TEC BACKGROUND PAPERS NO. 9

Water Management and Ecosystems: Living with Change

By MALIN FALKENMARK

Global Water Partnership
Technical Committee (TEC)

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PREAMBLE

Integrated Water Resources Management (IWRM) may be defined as "a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP TAC Background Paper 4, 2000).

IWRM aims to strike a balance between the use of resources for livelihoods and conservation of the resources to sustain their functions for future generations. The definition of IWRM promotes economic efficiency, environmental sustainability and societal equity – the three E's.

Water resources have to be used to increase economic and social welfare but without compromising the sustainability of vital ecosystems. The focus of this paper is to analyse the relations between human society, water resources and ecosystems, to clarify why and how vital ecosystems have to be protected and to indicate how this effort can be better incorporated in integrated water resources management, IWRM.

Since the 1970's attention has been focused on the effects of *water resources development* on the environment and methods have been developed for environmental impact assessment (EIA) of water projects. Much less effort has been directed to assessing environmental impacts of *water resources management* strategies. Often, water management and ecosystem protection have been approached by different professional communities. Fundamental differences in their worldviews have made it difficult for them to work closely together, even when they have the same aims. In recent years however, there have been joint efforts to address several problems in primarily aquatic ecosystems and to develop minimum flow criteria for their protection.

Terrestrial ecosystems have traditionally been addressed as components of land use, without focus on the huge amounts of water that they consume through photosynthesis. However, in South Africa forest plantations have been addressed as potential streamflow reducing activities.

Malin Falkenmark, member of the Technical Committee of the Global Water Partnership (GWP), has prepared this paper to help to ensure that ecosystem protection is well incorporated into the IWRM approach. It has grown out of a paper given in a GWP seminar in November 1999, co-organised with the Department of Systems Ecology at Stockholm University (GWP, 1999). Special thanks are due to Dr Paul Roberts, South Africa, member of the Technical Committee of GWP, for his contributions on the innovative approaches being taken in South Africa, and to Professor Carl Folke, Department of Systems Ecology, Stockholm University for in-depth discussions on the links between water and ecosystems and on the ecological perspective of human livelihoods.

CONTENTS

1. INTRODUCTION

This report, based on the links between water and ecosystems, outlines how ecosystem-focused approaches may be incorporated into integrated water resources management (IWRM). It analyses to what degree water is involved in the relationship between society and the surrounding ecosystems, clarifies how humans and ecosystems are sharing the same water, and shows how ecosystem sustainability may be strengthened within the IWRM process. The report will provide a conceptual background to support land/water integration in a catchment based ecosystem approach to human activities. It indicates how, within the framework of IWRM, the needed ecosystem perspective has to be combined with adequate social and economic perspectives to a broader, more holistic approach to management of fundamental livelihood components in a catchment.

The main message of the report is that, by benefiting from the shared dependence of humans and ecosystems on water, IWRM can integrate land, water and ecosystems and promote the three E's of IWRM – two human-related E's (social equity, economic efficiency) and one ecosystem-related E (environmental sustainability).

2. THE BASIC DILEMMA

Human livelihood security

The water, food and raw materials needed for human livelihood security originate from the natural environment surrounding human settlements. These resources cannot be harvested however without modification of landscape components (digging of wells, channelling of water, building of reservoirs, clearing of natural vegetation for crops, clearing of forests for timber, drainage, levelling of land, etc.), and these modifications will disturb local ecosystems. As more food has had to be produced to feed a growing population, first fertilizers, and later herbicides were relied upon to increase the crop yields. In dry regions irrigation was introduced. These measures have also had environmental side effects (eutrophication, water pollution, water logging, salinization of soil and water, etc.). Some are avoidable whereas others are difficult to avoid. Waste production also tends to follow human activities (human waste, industrial waste, etc.), further disturbing local ecosystems. When populations grow these modifications intensify, and escalating ecological side effects cause increasing concern among segments of the population.

Rising concern

The ultimate challenge of a sustainability-oriented environmental management is to find a proper balance between humans and the impacts caused to the environment. It has however, turned out to be extremely difficult to come to grips with worldwide environmental degradation. In spite of massive infrastructural efforts in the temperate zone to minimize water pollution, the leaching of agricultural chemicals continues and is now causing regional scale eutrophication of coastal seas. In other parts of the world – besides serious water pollution problems – irrigation-dependent dry climate regions are seeing spectacular river depletion effects of the large-scale water diversion to irrigated crops. Examples are the Colorado River, Yellow River, the tributaries of the Aral Sea and many dwindling rivers in the developing world. Still another issue in the dry climate regions is the regional scale salinization of soil and water.

In the next few decades strong driving forces in terms of continuing population growth, globalisation, industrialisation and efforts to alleviate poverty and hunger can be foreseen to produce even larger landscape modifications. All this makes it essential to arrive at wiser approaches to the environment, by properly integrating issues that are interdependent.

Determined international concerns to stop environmental degradation were started thirty years ago at the 1972 Stockholm Conference on the Human Environment. The fragmentation of both existing knowledge and governance institutions is reflected in limited perspectives among different professional groups and is an intellectual heritage from the time of the great French 17th century philosopher Descartes. Physicists understand mainly physical phenomena in the landscape, chemists mainly chemical phenomena, biologists mainly biological phenomena, and so on. And since the worldviews of these different groups are vastly different they have major problems of communicating both with each other and with policy makers to build up a shared understanding of the dilemmas of the human environment.

Coping with two virtually incompatible imperatives

A fundamental problem in socio-economic development and development of quality of life and economic welfare is the unavoidable modifications of various phenomena in the landscape in which it occurs. Due to natural processes operating in the landscape – most of them water-related – these modifications tend to generate unintended side effects on local ecosystems. The result is sometimes strong interest divergences, disputes and even violence.

The message that the *ecosystem imperative* has to be respected is already widespread among water managers. The shared dependence on water of both humanity and ecosystems makes it natural that proper attention to ecosystems is being entered into water management. At the same time, the Millennium Declaration 2000, agreed upon by the world leaders in United Nations, involves a set of *human livelihood imperatives* that are all closely water-related: to halve by 2015 the population suffering from poverty, hunger, ill-health and lack of safe drinking water and sanitation. A particularly crucial question will be the water-mediated implications for different ecosystems of the growing food, biomass, employment and shelter needs for a growing humanity.

The most fundamental task is to realize humanity's dependence on the planet's life support system without which we would get no food, no fuelwood and timber, no wildlife, no pollination of our crops and so on. Water, through its many different functions, plays multiple roles in the dynamics of both ecosystems and social systems. It has the function of determinant and life elixir of terrestrial ecosystems, as a carrier of nutrients, and as a habitat of aquatic ecosystems. In social systems it has fundamental societal functions for human life support, food production, and energy production; and as a transport medium and mobile solvent; in continuity-related propagation of impacts as a microclimate moderator, a global scale energy carrier, and so on. Therefore, since both humans and ecosystems are genuinely water dependent, IWRM offers an opportunity to take an integrated approach to human livelihood security and the protection of vital ecosystems.

To achieve this a *catchment-based ecosystem approach* will have to be conceptualised. It will have to incorporate efforts to protect the production of essential ecosystem goods and services on which the welfare of the society is based. In doing this one has to remember that there are many entry points for human ecosystem interference: both directly through interference with local water flows and pathways, and indirectly through interference with soil permeability, vegetation and runoff generation. Since water's ecological functions are continuously being perturbed by human activities in terms of land use, biomass production, water pollution and quality degradation, a key challenge will be to face the biotic inter-linkages between the circulating freshwater and the ecosystems. Trade-offs will be needed between different water functions – a task even more complex than the more conventional efforts to deliver water for people, industry and irrigation.

3. HOW ARE HUMAN ACTIVITIES AND ECOSYSTEMS RELATED?

What is an ecosystem?

Basically, the term ecosystem refers to a *set of interacting organisms and the solar driven system that they compose, comprising both primary producers, and consumers and decomposers*. In combination they mediate the flow of energy, the cycling of elements (including water) and spatial and temporal patterns of vegetation. An ecosystem may be of any scale from global all the way down to local. At the upper end of the scale the life support system of our planet is an ecosystem energised by solar energy and kept together by the circulating water that functions as the bloodstream. At the lower end of the scale the local biotic systems are spoken of as ecosystems: a grassland, a forest, a lake, a stream, and so on. This is the kind of ecosystem that supports local societies with crops, fodder, fuel wood, timber, fish, meat, and so on and that local inhabitants care strongly about.

In a more generic sense, ecosystems may be seen as essential and dynamic "factors of production" for social and economic development (Folke, 1997). Ecosystems produce the bulk of both renewable resources and ecosystem services on which the well being of human society is based. This means that human use of these resources and services is dependent on the existence, operation and maintenance of a multifunctional ecosystem in which hydrological flows are the bloodstream.

Since ecosystems are genuinely water-dependent it is becoming essential that the linkages between water and ecosystems be properly clarified. The guidance from literature on the linkages between hydrology and ecology is, unfortunately, limited. Hydrology has been the domain of engineers with focus on river flow phenomena of societal relevance, while ecology has been the domain of biologists with focus on climate/ecosystem linkages and analysis of complex ecological systems. In their analyses they have seen water as just another environmental factor alongside all the other ones, and addressed by simple indices.

Ecological practitioners have been directing their main interest to visible landscape phenomena, primarily to aquatic ecosystems and wetlands. In terms of terrestrial ecosystems, their main focus has been on the encounter between water and plants at the soil surface and in particular, the so called "watershed function" in moderating flood flow and facilitating dry season flow. In low latitude water short regions the water dimension of terrestrial ecosystems has attracted interest, starting to question the statement that "forests create water". The photosynthesis process has not been much discussed in spite of the spectacular water consumption involved and the runoff production alterations to be discussed later following from changes in this consumption through land cover changes.

The growing water interest in the ecological community has its equivalent in a growing ecosystem interest in the hydrological community, and reflected in the World Water Action Report (December, 2002). Although stressing the need for an ecosystem-based management approach, this report essentially highlights actions related to water in wetlands and aquatic ecosystems and focussing on environmental flow, water pollution and the scale of infrastructural development.

Unfortunately, the term "ecosystem" is not very straightforward when seen from a water management perspective. When seen from a catchment perspective, the term can be given two complementary interpretations:

1) the life support system as such on which welfare depends in view of the essential ecological services that it provides
2) site-specific biological landscape components of special social value for local inhabitants (e.g., a wetland, a forest, a lake, etc.).

Humans and ecosystems share the same water

In the catchment the rainfall is shared between nature and human society and between terrestrial and aquatic system. This is therefore, a unit in which a balance between man and nature can be carried out. All the rain falling inside that water divide constitutes the water resource shared by all the water-dependent activities there, Figure 1. After reaching the land surface the rainwater is partitioned into the green water vapour flow supporting the terrestrial ecosystems and the blue water liquid flow supporting the aquatic ecosystems and accessible for human use.

The green water flow system reflects the water consumption by forests, grasslands and rainfed croplands. It sustains the terrestrial ecosystems in general and in particular rainfed crop production. The blue water moves as blue water flow from uphill to downhill, from land to water systems where it is accessible for societal use. By withdrawals water is "harvested" to support water-dependent human activities and carried to cities and to industries. After use it goes back to the water system as a return flow of wastewater loaded with pollutants, unless far-reaching wastewater treatment has been carried out. Blue water is also withdrawn to support irrigation. During use part of that water – the consumptive use – will turn into green water flow while the surplus (non-consumed part) forms a return flow of blue water. The return flow is often loaded with leached agrochemicals and soil nutrients causing eutrophication in the river water and the coastal waters where it empties.

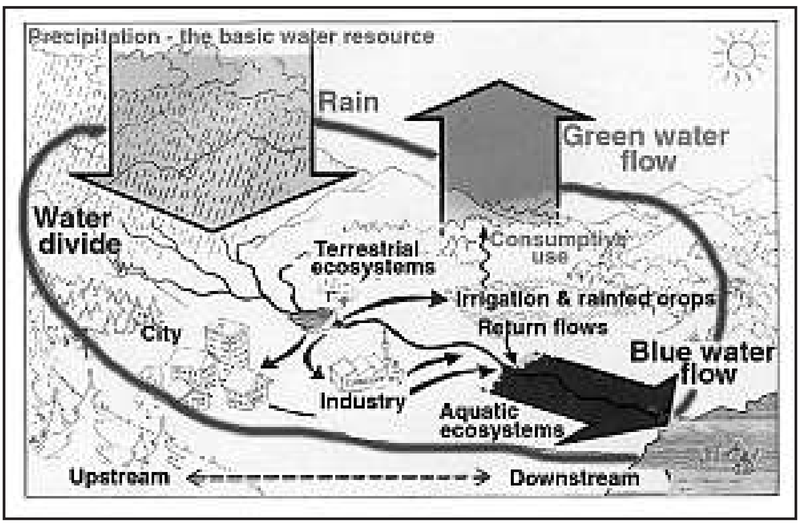

Figure 1. In a drainage basin perspective the precipitation over the area represents the proper water resource, part of which is consumed in plant production and evaporation from moist surfaces (green water flow) while the surplus goes to recharge aquifers and rivers (blue water flow), available for societal use and aquatic ecosystems.

The road to human security involves landscape modifications

As earlier indicated, humans are very active in their interactions with the blue water flow: on the one hand by their addition of contaminants, and on the other by their direct interaction with and modification of the landscape itself, in particular the vegetation, the soils and the water flows (Falkenmark and Mikulski, 1994). The vegetation may be cut down (deforestation) or altered (agricultural development, reforestation) in efforts to meet societal needs for food, fibre, fuel wood and timber. The soils are manipulated by remodelling the land surface by tilling, draining, impermeabalizing urban areas, and so on. And the water flows are manipulated by well drilling and groundwater pumping for rural and urban water supply by pipelines and canals to carry surface water to cities and industries and irrigation schemes, by reservoirs and dams to provide water storage from a season with water surplus and water use in a season with water deficiency. Reservoirs may be used for flow control both to reduce downstream flood risks and to secure water supply during dry periods of the year.

Human activities are driven by societal demands for life support – water, food, timber, energy and shelter. Societal leaders are expected to secure or at least facilitate access to these goods and services, fundamental for poverty eradication and human welfare (human livelihood imperative), see Figure 2 (Falkenmark, 1997). These efforts involve *physical interference* in both land (clearing, tilling, etc.) and water pathways (wells, pipelines, storages). *Chemical interferences* originate from exhaust gases, solid refuse, wastewater and agricultural chemicals. Basically, waste production tends to follow human activities and socio-economic development (Falkenmark and Lundqvist, 2000). Due to the natural processes going on in the landscape, these interferences will be reflected in unintended side effects, in particular water-related processes. The result will be air quality deterioration (e.g., acid rain), land productivity degradation (e.g., fertility degradation, soil crusting), water quality degradation (e.g., bacterial pollution, nutrient pollution, toxic pollution). When these phenomena change, ecosystems will be disturbed in response as higher order effects: ecosystem degradation (terrestrial, aquatic) and loss of resilience, i.e., ecosystem capacity to cope with disturbances, natural ones as well as human-induced ones. All these side effects may undermine the resource base for the society and are therefore serious. It is therefore, essential to find ways to reach an integrated land/water/ecosystem management that allows welfare without unacceptably undermining the life support system on which that welfare is based.

But there are also links back to the social system due to concern generated by failure in satisfying human needs or generated by unacceptable side effects. Responses may be seen as active or passive: passive ones like morbidity, famine, disputes, or active ones like migration, altered expectations, fallow reduction or imports of food.

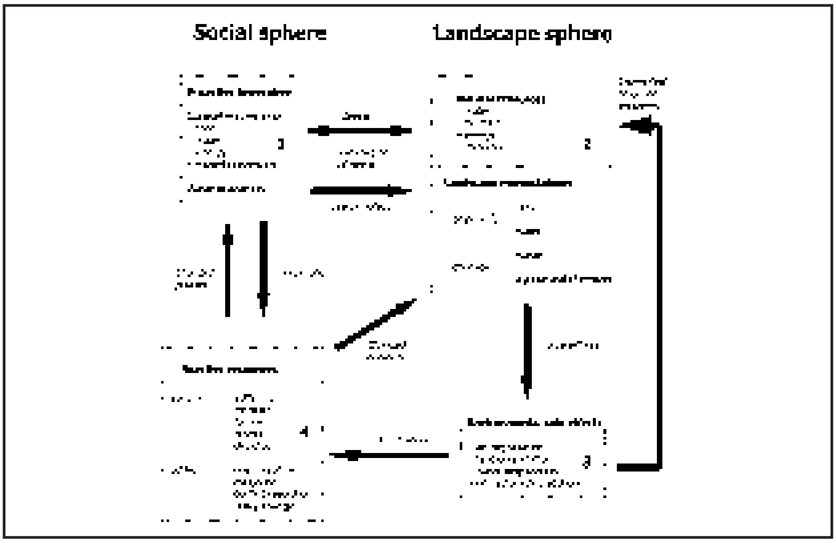

Figure 2. Human activities in the landscape (from Falkenmark, 1997).

It is interesting to note that in Figure 2 different professional groups have tended to concentrate their interest in different areas: engineers in box 2 (upper right), environmental professionals and ecologists in box 3 (lower right), business leaders in box 1 (upper left), and social scientists and politicians in boxes 1 and 4 (lower left). Such sectoralization evidently contributes to the difficulties in coping with environmental side effects of human activities and reach sustainable development.

Altering worldview

The fact that human activities always involve landscape modifications is now being increasingly realised and causing a shift in thinking among ecologists. While it is being increasingly understood that humanity will have to live with change, sustainable development is about sustaining the potential and capacity for prosperous social and economic development. It relies on ecosystem services and support and will continue to do so in the foreseeable future. Current approaches are getting more process-oriented with stress on the biophysical interactions between water – the bloodstream of the biosphere – and ecosystems.

The conventional idea from recent decades of securing "ecosystem balance" is now being abandoned for the reasons explained in Box 1: humanity has to learn to live with change. Stability has been found to be an exception in view of the resonance linkages between human action and local ecosystems. Similarly, the idea of mere preservation of ecosystems is successively weakening in favour of more ecosystem based management approaches.

Box 1. CO-EVOLUTION OF SOCIETY AND ENVIRONMENT

A fundamental building stone in the ongoing shift in thinking is a recent study by van der Leeuw and colleagues of land degradation in the *Mediterranean region over a period of human activities during 20,000 years*. The study covers bad lands, droughts and flash floods in Spain, salinization and water mismanagement in southern Greece, a mix of tectonic activity and human interactions with vegetation in NW Greece, and 7000 years of human activity in the Rhone Valley in France. It is suggested that no single set of natural dynamics could be identified to be responsible for the observed land degradation. It was rather the result of a converging set of social processes interacting with the surrounding environment, i.e., a *co-evolution of social and environmental processes*. The research group realized that human reaction to environmental change is less direct than other species because society has to become aware before it can consciously respond. The interrelationship is therefore, more of resonance character than of cause/effect. The study also questioned the idea of sustainability in the meaning to continue living as we do forever; an idea that rests on the assumption that stability is natural and humanly achievable. The long-term perspective of the study however, suggests this to be an illusion. Since it has been realized that human actions have become a major structuring factor of the dynamics of ecological systems, the earlier worldview of nature and society as systems near equilibrium is now being replaced by a dynamic view. Stability is probably an exception worth particular analysis. The consequence is that rather than assuming stability and analysing change, one needs to assume change and analyse stability.

Overexploitation of natural resources in early civilisations has through millennia resulted in environmental degradation, sometimes so severe as to cause the downfall of whole societies. One example is the rise and fall of the human society on Easter Island in the Pacific Ocean. A centralised and well-organised society, driven by the urge to demonstrate power to neighbouring clans and led by a leader trying to outdo the next, was able to shift an ecosystem from a natural open forest system to a state of almost complete desertification. The main cause was extensive deforestation to harvest the timber required for transporting huge stone statues from inland queries to platforms along the coast where they were raised. Two hundred enormous statues still remain while seven hundred more were left in some stage of preparation in the collapsing ecosystem. Deforestation most probably resulted in increased wind and water erosion, increasingly degrading the soils that, due to their natural condition, were inherently vulnerable to erosion.

Sources: van der Leeuw (2000), Redman (1999)

4. ECOSYSTEMS' WATER DEPENDENCE

Human society is a subsystem of the biosphere in which water is a key element. Humanity critically depends on the global ecosystem offering renewable resources and producing ecological services, Figure 3. Human activities to improve welfare are driven by societal driving forces and influenced by the institutional system but involve the production of waste and other disturbances that influence the functioning of the ecosystems. While the ecosystem concept is biologically defined as referring to the interaction between groups of organisms living in a certain bio-physical environment, the link to hydrology and water management is the *water determinant* of a specific ecosystem, i.e., the water characteristics that determine the habitats, the growing conditions, and so on.

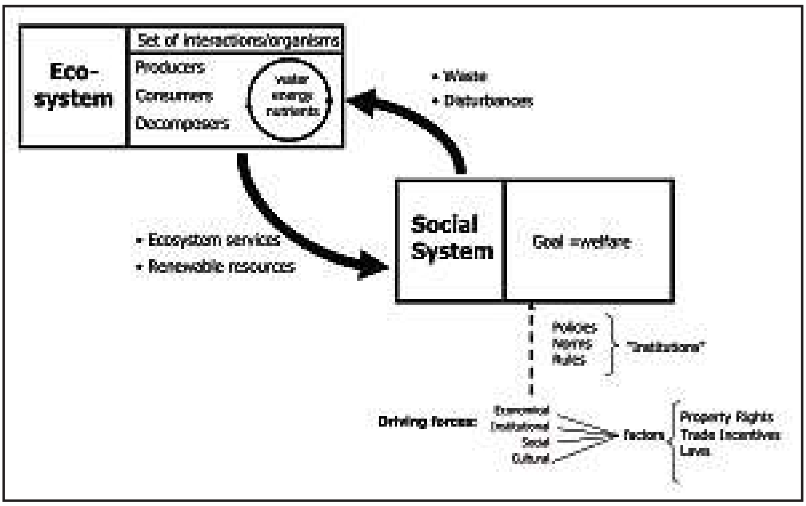

Figure 3. Humanity critically depends on the ecosystem offering renewable resources and producing ecological services. Human activities to improve welfare are driven by societal driving forces and influenced by the institutional system, but involve the production of waste and other disturbances that influence the functioning of the ecosystems.

Ecosystems provide ecological "services" in terms of terrestrial ecosystem productivity (timber, fuel wood, drugs, crops etc.) and aquatic system productivity (fish, seafood etc.). Both types of productivity have to be kept operational. Other ecological services refer to processes of vital importance for the functioning of the life support system (Box 2). While uphill terrestrial ecosystems are involved in rainwater partitioning between the evaporating part, the flood flow part and the groundwater part, aquatic ecosystems in the valley bottom are carrying the burden of upstream human activities as reflected in both water quality degradation, and river depletion and seasonality changes.

Box 2. SOME WATER DEPENDENT ECOSYSTEM SERVICES

The water cycle

A more successful coping with the complex roles of water in the life support system should begin by paying larger attention to the water cycle in its role as the *bloodstream of the biosphere*, i.e., take a water-cycle-based approach to human interaction with the natural system. First of all, through its physical, chemical and biological involvement, water has absolutely *fundamental balancing functions in the water cycle*. It dissipates solar energy variations in space and time through three main process properties with mutually balancing component processes:

- *physical* ones through the interaction between evaporation and condensation of major importance for the redistribution of energy over the planet
- *chemical* ones through the interaction between crystallization and dissolution of fundamental importance for the redistribution of soluble substances over the planet
- *biological* ones through the interaction between the water molecule splitting as the first step in the photosynthesis process and the later re-assemblage through respiration. The liberated hydrogen forms cellulose, in the process liberating oxygen.

Key functions and linkages

Ecosystem services are of decisive importance for the functioning of the life-support system. Some ecological services are evident, others have remained mentally hidden. By a systematic approach they can be structured as follows:

- *physical* services such as phosphorous absorption in the soil; erosion and sedimentation of silt; interception of rainfall; facilitating rainwater infiltration into the soil
- *chemical* services such as oxygen production and carbon dioxide uptake in the photosynthesis process; denitrification; nutrient release through biodegradation
- *biological* services like photosynthesis, pollination, seed dispersal, pest control, production of biomass, and macropore creation in the soil.

Sources: Ripl (1995), Daily (1997), FAO (2000)

Terrestrial ecosystems

The terrestrial ecosystems play a fundamental role in the runoff generation process since they consume huge amounts of green water, in fact two thirds of the continental precipitation, see Box 3.

The photosynthesis process involves a consumptive use of water that is climate dependent. Water is one of the two raw materials in the process with carbon dioxide being the other. The process starts by the splitting of the water molecule followed by a second biochemical reaction where the freed hydrogen reacts with carbon dioxide from the air, forming sugar molecules that constitute the basic building blocks of plant biomass (Waterlow et al., Eds, 1998). However, when opening the stomata in the leaves to take in carbon dioxide the plant looses water by diffusion and the lost water is replaced through a water flow up the plant from the roots.

Landscape ecosystems may be quite different in character with a main distinction between grasslands and forests and in terms of characteristic vegetation with dominating species shifting with climate.

Grasslands

Grasslands include steppe, prairie and grassland savannah. Of major interest in the least developed countries are terrestrial ecosystems in drylands, characterized by low biological productivity. In the tropics rainfall is subject to strong seasonal, inter-annual and long-term variability and the evaporative demand of the atmosphere is high so that canopies are open with often less than 30 percent plant cover. Vegetation patterns are quite complex with large bare patches (Wainwright et al., 1999). The supply of water forms the dominant control on growth and maintenance of the plants. Due to the extreme variability plants must adapt, i.e., try to minimize the impact of climatic variability by delayed responses, growth cycles, clumped or banded structures and so on.

The timing, intensity, seasonality and so on of rainfall determines the hydrological fate of the rainwater. Even lichens can be significant vegetation components with a capacity to take up rain, dew and water vapour. Due to the open canopy patterns and large exposed soil surfaces, sediment yield is of especial importance in drylands. The low vegetation cover makes the soil-vegetation-atmosphere transfers complex and land–surface degradation may have atmospheric feedbacks in terms of altering leeward rainfall patterns (Savenije, 1995).

Forests and woodlands

In forests and woodlands interception losses from the foliage may be considerable but are rather different in the temperate as opposed to the tropical zone. The losses are often less from seasonal canopies (Roberts, 1999). Transpiration tends to be well below the potential evaporation and without large differences between temperate and tropical forests. Tropical forests may have 15 m deep roots but the function of such deep roots remains unclear. In dry conditions, infiltration may be aided by root shrinkage during dry periods but there may also be other conduits in the soil. Soil moisture is subject to considerable variations caused by differences in infiltration and root uptake. The most woody vegetation may have 50 percent of roots in the upper 30 cm. The lateral spread of its roots corresponds in size to the canopy of humid forests but in semi-arid woodlands it is much larger and defines the distance between the trees on the savannah (Eagleson and Segarra, 1985).

Box 3. TERRESTRIAL ECOSYSTEMS CONSUME WATER

Terrestrial ecosystems basically feed on infiltrated water. Seen on a global scale they consume two thirds of the precipitation over the continents:

– croplands (including weeds and periphery)	6800 km³/yr
– temperate and tropical grasslands	15100
– temperate and tropical forests, woodlands	40000
– bogs, fens, swamps and marshes	1400
– tundra and desert	5700
– other systems	2000
Altogether	71000

These 71,000 km^3/yr constitutes the total green water flow from the continents, i.e., continental evapotranspiration. Figure 4 visualizes the continental water partitioning showing the fundamental importance for the blue water flow of the green water flows involved in consumptive water use by terrestrial ecosystems including crop production. It also puts in proportion the tiny relative scale of water use that has been the focus of past water management and was discussed by the World Water Commission. The overall water withdrawals were estimated to 3900 km^3/yr out of which 2600 is consumptive use and the remaining 1300 constitutes the return flow.

Sources: Rockström et al., (1999), Cosgrove and Rijsberman (2000)

Aquatic ecosystems

Blue water systems and the aquatic ecosystems that they host offer not only in-stream benefits such as recreational use, navigation, dilution of pollutants, and habitat provision for example in terms of wetlands, but also living resources that can be extracted such as fish, water fowl, shellfish, pelts, and so on (Postel and Carpenter, 1997).

Streams

In streams, water movement is considered to be the most important factor affecting plant distribution (Large and Prach, 1999). Stream habitats tend to have patchy macrophyte distribution due to a mix of locally low and high flow velocities and sediment distribution differences. But conditions are at the same time interactive in the sense that the macrophytes tend to reduce flow velocity and enhance sedimentation thereby offering habitats for invertebrates and fish. Flow variability is one of the primary determinants of species distribution in riverine systems but also the relative contribution of groundwater outflow has importance (Wood et al., 2001).

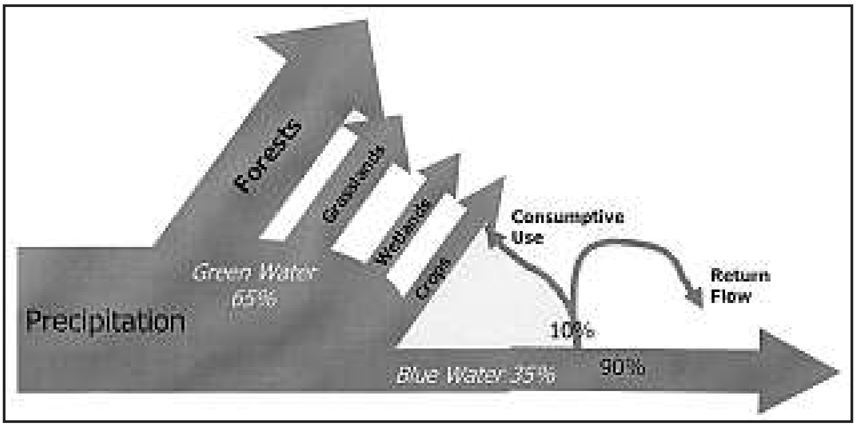

Figure 4. Consumptive water use by terrestrial ecosystems as seen in a global perspective (from Falkenmark, SIWI Seminar 2001).

When biotic integrity and ecosystem function is to be maintained invertebrate communities may have to be protected (Buffagni, 2001). Habitat requirements in terms of flow, oxygen and temperature preferences of particular taxa can then be evaluated so as to secure both respiration and nutrition (Freistühler et al., 2001). In this way ecologically acceptable flows may be determined against benthic invertebrate production and future existence of individual species. The dynamics of flood/drought seasonality is essential for biota, which has adapted to the fact that the bulk peak flow only occurs over a couple of months each year. Any change in timing and magnitude of flooding therefore, will affect biodiversity in tropical rivers.

In the Mekong River, for example, many fish species make upstream breeding migrations during flooding in the wet season and make downstream migrations during the dry season. Upstream migrant fish spawn in inundated areas during the rainy season and then gather in river channels or lateral lakes during the dry season. Other fish species use the rising waters to reach swamps, inundated forests, rice fields, oxbows, all of which function as feeding grounds, shelter and spawning sites (Dudgeon, 2000).

Lakes

A lake ecosystem is closely linked to the water and chemical inflows from the catchment (Wetzel, 1999). Lakes are basically topographic depressions that have been filled with water from a drainage basin. They are modified by vertical water exchange through the combination of precipitation and evaporation. The drainage basin provides an ionic input that characterises the chemical composition of the inflowing water. Once in the lake the water quality is modified by the vertical water exchange. In lakes where there is a net vertical input the ionic inflow is diluted by the precipitation. In lakes where there is a net vertical loss of water, there is a hydrological enrichment increasing the ionic concentrations.

As a consequence, habitat characteristics of lakes differ according to the relative roles of horizontal as opposed to vertical water exchange. Some lakes are dominated by horizontal water exchange with negligible vertical influences and are therefore, characterized by the throughflow system with a fairly rapid overall renewal of the lake water mass. Other lakes with small drainage basins are dominated by the vertical exchange that makes them climate-controlled and vulnerable to climate fluctuations. Most mountain lakes are throughflow-dominated whereas the Aral Sea is climate dominated. Also, the biological structure and the metabolism of a lake are closely coupled to the hydrological flows and the chemical loads that they carry from the drainage basin (Wetzel, 1999). The lake may be influenced by responses of the groundwater system originating from land use changes in the catchment. Biologically mediated water losses to the atmosphere in combination with sedimentation in the littoral zone will lead to a slow transition of shallow lakes into terrestrial ecosystems. Such processes make shallow lakes transient features in the landscape.

Wetlands

From the water manager perspective wetlands are difficult to cope with because of their large variety as seen from a hydrological viewpoint (Mitsch and Gosselink, 2000). Wetlands are a biologically defined phenomenon characterised by anoxia and low redox potential (Wheeler, 1999), and mainly stands for rather wetland irrespective *of what water keeps the wetland wet*. From a hydrological aspect a basic distinction can be made between aquatic wetlands on the one hand which are part of an aquatic ecosystem (shallow water bodies), and *telmatic* wetlands on the other which are basically wet terrestrial systems. What is characteristic of a wetland is that the land is wet enough to support typical wetland vegetation which differs clearly from the vegetation of well-drained land (Pielou, 1998). *A wetland is, in other words defined by its vegetation, not by its hydrology*.

Wetlands form wherever poorly drained land collects enough water to be submerged or saturated most of the time. They are particularly abundant in regions where drainage systems are incompletely developed. North American wetlands are, for example, more productive in terms of plant growth compared to either agricultural land or natural grassland (Pielou, 1998). They are storehouses for biodiversity. They are irreplaceable habitats for vast numbers of birds that breed there or stop there to feed while migrating.

There are several main types of wetlands (Pielou, 1998): bogs, fens, marshes and swamps. The two first ones are known as peatlands. The difference between them is that the water in a bog is mainly rainwater, stagnant and poor in nutrients, while the water in a fen can be either seeping groundwater or slowly flowing surface water, nutrient rich and slowly moving. The result is spectacular differences in vegetation. The second group of wetlands dries out from time to time and peat cannot form since the land is only seasonally flooded. Such non-peaty wetlands tend to develop in warmer, drier climates than peatlands. There are two main forms: swamps and marshes, differing in their vegetation. The former is vegetated with trees, the latter with grass-like plants. In swamps the water table sinks below the root zone during the dry season whereas marshes have vegetation that grows in constantly wet soil. Intermediate between marshes and dry land are wet meadows that have waterlogged soil a few centimetres below the surface and a greater variation in vegetation.

It follows from the above distinctions, that main *water determinants* of terrestrial wetlands may be rainfall (bogs), lateral water flow (fens), flood water (swamps and marshes), and groundwater seepage (fens and wet meadows). Many wetlands exist because infiltration of rainfall has been inhibited by impermeable layers of soil or rock that restricts the downward percolation of rainwater.

Wetlands may have important hydrological functions in a catchment like groundwater recharge when the water table of the wetland area is reduced, flow regulation where wetlands allow active water storage, and water quality modifications due to biochemical reactions in the wetland ecosystem (denitrification, absorption of phosphorus and metals).

5. HOW TO BALANCE HUMAN ACTIVITIES AND ECOSYSTEM PROTECTION

As explained above, landscape modifications are essential elements in the socio-economic development process but tend – due to natural processes at work in the landscape – to develop side effects on water flow, pathways and quality and therefore on water-dependent ecosystems. Most of these consequence-producing processes are water-related: the rainwater partitioning in contact with the vegetation; the lift-up/carry-away function, mirroring water's role as a unique solvent on continuous move and as an eroding agent; and the continuity-related ability of the water cycle to produce chain effects. Since ecosystems tend to change as the outcome of this overall process, landscape modifications are often in conflict with preservation of existing ecosystems.

Learning how to live with change

At the present stage in developing countries, key environmental challenges tend to be closely linked to sustained economic development and improved human livelihoods (IUCN ROSA, 2002) threatening sustainable use of natural resources and conservation of biological diversity. In addressing the particular challenges in developing countries, adequate attention has also to be paid to fundamental hydro-climatic differences between the tropics where they tend to be located and the temperate zone hosting many of the industrialized countries (Falkenmark and Chapman, 1989; Ayebotele and Falkenmark, 1992). The main factors of importance here is the much larger rainfall variability and the much larger evaporative demand.

Three human activities threaten ecosystems

The water-related determinants of ecosystems indicate the way in which ecosystems may be disturbed by human action. They include water flow, water pathways, flow seasonality, water table, and water quality/chemical composition. They may be impacted by both direct and indirect water-related activities.

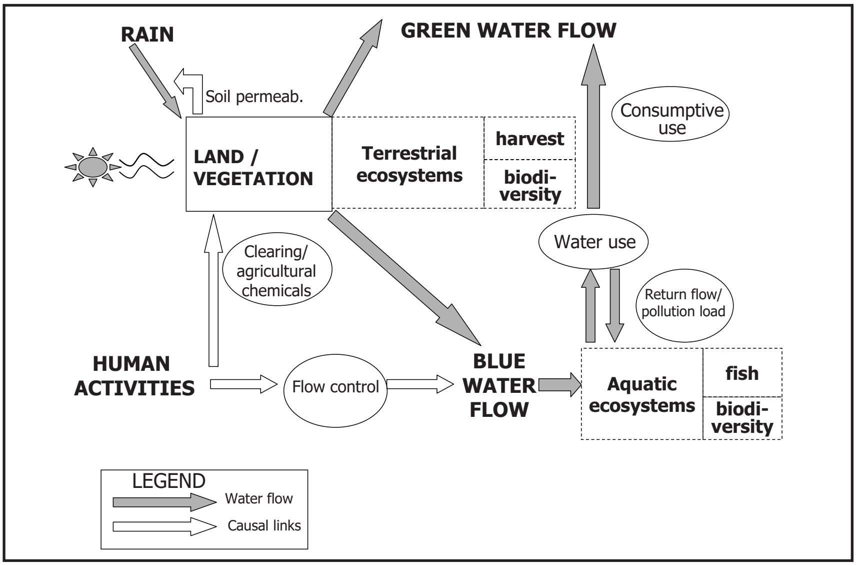

Figure 5. Human activities in the landscape modify blue water flow both directly through flow control structures and consumptive use, and indirectly through land/vegetation manipulations.

Figure 5 visualizes causal chains between alterations of ecosystem goods and services on the one hand, and the causing human activities in the landscape related to the supply of food, water and energy and to the generation of income, on the other. Essentially, three entry points are involved in these modifications of ecosystem water determinants:

- flow control measures to fit flow seasonality to water demand seasonality
- land cover changes influencing soil permeability and rainwater partitioning, and consequently runoff generation
- water withdrawals and after use alterations in terms of consumptive water use and pollution load respectively.

Two types of land cover changes that have attracted plenty of attention are deforestation (see Box 4) and dryland salinization as a consequence of woodland clearing (see Box 5). Forest conversion may produce considerable changes in runoff (GWP, 1999). The impact on local water balance of deforestation has been extensively documented with substantial increases in long-term runoff and storm flow as typical results. While the total runoff increases after deforestation the principal source of increase is from savings in transpiration by the replacement of deeper-rooted trees by shallower-rooted low crops. Thus the largest increase is concerned with the delayed flow component of the stream hydrograph. In the tropical forest ecosystem the surface soil hydraulic properties may be vulnerable to change through compaction on removal of the forest and the loss of macropores in the soil when the biological activity stops.

Environmental circles often claim that forests are necessarily good for the water environment, that they increase rainfall, increase runoff, regulate flows, reduce erosion, reduce floods, "sterilize" water supplies and improve water quality. These views are reflected in for example IUCN's report "Vision for Water and Nature" (2000) to the Second World Water Forum.

Box 4. FORESTS AND WATER

The perception that forests are good for the water environment and for water resources has grown out of observations that link land degradation with less forest, and rehabilitation and conservation with more forest. In arriving at that view focus has been limited to visible phenomena at the soil surface rather than on invisible root zone events. This misleading perception has been supported by the forestry sector, and has become deeply ingrained in public awareness, and even "enshrined in some of our most influential policy documents" (Calder, 1999). Calder has scrutinized a number of "mother statements" on forests and water against scientific evidence and made the following observations:

1. *Forests increase rainfall*: the rain originates from the air moisture that contains marine evaporation and green water flow from upwind vegetation. Since hills and mountain areas usually have more rainfall than adjacent lowlands their natural vegetation tends to be forests. The water evaporated from forests feeds the water vapour flow in the atmosphere and returns as precipitation elsewhere. Through such atmospheric feedback deforestation may be reflected in less precipitation somewhere downwind.
2. *Forests increase runoff:* the runoff is the rainwater surplus over water evaporated from intercepted water on the foliage and water transpired from the plants. It is generally larger from trees with larger foliage and deeper roots than from annual crops. The runoff from forested areas tends to be lower than from those under shorter vegetation.
3. *Forests regulate flows*: what is generally referred to is the role of vegetation in determining the infiltration properties of the soil and the dry season flow, fed by groundwater seepage. The flow is the outcome of a site-specific system of often competing processes. It is not generally true that afforestation will increase dry season flow.
4. *Forests reduce erosion*: competing processes are at work: rainfall rates, surface runoff generation, soil water pressure, binding effects of tree roots on slope stability, logging technique compacting the soil etc. The integrated effects are both site- and species-specific.
5. Forests reduce floods: hydrological studies show little linkage between land use and stormflow, especially in large catchments with mixed land cover, and several sub-catchments superimposing their flood waves. Competing processes at work include high infiltration rates under natural forests, drainage and soil compaction under forest plantation projects. There is little scientific evidence to show that for the largest flood events deforestation is being the cause.

In summary, a more questioning attitude is advised to the simplistic "old paradigm" perceptions about forests and water resources.

Sources: Calder (1999), GWP (1999), Savenije (1995)

Box 5. AUSTRALIA'S DRYLAND SALINITY – WATER-MEDIATED EFFECT OF LAND COVER CHANGE

One of Australia's dominant environmental problems is the dryland salinization of soils and water systems. The relationship between land clearing and salinity has been widely recognised for almost a century but action is difficult to realize due to poor stakeholder incentives. The landscape has for millennia been accumulating windblown salts from the ocean. 10,000 years of salt accumulation at the estimated rate of input from the sea is enough to explain the salt concentration measured in the coastal zone. The water balance of the indigenous eucalyptus vegetation represents a close match between rainfall and green water flow. As a result, the groundwater recharge that flushes the salts left behind after evaporation is very low and the water table therefore deep down in the soil profile. In this vulnerable environment, deforestation has had ominous results in radically changing the well-balanced system. Clearance of the land reduced green water flow, and increased groundwater recharge and rising water table. The result has been incidents of saline seeps in low-lying areas - in some places even threatening drinking water reservoirs.

Reversing this development by land management measures is not easy. Replanting in specific recharge areas is seen as one possible control method where economic consequences would be limited. In other areas, changed cropping patterns have been advocated, replacing shallow-rooted crops by deep-rooted ones like alfalfa or lupins. The ambitions have met very limited success, however, due to lack of incentives of local stakeholders. In spite of the existence of both technology and awareness, the salination problem has not been contained, therefore, a fact that is all the more disturbing in view of Australia's leading position in understanding the links between land use and water, its ambitious land care program etc. In order to get out of this regional scale environmental pitfall of Australian economy, the human dimension of necessary land use changes in terms of aspirations, motivation and incentives of local landholders is a fundamental dimension to address.

Source: Calder (1999)

Three sets of considerations

It follows from the interactions between humans and the ecological phenomena in the life support system that trade-offs will have to be struck in the IWRM process. In that process, attention has to be paid to the important upstream/downstream dimension (Falkenmark, 1999). The upstream part of a catchment or river basin hosts a number of *water-impacting* activities: land use conversions, flow modifications, pollution load, and so on. Together they influence the river flow, seasonality and quality of the water flowing into the downstream area. The downstream stakeholders are involved in a number of *water-dependent* activities and phenomena: both direct water use for households, municipalities, industry, irrigated agriculture etc, and ecological services within riparian wetlands, aquatic ecosystems and coastal ecosystems.

As already indicated, two complementary focuses have to be distinguished in terms of ecosystem scale: on the one hand where focus is on certain site-specific ecosystems in particular need of being protected; on the other hand where focus is on the sustainable productivity of the life support system in the catchment.

Securing long-term productivity of the life support system
This paper has clarified that a key function to secure for future generations is the capacity of the life support system to deliver food and biomass, ecological services of various kinds while enduring disturbances and variability. Ecological systems in the landscape are linked by flows of water in an upstream/downstream pattern. Freshwater flows, crop production and other terrestrial ecosystem services are interconnected and interdependent. Aquatic ecosystems downstream respond to the integrated result of all upstream activities. Key questions to be raised will have to include for instance how much water needs to be left in the river and why? What pollutants have to be avoided and why?

One way of seeing the linkage between integrated water resources management and ecological services is to manage catchments as an asset that delivers a bundle of water and ecological goods and services. Some of these services work in synergy; others are in conflict (GWP, 1999). Hence, intentional trade-offs need to be made based on the view of humans as embedded in the eco-hydrological landscape. One can even envisage a situation where landowners should be given the task of managing the natural resources for the society as a whole and be paid for that. Ecosystem services and water have to be managed in an integrated way. The catchment has to be managed in an adaptive way to protect resilience of the life support system to surprises and shocks, and avoid ecosystem flips to a more vulnerable state.

Criteria have to be developed for the protection of the capacity for sustainable production of life support. This means identification of what key functions are essential for the production of terrestrial ecosystem's goods of social and economic importance, terrestrial ecosystem's services of ecological importance, aquatic ecosystem's goods of social and economic importance, and aquatic ecosystem's services of importance from different aspects. Humanity through its activities tends to alter disturbance regimes with which organisms have evolved over time. Disturbances may be quite diverse: natural disturbances, unnatural ones, and combined ones. There is therefore, a need to secure enough "elasticity" of ecosystems to sudden change in the surrounding conditions like storms, fire, drought or sudden pollution events. Ecologists speak of this "elasticity" as resilience to disturbances. The key issue therefore, is to *secure capacity to absorb continuous change without loss of the dynamic capacity of ecosystems to uphold the supply of ecological goods and services*. It is evident from the above that a crucial consideration will be how to protect the resilience of the catchment's life support system or more particularly, the key productive functions of that system. The overriding task here is a catchment-based adaptive management with the aim to move the system in such a direction that future options are protected and secured. Collapses have by all means to be avoided by action as early as possible and land and water resources have to be protected for the next generation (see Box 6).

Box 6. LONG-TERM RESILIENCE AGAINST CHANGE

There are two kinds of resilience: social resilience, i.e., the coping capacity of society and its institutions, and ecological resilience, i.e., the coping capability of ecosystems. Resilience provides the capacity to absorb change without losing functions and basic properties under stress, and to recover from damage by the self-organizing ability for renewal and reorganization following change. When a social or an ecological system loses resilience it becomes vulnerable to change that could earlier be absorbed. A change of state takes place that may cause societal problems due to disruption of previous ways of life. As resilience declines it takes progressively smaller external events to cause catastrophe. Reducing resilience in other words, increases vulnerability. For instance, increase in social and economic vulnerability as a consequence of reduced resilience through land degradation and drought may cause loss of livelihood and trigger tension and conflict over critical resources such as freshwater and food.

The golden rule will be not to allow degradation to proceed too far, i.e., come too close to a collapse of the ecosystem state. The goal of the catchment management has to be to protect the basis for the life support system of the region. The ecosystems have to be protected from creeping changes that might make them flip into a different state with less elasticity/resilience to unavoidable changes appearing as surprises. At the present level of understanding, focus should be on slow variables influencing the functioning of the particular ecosystem in question. These variables include land use, nutrient stocks, soil properties, and biomass of long-lived organisms. Since both land use and soil properties are intimately linked to water processes and functions, water variables will have to be added at the next level of understanding, primarily water flow regime, green water flow and toxic water pollution.

While resilience is a buffer to disturbance this buffer is provided through *biological diversity*, which acts as an insurance in this context. Biological diversity is also important in providing overlapping functions for restoring ecosystem capacity to generate essential ecological services. Loss of biodiversity reduces ecosystem resilience to change, and threatens the function of the system as a foundation for economic activity and human welfare. In a particular ecosystem many species may have similar functions, i.e., to a certain degree duplicating each other. A minimum composition of organisms has therefore, to be retained to secure that the relations between the primary producers, consumers, and decomposers be sustained to continue mediating the flow of energy, the cycling of elements and spatial and temporal patterns of vegetation.

For any ecosystem function to be sustained freshwater provides the foundation for the processes involved – a foundation that has largely been neglected in the past.

Source: Folke et al., (2002)

Local ecosystem protection

In a catchment there might be particular site specific biological landscape components that need to be protected due to interesting endemic species, valuable biodiversity, beautiful landscape or riverscape, particular social values, and so on. Protection of a local ecosystem may be emotionally and/or ecologically motivated. In either sense protection would basically mean to protect it from the risk of collapse or flip to a different, unwanted state, for instance a clear lake turning turbid; a cloud forest that collapses; a semi-arid rangeland turning from pasture to woody vegetation; a savannah agro-ecosystem that flips to a lower yield level; a savannah ecosystem that suffers reduced rainfall due to atmospheric moisture feedback from upwind deforestation (Savenije, 1995). The flip signals may appear as complete ecosystem collapse, altered crop yields, altered vegetation mix, and lake turbidity change. Water cycling is essential in the ecosystem degradation process. On the one hand it transmits disturbances; on the other it provides a set of different entry points for the disturbance.

To master the different ecosystems their water determinants have to be identified (water flows, water pathways, flow seasonality, water table, water quality/chemical characteristics, etc.), determinants that may be impacted directly as well as indirectly through water withdrawals, consumptive water use, pollution load, land use influencing water partitioning, flow control measures, and so on.

Internal catchment compatibility

Within the catchment biophysical links influence the internal compatibility of land use, water use and protection of ecosystems. What is referred to is the various water flow linkages: land use influences runoff generation, consumptive water use influences remaining river flow, pollution load influences water quality, and the general catchment flow links upstream and downstream opportunities. Regarding the *aquatic* ecosystems it will be essential to secure acceptable habitat situations by avoiding any water pollution that would degrade them. Environmental flow will have to be secured both in terms of flood episodes and uncommitted river flow. The *terrestrial* ecosystems are of importance due to their role in runoff production. They may also be important to protect and secure groundwater recharge and dry season flow. The more green water they consume the less will be the rainwater surplus left for runoff production. Protecting them is basically an issue of putting constraints on land use change.

The overall problem boils down to finding ways to meeting at the same time both societal needs and ecosystem protection needs. The societal needs generally involve manipulation of landscape components in terms of water pathways and land cover. Due to water's consequence-producing functions side effects will be unavoidable, disturbing water-dependent ecosystems. At the same time beneficial ecosystem functions in the water cycle have to be taken into account: terrestrial ecosystems are water-consuming but may facilitate groundwater recharge thereby securing dry season flow; aquatic ecosystems are blue water dependent and therefore vulnerable to change when river flow, seasonality and/or water quality are altered, but are also at the same time interacting with certain water pollution components, partially reducing water pollution problems.

The catchment can basically be seen as a mosaic of partly incompatible land and water demands so that the overall challenge is to *orchestrate this complex system for compatibility*. This will involve three different types of balancing to:

- satisfy societal needs while minimizing the pollution load added and accepting the consumptive water use that is involved
- meet ecological minimum criteria in terms of fundamental ecosystem determinants: environmental flow to be left uncommitted in the rivers, secured flood flow episodes, and acceptable river water quality
- secure hydrosolidarity between upstream and downstream societal and ecosystem needs (SIWI Seminar, 2001).

The catchment functions as a *socio-ecohydrological system* (Falkenmark and Folke, 2002) in which intentional trade-offs have to be made. At the same time social acceptance of the results of those trade-offs has to be secured, implementation be made possible in terms of institutions, regulations and financing needed, and the implementation be realized by securing adequate incentives and education efforts. In these efforts however, complications will emerge, *inter alia* continuous change in terms of further land use and water use modifications driven by ongoing population growth, urban migration and increasing expectations. Moreover, response delays will complicate the efforts: delays in societal response, which has to be minimised, and in terms of hydrologic response and ecosystem response which have to be accepted (Meybeck, 2001). Finally, triggering events will have to be expected in terms of intervening drought events, flood events and pollution episodes.

Practical approaches

Three key directions have consequently to be incorporated in the emerging management system (secure-avoid-foresee): *securing* water-related services to the population, *avoiding* ecosystem degradation, and *foreseeing* changes and variability. Adequate attention has to be paid to the fact that water is deeply involved from many different perspectives through its many parallel functions:

- as societal support: health, socio-economic production, food/timber production, and energy production
- in ecological services, both in terrestrial and aquatic ecosystems
- in environmental threats from floods, droughts, diseases
- in its function as a "silent destroyer" through its two lift up/carry away functions (erosion/sedimentation and solute transport).

A fundamental way of approach must be to identify minimum criteria or "bottom lines" for ecosystems and their functions, terrestrial as well as aquatic. When balancing upstream against downstream interests one has to work from the downstream end after identifying bottom lines for the aquatic ecosystems there in terms of uncommitted environmental flows and minimum water quality. The approach then, has to be to move segment-wise upstream (*cf*., Box 7). A particular challenge here is to identify resilience determinants to avoid ecosystem collapses.

Incorporating green water influences

Substantial focus on green water flows is needed. For practical reasons however, the management has to address the resulting blue water situation. This means that green water influences on blue water flows, *inter alia* altered runoff generation, have to be incorporated. Attention has to be paid to runoff added along particular river stretches, to demand sites and the partitioning of the diverted water into consumptive use versus return flows, to the pollution load added, and to instream uses. The basic water resource is the precipitation captured within the catchment's water divide. The water has to be routed through the catchment. In this routing "ecological bottom lines" that have to be secured have to be incorporated, upstream/downstream relations attended to, and resilience criteria respected.

Box 7. YELLOW RIVER BASIN MOVING TOWARDS RESOURCE-ORIENTED WATER MANAGEMENT

The Ministry of Water Resources in China is trying to introduce a new way of thinking into the management of Yellow River. It aims to move the river management from the present project-based management towards a resource-based water management. Three major problems will have to be mastered in the river basin: floods where water is seen more as a problem than a resource; severe water pollution and silt loads; and severe water shortage with drying up of the downstream stretch.

According to the vision the Yellow river should be managed based on minimum criteria for both quantity and quality, starting from the downstream end. Moving stepwise upstream, province-by-province, inflow and outflow to each stretch will be defined. The downstream "bottom line" will be the minimum outflow necessary to keep the river mouth open to protect *inter alia* its wetland preserve and avoid disappearance of the birds; and to avoid sea water erosion and salt water intrusion into the groundwater. Each stretch will then be allocated an inflow from upstream and be responsible for leaving a certain outflow for the downstream neighbour. Cross-sector controls should include both water quantity and quality. In a case when too little would remain at the downstream end of a province, it should be responsible for reducing the consumptive use and/or the wastewater emissions. This would call for an integrated management of often thousands of water intakes along the river, a task that should be in the hands of the provincial government.

The approach distinguishes between ecological and environmental flow requirements. The former refers to the flow needed to protect an aquatic ecosystem, the latter to the flow needed to dilute the wastewater emissions – with due attention to self-purifying capacity – down to a usable quality state acceptable for a sound ecological system. The idea is, finally, that highest priority should be given to water's ecological function while the priority relations between all the other water uses will have to be further debated.

Source: Wang (2002)

The working river concept

The challenge of living with change can be exemplified by the approach taken in Australia by the Cooperative Research Center for Freshwater Ecology in Canberra. They have introduced the concept "working rivers" (Whittington 2002), and define a healthy working river as "a managed river in which there is a sustainable compromise, agreed to by the community, between the condition of the natural ecosystem and the level of human use. . . . We work our rivers to produce hydroelectric power, we divert their waters for town water, manufacturing and for irrigation and we farm the rivers' fertile floodplains . . . Working rivers will not look like nor will they function in the same way as pristine rivers. In general, the more work the river is made to do the less natural it becomes . . . A different compromise may be struck between the level of work and the loss of naturalness, depending upon the values the community places on any river."

A crucial component of this healthy working river concept is that the river is managed to sustain at the same time an agreed level of work and river health.

Water reserve

One challenge to the water manager in the future lies in the optimal development of water resources, including the water required for responsible environmental management. A new water resources management program in South Africa has been codified in the National Water Act of 1998. This act abolishes the earlier riparian principle and provides for periodically reviewed licenses for water use and periods. The only remaining water right in that legislation is that of the so-called *Water Reserve*. The Reserve includes water to meet basic human needs and water to protect aquatic ecosystems. It has priority over all water uses and the requirements of the Reserve must be met before water can be allocated for other uses. However, where water is already allocated for use the requirements of the ecological reserve may be met progressively over time. Management options are the reduction of water use authorisations to specific users via a catchment-wide compulsory licensing process involving extensive public consultation, the development of additional water resources or a combination of the two. Water conservation and water demand management will also play a key role in this regard to reduce/contain water demand. The Reserve to protect aquatic ecosystems refers both to the quantity and quality of the water resource and varies according to the management class: natural, good, fair, poor and severely modified. The latter two are considered unable to sustain functional ecosystems. The determination of the management class, the related resource quality objectives and the Reserve will normally be undertaken as an integrated exercise. Procedures will range from rapid, low resolution methods to more time-intensive and higher resolution methods that can be flexibly utilised depending on management requirements. They will be applied in a phased approach to attain full coverage of all significant water resources in accordance with the programme for compulsory licensing – which will probably extend over a period of 20 years. The reserve has therefore, superseded all other water resources management requirements in terms of setting instreamflow requirements and has introduced a new element of urgency with respect to the need to quantify ecological flow requirements for many rivers of South Africa. Together these two needs are given first priority. The ecological reserve has been quantified for each river and amounts to on the average 20 percent of mean annual flow (see Box 8).

Streamflow reducing activity

The South African water law recognizes as a water use any land-based activity that reduces streamflow, e.g., commercial afforestation or dryland agricultural crops using more water than the natural vegetation (see Box 9).

In highly water stressed situations even invasive vegetation may have to be managed, as exemplified by the Working for Water Programme in South Africa (see Box 10).

Box 8. SOUTH AFRICAN WATER RESERVE

The National Water Act (1998) defines the Reserve that consists of two parts – the basic human needs reserve, and the ecological reserve. The basic human needs reserve provides for the essential needs of individuals and includes water for drinking, for food preparation and for personal hygiene, altogether 25 litre/person/day. The ecological reserve relates to water required to protect the aquatic ecosystem of the water resource. The Reserve will vary depending on the management class of the resource. The protection of water resources is fundamentally related to their use, development, conservation, management and control. The Minister must, in terms of the Act, develop a system to classify the nation's water resources and determine the class and resource quality objectives. In determining these objectives a balance must be sought between the need to protect and sustain water resources on one hand, and the need to develop and use them on the other. Provision is made for preliminary determinations of the class and resource quality objectives before the formal classification system is established, as the latter will be a time-consuming process. Once the class and resource quality objectives have been determined they are binding on all authorities and institutions when exercising any power or performing any duty under the Act.

Four management classes for water resources are being considered: Natural; Good; Fair; Poor and Severely modified. Each management class will represent a range of values for each characteristic. Water resources will, as far as possible, be managed within the boundaries of their management class. However, in the case of Poor resources, the management class may be set as a minimum of Fair, and management will aim to rehabilitate the resources to this status.

Resource quality objectives provide numerical or descriptive statements about the biological, chemical and physical attributes that characterise a resource for the level of protection defined by its class. They include:

- The quantity, pattern, timing, water level and assurance of instreamflow (the ecological reserve);
- The water quality, including the physical, chemical, and biological characteristics of the water;
- The character and condition of the instream and riparian habitat; and
- The characteristics and condition of the aquatic biota.

Source: Dr Paul Roberts, South Africa, memorandum to author, November 2002.

Box 9. SOUTH AFRICA: LAND USE CHANGE AS STREAM FLOW IMPACTING ACTIVITY

The streamflow reduction activity is any land-based activity that reduces streamflow. After public consultation, the Minister may declare such an activity to be a streamflow reduction activity. Whether or not an activity is declared to be a streamflow reduction activity depends on various factors such as the extent of the streamflow reduction, its duration and its impact on any relevant water resource and any other water users. The control of commercial afforestation for its impact on water resources is currently exercised in terms of the Act and has been declared as a streamflow reduction activity (SFRA), and is regulated by means of a SFRA Water Use Licensing System. Conceptually speaking streamflow reduction activities are broadly defined as dryland agricultural crops (perhaps maize or dryland sugar) using more water than the natural vegetation that would otherwise grow there (e.g., dryland sugarcane). None of these, besides commercial afforestation, has yet been declared, but the spotlight is presently on dryland sugarcane. In South Africa commercial afforestation covers approximately 1% of the land area and uses about 3% of the mean annual runoff with a total use of about 1400 million m^3/annum or 100 mm on average. The SFRA Water Use Licensing System has replaced a permit system that has been in use since 1972 and which was regulated under the Forestry Act (Act No. 122 of 1984). At present only commercial plantation forestry is licensed. The original permit system was geared towards determining areas available for commercial afforestation, based on the calculation of the percentage reduction in flow regimes caused by tree planting at primary catchment scale, without the consideration of the detail of impact on other water users, for example, low flows or in smaller catchments. The 1972 classifications of 0%, 5% and 10% reductions in Mean Annual Runoff (MAR) from whole or part of primary catchments guided decisions on determining areas to be planted. The approach had no concern for low flows: perennial streams could be converted to seasonal streams, with concomitant effects on those relying on the run of the river. As a result of the various shortcomings, especially local participation in decision-making in the original (1972) system, the Minister of Water Affairs and Forestry made an announcement in January 1995 that heralded the development of a new procedure and system.

The new SFRA *Water Use Licensing System* is subject to rigorous and continual auditing, both internally and externally, in conjunction with interested and affected parties. Since 1 October 1999, when Chapter 4 of the National Water Act (No. 36 of 1998) was implemented, the Afforestation Review Panels (established in 1995) became known as Streamflow Reduction Activity *License Assessment Advisory Committees (SFRA LAACs)*. In conjunction with the normal functions related to SFRAs, a *Strategic Environmental Assessment (SEA)* has been commissioned to deal not only with SFRAs, but with *all* water uses as described in Section 21 of the National Water Act. The SEA integrates three areas of assessment, namely the biophysical, economic and social components.

Source: Dr Paul Roberts, South Africa, memorandum to author, November 2002.

Box 10. SOUTH AFRICA: CONTROL OF INVASIVE ALIEN VEGETATION

Estimates indicate that about 10 million hectares of land in South Africa are infested with invasive alien plants and that they can cause significant reductions in runoff in some of the catchments where they occur. Chapman et al., (2001) estimate that the impact on water resources in South Africa is particularly deleterious, using an additional 3300 million m3 per annum, or 7% of South Africa's runoff. The problem is already significant, and will worsen if no action is taken. The individual area is expanding rapidly at a rate of about 5% per year, leading to a doubling of invaded area in 15 years.

Invasive vegetation is a land management issue with strong environmental considerations, and its management must be approached in a co-ordinated multi-sectoral way. The Working for Water Programme, a joint programme of the Department of Environmental Affairs and Tourism, the National Department of Agriculture and the Department of Water Affairs and Forestry, aims to progressively clear infestations of invasive alien plants everywhere in the country, and ensure that follow-up work is undertaken so that they do not recur. The Programme's activities also contribute to social development by creating employment and training opportunities and promote the establishment of secondary industries to use the harvested wood. The Programme also has direct environmental benefits in maintaining and restoring indigenous species.

Clearing work is undertaken on State owned land, and also on privately owned land by agreement with the landowner. Where necessary regulations under the Conservation of Agricultural Resources Act are used to enforce follow-up work. The Programme is currently funded largely through National Government special poverty relief funds, but the intention is for the costs of vegetation clearing activities which contribute to increasing water availability to be partially funded from water resources management charges on water users as discussed above. Control and removal of the invasive alien vegetation is very expensive and Chapman et al., (2001) estimate that some 60 million USD will be needed each year over 20 years to bring the problem under control using current practices. These practices include both mechanical removal and biological control.

Source: Dr Paul Roberts, South Africa, memorandum to author, November 2002.

6. ECOSYSTEM DIMENSIONS OF IWRM

When looking at ecosystem protection within IWRM one has to start by clarifying more exactly:

- WHAT needs to be protected: valuable landscape components, resilience of catchment systems
- HOW: what tools (terrestrial = land use control, aquatic = environmental flows, non-consumable reserve, quality bottom lines, intersectoral water transfers), and what ways to address the unavoidable trade-offs between incompatible aspects: legalising priorities, working healthy rivers.

Integrated approach by merging water, land use and ecosystem management

It follows from the above discussion that freshwater management and the management of ecosystem dynamics have to be integrated. This is equivalent to finding ways and means to merge water management, land use management, and ecosystem management (terrestrial as well as aquatic) within a socio-ecohydrological catchment management – with full awareness of the different ethical and political dilemmas involved. Since land use and terrestrial ecosystems are green-water related while societal water needs and aquatic ecosystems are blue-water related, and the blue and green water flow branches are the result of the partitioning of incoming precipitation, the ultimate resource is the precipitation over the catchment.

The changes with which we have to learn to live without destroying the capacity of the ecosystems to provide life support involve two basic categories of anthropogenous manipulations (*cf*., Figure 2): change of water components in the landscape and change of land/vegetation. Both types of manipulations will produce water-related side effects on both water flow components and blue/green water partitioning. Both of these represent water determinants of ecosystems and therefore, will generate higher order ecological change. Finally, water flows through the landscape are involved in linking upstream and downstream activities and ecosystems in the catchment. The approach has to be land/water integration in a catchment-based ecosystem approach (GWP, 2000).

Preparedness for change

In developing countries, strong driving forces will produce large changes in land and water use and management. The changes ahead may be considerable, especially in terms of changes involved in growing more food for a human population, projected to continue to grow for another half a century. But due to hydroclimatic constraints these changes may spill over to the industrial countries, which might be expected to involve themselves in virtual water export, i.e., grow more food in order to export to water short developing countries (see Box 11).

Box 11. ADDITIONAL GREEN WATER NEEDED TO ERADICATE HUNGER

According to the Millennium Declaration, agreed by the world leaders in the UN General Assembly, the number of people suffering from hunger should be halved by 2015 and subsequently hunger should be eradicated altogether. A highly relevant question is to what degree will this increase the green water needs for food production?

An estimation by Rockström indicates that today's diet involves a green water flow in the interval 600–1800 m^3/yr, on the average 1200, summing up to a green water flow of almost 7000 km^3/yr for food production. The water needed to produce food on an FAO-based acceptable nutritional level would have to increase to 1300 m^3/yr. With the world population as projected for 2050 (9 billions), this would mean that an additional 5600 km^3/yr would have to be appropriated for food production to allow eradication of hunger by 2050. Of this, 2200 km^3/yr would be needed for eradicating malnutrition and another 3400 km^3/yr to feed the expanding population. While increased irrigation might possibly contribute up to 800 km^3/yr, efforts to increase crop-per-drop of green water flow has been estimated to contribute maximum 1500 km^3/yr. The remaining 3300 km^3/yr will have to be contributed from today's green water flow from arable land reserves, i.e., land now vegetated by grasslands and forest and involves horizontal expansion of croplands into these areas.

On the regional level, the water needs to feed the population – whether by more irrigation or by improved rainfed production – would more than threefold in Sub-Saharan Africa and more than double in Asia. To what degree these needs may be met by respectively expanded irrigation, by more crop-per-drop efforts, by horizontal expansion of crop production, or by virtual water through food import will differ largely between regions. These estimations of increased water needs to feed the world population clearly illustrate the scale of future challenges of integrated land/water/ecosystem management and the need to be well prepared for "living with change".

Source: Rockström (2002)

Catchment as a mosaic of ecosystems and hydronomic zones

Based on the new insights concerning social-ecological linkages it is essential to learn how to strike a balance between socio-economic development and maintenance of the productive capacity of ecosystems. We need to better understand the *mosaic of ecosystems in catchments* and how they affect and are affected by human activities, and how they are linked by water flows. Tools and techniques are needed that illuminate, quantify and evaluate the dependence of society on life-support ecosystems. There are a diversity of management practices that can be based on ecological knowledge, including protection of certain species and habitats, restriction of harvests, management of landscape patchiness, and whole catchment management. The implementation of such practices has to be supported both by social mechanisms and institutions, and by social learning.

This makes it necessary to properly understand landscape functions and interactions and in particular, the role of freshwater in securing the system capacity to sustain both the production of food and the protection of essential ecological services under conditions of change and uncertainty. We have to find out how to link water security, ecosystem security and food security, all of them closely related through the water cycle, but now treated as separate issues.

In a river basin with its ecosystem mosaic and its mix of societal activities there are areas with hydrological, topographical and hydrogeological differences to be aware of for which the International Water Management Institute (IWMI) introduced the concept *hydronomic zones* (Molden et al., 2001). These zones are defined primarily on what happens to blue water after withdrawal and use (Figure 6): whether the return flows are recoverable and can be reused downstream, or whether they are non-recoverable and cannot be reused because of a location implying that the return flows go to sinks or involve a poor water quality. There are three zones where the outflow can be used or reused downstream:

- the water source zone in the upstream basin
- the natural recapture zone where the water drains back to the water system through gravitational flows
- the regulated recapture zone where the water has to be pumped back.

There are furthermore, three additional zones:

- the final use zone where there are no further users downstream
- stagnation zones in dead end or depression areas from where there is no drainage
- environmentally sensitive zones with particular water requirements for ecological or other environmentally sensitive purposes.

The three E-pillars in IWRM

To conclude, the challenge is to manage the water flowing down a catchment while orchestrating for compatibility between land use/water, humans/ecosystems, upstream/downstream, present generation/coming generations with adequate attention paid to hydroclimatic and biophysical catchment realities linked to the water balance and the water flow system through the catchment. The management includes: a) ability to strike trade-offs, b) to define ecological "bottom lines" and sustainability principles based on an understanding of what resilience will demand, and how societies and ecosystems can adapt to change, and c) to identify criteria that can be respected in terms of human rights and hydrosolidarity principles.

The *social perspective* involves the need to meet fundamental human needs in terms of safe household water, water-dependent food production, and – in view of present techniques deficiencies – water-polluting income generation activities. Securing societal acceptance of necessary trade-offs is essential by effective ways of stakeholder participation in planning and decision making.

The *ecological perspective* involves attention both to terrestrial ecosystems and their involvement in local runoff generation and to aquatic ecosystems and their dependence on uncommitted environmental flows. Certain highly valued local ecosystems may have to be protected and therefore their particular water determinants. The long-term resilience of the overall system has to be secured for the benefit of coming generations.

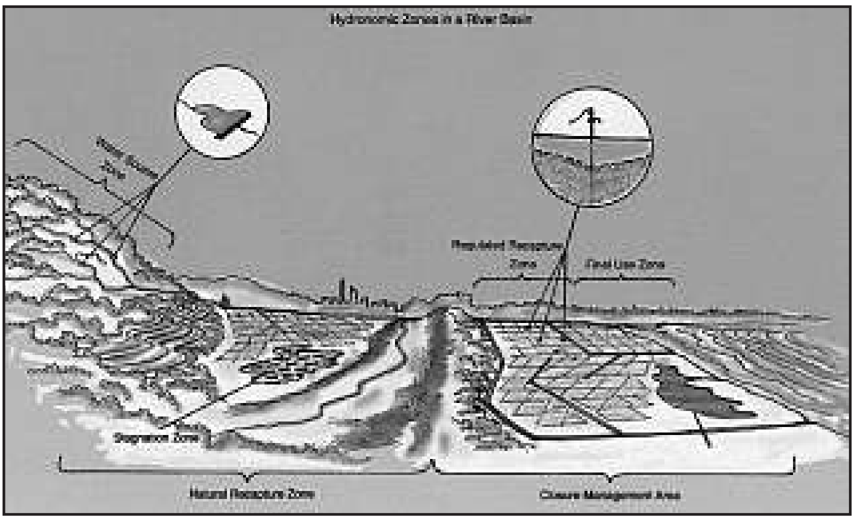

Figure 6. Different hydronomic zones in a catchment, relating to what happens to water after use, whether it can be reused or not (from Molden et al., 2001).

The *economic perspective* involves not only economic development in general but also attention to benefit-costs relations, financing challenges, cost coverage to secure operation and maintenance of water in infrastructures, incentives to encourage implementation, and guidance from the values of water in different functions.

Water flow linkages that influence the potential compatibility of human activities and ecosystem perspectives connect the three E's. Attention has to be paid to blue water accessibility: how much blue water is there that can be mobilised and put to societal use when respecting the need for uncommitted environmental flow that has to remain in the river? The management efforts will have to include preparedness for a policy switch when a basin goes from being open to being closed, i.e., when there remains no blue water surplus available for beneficial consumptive use.

Conceptual challenges

Strengthening the sustainability of vital ecosystems in IWRM will have to involve considerable conceptual challenges as well. Focus has to be moved from withdrawals to what happens to water after use, to ecosystems' water determinants and to their hydrological functions (influencing flooding, groundwater recharge, water quality modifying functions). In order to facilitate bridge building between ecologists and water managers, a more practical and cautious usage should be encouraged of the very broad ecosystem concept.

Finally, the links between water and resilience have to be looked into more closely in order to better understand both water-related determinants of resilience and water's involvement in resilience erosion and the collapse of ecosystems (salination of fertile soils, collapse of cloud forests, scrub development of savannahs, eutrophication of lakes, etc.).

7. CONCLUSIONS FOR IWRM

IWRM aims at ensuring a coordinated development and management of water, land and related resources by maximizing economic and social welfare without compromising the sustainability of vital ecosystems. In this sense an ecosystem approach can be seen as similar to IWRM but viewed from a different perspective and with less focus on economic efficiency.

Ecosystem protection

A key question to pose is: how should policy makers interpret the phrase in the IWRM definition: "without compromising the sustainability of vital ecosystems"? The question will have to be answered for both of the two complementary ecosystem perspectives that have been addressed in this report:

- *biological landscape components of particular local value*: What is referred to be a particular site-specific forest, lake, savannah, wetland, and river stretch and so on of large biodiversity and/or social value. Its sustainability depends on safeguarding the interplay of crucial organisms that have to be identified together with the water determinants of their particular habitats (for aquatic ecosystems river water quality, silt load, environmental flow, flow seasonality and extremes; for terrestrial ecosystems precipitation, evapotranspiration, groundwater table and quality, soil moisture). The relevant question will be how to protect the critical determinants and to what degree it is realistic.
- *catchment as an ecosystem*: The issue here is to safeguard long-term productivity and the key ecological services involved, i.e., pollination, denitrification, flood storage, soil moisture, groundwater recharge. The task involves identification of the core ecosystems of particular ecological value in the catchment that provide critical ecological services. The underlying key processes have to be secured enough elasticity/resilience to variability in terms of fires, extreme drought, pollution events and so on.

Bridge-building

The *ecosystem concept* needs to be strengthened, better understood and firmly embedded in the minds of water resources managers. In this respect there is a challenge in extending and consolidating the cooperation between the ecological community and the water community. Recently bridges have been built between the two and need to be strengthened, and practical ways of approaching the common goals of sustaining life support systems have to be found.

Ecological *minimum requirements* or "bottom lines" and sustainability principles have to be identified based on an understanding of what adequate resilience will require. Societal resilience is linked to the Millennium Declaration Goals for example, and will have to be defined by politicians while ecological resilience has to be determined by the scientific community.

The whole area is in need of further development from a water perspective. This warrants further *research* (perhaps within UNESCO/WMO's HELP programme) focusing on essential tools for use in practical cases and incorporation in the GWP ToolBox for IWRM.

Mapping vital ecosystems in different regions is needed as well as means for better protection. By such analysis a strong link will be made between water management and ecosystem management and dreams separated from realistic action. Identifying the way forward in the particular situations at national level will have to be guided by *assessments and evaluations* of exactly which site-specific ecosystem to protect, what the key threats to these ecosystems are and to what degree and through what action those threats can be mitigated or avoided. Upland ecosystems will principally be easier to protect because the threats are more limited while downstream aquatic ecosystems are much more difficult to protect since they are subjected to the accumulated effects of human activities in the entire upstream part of the catchment. In some cases local restoration may be possible, in others crucial determinants such as flood episodes might be mimicked.

Broad enough understanding

A *shared image* should be developed incorporating the water-mediated linkages between terrestrial ecosystems, urban areas, and aquatic ecosystems. Such an image will be essential as a base for a deepened dialogue between stakeholders, ecologists and water managers, also incorporating hydrosolidarity principles.

The level of understanding and knowledge of the ecological challenges by the general public is quite low and political decision making is in danger of relying on an uninformed public opinion without knowledge of the substantial facts and functions of the ecosystems. Many “myths” regarding the functions of terrestrial and aquatic ecosystems have developed over the years both in the general public and among practitioners. The function of forests vis-à-vis water is one clear example. Therefore, it will be important to stress information campaigns, public outreach and education in the quest for dissemination of knowledge.

Key links between water use and ecosystems

Two types of water related human activities need particular consideration:

- evacuating waste
- growing food.

Nature is processing waste and reintroduces it in the living cycle. Humans produce waste of their own from all their activities, in fact they produce more waste than useful products. According to the available technologies, the regulations and the way they are applied, the waste may be disposed of in water, on land or into the air, in various stages of processing. Defining a clear strategy in the field of *waste disposal* is an important step towards implementing an ecosystem approach within IWRM.

Growing food is the main consumptive user of water. Means exist to import *"virtual" water* by importing food from water rich regions, to desalinate brackish or seawater or to reuse adequately treated wastewater for irrigation. In rainfed agriculture means exist for protection against dry spell damage based on rainwater harvesting. Some of these means, which can considerably reduce water shortage problems and protect aquatic ecosystems, are capital hungry and require investment and substantive operations expenses. The impact on the social structure of the country should be carefully evaluated.

Institutions

Institutions are shaped by people's needs and perceptions. Present water institutions are to a large extent based on the assumption of unlimited water, unrestricted room for waste disposal, and ignorance of systemic roles. They emphasize individual appropriation, without curing externalities. Taking better account of ecosystems in integrated water resources management will require flexible, conditioned, adaptive and time bound appropriations, control of externalities and system-based organizational design.

Ability has to be developed on the decision-making and political level to *strike trade-offs* and take the hard decisions required for balancing of development and ecosystem functioning within the framework of IWRM. The ability to strike trade-offs and defining ecological "bottom lines" between social, ecological and economic uses of water depends on the flexibility, resilience/adaptability of social/political organisations and institutions. It would also require a "new" systemic approach and organisational design towards water management that integrate ecological perspectives. These efforts should be reflected in legislation, policies and institutions related to water resources. Legitimate trade-offs would require *participatory approaches* and the active involvement of all relevant stakeholders.

Politics make the trade-offs and balances. *Win-win solutions* cannot always be achieved. Change is inevitable but should be done in a way that ensures ecological resilience of essential ecosystems. The IWRM approach can help to do this but the ultimate definition of societal resilience will be political.

Definitions

Biodiversity: Refers to the uniqueness and variability of all life with particular emphasis on genes, species, landscapes or ecosystems.

Ecosystem: A dynamic complex of organisms and their associated non-living environment, interacting as an ecological unit composed of primary producers, consumers and decomposers.

Elasticity: Refers to the ability of an ecosystem to accommodate change while maintaining its structure and function.

Resilience: Refers to the capacity of an ecological or social system to accommodate change, stress and variability without altering its structure and function. Ecological resilience refers to the capacity of natural ecosystems, social resilience to the capacity of human communities to cope with change.

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Global Water Partnership (GWP), established in 1996, is an international network open to all organisations involved in water resources management: developed and developing country government institutions, agencies of the United Nations, bi- and multilateral development banks, professional associations, research institutions, non-governmental organisations, and the private sector. GWP was created to foster Integrated Water Resources Management (IWRM), which aims to ensure the co-ordinated development and management of water, land, and related resources by maximising economic and social welfare without compromising the sustainability of vital environmental systems.

GWP promotes IWRM by creating fora at global, regional, and national levels, designed to support stakeholders in the practical implementation of IWRM. The Partnership's governance includes the Technical Committee (TEC), a group of 12 internationally recognised professionals and scientists skilled in the different aspects of water management. This committee, whose members come from different regions of the world, provides technical support and advice to the other governance arms and to the Partnership as a whole. The TEC has been charged with developing an analytical framework of the water sector and proposing actions that will promote sustainable water resources management. The TEC maintains an open channel with its mirror bodies, the GWP Regional Technical Advisory Committees (RTACs) around the world to facilitate application of IWRM regionally and nationally. The Chairs of the RTACs participate in the work of TEC.

Worldwide adoption and application of IWRM requires changing the way business is conducted by the international water resources community, particularly the way investments are made. To effect changes of this nature and scope, new ways to address the global, regional, and conceptual aspects and agendas of implementing actions are required.

This series, published by the GWP Secretariat in Stockholm, has been created to disseminate the papers written and commissioned by the TEC to address the conceptual agenda. Issues and sub-issues associated with them, such as the understanding and definition of IWRM, water for food security, public-private partnerships, and water as an economic good have been addressed in these papers.

Global Water Partnership

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