drainage density would be an informative variable. However, due to the difficulties in assessing this value across the region with data of different origin, it is suggested that this variable is not used for the comparative analyses. This is also the reason why the concept of the relative contributing areas has to be dropped for these analyses.

Land-use characteristics

For the assessment of the impact of land use on hydrological event parameters, the percentage of each land use, the ratio of cultivated to uncultivated land, and the ratio of rainfed to irrigated land were used as parameters. Several significant and strongly correlated relations were observed for these characteristics in relation to all flood events (Table 3.95). The strongest and most significant correlations are observed between the ratio of rainfed and irrigated agricultural land and the hydrological parameters α and Q_{tot}. The percentage of irrigated land in a catchment also shows significant and strong correlations with the runoff coefficient and the peak event runoff Q_{Emax}. The correlations show a decreasing α and a decreasing Q_{Emax} with an increasing portion of irrigated land in the catchments (see also Figure 3.121). The other land use which seems to show an impact on event behaviour is grassland. Generally, an increasing portion of grassland results in an increase in α and Q_{tot}.

Table 3.95: **Spearman correlation coefficients r for land-use related catchment characteristics in relation to hydrological event characteristics**

Parameters		Median of all events				Median of 10 largest events		
		α	Q_{tot}	Q_{Emax}	Q_E	Q_{tot}	Q_{Emax}	Q_E
Cultivated/uncultivated	r	**-0.77****	-0.57***	-0.50	-0.17	-0.12	0.12	0.03
	Sig.	**0.07**	0.11	0.17	0.67	0.77	0.77	0.93
Rainfed/irrigated	r	**-0.93***	**-0.88***	-0.46	-0.44	-0.11	0.32	0.04
	Sig.	**0.01**	**0.00**	0.21	0.23	0.78	0.40	0.92
Irrigated area	r	**-0.81***	-0.28	**-0.66****	-0.12	0.08	-0.07	-0.01
	Sig.	**0.05**	0.47	**0.05**	0.75	0.85	0.86	0.98
Rainfed area	r	-0.66	-0.47	-0.28	-0.12	-0.08	0.15	0.10
	Sig.	0.16	0.21	0.46	0.77	0.83	0.70	0.80
Forest area	r	0.09	0.15	0.10	-0.18	-0.15	-0.17	-0.27
	Sig.	0.87	0.70	0.80	0.64	0.70	0.67	0.49
Grassland area	r	**0.77****	0.48	0.23	0.52	**0.72***	0.27	0.53
	Sig.	**0.07**	0.19	0.55	0.15	**0.03**	0.49	0.14
Other areas	r	**0.77****	**0.65****	0.45	0.13	-0.20	-0.28	-0.32
	Sig.	**0.07**	**0.06**	0.22	0.73	0.61	0.46	0.41
Shrub area	r	0.66	0.58***	**0.65****	0.42	0.05	-0.13	0.07
	Sig.	0.16	0.10	**0.06**	0.27	0.90	0.73	0.87

r = correlation coefficient according to Spearman, Sig.= significance level
* Correlation is significant at the 0.05% level (Sig.<0.05%)
** Correlation is significant at the 0.1% level (Sig.<0.1%)
*** Correlation is significant at the 0.15% level (Sig.<0.15%)

In addition, Q_{Emax} and grassland show a correlation at a significance of 0.22%. Shrubland shows a significant and strong correlation with Q_{Emax} as well as Q_{tot}. The correlation with α is significant at the 0.16% level. The other areas in the catchments, including settlements, landslides, gullies and the like, show a strong a significant correlation with α and Q_{tot} as well as rather a strong correlation with Q_{Emax}. The ratio between cultivated and uncultivated land shows very strong and significant

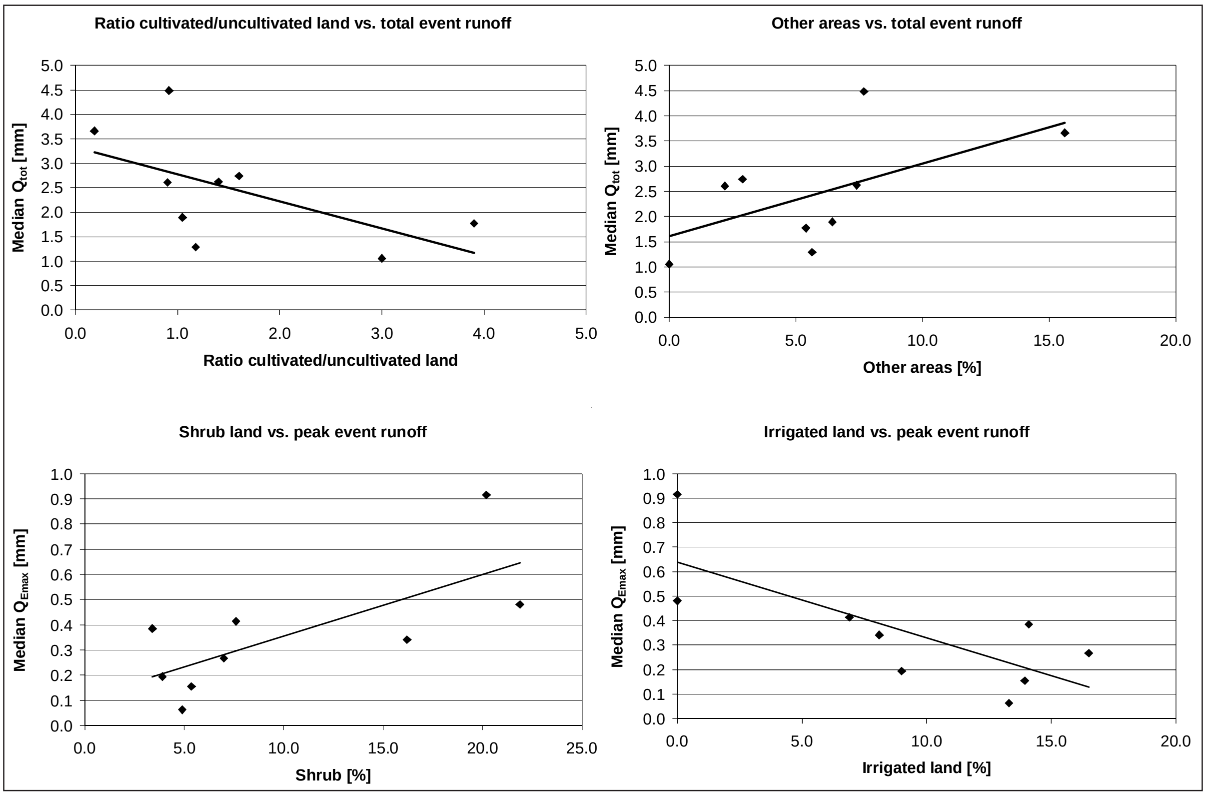


Figure 3.121: **Linear relationships between selected land use catchment characteristics and hydrological event parameters**

correlation with the runoff coefficient. At the same time, the correlations with Q_{tot} and Q_{Emax} are not as strong, but are still quite significant.

Four of the above correlations have been visualised in Figure 3.121. The linear trend line is only presented to display the linear relationship, and by no means should be thought of as a prediction model. The two relations showing the impact of agricultural land, in general and irrigated land, in particular, on the total event runoff and the peak event runoff, respectively, have a decreasing trend, i.e., the more cultivated the land, the lower the $Q_{tot,}$ and the more irrigated the land, the lower the Q_{Emax}. Shrubland and other land uses or covers show the opposite trend, with increasing Q_{tot} and Q_{Emax} on increasing percentages of shrub and other land use/cover.

The only strong and significant correlation observed in the case of the ten largest events is established for the percentage of grassland and the total event runoff Q_{tot}. An increase in grassland leads to an increase in Q_{tot}.

Discussion of the results

Although these relationships have to be considered with caution due to the correlation problem mentioned above and the small sample number, the determined relationships seem plausible. They seem plausible on the basis of the observations on the erosion plots, where degraded land and grassland produce considerably more runoff on an aggregated basis as well as on an event basis than rainfed agricultural land. They also seem plausible on the basis of the fact that irrigated land, with its level terraces, is designed to keep water back and an enhanced water storage effect for rainfall is therefore not surprising.

The results also seem plausible on the basis of published results in literature. For the estimation of design floods on the basis of catchment characteristics in Switzerland, Duester (1994) based his calculations on the elongation factor, mean slope, areal precipitation, area of grassland and others, as well as relative contributing areas. Elongation, here expressed as width/elongation ratio, and the area of grassland and others were also established as potential factors influencing the hydrological event characteristics. Instead of mean slope, which only shows low correlation, the Topoindex (also a product of the slope conditions in the catchments) showed high correlation with the hydrological event parameters.

In general, the correlations between the median values of the hydrological event parameters and the catchment characteristics are stronger and more significant for all events than for the ten largest events. This observation would support the conclusions of Merz et al. (2000a) or Dangol et al. (2002). They concluded that the biggest events are a function of meteorological parameters and the human influence through different land use would be negligible during these events. They also said that human impact could be observed during minor and intermediate events. These observations are presumably true for the process of flood generation in the rural context as well as natural channels. In-channel changes, e.g., bridge construction, embankments, and so on, may have considerable impact on flood behaviour as for example shown by Hofer (1998a).

It is, however, the largest events that are the most destructive. To get an idea of the relevant parameters during the largest events, the ten largest flood events at Site 1 of each catchment are discussed below.

3.4.9.2 The ten largest events at the outlets of the Yarsha and Jhikhu Khola catchments

As frequently shown above, only the largest events have the potential for destruction at a larger impact scale. It is therefore these events that it is desirable to reduce. But as shown in the section on the impact of catchment characteristics on hydrological parameters and in the literature, these events do not show any relation to land use and the influence of humans is only limited. This section aims to compare the largest events and to identify common and different denominators. The section begins with the analyses of the largest events in the Jhikhu Khola catchment followed by the largest events at the outlet of the Yarsha Khola catchment. The section concludes with a cross-catchment synthesis.

Description of the largest events in the Jhikhu Khola catchment

In the Jhikhu Khola catchment, the largest event that was observed in the period from 1997 to 2000, on September 6 to 7, 1998, unfortunately showed an incomplete hydrograph due to instrument failure and sediment clogging. Therefore the analyses below are based on the events ranked 2 to 11. These events all have a peak discharge of more than 50 m^3/s as shown in Figure 3.122 as well as in Table 3.96. Eight out of the ten largest events occurred during the monsoon season, with one event each in the pre-monsoon and the post-monsoon seasons.

Except for the event magnitude parameters used for the selection of the largest events, Q_{Emax} and Q_{max}, the parameters tend to vary considerably (Table 3.96). The duration of the events varied from 10 to 38 hours. Q_{start} was generally high, shown by a median value of 2.831 m^3/s with an overall mean flow of about 1.4 m^3/s at this site. However, four of the events occurred during conditions below average flow. Most of the events showed a high proportion of direct runoff in the total event runoff, as expressed with the Q_E/Q_{tot} ratio. Generally, the values tend to be higher than 75%, with only one value below. The rising limbs as well as the receding limbs of the hydrographs tend to vary in the order of one magnitude.

From a first overview of the hydrological parameters, no distinct similarity between the ten events could be established. Events 3, 7, 8, and 11 show a similar pattern with shorter event durations, lower starting conditions, and low baseflow contribution. The remaining events do not show any particular pattern.

Antecedent precipitation conditions of the events in the Jhikhu Khola catchment

The API1, the key variable for short-term antecedent precipitation conditions, shows very variable conditions for the situation prior to the largest events (Figure 3.123). Some of the events show up to 14 times the median of API_1. The API_{14}, key variable for long term rainfall conditions, shows likewise variable behaviour, but not to the same extent as API_1. It generally ranges between 0% and 200% of the median API_{14}.

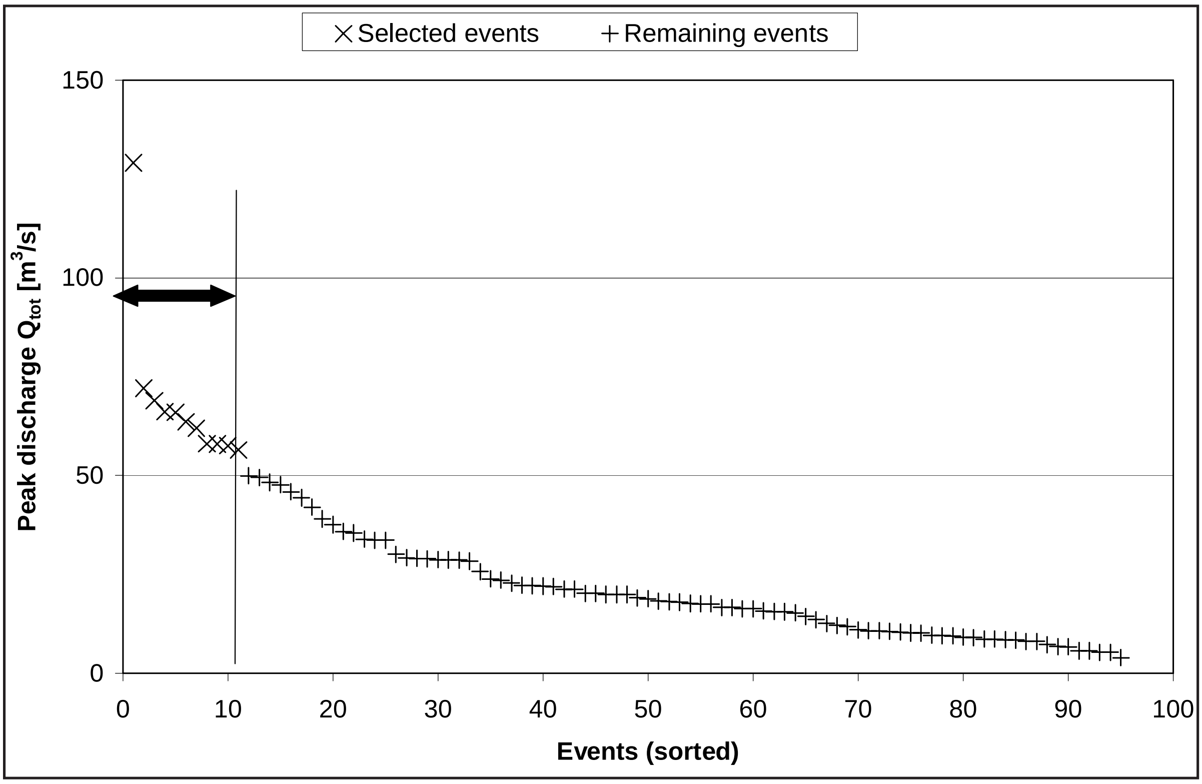


Figure 3.122: **The largest flood events at Site 1, Jhikhu Khola catchment**

Table 3.96: **Hydrological event parameters for largest events at Site 1, Jhikhu Khola catchment**

	Q_{tstart}	Q_{tend}	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	t_{Peak}	Q_{tot} / Q_E	t_{rise} [min]	t_{rec} [min]
Event 1	incomplete hydrograph													
Event 2	30/06/97 08:00	01/07/97 13:30	1770	4.635	1.501	23.2	3.0	20.2	1.1	72.093	30/06/97 14:30	0.87	390	1380
Event 3	28/07/97 16:00	29/07/97 14:30	1350	0.815	2.519	11.6	1.2	10.4	1.1	68.982	28/07/97 23:00	0.89	420	930
Event 4	24/07/00 14:30	25/07/00 05:30	900	5.525	7.263	10.2	3.2	7.0	1.0	66.142	24/07/00 17:00	0.69	150	750
Event 5	01/08/99 21:30	02/08/99 16:30	1140	2.664	2.674	8.7	1.7	7.0	1.0	65.988	02/08/99 02:30	0.81	300	840
Event 6	20/08/98 16:00	21/08/98 17:30	1530	5.766	8.494	14.5	6.0	8.5	0.9	63.641	20/08/98 18:00	0.59	120	1410
Event 7	14/05/98 18:00	15/05/98 06:30	750	0.446	1.944	5.6	0.5	5.1	1.0	62.022	14/05/98 20:30	0.91	150	600
Event 8	26/06/98 01:30	26/06/98 12:00	630	1.052	3.115	5.5	0.7	4.7	0.9	58.018	26/06/98 03:00	0.86	90	540
Event 9	27/06/99 21:00	28/06/99 18:00	1260	2.998	7.875	15.3	3.8	11.5	0.8	57.996	28/06/99 08:00	0.75	660	600
Event 10	19/10/99 18:30	21/10/99 08:30	2280	4.369	5.388	26.6	6.1	20.5	0.8	57.554	20/10/99 16:30	0.77	1320	960
Event 11	21/09/97 01:00	21/09/97 16:30	930	0.981	1.944	6.5	0.8	5.8	0.9	56.501	21/09/97 02:30	0.88	90	840
Median			**1200**	**2.831**	**2.895**	**10.9**	**3.0**	**8.5**	**1.0**	**62.832**		**0.84**	**225**	**840**
Maximum			**2280**	**5.766**	**8.494**	**26.6**	**6.1**	**20.5**	**1.1**	**72.093**		**0.91**	**1320**	**1410**
Minimum			**630**	**0.446**	**1.501**	**5.5**	**0.5**	**4.7**	**0.8**	**56.501**		**0.59**	**90**	**540**

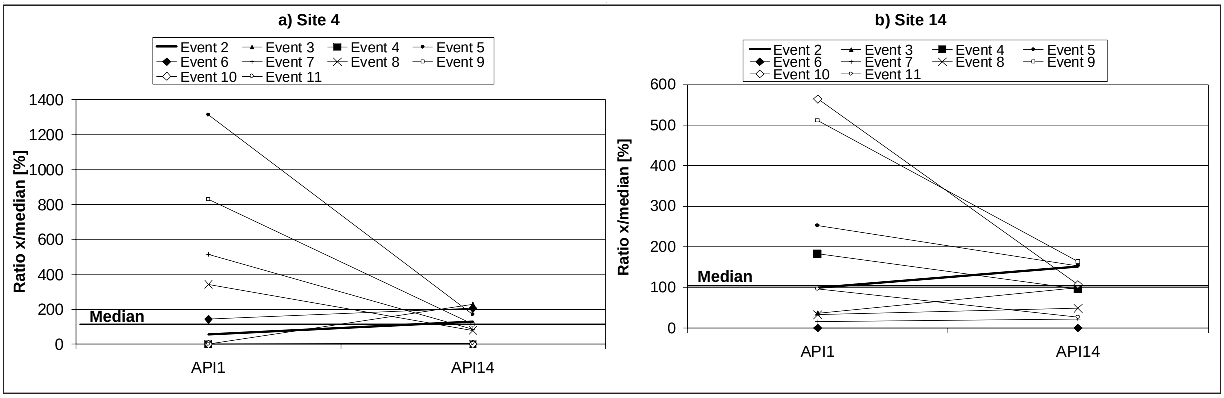


Figure 3.123: **Antecedent precipitation conditions of the largest events**

On the basis of these results it can be concluded that the antecedent precipitation, and herewith the antecedent moisture conditions, do not play a major role in the generation of the largest events in the catchment.

Precipitation during the largest events in the Jhikhu Khola catchment

The precipitation triggering the largest events in the Jhikhu Khola catchment is described spatially in Figure 3.124. These isohyets are indicative and are mainly for visualisation of the approximate spatial distribution of the event rainfall. The isohyets show no particular pattern. There are events where heavy rainfall occurred throughout the entire catchment, such as event 9 in June 1999 and event 10 in October 1999. During the latter, all sites measured more than 100 mm rainfall. During other events, only pockets within the catchment had heavy rainfall, such as event 6 in August 1998 or event 7 in May 1998. During event 6 heavy rainfall was observed in the upper part of the catchment in the area of Dhulikhel and Rabi Opi. During event 7 the concentrated, heavy rainfall was observed on the south-facing slopes of the catchment.

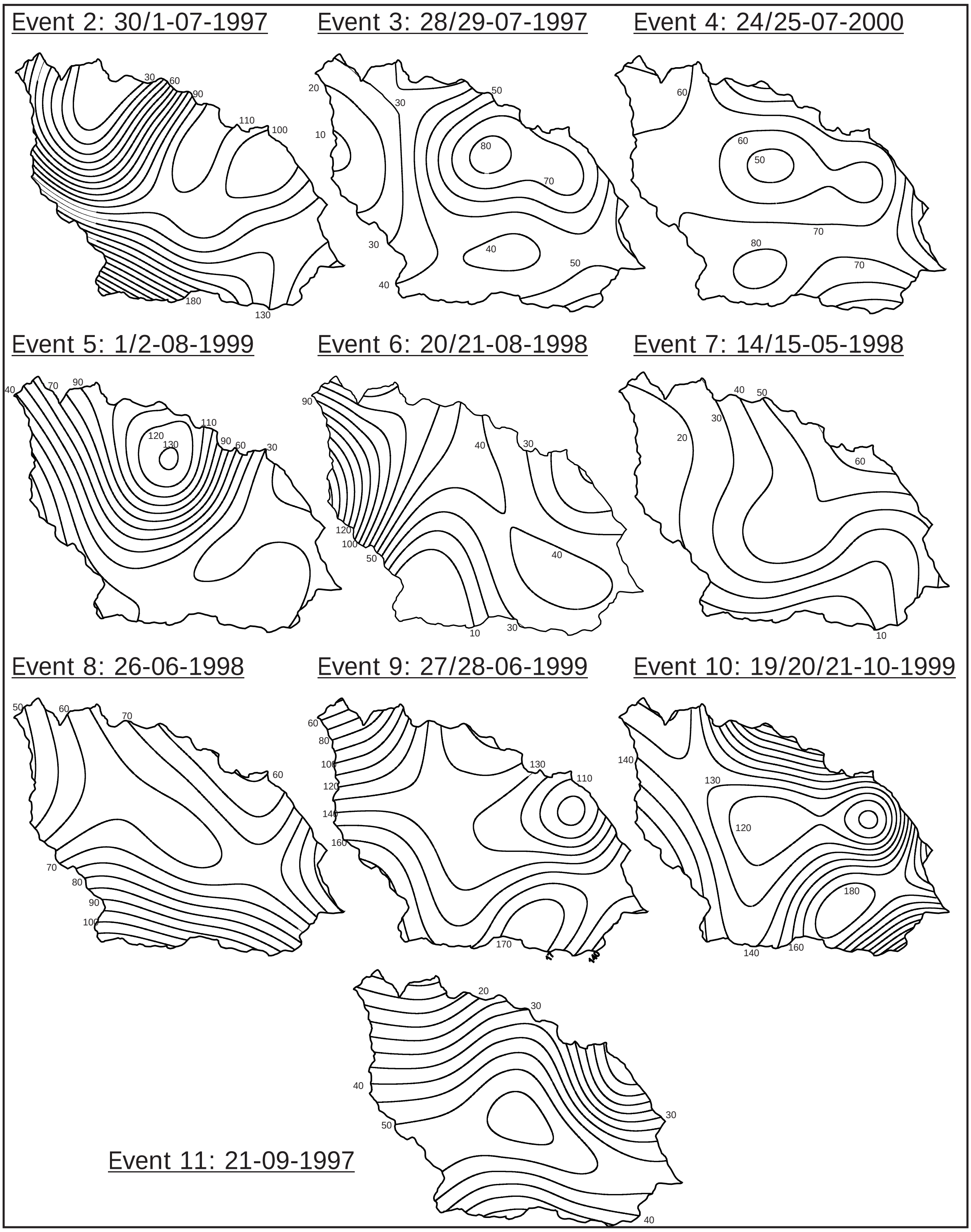
The rainfall events relevant for these flood events generally belong to rainfall clusters 3 and 4 at all sites, i.e., the high intensity and the high amount rainfall events (Table 3.97). There are three exceptions (see also Figure 3.124):

Table 3.97: **Rainfall clusters for the rainfall events triggering the largest flood events in the Jhikhu Khola catchment**

	Event number									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Site 4	2	3	3	2	2	2	3	4	4	3
Site 6	4	3	3	2	2	2	3	4	4	3
Site 12	-	-	3	-	2	3	3	4	4	-
Site 14	4	3	3	3	-	3	3	4	4	3

- during event 5 the sites on the north-facing slopes observed only events of cluster 2, while the upper and south-facing slopes received heavy rainfall of cluster 3;
- during event 6 none of the observed sites received high amounts of rainfall, while the upper catchment received heavy showers;and
- during event 7, the rainfall was concentrated on the south-facing slopes and at sites 4 and 6 on the north-facing slopes only medium events were observed.

Comparing the different rainfall parameters with each other at selected sites (Figure 3.125), it is apparent that the high amount and long duration events generally show low maximum intensities. Events 2, 9, and 10 belong to this class, with amounts and durations above the median to a considerable degree at all sites. The maximum intensities are below median during these events.


Event 2: 30/1-07-1997

Event 3: 28/29-07-1997

Event 4: 24/25-07-2000

Event 5: 1/2-08-1999

Event 6: 20/21-08-1998

Event 7: 14/15-05-1998

Event 8: 26-06-1998

Event 9: 27/28-06-1999

Event 10: 19/20/21-10-1999

Event 11: 21-09-1997

Figure 3.124: **Spatial rainfall during the 10 largest events in the Jhikhu Khola catchment**

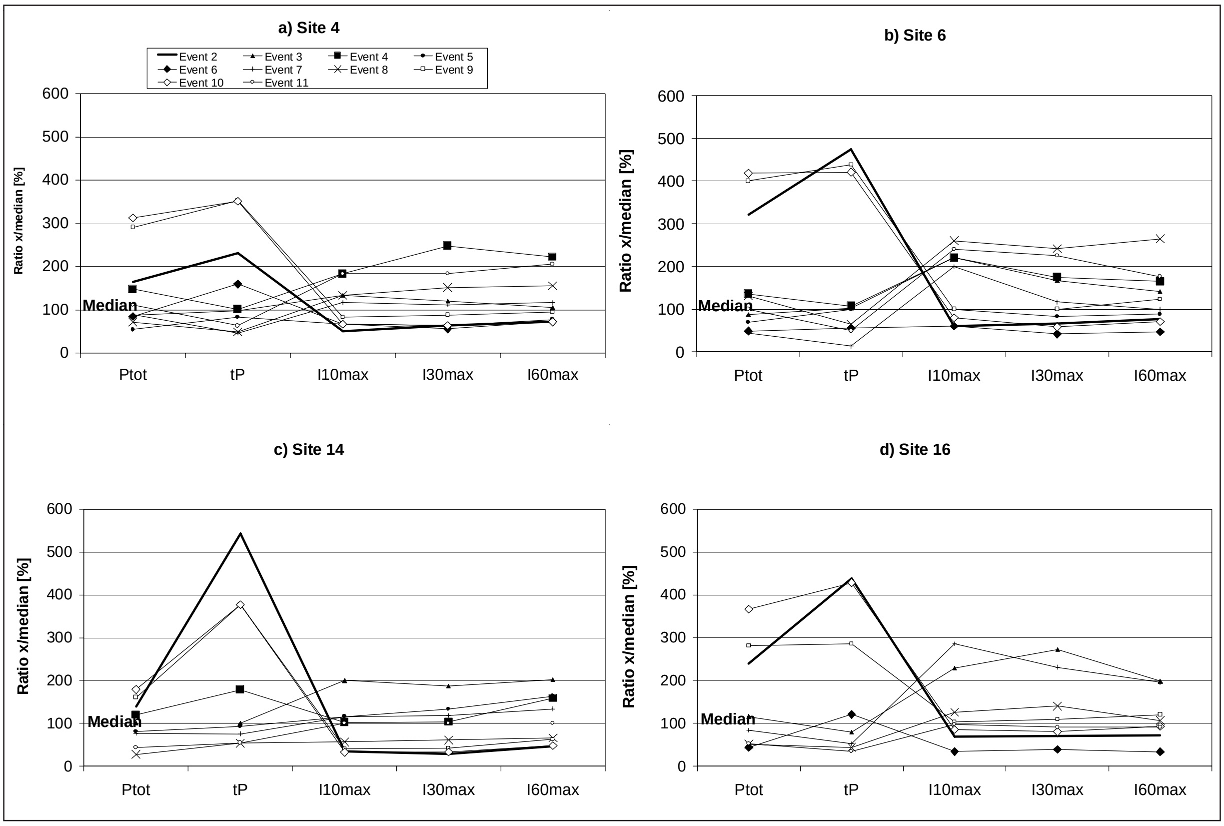


Figure 3.125: **Rainfall parameters during the largest events in the Jhikhu Khola catchment**

The events with below median amount and below median duration generally show above average intensities. The variability of the maximum intensities between the events is smaller compared with the other parameters, suggesting that heavy intensities are a major pre-condition for a large flood event. This is also shown by the fact that most large events were generated by cluster 3 rainfall events, i.e., heavy intensity, medium to large rainfall volumes (Table 3.97).

These results suggest that a large flood event is triggered at Site 1 by a rainfall event of high quantity and long duration throughout the catchment, or a concentrated shower with heavy intensities at least in some major parts of the catchment. At least some major areas of the catchment have to experience a cluster 3 event or most of the sites have to experience a cluster 4 event. This suggests the following thresholds, which may generate a large flood event (for more detail on the rainfall clusters refer to Section 3.4.3):

- for concentrated events in a major area of the catchment:
  - P_{tot} > 10 mm
  - I_{30max} > 20 mm/h
- for long duration and high amount events throughout the catchment:
  - P_{tot} > 50 mm
  - I_{30max} > 10 mm/h

__Runoff during the largest events on the erosion plots of the Jhikhu Khola catchment__

Sites 6 and 16 showed very variable surface runoff behaviour during the largest flood events at the outlet of the catchment (Figure 3.126). The runoff on these plots ranged from 4 to 100 m^3/ha (= 0.4 to 10 mm) at Site 6; and from 1.5 to 40 m^3/ha (=0.2 to 4 mm) at Site 16.

The variability is limited on the degraded plots, showing a range of 87 to 387 m^3/ha at Site 4 and a range of 40 to 256 m^3/ha at Site 14. The median of the largest events at these sites was 224 and 250 m^3/ha at Sites 4 and 14, respectively. These medians are ranked at positions 15 at Sites 4 and 9 at Site 14. On the rainfed agricultural land the median of Site 6 is rank 36 and at Site 16 rank 53. This

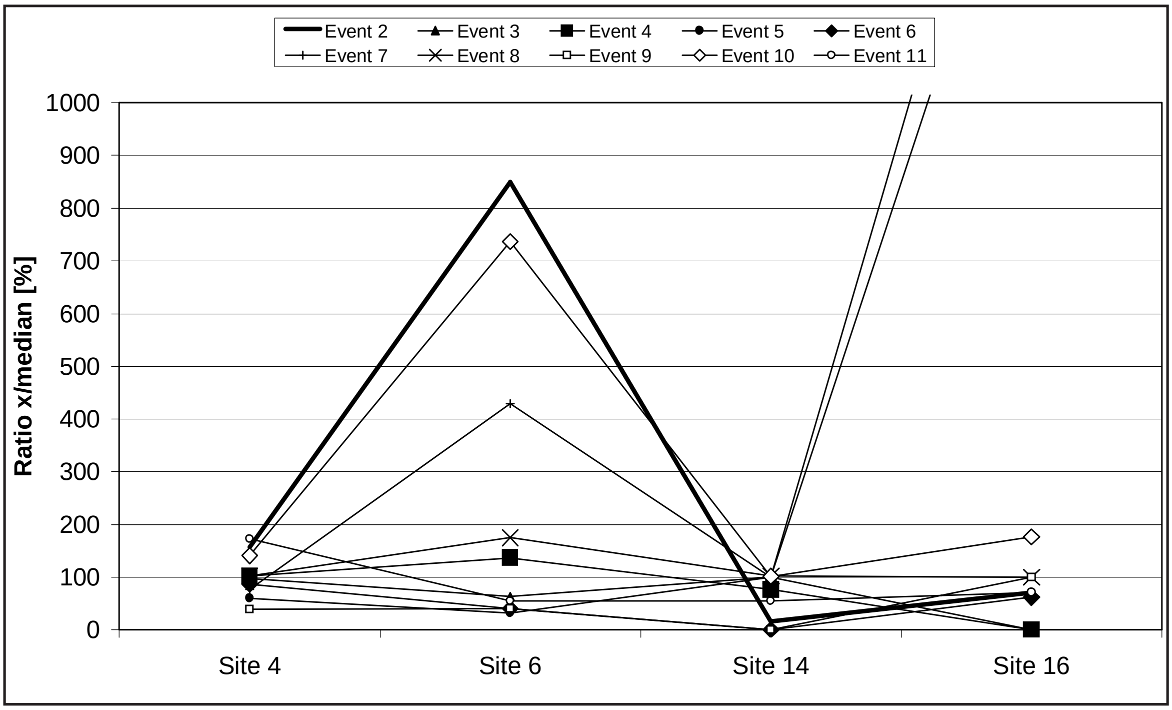


Figure 3.126: **Runoff during the largest events in the Jhikhu Khola catchment**

shows that the largest events tend to coincide roughly with the largest runoff events on the degraded plots, while in the case of the agricultural land, no relation or only a weak relation can be observed. This was also discussed above in Section 3.4.4 and suggests that the rainfed agricultural land does not decisively contribute to large flood events. Surface runoff on the degraded land, on the other hand, seems to play a major role.

Sub-catchment runoff during largest events in the Jhikhu Khola catchment

During the largest events at the outlet of the catchment, high flow was generally recorded at the four monitored sub-catchments as well. The ranks of the largest events at Site 1 at the sub-catchment outlets are compiled in Table 3.98. Site 13 generally showed high flows at the time of a flood event at Site 1 for the events 3, 4, 5, 7, and 11; in other words during these events there were high flows observed both at sites 1 and 13. During events 8, 9, and 10 only medium flow was observed at this site. Sites 2, 7, and 8 show similar behaviour, which is not surprising given their location. The events 5, 6, and 7, which mainly occurred in the upper catchment and on the south-facing slopes, did only show marginal peaks at the sites in the Andheri Khola sub-catchment.

Table 3.98: **Rank of flood events in the sub-catchments during the time of the largest events at Site 1, Jhikhu Khola catchment**

	Event number									
	2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Site 2	16	8	9	57	38	31	4	15	21	6
Site 7	10	16	-	38	64	46	3	6	15	11
Site 8	14	15	1	89	77	107	3	5	8	6
Site 13	-	1	4	5	-	3	24	72	44	13

The variability of the parameters would be between 50 and 150% of the median for most of the parameters, had there not been events 9 and 10 (Figure 3.127). These two events, both long duration and heavy rainfall amount events, showed very different values for most of the parameters except the peak event runoff and the peak discharge. The other cluster 4 rainfall event, event 2, is not included in the figures below, as it was caused by a double peak event in the sub-catchments.

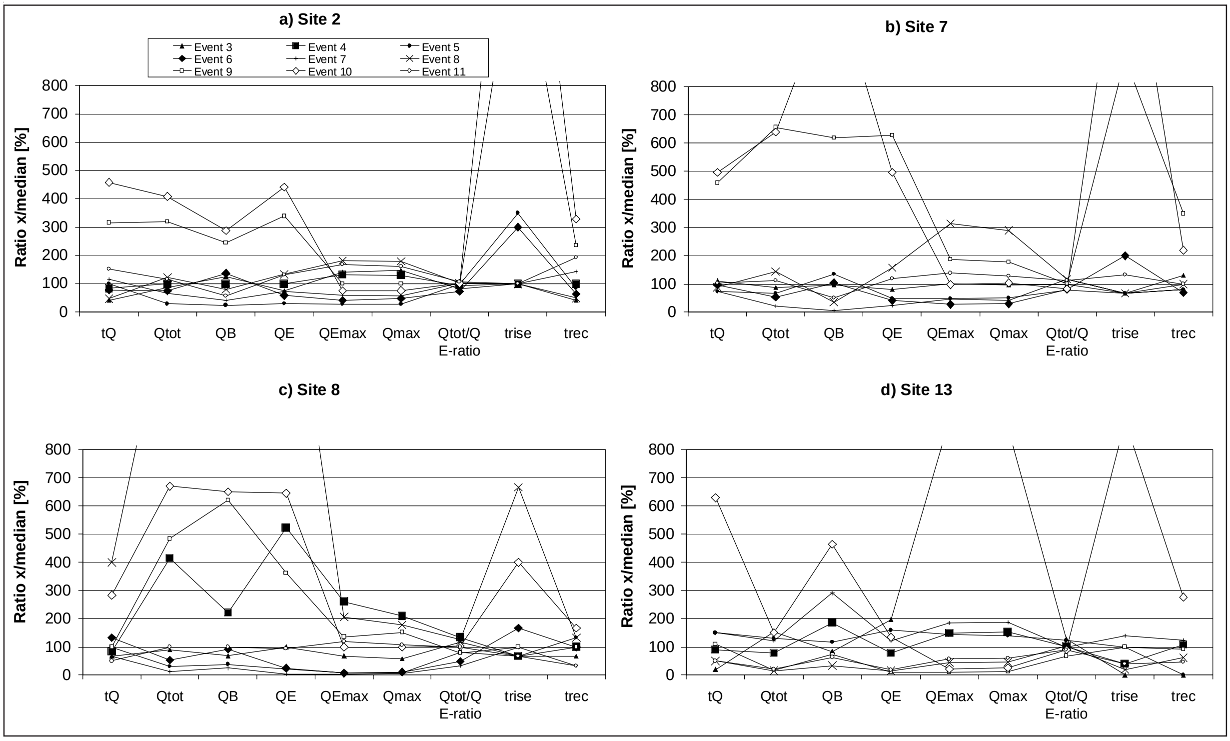


Figure 3.127: **Sub-catchment runoff during the largest events at the outlet of the Jhikhu Khola catchment**

Description of the largest events in the Yarsha Khola catchment

The largest events at Site 1 of the Yarsha Khola catchment were generally observed during the monsoon season. The ten largest events have a peak discharge of about 25 m^3/s or more (Figure 3.128) and a median value of 28.6 m^3/s (Table 3.99). The largest event that was observed during the study period had a peak discharge of 64.6 m^3/s.

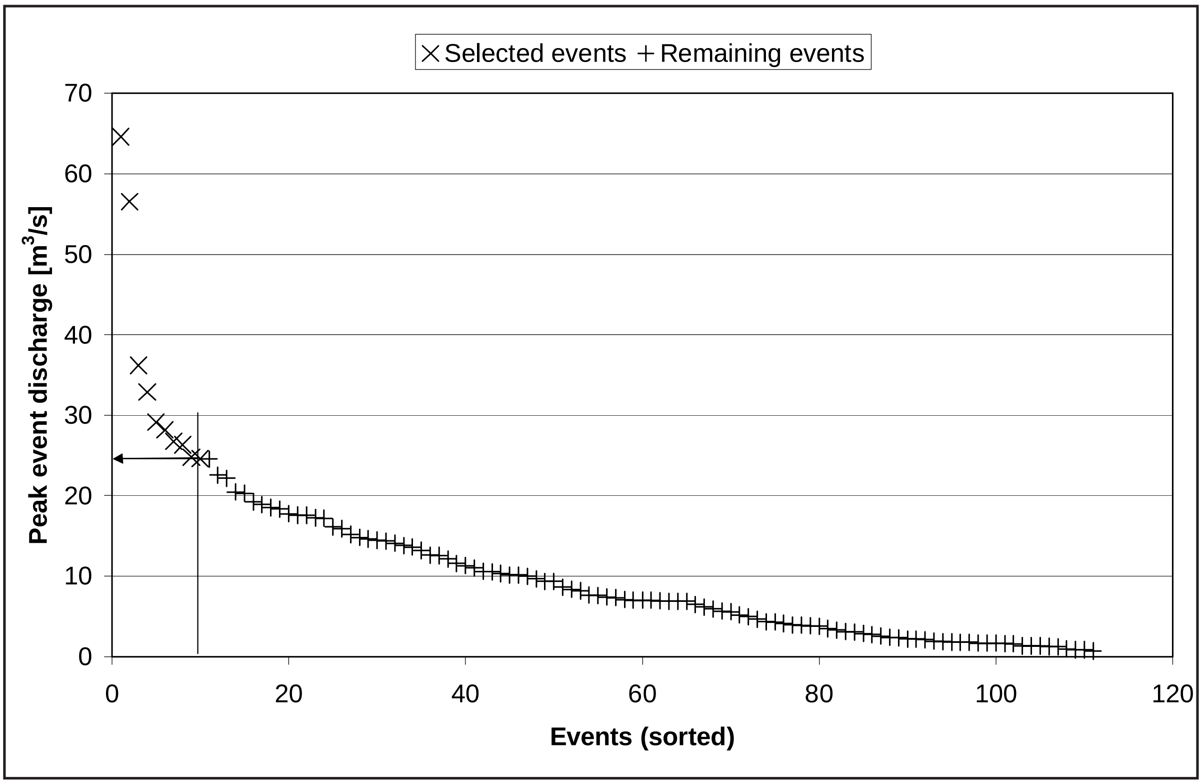


Figure 3.128: **The ten largest events at Site 1, Yarsha Khola catchment**

Table 3.99: **Hydrological event parameters for largest events at Site 1, Yarsha Khola catchment**

	Q_{tstart}	Q_{tend}	t_Q [min]	Q_{start} [m^3/s]	Q_{end} [m^3/s]	Q_{tot} [mm]	Q_B [mm]	Q_E [mm]	Q_{Emax} [mm]	Q_{max} [m^3/s]	Q_{tot}/Q_E	t_{rise} [min]	t_{rec} [min]
Event 1	21/09/99 23:30	22/09/99 09:00	570	3.949	12.096	11.6	5.4	6.1	2.0	64.601	0.53	180	390
Event 2	24/08/99 16:30	25/08/99 09:00	990	5.538	12.096	19.0	10.1	8.9	1.6	56.543	0.47	660	330
Event 3	01/07/98 22:30	02/07/98 11:30	780	3.099	7.318	11.2	4.7	6.4	1.1	36.189	0.58	210	570
Event 4	08/07/98 22:30	09/07/98 14:00	930	6.149	9.927	15.9	8.7	7.3	0.9	32.873	0.46	330	600
Event 5	27/07/99 22:30	28/07/99 08:30	600	5.418	11.864	10.5	6.1	4.4	0.7	29.120	0.42	270	330
Event 6	20/09/99 15:30	20/09/99 19:00	210	5.786	8.119	3.5	1.9	1.6	0.7	28.161	0.47	60	150
Event 7	04/09/99 15:30	04/09/99 20:30	300	6.309	8.634	4.4	2.8	1.6	0.7	26.773	0.37	60	240
Event 8	01/09/99 00:30	01/09/99 07:00	390	6.309	10.345	7.8	3.9	3.8	0.7	26.323	0.49	30	360
Event 9	05/07/98 14:00	05/07/98 23:00	540	3.244	7.501	7.3	3.4	3.9	0.7	24.785	0.53	90	450
Event 10	20/07/99 20:30	21/07/99 09:00	750	3.596	8.288	11.7	5.2	6.5	0.7	24.586	0.55	210	540
Maximum			**990**	**6.309**	**12.096**	**19.0**	**10.1**	**8.9**	**2.0**	**64.601**	**0.58**	**660**	**600**
Median			**585**	**5.478**	**9.280**	**10.8**	**5.0**	**5.3**	**0.7**	**28.641**	**0.48**	**195**	**375**
Minimum			**210**	**3.099**	**7.318**	**3.5**	**1.9**	**1.6**	**0.7**	**24.586**	**0.37**	**30**	**150**

The event duration ranged from about 3 to 15 hours, of which about 30 minutes to 11 hours was the rising limb and 3 to 10 hours was the receding limb. The ratio between Q_E and Q_{tot} was rather stable over the number of largest events ranging from 37 to 58%. This suggests that there is a considerable baseflow component in each event. This assumption is supported with the values for Q_{start} and Q_{end} of 3 to 6 m^3/s and 7 to 12 m^3/s, respectively. Expressed in mm, Q_B, the event baseflow, shows values from 2 to 10 mm, which is higher than the direct event runoff of 1.5 to 9 mm. Otherwise, no particular pattern can be observed in the distribution of the hydrological parameters.

Antecedent precipitation conditions of the events in the Yarsha Khola catchment

The antecedent precipitation conditions of the largest events in the Yarsha Khola catchment are very variable. At both sites, Site 5 (Figure 3.129a) and 9 (Figure 3.129b), the one-day rainfall prior to the event expressed by the index API_1 ranged from 20 to 160% of the median value. The API_{14}, the long term antecedent precipitation index, showed a range of 80 to 100% at the two sites. This suggests that the antecedent moisture conditions are not decisive over the generation of a major flow event.

Precipitation during the largest events in the Yarsha Khola catchment

The spatial event precipitation shown in Figure 3.130 likewise does not yield any obvious pattern between the largest events in the catchment. Certain events show heavy rainfall in the upper part of the catchment and only low rainfall in the southern and the lower part of the catchment, e.g. events 7 or 9.

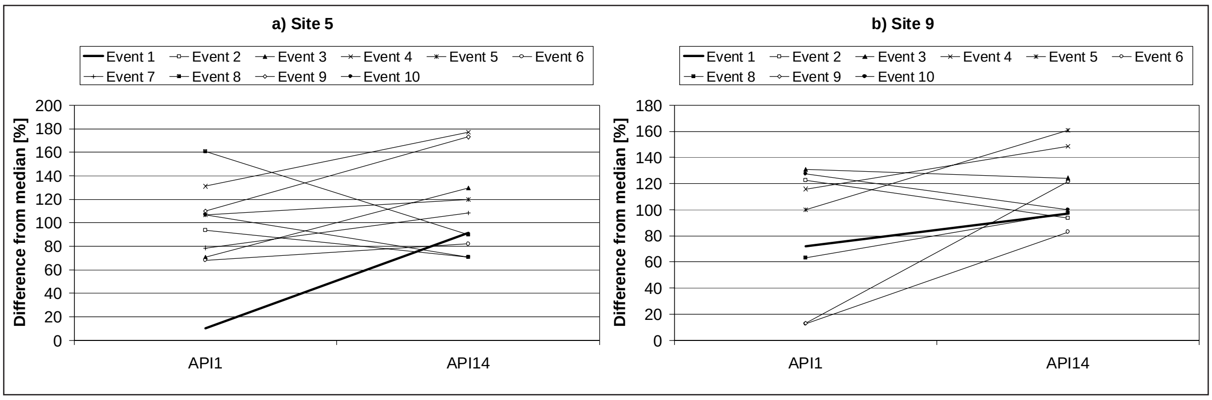
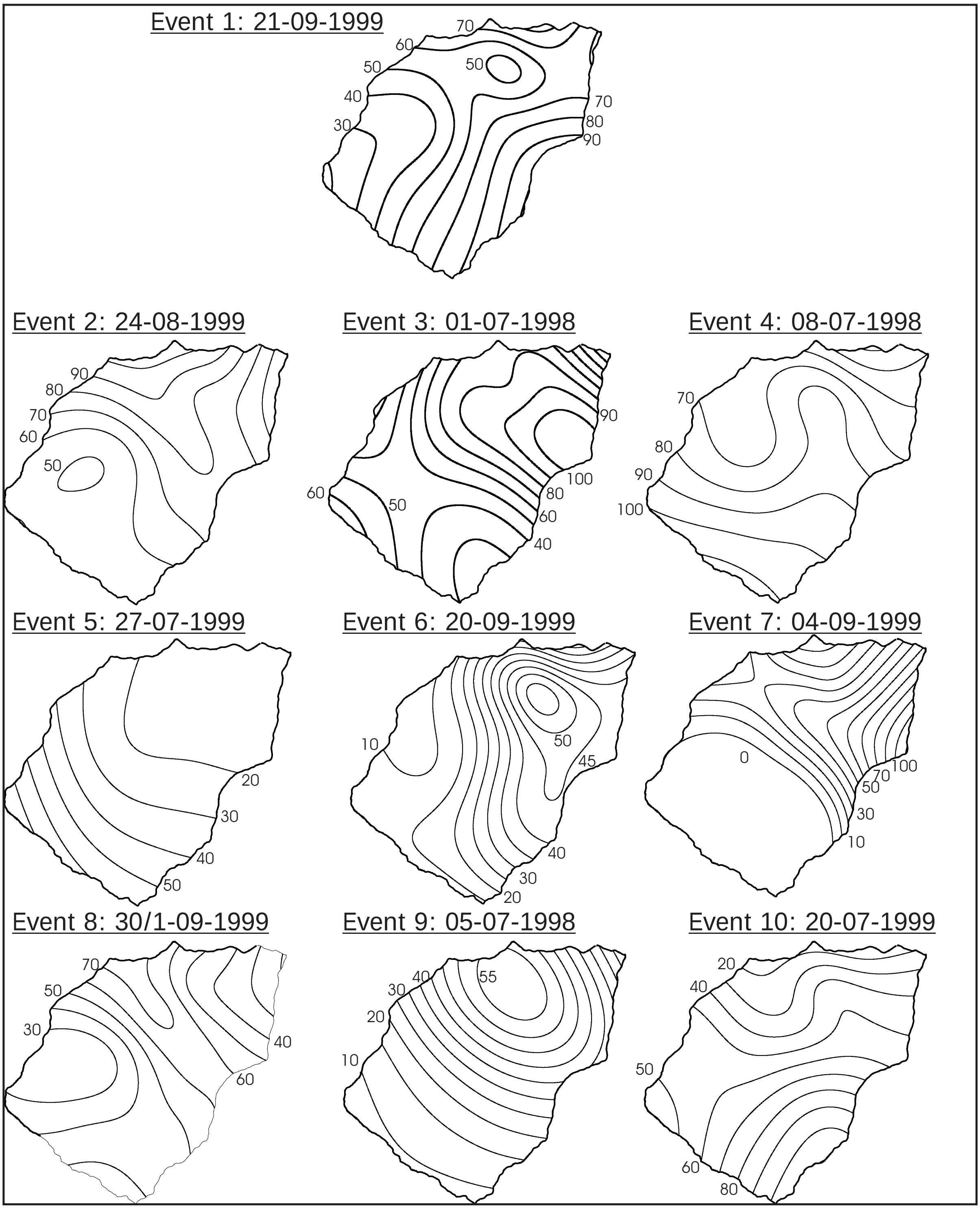


Figure 3.129: **Antecedent precipitation conditions of the largest events**



Event 1: 21-09-1999

Event 2: 24-08-1999

Event 3: 01-07-1998

Event 4: 08-07-1998

Event 5: 27-07-1999

Event 6: 20-09-1999

Event 7: 04-09-1999

Event 8: 30/1-09-1999

Event 9: 05-07-1998

Event 10: 20-07-1999

Figure 3.130: **Spatial rainfall during the 10 largest events in the Yarsha Khola catchment**

Other events show the opposite, with low rainfall in the upper part and heavy rainfall in the lower part of the catchment, e.g., events 5 or 10. The largest events are observed when rainfall is medium to high throughout the catchment, e.g., events 1, 2, 3, or 4.

Generally, the rainfall events causing major floods at the outlet of the catchment belong to the rainfall clusters 3 or 4 (Table 3.100). At least one of the selected stations generally shows a high intensity or a large volume event, with the exception of event 7. During this event, the rainfall was particularly heavy and was concentrated on the upper north-facing slopes.

Table 3.100: **Rainfall clusters for the rainfall events triggering the largest flood events in the Yarsha Khola catchment**

	Event number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Site 5	4	4	3	2	1	3	2	3	3	2
Site 6	4	4	3	3	1	3	2	4	3	4
Site 9	3	4	3	4	4	1	-	3	1	4

In terms of rainfall event parameters, no particular pattern can be observed for the largest events (Figure 3.131). Low duration events often show the heaviest rainfall intensities. The only pattern that can be shown is that either rainfall was high or intensity was high, which was already observed with the clusters in Table 3.100. The thresholds for the two types of events are noted again below:

- for events throughout the catchment with high rainfall volumes:
  - P_{tot} >25 mm
  - I_{30max} > 10 mm/h
- for events concentrated in one particular major area of the catchment:
  - P_{tot} >20 mm
  - I_{30max} >20 mm/h

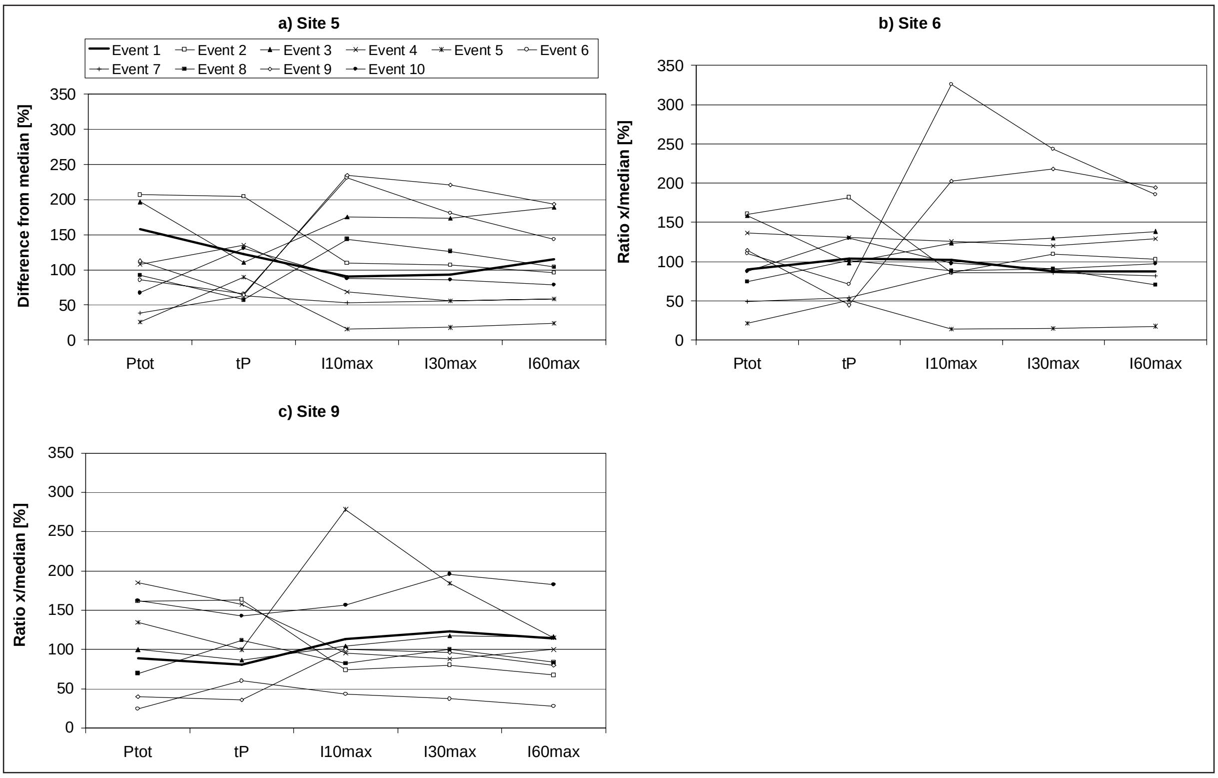


Figure 3.131: **Rainfall parameters during the largest events in the Yarsha Khola catchment**

<u>Runoff during the largest events on the erosion plots of the Yarsha Khola catchment</u>

The runoff on the erosion plots varies considerably during the largest flood events at Site 1 and no particular pattern can be observed (Figure 3.132). The runoff on plot 5 varied from 3 to 30 mm in the 10 events with a median of 20 mm. On the other grassland plot it varied from 6 to 28 mm with a median of 10 mm. The agricultural plots varied from 1 to 28 mm, with a median of 5 at Site 6 and from 4 to 27 mm and a median 3 mm at Site 9a.

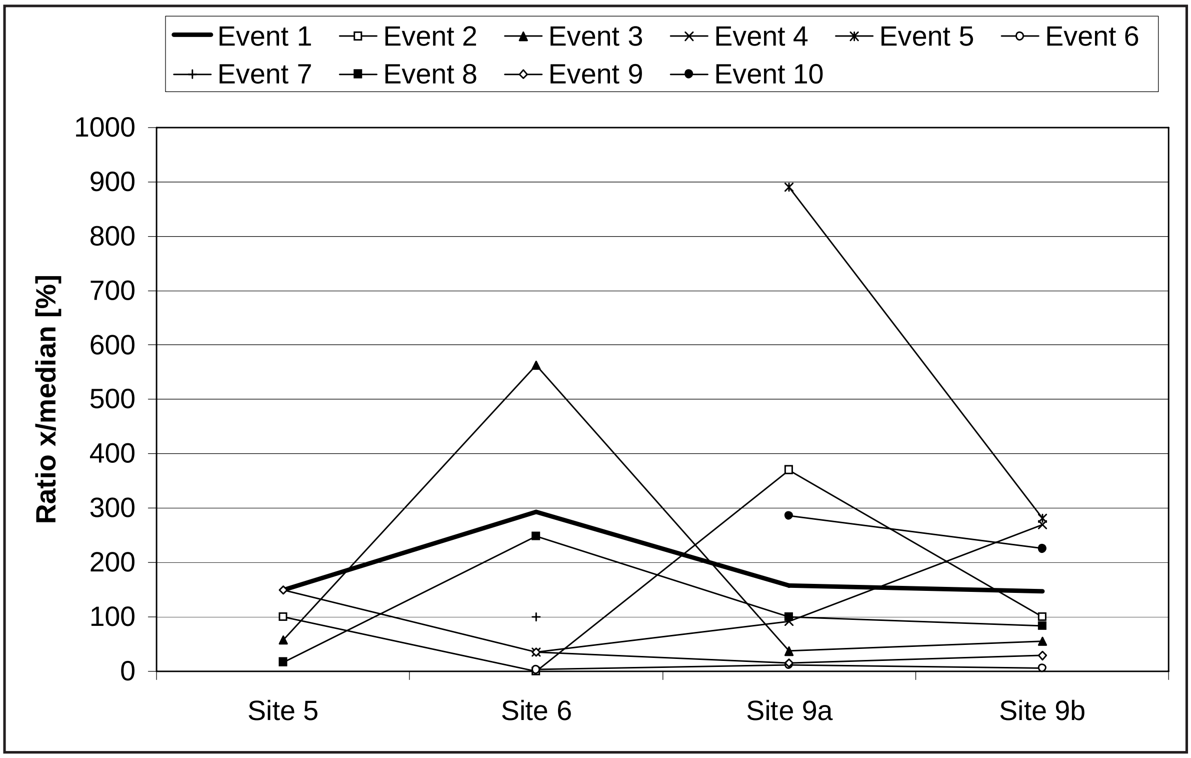


Figure 3.132: **Runoff during the largest events in the Yarsha Khola catchment**

Lessons learned from the largest events in the two catchments

Large flood events in the two catchments only occur when either the entire catchment receives high rainfall amounts over a long duration, or if a part of the catchment experiences a heavy shower. On the basis of the rainfall clusters determined in Sections 3.4.3 for the Jhikhu Khola catchment and 3.4.6 for the Yarsha Khola catchment, the following thresholds can be derived for large floods in these meso-scale catchments:

- for events throughout the catchment with high rainfall volumes:
  P_{tot} >25 mm
  I_{30max} > 10 mm/h
- for events concentrated to one particular major area of the catchment:
  P_{tot} >10 mm
  I_{30max} >20 mm/h

No particular pattern could be observed in terms of antecedent moisture conditions. In both catchments there were large events with no particularly high rainfall prior to the event, as well as events with high antecedent precipitation.

The largest events that were observed during the study period are probably still very low. Referring to the design rainfall amounts and the PMPs derived in Section 3.1 with values of 300 to 500 mm, the rainfall events that were observed were only representative for a lower segment of the potential events. It is, however, important to note that already these rather small events do not show any major reason to believe that land use and cover have made a big difference.

3.4.10 Summary of the event analyses and outlook

The event analyses were divided into the three sub-sets of rainfall, surface runoff from the erosion plots, and hydrological event analyses. The analyses of each subset are concluded with a small summary. The summary below therefore only mentions the main points.

- Rainfall events in both catchments can be clustered in four clusters: low, medium, high intensity, and large events. The cluster centres and their limits are tabulated above.

- Both surface runoff on the plots as well as from the sub-catchments is strongly correlated with the rainfall volume and the maximum rainfall intensities. This is shown not only with correlation matrices, but also in relation to the rainfall event clusters.
- The degraded plots in the Jhikhu Khola catchment as well as one of the grassland plots in the Yarsha Khola catchment show the highest events occurring during cluster 3 events, suggesting that infiltration excess overland flow may be the main surface runoff generating mechanism.
- The agricultural land in both catchments shows the highest runoff events during cluster 4 events, which suggests that on these areas saturation excess overland flow may be the main runoff generating mechanism.
- The degraded plots show good correlation with the high flow events at the sub-catchment and the catchment outlets. This suggests that these areas play a major role in the generation of floods or areas with similar flood generation mechanisms.
- On the catchment and sub-catchment scale the area of the catchment under grassland, degraded land and other land uses has an enhancing effect on the floods, while the cultivated land and irrigated land in particular tend to dampen the flood peaks as well as the average event parameters. This would suggest that terracing by Himalayan farmers actually reduces the flood peaks rather than, as often postulated (see Chapter 1) increases them.
- Amongst the topographic and morphometric parameters the drainage density and the Topoindex show an increasing effect.

The analyses above support the use of different land-use characteristics in the development of a Flood Generation Index as well as the use of the Topoindex (see Table 5.2, Chapter 5, p. 292, this volume, for a complete list of proposed indicators).

3.5 SEDIMENT MOBILISATION AND TRANSPORT

This section discusses sediment mobilisation and sediment transport as measured in the catchments. Sediment mobilisation rates are derived from erosion plot and surface flow collector measurements. Sediment transport rates are derived from suspended sediment concentration measurements at the hydrological stations and the subsequent establishment of a sediment rating curve.

3.5.1 Sediment issues in Nepal and the HKH

According to Galay et al. (2001), the Lesser Himalaya — including the high mountains, the middle mountains, and the Siwaliks — is one of the highest sediment production zones in the world, as shown by the example of the Karnali River in Western Nepal. This river has one of the highest sediment yields per square kilometre in the world, attributed to uplift and weak geology. In general, the high loads of Himalayan rivers are attributed to (WECS 1999):

- geologic factors (rapid uplift, generally weak strength of the rock, extensive mass wasting);
- hydrologic factors (exceptionally high rainfall over short periods, high seasonal rainfall in the monsoon, and frequent debris torrents);
- topographic factors (rivers having very steep slopes as they pass through mountain ranges); and
- human interference (road construction, deforestation in the Siwaliks).

The rivers of the entire Ganges-Brahmaputra-Meghna basin yield about 1000 * 10^6 t/y of sediment at a point about 200 km from the ocean in Bangladesh (Milliman and Syvitski 1992). A similar estimate is given by WECS (1999), according to which about 1670 * 10^6 t/y of sediment comes out of the Himalayan range into the Ganges and Brahmaputra system. Narayana and Babu (1983) report sediment loads for the Ganges and the Brahmaputra of 586 * 10^6 t/y and 470 * 10^6 t/y, respectively. Lauterburg (1993) estimated different sediment deliveries on the basis of published data (Figure 3.133) with the highest values in the Central Himalayas of the Garwhal-Kumaon and the Nepal Himalaya.

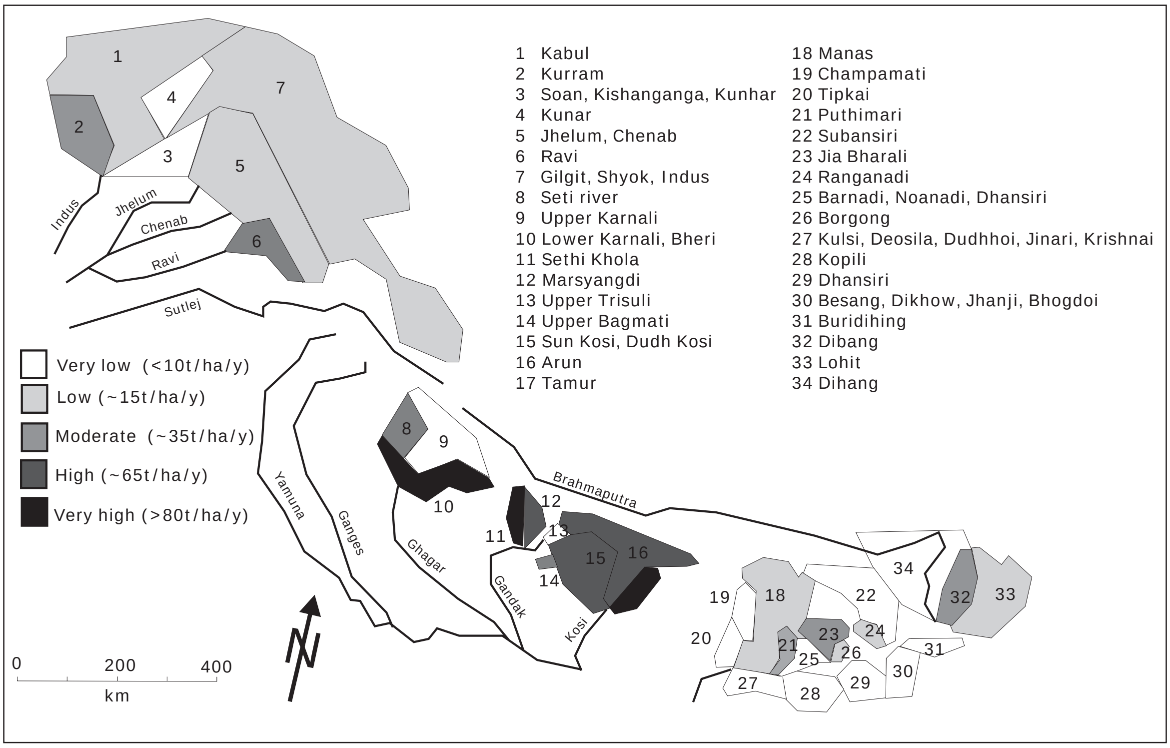


Figure 3.133: **Suspended sediment delivery for some Himalayan rivers** (Lauterburg 1993)

The two critical parameters for large sediment yield are both the rates at which sediment is mobilised in the catchment as well as the efficiency of the river system to transport the sediment downstream.

3.5.2 Sediment mobilisation

Sediment is mobilised from different sources as a result of different processes. In the context of PARDYP, where soil fertility and loss of fertile topsoil were of particular interest, surface erosion was monitored in detail using the method of erosion plots (see details on the method in Section 2.4). Other forms of erosion such as streambank erosion and gullying have not been monitored in detail to date. Landslides in the catchment occur mainly in relation to roads and are only rarely seen on agricultural land. To date, no programme for monitoring and investigating landslides in the PARDYP catchments has been initiated, although it is acknowledged that landslides may be a major source of sediment during large storms. The impact of roads, the construction phase, in particular, is discussed in more detail at the end of this section in a case study.

3.5.2.1 Sediment source areas and processes

In 2001, an area wide assessment of the vulnerability of the entire Jhikhu Khola catchment, including the expected erosive processes, was carried out during the sediment source mapping campaign (MRE 2002). In general, an empirical relationship between altitude, weathering, transport rate, and deposition rate was observed (Figure 3.134).

Depth of weathering increases as altitude decreases, with particularly intense weathering on gentle slopes that are east or south facing This suggests that climatic parameters important for weathering (rainfall and temperature) tend to show a difference according to aspect (see also Sections 3.1 and 3.2). Residual soils are well developed in the middle and lower reaches of the catchment. Additionally, residual soils can be observed on the ridges and spurs of the upper reaches. In these areas bedrock is generally exposed on steep slopes with surrounding colluvial soils. Weathering on the valley floor is subdued due to frequent flooding and material deposition.

The rate of material transport is directly related to slope, precipitation, and morphology. It is the lowest on the flat valley floor and peaks on the highest and steepest slopes. While in the upper

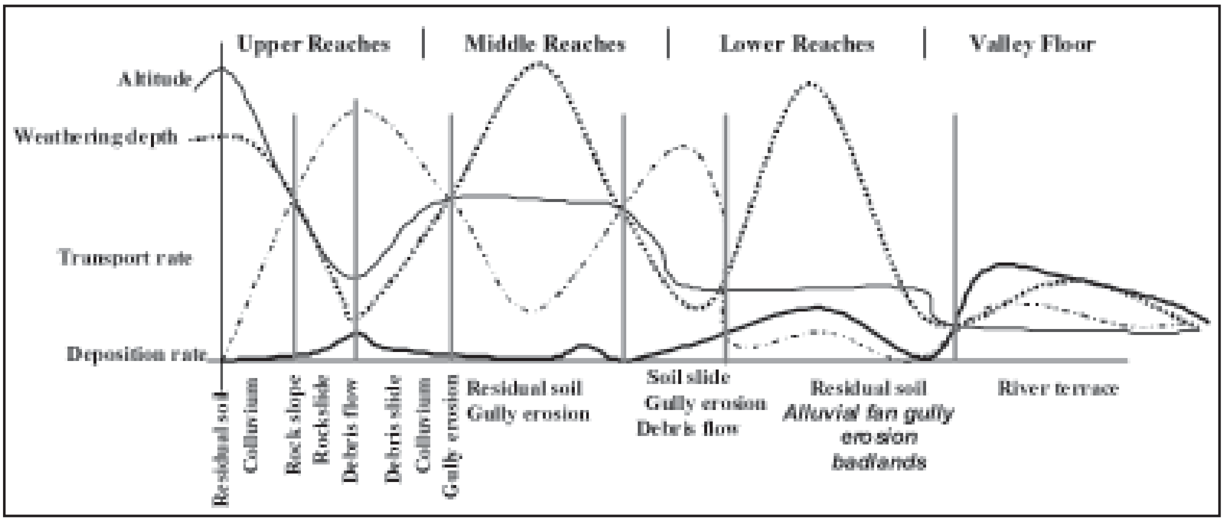


Figure 3.134: **Empirical relationship between altitude, weathering, transport rate and deposition rate observed in the Jhikhu Khola catchment (from MRE 2002)**

reaches debris flows contribute to the mobilised material, the steep soil slopes of the middle and lower reaches are the preferred areas for gully erosion and the formation of badlands.

The rate of sediment deposition again is based on slope, morphology, and the amount of transported material. Generally, sediment depositions increase from the upper reaches to the valley floor, where most of the sediment is deposited in the form of alluvial fans and river terraces. The rate of sediment deposition shows the opposite behaviour from the rate of material transport rate.

The observed processes include rockfall (f; in Figure 3.135), topple (t), debris flow (w), landslides (s), undercutting by streams (u), and surface erosion including gullying (e). The study showed that the Jhikhu Khola is mainly vulnerable to surface and gully erosion and the formation of badlands. About 92% of the catchment's area was identified to be prone to surface erosion and gullying. The most vulnerable areas for soil erosion are the middle and lower reaches of the catchment, while the upper areas are most vulnerable to mass movements. About 52% of the area is considered to be susceptible to landslides. Debris flows are considered to potentially affect 18%, rock falls 10%, undercutting of streams 9% and toppling 2% of the catchment area. In general, MRE (2002) conclude that the Jhikhu Khola catchment in comparison with other catchments is one of the least vulnerable catchments in the middle mountains of Nepal. Therefore only little soil loss and small amounts of sediment have to be expected from this catchment.

In the Yarsha Khola catchment Tschanz (2002) mapped only the south-facing slope of the catchment (Figure 3.136). Interestingly, in this catchment the mass movements are mainly expected in the lower areas of the catchment and mainly along the stream network. The middle part seems to be very stable or subject to accumulation of debris and sediment from areas above. The main processes in the upper reaches of the catchment are surface erosion, including gullying, and rill and sheet erosion, as well as erosive processes on rainfed agricultural land. In terms of sediment sources the areas along the stream network seem to be most important, along the Padu Khola, Kahare Khola, and along reaches of the main river in particular. On the basis of Tschanz's observation, surface erosion on rainfed agricultural land is high as the farmers have to compromise a certain topsoil loss with slope stability. Surface erosion is minimised on irrigated land, but slope stability may in certain cases be of major concern due to high water pressure in the soil column. This also often leads to slumping of irrigated terraces in the area, as was reported in Tschanz et al. (1999).

The different processes are discussed in Carson (1985) in terms of adverse impacts on farmers' livelihoods. In this context, the uncatastrophic and annual loss of topsoil is rated highest in terms of damage to local farmers, followed by different forms of mass wasting. Rockfalls, mostly occurring in uncultivated and very steep, rocky areas, affect the farmers' livelihoods least.

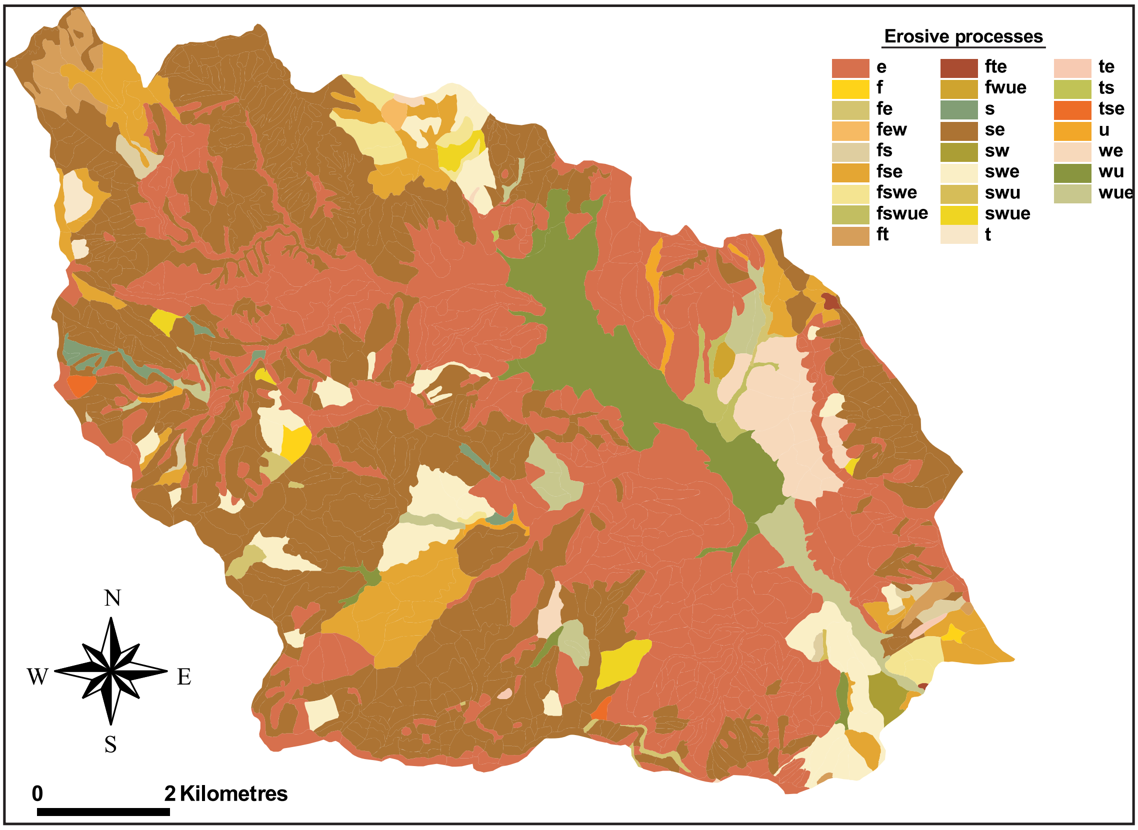


Figure 3.135: **Erosive processes in the Jhikhu Khola catchment. Legend: f = rock fall, t = topple, w = debris flow, s = landslides, u = undercutting by streams (u), s = surface erosion including gullying** (data source: MRE 2002)

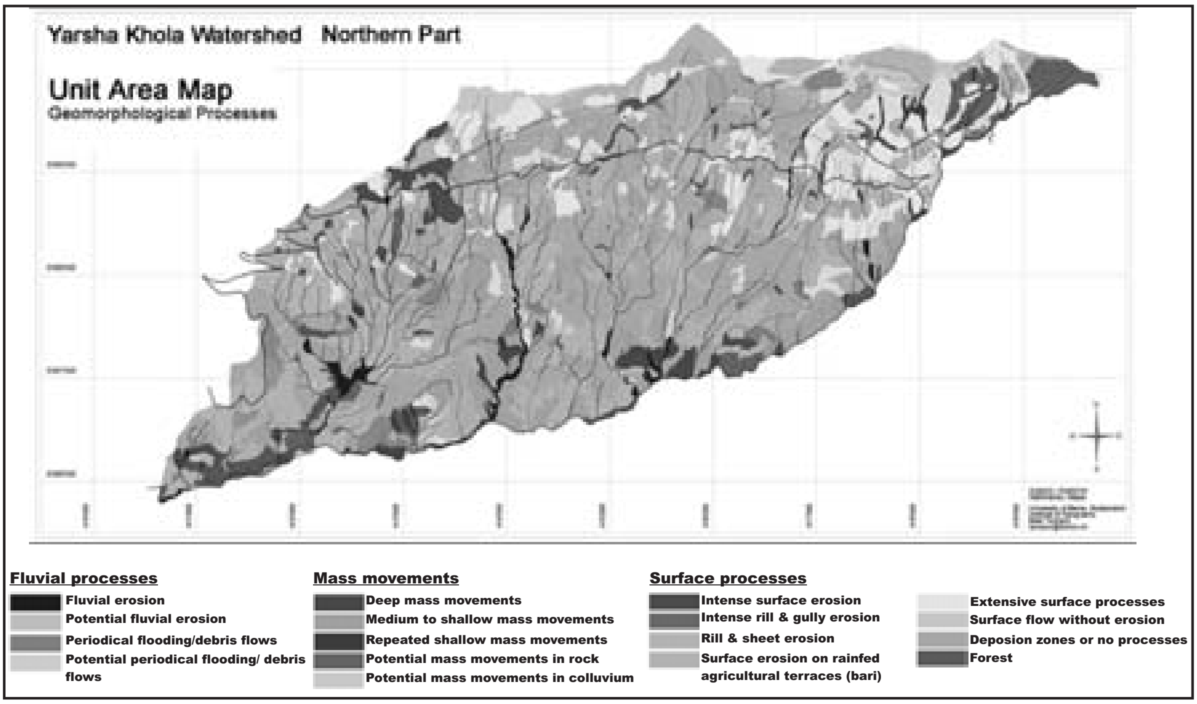


Figure 3.136: **Geomorphological processes on the south-facing slope of the Yarsha Khola catchment** (modified from Tschanz 2002)

In terms of sediment output, Gerrard (2002) identified landsliding and debris flows as the most important sediment source in the Likhu Khola catchment, a steep catchment to the north of Kathmandu. Debris flows are rated higher in terms of sediment outputs due to their high water content, high viscousity, and their often high likelihood of reaching the stream. This is also the reason why stream bank erosion was ranked high in terms of sediment source, as by definition this erosive process has a high connectivity to the drainage system. On the basis of personal observations in the Jhikhu Khola and Yarsha Khola catchments (Table 3.101), landslides are not as important as in the Lhikhu Khola mainly due to the lower slopes in these catchments. Surface and streambank erosion seem to be the most important sediment sources, as also suspected by Carver (1997). Rockfalls were rated lowest as their debris usually does not leave the catchment, but produces debris scree slopes. The importance of surface erosion (including gully erosion) in large parts of the Jhikhu Khola catchment is also supported by a study by Saijo (1991).

Table 3.101: **Priorities of the occurrence of erosive processes and their importance as sediment sources in the Jhikhu and Yarsha Khola catchments (rating 1 to 5)**

	Occurrence of processes		**Importance as sediment source**	**Impact on local farmers' livelihoods**
	JKW	**YKW**		
Surface erosion	1st	1st	1	1
Landslides	2nd	2nd	4	2
Debris flows	3rd	Not assessed	3	2
Streambank erosion	5th	4th	1	4
Rockfalls	4th	3rd	5	5

Note that the occurrence of processes was identified in the field. The importance as well as the impact were assessed on the basis of literature and general process understanding. For future work this assessment should be verified with field data.

3.5.2.2 Sediment mobilisation rates by surface erosion

Note: As in this section land use and slopes of the erosion plots are very important, in all graphs and in all tables the plot names are always accompanied with the respective land use and slopes in short form:- d/x degraded, x degrees - r/x rainfed, x degrees

From a literature review on erosion plot and small catchment studies, it is apparent that the soil losses vary tremendously depending on numerous factors such as land cover, land management, topographic setting, and climate (see the summary of this section and Appendix A1.1). In general, however, it can be said that the more vegetation cover, the flatter the slope, and the fewer the land management practices, the lower the soil erosion rates will be. If land is cultivated, level terraces prove to be less likely to contribute to soil erosion than sloping terraces. This, however, again depends on the quality of the land management. Poorly managed terraces provide a basis for increased soil erosion rates.

Surface erosion losses in the Jhikhu Khola catchment

Acknowledging the differences between the plots, including land use, slopes, management, and soils, the sediment yield between them was compared briefly. This was carried out mainly to understand the order of magnitude of soil erosion in the catchment. Five plots within the Jhikhu Khola erosion plot network were selected for further analysis. This includes two plots on degraded land (Plots 4a and 14a) and three plots on rainfed agricultural land (Plots 6a, 16a, and 17a) (Table 3.102). At this point it is important to note that the plots on rainfed agricultural land extend over at least two terraces in order to incorporate at least one terrace riser. This excludes the 'terrace riser problem' (Critchley and Bruijnzeel 1995), i.e., the assumption that terraced land is *a priori* beneficial to sediment conservation although the terrace risers may contribute substantially to sediment losses by integrating a whole system, including the field and the corresponding terrace risers. The annual distribution of soil loss shows that degraded plots on average yield more sediment than rainfed agricultural land. In 1998, Plot 14a yielded on average the highest sediment yield, at 17 t/ha. The same plot showed the maximum annual soil loss of 34.3 t/ha.

Table 3.102: **Annual soil loss [t/ha] (in brackets the annual rainfall in mm at the plot)**

Year	Plot 4a (d/11.5)	Plot 6a (r/20.4)	Plot 14a (d/14.0)	Plot 16a (r/6.7)	Plot 17a (r/9.2)
1993		37.2* (1045)		0.1* (949)	
1994		7.0 (1136)		3.2 (1173)	
1995		1.9 (1176)		0.6 (1157)	
1996		18.7 (1291)		3.4 (1287)	
1997	27.6* (1084)	8.4 (1294)	39.2* (1195)	1.1 (1313)	1.2* (1313)
1998	7.4 (1111)	20.1 (1288)	34.3 (1292)	1.4 (1217)	3.2 (1217)
1999	5.9 (1442)	2.8 (1546)	6.4 (1481)	0.1 (1464)	0.6 (1464)
2000	22.8 (1069	13.9 (1213)	10.2 (1188)	0.0 (1296)	0.4 (1296)
Average**	**12.0 (1207)**	**10.4 (1278)**	**17.0 (1320)**	**1.4 (1272)**	**1.4 (1326)**
Average 98-00	**12.0 (1207)**	**11.8 (1349)**	**17.0 (1320)**	**0.7 (1326)**	**1.4 (1326)**

d = degraded r = rainfed agricultural land

* This figure should not be used for calculations as this represents the data of the first year of the plot where the soil was disturbed during set up.

** This average is calculated excluding the first year's soil loss.

Comparing the plots with the same land use, Plot 14a yields considerably more sediment on average than Plot 4a, which has very similar rainfall conditions. The variability is very high on these plots, which show a range of 6 to 23 t/ha at Site 4, and 6 to 35 t/ha at Site 14. The plots on rainfed terraces vary in the order of one magnitude, where Plot 6a shows ten times more soil loss than the other two plots on the same land use. The cause for this difference is presumably the difference in slope, with 20.4 degrees on Plot 6a and 6 to 10 degrees on Plots 16a and 17a. There is also great variation within the plots on rainfed agricultural land. While Plot 6a varies from 2 to 20 t/ha, at Sites 16 and 17 the soil loss ranges from 0 to 4 t/ha with very similar rainfall. Plot 6a produces nearly as much sediment as plot 4a on degraded land, which again is presumably the direct impact of the high slope of this plot. Plots 4a and 14a only have slopes of 11.5 and 14.0 degrees, respectively. This has a practical relevance as the rainfed agricultural land is mainly located in the upper parts of the catchments with higher slopes, while the degraded areas are mainly located on the foot slopes of the catchment. Due to this reason there is no major difference expected between the sub-catchments of the foot slopes (e.g., Kubinde Khola sub-catchment) and the upland sub-catchment (e.g., Kukhuri Khola or Upper Andheri Khola) in terms of sediment loads.

Seasonally, soil loss occurs mainly in the two wet seasons of the pre-monsoon and the monsoon itself (Figure 3.137a). On average, the highest soil losses occurred in the pre-monsoon season, with the exception of Plot 4, where the monsoon season accounted for more soil loss. In terms of maximum soil losses (Figure 3.137b), losses in the pre-monsoon and monsoon seasons are similar in the case of the degraded plots. On the rainfed agricultural land, maximum pre-monsoon soil losses are still higher by about 40% than the monsoon soil losses.

All the plots show their highest soil losses in the late pre-monsoon – early monsoon in the period 1998 to 2000, i.e., the months of May and June (Figure 3.138a). The two plots on agricultural land produce almost more than 50% of their annual soil loss during the month of May. The plots on degraded land produce about 30% during this month and erosion activities extend up to July. This distinct difference between the plots on degraded land and the ones on rainfed agricultural terraces in terms of the soil loss regime is also shown by the month with peak erosion in this period (Figure 3.138b). While the plots on agricultural land have a distinct erosion peak in May and then June, the plots on degraded land have their peaks either in May, June, or July. Gardner et al. (2000) likewise identified the pre-monsoon to be the most susceptible season for soil loss due to bare and recently prepared land.

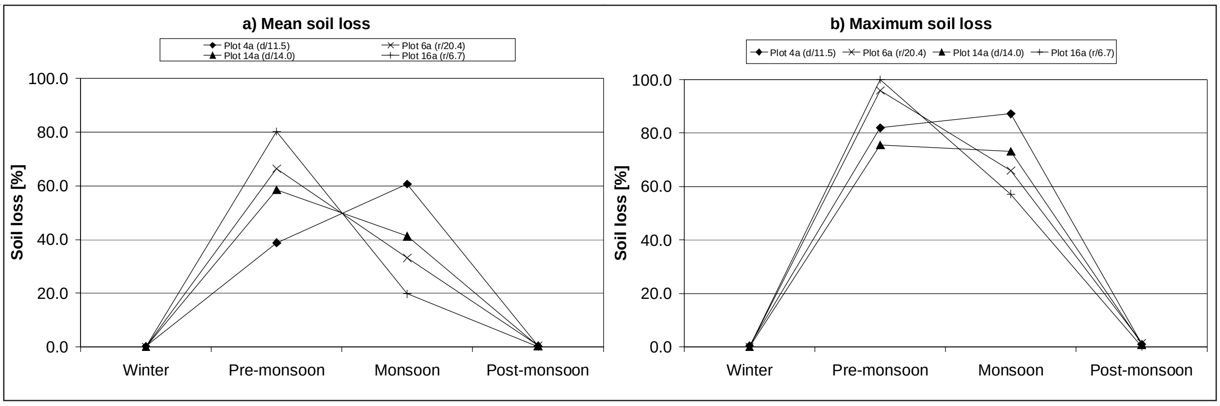


Figure 3.137: **Seasonal soil loss Jhikhu Khola; a) average soil loss, and b) maximum soil loss in the period 1998 to 2000**

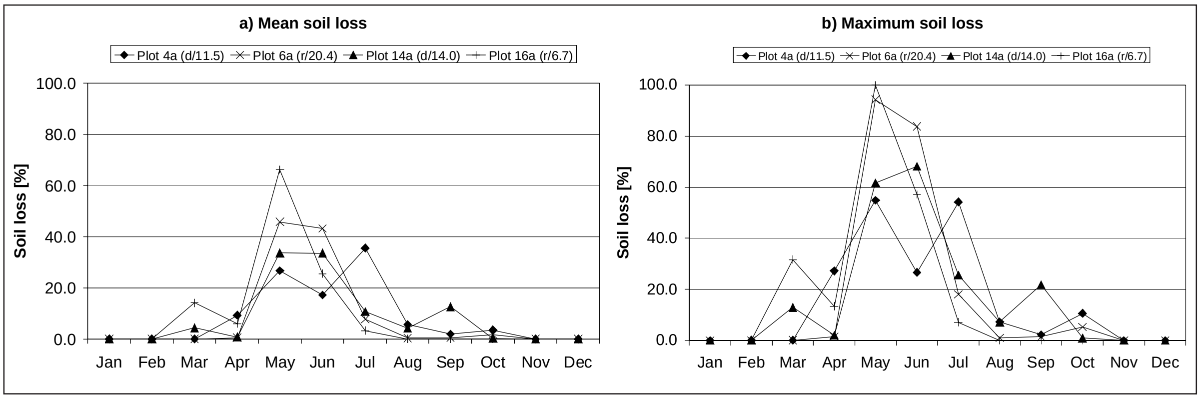


Figure 3.138: **Monthly soil loss Jhikhu Khola; a) average soil loss, and b) maximum soil loss in the period 1998 to 2000**

In the case of the agricultural plots, maximum soil erosion in May reached 95% of the annual total in Plot 6a in 1998, and 100% in plot 16a in 2000. However, this 100% in 2000 is not as explicit as the 95% during 1998 as only 0.04 t/ha soil loss was measured in 2000 and all of it occurred in May. These findings are best explained by the annual dynamics of vegetation cover in relation to rainfall, as for example is shown in Figure 1.5 in Chapter 1. However, the reasons for the behaviour of degraded lands without any vegetation, as for example in Plot 14a, are not yet well documented, but are assumed to be directly related to rainfall parameters (see Section 3.4 or event analyses below).

As Nakarmi et al. (2000) reported on the basis of the 1998 data from the Jhikhu Khola catchment, 10 events were responsible for 90% of the annual soil loss from agricultural plots. Degraded lands needed more events to reach the same level. However, these authors indicate that 60 to 70% of the total soil loss occurs in only 2 to 3 events. Gardner et al. (2000) note that 75% of the soil loss is generated by 6 or fewer storms, usually early monsoon storms.

These findings can be supported by results calaculated on the basis of data from 1998 to 2000. In 1998 (Figure 3.139a), 75% of the soil loss was generated by 2 to 3 events on Plot 6a. On Plot 16a, 4 to 5 events contributed about 75% of the annual soil loss. About the same number of events was responsible for 75% of the annual soil loss on Plot 4a, while on Plot 14a about 6 events were required. In 1999, 2 events generated more than 75% of the annual soil loss on Plot 6a and 8 events were required for 75% annual soil loss on Plot 16a (Figure 3.139b). In the same year, 4 events generated 74% of annual soil loss on Plot 14 and the same percentage was produced by 10 events on Plot 4. In 2000 (Figure 3.139c), the degraded plots behaved very differently from plots on agricultural land, with 2 events on agricultural land, and 5 and 9 events on the degraded plots. On average (Figure 3.139d), on agricultural land about 3 events were responsible for more than 75% of the total annual soil loss. The same percentage is reached by 5 to 7 events on degraded land.

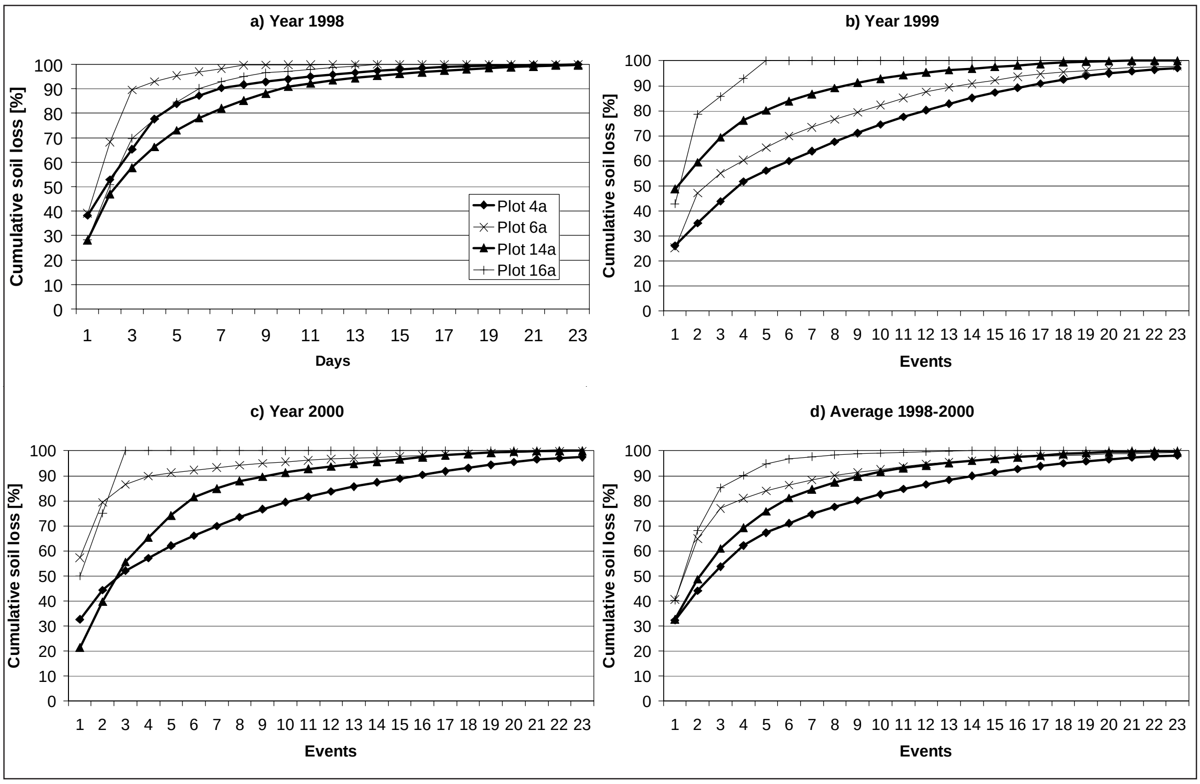


Figure 3.139: **Average cumulative soil loss of four plots in the Jhikhu Khola catchment, 1998, 1999, and 2000; and average for 1998-2000**

Comparing the number of events generating about 75% of the annual runoff with the total number of events per year, it can be said that about 10% of the annual events cause about 75% of the annual total soil loss on all plots.

The overview of the sediment mobilisation rates by surface erosion in the Jhikhu Khola catchment can be summarised as follows.

- Degraded plots show greater soil loss (6 to 35 t/ha) than agricultural land (0 to 20 t/ha).
- With increasing slope, agricultural plots show similar soil loss to degraded land
- Soil loss on the agricultural slopes mainly occurs in the pre-monsoon season and in particular during May and June.
- Soil loss on the degraded plots is well distributed throughout the early wet season with peaks in May, June, and July.
- About 3 events (about 10% of the events) cause more than 75% of the annual soil loss on the agricultural land.
- Five to seven events (about ten per cent) cause more than seventy-five per cent of the annual soil loss on the degraded land.

Surface erosion losses in the Yarsha Khola catchment

In the Yarsha Khola catchment, four erosion plots were monitored from 1997 to 2000. Two plots, Sites 5a and 9b, were established on grazing land and two plots, Plots 6a and 9a, on rainfed agricultural terraces (for more detail refer to Section 2.4). In general, there is a large variation in terms of elevation and rainfall between the plots (Table 3.103). In this context, the comparison between Plots 9a and 9b is particularly interesting, as these plots are located about 20 m apart from each other and the rainfall is measured at the same site. The general overview of the data in Table 3.103 shows that the grazing land consistently yields lower soil losses than rainfed agricultural land. This is also true for the plot with the highest rainfall at Site 5a. Although it has nearly double the rainfall than Plot 9a, Site 5a only shows a fraction of the soil loss. The same is also true when comparing the Plots 9a and 9b. With the same rainfall, the grazing land Plot 9b shows about 10 times less soil loss in the order of magnitude.

Table 3.103: **Annual soil loss [t/ha] (in brackets the annual rainfall in mm at the plot)**

	Plot 5a (g/19.1)	Plot 6a (r/17.0)	Plot 9a (r/17.5)	Plot 9b (g/17.5)
1998	0.2 (2940.0)	13.9 (2496.0)	11.3 (1691.9)	1.4 (1691.9)
1999	0.4 (2863.6)	0.7 (2315.7)	26.3 (1693.4)	0.7 (1693.4)
2000	0.1 (2855.0)	5.7 (2392.8)	18.6 (1738.4)	0.6 (1738.4)
Average	**0.3 (2886.2)**	**6.8 (2401.5)**	**18.7 (1707.9)**	**0.9 (1707.9)**

g = grazing r = rainfed agriculture

In terms of seasonal variation of soil loss there is a no distinct pattern visible between different plots with the same land use. The mean seasonal soil loss shown in Figure 3.140a peaks either in the monsoon season or in the pre-monsoon season with 35 to 55% of the annual soil erosion in the pre-monsoon season and 45 to 65% during the monsoon season. The maximum seasonal soil loss (Figure 3.140b) is generally observed in the monsoon season with the exception of Plot 9a, where the maximum was observed in the pre-monsoon season. The maximum soil loss in any season can reach 90%, ranging from 60 to 90% in the monsoon season and 45 to 75% in the pre-monsoon season.

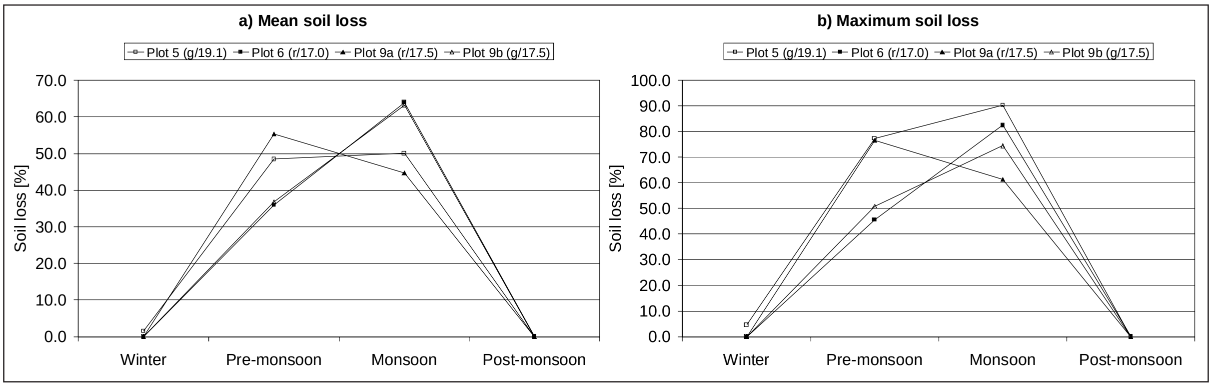


Figure 3.140: **Seasonal soil loss Yarsha Khola; a) average soil loss, and b) maximum soil loss in the period from 1998 to 2000**

The highest average monthly soil losses during the study period were observed either in the pre-monsoon month of May or the monsoon season month of July, with a big drop in June (Figure 3.141a). This pattern, however, should be considered with caution as only three years of data were observed, and this rather peculiar pattern first has to be validated with more data. The maximum monthly soil loss shows the same pattern with the maximum either in May or in July, with the very low values in June. On average, 20 to 40% of the annual soil loss occurred during May and about the same percentage in July. The maxima observed in May reached about 75%, with the lowest maxima observed at Plot 9b with about 30%. The highest maximum observed in the month of July was more than 80% at Plot 5a. It has to be remembered that the overall soil loss on this plot was minimal.

In the Yarsha Khola catchment, 5 to 11 events are, on average, responsible for about 75% of the annual soil loss depending on the plot (Figure 3.142). Plot 5a, with very low soil losses, observes about 75% of its annual soil loss during an average of 5 events. In 1999, only 1 event caused about 80% of the annual soil loss. In 2000, the same percentage was reached by 9 events. At 9b, the other grazing land plot, 11 events were needed on average, with 15 events in 1999, to produce 75% of the annual soil loss. On the agricultural land about 8 events at both plots produced this percentage of the annual soil loss, ranging from 5 events in 2000 at Plot 6a, to 12 events in 2000 on the same plot.

On average, 128 events were observed annually at the erosion plot 5a. This suggests that about 5% of the annual events in the erosion plots generate 75% of the annual soil loss. On the agricultural plots, about 7 to 8% of the annual events were responsible for the same percentage, while at Plot 9b about 12% of the annual events caused this soil loss.

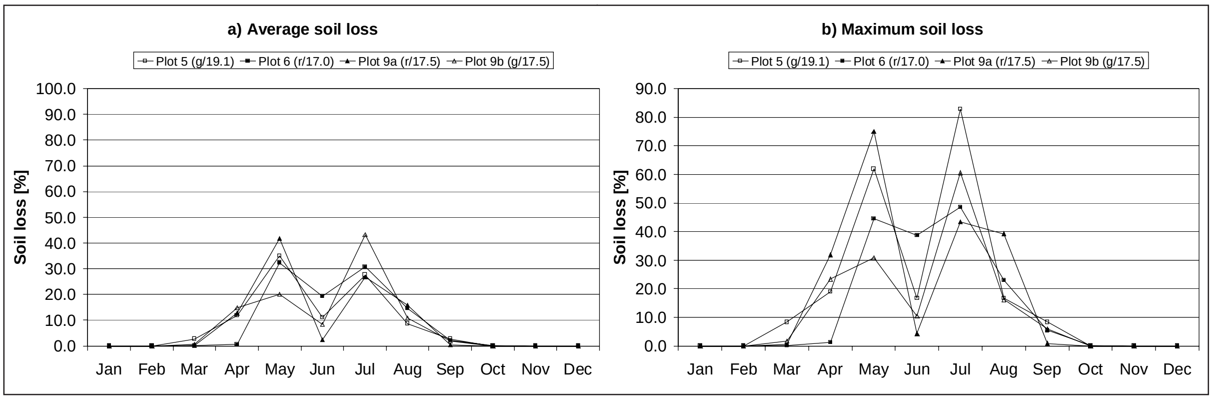


Figure 3.141: **Monthly soil loss Yarsha Khola; a) average soil loss, and b) maximum soil loss in the period 1998 to 2000**

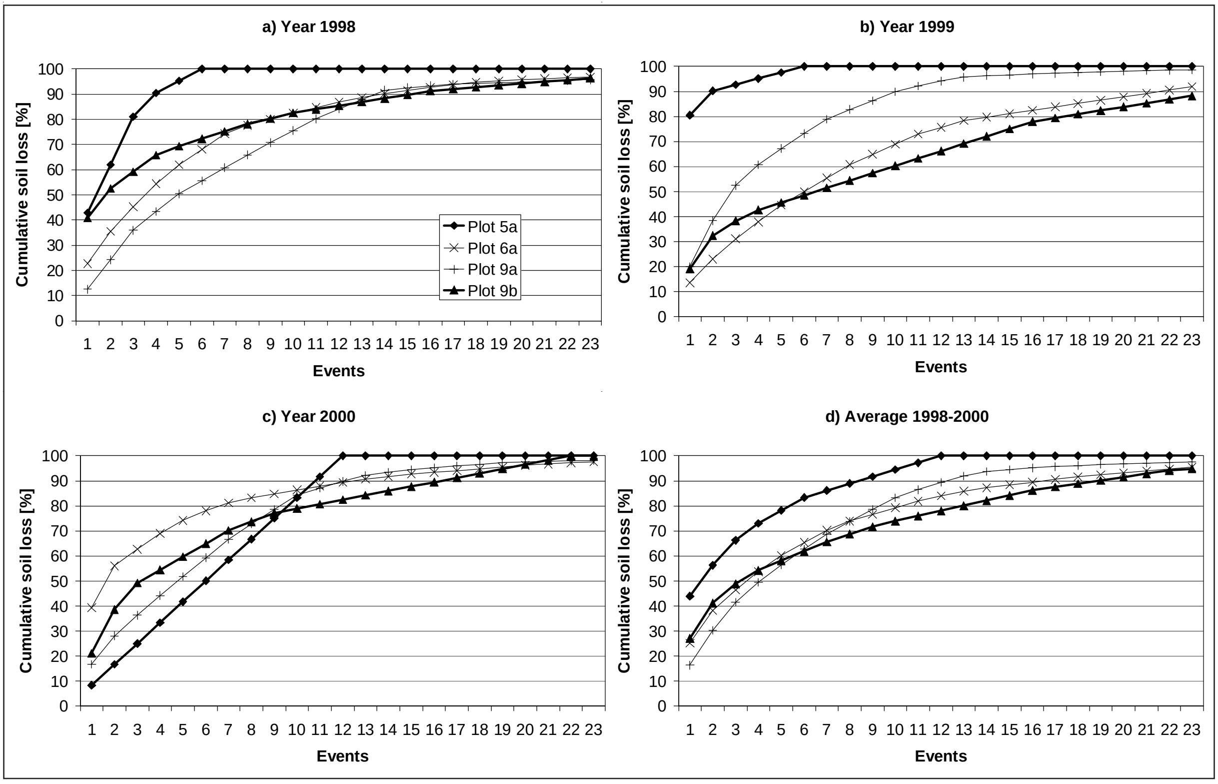


Figure 3.142: **Average cumulative soil loss of four plots in the Yarsha Khola catchment, 1998, 1999, 2000 and average for 1998 to 2000**

An overview of the soil losses in the Yarsha Khola catchment can be summarised as follows.

- The soil loss on agricultural land is in the order of magnitude higher (5 to 26 t/ha) than on the grazing land (0 to 2 t/ha).
- The soil losses occur both in the pre-monsoon and the monsoon season, mainly in the months of May and July.
- There is no seasonal difference observed between the plots on grazing and agricultural land.
- Five to 11 events generate, on average, about 75% of the annual soil loss, which corresponds to about 5 to 10% of the total number of events observed on the plots per year.

Event soil loss on erosion plots of the Jhikhu Khola catchment

Carver (1997) identified rainfall events of 3 mm in the Jhikhu Khola catchment as the lower threshold for soil erosion on the basis of the erosion plot data from 1993 to 1995. This was confirmed by the longer time series from 1993 to 2000. However, a difference has been observed between the degraded plots and the rainfed agricultural plots. While on the degraded plots, soil mobilisation is initiated at events of about 3 mm, on the rainfed agricultural land events of minimum 5 mm rainfall are required to initiate soil loss.

Figure 3.143a shows the median values and the range for all events during the study period from 1993 to 2000 at Plots 6a and 16a, and for 1998 to 2000 at Plots 4a and 14a. In order to ensure that the observations are not affected by the different study period, Figure 3.144a shows the results of all plots only for the period 1998 to 2000. The highest soil loss events were observed at Site 14 with a median value of 0.11 t/ha and a 75% quartile of 0.65 t/ha. At Site 4a, the other degraded plot, the observed median value was also 0.08 t/ha with a 75% quartile of 0.42 t/ha. On the rainfed agricultural plots, the median event soil loss was 0.05 t/ha at Site 6a and 0.03 t/ha at Site 16a. The range on these plots was much lower, with a 75% quartile of 0.17 t/ha at plot 6a and 0.09 t/ha at Site 16, respectively.

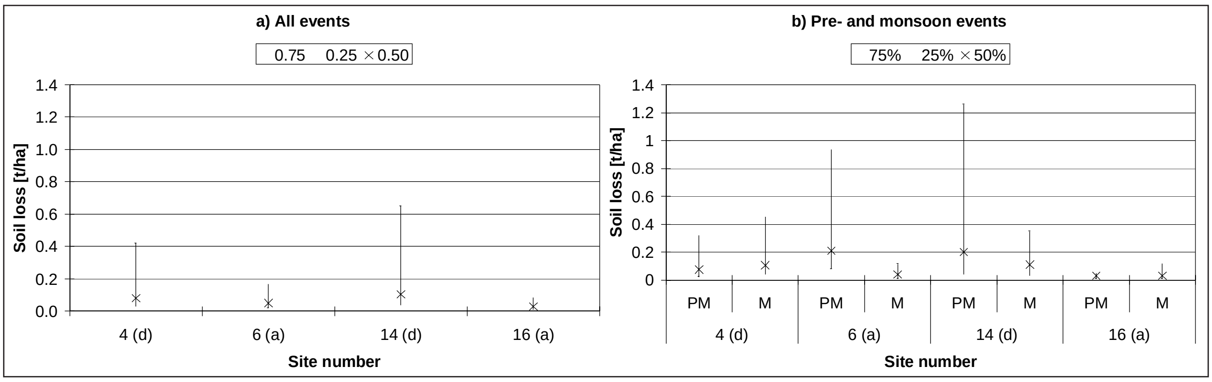


Figure 3.143: **Event soil loss for a) all events, b) all pre-monsoon and monsoon events of the entire study period, Jhikhu Khola catchment**

These medians as well as the 75% quartiles only differ slightly between the different periods. The median tends to be the same as the 75% quartile is slightly reduced in the shorter period (Figure 3.144a), indicating that a number of larger storms were observed between 1993 and 1997. The comparison of the pre-monsoon and monsoon events at the different sites as presented in Figure 3.143b and Figure 3.144b shows that the highest range of event soil loss is observed at Site 14a, followed by Site 6a during the pre-monsoon season. These events also show the highest median values of about 0.2 t/ha. Looking only at the period 1998 to 2000, the highest soil loss was observed at Site 6a with about 0.85 t/ha soil loss in one event. The monsoon events on the agricultural plots tend to show lower soil loss per event than during the pre-monsoon season. Site 4a shows the same result for both study periods. At Site 14a this could also be observed for the period 1998 to 2000, but during the entire study period at this plot, which was established in 1997, pre-monsoon soil loss was higher than during the monsoon season.

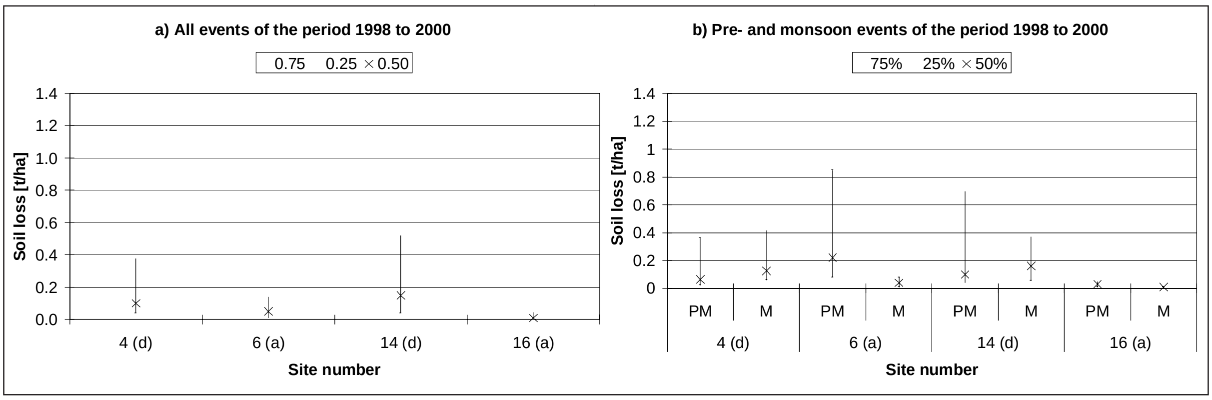


Figure 3.144: **Event soil loss for a) all events of the period 1998 to 2000, b) pre-monsoon and monsoon events of the period 1998 to 2000, Jhikhu Khola catchment**

The largest ten events observed at each site out of all events (Figure 3.145a) and during the period from 1998 to 2000 (Figure 3.145b) shows that event soil loss at the rainfed agricultural Site 6a is comparable to the soil loss at the degraded Sites 4 and 14a. For both periods, the 10 largest events at this site showed the biggest range, from about 3.5 to 7.5 t/ha, and a median of about 5 t/ha for all events; and from 1 to 5.5 t/ha and a median of 2 t/ha for the period 1998 to 2000. At Site 14a, event soil loss of the 10 largest events ranged from 3 to 6 t/ha (2 to 3.5 t/ha; 1998 to 2000) and a median of 4 t/ha (2.5 t/ha). The largest 10 events at Site 4a showed between 1 and 2 t/ha soil loss, while at Site 16a the soil loss was below 1 t/ha.

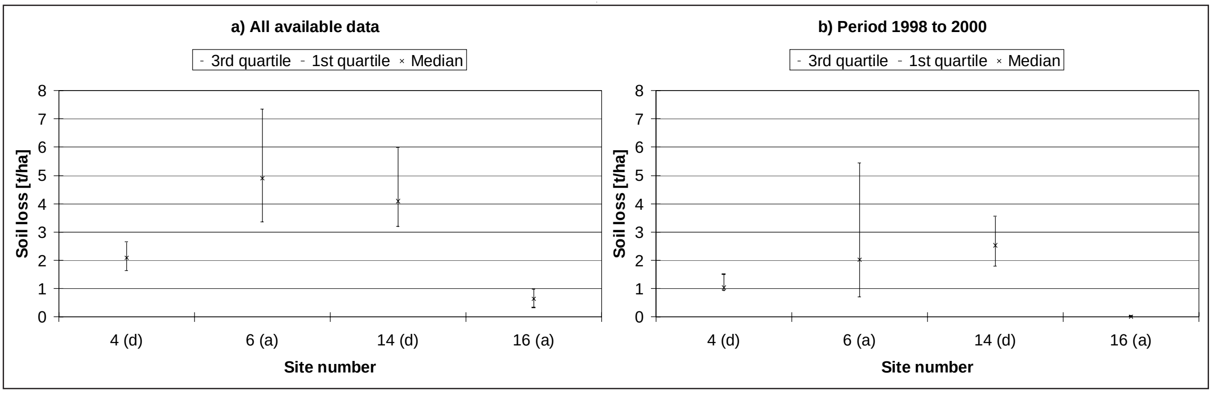


Figure 3.145: **Ten largest events for a) all available data, b) period 1998 to 2000, Jhikhu Khola catchment**

On the basis of the joint analyses of rainfall parameters with erosion plot parameters, it can be shown that soil losses are directly and significantly correlated with rainfall intensity parameters and runoff (Table 3.104; see also Section 3.4). The highest correlations are however achieved by the intensity parameters. I_{10max} shows slightly higher correlations than I_{30max}. This is different from the runoff on the plots, which is more highly correlated with I_{30max} and even I_{60max}, which shows here the lowest correlation with soil loss. Due to this reason, it is suggested that using I_{30max} for all analyses would be sufficient and the additional benefit in terms of increased understanding of measuring at the 10-minute interval is not significant. This is important to note for other projects. For PARDYP however, the 10 minute data are readily available.

Table 3.104: **Correlation coefficients of significant correlations between event soil loss and selected parameters**

	RO	P_{tot}	t_P	α	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_2	AP_3	AP_4
Site 4	0.57	0.41		0.54	0.49	0.66	0.65	0.59	0.17	0.24	0.42	0.23					0.22	0.16	0.16
Site 6	0.63		-0.15	0.51	0.31	0.36	0.33	0.28		0.15	0.21					-0.18			
Site 14	0.45	0.33		0.32	0.51	0.63	0.56	0.49		0.23	0.31		-0.15	-0.21	-0.25	-0.37			
Site 16	0.69	0.29	-0.22	0.64	0.48	0.61	0.58	0.56	0.21	0.20	0.30							0.19	

The correlations between the soil losses from the agricultural plot at Site 6 and the rainfall intensity parameters are low, suggesting that other processes are more important. Runoff shows a high correlation at all plots except at Site 14, generally with a higher correlation on the agricultural plots. None of the other parameters shows high correlations, although the shape of the hyetograph shows mostly significant correlations. The antecedent precipitation does not show any correlations, or only very weak ones in the case of Site 4.

The event soil loss data from the four erosion plots were classified according to the precipitation clusters established in Section 3.4 (Figure 3.146; note different scales for degraded plots and agricultural plots). Firstly, it is clear that events belonging to cluster 3 (i.e., high intensity rainfall events) are the main producers of mobilised sediment on all plots. The difference between the degraded plots and the agricultural land, however, is once more evident. Median event soil losses on degraded land were 0.5 to 1 t/ha, with 75% quartiles reaching up to 2.5 t/ha on Plot 14. Plot 4 produces up to 1 t/ha according to the 75% quartile. On agricultural land, these values are more than a magnitude less with medians of 0.05 t/ha on plot 6 and 0.02 t/ha on plot 16. For clusters 1, 2, and 4, the sediment mobilisation on plots 4, 6, and 14 is very similar, with medians of 0.02 t/ha and a range of 0 to 0.05 t/ha.

Annually, about 9 events, 2 during the pre-monsoon season and 7 during the monsoon season, belonging to cluster 3 can be expected according to Table 3.42 in Section 3.4.

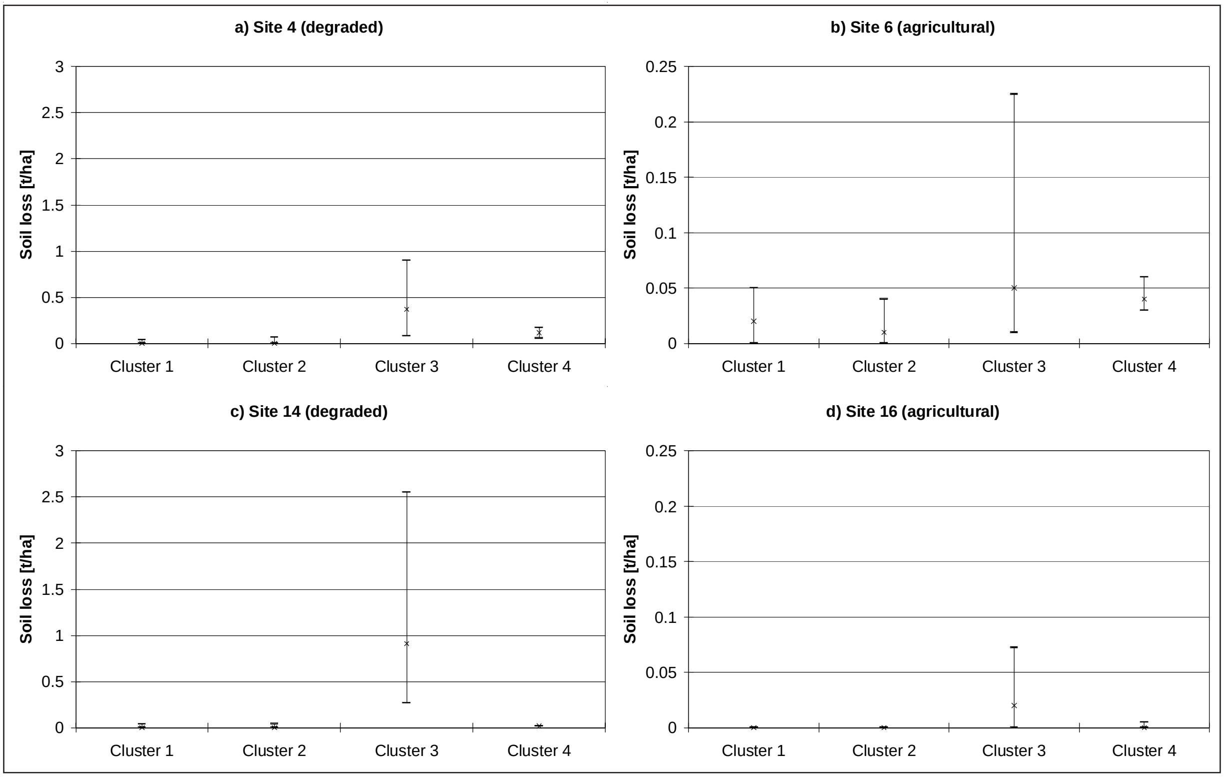


Figure 3.146: **Comparison with precipitation clusters (note: different scales for degraded plots and agricultural plots)**

Event soil loss on erosion plots of the Yarsha Khola catchment

In the Yarsha Khola catchment, plots on grassland and agricultural land were compared. In general, the grassland shows lower event soil loss than the agricultural land, as shown with the median values and the range between the 25 and the 75% quartile in Figure 3.147a. Although the difference between the medians appears to be minimal, with a median on the grassland plots of 0.01 t/ha and a median of 0.02 t/ha on the agricultural plots, the difference between the event soil loss on the plots is assured by a comparison of the values by means of the rank-sum test according to Helsel et al. (1993). The null hypothesis that the median of the four plots at Sites 5, 6, and 9 are the same has to be rejected at a 5% significance level.

There is a notable difference between the plots in terms of number of events that generated soil loss. During the study period from 1998 to 2000, only 11 events which generated soil loss were observed at Site 5, although this site has the highest rainfall regime at 2300 masl. A marked difference was observed between the two adjacent plots, 9a and 9b. While on Plot 9a a total 115 events with soil loss were observed between 1998 and 2000, on the grassland Plot 9b only 62 soil loss events were recorded for the same time period. At Site 6, 56 events were recorded for the study period.

In terms of seasonal difference, a variable picture is apparent (Figure 3.147b). On Plot 6, slightly higher soil losses were observed during the monsoon season, while on Plot 9a the opposite can be seen, with higher soil losses during the pre-monsoon season. On the grassland no particular seasonal difference was observed.

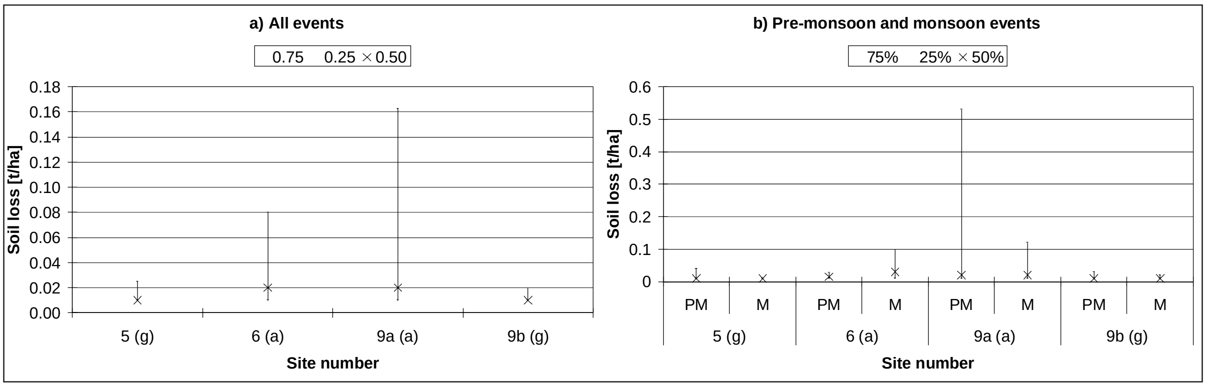


Figure 3.147: **Event soil loss for a) all events, b) all pre-monsoon and monsoon events for the period 1998 to 2000, Yarsha Khola catchment**

The ten largest soil loss events on each plot again differ considerably (Figure 3.148). The highest soil losses were observed at Plot 9a, with soil losses of 1.5 to 3 t/ha during the largest events. At Site 6 the soil losses were between 0.2 and 0.5 t/ha. The two grassland plots showed a 75% quartile of 0.03 t/ha at Site 5 and 0.11 t/ha at Site 9b, respectively.

The event soil loss shows considerably different correlations with the varying rainfall and runoff parameters at the different sites (Table 3.105). While at Site 9a and Site 9b event soil loss shows a high correlation with both runoff as well as with rainfall intensity, this observation cannot be made at Site 5 at all, and only to a lesser extent at Site 6. The highest correlations at Site 9 are observed for I_{30max} and I_{60max}, followed by event runoff RO and total event rainfall P_{tot}. It is interesting to note that I_{10max} shows a lower correlation with the soil loss than the other maximum intensity parameters. Antecedent precipitation conditions show generally only weak correlations with an acceptable correlation coefficient for API_1. The difference between the correlation coefficients on the grassland and the agricultural land at Site 9 are negligible, although the correlations on the grassland plot tend to be lower.

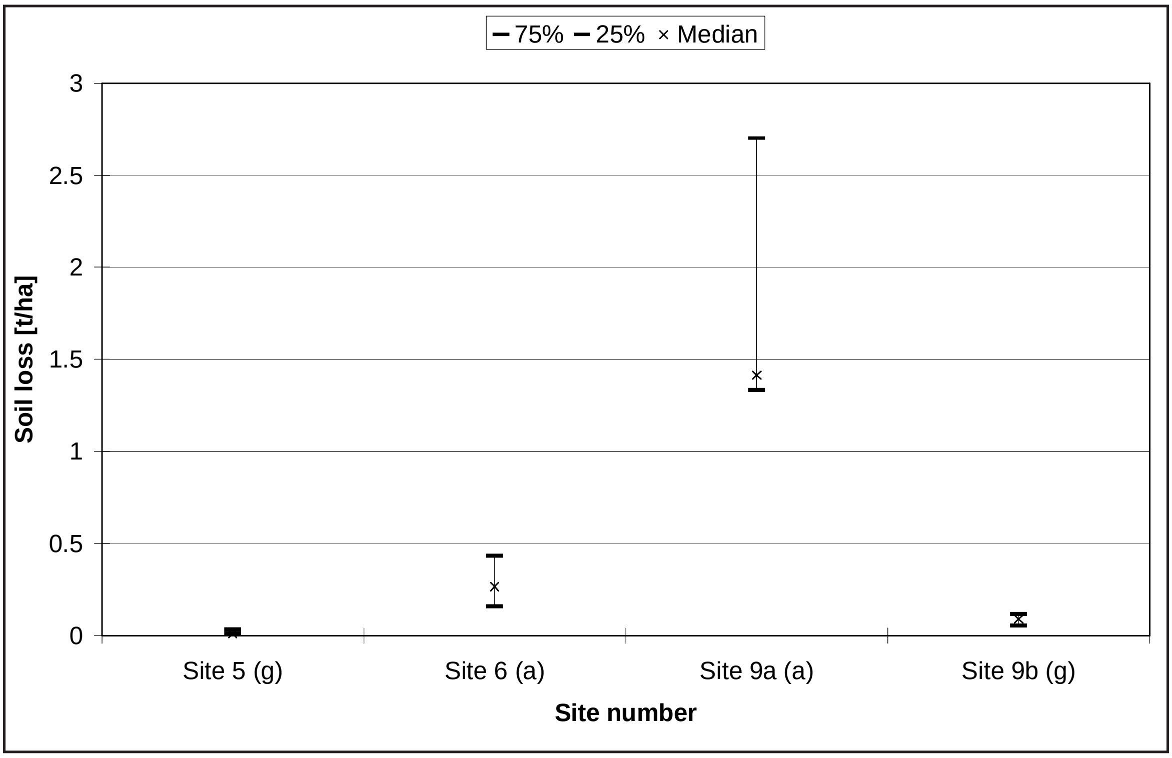


Figure 3.148: **Ten largest events for the period 1998 to 2000, Yarsha Khola catchment**

Table 3.105: **Correlation coefficients between soil loss and selected parameters**

	RO	P_{tot}	t_P	α	I_{ave}	I_{10max}	I_{30max}	I_{60max}	P_{25}	P_{50}	P_{75}	API_1	API_7	API_{10}	API_{14}	API_{30}	AP_2	AP_3	AP_4
Site 5	0.22	0.18		0.20	0.18	0.17	0.19	0.18					-0.15	-0.15	-0.14	-0.14			
Site 6	0.41	0.31		0.28	0.35	0.46	0.48	0.44	-0.18	0.20						-0.20			
Site 9a	0.67	0.63		0.45	0.49	0.69	0.70	0.70				0.33					0.25	0.17	0.16
Site 9b	0.65	0.61	0.16	0.56	0.46	0.61	0.64	0.65				0.33					0.26	0.22	0.16

The reason for the low correlation between the rainfall and runoff parameters at Site 5 is the large difference in number of events that caused runoff and that caused soil loss. Only 11 soil loss events were observed in the period between 1998 and 2000, while a total of 229 runoff events were recorded in the same period. It seems that on this grassland of the plot no soil can be mobilised whatever runoff and whatever rainfall may occur.

A comparison of the runoff during events of different rainfall clusters shows that generally the cluster 4 events tend to produce the highest soil loss. It should be noted that cluster 4 events in the Jhikhu Khola and the Yarsha Khola are slightly different in terms of rainfall intensity (Figure 3.149). While in the Jhikhu Khola catchment cluster 4 events show high rainfall volume and medium rainfall intensity, in the Yarsha Khola catchment cluster 4 events are characterised both by high rainfall volume as well as high rainfall intensity. The rainfall intensities between clusters 2 and 3 are very similar with the slightly higher values for cluster 3. This explains the high values for cluster 2 at Site 6.

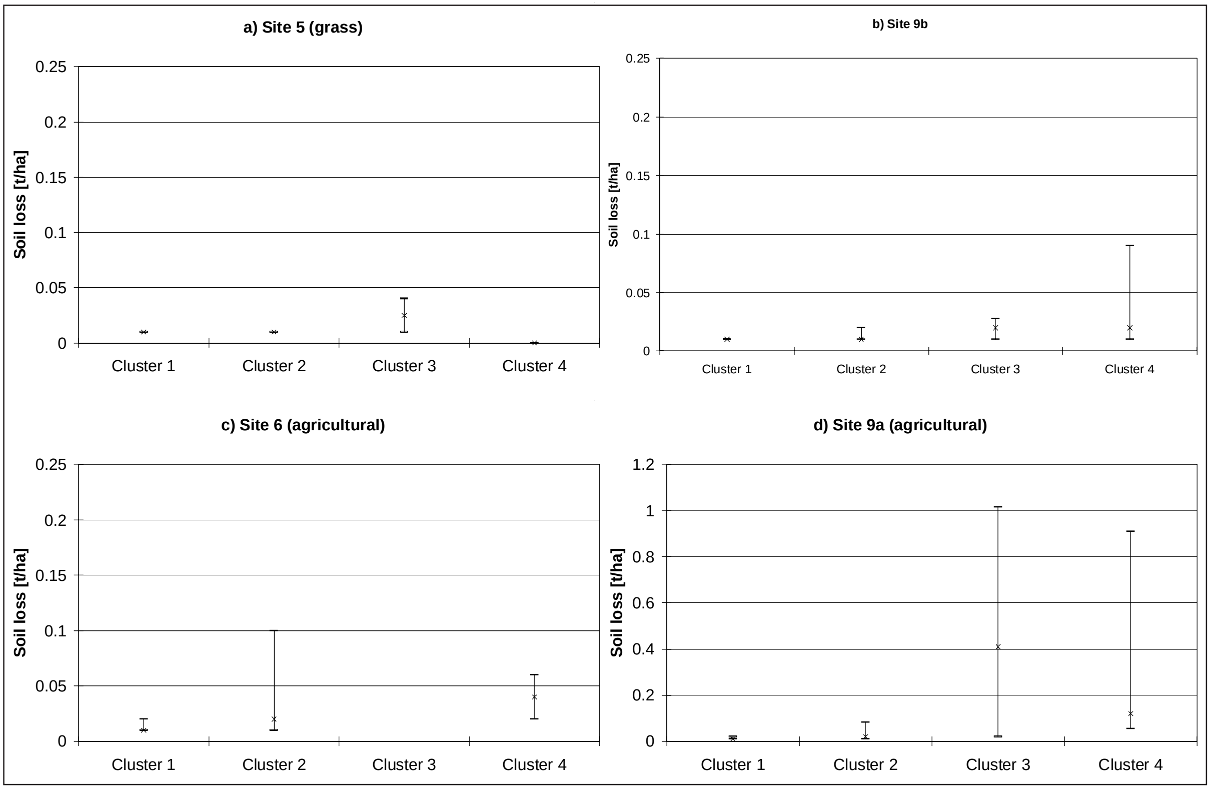


Figure 3.149: **Comparison with precipitation clusters (note: different scale for plot 9a)**

3.5.2.3 Summary of sediment mobilisation

The most important erosive process in the PARDYP Nepal catchment is surface erosion. This is both in terms of occurrence as well as in terms of importance as a sediment source. Comparing the erosion plot results of the PARDYP Nepal sites with results compiled from the other PARDYP catchments and from the literature shows that these values are well within the large variability of soil loss observed in many other studies (Table 3.106). According to these results, the lowest soil losses are generally observed in natural forests and well-managed pasture. Irrigated land follows, with rainfed agricultural land showing the highest soil loss values for cultivated land. By far the highest soil losses are experienced from degraded land. Poorly managed agricultural land can also lead to considerable soil loss amounts.

Table 3.106: **Comparison of annual soil losses [t/ha] of PARDYP Nepal data with other sources**

Land use	Results		
	PARDYP Nepal	PARDYP*	Literature*
Irrigated agricultural land			
- well managed	-	-	5-10
Rainfed agricultural land			
- well managed	0-26**	1-6	0-15
- poorly managed		-	20-100
Forest land			
- natural	-		0-2
- well managed	-	1-5	1-10
- degraded	6-35	-	3-45
Grassland			
- well managed pasture	0-2	1-5	0-10
- degraded	5-25	1-20	10-200
Badlands/gullies	-	-	125-570

* Based on the compilation of literature in Appendix A1.1. References are given in this compilation.
** No differentiation between well and poorly managed was made for the plots in PARDYP Nepal.

On the agricultural land in the Jhikhu Khola catchment, a seasonal difference can be observed in terms of soil loss. This seasonality cannot be observed on the plots in the Yarsha Khola or on the degraded plots, or the grassland plots. While on the agricultural plots in the Jhikhu Khola catchment the highest soil losses are observed during the pre-monsoon season and there during the months of May and June in particular, on the other plots — both in the Jhikhu Khola and Yarsha Khola catchments — soil loss is mainly observed during the monsoon season.

The event-based analyses showed the following.

- Most of the annual soil loss (>75%) on the agricultural land is observed in a few events only. In the Jhikhu Khola during about 3 events, in the Yarsha Khola during about 5 to 11 events.
- The event soil loss on the agricultural plots in the Jhikhu Khola catchment is highly correlated with event runoff on the plot, as well as with rainfall intensity. In the Yarsha Khola the two agricultural plots differ, but one of them also shows high correlation between soil loss and rainfall event maxima parameters.
- The event soil loss on degraded land is highly correlated only with rainfall intensity.
- Vegetation cover plays a major role in the magnitude of soil loss.

As the above studies were all conducted on closed plots, it was deemed important to briefly mention the reasons for high soil losses as identified by Gardner et al. (2000) in the case of open plots. These are as follows:

- exceptional events;
- emergence of subsurface seeping and piping to generate excess runoff;
- heavy and uncontrolled run-on;
- concentrated water flow down steep slopes not arrested by bench terraces;
- short, steep terraces that do not flatten at their lower end;
- poorly developed ground/weed cover;and
- fine-textured, reddish coloured soils.

3.5.3 Sediment transport and output

Note: The sediment sampling programme of PARDYP and its predecessors has provided sediment data since 1993 in the Jhikhu Khola catchment. However, due to the construction of a road from Dhulikhel to Bardibas, the sediment regime has changed and has not yet reached its equilibrium. Furthermore, the sampling at Site 13 only commenced in 1997. Therefore the analysis below is presented in two sets after an overview including all available data at Site 1, one set before construction of the road (1993 to 1999) for Sites 1 and 2, and a comparison of the data from 1998 to 1999 at Sites 1, 2, 7, 8, and 13. Data from Site 13 are analysed in relation to Site 1 for the period 1998 to 2000. Finally, a brief comparison of the results is attempted, which should be interpreted with caution.The measurement programme in the Yarsha Khola started in 1997. Complete annual data are therefore only available from 1998.

In order to obtain an idea of the sediment losses from the sub-catchment and catchment level, regular sediment sampling was carried out at the hydrological stations in the catchments (for more detail on the method refer to Section 2.4). The measurement programme only included the suspended sediment load and did not obtain any information on the bedload. Carson (1985) reported that about 20% of the total sediment load in different catchments of Nepal is transported as bed load. Galay et al. (2001) also presented a value of 20% measured by Ries (1993) in the Chhukarpo Khola (catchment size 270 ha). However, they indicated that bed load may vary from 5 to 60% for different catchments.

3.5.3.1 The suspended sediment data

As mentioned above, a sudden change in the sediment regime of three sites in the Jhikhu Khola catchment was observed. The data were therefore split into different datasets accounting for these regime differences and the different periods (Table 3.107).

The relationship between discharge and sediment concentration is called a sediment rating curve (Morris and Fan 1998). As sediment concentration is seasonally variable (Carver 1997), the annual

Table 3.107: **Number of sediment samples in the Jhikhu Khola and Yarsha Khola catchments**

Site	**Yarsha Khola**				**Jhikhu Khola**				
	Site 1	**Site 2**	**Site 5**	**Site 7**	**Site 1**	**Site 2**	**Site 7**	**Site 8**	**Site 13**
Period	**not in operation**				*93-99*	*93-99*	**not in operation**		
Pre					56	41			
Monsoon					1022	672			
Post					23	19			
Winter					6	3			
Total					1107	735			
Period	*98-99*	*98-99*	*98-99*	*98-99*	*98-99*	*98-99*	*98-99*	*98-99*	*98-99*
Pre	9	14	6	20	0	0	11	7	36
Monsoon	189	82	54	72	125	170	145	175	152
Post	0	0	0	0	9	9	11	12	13
Winter	0	0	0	0	0	0	0	0	0
Total	198	96	60	92	134	179	167	194	201
Period	*98-00*	*98-00*	*98-00*	*98-00*	*98-00*	**disturbed due to road construction; only used for case study on impact of road construction**			*98-00*
Pre	18	23	10	22	18				66
Monsoon	274	149	66	95	196				187
Post	0	0	0	2	9				13
Winter	0	0	0	0	0				0
Total	292	172	76	119	223				266

sediment data are disaggregated to seasonal sediment rating curves. For their calculation, Carver (1997) applied a land response definition of the seasons. In this study, seasons were based on the meteorological information with the official on- and offset of the monsoon rains (see Section 3.1 and Appendix A3.8). More details on sediment rating curves, including the problem of hysteresis, is discussed in Carver (1997).

3.5.3.2 Sediment rating curves in the Jhikhu Khola and Yarsha Khola catchments

Sediment concentrations in the Jhikhu Khola at the main hydrological station are seasonal (Figure 3.150a). The highest sediment concentrations are measured during the pre-monsoon season (74 samples), followed by concentrations during the monsoon season (1094 samples). The lowest concentrations were measured during winter from December to February, where only six samples were collected. The same can be shown at the other sites, except at Site 2 where the number of pre-monsoon samples did not warrant the establishment of a sediment rating curve for that season (Figure 3.150b to e). The largest seasonal differences can be observed at Site 7 (Figure 3.150c). The seasonality of sediment concentration was described and discussed in detail in Carver (1997) and will therefore not be repeated here. However, for identification of the different behaviour of the different sub-catchments, the sediment rating curves of the different sub-catchments will be compared and discussed briefly. This comparison shows the following (Figure 3.151 and Table 3.108).

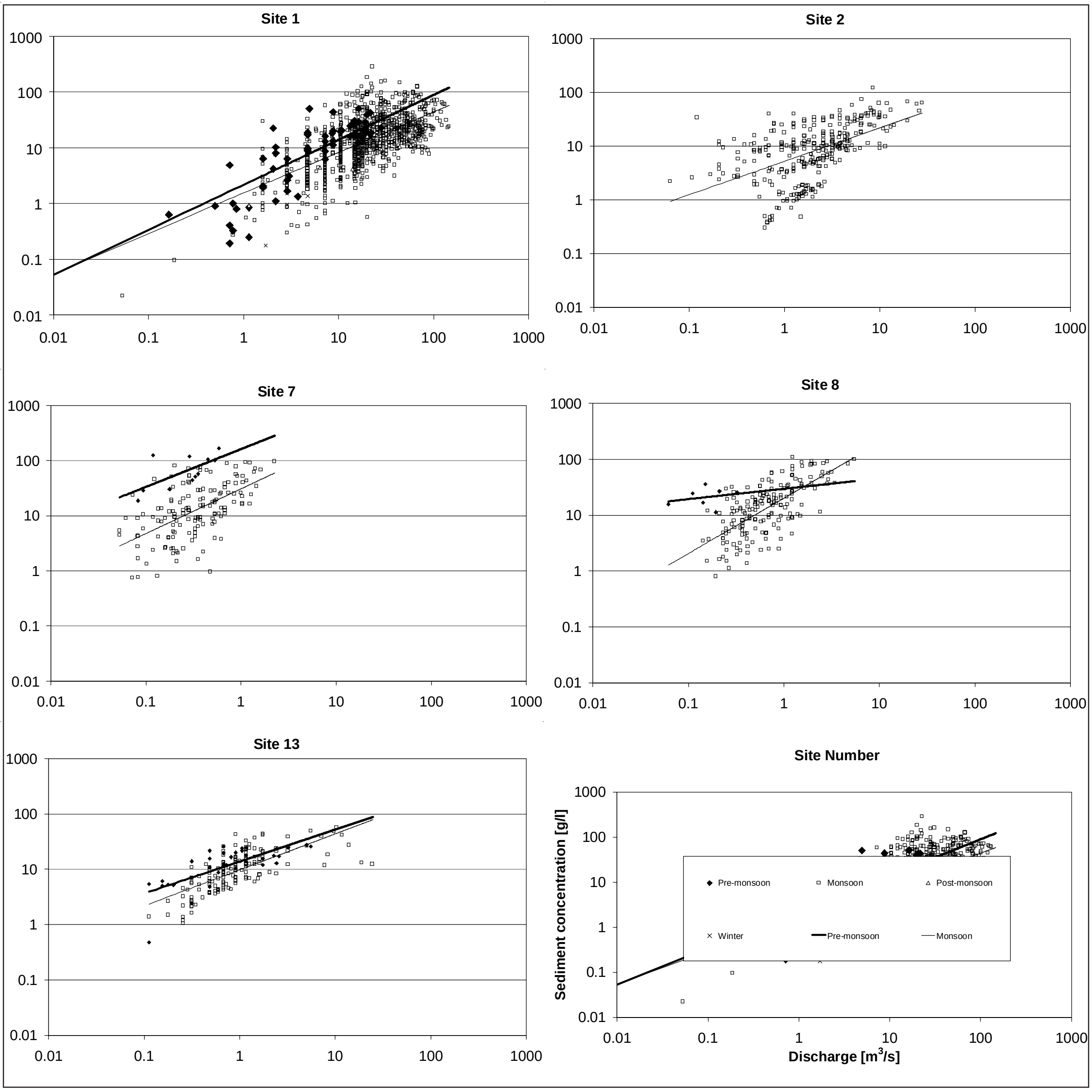


Figure 3.150: **Overview of seasonal sediment concentrations at all sites, Jhikhu Khola catchment**

- Site 1 shows generally the lowest sediment concentrations of all sites, both in the pre-monsoon season as well as in the monsoon season.
- The highest concentrations per unit area are observed at Sites 7 and 8. While during the pre-monsoon season the high flows (maximum flows at this site may reach up to 5 m^3/s) are considerably higher at Site 7, they only marginally differ during the monsoon season between the two sites.
- The larger the catchment, the lower the sediment concentration, suggesting that there is an effect of scales, i.e. the scale has a major influence on the processes.

The concentrations calculated from the seasonal rating curves tend to decrease with catchment size as shown in Figures 3.151 and Table 3.108. This is the case for both the pre-monsoon and the monsoon season concentrations (Figure 3.151).

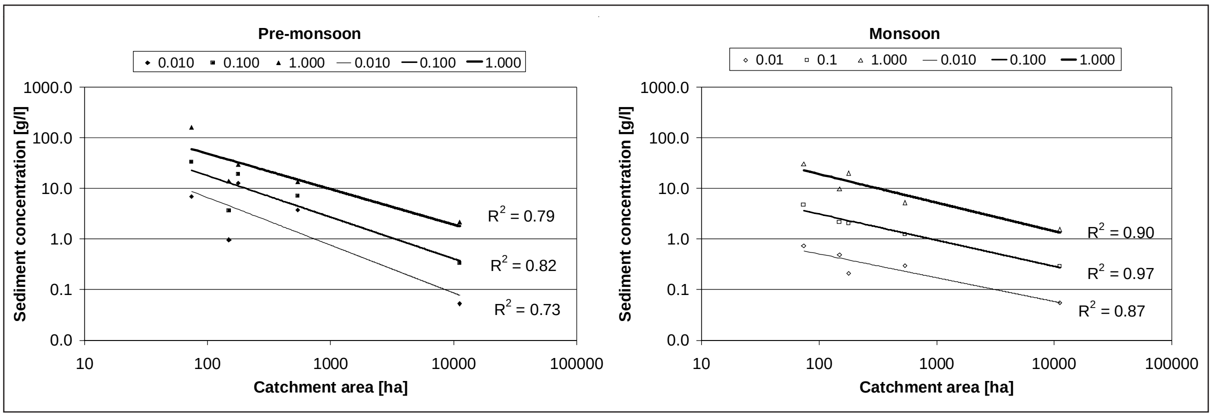


Figure 3.151: **Relationship between sediment concentration and catchment area in the Jhikhu Khola catchment**

Table 3.108: **Empirical sediment concentrations at different discharge on the basis of the above sediment rating curves in Figure 3.150, Jhikhu Khola catchment [g/l]**

	Pre-monsoon				Monsoon			
Discharge [m^3/s]	**0.010**	**0.100**	**1.000**	**10.000**	**0.010**	**0.100**	**1.000**	**10.000**
Site 1 (11141 ha)	0.1	0.3	2.2	13.9	0.1	0.3	1.5	8.2
Site 2 (539 ha)	3.7	7.1	13.7	26.2	0.3	1.2	5.2	21.9
Site 7 (74 ha)	6.9	33.4	161.9	784.8	0.7	4.8	30.8	199.7
Site 8 (178 ha)	12.6	19.3	29.6	45.2	0.2	2.1	20.1	195.8
Site 13 (149 ha)	1.0	3.6	13.8	52.0	0.5	2.2	9.7	43.5

Only three years of data were available in the Yarsha Khola catchment, with only 18 samples at Site 1 during the pre-monsoon season and 274 samples during the monsoon season. At Site 2, 23 samples were taken during the pre-monsoon season and 149 samples during the monsoon season. At Site 5, 10 samples were taken in the pre-monsoon season and 66 during the monsoon; while at Sites 7, 22 and 95 samples were taken in the pre-monsoon and monsoon respectively. The seasonality shown above in the Jhikhu Khola catchment is also apparent at all sites in the Yarsha Khola catchment (Figure 3.152). The concentrations during the pre-monsoon season are at all sites considerably higher than the concentrations during the monsoon season. Both in the pre-monsoon season and in the monsoon season, Site 2 shows the lowest sediment concentrations with the exception of the flows above 10 m^3/s (Table 3.109). However, the highest measured flows during this season at this site are well below 10 m^3/s and therefore are only of a theoretical nature. The highest concentrations were seen at Site 1 during the pre-monsoon season, while Site 7 shows the highest concentrations during the monsoon season.

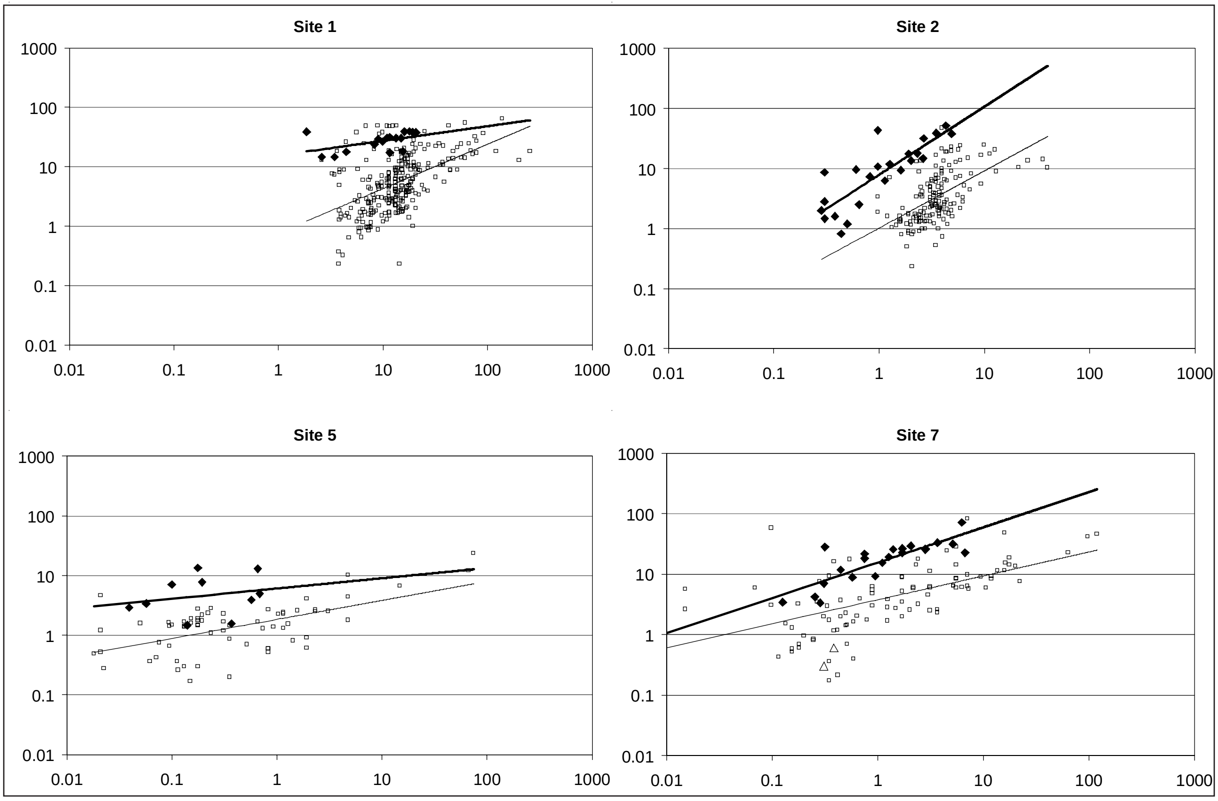


Figure 3.152: **Overview of seasonal sediment concentrations at all sites, Yarsha Khola catchment (for the legend refer to Figure 3.161 f)**

Table 3.109: **Empirical sediment concentrations at different discharge on the basis of the above sediment rating curves, Yarsha Khola catchment [g/l]**

	Pre-monsoon				Monsoon			
Discharge [m^3/s]	**0.010**	**0.100**	**1.000**	**10.000**	**0.010**	**0.100**	**1.000**	**10.000**
Site 1 (5338 ha)	4.97	8.77	15.48	27.31	0.02	0.14	0.77	4.28
Site 2 (1737 ha)	0.04	0.58	7.88	107.23	0.01	0.11	1.02	9.14
Site 5 (32 ha)	2.75	4.09	6.07	9.02	0.42	0.88	1.84	3.84
Site 7 (208 ha)	1.05	4.03	15.45	59.29	0.61	1.51	3.75	9.33

The relationship between catchment size and sediment concentration shows a very good power fit for the case of the monsoon concentrations (Figure 3.153). This shows that sediment concentration generally tends to decrease with catchment size. In the case of the pre-monsoon data this relationship cannot be observed and other factors may be more important.

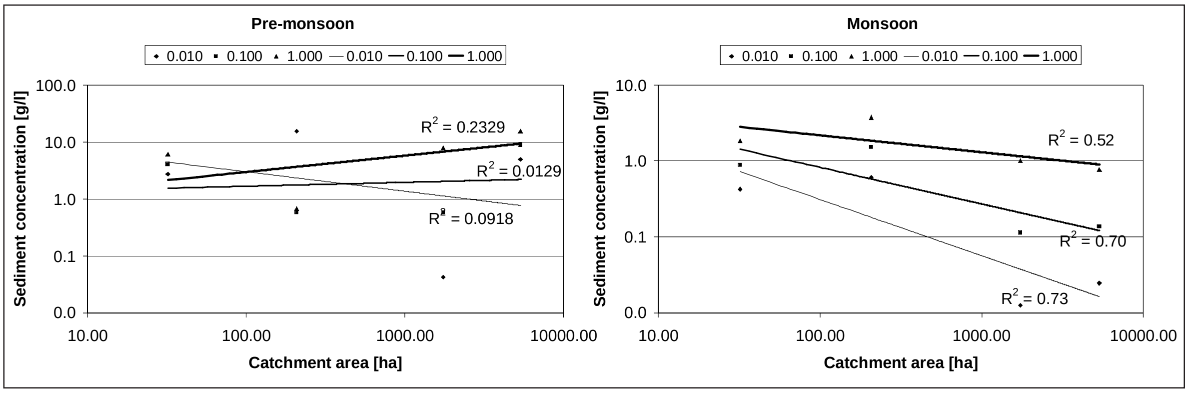


Figure 3.153: **Relationship between sediment concentration and catchment area in the Yarsha Khola catchment**

3.5.3.3 Sediment loads

On the basis of the seasonally disaggregated sediment rating curves, seasonal sediment loads were calculated for the different sub-catchments (Table 3.110). In the Jhikhu Khola catchment, the highest loads were estimated for sub-catchment 2 with about 34 t/ha during the pre-monsoon and monsoon seasons. This load can be explained by the large degraded area, which makes up about 12% of the total catchment area, and is located in close proximity to the outlet of the catchment. This suggests that the deposition possibilities for the sediment mobilised in these degraded areas are limited and most of it is washed out of the catchment. These sediment loads from sub-catchment 2, the Lower Andheri Khola, are followed by the sediment loads from Site 8, the Upper Andheri Khola, with about 24 t/ha during the pre-monsoon and monsoon seasons. Suspended sediment load is observed to be about 19 t/ha for the two seasons at the outlet of the catchment. The lowest figures are estimated for Site 7, the upland sub-catchment of the Kukhuri Khola.

Table 3.110: **Seasonal sediment loads of the Jhikhu and Yarsha Khola catchments, 1998-1999 (mean±standard deviation)**

Site	Catchment area [ha]	Pre-monsoon [t/ha/y]	Monsoon [t/ha/y]	Sum [t/ha/y]	Carver (1997)
Jhikhu Khola catchment					
Site 1*	11141	1±1	18±2	19±2	11±1
Site 2*	539	2±3	32±17	34±20	15±5
Site 7**	74	3±4	10±5	13±9	17±11
Site 8**	178	9±1	15±11	24±12	-
Yarsha Khola catchment					
Site 1***	5338	14±4	33±15	37±19	
Site 2***	1737	1±1	14±5	15±5	
Site 5***	32	-	18±3	-	
Site 7***	208	5±3	22±7	27±10	

* on the basis of 1993 to 1999 data
** on the basis of 1997 to 1999 data
*** on the basis of 1998 to 2000 data

In the Yarsha Khola catchment, the highest loads were estimated at Site 1, the outlet of the catchment, followed by the loads at Sites 7 and 5, both of the Khahare Khola, and finally Site 2 of the Gopi Khola sub-catchment. The reason for the highest loads at the outlet are believed to be the very steep lower slopes, which are often dissected from gullies, of the south-facing part of the Yarsha Khola catchments as well as the quite extensive streambank erosion along many streams of this slope.

The values presented for the Jhikhu Khola catchment and its sub-catchments differ from Carver (1997). However, Carver's study was carried out during the driest time of the study period between 1992 and 1994 (also see Section 3.1). By averaging the first two years of the annual sediment loads as calculated on the basis of the sediment rating curves established for this study, a mean sediment load of 16 t/ha during the pre-monsoon and monsoon seasons was estimated for Site 2, in contrast to a value of 15 t/ha for the two seasons by Carver (1997). At Site 1 the average estimate proposed by this study for 1993 and 1994 is 12 t/ha for the pre-monsoon and monsoon seasons, compared to 11 t/ha by Carver (1997). For Site 7 no estimate was proposed for the years prior to 1997 as the discharge data were not adequate to produce a rating curve.

The sediment loads shown in Table 3.110 compare with other studies from the region as described below.

- Galay et al. (2001) compiled the sediment yields of a number of small catchment studies in Nepal. Two of the catchments are of the size of the Jhikhu Khola catchment, i.e., the Kulekhani catchment (12,500 ha), which had a sediment delivery of 20.5 t/ha/y, and the Harpan Khola (12,000 ha) which showed a sediment delivery of 8.9 t/ha/y. The Bagmati at Sundarijal (1553 ha), comparable to the Lower Gopi Khola in the Yarsha Khola catchment, showed a sediment delivery of 13 t/ha/y. The Godavari catchment only showed 3 t/ha/y with an area of 1231 ha.
- Sharma (1988) reports 45 t/ha/y for the entire Sun Koshi system with a catchment area of 19,230 km^2.

These few figures show that the data from the Yarsha and the Jhikhu Khola catchment sare plausible and within range of the other studies undertaken in the country.

The sediment loads calculated above were related to selected catchment characteristics using the correlation coefficient according to Spearman (Table 3.111). In general, the correlations are weak and insignificant. For the pre-monsoon season sediment yields, only the Topoindex showed significant correlation at the 10% level. For the monsoon season and the annual sediment yields, grassland and the ratio of cultivated to uncultivated land showed significant correlations. While grassland showed a positive correlation, which means the more grassland the higher the sediment yield, the cultivated/uncultivated ratio showed a negative correlation, suggesting that an increase in cultivated land leads to lower sediment yields. This result is rather interesting if compared to the plot results of the Yarsha Khola catchment where rainfed land produces much more sediment than grassland. This discrepancy can be explained in different ways, as set out below.

- The correlation observes a splur correlation.
- The grassland plots observed in the Yarsha Khola are not representative for the soil loss generally observed on grasslands. Literature suggests 10 to 200 t/ha for degraded grassland, while well-managed pasture shows values of 0 to 10 t/ha. Joshi and Negi (2002), for example, observed higher soil loss on grassland than on shrubland. In case of high stocking densities, soil loss can also increase.
- The sediment mobilised on the rainfed agricultural land is successfully kept on the slopes by the lower terraces or the irrigated land (as for example shown by Carver 1997, who showed accumulation of soil on the irrigated terraces).

Table 3.111: **Correlation coefficients according to Spearman of sediment yield per unit area with selected catchment characteristics**

		Pre-monsoon	**Monsoon**	**Annual**
Catchment area	r	-0.29	0.35	0.32
	Sig.	0.54	0.36	0.48
Irrigated land	r	-0.14	-0.18	-0.11
	Sig.	0.76	0.65	0.82
Rainfed land	r	0.21	-0.65*	-0.57
	Sig.	0.65	0.06	0.18
Forest land	r	-0.18	0.38	0.46
	Sig.	0.70	0.31	0.29
Grassland	r	0.11	0.77**	0.75**
	Sig.	0.82	0.02	0.05
Shrubland	r	-0.04	0.28	0.00
	Sig.	0.94	0.46	1.00
Other land use	r	0.14	0.25	0.14
	Sig.	0.76	0.52	0.76
Ratio cultivated/uncultivated	r	0.00	-0.77*	-0.75**
	Sig.	1.00	0.02	0.05
Ratio rainfed land/irrigated land	r	0.11	-0.44	-0.29
	Sig.	0.82	0.23	0.54
Degraded land	r	-0.60	0.70	0.80
	Sig.	0.40	0.19	0.20
Mean slope	r	0.36	-0.18	-0.11
	Sig.	0.43	0.64	0.82
Topoindex	r	-0.95*	0.56	0.21
	Sig.	0.05	0.32	0.79

r = correlation coefficient according to Spearman, Sig. = significance levels

* Correlation is significant at the 0.05% level (Sig.<0.05%)

** Correlation is significant at the 0.1% level (Sig.<0.1%)

*** Correlation is significant at the 0.15% level (Sig.<0.15%)

- The high runoffs generated on the grassland are responsible for increased streambank erosion and herewith increase the total catchment sediment outputs.

Conclusive answers cannot be provided at this stage. It can be only be suggested that the above relations be tested with a bigger sample from other middle mountain catchments and additional observations on grasslands.

3.5.4 Relation between mobilised sediment and sediment load

Not all the material that is eroded will leave the catchment, as quite a lot of the eroded material is redeposited within the catchment itself. To account for this interaction of erosive and depository processes, the sediment delivery ratio (SDR) must be calculated. The SDR represents the fraction of the material eroded from a particular catchment which reaches the outlet of the given catchment and where the sediment is measured (Morris and Fan 1998). It herewith relates total erosion from a given unit of land to the sediment transport. The SDR is defined as (Schreier et al. 1997)

$$SDR = Y_s/T_e \qquad \textbf{Equation 3.14}$$

where

SDR = sediment delivery ratio [%]
Y_s = sediment yield [t/ha*year]
T_e = total erosion from the catchment where sediment yield is measured [t/ha*year]

The major difficulty in the calculation of the sediment delivery ratio is the estimation of the total production of sediment in the catchment.

Carver (1997) suggests breaking the sediment production into two regimes, the normal regime production and the episodic regime production. The normal regime production is based on the erosional mechanisms that occur persistently throughout the rainy season. This includes surface erosion from the different land uses and the chronic gullying on degraded sites. The episodic regime includes the infrequent process of mass wasting and severe rill and gully erosion.

For this purpose, for a first assessment of the importance of surface erosion and to relate the sediment mobilised at the plot scale with the sediment output at the sub-catchment and catchment scale, the plot results were extrapolated to the area of the catchments and sub-catchments (Table 3.112). According to these obviously very arbitrary figures, the rainfed agricultural areas produce the bulk of the sediment in the Jhikhu Khola catchment, followed by the degraded areas. The importance of the agricultural areas is mainly due to the high per unit area soil losses as well as the extensive areas under rainfed agricultural land in the catchments. As shown in Table 3.112, the total sediment loss from the normal regime only accounts for parts of the total sediment observed at the outlet of the sub-catchments. The differences are greatest in the Yarsha Khola catchment and the Lower Andheri Khola catchment. In the case of the Lower Andheri Khola catchment, this discrepancy can be explained with the large degraded and gullied area in the vicinity of the hydrological station. In the Yarsha Khola catchment, the main channel shows large stretches of severely eroded streambanks (Tschanz 2002). According to Ross and Gilbert (1999), in the case of the 117 km^2 Phewa Tal catchment, 6 to 10% of the total sediment is believed to originate from surface erosion. This value in the context of the Jhikhu and Yarsha Khola catchments however seems to underestimate the importance of surface erosion. As mentioned above, surface erosion (including gullying) is believed to be the main source of sediment in the catchments, followed by stream bank erosion. Landslides are only believed to be a marginal issue in the catchment. Mass wasting in the riparian zone and direct erosion by the rivers were observed to be major sediment sources in the Eastern Himalayas (Brunsden et al. 1981). This is also in line with findings by Brasington and Richards (2000) in the Likhu Khola catchment of Central Nepal.

The difference in the case of the Kukhuri Khola is only small, which makes sense in a small and steep catchment. The delivery of sediment mobilised on the slopes in this catchment is likely to be higher than in larger catchments. The main catchment has large deposition zones, which are also shown here, with a small difference between the measured and the calculated sediment.

Table 3.112: **Estimated sediment production (normal regime) at the outlet of the Jhikhu and Yarsha Khola catchments**

Land use	Area	Erosion rate [t/ha]*	Estimated soil loss [t]	Total estimated soil loss [t]
Jhikhu Khola				
Irrigated land	1838 ha	7.5±2.5	13,785 ± 4,595	148,245 ± 87,920
Rainfed land	4266 ha	15.0±10.0	63,990 ± 42,660	
Forestland	3317 ha	2.5±2.5	8,293 ± 8,293	
Grassland	612 ha	1.0±1.0	612 ± 612	
Shrubland	782 ha	7.5±5.0	5,865 ± 3,910	
Degraded land	5%	100±50	55,700 ± 27,850	
Estimated sediment loss from normal regime				13± 8
Measured sediment load				19±2
Difference				***-6***
Lower Andheri Khola				
Irrigated land	37 ha	7.5±2.5	278 ± 93	9,521± 5,548
Rainfed land	198 ha	15.0±10.0	2,970 ± 1,980	
Forest land	215 ha	2.5±2.5	538 ± 538	
Grassland	37 ha	1.0±1.0	37 ± 37	
Shrubland	41 ha	7.5±5.0	308 ± 205	
Degraded land	10%	100±50	5,390 ± 2,695	
Estimated sediment loss from normal regime				18± 10
Measured sediment load				34±20
Difference				***-16***
Kukhuri Khola				
Irrigated land	6 ha	7.5±2.5	45 ± 30	779± 529
Rainfed land	41 ha	15.0±10.0	615 ± 410	
Forest land	11 ha	2.5±2.5	28 ± 28	
Grassland	1 ha	1.0±1.0	1 ± 1	
Shrubland	12 ha	7.5±5.0	90 ± 60	
Degraded land	0%	100±50	0 ± 0	
Estimated sediment loss from normal regime				11± 7
Measured sediment load				13±9
Difference				***-2***
Yarsha Khola				
Irrigated land	744 ha	7.5±2.5	5,580 ± 1,860	58,170 ± 35,755
Rainfed land	1996 ha	15.0±10.0	29,940 ± 19,960	
Forest land	1679 ha	2.5±2.5	4,198 ± 4,198	
Grassland	307 ha	1.0±1.0	307 ± 307	
Shrubland	286 ha	7.5±5.0	2,145 ± 1,430	
Degraded land	3%	100.0±50.0	16,000± 8,000	
Estimated sediment loss from normal regime				11 ± 7
Measured sediment load				37±19
Difference				***-16***

* Estimated on the bases of the erosion rates identified in Table 3.106

Carver (1997) undertook a first estimation of the episodic sediment production on the basis of field assessments after large storms. He identified that, in the Kukhuri Khola and Lower Andheri Khola sub-catchments, the episodic sediment production was between 20 and 90% of the annual sediment production in the years 1992 to 1994. The average over the years was about 40% in the Kukhuri Khola sub-catchment and about 50% in the Lower Andheri Khola sub-catchment. The differences between the years are mainly due to large differences in the number and intensity of storms that produced this episodic soil loss. Using these rough averages for the two sub-catchments and using the data as calculated above would result in the values compiled in Table 3.113.

This approach would yield sediment delivery ratios of 0.94 in the case of the Lower Andheri Khola sub-catchment and 0.72 in the case of the Kukhuri Khola sub-catchment. Carver (1997) identified SDRs of 0.61 for the former and 0.68 for the latter.

Table 3.113: **Calculation of SDR**

	Lower Andheri Khola	**Kukhuri Khola**
Normal regime	18 t/ha	11 t/ha
Episodic regime (rates from Carver, 1997)	18 t/ha (50%)	7 t/ha (40%)
Total	**36 t/ha**	**18 t/ha**
Measured	34 t/ha	13 t/ha
SDR	**0.94**	**0.72**

Another approach would be to use the average value of overall erosion rates for the middle mountains of 27 to 45 t/ha as proposed by Laban (1978). The Jhikhu Khola catchment could probably be assumed to be at the lower end of the scale due to its topography and extended valley bottom. This would suggest an SDR of 19/27 = 70%. Assuming that the Yarsha is at the upper end due to its steep topography, the SDR could be calculated as 37/45 = 82%. The two sub-catchments of the Lower Andheri Khola and the Kukhuri Khola show similar catchment conditions as the Yarsha Khola catchment, as shown in Chapter 2. This therefore suggests a high overall erosion rate, resulting in an SDR of 0.76 for the former and 0.29 for the latter. The value for the Kukhuri Khola on the basis of Laban's average erosion rates seems to be too low.

This section on the relationship of mobilised sediment to total sediment load is a simplistic assessment. The reason for this is the currently very limited knowledge on the relevant processes. While the surface erosion has been studied in-depth over decades, the importance of stream bank erosion and other linear features has been neglected in Nepal. It is therefore suggested that efforts towards improved understanding of the impact of linear erosion be increased, in order to provide improved management tools for soil conservation. A first attempt is made in a case study on the impact of road construction on the sediment regime in middle mountain catchments (Merz et al. submitted_a). This case study concluded that the visual comparison of sediment rating curves before and after the road construction showed a clear impact of the road on the sediment regime. The same could be supported by statistical analysis of the means and the rating curve parameters, although not with rigorous statistical treatment as the sediment concentrations are too variable in nature. Other reasons, such as change in precipitation pattern, increased surface runoff and erosion, large land-use changes, or mass wasting could be excluded as possible reasons for this change in sediment regime. The current impact of 200 to 400% increase in sediment yield at the three monitored sites would have been even higher if protection measures had not been taken. This was also shown by comparing the calculated sediment yields for the sites in the catchment with values for sediment yields due to careless road construction reported in the literature.

In order to monitor the effectiveness of the erosion and landslide control measures along the road it will be interesting to review the data in 5 to 10 years, when the vegetation can be expected to have stabilised the road slopes and the loose excavation deposits.

3.5.5 Summary of sediment dynamics

On the basis of catchment-wide sediment source mapping, surface erosion, including gullying, was determined to be the main erosive process in both catchments. In terms of importance as a sediment source, surface erosion was likewise determined to be of major importance, followed by streambank erosion and occasional landsliding. This assessment has to be further investigated as the relative importance of the streambank erosion and landsliding has not yet been conclusively established as was also shown with the sediment budgets.

The soil loss that was observed on the erosion plots on degraded, agricultural land and grassland showed national average compared with studies from the literature. Degraded land produced the highest soil losses throughout the rainy season, followed by the rainfed agricultural land, while finally only very small amounts of soil loss were observed on the grassland. Soil loss was especially prevalent during the pre-monsoon season on the agricultural land in the Jhikhu Khola catchment. This seasonality could not be observed in the Yarsha Khola catchment. Only a few large events are responsible for most of the annual soil loss. On all plots about 5 to 10% of the annual events produce about 75% of the annual soil loss.

The event analysis stressed again the importance of rainfall amount and rainfall intensity for sediment mobilisation. This was observed on all erosion plots. However, the importance of these rainfall parameters on the degraded land was more pronounced due to the lack of vegetation cover and therefore protection from the force of the rain drops. In general, a good match can be seen with the rainfall clusters based on rainfall amount and intensity. Antecedent precipitation conditions generally showed no correlation with the event soil loss from the plots.

Sediment transport was discussed by means of sediment rating curves, which showed clear seasonal differences with higher sediment concentrations during the pre-monsoon season. Overall, the sediment concentrations tended to decrease with catchment area, so that the highest concentrations were observed in the small upland catchments.

The analyses of the sediment loads and the sediment delivery suggests that there needs to be more emphasis on the linear sediment production factors such as streambank erosion and gullying. To assess their importance in the sediment budget, a measurement programme focusing on these issues has to be implemented. The impact of road construction on the sediment regime was discussed briefly. More detail on this can be found in Merz et al. (submitted_a). It was shown that although all precautions were taken by the constructors, the sediment regime was still changed considerably in the two years after the intervention.

3.6 WATER DEMAND AND SUPPLY FOR HUMAN NEEDS

This section presents human water needs for domestic purposes, agriculture, and livestock. Water supply is discussed on the basis of the supply systems and the irrigation network. Finally, the impact on water quality is discussed.

In the rural catchments of the middle mountains of the HKH, water is mainly used for domestic and agricultural purposes. In the selected catchments this includes livestock watering at a household scale as large poultry farms or any other form of large scale livestock breeding is not practised. Small-scale industries exist only to a limited extent in the selected catchments. These include flour mills and other small agro-processing units, which only withdraw but hardly consume any water, i.e., they release the same amount of water at the same quality back into the stream after using it. In this context, the discussion below will focus on domestic, livestock, and agricultural water demand and supply. A brief discussion of water quality will shed some light on some of the issues present in the catchments in this respect.

3.6.1 Water demand

The estimated water demand for domestic and agricultural purposes is based on results from the water need and supply survey as briefly discussed above in Box 3.1. The results of this survey have also been discussed in Merz et al. (2002) and Merz et al. (2003a).

3.6.1.1 Domestic use

Water demand for domestic use is very low in the study catchments. On average, the respondents in the Jhikhu Khola catchment only use 23.2 l day^{-1} water per person. In the Yarsha Khola, water use is estimated to be 21.1 l person^{-1}day^{-1}. These water demands are below the recommended value of the Department of Water Supply and Sewerage (DWSS; RWSSSP 1994) of 45 l person^{-1}day^{-1} by a factor of about 2. This value includes 20% for losses and wastage (Table 3.114). On the basis of these values, overall water demand for domestic use per year can be assumed to be 412,629 m^3 in the Jhikhu Khola catchment and 158,805 m^3 in the Yarsha Khola catchment.

Table 3.114: **Water demand for domestic use**

Catchment	Population* (year)	Domestic water use** [l person^{-1}day^{-1}]	Annual domestic water use [m^3]	[mm]
Jhikhu Khola	48,728 (1996)	23.2	412,629	3.7
Yarsha Khola	20,620 (1996)	21.1	158,805	3.0

* From Allen et al. (2000)
** From Merz et al. (2002)

Box 3.1: **Water Demand and Supply Survey**

For the assessment of the current situation in terms of water demand and supply of rural catchments in Nepal, a survey was conducted in the Yarsha Khola and the Jhikhu Khola catchments. The survey in the Yarsha Khola catchment was initiated in December 1998, the survey in the Jhikhu Khola catchment in September 1999. The survey was based on household interviews involving the female and male household heads of each household frequented. Questions related to water and agriculture, water and domestic use, water and livestock, and perceptions of water and related issues were asked. In the Yarsha Khola catchment, 436 respondents (218 female/218 male) were interviewed and in the Jhikhu Khola catchment 356 (178 female/178 male) were interviewed.

The survey revealed that:

- irrigation water supply is of major concern in both catchments;
- drinking water supply is a problem in parts of the catchments but mainly on the ridges along the divide and spurs within the catchment;
- drinking water quality is increasingly becoming an issue throughout the Jhikhu Khola catchment and around main settlements in the Yarsha Khola catchment;
- agricultural intensity as well as productivity in the Jhikhu Khola is a great deal higher than in the Yarsha Khola catchment; and
- soil erosion is only marginally an issue in both catchments.

This survey was the basis of similar surveys in PARDYP China (Ma et al. 2002), India and Pakistan.

For further details on this survey refer to Merz et al. (2002) and Merz et al. (2003c)

This water use is above average in comparison with the estimated water use of Nepal of 12 l person^{-1} day^{-1} (Gleick 2000). The amount includes primarily the water requirements for drinking, cooking, and food preparation. Other water-related activities, such as washing and personal hygiene, mostly take place at the watercourses or taps themselves. RWSSSP (1994) estimated the water demand at 45 l person^{-1}day^{-1} for areas where piped water supply is possible. In areas with difficult access to water and collection times of more than 15 minutes they assumed 25 l person^{-1}day^{-1} and in local markets ('bazaars') and townships 60 l person^{-1} day^{-1}.

3.6.1.2 Agricultural use

Agriculture is largely dependent on water resources because of water demand for irrigation and water use for extensive agriculture on rainfed terraces. The crops usually grown in the Jhikhu Khola on irrigated land are rice during the monsoon followed by potato or wheat (Figure 3.154). This crop is then followed by maize, potato, or tomato. Maize, the main monsoon staple crop, is grown on rainfed terraces, followed by wheat, tomato, potato, or barley. Wheat is often intercropped with mustard.

The theoretical crop water demand of different crops differs tremendously depending on the climatic conditions in the catchment. For the presentation in Table 3.115 and Table 3.116, average climatic

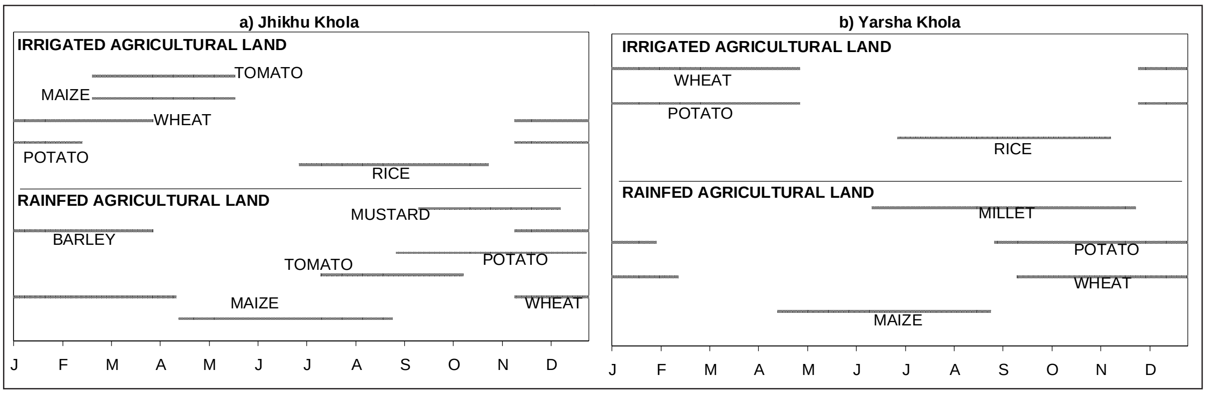


Figure 3.154: **Cropping calendar in the selected catchments a) Jhikhu Khola, b) Yarsha Khola**

conditions were assumed on the basis of the data for 1993 to 2000 in the case of the Jhikhu Khola catchment, and 1998 to 2000 in the Yarsha Khola catchment and used the data of the respective main meteorological stations. It is important to note that these water requirement values were calculated in view of maximum yield under the given conditions. It is understood that the crops in the field may grow with less amounts of water, however, this has a major impact on the yields. The impact of water stress on yields can be estimated by the use of the yield response factor, which calculates the actual expected yield on the basis of the yields estimated for optimum water supply conditions (Doorenboos et al. 1979). Here, optimum water conditions are assumed for maximum growth and yield.

Table 3.115: **Water requirements of the main crops in the Jhikhu Khola***

Crop	Crop water requirements [mm / month]												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrigated													
Rice						230.0	404.4	332.3	269.7	168.1			**1404.4**
Wheat	80.3	94.7	72.4								10.7	43.8	**301.8**
Potato	78.5	28.2									17.9	56.8	**181.4**
Tomato		17.2	83.3	145.7	98.6								**344.8**
Maize		8.6	58.7	150.0	94.2								**311.4**
Rainfed													
Maize				21.4	84.7	165.8	171.8	91.7					**535.4**
Wheat	80.3	94.7	72.4								10.7	43.8	**301.8**
Potato									54.0	82.9	80.5	54.9	**272.3**
Tomato							46.5	107.5	121.7	36.6			**312.3**
Barley	80.3	94.7	69.5								10.7	43.8	**298.9**
Mustard									37.8	74.5	73.4	27.1	**212.9**

* Calculated by CROPWAT 4 for Windows 4.3 for all crops except rice using average climatic conditions of the main meteorological station at Panchkhal (Site 12) and crop specifics in Appendix A2.1. Rice water requirement was calculated according to MacDonald & Partners (1990).

Table 3.116: **Water requirements of the main crops in the Yarsha Khola***

Crop	Crop water requirements [mm]												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrigated													
Rice						197.0	363.6	300.2	242.7	225.6	129.1		1458.3
Wheat	21.6	54.3	83.5	96.1	60.1								315.6
Potato	47.5	76.2	103.2	90.2								25.8	342.8
Rainfed													
Maize				15.4	62.2	123.8	129.5	72.9					403.8
Wheat	47.9	9.9							12.6	53.9	65.5	59.1	248.9
Potato	47.0								40.8	55.6	65.3	59.1	267.7
Millet						17.5	47.5	88.9	81.6	68.7	30.0		334.2

* Calculated by CROPWAT 4 for Windows 4.3 for all crops except rice using average climatic conditions of the main meteorological station at Bagar (Site 7) and crop specifics given in Appendix A2-1. Rice water requirement was calculated according to MacDonald & Partners (1990).

By far the most demanding crop on irrigated land is rice, with about 1400 mm/crop. This value corresponds well to the values of 1200 to 1800 mm/crop given by ILACO (1981). The impact on the annual availability of water resources is, however, limited as this crop is grown during the monsoon season. The recently introduced cash crop, tomato, follows with an assumed 345 mm. Another cash crop on the other hand, potato, requires less water than the traditional wheat crop at that time of the year mainly due to its shorter growing season. It is, however, important to note that in the field the potato crop uses more water than wheat under the current management practices on irrigated land. Due to the drought resistance of the wheat crop and the potato's relative sensitivity to soil water deficits, farmers tend to keep the soil for a potato crop moist, whereas only one to two irrigations are supplied for the wheat crop (Doorenbos et al. 1979). On rainfed land the monsoon crop maize has the highest water demand, followed by wheat and tomato.

There are a several different crop rotations in the Jhikhu Khola catchment. Pujara and Khanal (2002) identified ten different crop rotations on irrigated land, always including rice, and thirteen different rotations on rainfed agricultural land, including one maize crop. Water use is therefore only given for some major crop rotations as identified during the water demand and supply survey:

rice-potato-maize	1897 mm/12 months	(= 158 mm/month in 12 months)
rice-wheat-maize	2018 mm/12 months	(= 168 mm/month in 12 months)
rice-potato-tomato	1931 mm/12 months	(= 161 mm/month in 12 months)
rice-wheat	1706 mm/10 months	(= 171 mm/month in 10 months)

average = 165 mm/month in 11.5 months = 1898 mm/a

On rainfed agricultural land, the following crop rotations are common in the Jhikhu Khola catchment according to the water demand and supply survey:

maize-wheat	837 mm/10 months	(= 84 mm/month in 10 months)
maize-tomato	848 mm/7 months	(= 121 mm/month in 7 months)
maize-potato	808 mm/9 months	(= 90 mm/month in 9 months)
maize-mustard-wheat	1050 mm/12 months	(= 88 mm/month in 12 months)

average = 96 mm/month in 9.5 months = 912 mm/a

Recently, different vegetables have been introduced in the catchment, such as bitter gourd, chilli, eggplant, and others. On the basis of the above figures and the entire catchment area, annual demand for the irrigated areas (1838 ha) is therefore estimated to be about 313 mm/year. The water demand of the rainfed areas (4267 ha) can be estimated at roughly about 349 mm/year.

In the Yarsha Khola catchment, the main crops on irrigated land are rice, wheat, and potato (Table 3.116). The highest water demand has rice followed by potato and wheat. On rainfed land the traditional crops are maize, millet, wheat, and potato with maize demanding the highest water amounts. Millet is relayed with the maize crop and requires about 340 mm per crop.

Water use for a specific crop rotation on irrigated land as identified by the water demand and supply survey:

rice-wheat	1774 mm/12 months	(148 mm/month in 12 months)
rice-potato	1801 mm/11 months	(164 mm/month in 11 months)

average = 156 mm/month in 11.5 months = 1794 mm/a

and on rainfed agricultural land:

maize-millet	738 mm/a in 8 months	(92 mm/month in 8 months)
maize-millet-wheat	987 mm/a in 11 months	(90 mm/month in 11 months)
maize-potato	672 mm/a in 10 months	(67 mm/month in 10 months)

average = 83 mm/month in 9.5 months = 789 mm/a

The total water demand for the irrigated areas in the Yarsha Khola (742 ha) is estimated to be 249 mm/year on the basis of the entire catchment area. The demand for the rainfed areas (1996 ha) is estimated to be 295 mm/year.

3.6.1.3 Livestock

As mentioned above, livestock are an important aspect of mountain agriculture in the HKH and therefore an important factor in the calculation of water demand. The animals are also often brought to the watering point, as in the case of cows. However, with the increase in stall feeding, goats and especially buffaloes (which are less adapted to moving up and down the slopes) and even cows are very often watered on-site (Merz et al. 2002; RWSSSP 1994).

The water demand for the different animals in Table 3.117 was estimated from a survey conducted in the Jhikhu Khola and Kathmandu Valley (N = 23) and verified in the literature (ILACO 1981;

RWSSSP 1994). In general, the values are slightly higher than the values in the literature, which seems to be appropriate given the hot conditions in the Jhikhu Khola.

Table 3.117: **Water demand for watering livestock**

	Water demand [l/day]	Jhikhu Khola		Yarsha Khola	
		HH*No.[#]	m^3/day	HH*No.[*]	m^3/day
Buffalo	61	8,002* 1.2	585.7	4,362* 1.1	292.7
Bullock	49	8,002* 0.8	313.7	4,362* 1.5	320.6
Cow	23	8,002* 0.9	165.6	4,362* 0.9	90.3
Goat	12	8,002* 3.5	336.0	4,362* 3.3	172.7
Pig	10	-	-	-	-
Annual water use [m^3]		511,365		319,849	
Annual water use [mm]		4.6		6.0	

[#] Number of households (HH) from PARDYP times average number of animals per household (No.) from Merz et al. (2002)

3.6.1.4 *Overall demand of human activities*

The overall demand for water, including domestic, agricultural, and livestock water requirements adds up to about 670 mm per annum in the Jhikhu Khola and 553 mm per annum in the Yarsha Khola catchment (Table 3.118). The difference is mainly due to the higher evapotranspiration rates and therefore crop water requirements in the Jhikhu Khola catchment, which differs by about 60 mm/year on irrigated land and 50 mm/year on rainfed land.

Table 3.118: **Overall water demand of human activities (all values in mm)**

Catchment	Domestic	Agriculture			Total
		Irrigated land	Rainfed land	Livestock	
Jhikhu Khola	3.7	313	349	4.6	670.3
Yarsha Khola	3.0	249	295	6.0	553.0

3.6.2 Water Supply

The people in the two catchments of the Jhikhu and Yarsha Khola perceive water shortage in terms of both agricultural and domestic water supply (Table 3.119). Their concern is not only in terms of water quantity, but also increasingly in terms of water quality. Over the past 5 to 25 years in general they perceived a decrease in water supply. While this is true for both domestic as well as agricultural supply in the case of the Jhikhu Khola catchment, domestic water supply in the Yarsha Khola is perceived to have improved over this period. Water shortage was particularly felt during the pre-monsoon and early monsoon months of April to June. That is the time when many sources either dried up or showed lower yields. The perceptions of the local residents of the two catchments are documented in detail in Merz et al. (2002) and Merz et al. (2003a).

Table 3.119: **Water-related problems, Yarsha Khola and Jhikhu Khola catchments [%; multiple answers possible]**

		Jhikhu Khola	Yarsha Khola
Total number of respondents		356 respondents	436 respondents
No problems		12	4
Irrigation water	Quantity	41	33
	Quality	0	7
Drinking water	Quantity	37	27
	Quality	9	17
Flooding		0	1
Surface erosion		0	3
Slumping		1	8

3.6.2.1 Domestic supply

Domestic water supply in both the Jhikhu Khola and the Yarsha Khola catchments is widely met by the extensive network of taps (both proper tap stands and improvised, simple pipe ends) as well as traditional spring boxes, called 'kuwas' in Nepali. According to Shrestha et al. (2000), more than 400 public water sources were identified in the Jhikhu Khola catchment during a mapping campaign in November/December 1999. Out of these 400 sources, 319 were documented on the basis of relevance to local residents (Figure 3.155). Most of the sources observed were perennial, but according to the users, flow decreased in March to May/June. The source yield varied tremendously from site to site, from a minimum of 0.6 to a maximum of 270 l/min. The combined yield of all sources was 3492 l/min during the survey. The average flow was slightly higher in the case of taps (11.6 l/min) than in the spring boxes (8.2 l/min) and the natural springs (6.5 l/min). These values can be considered average as it is in the middle between the end of the wet season and the driest time of the year in May/June.

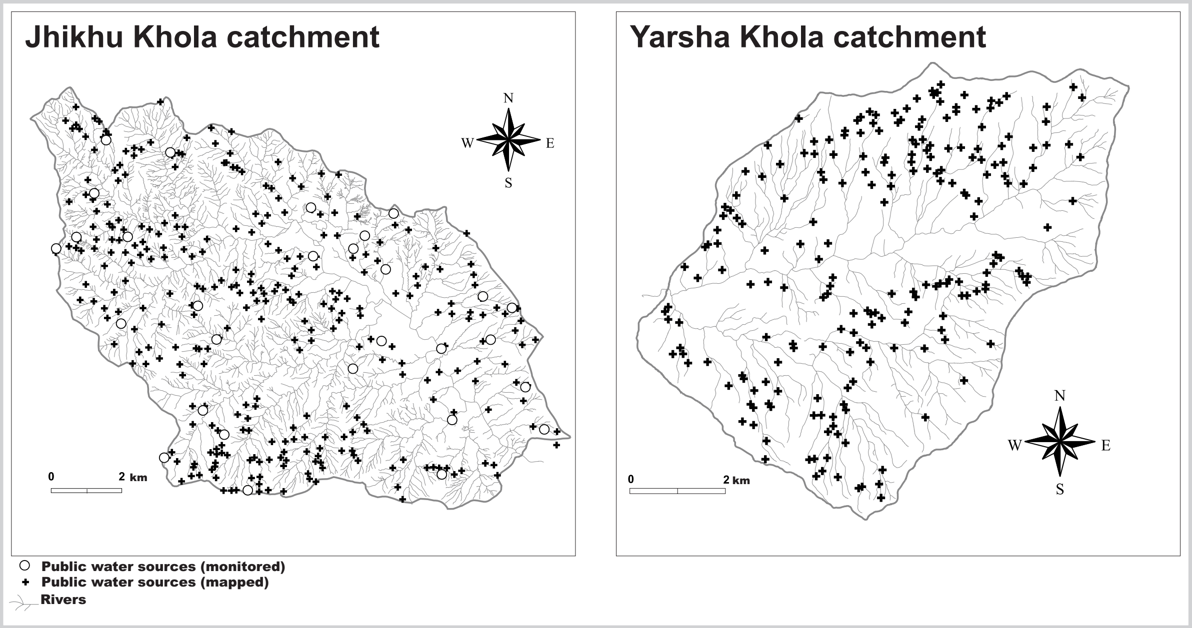


Figure 3.155: **Public water sources documented in the Jhikhu Khola catchment (December 1999) and the Yarsha Khola catchment (May 2000)**

Average distances from the dependent households to the water sources vary from 3 to 600 m. The long distances to the water sources put pressure on women's workloads as mostly women fetch the water. Children are often observed to support their mothers in this duty. According to Merz et al. (2002), in 79% of the cases in the Jhikhu Khola, a female of the household fetches water, in 34% of the cases in Jhiku the female is the household head. Only in 21% of the cases does a male of the household perform this duty. The long distances to the sources are not only critical in terms of time, but also in terms of danger during the wet season. During this time the often steep and muddy paths become slippery and pose a major risk during water collection. Some of the sources provide water for up to 290 households. On average, however, 18 households depend on the same water source.

In the Yarsha Khola catchment, 215 public water sources, mostly taps and natural springs, were documented in May/June 2000 (Figure 3.155). Most of these sources are perennial with a seasonal decrease of flow at the end of the dry season from March to May/June. This is the problematic time when many local residents face hardship fetching adequate supplies of water. The yields during the survey period varied from 0.06 to 216 l/min with a combined yield of 2242 l/min (Shrestha et al. 2001). Springs yielded on average 17.9 l/min followed by taps with 15.1l/min. The spring boxes in the Yarsha Khola catchment only yielded about 1 l/min. These results are to be taken as values representative for the dry season as the survey was carried out during the driest time of the year.

About 45% of the water sources are managed by communities and another 45% are owned privately. The remaining water sources are being looked after by government agencies. Many sources are conveniently located close to the settlements. However, some of the sources are at a considerable distance from the household. This affects women's workload, since in 60% of the cases in Yarsha Khola water is brought by women. The maximum number of households relying on one single source was 150 on the southern slope of the catchment. On average, 16 households depend on the same water source.

In general, there is adequate water supply for domestic purposes in both catchments. This is also shown on the basis of the service levels determined using the RWSSSP (1994) approach (Table 3.120).

Table 3.120: **Description of service level for water supply** (from RWSSSP 1994)

Category*	Quality	Quantity [l person^{-1}*day^{-1}]	Accessibility [min]	Reliability [months/y]	Continuity [h/day]
Service level 1 Good	protected source	≥ 45	≤ 15	12	≥ 6
Service level 2 Intermittent	spring or better	≥ 25	≤ 30	≥ 11	≥ 5
Service level 3 Poor	any source	≥ 15	≤ 60	≥ 10	≥ 4
Service level 4 Very poor	all water supplies	All other water supplies			

* The service level of a source is determined by the lowest score in any of the five parameters.

The service levels in RWSSSP (1994) are given on the basis of the population having access to the respective water sources. In this study, the public water sources themselves were documented instead of the population, and the service level of each source determined. This approach slightly overestimates the service level in terms of accessibility, as an average distance had to be used for the assessment.

For the Jhikhu Khola and the Yarsha Khola catchments the following service levels were determined:

		Jhikhu Khola	Yarsha Khola
Service level 1	good	57.4%	43.7%
Service level 2	intermittent	15.0%	9.8%
Service level 3	poor	4.7%	5.1%
Service level 4	very poor	14.4%	5.1%
Not assessed (as one or more parameters were missing)		8.5%	36.6%

In the case of the 36.6% unassessed sources, most of them will contribute to service levels 1 and 2, as the main reason for not assessing was the fact that these were either taps from sources with multiple sources or several springs feeding into one distribution system. The surveyors therefore decided not to assess the yield and therefore a proper assessment of the service level is not possible.

3.6.2.2 Agricultural supply

The most important water supply for agriculture is river discharge, which is supplied to the fields through a number of irrigation systems. In the Jhikhu Khola catchment, some of the farmer managed irrigation systems (FMIS) have been operational for over 100 years. Most systems are 50 to 65 years old. In the steep upland areas of Nepal, there is little possibility of extended, large-scale irrigation development. Therefore FMIS still play a crucial role in agricultural production. It is estimated that FMIS accounted for over 80% of the total irrigation development in the hills and mountains of Nepal in 1997 (Shah and Singh 2001).

In 1988, a total of 51 irrigation systems was operational in the Jhikhu Khola catchment with one of the best-developed irrigation infrastructures in Kavrepalanchok District (Multidisciplinary Consultants 1988). These systems catered for a total gross command area (GCA) of 1491 ha. The main rivers acting as sources for these systems are the Danfey Khola, the Dhod Khola, the Dhital Khola, the Dhap Khola, the Subarno Khola, the Namde Khola, the Andheri Khola, and the main Jhikhu Khola. The capacity of these systems ranged from 0.038 to 1.719 m^3/s at the intake with GCAs from 10 to 186 ha. Of these systems, 65.4% were perennial and the remaining 34% seasonal, only supplying water to the monsoon crops. The cumulative capacity of all schemes during the monsoon season for the planting of rice was therefore calculated as 9.76 and 4.95 m^3/s for the winter crops.

Upadhyay (2001) conducted a detailed survey of the efficiency in terms of water adequacy, equity in water allocation, and technical aspects of two irrigation systems in the Jhikhu Khola catchment in 2000. The Devbhumitar irrigation system within the sub-catchment of the Andheri Khola has 43 users and a GCA of 33 ha. At present, only 16% of the farmers reported receiving adequate water for their winter crops, while all of them receive ample supply for their monsoon crop. This has changed considerably in the last 30 years. Thirty years ago, 73% of the users reported adequate supply for their winter crops and 66% said they had enough water 15 years ago . The same situation was shown in the Raj Kulo irrigation system in the upper Jhikhu Khola catchment. This is the largest irrigation system in the catchment with 1500 users and a 210 ha GCA. In this system the users at the head end usually receive sufficient water throughout the year. This reduces dramatically towards the middle part and the tail end of the system, where only 35% receive adequate water supply during the dry season. A similar trend as in the Devbhumitar system was observed in terms of water supply over the last 30 years. In addition, unequal water allocation is strongly felt by the users of this system.

However, conveyance losses have to be assumed to be high. Out of 76 km of irrigation canals, 75% were boulder lined and 24% were unlined (Teuling 2001). Only the remaining 1% of the total canals was concrete lined. These losses were documented in the Andheri Khola sub-catchment by Nakarmi (1995). He studied two irrigation systems, where in one system a 35% loss occurred over a distance of about 500 m. In the other system the initial losses were small, but over a distance of 1 km, 90% was lost through seepage. The main losses occurred when the channels crossed fractured bedrock or sections of sandy and gravelly soil material. Mac Donald & Partners (1990) compiled the seepage losses on soils of different textures, showing that the higher the clay contents the lower the expected seepage losses (Table 3.121). In addition, the role of preferred pathways is unclear in this context.

Table 3.121: **Seepage in irrigation canals**

Types of soil	**Seepage losses***
Rock	< 0.5
Impervious clay loam	0.8 to 1.2
Medium clay loam	1.2 to 1.7
Clay loam or silty soil	1.7 to 2.7
Gravelly clay loam, sandy clay or gravel cemented with clay	2.7 to 3.5
Sandy loam	3.5 to 5.2
Sandy soil	5.2 to 6.4
Sandy soil with gravel	6.4 to 8.6
Pervious gravelly soil	8.6 to 10.4
Gravel with some earth	10.4 to 20.8

* m^3/s per mm^2 of wetted perimeter or l/s per km per m of wetted perimeter

source: MacDonald & Partners 1990

In the Jhikhu Khola, the soils in the valley bottom (the area with the most irrigation canals) are of loamy texture (see above). Seepage losses therefore have to be expected in the order of 1 to 5 m^3/s per 1000 m^2 of wetted perimeter. The Yarsha Khola catchment with mainly sandy loamy textured soils has to expect seepage losses of 3 to 5 m^3/s per 1000 m^2 of wetted perimeter. For a detailed seepage assessment of the different systems, a detailed soils map would however be required. The intakes mapped by Teuling (2001) are of a temporary nature, i.e., they often do not withstand monsoon floods. He mapped 30 intakes catering for the irrigation systems in the main valley floor of the catchment. Nakarmi (1995) documented 72 diversion dams in the Andheri Khola sub-catchment feeding 58 ha of irrigated agricultural land. No irrigation-related activities have been conducted yet in the Yarsha Khola during the study period.

Box 3.2: **Water Demand and Supply Management Follow-up in PARDYP**

For water demand and supply management PARDYP has conducted a number of studies in the fields of rainwater harvesting, surface runoff harvesting, and the application of drip irrigation (see also Merz et al. 2003d).

- *Roof- rainwater harvesting*
  PARDYP initiated training and demonstration of roof-water harvesting in collaboration with the Water Harvesting Project of ICIMOD and the Rural Water Supply and Sanitation project of HMG/Finnida in the Jhikhu Khola catchment. Twenty local masons were trained in July 2000. During the training, 13 water harvesting jars of 2000 l each were constructed for demonstration and a couple of months later an additional 9 units were constructed in an adjacent district.Since termination of this activity in late 2000, due to persistent water shortages in the catchment, farmers have initiated construction at their own expense. In the meantime, three families have constructed jars at their own expense. Two schools provide drinking water for their school children from their own jars. Two families, who had benefited from a demonstration jar, have in the meantime constructed another jar to increase their self-sufficiency in water.
- *Surface runoff harvesting*
  Trials with surface runoff harvesting were conducted to provide a marginal farmer with the chance to produce an off-season vegetable crop. Firstly, trials were conducted with a 10,000 l tank harvesting overland flow from a badly degraded area. For proper use of the harvested water, drip irrigation technology as introduced by International Development Enterprises (IDE) – Nepal was used. These drip sets, developed especially for Nepal, only cost 1400NRs. (~ 20 US$). The storage tank for the water harvested is a major investment and costs about 24,000 Nr. (~325 US$). However, it was shown that two cash crops could be grown in one year with the water harvested, a cauliflower crop in the post-monsoon-winter season and a bitter gourd crop in the pre-monsoon season. From the sale of these crops, 2/5ths of the capital expenses could be returned per annum. This includes all the costs including labour. Still, the problem of the initial investment remains. So far no farmer has built one of these tanks himself.
  (*for further details refer to Adhikari et al. 2003)*

In PARDYP Phase 3, drip irrigation with different crops will be studied on different soil types and at different locations in the catchment. In addition, participatory action research (PAR) will be conducted in the field of water supply and demand management.

3.6.3 Water quality

Water quality has become a major concern in recent years from both the perception of the local farmers as well as scientific data. Seventeen per cent of the respondents indicated that they perceive water quality to be a problem in the Jhikhu Khola catchment (Merz et al. 2002). In the Yarsha Khola the percentage is lower with 9% of the respondents and only around the main settlements in the catchment. For human health the main concern is the high microbiological contamination of most public water sources exceeding the guidelines often in orders of magnitudes (KU/ICIMOD 2001). Thirty-one public water sources were monitored in four seasons over a one-year period (see Figure 3.155). During this time, only two sources were free of faecal coliform during one of the seasons. Phosphate and nitrate levels are often elevated and exceed the guidelines mainly in dug wells and other water sources in agricultural areas (Dongol et al. 2003). Most of the surface waters in the lower stretches of the Jhikhu Khola catchment and selected tributaries show elevated levels (Merz et al. 2003c). Signs of eutrophication are omnipresent in the catchment.

Schaffner (2003) studied different water sources–including springs, taps, dug wells, and water harvesting jars–in selected areas of the Jhikhu Khola catchment. This study concluded that microbiological contamination is the single main parameter of concern in all drinking water systems, with the highest contamination risk during the pre-monsoon and monsoon. Most affected are traditional public water sources, followed by dug wells, with the lowest risk at pipe-tap systems and water harvesting jars. Turbidity is commonly elevated during the pre-monsoon and monsoon in all drinking water systems, but is mainly related to heavy rainfall. Agrochemical and human-induced pollution, indicated by high nitrate and phosphate levels, is of concern mainly at dug wells. Basic water quality parameters show very variable electrical conductivity and total hardness, locally low pH and seasonal variations in yield. Analysis of trace elements (total iron, arsenic in dug wells, zinc, lead in water jars) revealed no levels of concern.

According to recent studies by Apel et al. (2002) and Schumann et al. (2002), the high doses of different pesticides applied in the Jhikhu Khola catchment do not seem to pose a risk to either groundwater or surface water contamination. The main risks to human health in connection with pesticide use are the residues on the crops as well as unsafe handling and application.

Box 3.3: **Water Quality Follow-up in PARDYP**

Water quality has become a major issue in the PARDYP catchments. Different surveys have shown that microbiological contamination in particular is of great concern. The project, therefore, decided to focus deliberately on this parameter and will conduct a series of studies in all PARDYP catchments with the solar disinfection (SODIS) method as proposed by the Federal Institute of Environmental Science and Technology (EAWAG).

In terms of the impact of agrochemical inputs on eutrophication, seasonal monitoring of major nutrients in the main rivers of all catchments will continue. If possible, a detailed study on agrochemicals and their impact on surface and groundwater in the catchments will be conducted at a later stage within the PARDYP project or a separately funded, new project.

For further details on the water quality assessments refer to KU/ICIMOD (2001; Appendix B.2), Schaffner (2003) and Merz et al. (submitted_b)

A survey of the health posts in the Jhikhu Khola catchment has shown that about 25% of the patients of these health facilities suffer from diseases most probably related to bad water quality (Tripathi et al. 2002). Diarrhoea and dysentery collectively stand as the second biggest ailments faced by the population of this catchment. The biggest problem is malaria. Pre-monsoon from Falgun to Jestha (February to June) and the monsoon season from Asadh to Bhadra (June to September) are the seasons with the highest numbers of patients.

3.6.4 Summary

Overall water demand in the Jhikhu Khola catchment for human activities is estimated at about 671 mm per annum including 662 mm/year for agricultural supply, 4 mm/year for domestic supply, and 5 mm/year for livestock. In the Yarsha Khola catchment, the overall water demand is estimated at about 553 mm/year with 544 mm/year for agriculture, 3 mm/year for domestic use, and 6 mm/year for livestock. The local residents perceive irrigation water shortage as key issue number one related to water, followed by domestic water shortage. Increasingly, people perceive water quality as a threatening issue.

In general, the major reasons for concern in the two catchments in terms of public water supply for domestic use are:

- convenient access to water, which mainly affects women's workload;
- water quality, mainly microbiological contamination, leading to poor health and affecting infants and the old in particular;
- seasonal water shortage for domestic water supply in pocket areas of the catchments.

The agricultural water supply is organised by user groups, who manage the large number of FMIS in the catchments. These FMIS face inadequate water supply leading to unequal water allocation, mainly due to increasing demand throughout the catchment as well as often inefficient canal systems.

3.7 WATER BALANCES – HOW MUCH WATER IS AVAILABLE AND WHEN?

This section discusses the water availability in the catchments based on three different approaches, a climatological, a hydrological, and a water resource management approach. Finally, the results of the different approaches are compared and synthesised.

The determination of water balances is an important tool for assessing water availability, and also for understanding potential conflicts between different water users. For flooding as well as the degradation of land resources, these balances play a minor role as such issues only occur during times of surplus water. Surplus water in this context is understood as excessive rainfall after subtraction of the potential evapotranspiration, which results in runoff (see below for more discussion). For the Koshi basin in eastern Nepal, Sharma (1997) attempted to produce a water balance on the basis of scarce data, particularly for the part of the catchment on the Tibetan plateau and the higher elevations of the basin. For the entire Sapta Koshi system with runoff measurements at station 695, he determined 1288 mm precipitation, 919 mm runoff, and 369 mm evapotranspiration (measured as precipitation minus runoff).

In the preceding chapters, the single balance parameters of precipitation, evapotranspiration, and runoff were discussed in detail. In this chapter, a comprehensive assessment of the inherent water availability is attempted using three different methods by using only climatic parameters, hydrological parameters, and finally water-use components. While the climatic water balance is determined for monthly values as well as annual values, the other balances are only generated for annual values.

3.7.1 Discussion of applied approaches

3.7.1.1 Climatological water balance

To calculate climatic water balances, the book-keeping procedure after Thornthwaite and Mather (1955) is used. This method has many limitations, especially in the calculation of potential evapotranspiration. In this study the reference evapotranspiration was therefore used instead. However, to compare different locations and rough ideas on the water surplus and deficiency periods of the year it seems a good method. This method is not suitable for the calculation of irrigation water requirements.

The climatic water balance is the relationship between rainfall, potential evapotranspiration, and actual evapotranspiration from which water surplus and water deficiency can be worked out at any place or region over a given period of time. Rainfall as the major input into the system is put into relation with the output evapotranspiration. Water deficit deals with the additional water demand for vegetation which cannot be supplied by rainfall and therefore has to be supplied by irrigation. The water surplus is that part of the water balance that can be collected by constructing suitable hydraulic structures such as tanks and reservoirs.

Water deficiency can be expressed as the difference of the reference evapotranspiration ET_0 and the actual occurring evapotranspiration AET.

$$WD = ET_0 - AET \qquad \textbf{Equation 3.15}$$

Water surplus occurs only after the soil has been recharged to its field capacity, i.e., whenever precipitation P is higher than ET_0 and the soil is at field capacity (DST is the available soil storage capacity). Before producing water surplus, soil moisture is recharged.

$$WS = (P - ET_0) - \Delta ST \qquad \textbf{Equation 3.16}$$

The climatological water balance is assessed for a point location — in this study for selected meteorological stations in the catchments — on the basis of average data. The results of the water surplus and deficit assessment are then interpolated spatially.

3.7.1.2 Hydrological water balance

The hydrologic cycle is extremely complex and may therefore be represented in a simplified way by means of the systems concept (Chow et al. 1988). The components of this system are precipitation, evaporation, transpiration, runoff and other phases of the hydrologic cycle. Each of these components can be further broken up into sub-systems describing the respective components in further detail. At the catchment level the hydrologic system can be presented as in Figure 3.156. This system can be expressed as the water budget equation or hydrological water balance (Subramanya 1994)

$$P - Q - G - E - T = \Delta S \qquad \textbf{Equation 3.17}$$

where

P = precipitation
Q = streamflow
G = net groundwater flow
E = evaporation
T = transpiration
ΔS = change in storage

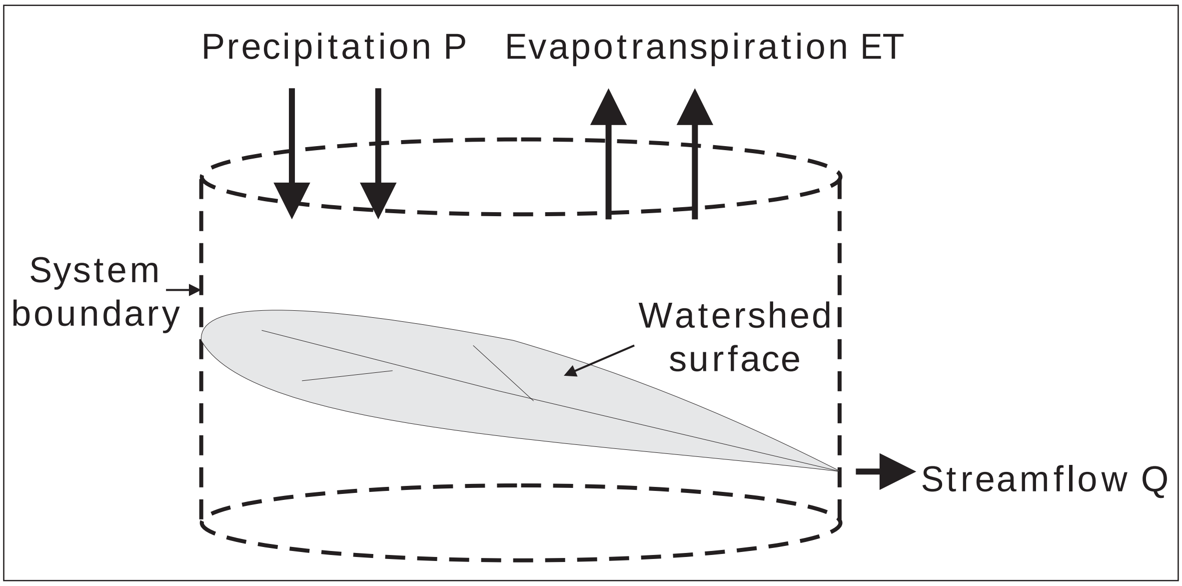


Figure 3.156: **The catchment as a hydrologic system (adapted from Chow et al. 1988)**

In this study a simplified equation is used, assuming that:

1) change in storage is negligible over the period of one year (see also Section 3.3),
2) there is no groundwater outflow other than through return flow at the outlet of the catchment, and
3) evaporation from open water surfaces is negligible as large water bodies are missing in the catchments (see also Chapter 2).

The equation can then be written as

$$P = Q + ET \qquad \textbf{Equation 3.18}$$

where

P = precipitation
Q = streamflow
ET = evapotranspiration

As shown above, the annual runoff data is adversely affected by the inadequate discharge data for low flows. For this reason, precipitation and evapotranspiration were used for the calculation of runoff and compared with the runoff as measured at the outlets of the different catchments and sub-catchments. At Site 13 in the Jhikhu Khola catchment, the adjusted runoff on the basis of the estimated specific discharge (see Section 3.3) was used for this purpose.

3.7.1.3 Water accounting for water-use assessment

The method used for accounting of water use is based on Molden (1997). It is basically a hydrological water balance approach considering water inflows and outflows from different spatial levels in addition to water-use components. The following water accounting definitions are important in this context (Molden 1997; for further details refer to this publication).

• *Gross inflow*	Total inflow into the catchment from precipitation, surface, and subsurface sources
• *Net inflow:*	Changes in storage in addition to gross inflow
• *Water depletion*	The use or removal of water from the catchment that renders it unavailable for further use (e.g., evaporation, flows to sinks, pollution, incorporation into a product). The water can be *process depleted*, i.e., the use of water to be used for production of a certain good such as agricultural crops, energy, or industrial produce. *Non-process depleted* water is considered to be the water lost through processes not directly in relation to the process it was diverted for. This, for example, includes evaporation from soil and water surfaces and deep percolation in irrigated land if groundwater cannot be used anymore.
• *Non-depleted water*	This includes water that is not lost after the diversion, e.g. hydropower, in-stream environmental uses.
• *Committed flow*	Part of the water that is bound to certain commitments such as environmental use, fisheries or downstream rights to irrigation water.
• *Uncommitted flow:*	Water that is neither depleted nor committed and thus available for use within the catchment or for downstream users.

Both the Jhikhu and the Yarsha Khola catchments, are open, i.e., there is uncommitted flow downstream even in the low flow period. In a closed basin all usable water is committed to different users (Molden et al. 2001). Note that this water accounting definition differs from the strict hydrologic definition according to which a closed basin allows only outflows to internal sinks (Chow et al. 1988).

This method was, for example, applied in four river basins of India, Pakistan, and Sri Lanka to identify opportunities for water savings and increased productivity of water (Molden et al. 2001). The results show that the applied method is thorough and robust and can be applied to other basins. Molden (1997) used the method at three different scales for field-level accounting of a wheat-cotton rotation in India, for an irrigation service-level accounting in the same area, and for a basin-level accounting of the river Nile.

3.7.2 Temporal distribution of water surplus and deficits

As shown above in the description of the methodology, the input parameters include precipitation P and evapotranspiration ET_0. For a temporal and spatial distribution of these parameters, refer to Sections 3.1 and 3.2, respectively. The climatic water balance calculates the potential water deficit and surplus periods of the year with the results shown in Figure 3.157. A general overview of the five stations shows that the main months of water surplus are June, July, and August at all five sites. Surplus in June is only marginal. During the late monsoon and post-monsoon season months of September and October, both deficit as well as surplus can be observed in different sites. Water deficit is observed in the remaining months from November to May with a peak deficit of up to 100 mm in March, April, and May. For detailed climatic water balances of all sites refer to Appendix A3.27.

The highest deficits can be observed in April at Site 15, representing the low altitudes on the south-facing slopes in the Jhikhu Khola catchment. This site is followed by Site 12 and the month of April. This site represents the valley bottom. The highest surplus was observed in July at Site 16, the upland and south-facing site, followed by the upland site on the north-facing slope, Site 6.

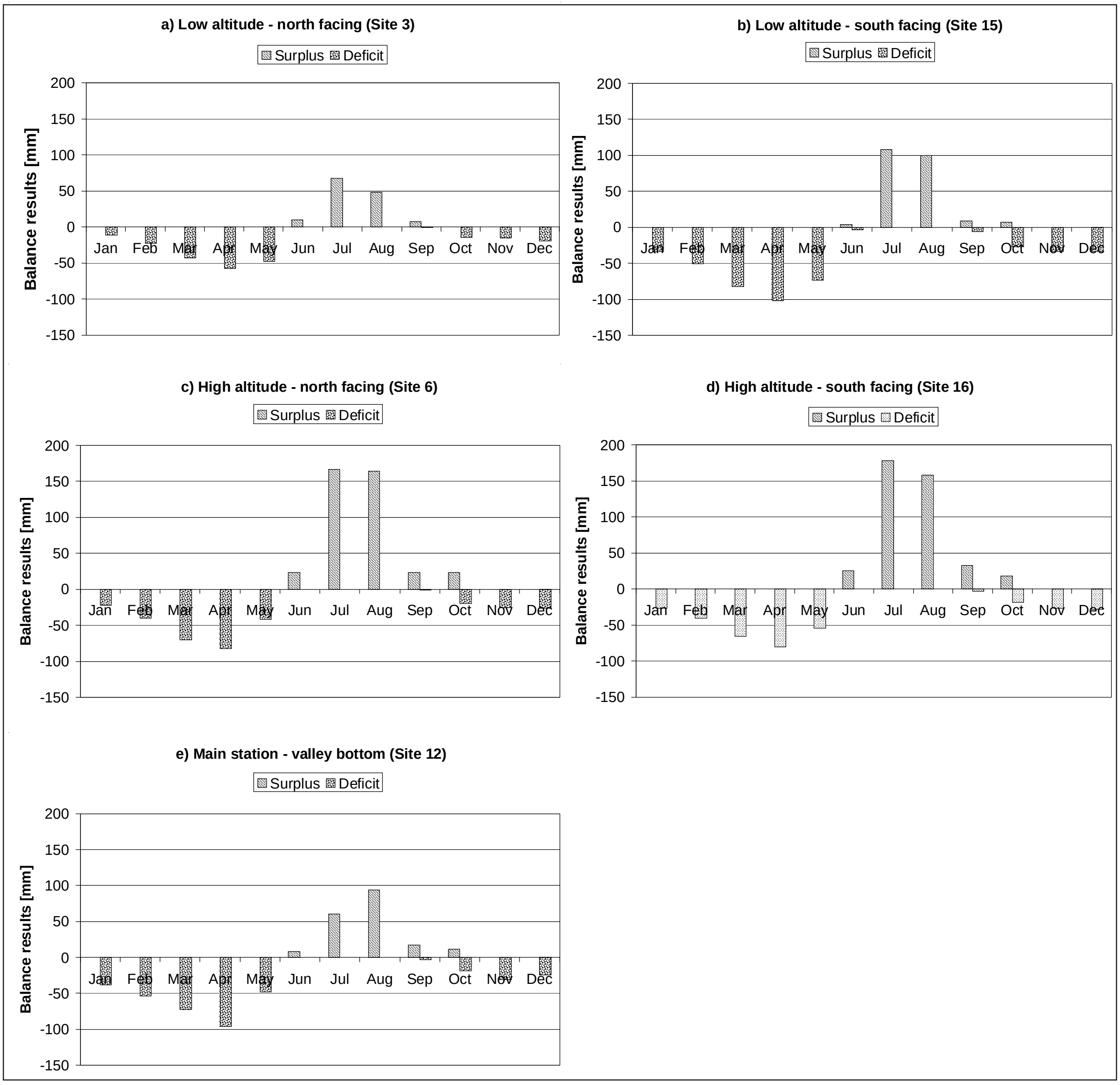


Figure 3.157: **Average water surplus and deficits at selected sites in the Jhikhu Khola** (period 1993-2000)

The above figure shows the average conditions in the Jhikhu Khola catchment. During the study period no particular drought year was observed that could show the worst case scenario. In the Indian PARDYP catchment, for example, a drought year was observed in 2002 with a late onset of the monsoon rains and very short duration of the monsoon season(Kothyari 2003). Figure 3.158 shows the distribution of water surplus and deficit throughout the study period from 1993 to 2000. The longest surplus period was observed in 1999, when surplus started in June and extended up until October. The shortest surplus period was observed in 1997, where only two months, July and August, showed surplus. In 1993, the data for June and July was missing, therefore no assumptions for this year can be made. The highest surplus was achieved in July 1996, while the highest deficit was reached in April 1995 and April 1999. In this respect 1999 was a very interesting year, as it showed the highest deficit in the pre-monsoon season, but at the same time it showed the highest surplus due to this extension of the surplus up until October.

Aspect has a major impact on the deficits, as shown in Table 3.122 comparing Sites 3 and 15, which represent the low altitudes on the north and south-facing slopes, respectively. The average annual water deficit at Site 15 is about double the deficit from Site 3. At the upland sites, Site 6 on the north and Site 16 on the south-facing slopes, no distinct difference was observed. The site on the valley floor shows very high deficits approximately in the order of the south facing foot slopes. Surplus at

Table 3.122: **Mean annual water surplus and deficit [mm]**

	Site 3 (low-north)	Site 6 (high-north)	Site 12 (valley)	Site 15 (low-south)	Site 16 (high-south)
Water surplus	132.8	400.9	191.5	228.0	411.9
Water deficit	233.1	328.5	385.8	445.9	343.8

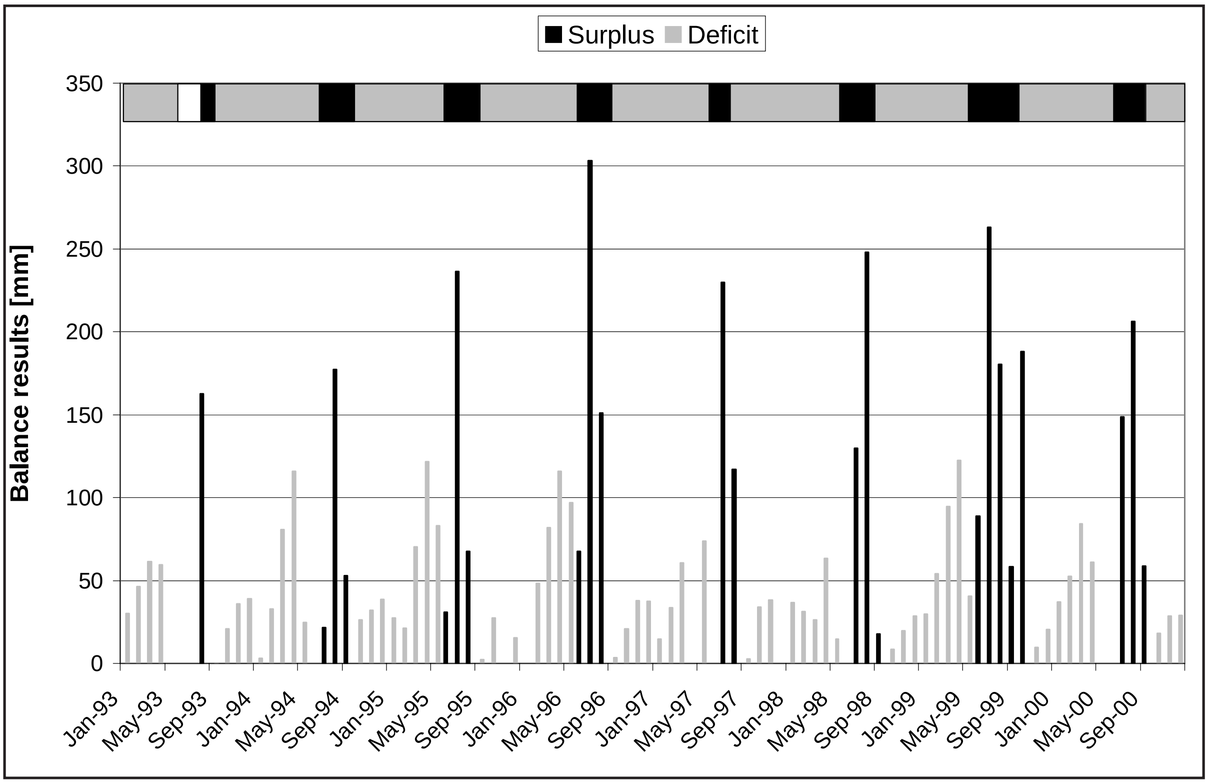


Figure 3.158: **Water surplus and deficit during the study period at Site 6, Jhikhu Khola catchment**

the upland sites is generally about double the surplus of the lowland sites comparing Sites 3 and 6, and Sites 15 and 16, respectively.

In the Yarsha Khola catchment, surplus extends from about May to September and often up until October (Figure 3.159). The highest surplus was observed at Site 5 at an altitude of 2300 masl. Deficits in this catchment are generally very low, reaching only about 50 mm in any month between November to April. At this location it is, however, important to be reminded that the study period from 1998 to 2000 in this catchment was wetter than normal (see Section 3.1). The detailed climatic water balances are presented in Appendix A3.28.

The water deficit was about 250 mm annually at all sites with the exception of Site 5, where the deficit was 128 mm (Table 3.123). Surplus was more than 1 m at all sites except Site 9, where the surplus was just below 1 m at 911 mm.

Table 3.123: **Annual water surplus and deficit at selected sites in the Yarsha Khola catchment [mm]**

	Site 3	Site 5	Site 7	Site 9
Water surplus	1026.7	2222.0	1524.1	911.5
Water deficit	256.1	128.2	242.4	257.5

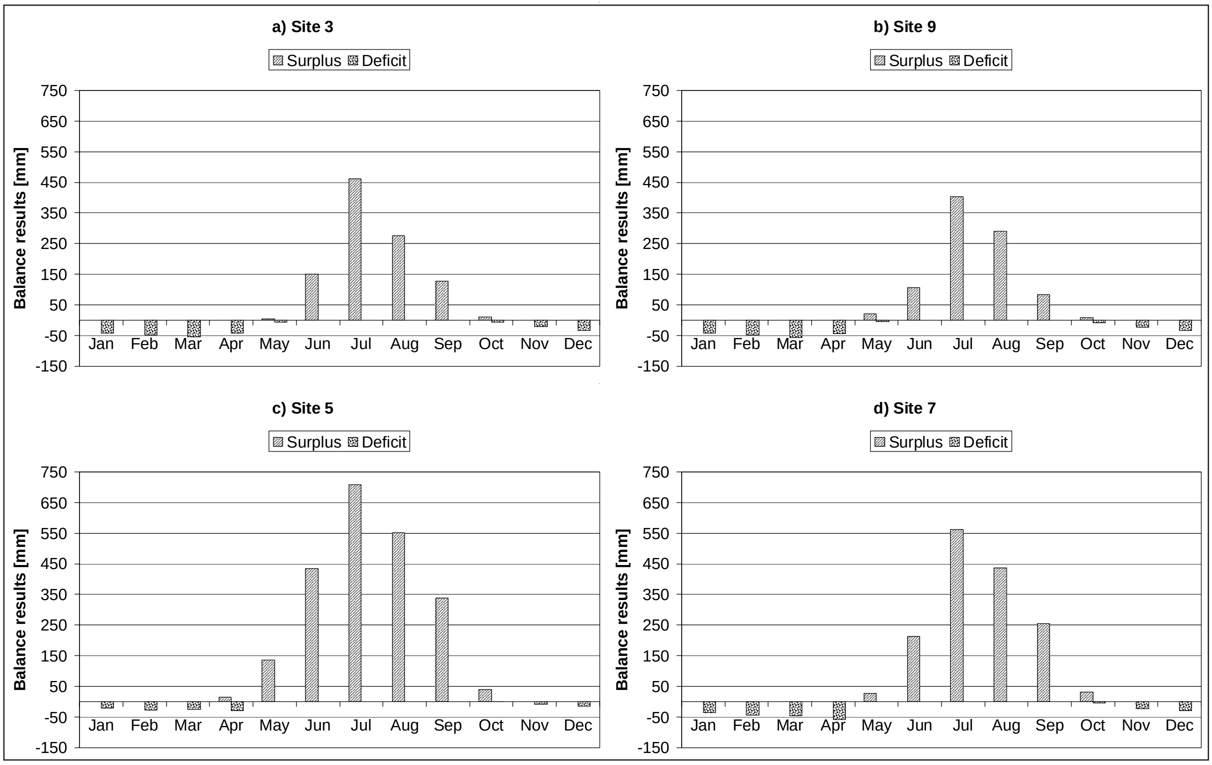


Figure 3.159: **Water surplus and deficits at selected sites in the Yarsha Khola (period 1998-2000)**

3.7.2.1 Summary

- In the Jhikhu Khola catchment eight to nine months of the year have a water deficit.
- June to August and sometimes September have a water surplus.
- Peak surplus is in July.
- Peak deficit is in April.
- The annual deficits are between 200 and 400 mm.
- The annual surpluses are between 100 and 400 mm;.
- During the study period, 1999 showed the highest deficits and simultaneously the highest surplus.
- In the Yarsha Khola catchment five to six months, from May to October, have surplus.
- Six to seven months from October to April have deficits.
- Peak surplus is in July.
- No distinct peaks for water deficits were observed. The highest levels were reached in April or May.
- Annually, water surplus is above 1 m and deficit is between 100 and 250 mm;
- The surplus difference between the Jhikhu and Yarsha Khola catchments is in the order of one magnitude.

3.7.3 Spatial distribution of water surplus and deficit

The water surplus and deficits differ according to elevation and aspect, as shown briefly above, on the basis of lowland and upland stations. The rates at which the deficits change with altitude were generally constant in the Jhikhu Khola catchment with an approximate 27 mm deficit decrease per 100 m elevation increase in the period 1993 to 2000 (Figure 3.160a). In the Yarsha Khola, the rates were an approximate 13 mm deficit decrease with 100 m increase in elevation during the period 1998 to 2000 (Figure 3.160b). For the same period, the rate in the Jhikhu Khola was only about 1 mm different from the rate determined for the entire study period.

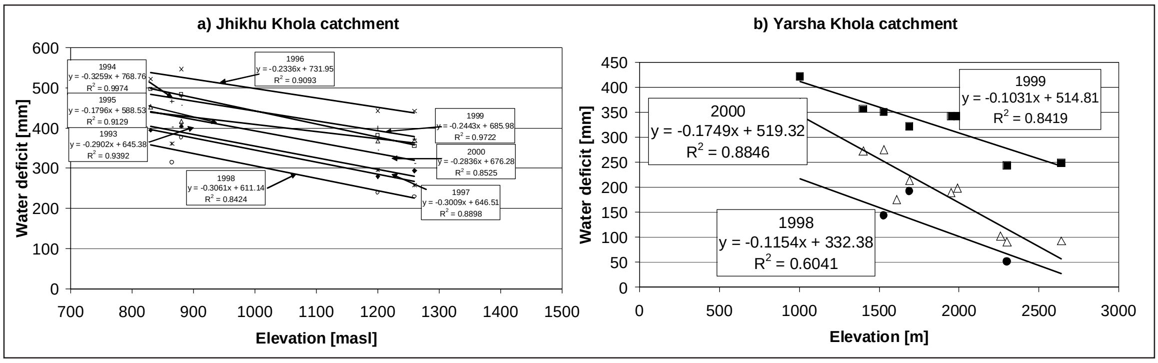


Figure 3.160: **Lapse rates of water deficit a) Jhikhu Khola catchment, b) Yarsha Khola catchment**

Water surplus showed, on average, a rate of 34 mm increase per 100 m increase in elevation in the Jhikhu Khola catchment over the study period from 1993 to 2000, and a 114 mm increase in surplus per 100 m elevation increase in the Yarsha Khola catchment in the period from 1998 to 2000 (Figure 3.161). For the same period from 1998 to 2000 the rate in the Jhikhu Khola catchment was 51 mm increase in surplus per 100 m increase in elevation.

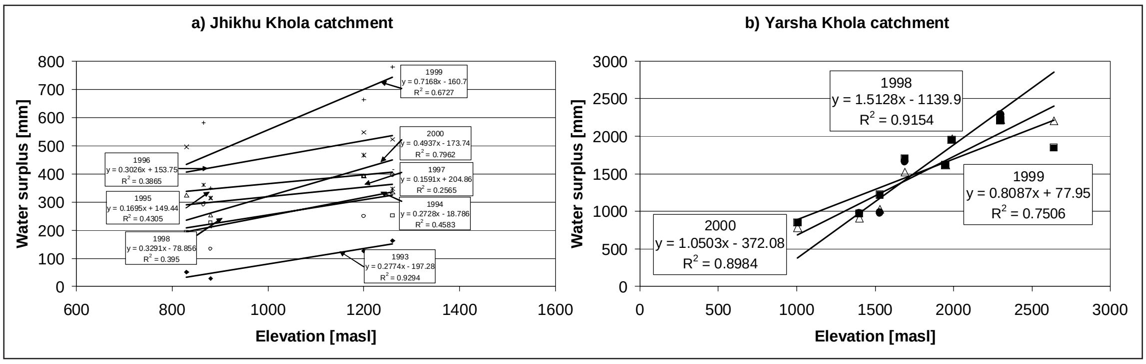


Figure 3.161: **Lapse rates of water surplus a) Jhikhu Khola catchment, b) Yarsha Khola catchment**

The spatial interpolation of the point results from the different sites is shown in Figure 3.162. The water surplus shown in a) increases from the minimum surplus of 250 mm in the lower end of the catchment to 600 mm surplus in the area of Tinghare at the highest point of the catchment. Water deficit peaks on the valley bottom at 450 mm per annum, and gradually decreases with increasing elevation down to 100 mm at the highest point of the catchment.

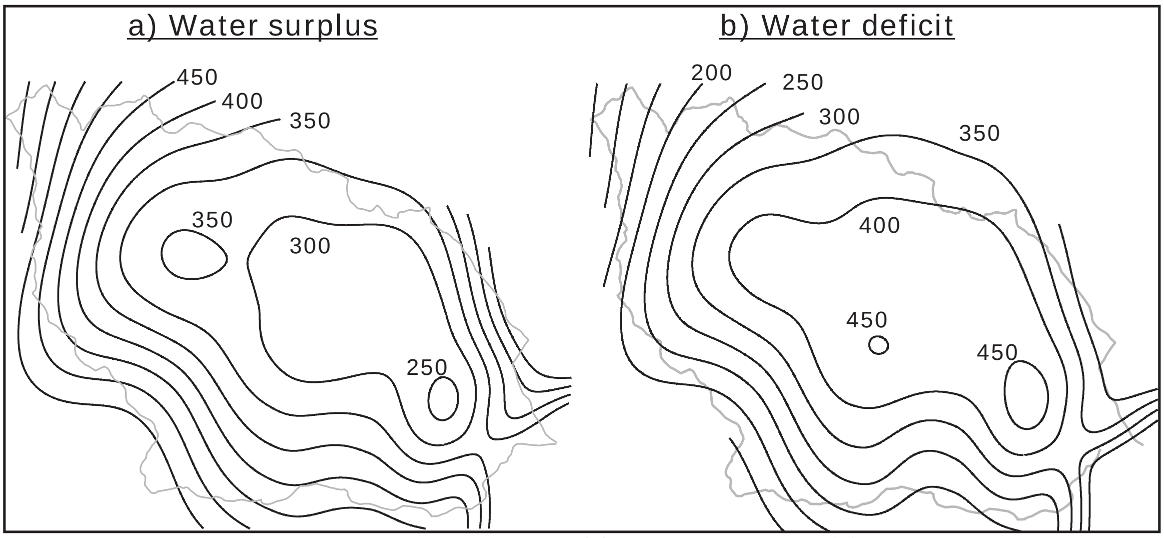


Figure 3.162: **Isolines of average water surplus (a) and water deficit (b) in the Jhikhu Khola catchment**

In the Yarsha Khola catchment, water surplus increases with elevation from a minimum of about 500 mm close to the outlet, up to 3000 mm at the highest point of the catchment in the north-eastern corner (Figure 3.163a). Water deficit peaks at the outlet with about 300 to 350 mm. The lowest deficits are estimated for the highest points along the divide (Figure 3.163b).

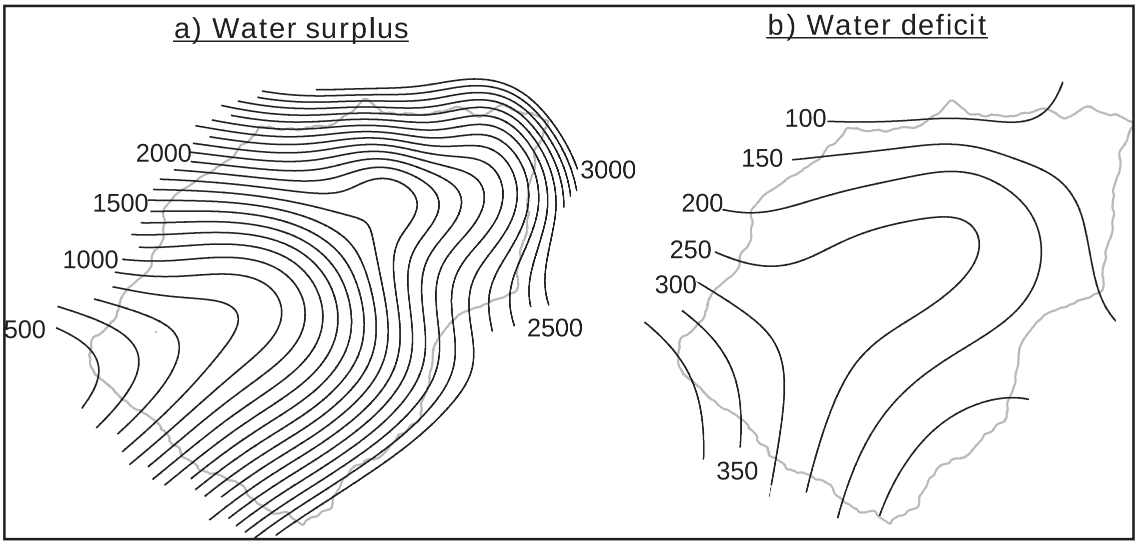


Figure 3.163: **Isolines of average water surplus (a) and water deficit (b) in the Yarsha Khola catchment**

The hydrological water balances of the Jhikhu Khola and the Yarsha Khola catchments with reference to the sites at the outlet are presented in Figure 3.164. The area monitored by Site 1 in the Jhikhu Khola catchment received about 1295 mm rainfall per annum on average during the study period. This amount was depleted by about 869 mm evapotranspiration and 411 mm runoff. This corresponds to about 67% lost through evapotranspiration and 32% lost in runoff. The difference of 15 mm between the measured runoff and estimated evapotranspiration may be due to various reasons, including inaccurate measurement of precipitation or runoff, inaccurate interpolation of rainfall or evapotranspiration, or inaccurate calculation of evapotranspiration. However, the difference is only 15 mm or 1% of the entire rainfall.

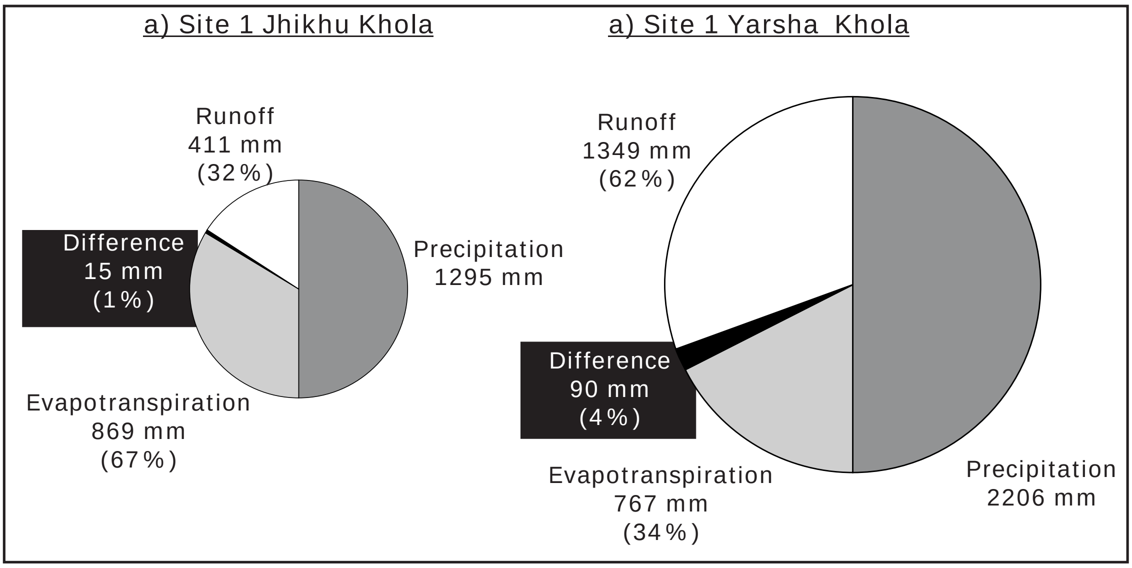


Figure 3.164: **Average hydrological water balance in the Jhikhu Khola (a), and the Yarsha Khola (b) catchments**

In the Yarsha Khola catchment, which receives nearly double the rainfall of the Jhikhu Khola catchment, 2206 mm rainfall was measured on average during the three-year study period. Of this input, 34% or 767 mm was lost through evapotranspiration and 62%, or 1349 mm, through runoff downstream. The errors in measurement, calculation, or interpolation were 90 mm, or 4% of the entire rainfall.

The sub-catchments of the Jhikhu Khola catchment show two different behaviours (Figure 3.165). The sub-catchments of the Lower Andheri Khola, the Upper Andheri Khola, and the Kukhuri Khola receive, on average, between 1250 and 1300 mm rainfall per annum. Out of this between 60 and 70% is lost as evapotranspiration, which corresponds to about 800 to 850 mm. Runoff accounts for about 30 to 40% of losses, corresponding to 400 to 500 mm of runoff. The Kubinde Khola shows a distinctly different pattern, with only 1200 mm of rainfall, out of which more the 75% is lost to evapotranspiration. Runoff therefore accounts for only about 20% or 230 mm. On the basis of the specific discharge of 4.9 $ls^{-1}km^{-2}$, as determined in Section 3.3 for this sub-catchment, the annual runoff corresponded to 156 mm for this catchment. On the basis of rainfall and evapotranspiration, 230 mm of runoff was calculated, which is a difference of 74 mm, or 6% of the entire catchment's rainfall. The differences for the other sub-catchments between calculated runoff and measured runoff were 113 mm (9%) in the Lower Andheri Khola sub-catchment, 237 mm (18%) in the Upper Andheri Khola sub-catchment, and 47 mm (4%) in the Kukhuri Khola sub-catchment. In general, the differences are acceptable, except in the case of the Upper Andheri Khola catchment. Here, the error between the calculated runoff and the measured runoff is too big. Both precipitation as well as evapotranspiration seem to be in the order of the other sub-catchments, which show quite good results. On this basis it must be assumed that the measured runoff is overestimated, and the estimated runoff is used for the calculations below.

Comparing the ratios between runoff and evapotranspiration in the different sub-catchments and catchments, it is evident that the ratio tends to increase with elevation, showing the lowest ratio at Site 13 with 0.24 and the highest ratio at Site 1 in the Yarsha Khola with 1.76, indicating that runoff is

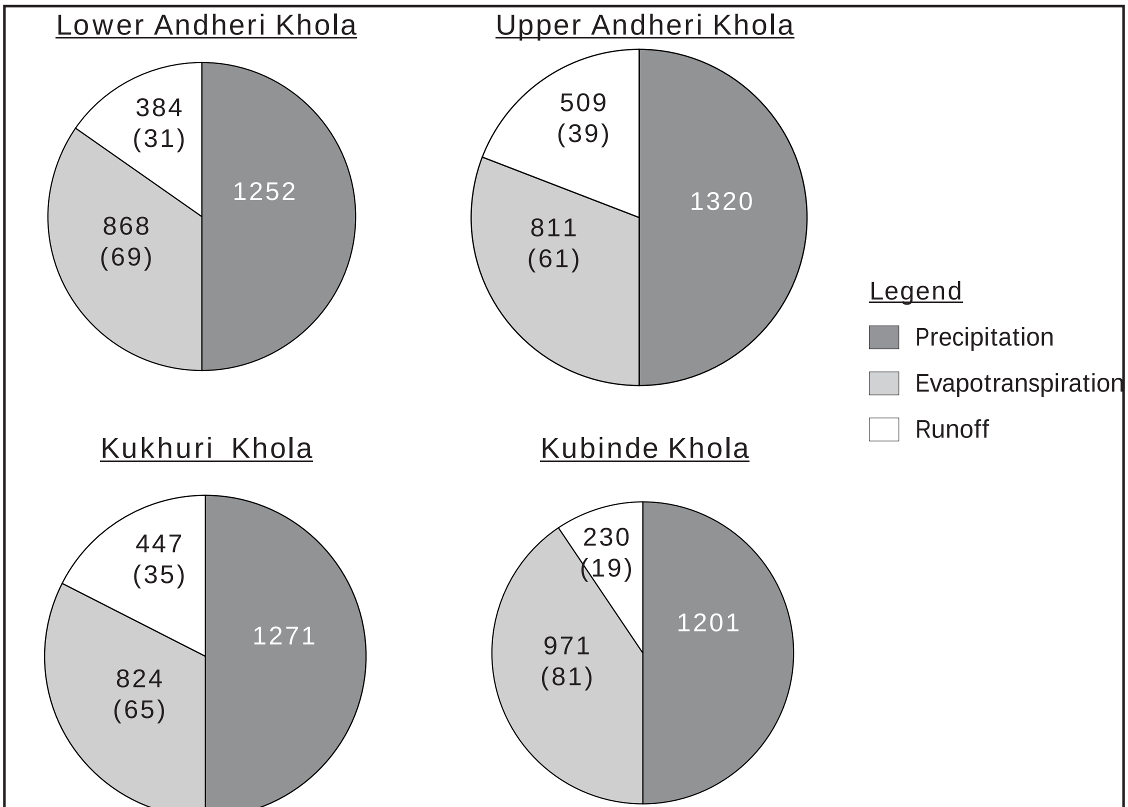


Figure 3.165: **Average hydrological water balance in the sub-catchments of the Jhikhu Khola catchment [mm (%)]**

bigger than evapotranspiration. Site 1 of the Jhikhu Khola shows a ratio of 0.47, the Lower Andheri Khola (Site 2) 0.44, and the Upper Andheri Khola (Site 8) 0.63 and the Kukhuri Khola (Site 7) 0.54.

The following summary can be made.

- Water deficit decreases with elevation at a rate of 27 mm per 100 m elevation increase in the Jhikhu Khola catchment, and 13 mm per 100 m elevation increase in the Yarsha Khola catchment.
- Water surplus increases with elevation at a rate of 34 mm per 100 m elevation increase in the Jhikhu Khola catchment and 114 mm per 100 m elevation increase in the Yarsha Khola catchment.
- Water surplus ranges from 250 to 600 mm in the Jhikhu Khola catchment and 500 to 3000 mm in the Yarsha Khola catchment.
- Water deficit ranges from 450 to 100 mm in the Jhikhu Khola catchment and 350 to 100 mm in the Yarsha Khola catchment.
- In the Jhikhu Khola catchment two-thirds of the rainfall is depleted in the form of evapotranspiration and one-third is lost through runoff.
- In the Yarsha Khola catchment one-third of the rainfall is depleted in the form of evapotranspiration and two-thirds of the rainfall is lost through runoff.
- The sub-catchments of the Jhikhu Khola catchment show a similar ratio to that of the entire catchment, with the exception of the Kubinde Khola sub-catchment, where 80% is depleted by evapotranspiration and only 20% is lost through runoff.

3.7.4 Water accounting

The results of the water accounting analysis presented in Table 3.124 and Figure 3.166 reveal the following.

- Precipitation is the only inflow parameter accounting for the entire gross inflow.
- No storage change was assumed in the period of one year.
- This results in a net inflow of about 1300 mm in the Jhikhu Khola catchment and 2200 mm in the Yarsha Khola catchment.
- Crop evapotranspiration accounts for about 55% of the total process depletion of 886 mm in the Jhikhu Khola catchment.
- In the Yarsha Khola catchment crop evapotranspiration accounts for 356 mm or 46% of the 776 mm process depleted water.
- About 40% or 355 mm accounts for non-process and beneficial depletion by forest in the Jhikhu Khola catchment, and 348 mm or 45% is accredited to this parameter in the Yarsha Khola catchment.
- Only 38 mm, or 4%, is non-process and non-beneficially depleted in the Jhikhu Khola catchment, which includes evaporation from free soil surface and water bodies. In the Yarsha Khola catchment this portion accounts for 8%, or 63 mm.
- All outflows from the catchments are usable as no downstream water rights or needs have to be respected.

The results of this table are visually presented in Figure 3.166. The difference between the two catchments in terms of uncommitted flow as well as the percentage of beneficial depletion is evident. In the Yarsha Khola, more than 60% of the gross inflow contributes to uncommitted flow, suggesting that ample water is available in the catchment for further development. In the Jhikhu Khola this is only about 30% of the gross inflow. It is, however, important to note that these are annual values and include the monsoon flows. During the dry season the uncommitted flow is reduced to a minimum in the Jhikhu Khola catchment and accounts for about 7 mm only in the driest months of March and April. In the Yarsha Khola catchment the uncommitted flow in February, the driest month in this catchment's streams, is 20mm. For a discussion of the driest months in each catchment refer to the end of this section, below.

In terms of the performance of the two catchments based on the values in Table 3.124, the following indicators can be determined (Table 3.125).

Table 3.124: **Water accounting components of the Jhikhu Khola and Yarsha Khola catchments [mm]**

Description		**Jhikhu Khola**		**Yarsha Khola**	
		Total	**Parts**	**Total**	**Parts**
Gross inflow		1295		2206	
	Surface diversion		0		0
	Precipitation		1295		2206
	River inflow		0		0
	Subsurface flow		0		0
Storage change		0		0	
	Surface storage		0		0
	Subsurface storage		0		0
Net inflow		**1295**		**2206**	
Depletion		**886**		**776**	
Process		493		365	
	Irrigation-crop evapotranspiration		484		356
	Municipal and industrial		9		9
Non-process, beneficial		38		63	
	Irrigation-flows to sinks		38		63
Non-process, beneficial		355		348	
	Home gardens, forest		355		348
Beneficial		848		713	
Low and non-beneficial		38		63	
Outflow		**411**		**1349**	
	Committed outflow for downstream water rights		0		0
	Committed outflow for environment		0		0
	Uncommitted outflow	411		1349	
	Utilisable		411		1349
	Non-utilisable		0		0
Available water at catchment level (net – committed – non-utilisable)		**1295**		**2206**	
Available water for agriculture		**931**		**1849**	

Table 3.125: **Water-accounting indicators for the Jhikhu Khola and Yarsha Khola catchments**

Indicator	**Jhikhu Khola**		**Yarsha Khola**	
	Annual	**April**	**Annual**	**February**
Ratio gross/net inflow	1.00	0.42	1.00	0.16
Depleted fraction (gross)	0.68	2.16	0.35	3.28
Depleted fraction (available)	0.68	0.90	0.35	0.62
Process fraction (depleted)	0.56	0.39	0.47	0.29
Process fraction (available)	0.38	0.35	0.17	0.18
Beneficial depletion	0.38	0.35	0.17	0.18
For irrigated agriculture				
Process fraction (available)	0.52	0.69	0.19	0.27

In the Jhikhu Khola catchment:

- sixty-eight per cent of the gross inflow is depleted by different uses;
- all water from the gross inflow is available, therefore the same percentage of 68% is depleted by different uses with reference to available water;
- fifty-six per cent of the depleted water resources is process depleted by crop evapotranspiration, domestic, and livestock use;
- beneficial depletion accounts for more than 65% of the water available;and
- irrigated agricultural process depletion through crop evapotranspiration is responsible for 52% of the depletion of available water.

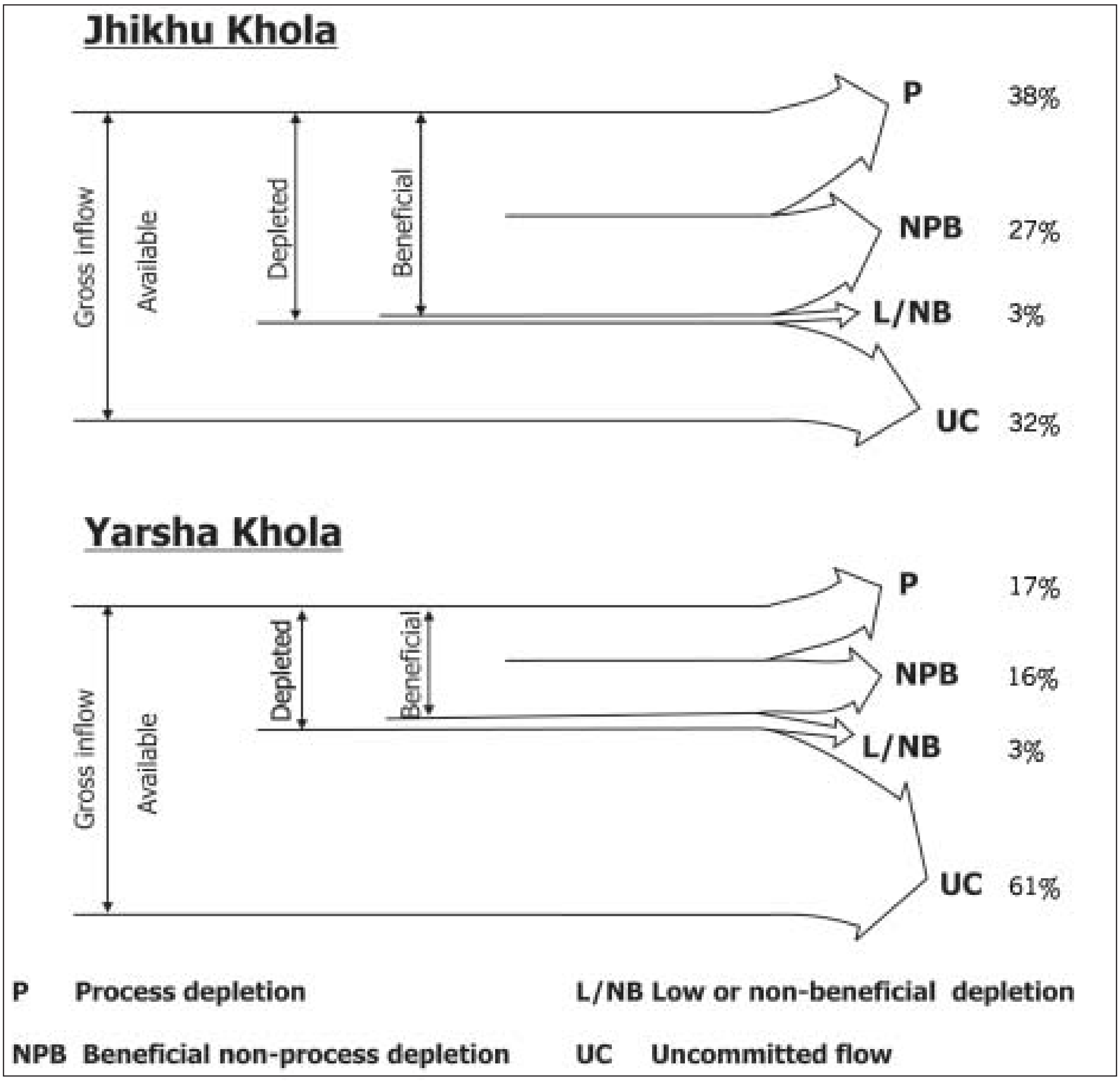


Figure 3.166: **Water accounting diagrams of Jhikhu Khola and Yarsha Khola catchments**

In the Yarsha Khola catchment:

- thirty-five per cent of the gross inflow is depleted by different uses;
- 47% of the depleted water resources or 17% of the available water resources are process depleted;
- beneficial depletion accounts for 32% of the water available in this catchment;
- only 19% of the available water resources are depleted by irrigated agriculture.

The performance indicators were also assessed for the month of April in the Jhikhu Khola catchment and February in the Yarsha Khola catchment, each representing the lowest monthly flows in the respective catchments. In general, there is not enough precipitation to meet the needs of the vegetation and for human consumption. This is shown by the high values above 1 for the depleted fraction of the gross inflow. It was therefore assumed that the total depleted fraction added to the total outflow of the catchment would determine the net inflow. Soil water and groundwater has to substantiate the atmospheric water during this month as precipitation only made up 42% of the net inflow in the Jhikhu Khola catchment, and only 16% in the Yarsha Khola catchment. The storage change within the catchment was then determined by subtracting the precipitation from the net inflow.

Most of the water during this month was depleted, shown by 0.90 for the depleted fraction on the basis of the water available in the Jhikhu Khola catchment. Beneficial depletion accounted for 85% of the available water resources with the remaining depletion caused by evaporation from the soil surface and from natural vegetation not directly beneficial to the residents. In the Yarsha Khola catchment, 55% of the available water resources were beneficially depleted, out of which 27% were accredited to crop evapotranspiration on irrigated land.

The results of this water-accounting exercise show that in both catchments water still needs to be used more efficiently . While during the dry season there is little scope for improvement in the Jhikhu Khola, as there is already a high degree of beneficial depletion with 85% of the available water in this catchment and hardly any uncommitted outflows from the catchment, there is scope for better use of the monsoon waters. Even during the dry season months in the Yarsha Khola catchment there is room to increase the beneficial depletion, as currently there is a high outflow as well as a low fraction of process depletion.

3.7.5 Summary and synthesis

Three different methods were used to assess the water balances in the catchments:

- the climatological water balance,
- the hydrological water balance, and
- the water accounting.

The climatological water balance was used to determine spatial water surplus and water deficit patterns in the catchments. Generally, these parameters show good regressions with elevation, with the highest water deficits on the valley floors and at the outlets, and the highest surplus at the divide and the peaks of the catchments. The Jhikhu Khola catchment shows annual water deficits of 200 to 450 mm, mainly confined to the late winter and the pre-monsoon season months and generally peaking in April or May. The water surplus during the monsoon months may reach 450 mm. In the Yarsha Khola catchment, annual water surplus may reach up to 3000 mm at the highest point of the catchment with values as low as 500 mm at the outlet. The deficits range from 100 mm at the top of the catchment to about 350 mm at the outlet.

The hydrological water balances show a distinct difference between the Jhikhu Khola and the Yarsha Khola catchments. While in the Jhikhu Khola catchment, including three of the four sub-catchments, roughly two-thirds of the precipitation is lost as evapotranspiration and one-third as runoff, in the Yarsha Khola catchment it is the other way round with one third of the precipitation lost as evapotranspiration and two-thirds as runoff. In the low Kubinde sub-catchment, only 20% of the precipitation leaves the catchment as runoff.

The water accounting underlines the importance of agricultural water use in the two catchments. This water use, in addition to the forests, accounts for most of the depleted water resources. While on an annual basis both catchments seem to have adequate water availability on the catchment scale, largely due to the large inflows during the monsoon season, during the driest months in both catchments the storage of water from the last dry season is crucial. From the water available most is depleted during this month in the Jhikhu Khola catchment. Therefore little scope is observed for this period of the year in this catchment. However, the vast amounts of water available during the monsoon season could still be managed more efficiently. PARDYP Phase 3 is looking into some of these aspects. In the Yarsha Khola catchment the water resources can still be used more efficiently, in both the dry season as well as in the rainy season.

For the indices, parameters of the water balances are only appropriate for the Water Poverty Index. Annual water surplus and annual water deficit, as well as the performance indicators of the water-accounting procedure, will be used (see Table 5.1 for a complete list).

3.8 SUMMARY AND SYNTHESIS OF CHAPTER 3

Chapter 3 discussed the main processes related to water availability, flooding, and water-induced land degradation from a water perspective. Each sub-chapter concludes with a summary as well as with a set of potential indicators for the proposed Water Poverty, Flood Generation, and Water Induced Degradation indexes to be discussed in Chapter 5. Below, a brief summary is given of the main findings of the process studies, which is important for later in this study.

3.8.1 Precipitation

- The Jhikhu Khola and the Yarsha Khola catchments show distinct seasonal differences with 75 to 80% of the annual rainfall during the monsoon season and 10 to 15% in the pre-monsoon season. The monsoon season rainfall is most secure with a C.V. of 0.1 to 0.2. The highest seasonal inter-annual differences are shown for the post-monsoon and the winter seasons with C.V.s of 0.5 to 1.2 and 0.8 to 1.6, respectively.
- About 70 to 75% of the days in the Jhikhu Khola catchment have no rain or only traces (< 1 mm). If 15 days without rain follow each other a dry spell occurrs. Annually, about 4 dry spells are expected with an average length of 44 days. The longest observed dry spell in this catchment was 141 days during the study period from 1993 to 2000. In the Yarsha Khola catchment no rainfall or traces occurred only on about 50 to 60% of the days. Annually, about 3 dry spells are expected with an average duration of 42 days.
- In terms of low rainfall, November and December show the highest probability of having no rainfall and the months October to April generally have less than 50 mm.
- Log-Pearson Type III distribution shows a better fit with the annual maximum daily rainfall values than the GEV using the Weibull plotting positions.
- Most of the precipitation parameters follow a rainfall-elevation relationship. This includes annual rainfall amount, rainfall amount during the monsoon and pre-monsoon seasons, erosivity, and number of rainy days. Rainfall intensity however did not show any distinct relationship with elevation.
- The IDF curves previously established by Chyurlia (1984) show similar results for the daily rainfall amounts and aggregates thereof. For data of higher temporal resolution these curves however underestimate the values by about 50% for the two cases in the Jhikhu Khola catchment. This suggests that up to the time of more widespread intensity-duration-frequency information the Chyurlia (1984) approach can be used for daily data, while for six-hourly and higher resolution data the Chyurlia estimates have to be doubled.
- The highest rainfall intensities were observed in the late pre-monsoon or the early monsoon season. Maximum 10-minute intensities reached up to 150 mm/h in the case of the Jhikhu Khola catchment and 175 mm/h in the case of the Yarsha Khola catchment.
- On the basis of the long-term data available for sites in the Jhikhu Khola catchment and sites close to the Yarsha Khola catchment, no trend can be observed in the case of the annual rainfall amounts or in the annual daily maxima. During the study period of eight years an increasing trend was observed.

3.8.2 Evapotranspiration

Due to missing data, evapotranspiration was calculated on the basis of a temperature approach. Potential evapotranspiration rates of 800 to 1400 mm in the Jhikhu Khola catchment and 600 to 1300 mm in the Yarsha Khola catchment were identified. Evapotranspiration at the actual rates were identified as 800 to 900 mm per annum in the Jhikhu Khola catchment and 600 to 800 mm in the Yarsha Khola catchment. Based on this approach it is not surprising that evapotranspiration shows a good relationship with elevation. It is important to note that this parameter of the hydrological balance needs further investigation in future in order to capture the local conditions, including the local crop and vegetation parameters.

3.8.3 Runoff

- Runoff in the two purely rainfed Jhikhu and Yarsha Khola catchments follows the same pattern as rainfall, with most of the runoff occurring during the monsoon season and peaking in August (one month later than rainfall) and showing the lowest flows in February to April. The most variable flows over the years were observed in the pre-monsoon season, namely in the months of March, April, and May.

- The baseflow recession shows an emptying of the storage in the catchments in 300 days in the Jhikhu Khola catchment and in 320 days in the Yarsha Khola catchment.
- In dug wells the biggest reliability in terms of water availability was shown in wells situated close to rivers in river valleys or on the foot slopes adjacent to the rivers. This reliability, however, is compromised by the fast interaction of river water with the groundwater, leading to worse water quality. The other dug wells at risk in terms of quality are the ones located in the vicinity of human settlements rather than close to one or two houses.
- Specific runoff is very low in the Jhikhu Khola catchment with 12 l/s*km^2, which can be attributed to the large pressure on the streamflow through irrigation requirements. In the Yarsha Khola catchment a specific runoff of 40 l/s*km^2 was observed. The specific yield shows a good relation with elevation, which can be attributed to the increasing rainfall with elevation shown above.
- The duration curve in the Jhikhu Khola catchment is very flat, i.e., most of the time the rivers in the catchment are in a low flow condition. The daily discharge with 5% probability of exceedance was determined to be about 53 l/s*km^2. In the Yarsha Khola catchment, baseflow is more sustained and therewith the duration curve shows a steeper slope throughout the year with a daily discharge of 5% probability of exceedance of about 160 l/s*km^2.
- The Log Pearson Type III distribution showed the best fit with the annual maximum daily flows. A 25-year return period discharge event was estimated to be about 40 m^3/s at the outlet of the Jhikhu Khola catchment.
- No particular trend could be observed on the basis of the discharge data, although personal observations suggest a clear decrease in low season flow. The reason for this is the low flow insensitivity of the hydrological stations as well as the instable cross-sections at places.

3.8.4 Event analyses

- Rainfall could be grouped into four clusters according to rainfall volume, intensity, and duration: minor, medium, high intensity, and large events. The cluster limits are compiled in Table 3.93 for both catchments, which showed a very similar response. These clusters showed a good relation to the events observed on the erosion plots as well as at the outlets of the sub-catchments.
- For runoff generation at the plot scale, maximum 60-minute rainfall intensity contributed the most information content as shown with the highest correlation of this parameter with runoff. Maximum 10 and 30-minute intensity showed lower correlations.
- The relationship between the clusters and the runoff observed on the erosion plots suggests infiltration excess runoff generation mechanisms on degraded land, while on the agricultural land saturation excess runoff generation mechanisms are suggested. Grassland observed both saturation as well as saturation excess runoff generation.
- The behaviour of the degraded erosion plots showed an overall good relation with the flood behaviour at the sub-catchment and catchment outlets, suggesting that runoff generation mechanisms as observed on the plots are most likely to contribute largely to flood events rather than the mechanisms as observed on the agricultural land.
- For flood peaks the total area of grassland and degraded land has an enhancing effect, while the area of cultivated land, irrigated land in particular, seems to dampen the flood wave.
- No distinct reason for the generation of high flow events could be established on the basis of the rainfall data, except the combination of high rainfall intensities with medium event rainfall volume, or prolonged events with large rainfall volume and only medium intensities. The following thresholds were determined:
- for events throughout the catchments, a total rainfall volume of more than 25 mm and maximum 30-minute intensities of more than 10 mm/h are required;
- for events concentrated on a part of the catchment the total rainfall event volume has to be more than 10 mm with a maximum 30-minute intensity of more than 20 mm/h;
- Antecedent precipitation did not show any particular effect on the size of the events.

3.8.5 Sediment mobilisation and transport

- The surface soil erosion rates from the agricultural land are in line with other studies and show only a small deviation from the natural soil development. It is therefore suggested that surface soil erosion on agricultural land is only a marginal issue.
- More than 75% of the annual soil loss on these terraces occurs in 5 to 10% of the annual events.
- Surface erosion and gullying from degraded land are serious problems in both terms of degrading resources in the catchments as well as in terms of downstream sediment enrichment.
- On all plots rainfall intensity and rainfall volume played a major role in soil mobilisation. On agricultural plots the vegetation cover additionally contributed to soil loss or soil conservation. On degraded land this soil cover was missing. On grassland soil loss was negligible. Antecedent moisture conditions did not show any particular correlation with soil loss.
- Surface erosion only accounts for a part of the total sediment load, while the importance of streambank erosion is identified, but not quantified. This aspect of the sediment budget was touched upon by Carver (1997), but needs further detailed investigation.
- An interesting relationship emerged between different land uses and sediment loads. Grassland in a catchment showed a positive trend with sediment load, while rainfed agricultural land showed a decreasing trend. These relationships are interesting in the light of the plot results, where grassland shows hardly any soil losses, while rainfed land shows medium soil losses. Possible reasons for this are discussed in Section 3.5.
- The construction of a highway through the upper parts of the north-facing slopes in the Jhikhu Khola catchment from January to March 2000 had a considerable impact on the sediment regime of the Kukhuri Khola, the Upper Andheri Khola, and the Lower Andheri Khola. The sediment concentrations in these streams increased in the order of magnitudes from 1999 to 2000 and the total sediment load increased by 300 to 600%. No impact could be shown at the scale of the entire Jhikhu Khola catchment.

3.8.6 Water demand and supply

Currently the domestic water supplies stand at about 4 mm/year in the Jhikhu and Yarsha Khola catchments. This represents very low daily water demand rates of only 20 to 25 l $\text{person}^{-1}\text{day}^{-1}$. Agricultural use stands at about 250 to 300 mm for irrigated land, and 300 to 350 mm for rainfed agricultural land (these values are calculated on the basis of the entire catchment area). Livestock water demands are between 4.5 and 6 mm/year. This demonstrates the greater demand for water for agriculture in relation to domestic water requirements. Water supply is organised on both a community and private basis, both for domestic as well as for agricultural purposes. With the decay of well-functioning community structures, water supply has become a major issue in the catchments. In addition, water quality is increasingly becoming a major concern.

3.8.7 Water balances

- On the basis of the climatological balances the Jhikhu Khola catchment displays water deficit conditions for most of the year (eight months from October to May) with a surplus during the monsoon season. In total, a water deficit of about 200 to 400 mm was calculated over these months. In the Yarsha Khola catchment the deficit ranged from 100 to 300 mm from November to April. The highest deficits were observed in both catchments at the outlet and on the valley floor, while the highest surpluses were seen along the divide.
- Hydrologically, the pressure on the Jhikhu Khola catchment can be seen by the high proportion of precipitation lost by evapotranspiration. Only about 35% of the annual precipitation leaves the catchment as runoff. In the Yarsha Khola catchment, runoff accounts for about 65% of the total annual precipitation.
- The most important users of water in both catchments are agriculture and natural and planted forests. Although water resources are sufficient every year in both catchments, there is no scope for increased water use in the Jhikhu Khola catchment during the dry season. In the Yarsha Khola catchment there is still scope for increased water use by agriculture or any other sector.

SYNOPSIS 3: UNDERSTANDING THE RELEVANT PROCESSES

The process understanding in these catchments firstly builds on the documentation of known facts for the middle mountain catchments, which have not been adequately documented and are important for the later chapters of the study. Additionally, new insights into the processes are provided. The main points to keep in mind are as follows:

- **all water resources are highly seasonal and during the critical times highly variable;**
- **there are extended dry spells with no rain for 40 to 50 days and up to 100 days;**
- **there is a high frequency of no rain or little rain in 8 out of 12 months;**
- **evapotranspiration peaks in the season where flows are lowest and rainfall is very variable;**
- **climatological water balances suggest 7 to 8 months water deficit per year with considerable surplus during the monsoon season months;**
- **very intense rainfall events can occur in any season, but are most frequent during the monsoon season;**
- **the IDF curves by Chyurlia (1984) largely underestimate the short period rainfall intensities of different return periods;**
- **high-volume events mostly occur during the monsoon season;**
- **rainfall intensity and rainfall volume of an event are decisive for both flood generation and surface sediment mobilisation;**
- **in general, good relations are observed between water resources' components and elevation excluding rainfall intensity and rainfall volume during the dry season months;**
- **highest runoffs are observed on degraded land followed by grassland and agricultural land;**
- **highest soil losses are observed on degraded land followed by agricultural land and grassland;**
- **surface soil erosion from rainfed agricultural land balances natural soil**
- **development and contributes to improved fertility of downstream irrigated land;**
- **floods in catchments are positively related to the area of grassland and degraded land, while a negative relationship is observed with cultivated land;**
- **streambank erosion may be of much more importance than assumed so far;and**
- **the Jhikhu Khola catchment is already under considerable pressure, as shown by the proportion of evapotranspiration losses in comparison to the runoff. In the Yarsha Khola catchment, intensification of water use can still consider large unused water resources.**

Overall, local residents perceive water shortages for both domestic and agricultural demands. Water quality is becoming an increasing concern. This is in contrast to the observed water supply expressed in service levels, according to which 45 to 60% of the population should have a good water supply. The main issue in this context is the high microbiological contamination of the entire water supply. Another factor related to this is the long distances to the water sources, which put major stress on women's workload. The water supply for agricultural use is mainly constrained by the seasonality of rainfall as well as the large number of users and the often inefficient water distribution in unlined and open irrigation canals. The intensively cultivated areas not only require large amounts of water, they are also a source of agrochemical pollution.

In summary, these processes suggest that:

- **appropriate water management has to address the issue of seasonality;**
- **dependency on rain as a direct water source for agriculture has to be reduced;**
- **farming should be considered beneficial for flood protection and therefore abandoning discouraged;**
- **soil conservation will have to pay more attention to farmers' other problems in order to be successful;**
- **more attention should be paid to stream banks as well as the road network for soil conservation;**

- **improvement of water supply service levels is crucial, which suggests more decentralised water supply schemes to reduce distances and improve management;**
- **the impact of high agrochemical inputs should be studied, and deserves better process understanding and improved and reinforced legislation;**
- **microbiological contamination should be reduced, which could be achieved by improved recharge and source catchment management as long-term methods or simple and cheap treatment methods such as SODIS;and**
- **there should be a focus on increasing irrigation efficiency with alternative irrigation methods for vegetable crops, sprinkler for potatoes, and potentially water saving approaches for staple crops: e.g., system for rice intensification (SRI) in early rice.**

Chapter 4: Impact of Future Scenarios

"Model results are only as reliable as the model assumptions"

(S. Sorooshian and V.K. Gupta)[1]

This chapter first presents a review of modelling exercises conducted in the HKH region. For the prediction of future parameters important to water availability, flood generation, and sediment transport in the catchments — water balance and streamflow in particular — three models were applied to the data observed from the Jhikhu Khola catchment. The models are briefly described and the calibration of all models is discussed. Three scenarios are presented and their impact on the water balance, water availability, and the streamflows estimated.

It is important to note that the calculation of scenarios is in its preliminary stages and will receive further attention in the coming Phase 3 of the project. Therefore the results below should be considered initial trials with first successes and failures.

In a time of great consciousness about change, the desire to predict the future is felt increasingly. Unprecedented changes are likely to occur, such as climate change (IPCC 1998), globalisation (Jodha 2000; in print), or the collapse of the natural resource base due to population pressure in many parts of the world (Allen 2000). The impact of these changes on the hydrological cycle and processes cannot be foreseen, due to the limitations of hydrological measurement techniques (Beven 2001). Such an impact can only be simulated and approximated by the use of various techniques. At the same time, computer power has increased many times over in recent decades and can now support complex systems analyses. Complex systems have to be described in order to minimise haphazard assumptions (see citation above).

Over the last century a large amount of data has been collected which can provide a firm underpinning to these analyses. This is certainly correct for large parts of the developed world. For developing countries, however, the database for this kind of analyses is limited and further marginalised in the mountainous parts of these countries. A number of global water availability scenarios have been presented (e.g., Alcamo et al. 2000; Shiklamonov 2000; Seckler et al. 1998) and were briefly discussed in Chapter 1. On a smaller scale, presentations of the likely impact of changes in driving forces, such as climate, population, or policy decisions in this region, have been detailed in numerous studies. Some of these studies with respect to hydrological modelling are discussed below.

Note: The modelling was only carried out in the Jhikhu Khola catchment, mainly for reasons of data availability. The first year will have to be set aside in order to be able to simulate the boundary conditions. For statistical reasons, Sorooshian and Gupta (1995) suggest that two to three years of calibration data are sufficient. This suggests that at least three complete years of data and a first monsoon are required, i.e., 1997 (monsoon) to 2000. An additional one to two years are then required for the validation of the models. With the availability of the 2001 and 2002 data the models can also be applied in the other catchments.

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[1] Sorooshian and Gupta (1995)

In order to assess the impact of possible future developments (here called scenarios) on water availability, flood generation potential, as well as to a limited extent sediment transport, three case studies in the form of three scenarios are presented. These scenario analyses by no means try to be representative, but merely strive to show possible ways of discussing up-coming issues in the PARDYP catchments and potential ways of treating forecasts of future developments.

4.1 METHODS OF ASSESSMENT

The approaches for assessing possible future developments in this study are based mainly on catchment modelling (see next section) as far as the impact on runoff and discharge is concerned. In terms of water demand, scenarios from the literature were extrapolated using local water demand figures for present and projected values taking into account increased living standards and possibilities for the rural population in the catchments.

4.1.1 Catchment modelling

Hydrologists have a long tradition of working with mathematical models for a variety of purposes (Jayatilaka and Connell 1995). In over one century, different models for different applications were developed. Ibbitt and McKerchar (1992) describe the role of models in hydrology as tools to describe hydrological processes and predict the system response to changes. One of three basic purposes for modelling according to WMO (1990) is prediction, planning, and design. For these the long-term prediction of hydrological parameters relevant to the planning process, including the extrapolation of the observed conditions or the prediction in view of changes (e.g., climate, land use), and the actual planning and design of the hydraulic structures are mentioned. Linsely (1982) includes such applications as record extension, operational simulation, data fill-in, and data revision under this category. Hydrological models present the opportunity to extend the range of hydrological research. At present, the influence of climate change or the El Nino/La Nina phenomenon on hydrological processes is of major interest to hydrological model users. The effect of land-use change has been the topic of a variety of model applications in the past for research. Models are also frequently employed in process studies.

4.1.1.1 Review of catchment modelling in the HKH

Many models for different purposes have been developed worldwide over the last decades. Most of these models were developed in areas completely different to the mountain ranges of the HKH. Jain (1990) discusses a number of models which were applied and which seem to be appropriate for mountainous catchments. He concludes that the use of models in the mountains has been limited due to limited access to data, either because of non-availability of data or problems typical of mountain areas. He sees a major opportunity in the improvement of remote sensing and GIS technology. He also cautions on the application of models without prior testing of the models for given conditions. He further recommends the development of a GIS rainfall-runoff model valid for Indian mountain catchments.

The trend to date has, however, been the application of existing models from other regions of the world. Many researchers have applied models to HKH mountain catchments. A number of recent modelling studies in the HKH are reviewed below.

Shah et al. (1998) used the UBC catchment model to simulate the flows into the Tarbela and the Mangla Dam in the Upper Indus Basin. The results, however, were not satisfactory due to lack of data. The same model was used by Singh (1998) and Singh and Kumar (1997) to simulate the hydrological response of the Spiti River basin, a tributary of the Sutlej, under changed climatic scenarios. The main reason for using the UBC catchment model was its capability to increase and decrease the accumulation of snow in a mountainous basin with only sparse meteorological data. The UBC model was also used for the Sutlej River in a study described by Singh and Quick (1993) and Quick and Singh (1992). They concluded that the complexity of the precipitation distribution in the Himalayas was a major problem during modelling. They argued that a semi-distributed approach dividing the catchment into sub-catchments with similar precipitation would give better results. Shakya (1997) investigated the impact of forest clearing on the hydrological behaviour of the Khageri River in Chitwan district in Nepal by applying the UBC catchment model. The results obtained are very interesting but, as the author admitted, they are biased under the given conditions with the lack of data from the catchment itself.

The Sacramento soil moisture accounting model (SAC-SMA) was used by Buchtele et al. (1998) to investigate the sensitivity of runoff towards environmental changes. This study was carried out in three experimental basins of the Nepal Himalayas: the Modi , the Langtang , and the Imja Khola. It showed that the selected modelling approach was adequate and able to simulate runoff in the complex environment of the Himalayas.

Braun et al. (1993) implemented the HBV/ETH model on the Langtang Khola. After further measurements of key parameters and sensitivity analysis, Grabs et al. (1998) applied the conceptual model in the same basins as above for the prediction of flow. The model successfully simulated the hydrograph of the rivers. The original HBV was used for the modelling of the inflow catchment into the Tarbela dam in Pakistan.

Parida (1998) applied the SRM model in the Goriganga catchment of the Middle Himalayas in India to estimate snowmelt runoff for successful planning and design of water resources projects. Kumar et al. (1993) applied the model on the Beas and the Parbati basins in Himachal Pradesh, India. They concluded that it is useful, especially in a basin with limited meteorological and hydrological data. Seidel et al. (2000) presented the application of SRM for the Ganges and Brahmaputra river basins and concluded that the model was able to handle these very large basins with acceptable accuracy, although some of the data were only available on a monthly basis.

Boorman et al. (1998) developed a rainfall-runoff model on the basis of the probability distributed storage principle as presented by Moore (1985). The model successfully simulated the general flow regime and the wetting up during rainfall events of the monitored catchments in the Lhikhu Khola catchment. Towards the end of the event the flow is underestimated, however.

In Bangladesh, which is affected by the flow behaviour from the Himalayan rivers, MIKE 11 was successfully used for flood modelling (DHI 1994; Paudyal 1994). A new version of MIKE11 is now used operationally in Bangladesh for flood forecasting.

The Xinanjiang model is widely used in China. According to Zhao et al. (1995), the model was successfully applied for many parts of China except the Loess plateau. The applications included river forecasting on the Yellow , the Huai , and Yangtze rivers with real-time adjustments in some cases. It also included water resources' planning, design flood estimation, and water quality accounting. Recently the model was used for macroscale hydrological modelling.

The Tank model was used in a study investigating the impact of land-use changes on the hydrology of headwater regions in Uttar Pradesh, India (Chander and Gosain 1995). It was also applied in other mountainous areas of India like the Western Ghats in South India. Ramasastri (1990) concluded that it is suitable for Indian catchments.

SHE has been extensively used in India (Refsgaard et al. 1992; Jain et al. 1992).

In recent years, the importance of GIS in hydrological modelling has increased. Several studies have been conducted using GIS in combination with different hydrological models. NIH (1998) applied the German NASMO model in the Western Ghats. The NASMO model uses the SCS curve number method for calculation of direct runoff. They concluded that this approach could be applied for other Indian catchments, therefore including catchments in the Himalayas. A study was recently completed applying GIS in connection with the SCS curve number method. Pradhan (2000) modelled daily runoff in the Bagmati River at Sundarijal. He concluded that this method was not satisfactory. A similar study was conducted by Kumar (1997) in the Bandel catchment. Another model, which has been often associated with GIS, is the TOPMODEL (e.g., NIH 1997).

For the assessment of water availability in the Sutlej River in India, Jain et al. (1998) used the Canadian SLURP catchment model. They have shown that the combined use of GIS derived input parameters and the model gave good results. Further studies on the model application in the area will be conducted for final comments.

The review of the modelling approaches in the HKH can be concluded as follows:

- data availability is a major constraint for the successful application of rainfall-runoff models in mountainous regions;
- many models have been successfully applied but a comparison of different models under the same conditions is widely missing;and
- distributed models seem to be more appropriate for mountainous conditions due to the highly variable and heterogeneous conditions in mountain areas; however, the data requirements are often not appropriate.

NIH (1988) lays down certain criteria for models to be applicable in the mountain regions of India. The model should have the capability to estimate snowmelt and incorporate it into the system. It should also be physically based on, or its parameters should be derived from, regionalisation. Interception has to be an important parameter, as many mountainous catchments have good forest growth. Distributed models seem to be better suited for local conditions.

4.1.1.2 The models selected

For the purpose of the catchment modelling in this study three different models were applied and their outputs compared (Table 4.1): the UBC Catchment model (Quick 1993); the Tank model (Sugawara 1995); and the PREVAH model (Gurtz et al. 1997). The selection of these models was according to:

- availability and support;
- applicability to mountainous terrain;
- different levels of conceptualisation; and
- different levels of spatial aggregation.

Table 4.1: **Compilation of the main characteristics of the models used**

Model name	Causality	Space distribution	Time resolution	Remarks
UBC	Deterministic conceptual	lumped	1 hour to 24 hours	adapted for limited data availability in mountainous areas
TANK	deterministic conceptual	lumped	24 hours	includes genetic optimisation algorithm
PREVAH	deterministic conceptual	distributed	1 hour to 24 hours	

4.1.2 UBC Catchment Model

The lumped continuous UBC catchment model was developed by the Mountain Hydrology Group of the University of British Columbia, Vancouver/Canada, to describe and forecast the catchment behaviour of mountainous areas (Quick 1993). This introduced several important design constraints because data in such regions are usually scarce, particularly at higher elevations. A major design consideration resulting from this was to provide the model with the ability to interpret meteorological data at a point in terms of basin-wide conditions.

The UBC model operates using the input of hourly to daily meteorological data, including maximum and minimum temperatures and precipitation. The basic structure of the model segregates the catchment into bands according to the elevation. The model simulates daily outflow from a catchment, soil moisture content, soil and groundwater storage, and information on contributions to runoff from different sections of the catchment, including surface and subsurface components. Given continuous meteorological input data the model will operate continuously, accounting and depleting the snow-pack and producing estimates of stream-flow. The model includes the following components (Quick 1995; a flow chart of the model is included as Appendix 4.1):

- *Meteorological sub-model*
  This module distributes the input data to all elevation bands on the basis of a temperature lapse rate algorithm and an algorithm for precipitation. The latter is divided into an algorithm describing purely the orographic enhancement of precipitation with elevation, and another algorithm modifying precipitation for variations in temperature.

- *Soil moisture sub-model*
  In this module, the evaporation losses and the subdivision of rainfall and snowmelt into four components of runoff (fast, medium, slow, and very slow) are controlled. The central control parameter is the soil moisture deficit (Figure 4.1). When this deficit reaches zero, the catchment reaches its maximum runoff potential (with the exception of flash and fast runoff, which depend on a defined precipitation intensity in the case of flash runoff or the impermeable area identified in the catchment in the case of fast runoff). Fast runoff generation is first priority, followed by soil moisture retention and evapotranspiration. When the soil moisture deficit is satisfied, groundwater percolation occurs. Only if excess moisture is available does interflow occur.

- *Catchment routing sub-model*
  The different components of runoff are subjected to a routing procedure based on the concept of linear storage reservoirs. The fast and medium runoff components are subjected to a cascade of reservoirs essentially identical to the unit hydrograph. The slow components of runoff use a single linear storage.

- *Routing sub-model*
  This module combines the different catchment flows and routes these flows through a river, lake, or reservoir system.

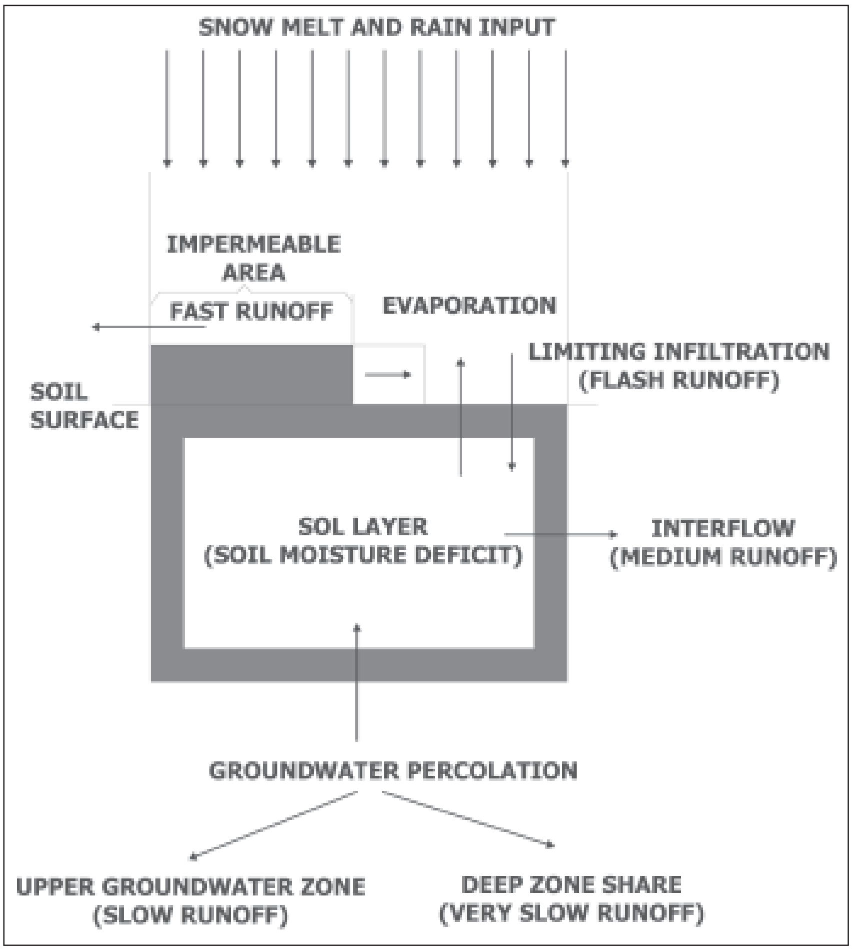


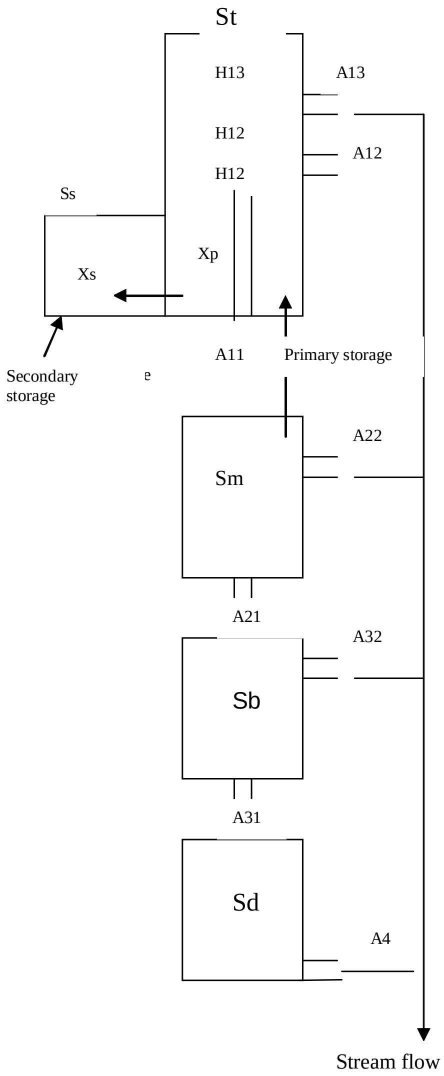
Figure 4.1: **Soil moisture model in UBC catchment model** (from Quick 1995) For more details refer to Quick (1993) or Quick (1995).

Model applications

A number of applications of the UBC model were referred to in the review of modelling in the region above. Further applications are listed in Quick (1995). In general, these applications were for the purpose of short-term river flow forecasting or estimating seasonal runoff volumes and the probable pattern of runoff for the purpose of supporting reservoir operation (Quick 1995). The model has also been used for the extension of time series, when streamflow records did not exist, but for which meteorological data have been available. Geographically, the model has been applied to catchments in Canada (British Columbia in particular) and catchments in South Asia.

4.1.3 Tank Model

The Tank model was originally developed by Sugawara (1961) and has since then undergone a lot of development. In general, the Tank model is very simple and is composed of a defined number of linear storages laid vertically in series with defined outputs from the side and bottom outlets. For the present study, the Tank model as coded by Bastola et al. (2002) was used. This model is a continuous, lumped, deterministic model and comprises four vertical tanks with the provision of primary and secondary storage (Figure 4.2.). The top and the second tank contribute to surface runoff, the third and fourth tank to base flow. Input data required are precipitation and temperature. The model uses automatic optimisation algorithms for calibration and therefore reduces time requirements to a minimum. For further details about the model used in this study refer to Bastola (2002) and to Sugawara (1995) for information on the Tank model in general.



Explanations:

St	Storage of the top tank
Ss	Storage of the secondary storage
Sm	Storage of the middle tank
Sb	Storage of the bottom tank
Sd	Storage of the lowest tank
Xp	Initital storage of primary storage
Xs	Initital storage of secondary storage
A11	Bottom outlet coefficient, top tank
A12	Middle outlet coefficient, top tank
A13	Top outlet coefficient, top tank
A21	Bottom outlet coefficient, middle tank
A22	Side outlet coefficient, middle tank
A31	Bottom outlet coefficient, bottom tank
A32	Side outlet coefficient, bottom tank
A4	Bottom outlet coefficient, lowest tank
H11	Bottom outlet level, top tank
H12	Middle outlet level, top tank
H13	Top outlet level, top tank
H2	Side outlet level, middle tank
H3	Side outlet level, bottom tank

Figure 4.2: **Schematic diagram of the Tank model** (from Bastola 2002)

4.1.3.1 Model applications

The Tank model has been widely used in the mountainous areas of Japan, the model's country of origin, but it has also been applied to basins in Asia, Africa, Europe, and the USA, giving good results (Sugawara 1995). The model has also been applied in the context of comparative studies of the conceptual models used in operational hydrological forecasting (WMO 1975) as well as for real-time forecasting (WMO 1992).
Several studies have applied the Tank model with optimisation algorithms, e.g., Bastola et al. (2002), Kim et al. (2001).

4.1.4 PREVAH Model

The spatially distributed **P**recipitation-**R**unoff-**EVA**potranspiration-**H**ydrotope (PREVAH) model was developed at the Institute of Geography at the Federal Institute of Technology (ETH) in Zurich (now the Institute for Atmospheric and Climate Science, ETH Zurich) with the aim of representing the heterogeneous characteristics of mountainous areas using parameters as far as possible based on physical principles (Gurtz et al. 1999).

PREVAH uses the hydrological response unit (HRU) or hydrotope approach (Ross et al. 1979; Engel 1996; Moore et al. 1993; Fluegel 1997; Zappa 2002) to represent the distributed catchment information. It basically overlays five layers of information to generate the HRUs, including the drainage network and catchment area, meteorological input data, topography, land use and vegetation, and soil and geological characteristics (Gurtz et al. 1999). The HRUs are generated with the help of the software package **HY**drological **RE**sponse **U**nit – **ETH** (HYREUETH) developed by Zappa (1999) for fast pre-processing of spatial information.

Temporal and spatial interpolation of the meteorological data is carried out by altitude dependent regression (ADR) and inverse distance weighting (IDW), applying the interpolation tool of WaSim-ETH discussed in further detail in Schulla and Jasper (1999). This tool is of particular importance for the accurate estimation of the input variables, as methods such as Thiessen often misrepresent the rainfall input in mountainous catchments.

The model's response is governed by five linear storages, including snow cover, interception, soil moisture, upper runoff, and lower runoff storages. The following modules are included in PREVAH (for more details, including the equations, refer to Zappa 2002; a flow chart of the model is included as Appendix 4.2. [only the modules relevant to this study are described]).

- *Adjustment of precipitation*
  The precipitation input can be tuned by adjusting the measured precipitation. This adjustment allows compensation for measurement errors and mistakes in the precipitation interpolation (Sevruk 1986).

- *Evapotranspiration module*
  PREVAH's evapotranspiration module offers different equations to calculate water losses through evapotranspiration: the Penman-Monteith equation (Monteith 1975); the Wendling equation (Wendling 1975); Turc equation (Turc 1961); and Hamon (1961). The Hamon approach was used for this study due to the non-availability of many required parameters for the Penman-Monteith approach. Hamon's equation is based only on mean daily temperature. For Wendling and Turc air temperature and global radiation are also required.

- *Snow accumulation module;* not required in the Jhikhu Khola catchment.
- *Snow melt module;* not required in the Jhikhu Khola catchment.
- *Glacial melt module; not* required in the Jhikhu Khola catchment.
- *Interception module*
  This module is based on Menzel (1997) where the interception storage varies with the vegetation type and water from this surface evaporates at the potential rate as long as there is sufficient humidity in this reservoir.

- *Soil module*
  The soil module was adapted originally from the HBV-model (Bergstroem 1976), which was further developed by Jensen (1982). At the conceptual level it consists of the plant-available water storage in the aeration zone of the soil (SSM; see Figure 4.3), which provides the link between the loss of water by evapotranspiration (E) and runoff (DSUZ). The inflow to this storage is provided by rainfall (P) that reaches the ground and snowmelt (SRM). The storage's capacity (SFC) is dependent on the soil depth, the effective root depth, and the plant-available field capacity of the soil. The moisture that is not able to evaporate or be withheld as soil moisture flows to the upper zone of the runoff generation module (DSUZ).

- *Runoff generation module*
  The model's structure provides three different flow mechanisms. The fastest runoff is fast surface runoff (RS), usually associated with an impervious surface, saturated overland flow, and Hortonian overland flow. This is followed by interflow (RI), governed mainly by the soil characteristics in the catchment. Finally, the slowest flow is the base flow (RG) generated by a combination of two linear groundwater reservoirs with a fast (SG1) and a delayed component (SG2). The percolation from the upper runoff storage (SUZ) to the groundwater storages is governed by the deep percolation rate (PERC).

PREVAH always runs at a one-hour time step (Zappa 2002). However, if only daily input data are available, 24 identical values are assumed. The model is described in more detail in Gurtz et al. (1997) and Zappa (2002) (see also Figure 4.3).

4.1.4.1 Model applications

The model has been applied in different studies under different conditions.

- Gurtz et al. (1997) and Gurtz et al. (1999) modelled parameters of the hydrological cycle in the Thur river basin, a pre-alpine basin in north-eastern Switzerland. Gurtz et al. (1997) aimed to study the impact of different climate variations on the hydrological cycle. The model successfully simulated possible changes in the behaviour of precipitation, snowfall, evapotranspiration, discharge, high and low flows, and different storages. Gurtz et al. (1999) mainly focused on discharge and evapotranspiration.
- Zappa (1999) applied the model to simulate the discharge of the Verzasca River, a snow and rainfed mountain river in southern Switzerland. In this study it successfully simulated the water balance and selected flood events.
- Vitvar et al. (1999) studied the water residence times in a small pre-alpine catchment of north-eastern Switzerland, the Rietholzbach catchment.
- Zappa (2002) used PREVAH to model hydrological systems of different spatial scales, including catchments of 3 to 1700 km^2 in the Swiss Alps, the Volga source area in Russia, and the whole of Switzerland. While in the different Swiss catchments the evaluation of single modules and the performance of the model in various conditions and smaller scales were targeted, the performance in simulating different water balance components at the large scale was evaluated in the simulation of the whole of Switzerland. In the Russian experiment, PREVAH was used in connection with regional climate (RCM) and global climate models (GCM), which provided the meteorological input data.

4.2 APPLICATION OF THE MODELS TO THE PRESENT

For calibration[2] and validation[3] of the catchment models, they were firstly applied to the current conditions as observed in the Jhikhu Khola catchment. For this purpose the daily data from 1996 to 1998 were used for calibration of the models (Table 4.2). The data from 1999 and 2000 were then used for validation. The selection of years was based on the analyses of Bastola (2002). The data from the years 1993, 1994, and 1995 had shown that the efficiency calculated by trial simulations with the Tank model of independent years was low. For the years 1996 onwards, the efficiency improved with

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[2] **Process of appropriate parameter selection (Sorooshian and Gupta 1995)**

[3] **Process of parameter verification on a new dataset previously not used in the calibration procedure (Sorooshian and Gupta 1995)**

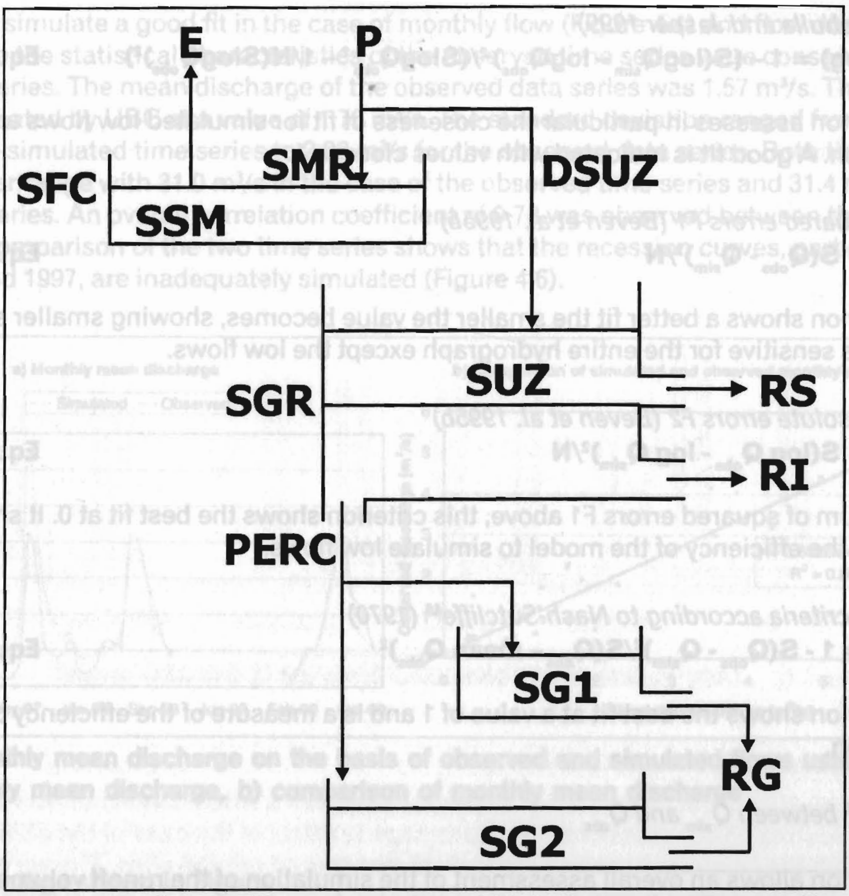

Figure 4.3: Schematic representation of the soil and runoff generation modules of the PREVAH model (all abbreviations discussed in the text; adapted from Zappa 2002)

Table 4.2: **Data used for modelling**

	1993	1994	1995	1996	1997	1998	1999	2000
Not used	X	X	X					
Calibration				X	X	X		
Validation							X	X
Base for simulation					X	X	X	

a problem of water balance calculation in 1999. The reason for this problem is assumed to be the exceptional event in October where, depending on the site, between 8 and 12% of the annual rainfall occurred.

To assess the performance of the models, the following criteria were used (* implemented in PREVAH and used for calibration; & implemented in Tank model and used for calibration; $ implemented in UBC model and used for calibration):

- *r^2 (lin)* (Schulla and Jasper 1999)*

$$r^2\ (\text{lin}) = 1 - (S(Q_{sim} - Q_{obs})^2/(S\,Q_{obs}{}^2 - 1/N(SQ_{obs})^2) \qquad \textbf{Equation 4.1}$$

This criterion ranges from –∞ to +1 with values below 0 indicating a bad fit and values close to 1 a good simulation with respect to the observed data set. r^2(lin) is important in the assessment of the model's performance in simulating the flood peaks.

- *r^2(log)* (Schulla and Jasper 1999)*

  $$r^2\ (\log) = 1 - (S(\log Q_{sim} - \log Q_{obs})^2/(S\log Q_{obs}{}^2 - 1/N(S\log Q_{obs})^2) \qquad \textbf{Equation 4.2}$$

  This criterion assesses in particular the closeness of fit for simulated low flows and the entire hydrograph. A good fit is indicated with values close to 1.

- *Sum of squared errors F1 (Beven et al. 1995b)*

  $$F1 = S(Q_{obs} - Q_{sim})^2/N \qquad \textbf{Equation 4.3}$$

  This criterion shows a better fit the smaller the value becomes, showing smaller errors. This criterion is sensitive for the entire hydrograph except the low flows.

- *Sum of absolute errors F2 (Beven et al. 1995b)*

  $$F2 = S(\log Q_{obs} - \log Q_{sim})^2/N \qquad \textbf{Equation 4.4}$$

  Like the sum of squared errors F1 above, this criterion shows the best fit at 0. It shows in particular the efficiency of the model to simulate low flows.

- *Efficiency criteria according to Nash-Sutcliffe$^{\&\$}$ (1970)*

  $$Eff = 1 - S(Q_{obs} - Q_{sim})^2/S(Q_{obs} - \text{mean } Q_{obs})^2 \qquad \textbf{Equation 4.5}$$

  This criterion shows the best fit at a value of 1 and is a measure of the efficiency of the entire hydrograph.

- *Balance$^{*\&\$}$ between Q_{sim} and Q_{obs}*

  This criterion allows an overall assessment of the simulation of the runoff volume.

4.2.1 Application of the UBC model

For the Jhikhu Khola catchment, the UBC model was calibrated and validated by Bastola (2002) using 1996 to 1998 data for calibration and 2000 data for validation. The reason for excluding 1999 data was mainly the availability of rainfall data for a high elevation site during that year. For the calibration period, the data for Site 9 at 1560 masl were used, while in 2000 the data for Site 19 at 1700 masl were used for validation as Site 9 was closed down at the end of 1998. For further details on the calibration and validation of the UBC model, refer to the report of Bastola (2002). The UBC model parameters suggested by Bastola (2002) for the Jhikhu Khola catchment are compiled in Appendix 4.3.

The overall efficiency of the simulation was poor, ranging from Nash-Sutcliff's criteria of 49% during calibration, to 67% after validation (Table 4.3). The peaks are modelled satisfactorily as indicated by higher r^2 values for the linear data. The low flows on the other hand were simulated very poorly. The water balances were very well predicted in 1998 and 2000, while they were largely overestimated for the year 1997.

Table 4.3: **Efficiency of the UBC catchment model on the basis of daily data**

	r^2(lin)	r^2(log)	Balance	F1	F2	EFF
			Calibration			
1996*	0.68	0.34	0.1	5.38	0.15	0.61
1997	0.59	0.28	-304.7	2.71	0.26	0.49
1998	0.73	0.49	2.8	2.44	0.13	0.61
			Validation			
1999	-	-	-	-	-	-
2000	0.82	0.52	18.2	1.09	0.13	0.67

* Initial year, required for setting the boundary conditions.

The model could simulate a good fit in the case of monthly flow (Figure 4.4) and flow duration curves (Figure 4.5), while the statistical characteristics of the observed time series were conserved by the simulated time series. The mean discharge of the observed data series was 1.57 m³/s. This was slightly overestimated by UBC at a value of 1.76 m³/s. The standard deviation ranged from 2.35 m³/s in the case of the simulated time series to 2.68 m³/s for the observed data series. Both time series observed a similar range with 31.0 m³/s in the case of the observed time series and 31.4 m³/s for the simulated time series. An overall correlation coefficient of 0.78 was observed between the two time series. A visual comparison of the two time series shows that the recession curves, particularly in the years 1996 and 1997, are inadequately simulated (Figure 4.6).

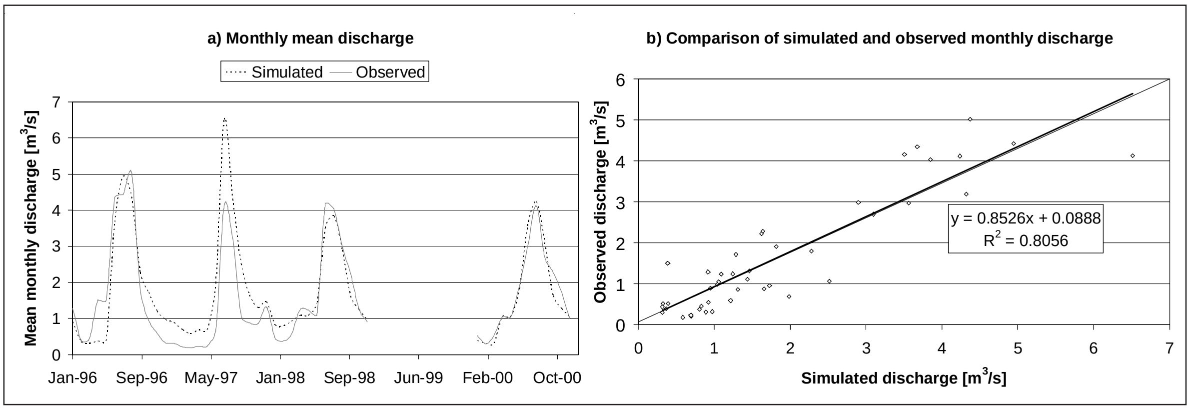

Figure 4.4: **Monthly mean discharge on the basis of observed and simulated flows using the UBC model: a) monthly mean discharge, b) comparison of monthly mean discharge**

The monthly discharge shown in Figure 4.4 shows, in general, a good fit with the exception of 1997. The overall correlation coefficient for monthly flow between the simulated and the observed time series was 0.90. The linear trend line comparing the two time series follows the ideal line with a regression coefficient of 0.81. In 1997, the monthly flow was overestimated by the model during the monsoon season and underestimated during the winter and pre-monsoon seasons.

The duration curve is very well simulated with a correlation coefficient of 0.99 between the observed and the simulated time series (Figure 4.5). The linear trend line follows the ideal line closely with a regression coefficient of 0.98. The flows of higher exceedance probability are, in general, well simulated up to about 7 m³/s. Above this the values are generally underestimated up to about 15 m³/s. The high flows are randomly estimated with good fits, underestimated, or overestimated values.

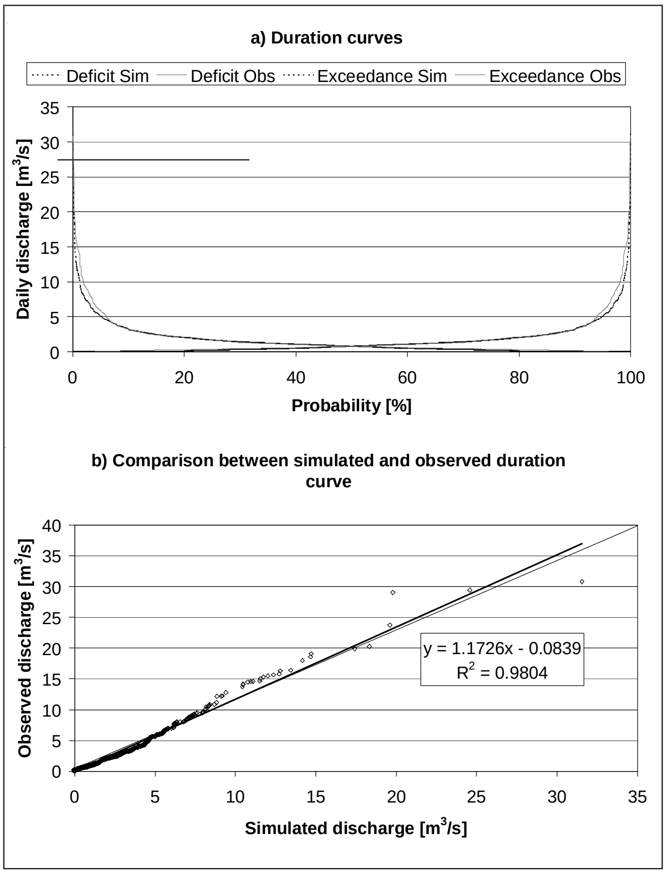

Figure 4.5: **Observed and simulated duration curve using UBC model: a) duration curves of exceedance and deficit, b) comparison between observed and simulated curves**

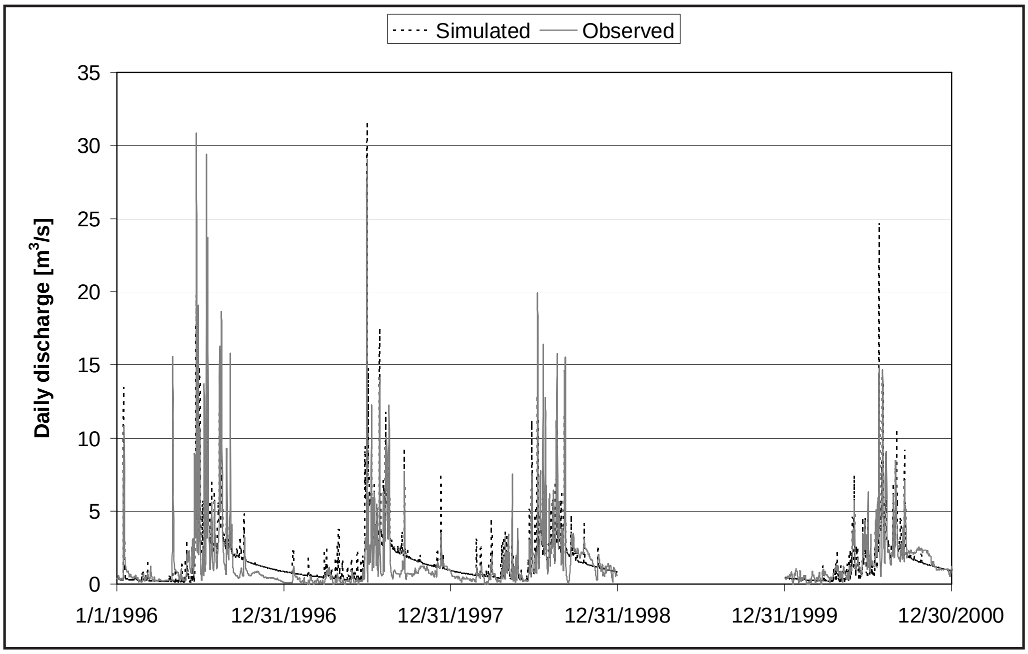

Figure 4.6: **Daily observed and simulated flows using the UBC model**

4.2.1.1 Remarks on the use of the model

The UBC model shows the largest advantages in catchments with a small number of rainfall stations. As Bastola (2002) mentions, this advantage is offset in the case of the Jhikhu Khola catchment with the large number and rather well-distributed rainfall sites. The very restrictive data input format and the calibration of the UBC model are demanding of time and labour. Improvements in the model's efficiency can be achieved mainly by better discharge data sets, particularly in the low flow regime.

4.2.2 Application of the Tank model

The Tank model was calibrated using the genetic optimisation algorithm implemented in the Tank model version 1.0.0 coded by Bastola et al. (2002) on the basis of the tournament selection process. The input data consisted of the daily precipitation interpolated using the interpolation module of WaSim-ETH (Schulla and Jasper 1999), monthly reference evapotranspiration calculated according to the FAO-Penman-Monteith method (FAO 1998), and the daily observed discharge at Site 1 of the Jhikhu Khola catchment. The model parameters suggested after the calibration and used in the validation of the model are shown in Appendix 4.4. For a first comparison of the observed and simulated flows using this model, refer to Figure 4.7, the daily observed and simulated flows.

The statistical characteristics of the observed hydrograph were preserved by the simulated hydrograph. A mean of 1.57 m^3/s was calculated for the observed discharge, while the mean of the simulated discharge was 1.41m^3/s. The standard deviation was 2.62 m^3/s for the observed discharge and 2.47 m^3/s for the simulated discharge. The range was about 30 m^3/s in the observed discharge and 27 m^3/s in the simulated discharge. The overall correlation coefficient between observed and simulated discharge was 0.78. These values roughly correspond with the values proposed by Bastola (2002) who used a different rainfall input series as well as a different evapotranspiration input series.

The qualitative comparison of the simulated and observed discharges on a daily basis shows that the simulated peaks are generally lower than the observed peaks. The simulated recession curves after the monsoon season reach the low base flows later than the observed recession curves. In addition, the simulated hydrograph is smoother than the observed hydrograph.

The comparison of the duration curves (Figure 4.8) shows that, in general, the model was able to simulate the duration curve rather well. An overall correlation coefficient between the observed and the simulated duration curve of 0.99 was achieved with a linear trend line approximately following

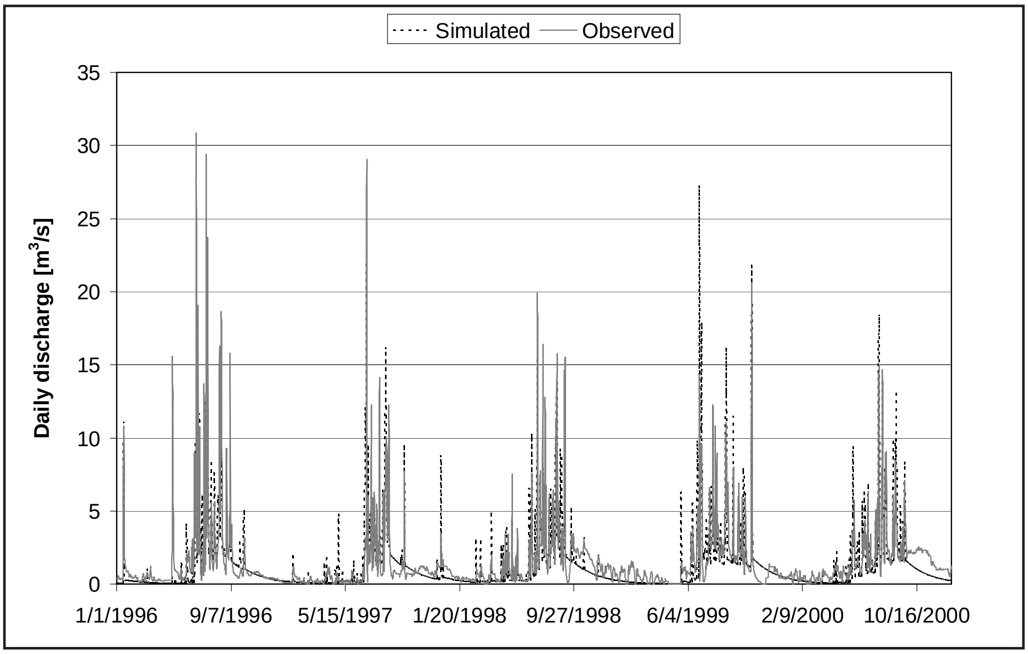

Figure 4.7: **Daily observed and simulated flows using the Tank model**

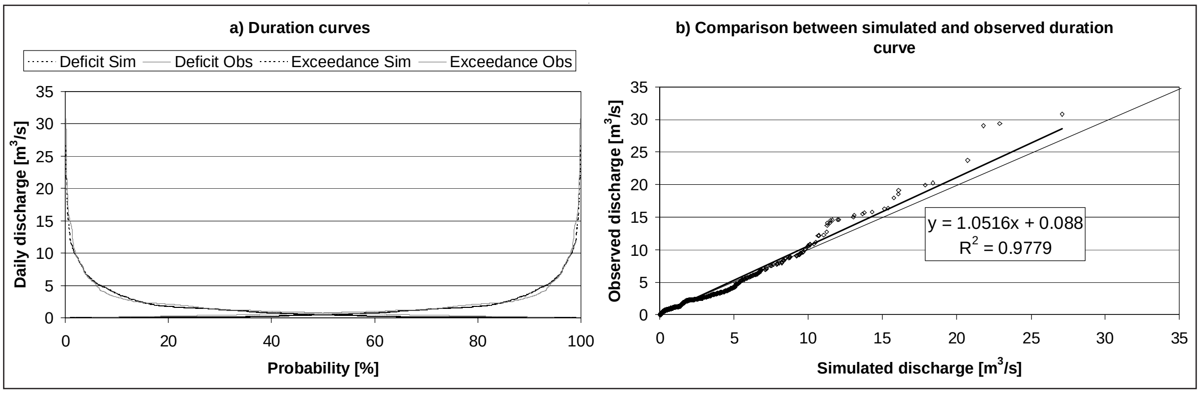

Figure 4.8: **Observed and simulated duration curve using the Tank model: a) duration curves of exceedance and deficit, b) comparison between observed and simulated curves**

the ideal line and a linear regression coefficient of about 0.98. The simulated discharge tends to slightly overestimate the high flows above about 10 m³/s, which corresponds to about $Q_{2(exc)}$.

A comparison of the monthly mean discharge shows that, in general, a good simulation can be achieved with the Tank model (see Figure 4.9). However, the low monthly flows during the dry season generally are underestimated by the model. The overall correlation coefficient between the observed and the simulated monthly mean discharge was 0.91 and the linear regression coefficient was 0.82 (Figure 4.9b). The linear trend line roughly follows the ideal line.

The efficiency of the model for the daily data expressed with different parameters was quite poor (Table 4.4) with an r^2 for linear data ranging from 0.66 to 0.80. This shows that the peaks are in general better simulated than the low flows as indicated by r^2 for logarithmic data ranging from 0.1 to 0.6.The efficiency expressed with the Nash-Sutcliffe criterion ranged from 0.53 to 0.63. Bastola (2002) obtained similar efficiencies with a rainfall dataset interpolated using the Thiessen polygon approach and a different evapotranspiration data set.

The annual water balance was simulated with an error of 5 to 20% in relation to the observed annual values, which corresponds to 24 to 110 mm (excluding the initial year 1996).

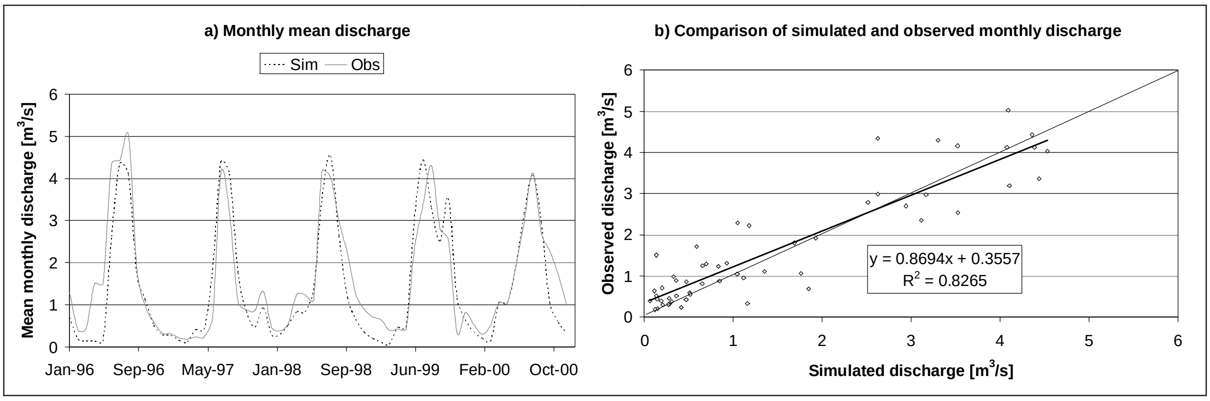

Figure 4.9: **Monthly mean discharge on the basis of observed and simulated flows using the Tank model: a) monthly mean discharge, b) comparison of monthly mean discharge**

Table 4.4: **Efficiency of the Tank model on the basis of daily data**

	r^2(lin)	r^2(log)	F1	F2	Balance	Nash-Sutcliffe
Calibration						
1996*	0.66	-0.30	5.79	0.30	167.2	0.58
1997	0.69	0.57	2.04	0.16	-65.2	0.61
1998	0.71	0.43	2.57	0.15	102.6	0.58
Validation						
1999	0.67	0.42	2.67	0.50	-24.1	0.53
2000	0.80	0.09	1.21	0.25	113.1	0.63

* Initial year, required for setting the boundary conditions

The validation period from 1999 to 2000 showed comparable values with the calibration period from 1996 to 1998.

4.2.2.1 Remarks on the use of the model

A major advantage of this model is the simple data input format, the low input data requirements, as well as the fast and simple calibration process through the application of the genetic algorithm. The simplicity in terms of data input, however, is on the cost of the use of this model for studies related to land-use change. The model does not allow the input of catchment characteristics as they are not required to run this model, but are necessary for land-use change studies. For the application of climate scenarios, however, this model can be used.

The low efficiency of the model is assumed to be a direct cause of the quality of the discharge data, mainly in terms of low flows. The differences in peak discharge can probably be attributed to the temporal resolution of the data. Most discharge events and herein the peaks of these events only last for a few hours and are often the direct cause of heavy rainfall intensities. In the temporal resolution of one day, this effect is not properly reflected. The efficiency of this model could presumably be enhanced with improved discharge data quality as well as with more adequate evapotranspiration input data.

4.2.3 Application of PREVAH model

4.2.3.1 Data preparation

The spatial data requirements of PREVAH are quite extensive. Besides the digital elevation model (DEM) it requires land-use and a number of soil parameters (Table 4.5). In the case of the Jhikhu Khola catchment, a DEM was generated from the 1:20,000 map with contours of 50 m equidistance (Integrated Survey Section 1989). The land-use maps (*.pus and *.use) were prepared from the 1:20,000 land-use map produced from 1996 aerial photos with detailed ground verification by Bhuban Shrestha, PARDYP, Nepal. Soil depth information for the entire catchment was derived from the

Table 4.5: **Input data information for the application of the PREVAH model**

Catchment	Jhikhu Khola
Period for calibration	1996-1998
Period for validation	1999-2000
Spatial input data ([unit]; PREVAH file extension)	- elevation ([m]; *.dhm) - land use/cover ([PREVAH categories]#; *.use) - land use/cover ([PREVAH categories]; *.pus) - soil depth ([m]; *.btk) - soil depth ([class]; *.pat) - soil depth ([class]; *.art) - available field capacity ([vol%]; *.pfc) - saturated hydraulic conductivity ([mm/h]; *.kwt) - saturated hydraulic conductivity ([m/s]; *.kms)
Spatial resolution	50 m * 50 m cell size --> 44,429 cells
Meteorological input data	- precipitation of 11 sites - temperature of 9 sites
Discharge data	- discharge of Site 1 main hydro station
Temporal resolution of input data	1 day

\# For PREVAH categories refer to Zappa (1999)

sediment source survey (MRE 2002). The remaining soil parameters were estimated from measured and mapped texture during the land systems' mapping (Maharjan 1991) using the soil texture triangle by Saxton et al. (1986). All base maps were provided as grids of 50 m*50 m cell size.

The meteorological input data consisted of the daily precipitation data of 10 sites and the daily temperature data of 9 sites in the Jhikhu Khola catchment. Additionally, the daily rainfall data from Nagarkot (DHM 2000) were used as there are no stations in the western and upper parts of the catchment at present. For calibration the daily streamflow data at the outlet of the Jhikhu Khola catchment at Site 1 were used.

The Jhikhu Khola catchment consists of 44,429 grid cells of the size 50 m*50 m. This is on the basis of the DEM generated catchment area of 111.1 km^2. The entire catchment was classified into 14 height zones with a range of 100 m, ranging from 800 to 2200 m, five aspect classes (NW-NE, NE-SE, SE-SW, SW-NW, flat), four slope classes (0-10, 10-22, 22-36, >36), and five classes each for soil topographic and area topographic index. On the basis of these classes, 1163 hydrotopes were generated using the criteria height zone (intersected with catchment ID), exposition, land use, and soil-topographic index.

4.2.3.2 Model calibration and validation

Although a number of parameters required for the model can be extracted from the catchment characteristics imported with the spatial data as discussed above, a number of other parameters have to be calibrated using the measured discharge as a reference. These parameters are compiled in Table 4.6 with the resulting values after the calibration and validation. For this purpose, the year 1996 as initial year and the years 1997 and 1998 as calibration years were chosen (see also above). The efficiency results achieved through this process are compiled in Table 4.7.

Table 4.6: **Parameters calibrated for the PREVAH model**

Value	Parameter	Description
0.0	PKORF	correction for rain [%]
0.8	CREDV	reduction factor for open and vegetated land
0.4	CBETA	exponent, soil moisture recharge parameter
0.1	Cu	relative part of field capacity below which EA<ET0
0.6	CRSZ	maximum portion
2	SGRLUZ	threshold content of SUZ for generation of surface runoff [mm]
5	K0H	storage time for fast runoff R0 [h]
100	K1H	storage time for delayed runoff R1 [h]
1500	K2H	storage time for slow runoff R2 [h]
700	CG1H	storage time for fast baseflow R [h]
0.0	SLZ1MAX	storage capacity for fast baseflow R [mm]
0.9	CPERC	infiltration intensity [mm/h]

Table 4.7: **Assessment of performance of the PREVAH model**

	r^2(lin)	r^2(log)	Balance	F1	F2	EFF
Calibration						
1996*	0.70	-1.73	5.06	0.63	80.5	0.63
1997	0.76	0.67	1.55	0.12	-44.6	0.71
1998	0.72	0.55	2.52	0.12	146.7	0.59
Validation						
1999	0.75	0.44	2.06	0.43	19.4	0.64
2000	0.73	0.45	1.66	0.15	-8.0	0.50

* initial year, required for setting the boundary conditions

The balance is simulated by PREVAH, with errors ranging from 1 to 25% with reference to the observed values. This corresponds to absolute errors of between 8 and 150 mm per year. The balance is very accurately predicted in the validation period. Overall, the efficiency of the modelling using PREVAH on a daily time basis is satisfactory but far from good. In all years a Nash-Sutcliffe efficiency of more than 0.50 was achieved with a peak of 0.71 in 1997. The peaks are generally simulated better than the low flows, as shown with higher r^2 values for linear data than r^2 values for logarithmic data.

A qualitative comparison of the daily flows shows that the general recession trend is picked up nicely by the model, but in general the model reaches the low baseflows later than the observed discharge (see also Figure 4.10). In addition to this, the peaks are generally underestimated by the model, which is also shown with a lower range for simulated discharge. While the range for the observed data set is about 30 m^3/s, it is only 26 m^3/s for the simulated data set. The simulated time series preserves the statistical characteristics of the observed time series. The mean of the observed discharge is 1.57 m^3/s. The simulated discharge mean is 1.46 m^3/s. Standard deviations are 2.62 and 2.47 m^3/s for the observed and the simulated time series, respectively. The overall correlation coefficient between the simulated and observed data series is 0.80.

Overall, the mean monthly discharge (Figure 4.11a) shows a generally good fit. This is not only shown visually, but also with an overall correlation coefficient between the observed and the simulated monthly time series of 0.91 and a linear regression, which roughly follows an ideal line (Figure 4.11 b), with a regression coefficient of 0.83. The visual comparison shows a major discrepancy in the monsoon flows of 2000, otherwise it shows a good fit (Figure 4.11a).

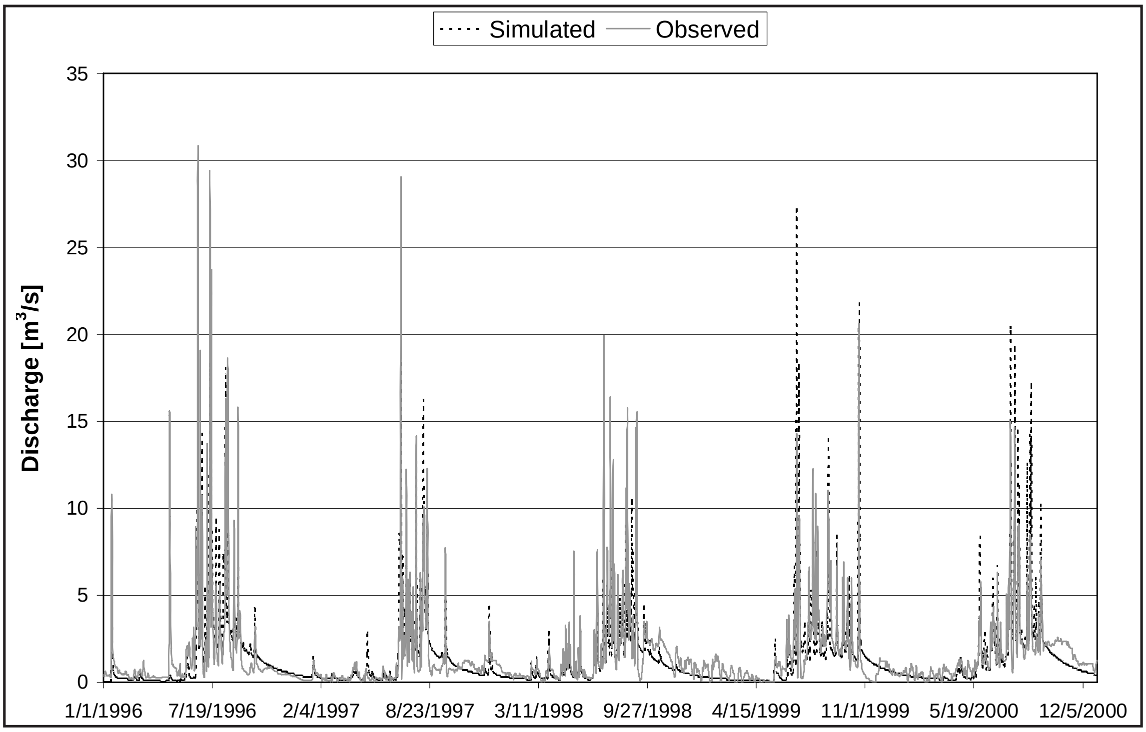

Figure 4.10: **Observed and simulated daily discharge at the main station, Jhikhu Khola catchment**

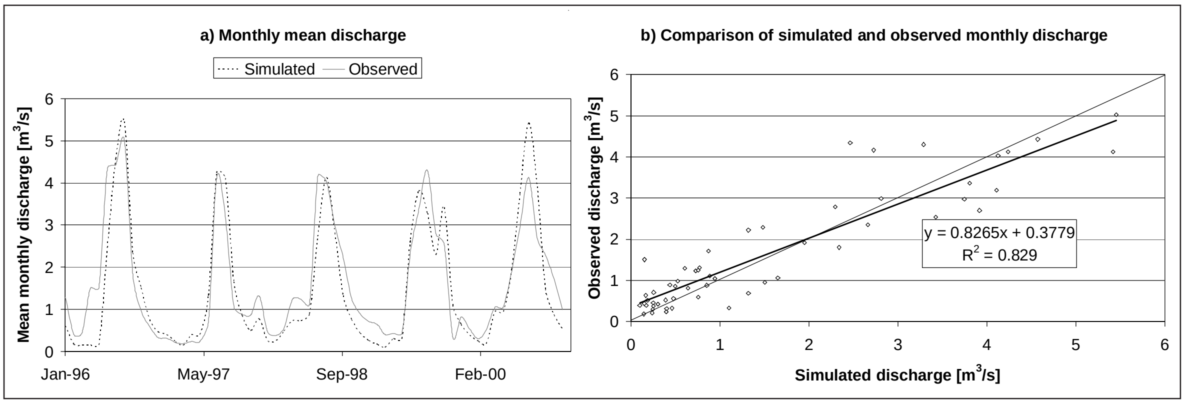

Figure 4.11: **Observed and simulated (PREVAH) monthly mean discharge at the main station of the Jhikhu Khola catchment: a) mean monthly discharge, b) comparison of mean monthly discharge**

The comparison of the duration curve (Figure 4.12) shows a nearly identical match between the observed and the simulated data series. The correlation coefficient between the duration curves of the two time series is 0.99. The linear regression shows nearly the same direction and position as the ideal line and has a regression coefficient of 0.99. The fit can be observed up to about 20 m^3/s. Only the four biggest events do not fit.

A comparison of the annual simulated evapotranspiration values at the potential rates with the ariel evapotranspiration rates, calculated according to the FAO (1998) method, showed that the simulated evapotranspiration rates are, in general, about 5% lower than the calculated rates. The actual evapotranspiration rates differ by about 20% on an annual basis. This suggests that more attention must be given to this part of the water balance.

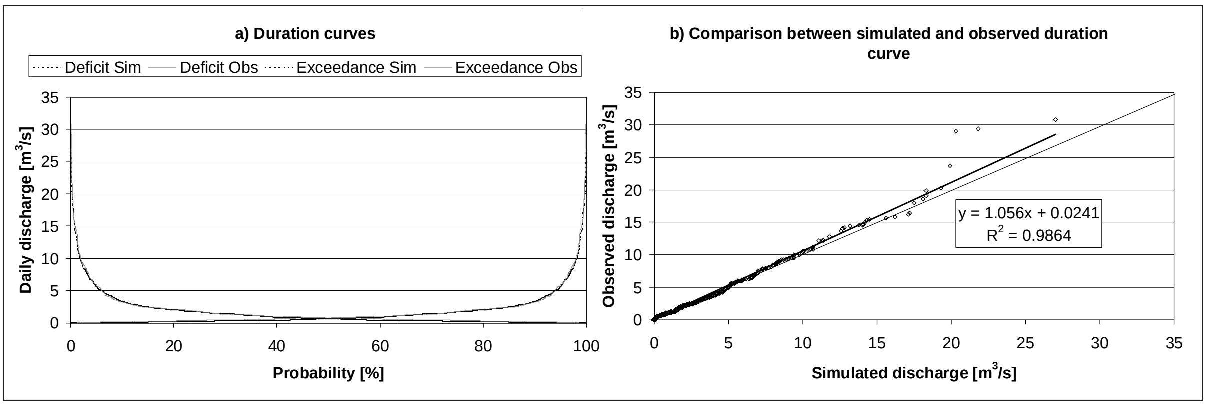

Figure 4.12: **Observed and simulated (PREVAH) duration curves at the main station of the Jhikhu Khola catchment: a) duration curves, b) comparison of duration curves**

4.2.3.3 Remarks on the use of the model

The PREVAH model has extensive data requirements and is therefore quite labour intensive. Not only the data preparation, but also the calibration process is time consuming. In terms of efficiency, a number of improvements can be made. These include the following.

- Currently the precipitation is imported on the basis of daily data (if daily data are modelled). This daily data are then converted to four equal rainfall amounts distributed equally throughout the day. This however does not take into consideration the large dependency on rainfall intensity or the particular daily rainfall distribution.
- Evapotranspiration in this application of PREVAH was calculated using the approach of Hamon (1961), which only requires temperature data. For better results, other approaches implemented in PREVAH should be used. The measurement network in the Jhikhu Khola has been upgraded accordingly, with relative humidity loggers at all sites and the installation of an automatic weather station additionally monitoring solar radiation and wind.

- The vegetation parameters were used according to the data sets implemented. It is acknowledged that the vegetation parameters for this agricultural system as well as for the prevalent forests in this region do not match. Due to the lack of the respective information, this was however necessary. In recent years, the Integrated Pest Management Project assessed a number of the necessary vegetation parameters, which will probably be available later this year (Herrmann, pers. comm.). The large differences in calculated and simulated actual evapotranspiration rates could herewith presumably be reduced.

4.2.4 Comparison of the models

In general, it has been seen that all models show rather low efficiencies. The low flows in particular tend to be modelled inefficiently, which generally is the easier part in a modelling exercise. In this section the performance of the three models will be compared. With respect to all the efficiency parameters compared, the PREVAH model showed, on average, the best performance (Table 4.8). This is followed by the Tank model and finally the UBC model. In terms of time and labour demand, the Tank model shows the best performance with its simple data input format and the implemented genetic algorithm. In terms of data requirements, the PREVAH model is most demanding and is also very labour intensive. However, this model shows the most scope for further improvement with the addition of a number of meteorological parameters as well as site-specific vegetation parameters. Additionally, improved discharge data quality would lead to an improved efficiency of this model. The efficiency of the other models can only be enhanced with improved discharge data quality.

Table 4.8: **Efficiency parameters compared between the three models**

	UBC				Tank				PREVAH			
	r^2(lin)	r^2(log)	Balance	EFF	r^2(lin)	r^2(log)	Balance	EFF	r^2(lin)	r^2(log)	Balance	EFF
1997	0.59	0.28	-304.7	0.49	0.69	0.57	-65.2	0.61	0.76	0.67	-44.6	0.71
1998	0.73	0.49	2.8	0.61	0.71	0.43	102.6	0.58	0.72	0.55	146.7	0.59
1999	-	-	-	-	0.67	0.42	-24.1	0.53	0.75	0.44	19.4	0.64
2000	0.82	0.52	18.2	0.67	0.80	0.09	113.1	0.63	0.73	0.45	-8.0	0.50
Mean	0.71	0.43	108.6	0.59	0.72	0.38	76.3	0.59	0.74	0.53	54.7	0.61

In Figure 4.13 the outputs of the different models are compared. While the simulated baseflows of the Tank and the PREVAH models are very similar, the baseflows of the UBC model are generally overestimated. It is important to note that all models show inadequate fit of the recession curves after the monsoon season. While the observed dataset immediately recedes to the low flow levels, the simulated results approach the low base flows more gently.

Table 4.9: **Correlation matrix for daily discharge simulated with different models**

	Q_{obs}	Q_{UBC}	Q_{Tank}	Q_{PREVAH}
Q_{obs}	1.00	0.78	0.78	0.80
Q_{UBC}		1.00	0.93	0.90
Q_{Tank}			1.00	0.95
Q_{PREVAH}				1.00

The most similar results are produced by the PREVAH and Tank model shown with the regression line in Figure 4.13a with a regression coefficient of 0.92 and a correlation coefficient of 0.95 (Table 4.9). The correlation coefficient between the observed data sets and the PREVAH model output is likewise the highest at 0.80.

The similar behaviour of the three models in terms of output efficiency suggests that the main limitations have to be sought in the input data set. With the problems of data collection and rating curve establishment as discussed in Appendix A3.1, the main reason has to be the discharge data set.

For further studies and to improve the efficiency of the models, the project should strive for more accurate discharge information mainly in the low flow season (see also Chapter 6). In addition, the impact of the numerous irrigation diversions have to be taken into consideration and further studied in detail.

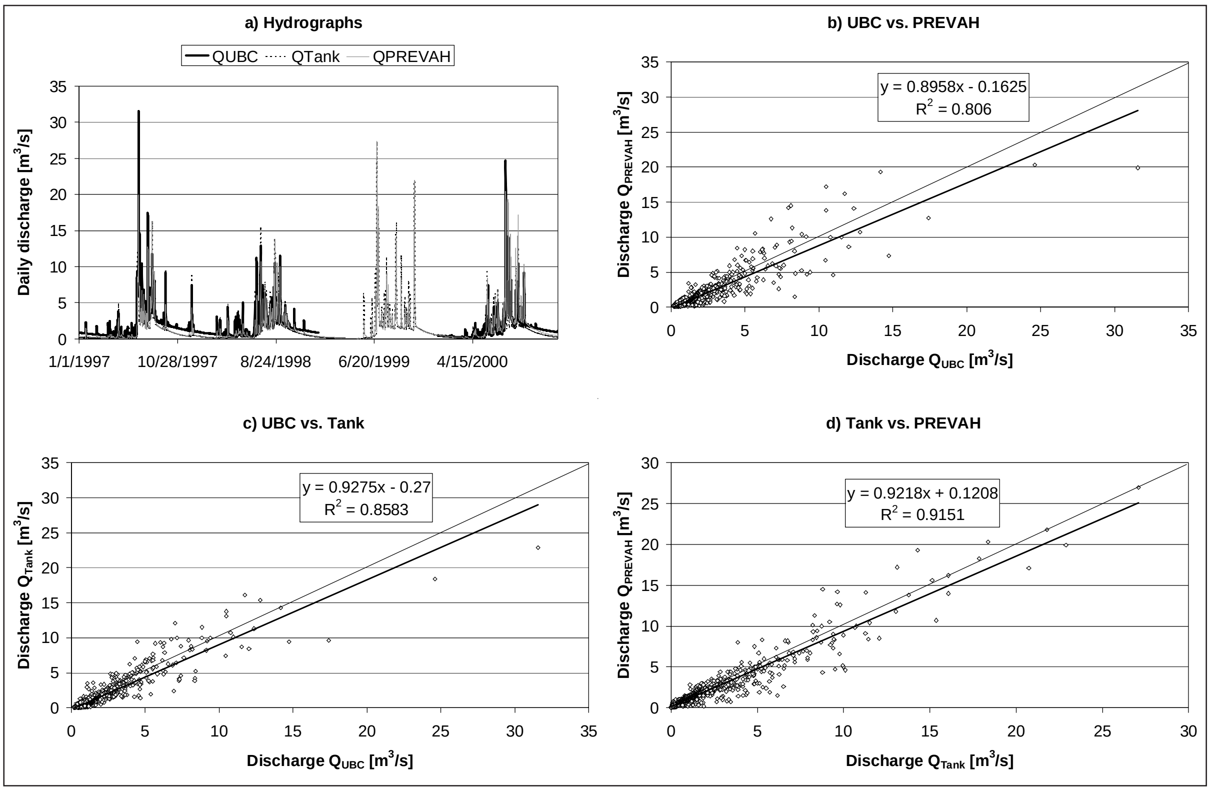

Figure 4.13: **Comparison of simulated daily discharge of UBC, Tank, and PREVAH models**

In terms of the models' use for the scenarios below, the PREVAH model can be applied both to the climate as well as to the land-use scenario. The remaining models, UBC and Tank, can only be applied to the climate scenario as land use/cover has no impact on the Tank model and only limited impact in the case of the UBC model through the percentage of forest cover and impermeable areas. For the sake of simplicity only the two models, PREVAH with the best performance and the Tank model with the easiest handling, were used for the scenario analyses.

4.3 SCENARIOS

A number of external driving forces are responsible for changing water supply and demand scenarios and the change in flood and land-degradation susceptibilities. Schultz (2000) mentions climate change, economic restrictions, ecological restrictions, land-use change, and difference sources of pollution which all have an impact on future water supply. Water demand, according to the same author, shows a major impact as a result of climate change, population growth, changing standards of living, and industrial development. The main external driving forces in the context of the middle mountains in Nepal are considered to be the climate, the population, the economic conditions, and national and district policies (see also Chapter 1). In this respect, three main scenarios were parameterised to assess their impact on the state of the water resources in the selected catchments. These scenarios do not represent a complete set of possible future development, but should show simple examples for the PARDYP Water and Erosion Studies which could be incorporated in the near future for the temporal as well as for the spatial up-scaling exercise proposed in Phase 3 (ICIMOD 2003).

The main questions to be answered below were as follows.

- How can the given scenarios be parameterisd for a middle mountain catchment in the HKH?
- What is the potential impact of the scenarios identified on indicators relevant to water availability, flooding, and land degradation?

4.3.1 Scenario 1: Climate Change

Climate change is one of the most publicised issues in recent decades. A large number of studies into the reasons, impacts, and scenarios of climate change have been undertaken in this time. A very good source for mainstream information on this issue is provided by the Intergovernmental Panel on Climate Change (IPCC). Most of the information below is therefore based on the work of IPCC.

Surface temperature change in the last 100 years ranged from 0.3 to 0.8 °C in the region of Tropical Asia, including the South Asian countries (IPCC 1998). According to the same report, the projected temperature changes for the entire globe between 1990 and 2100 are likely to be in the range of 1.5 to 4.5 °C. For South Asia an above average temperature increase is predicted (Figure 4.14). An even higher increase is foreseen for the Tibetan plateau. Lal (2002) suggests an increase in temperature of 3.5 to 5.5 °C by the end of 2100 of the land regions of the Indian sub-continent. For Nepal, Arun B. Shrestha noted an increase of 0.06 °C per year in the average temperature (Kathmandu Post 2003).

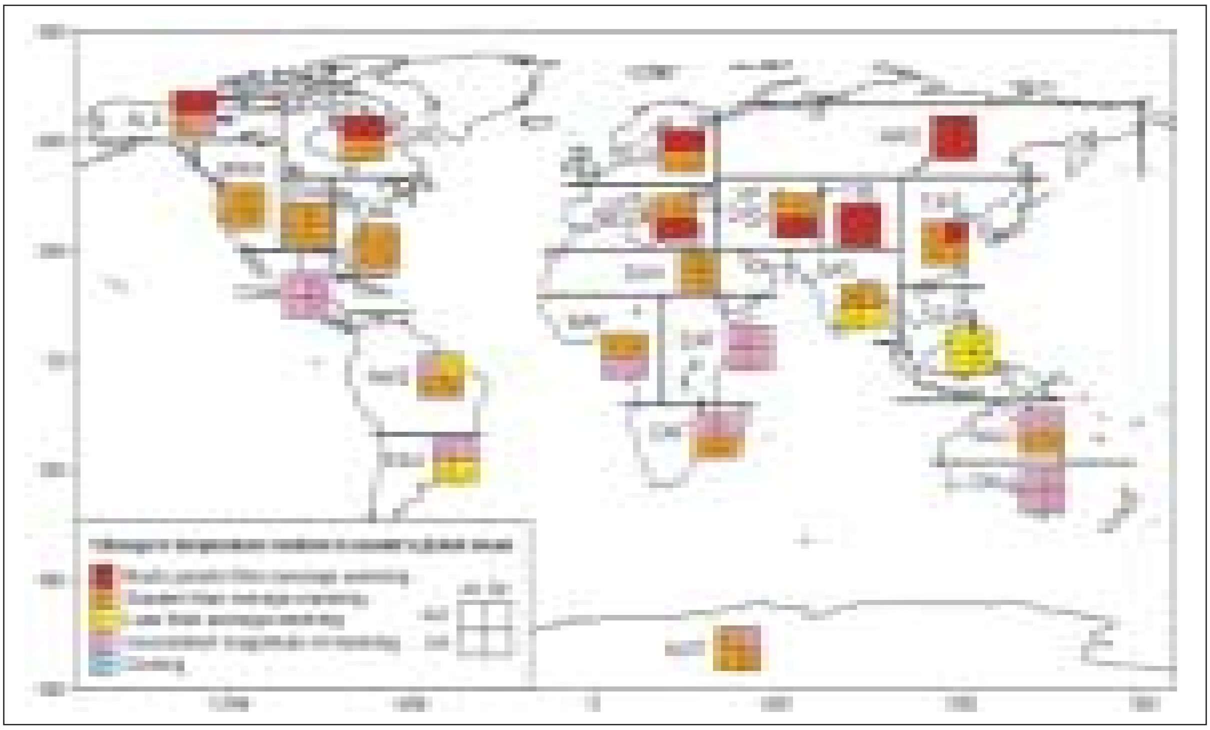

Figure 4.14: **Change in temperature relative to model's global mean** (from IPCC 1998)

Chalise (1994) stresses the importance of understanding the possible impacts of climate change as this will add to the already existing uncertainties of widespread environmental degradation in the region. This author further discusses some possible signs of climate change on the basis of:

- noontime temperature distribution in Kathmandu, which shows a slight increase over recent years;and
- glacier fluctuations in the region, which generally indicate a retreating trend and therefore a warming of the atmosphere.

For tropical Asia, IPCC (1998) suggests an impact on water resources as follows.

- The Himalayas play a critical role in the provision of water to continental monsoon Asia.
- Increased temperature and increased seasonal variability in precipitation are expected to result in accelerated recession of glaciers and increasing danger from glacial lake outburst floods.
- A reduction in the flow of snow and ice-fed rivers, accompanied by increases in peak flows and sediment yields, would have major impacts on hydropower regeneration, urban water supply, and agriculture.

- Availability of water from snow-fed rivers may increase in the short term, as glaciers recede, but decrease in the long term.
- Runoff from rain-fed rivers may change in the future. A reduction in snowmelt water would result in decreases in the dry-season flow of these rivers.
- Large populations and increasing demands in the agricultural, industrial, and hydropower sectors will put additional stress on water resources.
- Pressure will be most acute on drier river basins and those subject to low seasonal flows.

Recently, the focus of global climate change discussions has been on the type of precipitation, and in particular the proportion of precipitation, that falls as snow. Amongst others, Harrison et al. (2001) studied climate change and its impact on the snowfall pattern in Scotland. It is important to note that global climate change not only has negative impacts. Positive impacts could also be envisaged, such as longer growing seasons for higher altitudes.

Table 4.10: **Climate change parameters (by 2080)**

Scenario	Temperature	Precipitation	Reference
- annual	+5.6 °C	+9.9 %	Lal (2002)
- winter	+6.3 °C	-25 %	
- monsoon	+4.6 °C	+15 %	

Lal (2002) projects for the Indian sub-continent decreasing rainfall in winter and increasing rainfall during the monsoon (Table 4.10). A decrease of 10 to 20% in winter is simulated by 2050. During the monsoon an increase of 30% or more in precipitation over India is projected. Lal (2002) further suggests that the variability in the monsoon's onset will increase. However, there is conflicting information on the basis of different GCMs (global climate models). Lal et al. (1995) found a decline in mean summer monsoon rainfall of about 0.5 mm/day over the South Asian region. This decline in summer monsoon rainfall has also been suggested by some experiments referred to in IPCC (1998).

The changes in temperature and in precipitation are expected to have a major impact on the availability of water resources in the region. For the meso-scale catchments, the expected primary impact of this scenario as presented in Table 0.10 may show the following impact chain:

1) increase in temperature during dry season months/decrease in precipitation → increased evapotranspiration rates → faster reduction of seasonal soil moisture and groundwater storage → reduced groundwater and spring yield → reduced runoff → increased pressure on water resources;and
2) increase in precipitation during the monsoon season months → increased runoff → increased susceptibility to floods and land degradation caused by water.

The disaggregated scenario with different values for the winter and monsoon was calculated using the models Tank and PREVAH.

4.3.2 Scenario 2: Population

Population has been increasing tremendously in the Indian sub-continent. Many authors caution from further increase and project a collapse of the natural resource base in case of further population stress (e.g. Allen 2000). Other authors argue that, with increasing population, the people would introduce innovative management technologies and practices to cope with the worsening resource situation (Paudel and Thapa 2001). There is, however, no argument that more people need more water and more food.

In Nepal, the annual population growth rate for the eco-regional zone of the hills was calculated at 2% for the period between 1991 and 2001 (MOPE 2002). The annual population growth rate for the Jhikhu Khola catchment was assessed to be 3.1% for the period from 1947 to 1990 and 3.5% between 1947 and 1996. While these growth rates are important parameters, they are not very useful for long-term projections. For this purpose, a number of additional parameters such as fertility rate, number of births, number of deaths, and migration rates are required. These parameters are not available for the Jhikhu Khola catchment, therefore two population projections by Lutz and Goujon (2002) were used (Table 4.11). The two projections a1b1 and a2 were used for the emission estimates of the IPCC Special Report on Emission Scenarios (Nakicenovic and Swart 2000) as lower and upper estimates for the world's population. The projections firstly produced regional datasets for 13 world regions, which were then disaggregated to country level.

Table 4.11: **Population and water demand parameters (by 2080)**

Parameter	Value	Remarks	Reference
Population projection a1b1	196 % of the population in 1990	low fertility/low mortality/central migration	Lutz and Goujon (2002)
Population projection a2	344 % of the population in 1990	high fertility/high mortality/central migration	Lutz and Goujon (2002)
Low domestic water demand	20l person^{-1}day^{-1}	current water demand in the Jhikhu Khola catchment	Merz et al. (2002)
Medium domestic water demand	50l person^{-1}day^{-1}	basic water demand	Gleick (1996)
High domestic water demand	100l person^{-1}day^{-1}	double the basic water demand above	

The projection a1b1 shows a low fertility/low mortality/central migration scenario and projects a world population of 8.7 billion in 2055, which decreases to 7.1 billion in 2100 (IIASA 1999). The projection a1 represents a high fertility/high mortality/central migration scenario and projects a world population of about 15 billion at the end of the 21st century. The disaggregated data for the country level of Nepal forecasts a population of about 36,000,000 in the case of the a1b1 scenario and about 63,000,000 in the case of the a1 scenario by 2080. The population growth rates for the entire kingdom were used for the estimation of the population in the Jhikhu Khola.

It is further assumed that the people in the future will aspire to higher living standards and therefore use more water, e.g., for flush toilets (Verma et al. in prep). In addition to the population parameters a low, medium, and high water demand scenario was calculated and compared with the available water resources on the basis of existing as well as predicted water resources. The water demand values are based on the current water demand in the Jhikhu Khola catchment (Merz et al. 2002) in the case of the low water demand, and projected for medium and high water demands based on Gleick (1996). The basic water demand standard as proposed by Gleick (1996) is composed of 5 l/day for drinking, 20 l/day for sanitation, 15 l/day for bathing, and 10 l/day for cooking, all values per person. For the high domestic water demand, this basic water demand was doubled.

Expected primary impact of this scenario:

Increased population → increased demand for domestic water → increased demand for food (intensification of land use is hardly possible on the basis of the present intensities. Expansion is discussed as an impact on land use in scenario 3).

4.3.3 Scenario 3: Land-use change due to poverty and landflucht (migration from the land)

Land-use change may have a major impact on the water resources, at the micro- to meso-scale in particular (FAO 2002). As shown above, there is no clear evidence for a major land use shift at present in the catchments. However, as indicated in Chapter 2 and on the basis of the population projections, a change in land use could be well be possible. For future developments two different potential sub-scenarios were identified:

Landflucht (outmigration of people from rural to urban areas; urbanisation from the perspective of the rural areas)

In general, a trend towards increased urbanisation can be observed in Nepal and many other countries of South Asia (UNFPA 2001). The urban growth rate in Nepal for the period 2000-2005 is projected to be 5.1% (UNFPA 2001). In 2001, 14% of Nepal's population lived in urban centres (MOPE 2002). This process affects the rural population. Urban migration is also the reason for a high percentage of migrants in Nepal (K.C. et al. 1998).

In the Jhikhu Khola catchment, a number of fields are not being cultivated as their owners live in Kathmandu and have not given the land for tenancy. Often these owners have left their parental home for higher education or jobs in the capital or abroad. At the time of the parents death, or if the parents follow them to the city, the land remains uncultivated. Another reason for abandoning the land is the low economic return from many fields, in particular in the upper catchment areas. It is not likely that abandoned land will be taken over by another family, as the return is too marginal. Another reason for outmigration is poverty (Adhikari and Bohle 1999), although these people often do not leave large plots of land behind and therefore do not contribute to land-use change due to outmigration.

In terms of spatial distribution of the land, the most likely land to be abandoned is in the upper elevation areas. These are the marginal lands with steep slopes, often low soil fertility, and a high tendency towards soil erosion. The rainfed land on the border to the irrigated lands is more fertile and easier to cultivate due to accessibility and favourable slope. These lands would readily be taken over by other farmers in case of outmigration by the owners.

Expansion to marginal lands

Increasing population pressure and the need for cultivated land is believed to cause an expansion to marginal and less suitable land (UNEP 2001). This process occurred in Nepal during the 1970s and was the basis of the Theory of Himalayan Environmental Degradation (Eckholm 1970; Ives and Messerli 1989). However, many of the marginal areas on steep slopes have now been protected by inclusion into community forestry areas. For this reason, the community forestry regulations were incorporated in the scenarios and only shrub and grassland were subject to potential change to agricultural land (Table 4.12). It is acknowledged that some of these areas have also been included in the community forest areas as shown in Table 4.13, but in general these areas are small and negligible at the catchment scale.

On the basis of these two sub-scenarios the parameters compiled in Table 4.12 were determined.
Expected primary impacts of this scenario:
1) Landflucht → increased area of grassland → increased flood volume and more frequent peaks

or

2) Expansion to marginal areas → increased area of cultivated land → decreased flood volume and reduced number of peaks.

This scenario was only calculated by using the PREVAH model.

Table 4.12: **Land-use change parameters (by 2080)**

Scenario	Remarks
Landflucht 1(L1) – High rate of abandoning	All the rainfed land above 1250 masl is abandoned and becomes grassland
Landflucht 2 (L2) – Medium rate of abandoning	All the rainfed land above 1500 masl is abandoned and becomes grassland
Expansion 1(E1) – High rate of expansion	All shrub and grasslands below 1250 masl are newly cultivated and become rainfed agricultural land
Expansion 2 (E2) – Low rate of expansion	All shrub and grasslands below 1500 masl are newly cultivated and become rainfed agricultural land

Table 4.13: **Community forest areas in the Jhikhu Khola catchment**
(based on unpublished data by Bhuban Shrestha/PARDYP Nepal; all figures in km^2)

	Rainfed land	Forest	Grass	Shrub	Other
Total in the catchment	42.7	33.2	6.1	7.8	3.3
Protected by community forest	1.2	11.8	0.4	0.9	0.2

4.4 IMPACT ASSESSMENT

The impact assessment of the scenarios described above should show preliminary results of possible analyses to be further pursued and investigated in more detail in the PARDYP framework. For the calculation of the scenarios, the data of 1996 to 1999 was used as a base (Table 4.2). Results from 1996 were omitted as these data were used to set the boundary conditions, e.g., the soil moisture content or the groundwater.

4.4.1 Scenario 1: Climate change

The PREVAH and Tank models were used to assess the potential impact of a global climate change scenario as discussed above. The scenario was assessed on the basis of the data of 1997 to 1999. Overall, it can be observed that on a seasonal basis the runoff is considered to increase for the monsoon season and to decrease in the remaining seasons, particularly in the pre-monsoon season (Figure 4.15).

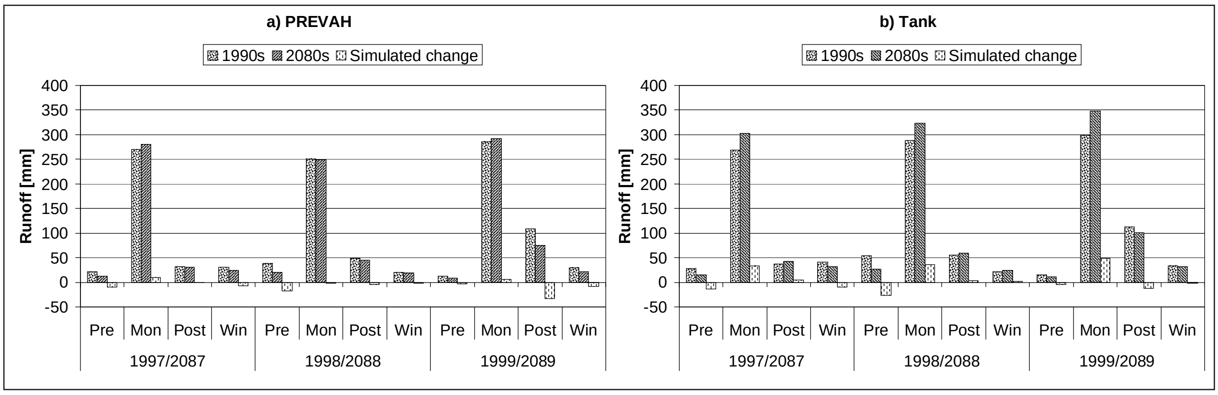

Figure 4.15: **Seasonal changes with global climate change applying a) PREVAH model, b) Tank model**

On the basis of the PREVAH model, potential evapotranspiration will increase by about 40% from 1990 to 2080 if the climate change scenario occurs. The actual evapotranspiration rates would change by about 10% on an annual basis. As these figures are still very preliminary due to the inappropriate vegetation datasets, no further disaggregation into different months or seasons is presented here, although this would be of particular interest for the different areas in the catchment.

Comparing the duration curves for the data in the 1990s with the predicted values on the basis of the climate scenario for the 2080s, no difference can be observed by applying the PREVAH model (Figure 4.16a). Using the Tank model on the other hand, the slope of the regression line has a slope greater than 1, which indicates that significantly higher discharge values are expected on the basis of this model's predictions (Figure 4.16b). The uncertainty shown by the results indicates that basing stream flows on the past data records may be inappropriate in future as the conditions may change. Great care will have to be taken in the design of structures.

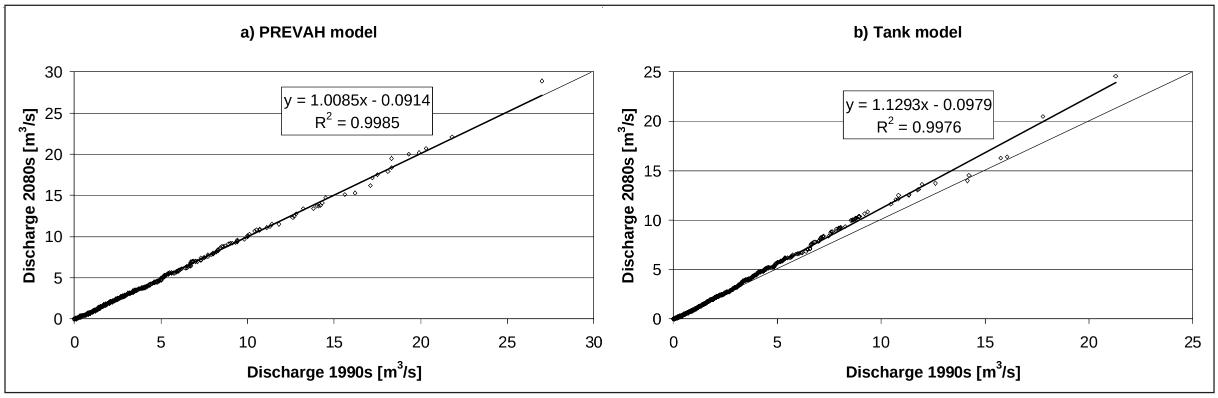

Figure 4.16: **Comparison of duration curves for 1990s and 2080s using a) PREVAH model, b) Tank model**

In terms of flood peaks, an increase in the number of peaks above 10 m^3/s daily discharge is expected on the basis of both models (Table 4.14). The simulated change in the number of peaks is greater in the case of the Tank model than the PREVAH model. It should be noted that the number of peaks observed is closer to the number of peaks estimated by the PREVAH model in the 1990s than the number of peaks simulated by the Tank model.

Table 4.14: **Number of peaks > 10 m^3/s for 1990s and 2080s with different models**

	1990s		2080s		Simulated change	
Year	**PREVAH**	**Tank**	**PREVAH**	**Tank**	**PREVAH**	**Tank**
1997/2087	4	2	5	5	+1	+3
1998/2088	3	2	3	2	0	0
1999/2089	7	7	8	11	+1	+4

In 1997, 6 peaks were observed; in 1998, 8 were seen; and in 1999, another 6. In addition, the PREVAH model shows slightly better fits for the high flows than the Tank model (see above in Table 4.8). Summarised, with a global climate change according to IPCC (1998) and changes in temperature/precipitation in South Asia according to Lal (2002):

- evapotranspiration rates are expected to increase;
- water availability during the dry season can be expected to decrease;
- water volume during the monsoon can be expected to increase;
- number of flood peaks can be expected to increase; and
- design flows based on the past data records may show underestimated flows.

4.4.2 Scenario 2: Population growth

On the basis of the two population projections by Lutz and Goujon (2002) and the three water demand classes of low, medium, and high-water demand, on the basis of the current water requirements and the basic domestic water requirements according to Gleick (1996), the following predictions can be made for the water requirements in the Jhikhu Khola catchment by 2080 (see also Table 4.15):

Table 4.15: **Projected population and water demand Jhikhu Khola catchment, 2080**

Population	Scenario a1b1	Scenario b2
Population	85,646	150,238
Population density [people/km^2]	769	1349
Water demand		
Low daily demand [mm]	5.6	9.8
Medium daily demand [mm]	14.0	24.6
High daily demand [mm]	28.1	49.2

- population in the catchment will be between about 85,000 and 150,000;
- this corresponds to a population density of 750 to 1400 people per km^2;and
- annual water demand will range from 5 to 50 mm depending on the different water demand scenarios.

The disaggregated information according to the VDCs in the Jhikhu Khola catchment shows that the highest increases in water demand are expected in the VDCs along the Arniko highway and soon also along the Dhulikhel – Bardibas highway where the population is concentrated (Figure 4.17). In 1996, the water demand in all VDCs was between 0 -6 mm. In case of a low daily water demand the VDCs Panchkhal, Patlekhet, Rabi Opi, Dhulikhel, and Phoolbari would show an annual water demand of about 6 -12 mm in the case of a low population growth rate according to scenario a1b1. In case of a high population growth rate as predicted by scenario a2, the same VDCs would experience a water demand of about 12 -18 mm per annum. The remaining VDCs are expected to have a water demand of 6 -12 mm per annum. In securing the basic water requirements, the water demand under scenario a1b1 would shoot up to 15-30 mm in the road-proximate VDCs and up to 15 mm in the remaining VDCs. In scenario a2, Rabi Opi, Panchkhal, Patlekhet, and Phoolbari would demand 30-45 mm per annum. In case of high water demand, the VDCs Devitar, Anaikot, Hokse, Kharelthok, and Methinkot, basically the VDCs along the north south-facing slopes, would show about 0-25 mm annual water demand in case of scenario a1b1. The remaining VDCs are expected to demand 25-50 mm water per annum. In case of high population growth rates, the VDCs on the

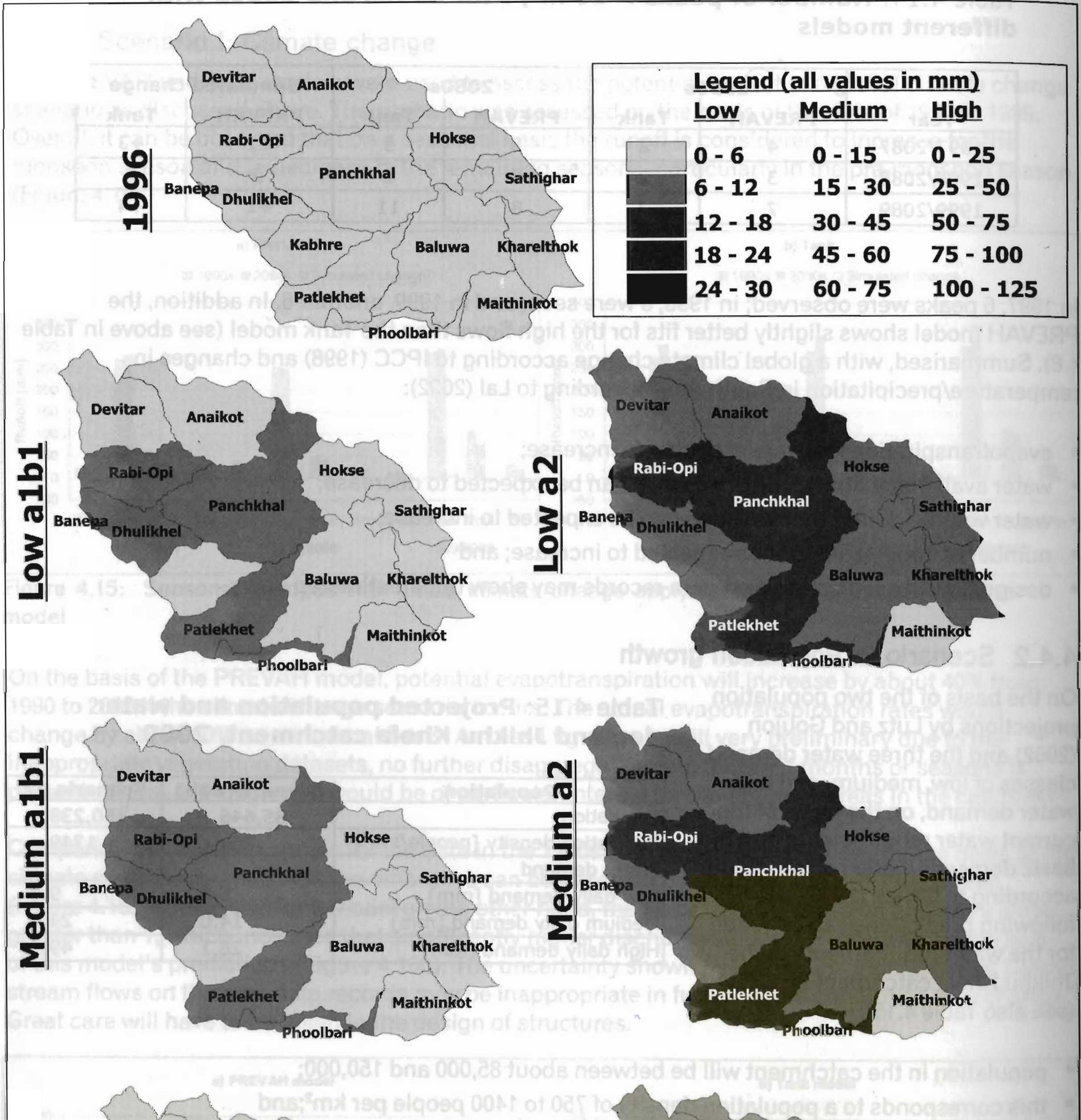

Figure 4.17: **Projected water demand in 2080 in the VDCs of the Jhikhu Khola catchment (note that the colours are the same only within the water demand category, e.g., within low, medium or high)**

south-facing slopes plus Baluwa would be expected to show about 25-50 mm water demand and the remaining VDCs 50-75 mm. Comparing these values with the annual precipitation values or even the monthly precipitation values, there seems no problem of adequate water availability for domestic purposes. However, in this context it has to be remembered that people generally do not use rainwater, but surface water or shallow groundwater for domestic purposes. In this respect, an increase in pollution as was observed in the Jhikhu Khola and documented by Merz et al. (2003b), would put further pressure on the available water resources. In addition, as was mentioned above, the agricultural water demand is more significant.

With the current very high level of agricultural intensity in the catchment (see Chapter 2), only expansion to more marginal lands is possible (see Scenario 3 E1 and E2) if the catchment is to remain self-sufficient in staple food production and still be able to produce cash crops for the markets in the city.

The following summary can be made.

- Water demand for domestic purposes will increase many times over with population growth.
- The main increase in water demand is not expected from population growth, but from increased water demand to achieve a basic water supply according to Gleick's (1996) figures.
- The main water demand increase in the Jhikhu Khola catchment is expected in the VDCs along the two highways crossing the catchment. The VDCs in the upper part will have an important function as recharge areas and water supply for the lower VDCs. This stresses the importance of local-level planning and management of the water resources at the catchment level.

4.4.3 Scenario 3: Land-use change

The calculation of this scenario with the PREVAH model generated a number of open questions, mainly in relation to the observation presented in Chapter 3. In terms of land- use change, the scenarios as presented above result in the expected changes shown in Table 4.16. The scenarios related to Landflucht result in a decrease of rainfed agricultural land with an approximate 10 to 34% decrease depending on the scenario. Grassland increases by 74 to 235% in scenarios Landflucht 2 (L2) and Landflucht (L1), respectively. No changes are expected in the area of shrub land due to grazing and cutting of grasses.

Table 4.16: **Land-use changes on the basis of the land-use scenarios**

Land use	1990s	L1	L2	E2	E2
Rainfed agricultural land	680 ha	448 ha	607 ha	876 ha	822 ha
		-34 %	-10 %	+29 %	+21 %
Grassland	98 ha	329 ha	171 ha	10 ha	37 ha
		+235 %	+74 %	-90 %	-62 %
Shrub land	125 ha	125 ha	125 ha	16 ha	44 ha
		±0 %	±0 %	-87 %	-65 %

Scenarios Expansion 1 (E1) and 2 (E2) are expected to result in the increase of rainfed agricultural land at 20 to 30% depending on the scenario. This is at the cost of grassland (- 60 to 90%) and shrub land (- 60 to 90%).

The impact of these land-use changes simulated with the PREVAH model yield only little change, as shown in Table 4.17. In general, the Landflucht scenarios reduce the runoff, while the expansion scenarios increase the runoff. These results are in strong contrast to the results observed on the basis of event analyses presented in Section3.4. According to these results, catchment runoff increases with an increasing proportion of grassland in the catchment and reduces with the proportion of agricultural land in the catchment. Here the opposite is observed, i.e., the runoff decreases with the proportion of grassland and is the smallest for scenario L1. It is interesting to note that the scenario L1 however shows the highest runoff during the monsoon season.

Comparing the maxima for the four years used for these calculations (Figure 4.18), in three out of four years the Landflucht scenarios, i.e., the scenarios with increased grazing areas, showed the

Table 4.17: **Comparison of the PREVAH outputs with scenarios Landflucht 1 and 2 and Expansion 1 and 2 [all values in mm]**

Season	1990s	2080s_L1	2080s_L2	2080s_E1	2080s_E2
Pre	27.0	26.1	26.7	27.6	27.5
Mon	291.1	291.6	291.1	291.4	291.2
Post	61.4	60.9	61.1	62.0	61.8
Win	26.9	26.4	26.7	27.3	27.2
Annual	*406.4*	*405.0*	*405.6*	*408.3*	*407.7*

peak runoffs. The differences, however, are marginal between the calculated discharges. These results confirm the findings in Chapter 3.4 on the basis of which grassland is decisive in flood generation and the size of a flood peak. For conclusive answers, the findings presented here are, however, not adequate and further improvements have to be made. It is believed that with the availability of the local vegetation characteristics in particular these results will become more conclusive.

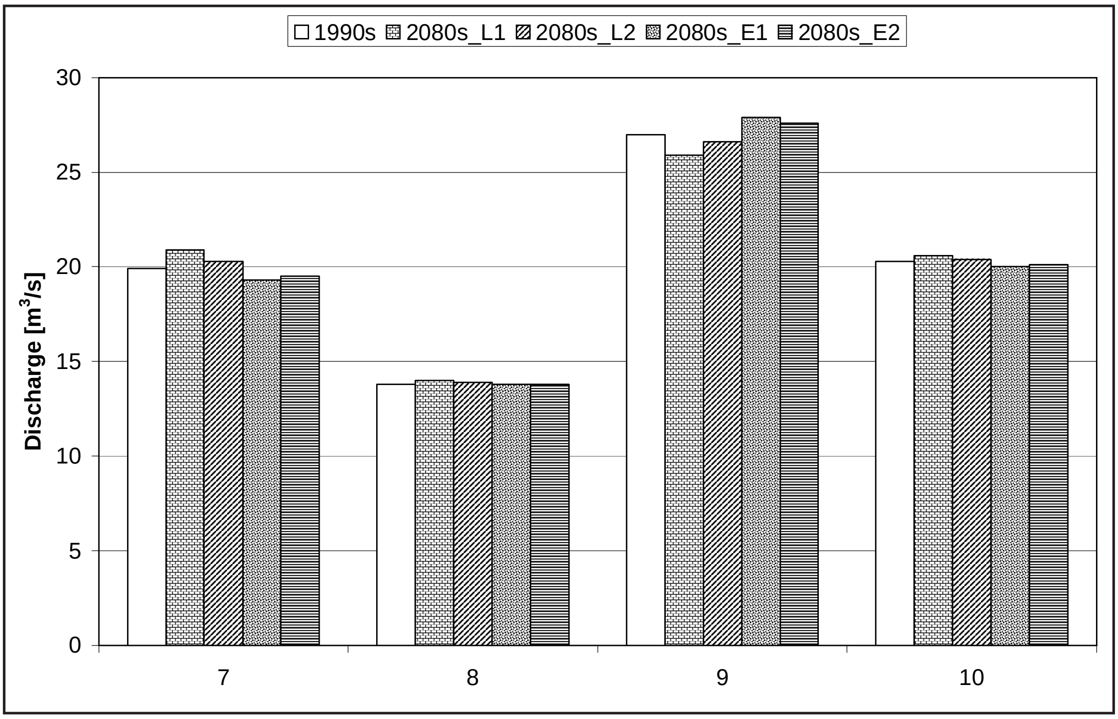

Figure 4.18: **Comparison of maxima**

4.4.4 Discussion

Three different scenarios were parameterised based on global climate change, population development, and land-use change. In brief, it was indicated that potential climate change as well as expected population development might lead to an overall decrease in water availability during the dry season. This is due to a decrease in precipitation during these months, which also has a negative impact on the runoff in the catchment. In addition, water demand is expected to increase many times over on the basis of increased population as well has higher water demands per capita. However, overall, the water demand for domestic purposes is expected to be covered. The parameterisation of agricultural water demand is difficult as the extent to which agriculture can be intensified further is unclear.

During the monsoon season more rain is expected, which leads to a higher susceptibility to flood generation and land degradation. Whether this increase in rainfall also leads to an increase in rainfall intensity and rainfall erosivity still has to be established. On the basis of observations in terms of relationship between maximum rainfall intensity and rainfall amount shown in Section 3.4; and between erosivity (which is calculated on the basis of rainfall intensity; see also Section 3.1) and rainfall amount by Ramprasad et al. (2000; an increase of both these parameters will have to be expected. This increase is further expected to lead to higher and more frequent peaks.

For improved results of the scenario analyses further efforts must be undertaken to improve the efficiency of the models as discussed above. The results of the land-use scenario calculation as presented above are not satisfactory at present, mainly due to the inadequate parameterisation of the local vegetation.

4.4.5 Summary and Outlook

A number of models have been applied for different purposes in the HKH, a detailed comparison with the same datasets as WMO (1975) or WMO (1990) however is missing. The most comprehensive studies undertaken by NIH further concluded that data availability is a major constraint for the successful application of rainfall-runoff models in the mountainous regions. In general, distributed models seem to be more appropriate for mountainous conditions due to the highly variable and heterogeneous conditions in mountain areas, however, the data requirements are often not appropriate.

In this study, three different models were calibrated and validated, the UBC, the Tank model, and the PREVAH model. Of these models, PREVAH showed the best performance, although overall the efficiency for all models was quite low. The main reason for this is the quality of the discharge data, mainly in the low flow regime. In addition, the evapotranspiration in all cases had to be estimated from temperature and none of the more sophisticated methods could be used. With the improvements of the hydrological stations to increase their low flow sensitivity and additional data to calculate evapotranspiration the efficiency could be increased. In the case of the PREVAH model the use of local vegetation characteristics could further improve its efficiency.

The three scenarios based on global climate change, population growth coupled with increasing water demand and rise in living standards, as well as land-use change— both abandoning of marginal land and expansion to marginal fields — showed that overall an increase in water demand has to be expected from all sectors at a time where water availability from precipitation and from runoff during the dry season is presumably going to decrease, and during the wet season is going to increase. This suggests that newly implemented water management options have to increase supply, reduce demand, and enhance water quality. This was discussed in some detail in Merz et al. (2003c).

The use of models on PARDYP data has only just begun, but will receive further attention in the on-going Phase 3. After a model review, which will build on the first overview of model applications in the region based on available literature, modelling exercises will be conducted in all catchments of the PARDYP network with the aim of predicting future developments and spatial up-scaling. In this context it seems to be important to further investigate the impact of the numerous irrigation diversions. Models like WaSim-ETH (Schulla 1997) provide the possibility of including irrigation in the modelling exercise. Other models that could provide good results are expected to be the SLURP model, where there is the possibility of using remotely-sensed data, and which is fully based on land use (Kite 1995); or the SWAT model (Arnold et al. 1998) implemented in an ArcView environment. The Chinese PARDYP team has first experiences with the VIC model, but have not yet produced any conclusive results.

First initiatives towards a regional comparison of hydrological catchment and rainfall-runoff models have been made in the context of the HKH FRIEND project with the aim of conducting a regional workshop on hydrological modelling, followed by regional training on modelling and a regional comparison of different, promising models (Merz 2003).

The impact of these scenarios will be further discussed in Chapter 5 with the impact on the proposed indices.

SYNOPSIS 4: IMPACT OF FUTURE SCENARIOS

Hydrological models were used to document the potential impact of three scenarios based on global climate change, population growth coupled with increased water demand to meet basic requirements, and local land-use change with expansion to marginal lands or abandoning of marginal fields. The preliminary results for the Jhikhu Khola catchment have revealed that:

- **during the dry season water is becoming more scarce due to decreased precipitation, increased evapotranspiration, and decreased runoff;**
- **flood events during the wet season are becoming more frequent and are of marginally higher magnitude;and**
- **dependency of lower lying administrative units in a catchment on upper administrative units is increasing due to the increase of water demand in these lower areas, which are generally more accessible and productive. This calls for the introduction of catchment-based management of water resources.**

These results suggest that more attention should be paid to the storage of surplus water in the wet season to be used during the dry season, as seasonality will probably become even more pronounced in future. While domestic water use is presently below basic water requirements according to Gleick (1996), water supply should take into consideration both a change in population as well as in terms of daily water demands. This suggests that water management options of the future are to tap all available resources, minimise losses and inefficiencies, and improve considerably the quality of the water.

Chapter 5: Synthesis – What is the State of the Water Resources in the PARDYP Catchments?

> ***"Indexes are important because they force decision-making"***
> ***(Canadian finance Minister Paul Martin)***[1]

This chapter first summarises the preceding chapters with two conceptual frameworks before the application of indexes for the assessment of water scarcity, flood generation, and water-induced land degradation in mountainous catchments of the HKH region are discussed. The proposed indexes are applied to the data of the Yarsha Khola and Jhikhu Khola catchments and discussed in view of a later application of the indexes in the other PARDYP catchments in Pakistan, India, China, and other catchments of the region. These indexes are by no means a final product, but serve more to inspire further studies towards the objective comparison of catchments. The data are not only synthesised across catchments, but also within catchments according to spatial and temporal considerations.

"What is the state of the water resources in the PARDYP catchments and how will they be affected in the future?" This question has guided this study on key water-related issues in the PARDYP catchments in the middle mountains of the HKH. The studied catchments all belong to a very fragile region with an important ecological function in a greater river basin context. It is this altitudinal and physiographic zone where rainfall is greatest and the highest specific runoffs are expected (Alford 1992). It is this zone where weak geology and high uplift are prevalent. At the same time, population density and population pressure on natural resources are largest in this altitudinal zone of the HKH region (see also Chapter 2). The function of these catchments is illustrated in Figure 5.1 by Andersson and Quinn (1999), which shows the water availability in a theoretical catchment.

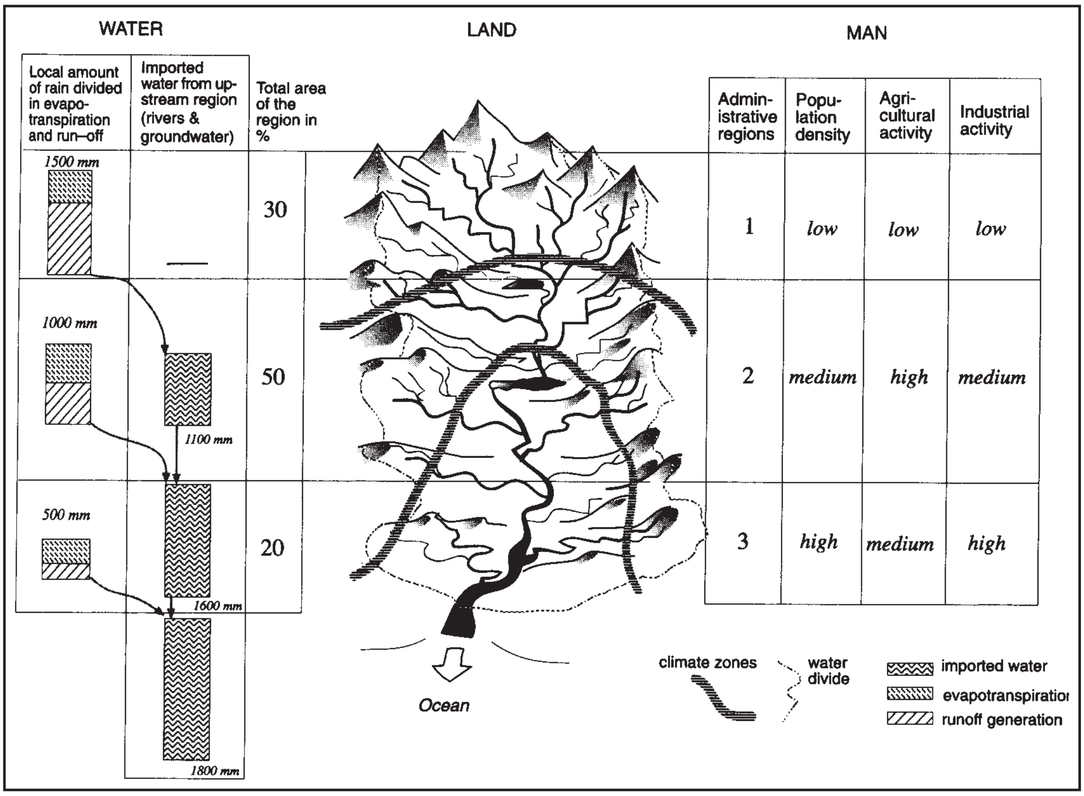

Figure 5.1: **Water availability in a theoretical catchment** (from Andersson and Quinn 1999)

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[1] Newcomb (2001)

7This figure demonstrates, in addition to the changed water availability, the changes in potential water need and the potential for water pollution downstream due to increased population as well as agricultural and industrial activities. The PARDYP catchments belong to the middle catchments and are indicative of administrative units in region 2. In the context of the middle mountains of the HKH region, the population density is high and industrial activities are generally low with the exception of some main valleys such as the Kathmandu or the Doon valleys. Agricultural intensity is often high as is also indicated in this figure. In this context, the studied catchments not only play an important role in the livelihoods of the residents, but also for people further downstream and signs of eutrophication are omnipresent. In terms of water, the PARDYP catchments are headwater catchments and therefore have no inflow from the regions above. All water resources in the catchments are from precipitation only, feeding the surface and groundwater resources.

Below, a summary of the main findings and discussions in the preceding chapters is given through the assessment of the three main susceptibilities related to water in the region — flood generation, land degradation, and water scarcity. The assessment is guided by three indexes based on a number of indicators identified during the course of this study. These indexes should provide a basis for further studies in the region by applying the methodology to other catchments of different size, location, and socio-political context.

The inter-catchment comparison is followed by an intra-catchment synthesis, which will be important for the development of a decision support system as planned for Phase 3. This intra-catchment synthesis focuses on the spatial dimension with particular stress on the topographic dimension, as well as the temporal dimension with particular focus on intra-annual variability.

5.1 CONCEPTUAL FRAMEWORKS

The results of the preceding chapters with particular reference to the key water issues of water availability, floods, and sediment transport are presented in two conceptual frameworks in Figure 5.2 and Figure 5.3.

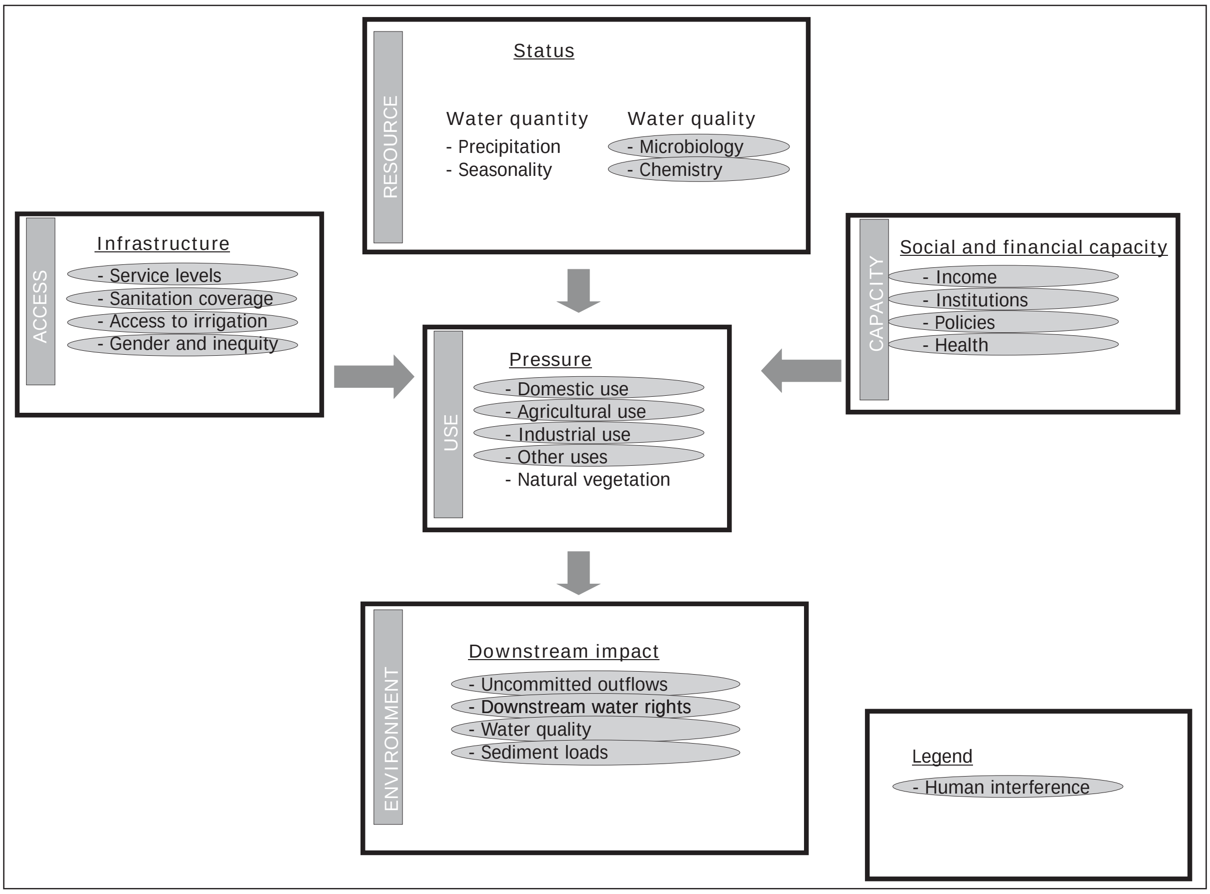

Figure 5.2: **Conceptual framework of water availability in middle mountain catchments of the HKH**

These frameworks are later translated to indexes in the next section. The conceptual framework describing the water availability generally follows a state-pressure-impact approach with the hydro-meteorological and water quality characteristics being the status, the use of water the pressure, and the downstream water availability and quality being the impact. The pressure component is additionally influenced by the infrastructure, which describes the overall access to water resources, and the social and financial capacity of the catchment's residents to cope with the current status and pressure. It is important to note that most of the components in the framework are heavily influenced by human impact with the exception of rainfall and its seasonality.

Flood generation and water-induced land degradation show a different picture in terms of human influence (Figure 5.3). Both processes are directly dependent on the potential hazard, which is mainly a function of hydro-meteorological characteristics. As shown in Section 3.4, there is a significant difference between major events and small to medium events. While the land condition (here also described as base condition) plays a role in the generation of small to medium events, for major events these land conditions can be neglected in the case of flood generation. The hazard coupled with the land conditions produces a certain flood magnitude as a consequence. Given that there is a risk within or immediately downstream of the catchment, potentially a loss has to be expected. The risk, by definition, is completely influenced by humans.

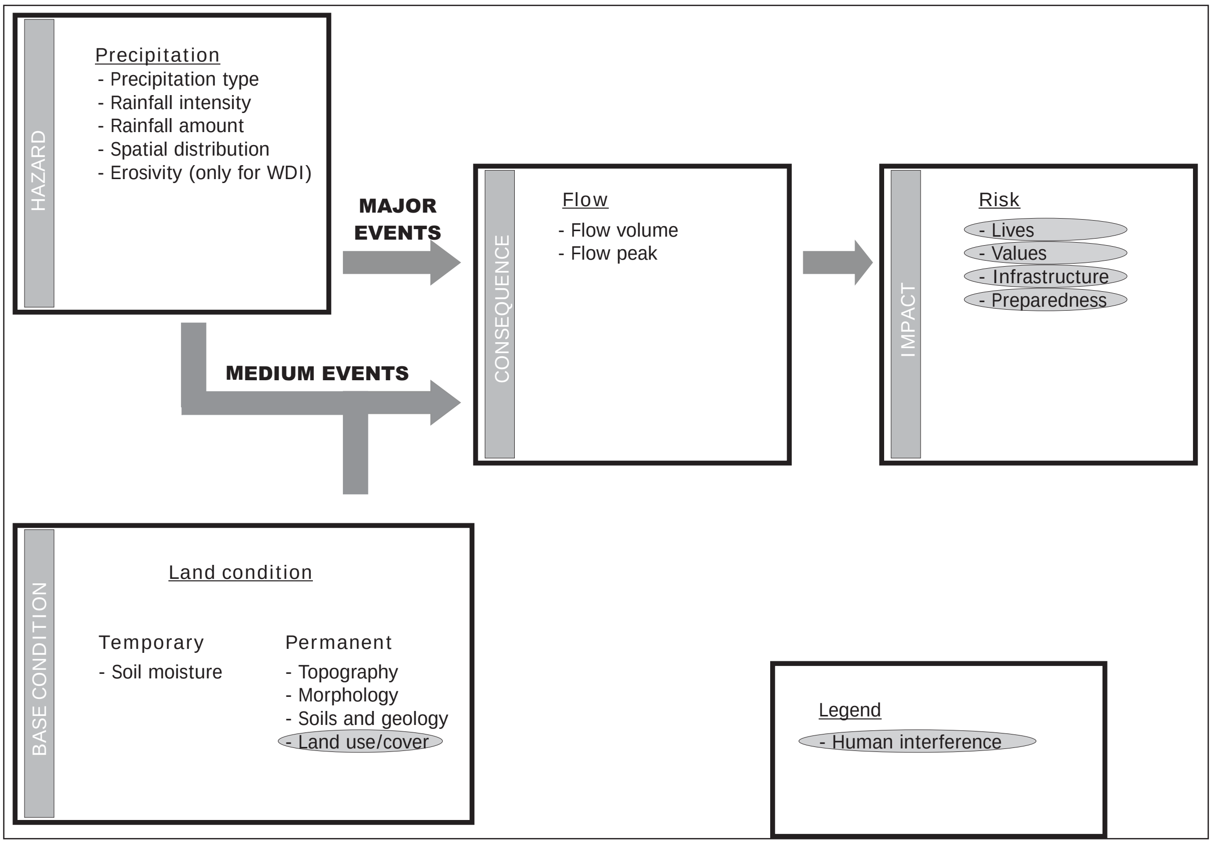

Figure 5.3: **Conceptual framework of flood generation and water-induced degradation in middle mountain catchments of the HKH**

5.2 ASSESSMENT OF DIFFERENT SUSCEPTIBILITIES FOR INTER-CATCHMENT SYNTHESIS

5.2.1 The use of indexes in environmental assessments

As briefly discussed in Chapter 1 the different susceptibilities can be expressed by a number of indicators and finally synthesised in an index for each susceptibility. These indexes can be compared between different catchments, and progress in terms of water resources development, soil conservation, and flood protection can be assessed.

The use of indexes is widespread in economic sciences for assessment and monitoring. The assessment and monitoring of gross domestic product (GDP) uses the WEF Current Competitiveness Index (WEF 2002); human development uses the Human Development Index HDI, the Human Poverty Index HPI, and the Gender Related Development Index GDI (all UNDP 2001); while environmental sustainability and sustainable development employ the Environmental Sustainability Index ESI (WEF 2002), and Indicators of Sustainable Development (CSD 2001). Environmental sustainability and sustainable development also use a number of other indexes mentioned in WEF (2002), as well as those from other fields such as the Living Planet Index (WWF 2002), or the Disability Adjusted Life Year DALY (WHO 2002). These indexes provide a holistic assessment of current conditions, including a set of predefined indicators. But, as Sullivan (2002) remarks, none of these indexes recognises the importance of water to all forms of life. A number of indexes incorporate indicators related to water, e.g., ESI, HDI, however they base the importance of water only on access to safe drinking water, overall water availability, sanitation, and a number of water quality parameters. Indicators such as workload for water fetching (which has a major impact on the amount of water used per household as well as the workload of women in particular; see Gleick 1996), water losses, livestock water demand, local perceptions, and others are generally missing.

In addition to the indexes mentioned, a number of global assessments of water-related issues without the target to determine an index have been presented with a set of interesting indicators (World Bank 1998; Seckler et al. 1998; Shiklamonov 2000; Gleick 2000; WSSCC 2000; OECD 2001; UNESCO-WWAP 2003).

In the literature a number of indexes are proposed for different applications related exclusively to water. Some examples are listed below.

- Sullivan (2002) proposes the Water Poverty Index as a tool to monitor progress towards development targets in water projects and improved satisfaction of the needs of the current generation while securing water availability for future generations (for more details about the WPI, see below).
- Yoffe and Ward (1999) propose an index related to water and conflicts with the aim of identifying river basins with conflict potential over water resources from both an intra-state and interstate perspective.
- Ohlsson (1999) proposes the Social Water Stress Index, which is calculated by dividing a water stress index such as the freshwater availability per capita by the HDI and dividing the result by two.
- Zandbergen (1998) discusses an approach to assessing the health of urban catchments using selected indicators such as imperviousness, riparian forest cover, water quality indexes and others.
- Salameh (2000) proposes another Water Poverty Index with a particular focus on the rainfed agricultural land and suitability in semi-arid and arid conditions.

5.2.2 The FGI, WDI and WPI

In order to capture the specificity of water as an important resource at the same time as a medium for destruction, three different indexes are proposed in the context of rural catchments in the mountainous areas of the HKH.

The proposed indexes with their respective indicators are suitable from the perspective of a middle mountain catchment in the HKH. From the major issues related to water within these catchments or under the direct influence of these catchments downstream it is important to note that water availability and land degradation have a direct impact on the livelihood of the local households and people. Floods, although in places a threat —as for example in the Kathmandu Valley — pose a risk mainly further downstream from these meso-scale mountain catchments. They also put infrastructure, such as bridges and roads, close to the rivers at risk.

In general, the three indexes have a score range from 0 to 100, showing the largest susceptibility with 0, i.e., the worst-case scenario. Each index consists of a number of components describing a general characteristic important for the calculation of the final index. Each component likewise has a score from 0 to 100 and can be weighted according to the user's requirements. The maximum scores of 100 are based on maxima mentioned in the literature, e.g., the potential evapotranspiration in the Tharr desert of 2000 mm according to Wyss (1993). In certain cases, maxima had to be assumed in the absence of any meaningful maxima in the literature. The indexes are calculated as shown in Equation 5.1:

$$I = (w_1 * C_1 + w_2 * C_2 + \ldots + w_i * C_i)/N$$ (adapted from Sullivan 2002) **Equation 5.1**

where

I = index
w_i = weight of the respective component
C_i = component
N = number of components

In Equation 5.1, weights are introduced, however, for the first use of the indexes below all weights were kept as 1.

The components consist of a number of measurable indicators. The most informative indicators and parameters for each index were identified in the course of this study and are discussed below for an assessment of the studied catchments and a comparison with other catchments of the region.

In terms of water availability, Sullivan (2002) proposes the Water Poverty Index (WPI-CEH) as discussed briefly in Chapter 1 and above, and this framework is adapted in this study. A first assessment of the nation-wide WPI-CEH assessment showed Finland at the top indicating it to be the most water-rich country, followed by Canada, Iceland, and Norway. The list ends with Eritrea, Ethiopia, Niger, and finally Haiti (WWC/CEH 2003). Nepal (ranked 90) shows an overall moderate score with a weak score for access and environment, a moderate score for capacity and resource, and a high score for water use. However, as the press release mentions, the final aim of the WPI is to provide a tool for monitoring progress in relation to development of water resources , mainly at the community or district level. The importance of indexes for this level of spatial aggregation and with particular focus on the mountain regions of the world was also stressed by Kreutzmann (2001). The above-mentioned indicators are generally based on national statistics. While this allows the use of regularly collected data and herewith decreasing amount of required funds, it does not cater for the specific conditions of the heterogeneous mountain conditions, and this was highlighted by Kreutzmann (2001) with examples from Nepal and Pakistan. The wide range of conditions amongst the different districts of Nepal in terms of development was also presented in Banskota et al. (1997).

The **Water Poverty Index (WPI)** in this study is a holistic measure of water supply conditions, including the availability of water resources adjusted for quality and reliability (*RESOURCE*); the water demand for different human purposes (*USE*); the effective access to water resources, e.g., in terms of distance and time (*ACCESS*); the human and financial capacity to manage the water supply system (*CAPACITY*); and finally the environmental demands and constraints related to water (*ENVIRONMENT*) (CEH, 2002). The WPI follows the conceptual model presented in Figure 5.2.

WPI = f(resource, capacity, use, access, environment)
- resource = f(hydro-meteorological characteristics, perception)
- capacity = f(income, social networks and user groups, health)
- use = f(water demand for different sectors)
- access = f(infrastructure, gender issues)
- environment = f(water quality, sediment)

In terms of flood generation, the main aim is to document the susceptibility that the catchment actively contributes in the generation of a flood and the threat that these floods pose to downstream areas. The latter is difficult to assess.

Duester (1994) and Weingartner (1999) propose the index 'Hochwasser-Disposition' (flood potential, also briefly discussed in Chapter 2), which indicates the susceptibility of a catchment to generating a flood. This index is based solely on the contributing area, which itself is based on the slope and the distance from the channel, and the total catchment area. Another index in this respect is the Topoindex, which relates the topography to the saturation potential of a catchment (Quinn et al. 1991; see also Chapter 2). This index is based on the slope of each cell and the area above draining into this cell. In certain studies, the soils have been included in the Topoindex framework to produce a soil topographic index (Schulla 1997). The two indexes above are purely based on topographical catchment characteristics (and soil characteristics), but they do not include any information about the potential hazard and the risk given in the catchments, hazard and risk being defined as in Chapter 1.

The proposed **Flood Generation Index (FGI)** is based on the inherent condition of a catchment and the channels towards generating a flood or becoming flooded (*BASE CONDITION*) as well as the related hydro-meteorological processes favouring flood generation (*HAZARD*); and the lives, values, or infrastructure at risk within the catchment or downstream within direct influence of the processes in the catchment (*RISK*). The risk in this context incorporates the people's preparedness and strategy for protection of their lives and infrastructure. This aspect could also be separated as human, social, and financial capital, but in the context of mountain catchments where flooding is only a limited threat, it was deemed possible to lump them together. The conceptual model for flood generation and flood risk is presented in Figure 5.3.

FGI = f(base condition, hazard, risk)
- base condition = f(catchment characteristics)
- hazard = f(hydro-meteorological characteristics)
- risk = f(infrastructure, capacity, perception, preparedness)

Similarly, the **Water Induced Degradation Index (WDI)** describes the condition of a catchment in terms of vulnerability to land degradation caused by water taking into consideration human activities as well as natural conditions. The inherent condition of the catchment favouring sediment mobilisation and transport (*BASE CONDITION*) is based on catchment characteristics. Hydro-meteorological characteristics describe the potentially hazardous processes (*HAZARD*). The people's preparedness to cope with the defined hazards as well as potential losses in terms of infrastructure and livelihoods are described in the sub-index *RISK*.

WDI = f(base condition, hazard, risk)
- base condition = f(catchment characteristics)
- hazard = f(hydro-meteorological conditions)
- risk = f(soil conservation, capacity, perception)

The parameters relevant to certain issues and indexes may change over time and therefore pose a new base for the relevant susceptibilities. With changed conditions the catchment has a new vulnerability to certain processes and therefore possesses a new susceptibility, shown by a new index value. The impact of project activities at the catchment or sub-catchment scale can also be assessed through examining changes in conditions and vulnerabilities and calculating a new index value. Other changes may be due to changes in driving forces, here understood as scenarios, e.g., climate change or policy change. These may impact on the status as well as the processes relevant to a key issue. This leads to an overall change in the respective susceptibility. With the understanding of a certain impact on susceptibility, adverse effects can be averted by employing the appropriate measures. This study will provide recommendations on the basis of the selected datasets and scenarios. However, solutions will not be discussed in this study as further investigation is still required, and is the main thrust of PARDYP's Phase 3.

For the interpretation of the indexes refer to Table 5.1. In general terms, it can be said that an index value of 100 indicates favourable conditions with adequate water supply, no flood, and no degradation threat. An index value of 0 indicates considerable water supply issues, a high likelihood of flooding, and land degradation through water. The values in Table 5.1 are theoretical, as these values are not likely to be achieved in any situation, but they should indicate the given trends towards maximum or minimum extremes.

Table 5.1: **Explanations for theoretical index extremes**

Score	WPI	FGI	WDI
100 **=‘good’**	Water supply is ample and the local demand can be met without impact on the environment; low susceptibility	Floods are not likely to be generated and flooding poses no risk; low susceptibility	There is no reason to believe that land degradation through water is occurring and no risk identified; low susceptibility
0 **= ‘bad’**	Water poses a major problem and neither the population’s demands can be met nor the demands of the environment; high susceptibility.	Flooding poses a high risk and flood events are likely to be generated; high susceptibility	Land degradation through water is likely to occur; high susceptibility

5.2.3 The indicators

On the basis of the analysis in the preceding chapters as summarised in Figures 5.2 and 5.3 and the literature, several indicators were identified that:

a) contribute relevant information towards the assessment of the respective susceptibility, and
b) can be easily measured, determined in a household survey, looked up in the literature, or in national, district or local statistics.

According to Yoffe and Ward (1999), when selecting the indicators it is important that they sufficiently simplify the target system characteristics and that they have adequate spatial and temporal coverage so they can be effectively represented and modelled. In addition, Zandbergen (1998) suggests that some of the indicators should be directly linked to human activities and management to provide an entry for possible intervention and improvement strategies. On the number of indicators he comments that “a fairly high level of integration using a small set of indicators is considered desirable”. Winograd et al. (1999) suggest the use of a small set of well-chosen indicators for the most effective results. Some of the indicators were used by Schreier et al. (2002) for a comparison of Himalayan and Andean catchments to identify those issues in eight catchments of the two mountain ranges that were common to both and those that were different. While this comparison was qualitative, here an attempt is made to provide a more ‘measurable’ and ‘objectively comparable’ means of assessment, but only focusing on the key issues of water resources. It is important to note that, according to Schreier et al. (2002), in all of the eight catchments either water availability, soil erosion, or both figure among the identified key issues. The same was shown by Merz et al. (2003d) in a preliminary and first comparison of the five PARDYP catchments. The selection of parameters and indicators is based on the catchment characteristics and process analyses of Chapters 2 and 3. Overall, 155 parameters are required to calculate the 95 indicators that describe the three indexes. These parameters, appended in Appendix A5.1, are preliminary and need to be tested on the basis of a number of catchments (see Chapter 6). The aim should then be to reduce the number of parameters and indicators.

5.2.3.1 Water Poverty Index (WPI)

As mentioned above, for the WPI, , five sub-index values are calculated: resource, access, use, capacity, and environment. These sub-indexes include the main parameters related to water scarcity and its causes. A complete list of indicators for the WPI is compiled in Table 5.2. In general, the naturally available water resources are assessed using precipitation input, evapotranspiration outputs, and general water quality. In terms of access to water resources, the service levels are assessed as discussed in Chapter 2. Sanitation coverage is also important. The water demand of different sectors gives a total of the overall water use in the catchment. The sub-index environment is mainly based on the integral response of the catchment at its outlet, including water quality, sediment loads, and downstream water availability. Altogether, 111 parameters are required to calculate the 45 indicators of the WPI. Twenty indicators are required for the sub-index resource, 4 indicators for access, 7 indicators for use, 7 indicators for capacity, and 7 for environment.

Table 5.2: **Indicators for the Water Poverty Index**

Indicators	**Unit**	**Relation[*]**	**Min**	**Max**	**Description/Reference**
Resource					
Precipitation	Mm	direct	0	27000	world record line; WMO(1994)
Evapotranspiration	Mm	inverse	0	4000	2000 mm in the Tharr desert; Wyss (1993)
Runoff	Mm	direct	0	3000	Preliminary value
Seasonality precipitation		inverse	0	3.46	maximum based on 100 % rainfall in one month
Seasonality runoff		inverse	0	3.46	minimum based on equal rainfall distribution
Water deficit	No	inverse	0	12	no. of months per year
Rainfall variability-pre-monsoon season		inverse	0	2	assumed maximum
Rainfall variability-post-monsoon season		inverse	0	2	assumed maximum
Rainfall variability-winter season		inverse	0	2	assumed maximum
Annual dry spells	No	inverse	0	24	maximum no. of dry spells possible per year
Average length of dry spell	Days	inverse	0	365	no. of days per year
Longest observed dry spell	Days	inverse	0	365	no. of days per year
Days without rainfall ($P < 1$ mm)	Days	inverse	0	365	no. of days per year
Microbiological contamination		inverse	1	4	four classes according the WHO (1997)
Water treatment coverage	%	direct	0	100	
Waste-water treatment coverage	%	direct	0	100	
Perception on water quantity–Female	%	inverse	1	2	yes/no
Perception on water quality–female	%	inverse	1	2	yes/no
Perception on water quantity--male	%	inverse	1	2	yes/no
Perception on water quality–male	%	inverse	1	2	yes/no
Access					
Service levels for drinking water supply		inverse	1	4	four classes according to RWSSSP (1994)
Access to sanitation facilities		direct	0	100	
Access to irrigation facilities		direct	0	100	
Percentage of women fetching water		inverse	0	100	
Use					
Annual water demand for crop production	mm	inverse	0	5000	2 crops of rice + another crop
Cropping intensity on irrigated land	%	inverse	0	400	maximum of 4 crops
Cropping intensity on rainfed land	%	inverse	0	400	maximum of 4 crops
Annual water demand for domestic use	l/person*day	inverse	0	500	
Annual water demand for livestock	mm	inverse	0	25	10 TLU/ha*61l*365days*area
Annual water demand for industries	mm	inverse	0	1000	assumed maximum
Other water demands	mm	inverse	0	1000	assumed maximum
Capacity					
Institutional organisation-irrigation	org./km^2	direct	0	5	preliminary value
Institutional organisation-drinking	org./km^2	direct	0	5	preliminary value
Patients with water related diseases	%	inverse	0	100	
Children under 5 with diarrhoea	%	inverse	0	100	
Infant mortality rate	per 1000	inverse	0	1000	
Household income	US$	direct	0	5000	preliminary value
Literacy rate	%	direct	0	100	
Environment					
Sediment load	t/ha/y	inverse	0	200	80 t/ha/y; Lauterburg (1993)
Phosphate load (as P)	mg/l	inverse	0	10	7 mg/l in Bagmati river (CEMAT, 2000)
Nitrate load (as N)	mg/l	inverse	0	100	100 mg/l (measured in New Zealand); Close et al. (2001); 60 mg/l in Bagmati River (CEMAT, 2000)
Phosphorous fertiliser	kg/ha	inverse	0	500	
Nitrogen fertiliser	kg/ha	inverse	0	500	
Water demand natural vegetation	mm	inverse	0	2000	preliminary value
Committed outflows/Average runoff	%	direct	0	100	

[*] The relationship indicates whether the respective parameter is directly or inversely related to the index, e.g., the more rain, the better for the WPI = direct relation, the more evapotranspiration, the worse for the WPI = inverse relation.

An example of how the sub-index Access of the WPI is calculated is shown in Table 5.3. In total, eight parameters (A) are required to calculate the four indicators (B) of this sub-index. The overall service level for drinking water supply valid for the entire catchment (C) is based on the percentages for each class from 1 to 4. It calculates thus: (57.4*1+15.0*2+4.7*3+14.4*4)/(57.4+15.0+4.7+14.4) = 1.7. On a scale from 1 to 4 (i.e., service levels 1 to 4), 1.7 lies at 24.6 %. As the relationship between the index and the indicator is inverse, i.e., the higher the index the worse the conditions, the indicator is calculated as 100-24.6 = 75.4. In the case of access to sanitation facilities, where the relation between the indicator and the sub-index is direct, i.e., the higher the percentage of households with access to sanitation the better, the indicator value is directly obtained with 30 %. The total score of this sub-index is calculated according to equation 5.1. For further discussion of the calculation refer to the MSExcel macro (see below).

Table 5.3: **Example for the calculation of the sub-index access of the WPI**

Parameter (A)	Unit	Value	Source	Indicator (B)	Value		
Service levels of water supply							
Service level 1-good	**%**	57.4	Merz et al. (submitted_b)	--> **Service levels for drinking water supply (C)**	**75.4**	--> ***Total score for Access:***	***52.8***
Service level 2-intermittent	**%**	15					
Service level 3-poor	**%**	4.7					
Service level 4-very poor	**%**	14.4					
Not assessed	**%**	8.5					
Access to sanitation							
People with access to sanitation facilities	**%**	30	Estimate	--> **Access to sanitation facilities**	**30.0**		
Access to irrigation infrastructure							
People with access to irrigation water	%	70	Estimate	--> **Access to irrigation facilities**	**70.0**		
Women's workload							
Percentage of women exclusively fetching water	%	64	Merz et al. (2002)	--> **Women exclusively fetching water**	**36.0**		

5.2.3.2 Flood Generation Index (FGI)

The FGI is based on the sub-indexes of hazard, basic condition, and risk. While the hazards are mainly based on rainfall and discharge parameters describing the potentially destructive forces, the basic condition describes the current state of the catchments. The risk parameters are preliminary and need more detailed investigations. This is in terms of actual values in the catchments as well as the scores. The parameters' values, bridges, and population describe the potential losses; while the preparedness and the mitigation coverage, as well as the perception, describe the overall ability to cope with the potential hazard. A complete list of indicators for the FGI is appended in Table 5.4. The index is based on 25 indicators, including 9 indicators describing the hazard, 8 describing the basic condition, and another 8 representing the risk.

5.2.3.3 Water-induced Degradation Index (WDI)

The WDI is calculated from 25 indicators made up of 10 indicators describing the hazard, 10 describing the basic condition, and 5 describing the risk. A complete list of indicators for the WDI is compiled in Table 5.5. This index consists basically of the same indicators as the FGI with the exception of erosivity and sediment load in the sub-index hazard. The basic condition additionally includes the population and livestock stocking densities. The risk sub-index of the WDI is described by the soil conservation coverage, showing the preparedness of the population as well as by the perception on soil erosion and the potential losses in case of severe soil erosion. This is described by the portion of the on-farm income in relation to the total income as well as the productivity of the land.

In order to simplify the calculation procedure, an MSExcel spreadsheet was prepared and appended as Appendix B8. This spreadsheet basically includes a navigation main sheet (Figure 5.4), data entry sheets, index calculation sheets, and summary sheets in both tabular and graphical forms. A brief

Table 5.4: **Indicators for the Flood Generation Index**

Indicators	Unit	Relation*	Min	Max	Description / Reference
Hazard					
Maximum 60 minute rainfall intensity	mm/h	inverse	0	401	world record line; WMO (1994)
20 year return period 60 minute rainfall intensity	mm/h	inverse	0	401	world record line; WMO (1994)
Maximum daily rainfall	mm	inverse	0	1825	world record line; WMO (1994)
Probable maximum precipitation (PMP)	mm	inverse	0	1825	world record line; WMO (1994)
20 year return period for daily rainfall	mm	inverse	0	1825	world record line; WMO (1994)
Daily discharge, maximum	$l/s*km^2$	inverse	0	1000	Preliminary value
Ratio maximum/average discharge	%	inverse	0	100	
Q5 (exc)	$l/s*km^2$	inverse	0	1000	Preliminary value
25 year return daily discharge	$l/s*km^2$	inverse	0	1000	Preliminary value
Basic condition					
Mean slope	deg	inverse	0	45	
Mean topoindex		inverse	0	30	
Elongation ratio (width/length)		direct	0	2	
Irrigated agricultural land	%	direct	0	100	
Ratio cultivated/uncultivated land	%	direct	0	100	
Grassland/pasture	%	inverse	0	100	
Degraded land	%	inverse	0	100	
Other land use/cover	%	inverse	0	100	
Risk					
Values [in % of total catchment income)	%	inverse	0	100	
Bridges	$bridges/km^2$	inverse	0	5	Preliminary value
Livelihoods (houses and agricultural land)	%	inverse	0	100	
Lives	%	inverse	0	100	
Population density	people/km2	inverse	0	5000	
Perception	%	inverse	0	100	
Flood preparedness	%	direct	0	100	
Flood mitigation coverage	%	direct	0	100	

* The relationship indicates whether the respective parameter is directly or inversely related to the index, e.g., the more rain, the better for the WPI = direct relation, the more evapotranspiration, the worse for the WPI = inverse relation.

Table 5.5: **Indicators for Water Induced Degradation Index**

Parameter (A)	Unit	Value	Source	Indicator (B)	Value		
Service levels of water supply							
Service level 1-good	**%**	57.4	Merz et al. (submitted_ b)	--> **Service levels for drinking water supply (C)**	**75.4**	--> ***Total score for Access:***	***52.8***
Service level 2-intermittent	**%**	15					
Service level 3-poor	**%**	4.7					
Service level 4-very poor	**%**	14.4					
Not assessed	**%**	8.5					
Access to sanitation							
People with access to sanitation facilities	**%**	30	Estimate	--> **Access to sanitation facilities**	**30.0**		
Access to irrigation infrastructure							
People with access to irrigation water	%	70	Estimate	--> **Access to irrigation facilities**	**70.0**		
Women's workload							
Percentage of women exclusively fetching water	%	64	Merz et al. (2002)	--> **Women exclusively fetching water**	**36.0**		

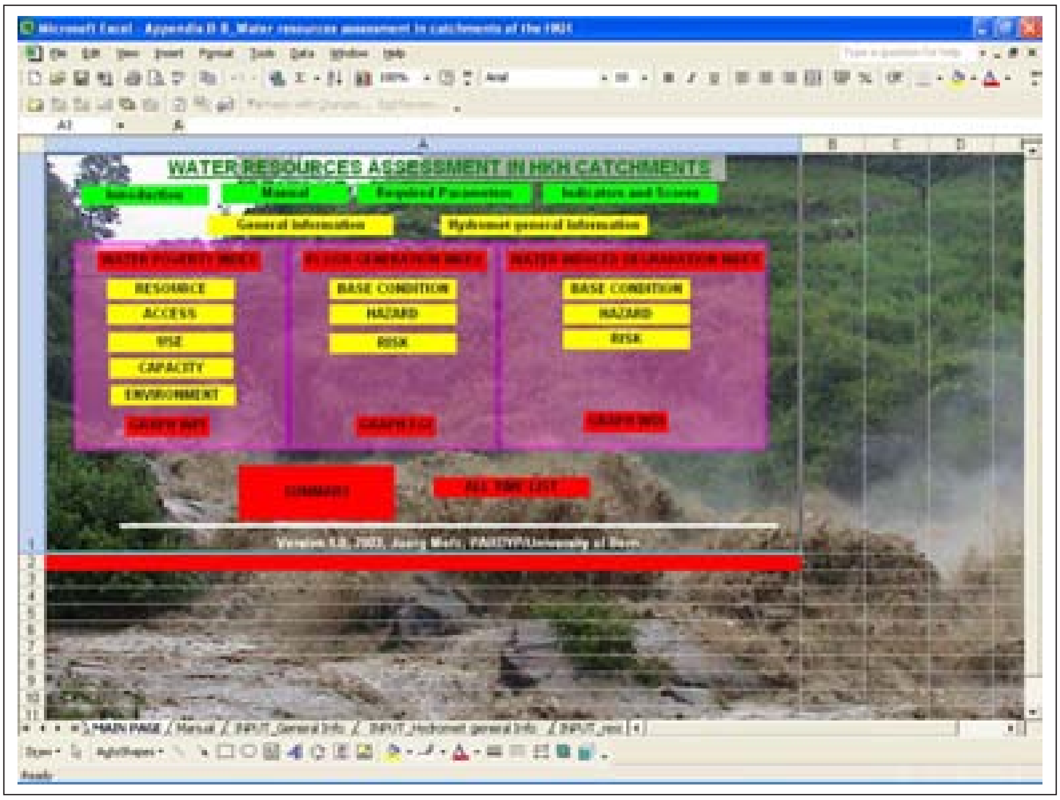

Figure 5.4: **Navigation main sheet for water resource assessment in HKH catchments**

manual explaining the colours used and the different functions is included as a separate sheet. The idea of this spreadsheet and the reason that it is coded in MSExcel is so that the project can test the approach in other catchments and develop it further for potential up-scaling.

5.2.4 Application of the proposed indexes

The three indexes were primarily applied to the two catchments in Nepal, the Jhikhu and Yarsha Khola catchments. For a first preliminary comparison they were also applied to the available information from the remaining PARDYP catchments. In addition the impact of two scenarios is assessed using the index approach and the WPI in particular.

5.2.4.1 Comparison of the indexes for the Jhikhu and the Yarsha Khola catchments

In the Jhikhu Khola catchment, the WPI assumed a value of 59.2 points with the following values for the sub-indexes: resource, 46.8 points; access, 52.8 points; use, 80.3 points; capacity, 49.9 points; and environment, 66.4 points. The complete file, including the input data and the score limits, is included as Appendix B.9. For the meaning of a high or low index value refer to Table 5.1; but it should however be remembered that the indexes are a relative measure and therefore show their best results in comparison with other catchments (see below).

The values of the sub-indexes show that in the Jhikhu Khola catchment a problem with water availability has to be expected, as indicated by the low resource value. The other values that are rather low are access and capacity. This is not surprising in the context of Nepal, with the often long distances to the water sources, the high burden on women's shoulders in terms of fetching water , generally poor access to sanitation and irrigation facilities, as well as low service levels for drinking water supply. The capacity is low due to low income, generally bad health, and low education status as shown with low literacy rates. Use shows a high value due to the low water demands for domestic, industrial, and other uses in the catchment. Agricultural demand is high in the catchment, although this is not shown by the index mainly because of the high maximum on the score board with two crops of rice and an additional crop. It is expected that this value will show low values in comparison with the other catchments.

The FGI assumed a value of 75.4 points with the following sub-index values: basic condition, 59.2 points; hazard, 81.2 points; and risk, 85.9 points. The hazard value results are quite low, although the rainfall characteristics on a first observation (see Section 3.1) indicate rather high rainfalls and high intensities. The WDI showed a value of 61.4 points with a basic condition of 74.8 points, a hazard value of 70.9 points, and a risk value of 38.6 points. For a graphical representation refer to Figure 5.5.

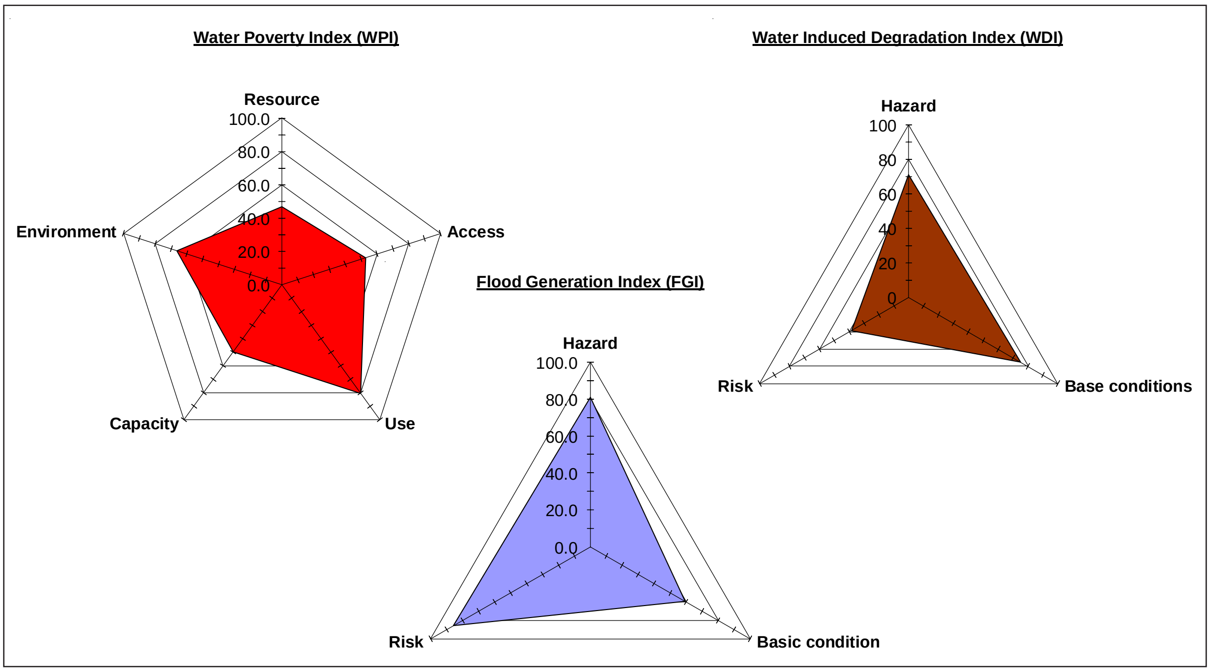

Figure 5.5: **WPI, FGI, and WDI of the Jhikhu Khola catchment**

In the Yarsha Khola catchment, the WPI assumed a value of 63.2 points with sub-index values of 54.5 points for resource, 55.6 points for access, 82.4 points for use, 47.6 points for capacity, and 76.1 points for environment (for the detailed file including the input data and the score board refer to Appendix B.10). A graphical comparison of the three indexes in the Yarsha Khola catchment is shown in Figure 5.6.

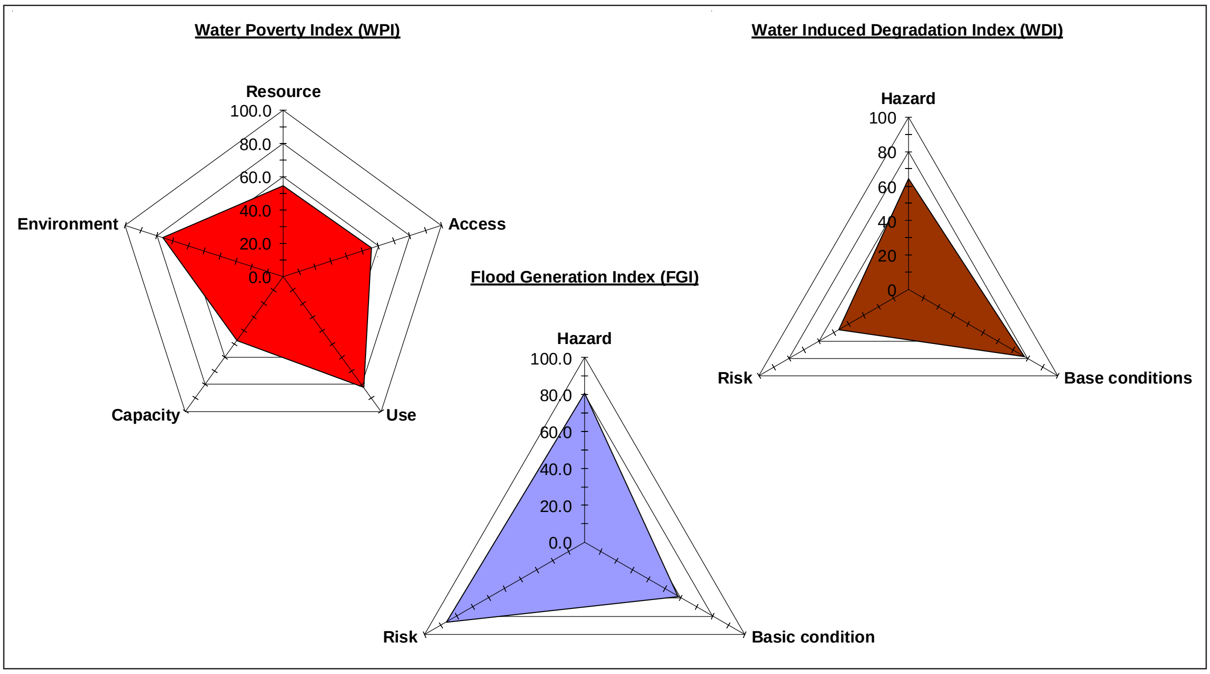

Figure 5.6: **WPI, FGI, and WDI of the Yarsha Khola catchment**

Water availability is an issue, particularly due to the high seasonal differences and the intra-annual variabilities. Access to water resources likewise shows a rather low value, mainly due to the low access to sanitation and irrigation facilities. The drinking water supply service levels are quite good in this catchment since most of the households depend on tap systems. Water demand is very low in the catchment. This is true for all sectors, including agriculture, as the farming systems in this catchment are not very intense. The low values for capacity are mainly due to the small number of irrigation and drinking water supply associations in the catchment, which may have an impact on the strength of the water supply organisation. The environmental flow conditions and the water demand and supply situation for the natural environment in this catchment are satisfactory.

The FGI assumed a value of 75.2 with the sub-indexes of 58.5 points for base conditions, 80.7 points for hazard, and 86.3 points for risk. The WDI assumed 62.8 points, with 77.7 points for base condition, 64.3 points for hazard, and 46.5 points for risk.

Comparing the two catchments in Nepal (Figure 5.7), the following is evident.

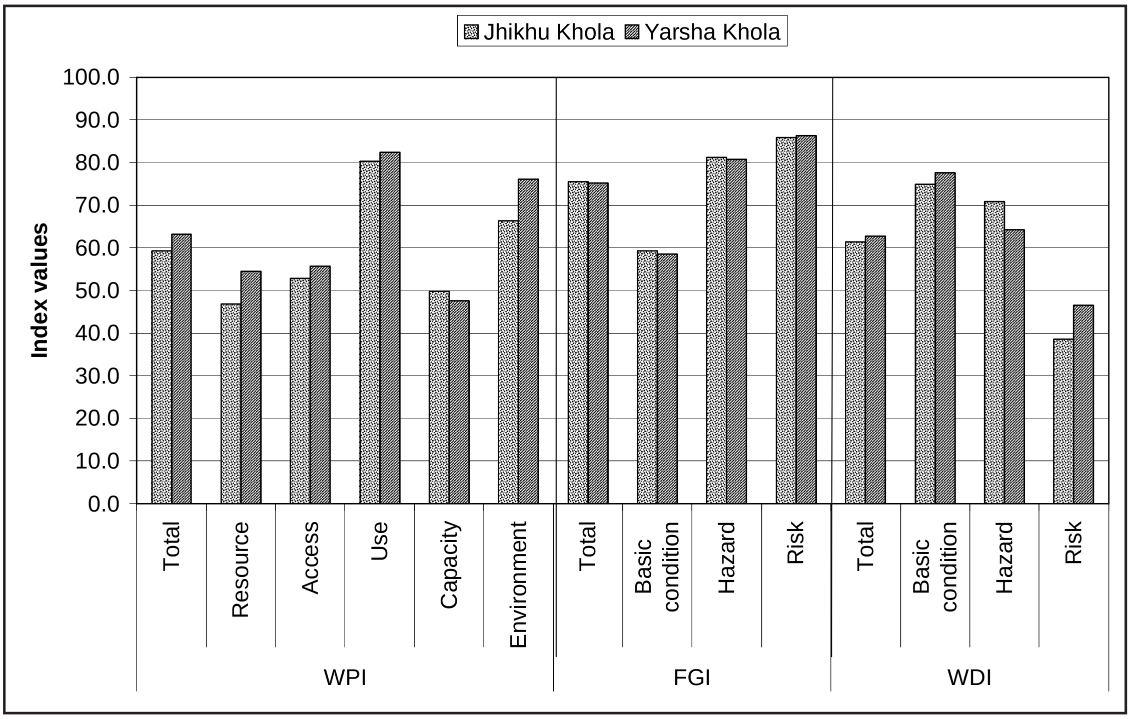

Figure 5.7: **The WPI, FGI, and WDI in the Jhikhu and Yarsha Khola catchments**

a) *The Jhikku Khola catchment is more prone to water scarcity than the Yarsha Khola catchment*
The Jhikhu Khola catchment shows, with 59.2 points, a slightly lower WPI than the Yarsha Khola catchment with 63.2 points. This shows that water scarcity susceptibility is higher in the Jhikhu Khola catchment than in the Yarsha Khola catchment.

The Yarsha Khola shows the higher resource score, which is mainly due to the higher rainfall in this catchment, the lower evapotranspiration rates, and the more pristine water quality. In addition, the water use is lower in the Yarsha Khola catchment than in the Jhikhu Khola catchment, mainly based on the lower agricultural water demands. The capacity to cope with these water issues is higher in the Jhikhu Khola catchment based not only on higher incomes, but also based on higher literacy rates. The sub-index values for environment are higher in the Yarsha Khola based on the lower fertiliser use and the lower water demand by natural vegetation.

The worse natural conditions in the Jhikhu Khola catchment are met with better social conditions such as higher education and better economic status than in the Yarsha Khola catchment.

b) *The Jhikku Khola catchment is about equally prone to flood generation as the Yarsha Khola catchment*
The lower hazard values in the Yarsha Khola due to more intense rainstorms, more rain in general, and the lower basic condition values are balanced by the higher risk sub-index due to lower values, population, and infrastructure at risk in the Yarsha Khola catchment. Basically, the Yarsha Khola flows continuously in a gorge, where only few people live and generally no infrastructure is found. In the Jhikhu Khola catchment, on the other hand, large areas of agricultural land and a number of houses and their owners are potentially affected by a flood.

c) *The Jhikku Khola catchment is more prone to land degradation than the Yarsha Khola catchment*
The Jhikhu Khola catchment shows a lower WDI than the Yarsha Khola catchment. This is based on the lower values for the sub-index risk as well as the basic condition. The hazard sub-index assumes lower values in the Yarsha Khola catchment than in the Jhikhu Khola catchment.

5.2.4.2 Assessment of scenario impacts

The two examples below should show how the impact of a change in a driving force such as climate change, a development project, or a policy could be monitored using the indicator approach. The first example shows the tremendous impact of a rural development project which aimed to improve the water supply situation in the Jhikhu Khola catchment. The changes of parameters are hypothetical and not based on a real situation. The second example shows the impact of climate change using the scenario by Lal (2002) as predicted by the PREVAH model (for more details about the modelling refer to Chapter 4). The parameters that changed in the two examples are compiled in Table 5.6.

Table 5.6: **Parameter values before and after the selected impact**
($^{\#}$ rural development project, $^{\&}$ climate change)

	pre-project	**post project**
Resource		
Public water sources below guideline value (no risk)	5$^{\#}$	15
Public water sources below guideline value (low risk; 1-10)	4$^{\#}$	33
Public water sources below guideline value (intermediate risk; 10-100)	10$^{\#}$	10
Public water sources below guideline value (high risk; 100-1000)	39$^{\#}$	0
Water treatment coverage	10$^{\#}$	50
Waste-water treatment coverage	5$^{\#}$	20
Water quantity adequate (female/male)	41/24$^{\#}$	75
Water inadequate (female/male)	59/76$^{\#}$	25
Water quality good (female/male)	56/75$^{\#}$	75
Water quality bad (female/male)	44/25$^{\#}$	25
Average annual areal reference evapotranspiration	1175$^{\&}$	1536
Average annual areal precipitation	1295$^{\&}$	1236
Average annual runoff at the outlet	411$^{\&}$	506
Annual dry spells	4$^{\&}$	6
Average length of dry spell	44$^{\&}$	60
Longest observed dry spell	113$^{\&}$	130
Days without rainfall ($P < 1$mm)	250$^{\&}$	280
Coefficient of variation for pre-monsoon season	0.5$^{\&}$	0.9
Coefficient of variation for post-monsoon season	1.2$^{\&}$	1.3
Coefficient of variation for winter season	0.9$^{\&}$	1.1
Access		
Service level 1-good	57.4$^{\#}$	80
Service level 2-intermittent	15$^{\#}$	20
Service level 3-poor	4.7$^{\#}$	0
Service level 4-very poor	14.4$^{\#}$	0
Not assessed	8.5$^{\#}$	0
People with access to sanitation facilities	30$^{\#}$	80
People with access to irrigation water	70$^{\#}$	90
Percentage of women exclusively fetching water	64$^{\#}$	10
Capacity		
Patients in health facilities with water related diseases	25$^{\#}$	5
Children under 5 with diarrhoea within 2 weeks before survey	15$^{\#}$	2
Infant mortality rate	64$^{\#}$	30

The hypothetical and highly successful rural development project achieved a total change of the WPI of 10.3 points, from 59.2 to 69.5 points, and overall conditions were improved. The main change was observed in the case of the sub-index access to 88.3 points, a change of 35.5 points. The sub-index resource changed to 57.5 points, a change of 10.7 points, while capacity became 55.1 points, a change of 5.2 points. Use and environment remained the same. A graphical representation of the changes is shown in Figure 5.8a.

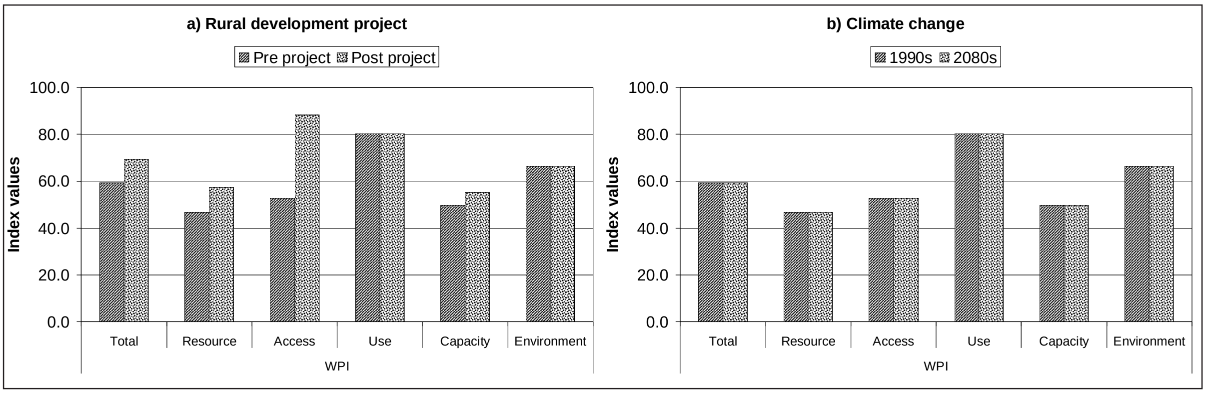

Figure 5.8: **Impact of the rural development project (a) and climate change (b) on the WPI in the Jhikhu Khola catchment**

The global climate change scenario was simplified to the extent that only resource parameters were changed. Other parameters such as demands for water for agriculture or for natural vegetation are presumably also subject to changes in case of higher evapotranspiration rates. In the case of this simplified version of global climate change impact, the total WPI changed by –0.7 points, from 59.2 to 58.6 points with all the changes that occurred in the sub-index resource. This sub-index changed to 43.3 points by –3.4 points.

This suggests that with a global climate change scenario as suggested by Lal (2002), availability of water resources would decrease and worsen the overall water supply conditions in the catchment. The same result was also obtained on the basis of the modelling results in Chapter 4.

5.2.4.3 Comparison of PARDYP catchments

The main benefit of these indexes is believed to be the objective comparison of catchments and the assessment of required action in the water resources' sector. A first preliminary comparison of the WPI was carried out in the four PARDYP catchments of India (data source: PARDYP India, pers. communication), Nepal, and Pakistan (data source: PARDYP Pakistan, pers. communication). The PARDYP China team unfortunately did not respond in time to include their data in this preliminary analysis. The FGI and the WDI could not be included as no estimates could be provided for the sub-index risk. The comparison showed clearly that the Jhikhu Khola catchment has the lowest resources of the four catchments, both based on the quality as well as quantity (Figure 5.9). In terms of access, the catchments in Nepal show much better values than the other two catchments, mainly because the percentage of households where water is exclusively brought by women is lower in these catchments than in India and Pakistan. The capacity is identified to be lowest in the Indian catchment mainly due to the low economic status in the catchment. The best conditions in terms of environment are given in the Hilkot catchment, followed by the Yarsha Khola catchment, and finally the two catchments of the Jhikhu Khola and Bhetagad.

5.2.5 Discussion

The proposed indexes are by no means believed to be a final product without any possibility of improvement. The introduction of these indexes is meant mainly to provoke thought about the PARDYP project and point a possible way forward in the discussion of the upscaling of project experiences and the objective comparison of catchments.

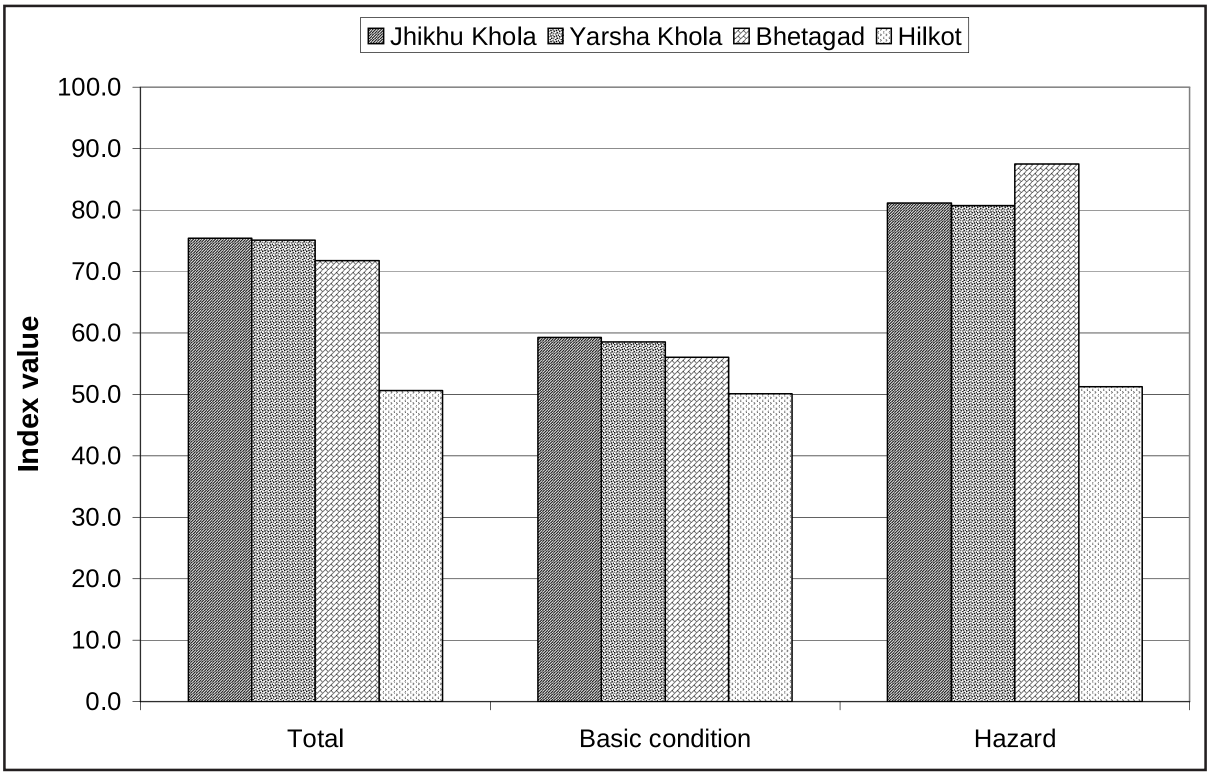

Figure 5.9: **The preliminary WPI in four PARDYP catchments (note: missing parameters in the Bhetagad and Hilkot datasets were also removed from the Jhikhu and Yarsha Khola datasets)**

At present, the sensitivity of the indexes is very low, i.e., the values of the Yarsha Khola and the Jhikhu Khola catchments are very close and similar. The reason for this is the choice of score maxima. For example, the use of the world record line of rainfall according to WMO (1994) showing a maximum of 27,000 mm annual rainfall is 25,705 mm more than the annual average rainfall in the Jhikhu Khola, and 24,794 mm more than in the Yarsha Khola catchment. This results in a score of 4.8 % for the Jhikhu Khola catchment and 8.2 % for the Yarsha Khola catchment. The difference between the Jhikhu and the Yarsha Khola catchments is therefore just 3.4 %, with an absolute difference of 911 mm. The use of this maximum figure is justified, as this value was observed in Cherrapunjee in the Meghalaya Hills and is therefore part of the HKH region, for which this method was prepared. However, for the choice of score maxima and minima, other rules could be used, such as the highest value amongst the catchments being automatically the score maximum. This would, however, reduce the applicability of that particular score board to other regions.

In terms of data requirements, it is important to note that the Indian and Pakistani data were compiled in just a few days. However, the indicators as well as the number of these will have to be further scrutinised in Phase 3 of the PARDYP project (also see Chapter 6). In order to successfully use the indicator approach, the most sensitive and the most easily collected indicators have to be included in the method.

The chosen equation for the calculation of the indexes shown in equation 5.1 is based on additions. This leads to an averaging of the conditions in the case of extremely high values on one hand and extremely low values on the other. In order to identify these extremes it is important not only to compare the final indexes, but also their sub-indexes.

The index approach has shown an interesting way forward where PARDYP could provide a useful method and show its comparative advantage as a project of a regional nature. In order to provide a final method, further activities and a firm commitment are required (also see Chapter 6).

5.3 SPATIAL AND TEMPORAL INTRA-CATCHMENT SYNTHESIS

5.3.1 Spatial synthesis

For all PARDYP activities and the activities of other watershed management projects, the unit of catchments is used. A method for the objective comparison of the catchments was discussed above. However, the catchments are of considerable spatial heterogeneity. This was discussed in Chapter 2 on the basis of catchment characteristics as well as in Chapter 4 in terms of modelling. The processes likewise differ spatially, which was discussed in Chapter 3. For the development of a decision support system (DSS), this heterogeneity has to be described and the necessary steps taken.

As shown in Chapter 3, there is often a good relationship between elevation and many water resources' related parameters. In the case of the two catchments in Nepal, this includes annual rainfall, erosivity, evapotranspiration, and others. However, these relationships tend to change from location to location as shown with a comparison of the relationships for the Jhikhu and Yarsha Khola catchments in Chapter 3. Merz and Nakarmi (2001) therefore propose the use of general topography and landforms for the DSS base, and the inclusion of rainfall and temperature from a simple measurement network of two to three sites or a locally available dataset. The reason for using the topography is based on the fact that different water sources are present at different locations in a catchment (Figure 5.10). Precipitation is the only conveniently located source of water along the divide and close to middle ridges. This zone is followed by a zone where natural springs can be found in addition to the precipitation. Simultaneously, rivulets start to form but they generally have low flows and often dry up during the late dry season. A next zone, on the foot slopes of the valleys, includes rivers that have reached a considerable size and can be harvested for various purposes. The last zone also includes groundwater. Keeping Figure 5.1 in mind, water quality changes along the way from precipitation to streamflow and groundwater. Precipitation has the best quality status (as shown by a few samples of Schaffner 2003), followed by springs. In the case of good aquifers, the groundwater is qualitatively better than the river water to a considerable degree.

Aspect was shown to play a minor role in terms of rainfall in the upper areas of the catchment; in the lower stretches or the foot slopes of the valley, on the other hand, a distinct difference was observed. Annual temperature extreme values (i.e., annual minimum and maximum) tend to differ according to aspect on the lower foot slopes with higher minimum and maximum temperatures on the south-facing slopes. The same as in the case of precipitation was shown for the upper slopes where temperature does not differ distinctly between the slopes.

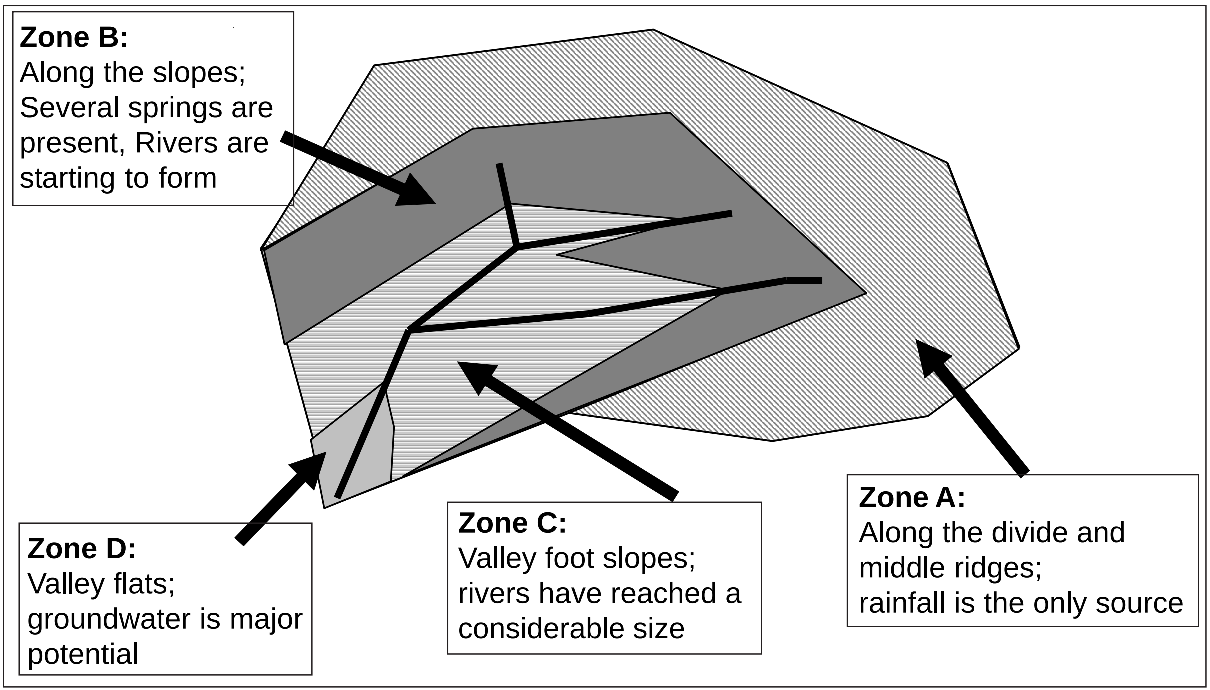

Figure 5.10: **Zones of different water sources in a hypothetical catchment**

The approach above suggests that different water management solutions have to be sought and proposed for each zone. Methods appropriate in a mainly rainfed zone may not be appropriate in a zone where groundwater is available. In the DSS this should be kept in mind and used to suggest the appropriate solutions as well as for upscaling the method.

5.3.2 Temporal synthesis

The processes vary not only spatially as shown above, but also temporally. The inter-annual variabilities of different water resource parameters are limited due to the stable macro-climatic conditions of the monsoon and the westerlies, which are primarily responsible for the summer and winter rains respectively. A note of caution has to be mentioned here as the impact of global climate change is being discussed and different scenarios have been identified (e.g., see Chapter 4 or IPCC 1998). The intra-annual temporal variability or seasonality of water resources, however, is a major constraint in the region, in catchments that depend entirely on precipitation in particular. Most of the hardship related to water availability can be attributed to this highly seasonal behaviour. The main question is, therefore, when is the most critical time of the year?

The critical times in a year are based firstly on natural conditions, and secondly on the farmer's expectations according to traditional farming practices. For considerations about the availability of water, the greatest risk of very dry conditions in the Jhikhu Khola catchment is during the early pre-monsoon season, in April and May (Figure 5.11a). During this time, rainfall is low and often variable and evapotranspiration is high. This results in the lowest runoff during the year and the highest water deficits. During the monsoon season the risk is low, as there is ample and secure rainfall resulting in a water surplus. The post-monsoon and winter seasons are dry from the point of precipitation. Due to the low evapotranspiration during this time of the year, soil moisture availability is high, resulting in low to medium water deficits and risk. Comparing the observed deficit (i.e., as determined from scientific data for precipitation and evapotranspiration) with the deficit perceived by the local residents, a nearly perfect match could be determined.

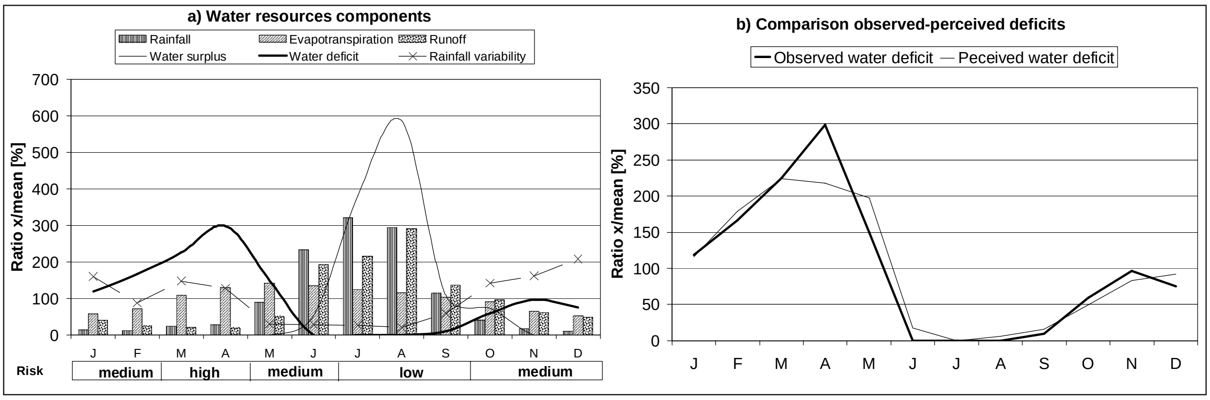

Figure 5.11: **Temporal distribution of selected water resource components (a), and comparison with perceived water shortages (b)**[2]

Linking the availability of water resources with the cropping calendar for the Jhikhu Khola catchment, it is evident, that the calendar is very well adapted to local water availability (Figure 5.12). On the irrigated land (Figure 5.12a) the pre-monsoon season crops of tomato and maize are only grown if adequate water is available to allow enough irrigation during the time of highest risk of water scarcity. The rainfed agricultural land (Figure 5.12b) during this time is fallow and ready for planting maize after the first good seasonal rains. From the point of view of agronomic interventions, it is this time period that allows changes. While the remaining seasons are important for the staple food production, these few months during the dry season could be used for an additional cash crop.

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[2] **The perceived water deficits are based on the answers of 178 male farmers in the Jhikhu Khola catchment to the question "In which months do you face water deficits for irrigation purposes?" (Merz et al. 2002)**

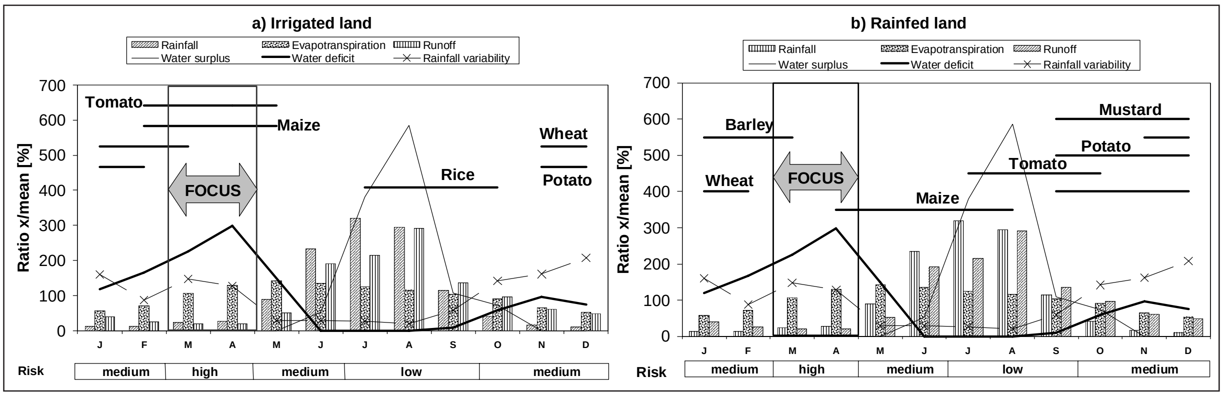

Figure 5.12: **Comparison of temporal distribution of selected water resource components with crops on a) irrigated land and b) rainfed agricultural land**

As water availability is the main concern, vegetables that can be grown with low cost drip irrigation (Polak et al. 1997) would be most suitable.

On the irrigated land on the valley floor, Prajapati-Merz et al. (2003) selected bitter gourd for a trial and suggested other cucurbits such as cucumber or other different gourds for this season. This crop is sown in February after the wheat or potato crop and is harvested in mid-May to July before transplanting the rice crop. For a plot of 12 m by 12 m Prajapati-Merz et al. (2003) planted a total of 96 bitter gourd plants. This produced a total of 612.1 kg of marketable fruit (excluding 2.7 kg of damaged fruit) which, at a price of 15 NRs (~0.2 US$), resulted in a total income of NRs 9182. Subtracting the total expenditure, including drip irrigation set, labour cost, seedlings, and fertiliser amounting to NRs 2712, a net benefit of NRs 6470 was realised.

On rainfed agricultural land where only a two- to three-month time slot is available between the wheat or potato and the maize crops, three months' cole crops are suggested. Adhikari et al. (2003) and Von Westarp (2002) made successful trials with cauliflower, though slightly earlier in the season, from October to January instead of the suggested February to April period.

Water for these off-season cash crops during the time of highest water scarcity risk could be provided from springs, rivers with very low flows, or water harvested in an underground cistern as proposed by Nakarmi and Neupane (2000). The bitter gourd trial by Prajapati-Merz et al. (2003) used a total of 2240 litres for a plot of 12 m by 12 m. Von Westarp's (2002) trial indicated that an additional cauliflower crop on a field size of 180 m^2 required about 11,000 litres of water. Under deficit irrigation, i.e., deliberate under irrigation of a crop for efficient use of water (Von Westarp 2002), this amount of water could be reduced to 6000 litres at similar yields. The link between water harvesting and drip irrigation will be further pursued by the project.

To reduce the risk to crops in the post-monsoon season , improved recharge of late monsoon showers with resulting increased soil moisture levels, water harvesting in connection with drip irrigation for cash crops, as well as the use of sprinklers for the post-monsoon potato crop are suggested.

For domestic water supply, no distinct temporal differences are expected from the requirements side. The supply, however, seems to decrease towards the end of the dry season on the basis of the perceived water deficit for domestic purposes (Figure 5.13). The same was reported during the public water sources' survey, according to which the yield in all sources tends to decline towards the end of the dry season in the months of April/May (Merz et al. submitted_b). The highest risk for water scarcity from a quantity point of view is therefore the pre-monsoon season during the months from March to May.

From the point of view of water quality, this period in the pre-monsoon poses a medium risk with the highest risk observed during the monsoon season where the highest coliform, turbidity, and nitrate levels were observed in the 33 public water sources investigated (KU/ICIMOD 2001).

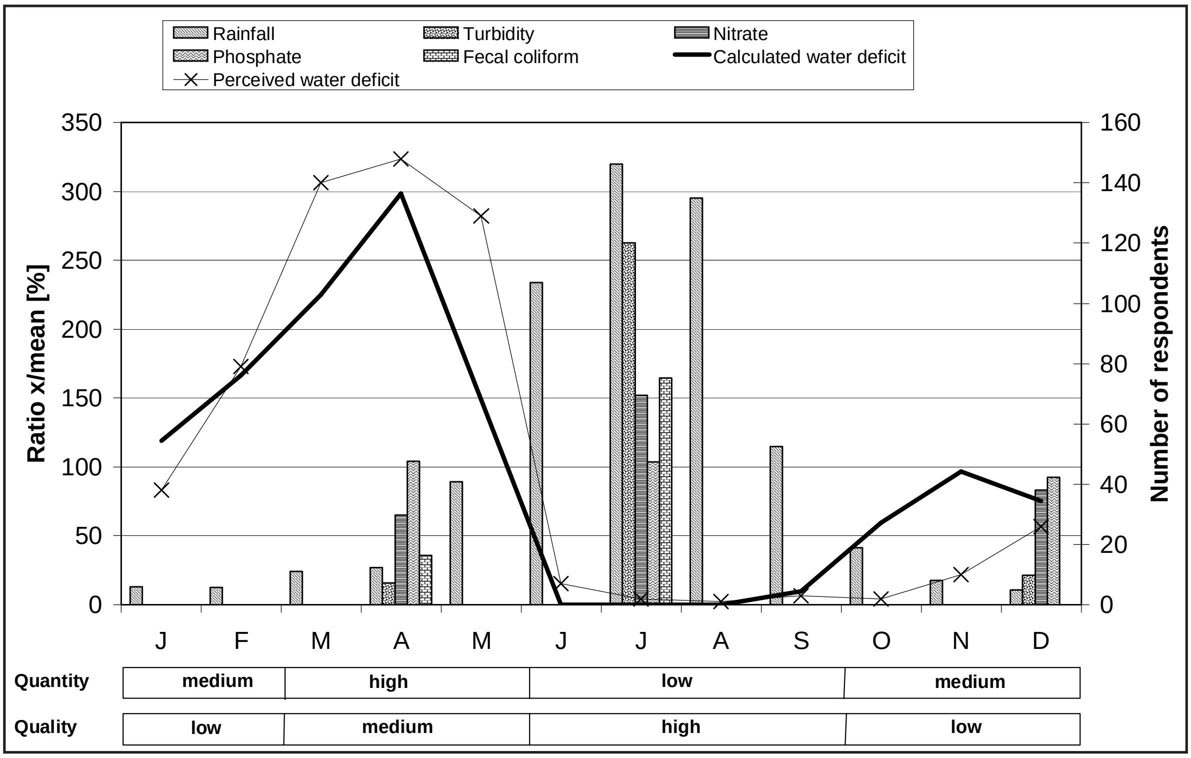

Figure 5.13: **Temporal distribution of selected water resource components related to domestic water supply[3] (note: right axis for perceived water deficit)**

In order to improve the water quantity and quality situation in these catchments, an integrated water supply, water demand, and water quality management approach is necessary. Different approaches are discussed in Merz et al. (2003c). While during the dry season supply has to be ensured — for example through improved catchment management or water harvesting — water quality during the monsoon season when the risk is highest could be improved through simple treatment methods.

From an erosion risk perspective, two different aspects have to be distinguished: surface erosion that mainly depends on the rainfall and vegetation characteristics (see Section 3.5) and streambank erosion and mass wasting that largely depends on major flood events as well as high soil moisture contents. In this context, the late pre-monsoon and the early monsoon season show the highest surface erosion risk (Figure 5.14). This is the time with generally the biggest rainfall events, intensities, and erosivities. At the same time, this is also the initial crop development stage for the maize crop with only little ground cover. In addition, farmers tend to weed their maize fields to reduce competition between the weed species and the maize plants. From a mass wasting and streambank erosion point of view, it is the late monsoon season that shows the highest risk. Flooding depends largely on rainfall characteristics, rainfall volume, and intensity in particular and therefore can occur anytime during the year. Most frequently the largest flood events occur during the monsoon season with some isolated events either in the pre-monsoon or monsoon season (for more detail refer to Chapter 3).

5.3.3 Summary

Three indexes, the WPI, the FGI, and the WDI were proposed to assess water availability, flood generation, and land degradation susceptibilities respectively in a middle mountain catchment. These indexes can be used for the comparison of catchments, for the assessment of impact by changes in driving forces, or changes induced by project activities. The parameters to calculate the indicators of the indexes are based on the analyses in the previous chapters.

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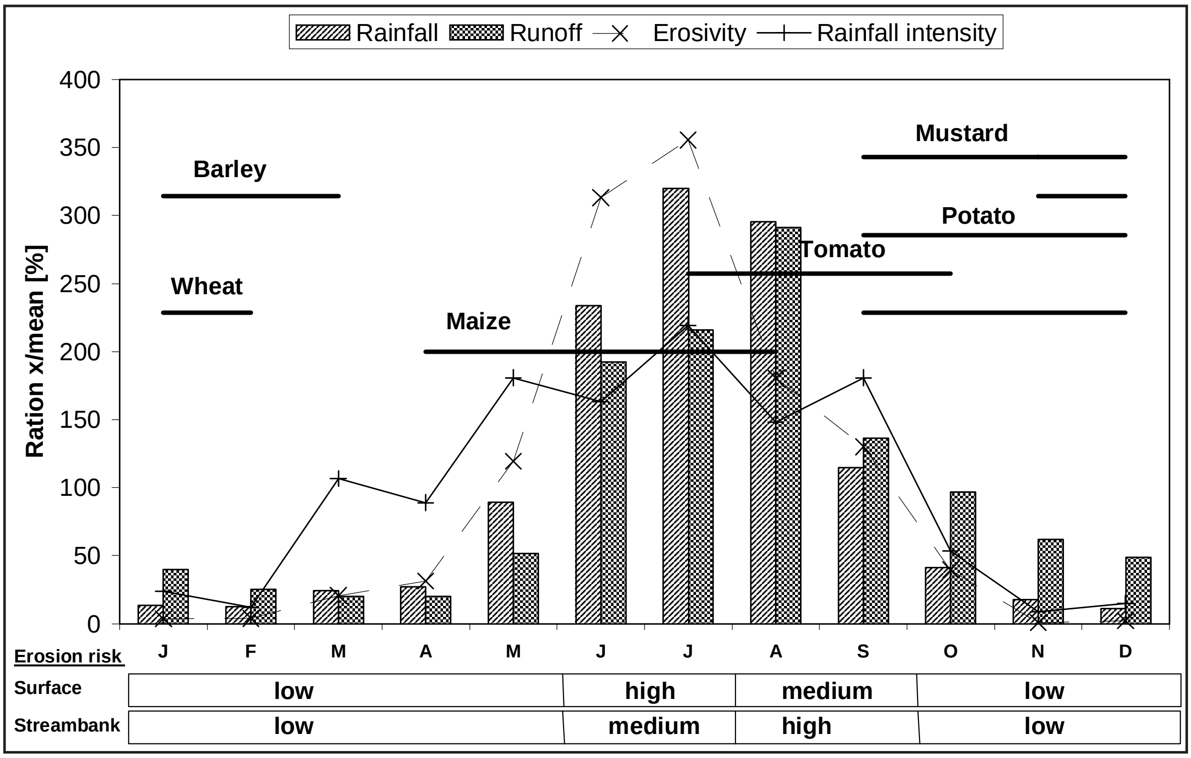
[3] The perceived water deficits are based on the answers of 178 female farmers in the Jhikhu Khola catchment to the question “In which months do you face water deficits for domestic purposes?” (Merz et al., 2002)



Erosion risk	J–M	J	J	A–D
Surface	low	high	medium	low
Streambank	low	medium	high	low

Figure 5.14: **Temporal distribution of selected water resource components relevant to soil loss**

A first assessment of the three indexes has shown that they present a plausible picture when comparing the Yarsha and Jhikhu Khola catchments. The Jhikhu Khola shows a higher water scarcity and higher degradation susceptibility, while the flood susceptibility in both catchments is similar. The indexes were also successfully applied to a climate change scenario and the impact assessment of a hypothetical development project. While the development project led to an increase in the WPI, the climate change reduced the WPI, mainly due to lower availability of water resources as modelled by the PREVAH model in Chapter 4.

Comparing the preliminary data from four PARDYP catchments, it was demonstrated that the Bhetagad catchment shows the lowest WPI score, followed by the Jhikhu, the Hilkot, and the Yarsha Khola catchments. It has to be noted, however, that the input data has to be reviewed and certain, currently missing parameters have to be included.

This index approach could further be useful in the up-scaling of the PARDYP results. At this point the indexes, however, have to be further tested on larger datasets and the indicator selection has to be verified and fine tuned on the basis of each parameter's sensitivity. For suggestions for this, refer to Chapter 6.

In terms of spatial and temporal intra-catchment synthesis in view of a DSS, it was found that the topographic location is of main importance, as it is here that the potential water sources are determined. Both elevation and aspect do not give conclusive answers at a regional scale, as their relationships with water resource parameters differ from location to location. Temporally, it is shown that the late dry season months are most susceptible to water scarcity. This led to a well-adapted cropping calendar in the Jhikhu Khola catchment. For an improved livelihood for local farmers, it is, however, noted that just the months of March and April could provide a chance for improved conditions through the application of water saved or harvested in the previous season.

It was learned that, for the development of a DSS for improved water management, particular focus should be given to the topographic location and the time of the year as well as the use of the water. Actual volumes of available water will additionally play a role but only after the consideration of the other aforesaid parameters.

SYNOPSIS 5: SYNTHESIS

In order to assess water resource issues in a more objective and holistic way, three indexes are proposed. The Water Poverty Index (WPI), the Flood Generation Index (FGI), and the Water Induced Degradation Index (WID) are suggested to assess water scarcity, flood generation, and land degradation susceptibilities. This approach has shown some promising first results, but will have to be further tested in other catchments of the region. The approach was successfully used to compare catchments in the region as well as to assess the impact of changes as a driving force mechanism.

For future reference in the PARDYP project and the development of a decision support system, topographic location with reference to the location of water sources and the temporal distribution of water availability and demand will be decisive. A potential model for this purpose was proposed.

Chapter 6: Conclusion and Outlook

> ***"This creation is because of water"***
>
> ***(Tulsi Dahal, Mrige, Yarsha Khola)***[1]

Based on the objectives and the needs of the different PARDYP clients, the study concluded by discussing the objectives of the study and answering the top three questions related to water scarcity, flood generation, and land degradation. This is followed by a discussion of the interactions between the water resource components and the three indexes. The main lessons learned are given addressing development actors, policy-makers, and the research community.

The outlook focuses on recommendations for the project in terms of measurement set-up, methodology, and future research. The chapter is concluded with a postscript documenting the most important lessons learned.

For a summary of the results refer to the summary at the end of each chapter. The concluding remarks and the outlook attempt a general discussion of the results and outcomes of this study. As mentioned in the foreword, the study was based on the analysis of data from the past six to ten years collected in the PARDYP catchments with the aim of contributing towards improved understanding of key water-related issues in meso-scale catchments of the HKH.

6.1 DISCUSSION OF THE OBJECTIVES

In Chapter 1 several objectives were presented which were central to this study. The objectives are mentioned again in the boxes below and are discussed in detail.

Contribution towards improved understanding

To synthesise water-related information towards an understanding of selected key issues related to water:

- ***to contribute towards the understanding of water availability issues in a meso-scale catchment of the HKH;***
- ***to contribute towards the understanding of land degradation through water and the relevant processes associated with this degradation;and***
- ***to contribute towards understanding flood generation processes, the role of a catchment in flood generation downstream of the HKH middle mountains, and possible future threats.***

(—> see Chapters 2 and 3)

The key issues related to water in the HKH region were identified as water availability (including water quality), floods, and soil erosion/sedimentation. In this context, the findings of this study contribute towards an improved understanding of processes from the perspective of middle mountain catchments in the HKH region. These catchments are mainly rainfed, with a distinct seasonality and one rainfall and runoff peak during the monsoon season in the east of the HKH and two peaks due to the influence of the westerlies and the monsoon in the west. All catchments are intensively used, are under a rice-wheat based cropping system, are densely populated and herewith show high pressure on the natural resources' base. This leads to the top three questions related to the key issues set out below.

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[1] **Merz et al. (2002)**

- **Is water in the selected catchments scarce?**
  The current water scarcity as perceived by the local residents is mainly a function of the seasonality of the water resources and the current management of the available resources rather than the natural water endowment.

  Water demand for domestic purposes is currently about 4 mm per annum in the Nepal catchments. This is based on the current daily water demands of about 20 to 25 l $person^{-1}day^{-1}$, which is about half the basic human requirement according to Gleick (1996). From an overall perspective of water availability, there should be no problem given the current annual rainfall of about 1300 mm in the Jhikhu Khola catchment and about 2200 mm in the Yarsha Khola catchment. The reasons why people perceive this resource to be scarce are mainly due to the often inconveniently located water sources, diurnal flow fluctuations in the supply systems, seasonality of flow, and, increasingly, water quality problems. While there is plenty of water in all water sources (e.g., natural springs, dug wells, spring boxes, rivulets) during the monsoon season, the flow decreases towards the dry season to reach a minimum in March to May. This seasonal difference forces many local residents to change water sources in the dry season, which are less conveniently located. Mainly people in the upper parts of the catchments along the divide face this hardship. In terms of water quality, the main risk of contamination is in the monsoon and pre-monsoon seasons. Microbiological contamination is of particular concern in most of the public and private water sources, while nitrate and phosphate are found in many sources as a result of major agronomic activities and the impact of human settlements. This microbiological contamination was shown to have a major impact on people's health with more than 25 % of the health unit patients suffering from water-related diseases.

  This suggests that a decentralised water supply based on different water sources such as rainfall, groundwater, and surface water (as well as additional, alternative sources such as fog) depending on the location of the beneficiary in combination with appropriate treatment methods and household or community-based management should be further supported. Traditional kuwas should be restored and their management institutionalised. Gravity systems tend to be expensive and inefficient due to the dispersed population. However, in bazaars these systems should be revitalised and put under strong community management. Case studies on access and management issues with particular reference to a large water supply system in the Jhikhu Khola catchment will be undertaken in PARDYP's Phase 3.

  From an agricultural perspective, water availability is adequate for the current cultivation practices. The cropping calendar is adapted to the seasonality of the rainfall as well as the low flows in the irrigation canals during the dry season. Recent intensification and increased cash crop production have led to water shortages in the Jhikhu Khola catchment as perceived by the local farmers. Further intensification of the agricultural production applying the current practices could lead to increased water shortages in the Jhikhu Khola catchment, while in the Yarsha Khola catchment there is still room for intensification. The most critical time from the perspective of natural water availability and the current cropping calendar is the time before the onset of the monsoon for planting maize, establishing rice nurseries, and transplanting rice. For good yields of post-monsoon crops, adequate soil moisture from the monsoon season and a few rains during the post-monsoon and winter seasons are critical. For an improvement of the situation, cash crop production using alternative irrigation methods should be further promoted, which would decrease the vulnerability of the farmers on rainfed agricultural land as well as decrease the demand for water on irrigated land. The storage of monsoon rains in ponds and cisterns should receive further attention in order to cater to the increased water demand during the dry season.

  An assessment of the impact of population growth has shown that future generations will face increased pressure in terms of availability of water resources. However, given that there is adequate management the projected water quantity requirements for domestic purposes will be a minor issue. For food production it is assumed that any further intensification of the agricultural production system in the Jhikhu Khola catchment will be limited, while the Yarsha Khola catchment still has adequate room to allow some intensification. Similarly, the impact of global climate change might reduce the available water resources during the dry season and further reduce the productivity during that time.

In order to satisfy the needs of the communities at the outlet of the catchments as well as support the requirements of the upland communities, water resources should be managed not only at the community, but also at the catchment level, with particular reference to the irrigation systems. Already the water availability in the lower stretches of the Jhikhu Khola catchment does not allow for the extraction of water by conventional canal irrigation.

Conclusively, it can be noted that improved and appropriate water management applying new as well as traditional knowledge in connection with the natural water endowment can support the water needs of the population in these catchments without the feeling of scarcity. This idea will be supported by the activities in PARDYP Phase 3 towards the development of a water management decision support system for rural catchments in the middle mountains of the HKH.

→ ***There is enough water in the catchments, if the resource is managed properly.***
→ ***The main issues related to perceived water scarcity are seasonality and water management.***

- **Is soil loss a problem in the selected catchments?**
  Sediment mobilisation and transport can be looked at in several ways. From the perspective of the farmer the loss of fertile topsoil is important, while from the perspective of downstream users the total sediment load in the river at the outlet is of main importance. Looking at these two perspectives separately it can be stated that farmers generally do not perceive soil erosion as a main issue. This view is supported by the soil losses from the agricultural plots, which balance the annual natural soil development. On average, an agricultural plot would lose about 10 t/ha per annum, while the tolerable soil loss rates in Nepal's middle mountains are estimated at about 11 t/ha per annum. Most of this soil loss from the upper catchments is then transferred to the lower irrigated terraces through run-on as well as through irrigation water (Carver 1997; Brown et al. 1999). In addition to this, surface erosion only accounts for a part of the total soil loss from a catchment. Stream bank erosion and gullying tend to be of greater importance and of more concern to the downstream users. These processes, however, only affect a small number of farmers who own land along the rivers. Gullying is often observed along public paths and on severely degraded, often community-owned, land. In addition, the impact of road construction is considerable. This includes not only the VDC road network, often constructed without necessary expertise, but also the national and DDC road network. In terms of nutrient losses on rainfed agricultural land, Brown et al. (1999) estimated that the nitrogen losses by erosion are about 10 % and the phosphate losses are about 1 % of the total losses. On the basis of the current mineral and organic fertiliser input rates, the nitrogen loss is significant, while the loss of phosphorous is negligible. As shown by Brown et al. (1999), the irrigated land recaptures a lot of the lost nutrients from the uplands and therefore gains from the soil losses in the uplands. Improved soil conservation could herewith reduce the requirements for adding mineral fertiliser on the uplands and increase the need for the same on the lowland irrigated land. From a farmer's point of view, it is important to assess which approach requires more inputs (monetary, labour) and has more unwanted side effects. From this perspective, the current surface soil erosion rates on the agricultural land do not warrant any major changes in land management. Carver (1997), however, warns that the current system could become more vulnerable in the near future with increasing intensification. The question is, however, how far can this intensification still go?

  From a downstream perspective, the total sediment output of the selected catchments is medium to high in relation to other catchments in the world. However, within the region, a number of rivers — particularly the ones originating in the Siwaliks — show much higher values. This suggests that in terms of upstream-downstream sediment linkages it is important to consider interventions to reduce the sediment loads from these middle mountain catchments in case of downstream development. As discussed above, the major source is believed to be the drainage system itself as well as the road and pathway network in the catchments. In addition, the degraded lands in the catchment were shown to be of particular importance by Carver (1997). To reduce the sediment loads, interventions should focus on the riparian zone as well as roads and paths in the catchments. Proper slope stabilisation of roads and punctual stabilisation of stream banks should be envisaged. The rehabilitation of degraded lands as well as the stabilisation of stream banks should be coupled with the need for fodder for the large number of livestock in the catchments, as the farmers are not likely to put any efforts into these hopeless patches if there is no immediate benefit. As Shrestha (2000b) pointed out, the need for fodder is felt increasingly acutely. First attempts have been reported in the past (Shah et al. 2000) and new approaches are tested in PARDYP's Phase 3 (Shrestha, pers. communication). At this point it should be remembered that the natural catchment soil erosion rates are high in the middle mountains of the HKH as discussed in detail in Chapter 2. The improved soil management will therefore only be able to reduce the losses to a limited extent.

It can be concluded that from the perspective of a farmer in the Jhikhu or Yarsha Khola catchments, improved soil conservation is not a first priority as the need is not obvious and the benefits of currently promoted soil conservation approaches are not directly visible. For the downstream perspective the need for soil conservation will only become important with the development of the water resources downstream. For this purpose the main target should be the degraded land, the stream banks, and the road network. If soil conservation simultaneously addresses a more severe — and by the farmer more clearly perceived — issue such as fodder availability, it will have more chances of success.

→ ***Surface soil loss is only a marginal issue for farmers in the selected catchments, while transported sediment may have an impact on downstream developments.***
→ ***The main sources of sediment are not the agricultural lands, but more the drainage and the road networks in addition to the severely degraded lands.***

- **Can farmers in the selected catchments be held responsible for floods downstream?**
  Himalayan farmers are often held responsible for downstream flooding. Many authors have shown that due to the scales involved and the in-channel processes on the flood plains, this hypothesis has to be rejected. In addition, on the basis of the data observed in the two catchments of PARDYP Nepal, this process cannot be demonstrated. In fact, the area of cultivated land in different sub-catchments showed a negative relationship with the flood peaks and flood volumes. Grassland as well as degraded land on the other hand showed a positive relationship, while the forest areas did not show a distinct relationship. The floods at the sub-catchments and the catchment outlet further show a very high correlation with the processes on the degraded and grassland plots. The runoff on these plots is mainly generated by the infiltration excess overland flow generation mechanism. The correlation, therefore, suggests that infiltration excess overland flow or processes similar to this are mainly responsible for flood generation. As the correlation between the floods and the agricultural land is rather low, it is suggested that they only contribute marginally to floods. This suggests that the proper management of agricultural land is beneficial to flood protection for small to medium events. While the importance of catchment characteristics is proven for small to medium flood events, at high events only rainfall characteristics are decisive. In general, these large floods are generated at rainfall events with high rainfall volume or high rainfall intensities. During these events all land uses contribute to the floods. This suggests that watershed management in the traditional sense with small-scale forest plantations may not have the effect required. Large-scale land-use changes have shown differences at this scale (FAO 2002), they may not be practical however in the context of rural catchments in the HKH. The upland conversion policy of the Chinese government discussed in Chapter 2 may potentially have an impact due to its spatial extent. For this the next 10 to 20 years will have to be awaited before first conclusions can be drawn. With respect to the abandoning of agricultural areas, as has been observed in parts of the catchments, an increase in flood volume as well as an increase in the number of flood peaks could be expected. However, this was not shown by the modelling exercise, and this was mainly due to inadequate vegetation parameterisation. In terms of the assessment of future changes it can be shown that a potential climate change may lead to an increase in the number of flood peaks and an overall increase in flood volume.

For improved flood management and protection downstream, flood plain planning and in-channel conditions are far more important and should yield a better response, particularly for large and destructive events.

→ ***Large floods are a natural phenomenon and their destructive force can be reduced by improved downstream planning.***
→ ***For small and medium flood events, cultivated land has shown reducing effects.***

Provision of data and results of analyses

To provide hydro-meteorological data and a number of basic analyses for further use by the project, e.g., diurnal temperature variation for agronomic trials and rainfall frequency for water-harvesting methods.

(—> see Chapter 3)

During the course of this study, the basic hydro-meteorological data collection was ensured culminating in the publication of a CD-based yearbook. These up-to-date data have been used by students, researchers, consultants, and development projects. To mention a few examples, they have been used for:

- culvert design for a DDC road in the Jhikhu Khola catchment;
- appropriate crop selection by CEAPRED;
- general climatic description for the District Livestock Office;and
- several local and international BSc and MSc theses (capacity building).

In addition, results of a number of basic analyses were presented which are themselves important for different actors:

- intensity-duration-frequency curves for engineering applications (Section 3.1);
- rainfall variability for agronomic applications (Section 3.1);
- rainfall frequency for water harvesting design (Section 3.1);
- annual and diurnal temperature variations for off-season vegetable production (Section 3.2);
- reference evapotranspiration rates for crop water requirements (Section 3.2); and
- seasonal groundwater assessment for potential exploration (Section 3.3).

The results of these analyses will further be used for the design of a water management decision support system planned for PARDYP Phase 3 as well as for a comparison of the catchments in a regional water and erosion synthesis (Merz et al., in prep.).

Modelling

To contribute towards the understanding of the dynamics of the above issues and their interaction.

(—> see Chapter 4)

First trials with different hydrological models were carried out to estimate the impact of future scenarios based on global climate change, population growth coupled with increased water demand to meet the basic requirements, and local land-use change with expansion to marginal lands or abandoning of marginal fields. The preliminary results for the Jhikhu Khola catchment have shown the following.

- Hydrological models can be applied to the data from the Jhikhu Khola catchment. Due to certain inconsistencies in the discharge datasets, the efficiencies achieved were rather low.
- The models performed very well on a monthly basis as well as for the identification of the duration curves. This property should be followed up for a possible application in ungauged catchments as proposed by WECS (1990).

- All models applied run at daily time steps due to inadequate data sets of high temporal resolution. However, it was shown that rainfall intensity plays a major role in the generation of floods. For this purpose the models currently applied will have to be modified accordingly to cater for the input of high temporal rainfall data.
- Calculated evapotranspiration rates are based on temperature approaches. These approaches must be substantiated with more physically based methods, with additional data to be collected in future in the Jhikhu Khola catchment (see below).
- Water during the dry season is becoming scarcer due to decreased precipitation, increased evapotranspiration, and decreased runoff.
- Flood events during the wet season are becoming more frequent and are of a marginally higher magnitude.
- The dependency of lower lying administrative units in a catchment on upper administrative units is increasing due to greater water demands in these lower areas, which are generally more accessible. This calls for the introduction of catchment-based management of natural resources.
- Expected land-use changes show only a marginal impact on the flow behaviour of the catchment. It is important to note that, with the current datasets, the model shows an opposite trend from what would be expected from the observed data. This difference will have to be resolved with additional information to be entered into the model later this year.

These results are preliminary, mainly due to the fact that the efficiency of the models used can be further improved with the availability of additional data. The results suggest that more focus should be paid to the storage of surplus water in the wet season so that this can be used during the dry season, as the seasonality will probably become even more pronounced in future. While domestic water use is presently below basic water requirements according to Gleick (1996), water supply should take into consideration both a change in population as well as in terms of daily water demands to improve living standards. This suggests that water management options for the future have to tap into all available resources, minimise losses and inefficiencies, and considerably improve the quality of the water.

Synthesis and upscaling

To provide a methodology framework for the synthesis of a large amount of data and information to be considered for the other project catchments, for comparison of catchments in the region, and potential up-scaling.

(—> see Chapters 4 and 5)

For an objective comparison of the catchments, two tools have been used in this study. An index approach was used to compare the current susceptibilities of the two catchments in Nepal and to a lesser extent in the remaining PARDYP catchments. Catchment modelling has only been used in the Jhikhu Khola catchment to date. The reason for this is the length of the time series available as discussed in more detail in Chapter 4. The issues and results of the modelling are discussed above.

The index approach using three different indexes — the Water Poverty Index (WPI), the Flood Generation Index (FGI), and the Water Induced Degradation Index (WDI), for assessing water scarcity, flood generation, and land degradation susceptibilities respectively — showed first good results and suggested that the chosen approach could be further tested for applicability to other catchments in the region and beyond.

Currently, the data requirements are high and may be a constraint in other catchments with less detailed information resources. It was,nevertheless, shown that, in the case of the PARDYP catchments, most of the data could be assembled within one week without any prior knowledge of the indexes. The indexes have been tested in detail in a comparison of the Yarsha and Jhikhu Khola catchments. It was shown that the Jhikhu Khola catchment has a greater susceptibility towards water scarcity issues, not only based on resources, but also due to more difficult access, greater use, and more degraded conditions. The capacity to deal with water scarcity, however, is estimated to be higher in the Jhikhu than in the Yarsha Khola catchment. These results seem to be plausible, but the sensitivity of the approach has to be improved. Currently the spreadsheet that has been developed incorporates score limits, which allow the input of any data from the region, e.g., the extreme rainfall conditions of the Meghalaya Hills. The application of the approach to two additional catchments showed that current data requirements have to be considered further. In addition, the WPI was used in an example to assess the impact of a hypothetical rural development project and climate change. This application yielded plausible results.

It was learned that for the development of a DSS for improved water management, particular attention should be given to the topographic location and the time of the year, as well as the use of the water. Actual volumes of available water will additionally play a role but only after the consideration of the other parameters mentioned.

6.2 LESSONS LEARNED

Over the period of this study a number of lessons were learned, which are compiled below according to the need of the different actors related to the PARDYP project. ICIMOD (2003) lists the following actors relevant to the PARDYP project:

- ***development actors***, who can translate PARDYP's research results into practice;
- ***policy-makers***, who can convert the research results into policies at different spatial levels;and
- ***the research community***, with whom research results and methodologies can be shared.

The message to all actors summarised from Section 6.1 is set out below.

- Adequate water resources are available in the catchments to meet human demand if these resources are properly and adequately managed.
- The major focus of all activities should be on reducing the dependency on water resources and so lessen the impact on human livelihoods by variability and seasonality in the vailability of water resources.
- The soil erosion rates from farmers' lands balance the soil formation, and thus do not warrant major efforts towards soil conservation per se. These methods need to be combined with other effects such as soil amelioration, income, and so on.
- Effective sediment control needs to focus on drainage, road networks, and severely degraded areas.
- Proper land-use planning in downstream areas of the mountains and hills is more effective in reducing risks than changing land use in the upper catchments.

This suggests that development actors:

- promote small-scale irrigation with a high probability of economic return during the off-season, combined with the harvesting of spring water or surface runoff;
- focus on decentralised and family or household-managed water supply based on seasonal groundwater, spring water, or roof water in combination with cheap water treatment;
- promote proper construction and stabilisation of roads of different categories in the catchments; and
- promote small-scale soil conservation with a combined soil amelioration or economic benefit.

The message to policy-makers is to:

- support credit for small-scale irrigation based on harvested runoff;
- support activities towards the achievement of safe domestic water supply for all on the basis of water as a human right;
- introduce adequate planning in flood plains and prohibit encroachment of the river channels;
- introduce a rainfall intensity measurement network for flood management and protection;
- introduce an objective measure to review the water resources' status in all areas of the country which will enable proper targeting of funds towards improved water supply, reduced flood damage, and reduced land degradation; and
- introduce catchment-based water resources management at different authority levels.

The message to the research community is to:

- identify and disseminate more water-saving approaches for staple crops during the dry seasons;
- identify the socioeconomic and political constraints that prohibit proper water management, and propose solutions;
- identify more cost-effective approaches for the storage of monsoon rains for use during the dry season;
- take more notice of local perceptions and include them in the research;
- identify the threat of agrochemical pollution to water resources in the middle mountains; and
- identify the role of groundwater in the middle mountains.

6.3 RECOMMENDATIONS FOR THE PARDYP PROJECT

6.3.1 Measurement network and stations

The comments on the measurement network and the stations are based on the Jhikhu Khola catchment only, as the activities in the Yarsha Khola catchment were closed down in 2001.

6.3.1.1 Meteorological stations

During the catchment-based analysis of meteorological parameters, including evapotranspiration, gaps in the network were identified. For water availability considerations with particular reference to the main settlements and the irrigated areas in the valley which all depend on the flows from the upper and western part of the catchment, more data has to be collected by:

- adding one to two meteorological sites in the western and upper part to obtain data for that part of the catchment;
- upgrading Site 20 to a full meteorological station, including tipping bucket and thermistor;
- adding relative humidity sensors at all sites for the purpose of evapotranspiration calculation;
- adding automatic radiation and wind sensors to at least one site in the catchment, preferably at the main meteorological station representing the remaining catchment area; and
- establishing an evaporation pan for evaluation of the calculated evapotranspiration rates.

6.3.1.2 Hydrological stations

During analysis, the main problem with the hydrological data from the Jhikhu Khola catchment was the low flow insensitivity of the hydrological stations, the missing discharge measurements for high flows, and the changing cross-sections. To solve these problems the following measures have been proposed.

- Improve the low flow sensitivity and at the same time the stability of the cross-section with fixed cross-sections at all sites. It is important to consider the lowest flows, e.g., with a v-notch weir or a v-shaped channel close to the recording device, while not forgetting the high sediment loads at high flows, which often clog up these low flow measurement structures.
- Take one low flow discharge measurement every month (no rain on the day before) at all sites to establish good baseflow information.
- Consider fixed and defined cross-sections which allow the use of formulas for high flows with a cross-check using occasional discharge measurements.

6.3.1.3 Erosion plots

The use of erosion plots in PARDYP Nepal is currently being reviewed (Nakarmi, in prep). While it is basically agreed that the use of erosion plots for the assessment of monthly, seasonal, and annual soil losses is outdated, their use in the context of the nested approach is still valid.

From a hydrological point of view, the plots should be further used for runoff generation and infiltration studies. With the temporally highly resolved datasets of rainfall and discharge, the daily data of the erosion plots limit the analysis potential for these studies. It would be interesting to consider an automatic approach by using large cup tipping buckets for automatic runoff assessment or an automatic water-level recorder in the first drum. A direct relation between rainfall intensity and runoff could then by established. Infiltration studies could further be refined. Automatic sediment sampling could show interesting results of when exactly the main soil erosion occurs during an event. These are obviously studies that do not fit into the present PARDYP Phase 3 context, nevertheless they should be considered, perhaps through finances from another project. In addition, soil moisture monitoring using time dependent reflectory (TDR) sensors could be considered.

In any case, it would be important to monitor the vegetation cover on all plots for later relation to runoff and soil mobilisation. In addition, it would be interesting to further monitor the degraded plots to study the effects of sediment exhaustion.

Overall, it is important to remark that a hydro-meteorological research monitoring network cannot address all questions that crop up in relation to water. If water availability is the main concern, more focus should be given to proper parameterisation of low flows, evapotranspiration, and soil moisture. For studies of floods and sediment, it is important to capture the most destructive storms. For a more detailed discussion of these issues refer to Merz (2002: Appendix B-6).

6.3.2 Methodological thrusts

In January 2003 PARDYP entered Phase 3 of the project, which will last up to December 2005. Phase 3 aims to “increase rural livelihood security and sustainability” (ICIMOD 2003). In this context, the component on water resources contributes to the objective to identify, test, and disseminate “water management options for more efficient use and equitable access” (ICIMOD 2003). In order to achieve the aims identified, the project team decided to:

- analyse the data,
- identify or produce a model for up-scaling the project experiences, and
- produce a decision support system (DSS) to guide the selection of the most appropriate water management options to be tested and improved by applying participatory action research (PAR) methodologies.

This approach roughly follows the applied research side in Figure 6.1 with the aim of solving problems at the local, the meso-catchment scale. The study presented follows mainly the research side of Figure 6.1 with the aim of detecting and describing problems that should be picked up by the applied research for resolution. For this purpose, the presented study has provided a first attempt of a possible base for the DSS, as described below.

- The ***index approach*** proposed in Chapter 5 of this study. The approach is preliminary due to the small number of catchments tested. In the author’s view, this approach has great potential for the up-scaling of PARDYP’s detailed project findings to the region and beyond, after rigorous testing of the methodology in a number of other catchments. During this process of verification, the number of indicators could be refined, more sensitive indicators included, and indicators that prove to be specific for the catchments in Nepal excluded. With a considerable number of catchments a factor analysis could be performed to identify the most informative indicators. Later, the most similar catchments could be identified with a cluster analysis approach. This would further support the development of a DSS and could be used for a preliminary screening of the catchments to identify the most applicable water management options.
- The results of the **spatial synthesis** at the catchment scale, which concluded that the topographic position of a selected location with access to particular water sources could be used as the entry point for the DSS.
- The results of the **temporal synthesis** at the catchment scale, which concluded that the understanding of the local cropping calendar in combination with the hydrological cycle will be important for the identification of potential solutions from the perspective of water requirements, water availability, economic return, and availability of land.

	Research	**Applied Research**
Aim	**"Detect problems"**	**"Solving problems"**
Spatial focus	Regional Key Issues	Watershed Key Issues
Focus	Methodological Focus (approach oriented) • Testing and evaluation of new and relevant technologies and methods • e.g., radar, automatic sediment monitoring, automatic nutrient monitoring • Modelling • Synthesis of interdisciplinary research	Water Supply Management • Water harvesting (rainfall, spring, surface runoff) • Groundwater • Catchment protection
		Water Demand Management • Alternative irrigation • Agricultural interventions
	Theme Focus (result oriented) • Water availability • Floods • Sediment • Nutrient build-up • Agro-chemical pollution • Role of institutions/gender in water management	Water Quality Management • Treatment • Source and catchment protection
		Soil Conservation • Bio-engineering methods • Engineering methods
Methodology	• Monitoring • Data analyses • Collaboration	• PAR • Training • Exposure • Collaboration • Testing • Demonstration
Partners	Universities, NARES,….. → research organisations	GO, NGOs,…… → Implementing agencies

⬇

Dissemination
to different stakeholders at different levels with different media

Figure 6.1: **Water and erosion studies in a watershed management research project**

Prior to wide dissemination and up-scaling of PARDYP results, rigorous testing of the approaches and methodologies is necessary. For this purpose it will be important to embark on a dialogue with those other projects and institutions in the region and beyond that entertain research catchments. First attempts for this could be undertaken in the catchments that supported the Andean-Himalayan comparison (Schreier et al. 2002) or based on the up-coming FAO consultation on watershed management.

6.3.3 Further research in the PARDYP catchments

From this study the following further research needs are formulated in order to substantiate the current knowledge. The list assumes that unrestricted fieldwork is possible and does not limit itself to the current PARDYP project objectives. Activities taken up in Phase 3 of PARDYP, such as the preparation of a DSS, are not mentioned again, although this study has been instrumental in identifying the most appropriate objectives and activities, to:

- improve the understanding of evapotranspiration and crop water requirements;
- investigate the impact of irrigation diversions on hydrological flow;
- evaluate the importance of stream-bank erosion in the overall sediment budget of a middle mountains catchment;
- relate the above findings to a larger catchment scale (e.g., the Sun Koshi basin);
- determine the impact of agrochemical pollution in the catchments; and
- make a detailed assessment of groundwater resources in the Jhikhu Khola catchment.

6.4 POSTSCRIPT

“There is a water crisis today. But the crisis is not about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people — and the environment — suffer badly.” (Cosgrove and Rijsberman 2000)

The study presented here is believed to be a strong basis for the improvement of the current situation in mountain catchments of the HKH. While it does not present solutions to water-related problems, it identifies the issues quantitatively as well as qualitatively. Often it provides thought provoking aspects and introduces methods from other parts of the world that could be used to improve our understanding of key issues in the region and support efforts made towards improved water conditions.

This study provides the ground for PARDYP Phase 3 to indulge in the testing of potential approaches, improving these approaches hand-in-hand with local farmers and finally promoting the most appropriate ways to improve the management of water resources. In all of these activities it is important to involve the different stakeholders — from the farmer to the local government and the line agency. It is evident that water management is crucial, both for improved water availability for agricultural and domestic purposes, as well as to reduce the risk from water masses during the wet season. The most important lesson learned is that the human activity of the rural population of the middle mountains in Nepal overall support the stabilisation of the hydrological system. Fine tuning the current system to cater for new water demands and newly created issues deserves the greatest attention of all those involved in the management of water resources in order to provide further stability and continuation.

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This study looks at the current situation of water resources in selected meso-scale catchments of the HKH in a biophysical and socioeconomic context. It focuses primarily on the Jhikhu Khola catchment in Kabhrepalanchok District in the middle mountains of Nepal and compares the results with those in the Yarsha Khola catchment in Dolakha District in Nepal as well as catchments in China, India, and Pakistan. The study showed that water resources are not actually scarce in the selected catchments, but a combination of water management issues and marked seasonality has led to perceptions of water scarcity. Land cultivation was beneficial and supported the reduction of minor to medium flood events. Major events are natural phenomena, and their effects could be managed by effective downstream planning. Soil erosion on agricultural land is often seen as a major issue in the middle mountains, but was of only minor concern to the farmers in the study areas. High sediment loads at the catchment outlet were mainly caused by stream bank erosion, unstable road alignment and severely degraded areas.

The publication is intended to contribute to increased understanding of water resources and water-related processes such as soil erosion and land degradation, and will help those working on integrated catchment development that focuses on reducing water-induced land degradation and the degradation of water resources.

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