GROUNDWATER *for* EMERGENCY SITUATIONS

A framework document

Edited by

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UNESCO

IHP-VI, Series on Groundwater No. 12

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Preface

The project Groundwater for Emergency Situations (GWES) is part of the activities of the International Hydrological Programme (IHP), sixth phase (2002–2007), Theme 2. The aims and objectives of Theme 2 are among others:

- To assess the impacts of extreme events (natural and man-induced) and proposed mitigation schemes.
- To develop a framework for reducing ecological and socio-economic vulnerability to hydrological extremes (floods, droughts, mud flows, ice jam, avalanches).
- To analyze extreme events by integrating various sources of data (historical. instrumental, satellite) to secure an improved understanding over large scales in time and space.

The objectives of the GWES project are introduced in the yellow box below. The GWES Framework Document is the first step in the preparation of the main document of the GWES project 'Guidelines for the identification and management of strategic groundwater bodies to be used for emergency situations resulting from extreme events or in case of conflicts'.

The GWES project is implemented by an International Working Group composed of experts from UNESCO, IAH, IGRAC and others. The activities and objectives of the GWES project were formulated at the first meeting of the Working Group held in UNESCO, Paris (February, 2004). The preparation of a framework document was proposed by UNESCO as one of the GWES project outcomes. The content of the document was discussed and approved and a timetable for its preparation agreed on at the above-mentioned Paris meeting. The second meeting of the Working Group took place at the UNESCO 0ffice in New Delhi, India (April, 2005). During this meeting the first draft of the GWES framework document was evaluated in depth and its final version agreed on. Experts from Indian water-related institutions and representatives of regional offices of WHO and UNICEF also participated in the meeting.

The framework document was prepared through the cooperation of the Working Group members representing the following countries and institutions: Wim van der Linden (IGRAC - International Groundwater Resources Assessment Centre), Klaus-Peter Seiler (Germany), Jan Šilar (The Czech Republic), Balbir Singh Sukhija (India), Balthazar Th. Verhagen (Republic of South Africa), Jaroslav Vrba (IAH - International Association of Hydrogeologists), Ryuma Yoshica (Japan), Wenbin Zhou (China). Case studies presented in the document were contributed by D.K. Chadba, A.K. Sinha and R.C. Jain (India), A.K. Keshari, Al. Ramanathan (India) and B. Neupane (UNESCO), Wim van der Linden (IGRAC), Klaus-Peter Seiler (Germany), and Balthazar T. Verhagen (Republic of South Africa).

Thanks are expressed to UNESCO for funding the project and for technical and administrative support. A special thanks to Ms. Alice Aureli, Responsible for Groundwater Resources Activities, Secretariat of the International Hydrological Programme, Division of Water Sciences, UNESCO, who cooperates actively in the implementation of the GWES project and in the realization of the GWES Framework Document. Gratitude is expressed also to the UNESCO New Delhi Office, particularly to Mr. B.R. Neupane, Programme Specialist, who organized the meeting of the GWES Working Group held in New Delhi. Thanks to his efforts the knowledge and experience of hydrologists and hydrogeologists from the South-East Asian region were incorporated into the GWES project activities.

Jaroslav Vrba

Editor of the GWES Framework Document
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Groundwater for emergency situations
Project of the Sixth Phase of the International Hydrological Programme

During the 15th session of the Intergovernmental Council of the International Hydrological Programme (IHP) the project 'Groundwater for Emergency Situations (GWES)' was approved and included in the Implementation Plan of the Sixth Phase of the IHP (2002–2007) under the title 'Identification and management of strategic groundwater bodies to be used for emergency situations as a result of extreme events or in case of conflicts'. The GWES project is implemented under Theme 2 'Integrated Watershed and Aquifer Dynamics'.

The aim of the GWES project is to consider natural and man-induced catastrophic events that could adversely influence human health and life and to identify in advance potential safe, low vulnerability groundwater resources which could temporarily replace damaged supply systems. This requires a special approach to the methods of project development. Water management projects normally consider *sustainable* water development. The priority in emergency situations is *risk management* with the objective of providing crucial first aid to the affected population.

The following are the main objectives of the GWES project:

- To propose effective methodologies for identifying groundwater resources of low vulnerability to extreme and/or catastrophic climatic and geological events and human impacts.
- To introduce effective hydrogeological, isotope-hydrological, remote sensing and other suitable techniques into the investigation of such groundwater resources.
- To set up an inventory of groundwater bodies resistant to natural and human impacts in selected pilot regions and present relevant GWES case studies.
- To publish guidelines for the identification, investigation, development and management of strategic groundwater bodies to be used in emergency situations resulting from extreme climatic and geological events and in case of conflicts.

Contents

1. Introduction

It is hard to imagine that one could suddenly be faced with the prospect of dying of thirst; that your life could be saved only by someone providing some water to drink. For this, you don't have to evoke medieval conditions, or remote desert environments. In quite recent times people have had to face severe drinking water shortages due to natural or man-induced catastrophic events, even in highly developed communities. Immediately after physically securing an endangered population, the first priority of aid workers following a disaster is the distribution of drinking water. Such emergency situations are reported from many parts of the world following floods, droughts, rain-induced landslides, earthquakes, pollution accidents and other extreme events (Box 1.1). It is often difficult to organise a replacement water supply when regular water systems are compromised, damaged or even destroyed by natural or man-made disasters. Their restoration may take months or even years. Transporting water in tankers to the affected regions to prevent epidemics, importing large quantities of bottled water – such measures take time to implement, they are expensive and only temporary solutions. Groundwater resources, proven safe and protected by the physical environment, with long residence times and the necessary infrastructure for their exploitation, would provide populations with timeous replacement of vulnerable water supply systems and make rescue activities more rapid and effective. Such resources have to be investigated and set aside if possible, as a substitute for affected drinking water supplies thereby eliminating or reducing the impact of their failure following catastrophic events. Development of such policy and strategy for human security – both long term and short term – is therefore needed to decrease the vulnerability of populations threatened by extreme events particularly in areas such as flood plains, coastal areas, mountain slopes, arid zones and/or highly industrialized areas.

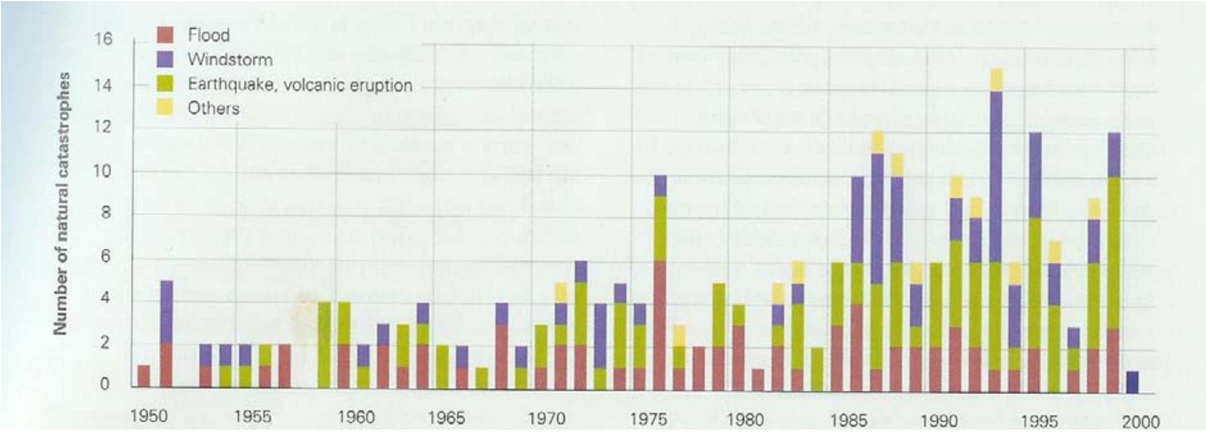
Box 1.1

Types and distribution of water-related natural disasters

Floods represented 50% of disasters in the period 1990–2001 worldwide, water related epidemics accounted for 28%, drought 11%, landslides 9% and famine 2%. Asia faced 35% of all water related natural disasters during the same period, Africa 29%, the Americas 20%, Europe 13%, and Oceania 3%. Global economic losses from registered natural catastrophes were estimated at around US$ 30 billion in 1990 rising to US$ 70 billion by 1999. Similar trends are seen in figures related to the number of people affected by natural disasters over the last two decades: 147 million per year (1981–1990) to 211 million per year (1991–2000). The World Bank estimated (2001) that 97% of deaths related to natural disasters occur each year in developing countries. 90% of people killed by natural disasters lost their lives in climatic events (floods, droughts, windstorms), which doubled since 1996. However, in terms of loss of life, droughts claimed the greatest number of victims. Increasing trends in major natural catastrophes are clearly visible in Figure 1.1.

Source: Affeltranger, 2001, WWDR, 2003.

*Figure 1.1. Increasing trends in the frequency of major natural catastrophes, 1950–2000 (*Water for People – Water for Life*, 2003)*



Therefore, a very important aspect of GWES in drawing the attention of governments, organizations, and individuals to the concept of preparedness for establishing alternative drinking water supplies, is empowerment. Very often a local population is helpless following a disaster, cut off from their traditional water supplies and faced with delays in aid from outside. This leads to destabilization and demoralization at the time when people need to rebuild their lives. The empowerment inherent in GWES enables people to take charge immediately, with own knowledge and infrastructural means, to restore water supply from their own groundwater resources, and thus release energies for general reconstruction.

2. Groundwater as an emergency resource

Modern hydrology was developed in countries with abundant water resources where water either posed a threat or could be harnessed for man's benefit. A large part of the earth's surface is arid and suffers from scarcity of water resources, as well as the possible threat of floods. Thus humanity developed an awareness of water as the most important component of the biosphere, as both a danger and an indispensable part of the environment, a valuable commodity and very often a strategic resource for social and economic development.

This awareness of the ambiguous role of water varies according to local and temporal circumstances. Arid areas such as the Middle East and North Africa, notorious for scarcity of drinking water resources, experience flash floods which have caused considerable damage to lives and property. The rise and fall of historical cultures of the Middle East were often driven by their ability to manage water, its supply and use in irrigation. This remains true right into modern times, and influences recent political and social activities in various parts of the world (Box 2.1)

Box 2.1

Natural and man-made impacts on water resources

During the so-called 'cold war' several countries gathered records on groundwater resources in view of a possible military attack. Such surveys considered deep aquifers carrying water of pre-Holocene origin. The study of palaeowater is to be found among the themes of research projects of the Isotope Hydrology Section of the UN International Atomic Energy Agency. Similar projects may have emerged elsewhere during recent years. **Floods** in Central Europe in 1997 and 2002 necessitated shutting down wells and water supply systems that had been inundated, and finding substitutes during their rehabilitation. Shallow aquifers in large alluvial plains of rivers were substituted by deeper confined aquifers of the underlying strata. Development of non-renewable groundwater resources is an appropriate solution in many arid regions to mitigate the impact of **drought**. A different hydrogeological approach should be followed in the case of hard rock aquifers in mountainous regions, affected by **earthquakes**; again another in the case of **tsunamis** in coastal regions; of l**andslides**, following e.g. **hurricanes and other atmospheric events** such as in the Caribbean, Japan, India and China; yet another in the case of **climatic changes**, which accompanied the El Niño events along the western seaboard of south America. **Man-made impacts** on water systems, such as military and terrorist activities, as well as large pollution accidents, require particular consideration.

We should, therefore, harness our present hydrogeological knowledge in proposing suitable methods of investigating reliable groundwater resources for emergency situations and lay out some basic rules for their exploitation.

Natural water resources are generally renewable. However, they are only renewable within limits; the extent to which increasing demands can be met is finite (*Water for People - Water for Life*, 2003). Groundwater renewability must be considered in terms of recharge, discharge and residence time. Each of these terms should be taken into account when studying groundwater on a regional scale and often on geological time scales. Increasing rates of extraction of groundwater for human consumption, agriculture and industry, tends to overexploitation of resources in many parts of the world. The balance between recharge and discharge is disturbed and groundwater levels in vast regions are declining. Sustainable development and management of groundwater resources is advocated in order to counteract this trend.

However, in emergency situations where human lives are at stake and drinking water supply systems are compromised, this policy of sustainability cannot strictly be adhered to. In such cases, renewability becomes a secondary consideration and groundwater from deep resistant aquifers or even non-renewable 'fossil' water bodies need to be addressed and tested for providing adequate yields. Such an emergency supply should not be seen as a substitute for a regular resource. It should be earmarked for, and exploited only during, emergencies – until the regular water supply system can be restored and re-activated both in quantity and quality.

Crisis water management during an emergency often finds groundwater supply initiatives poorly prepared to prospect for and develop alternative emergency resources – even where groundwater is readily accessible locally. Such an effort can be successful only if it is based on the availability of results of a systematic hydrogeological investigation, of monitoring and mapping of groundwater resources, often employing supportive techniques like isotope hydrology, geophysics, remote sensing and others.

The key to selecting a strategy for resuscitating regular water supplies during or following catastrophic events is the knowledge of regional hydrogeological circumstances. In many areas it will be difficult or impossible to provide emergency supplies from completely separate groundwater systems. In such cases, the existing supply system and aquifer would have been thoroughly investigated i.t.o. temporary extensive exploitation to tide over the emergency. An emergency such as a meteorological drought may lead eventually to a groundwater drought – failure of wells leading to increasing stress on others, affecting more or less all aquifers. Reserved and protected emergency boreholes, routine maintenance of equipment, and possible deepening of existing boreholes are some of the strategies available (SADC, 2003). Governmental and municipal authorities, civil defence and the army should know where such groundwater resources are available in the areas repeatedly affected by, and prone to, natural hazards. A timely investigation and community participation are essential in developing the emergency infrastructure that will function successfully in case of emergency.

'Out of sight, out of mind' is a common attitude, and 'if there was a one-hundred-year flood/ drought last year, we may be safe for the next 99 years'. A catastrophic event should be seen rather as a warning that should stimulate the public and the authorities alike to prepare water supply systems and strategies for exceptional circumstances.

Summing up: know your local hydrogeology, not only in terms of where groundwater circulates but also where it stagnates and yet can produce adequate, short-term yields with acceptable quality; and adjust your thinking beyond the traditional approach to hydrogeological investigation and the conventional appraisal of groundwater resources.

3. Groundwater origin, occurrence and movement

Subsurface water, the oceans and the atmosphere – the largest water reservoirs on earth – are linked through the water cycle, which provides renewable water for humans and ecosystems (Box 3.1). According to Shiklomanov (1999) the present-day water cycle turns over a yearly total of 577,000 km^3 of water (Fig. 3.1); this turn-over is driven by evapotranspiration, consuming 1.1×10^{24} J of the incoming solar radiation on earth; condensation of water vapour; and run-off.

Box 3.1

The global water distribution

There is some 1.386×10^9 km^3 of water on, or immediately below, the earth's surface; most of it is liquid, some occurs as ice, only a fraction as vapour. Ocean water constitutes about 97.5 vol.% and fresh water the remaining 2.5 vol.%.

Fresh water is mostly bound to the continents, of which:

- 68.9 vol.% is fixed in ice shields and glaciers,
- 29.9 vol.% stored as groundwater,
- 0.9 vol.% to soil moisture and atmospheric water vapour and
- 0.3 vol.% appears as surface water.

Groundwater amounts to about 8,300,000 km^3; it is known to occur to depths up to several kilometers beneath the surface of continents; its origin refers to present as well as past replenishment by rainfall (recharge) and some groundwater is trapped in aquifers since the formation of sediments (connate water).

The distribution of recharge to groundwater resources is uneven across the latitudes, controlled by climate belts, ocean/atmosphere interactions, vegetation as well as physiographic and orographic conditions. Recharge occurs:

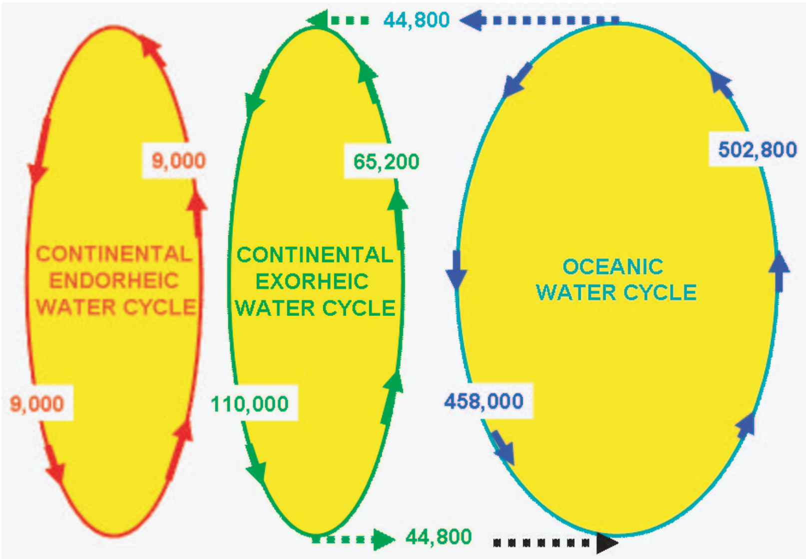
- in desert regions (Verhagen et al., 1979), though highly irregular in time and space, and at very low rates (<5 mm/a);
- in semi-arid and tropical regions with major annual fluctuations and a ranges from less than 30 mm/a to some150 mm/a;
- in humid regions at an average of less than 300 mm/a;
- even through permafrost, albeit minimal, as shown by Michel and Fritz (1978).

Groundwater recharge, along with tectonic, morphologic and eustatic settings, constitutes the driving force for groundwater motion, which can be either steady state or transient.

Shiklomanov (1999) reports a yearly excess discharge from exorheic continental catchments of 44,800 km^3 (Fig. 3.1), which is equivalent to the contribution of the oceans to the continental water cycle. This excess discharge is low as compared to 8,300,000 km^3 of groundwater beneath continents: Hence, turnover times of groundwater are either high generally or are distributed unevenly with depth; environmental isotope investigations and numerical modelling (Fig 3.2) have shown that water ages or turn-over times increase significantly and even discontinuously with depth, on account of abrupt hydraulic conductivity changes with depth.

Taking the average global value of excess discharge from continents as the maximum available water resource and comparing it with global water demand plus waste water disposal (Box 3.2), our world is in or close to a water stress situation. This is already evident in the scarcity of water, both in quantity and quality, in many warm and some humid climates.

Figure 3.1 ***The global oceanic and continental water cycles and the links between them (all numbers expressed in km^3) (Shiklomanov, 1999)***



Note: 'Endorheic' and 'exorheic', see glossary.

Box 3.2

Human water demand amounts to (per capita)

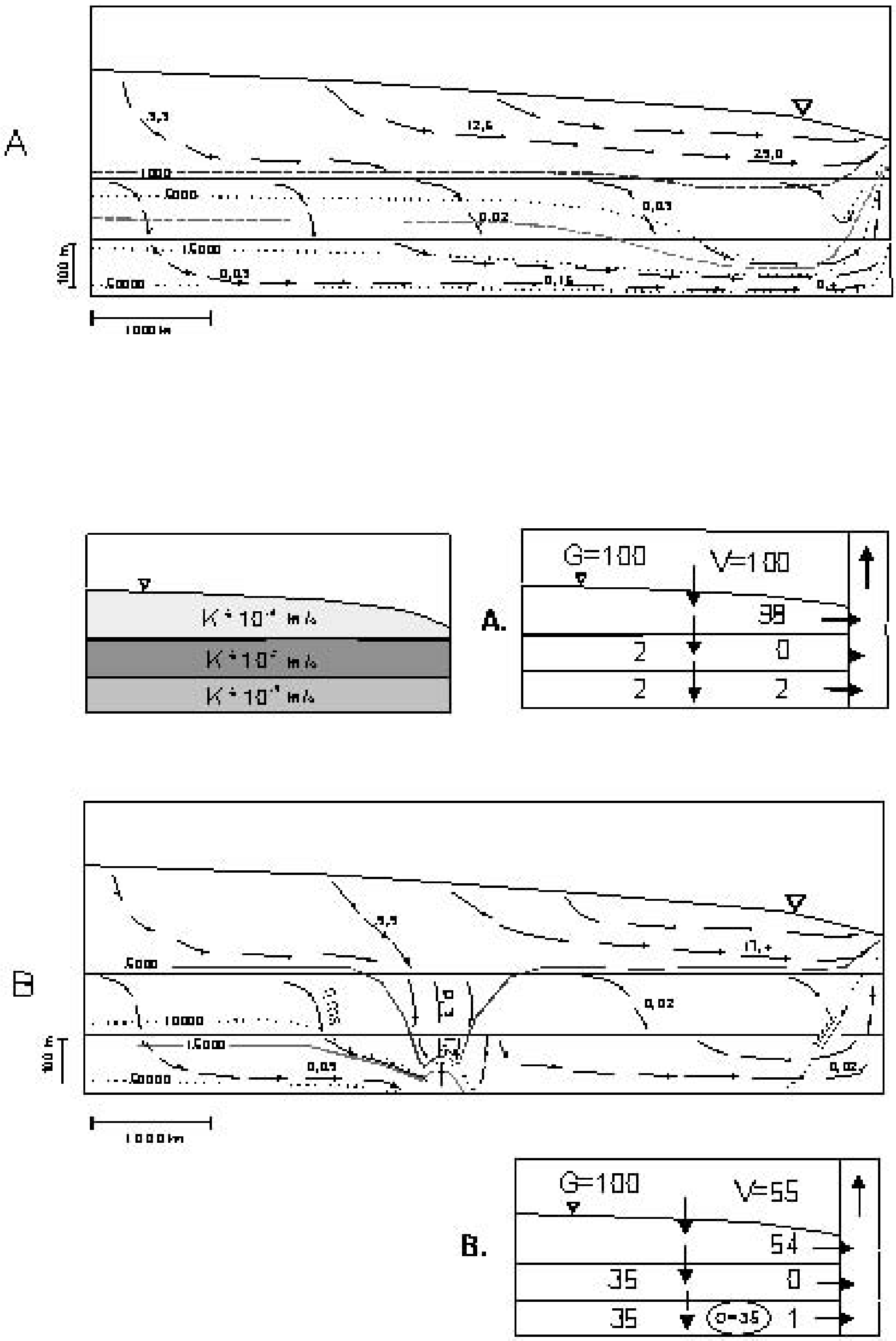
- Total (all activities) about 1,000 to 1,500 m^3/year, including the demand for
  - Households of about 50 m^3/year and
  - A minimum for survival of about 10 m^3/year.

Global water demand approached 5,000 to 6,000 km^3 at the beginning of the 21th century, which is close to 1,000 m^3/capita/year. Although this demand of 6 billion souls is lower than the continental discharge, it should be kept in mind that any use of blue water (water which fulfils health and ecosystem requirements) produces gray (waste) water.

Empirically, 1 m^3 of untreated gray water needs:

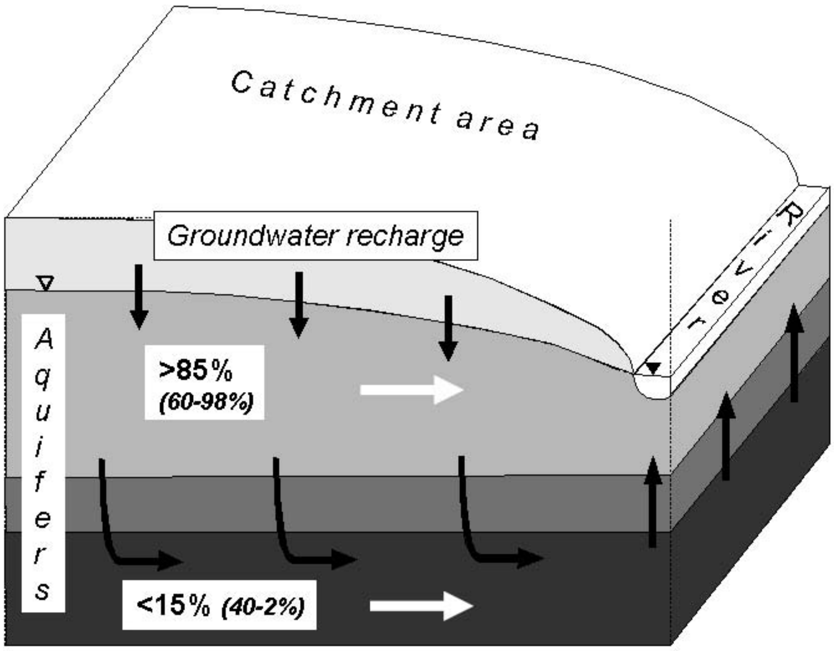
- About 9 m^3 of blue water if released untreated to the environment and
- About 3 m^3 of blue water if released after physical, chemical and biological treatment, to still undergo efficient natural attenuation.

Figure 3.2 ***Groundwater flow vectors (arrows) with flow velocities in m/day and isochrones (lines of equal age in years) for an aquifer system with hydraulic conductivities of 10^{-4}, 10^{-7}, 10^{-6} m/s (from top to bottom).***
A: Unexploited system and the turn-over quantities in the three aquifers.
B: The same system as under A but with deep groundwater extraction of 35% of the total groundwater recharge over the catchment.



The distribution of groundwater recharge is also uneven vertically (Fig. 3.3). The unevenness is enhanced by differing hydraulic properties of the aquifer system. Numerical modelling for typical sequences of hydraulic conductivities in aquifer systems shows that on average more than 85% of the recharged groundwater discharges through near-surface (active recharge zone), and less than 15% through deep aquifers (passive recharge zone) (Seiler and Lindner, 1995). Both of these generalised recharge zones in turn overly connate water and are encountered in all continents, climate zones and rock types.

Figure 3.3 ***Block diagram of a catchment (400 m deep and 15,000 m in width) underlain by an aquifer system. Numbers without brackets indicate the average percentage, in brackets minimum and maximum percentage of turn-over of recharged groundwater. These figures are the result of some 100 numerical runs with different distributions of hydraulic conductivities.***



Groundwater in

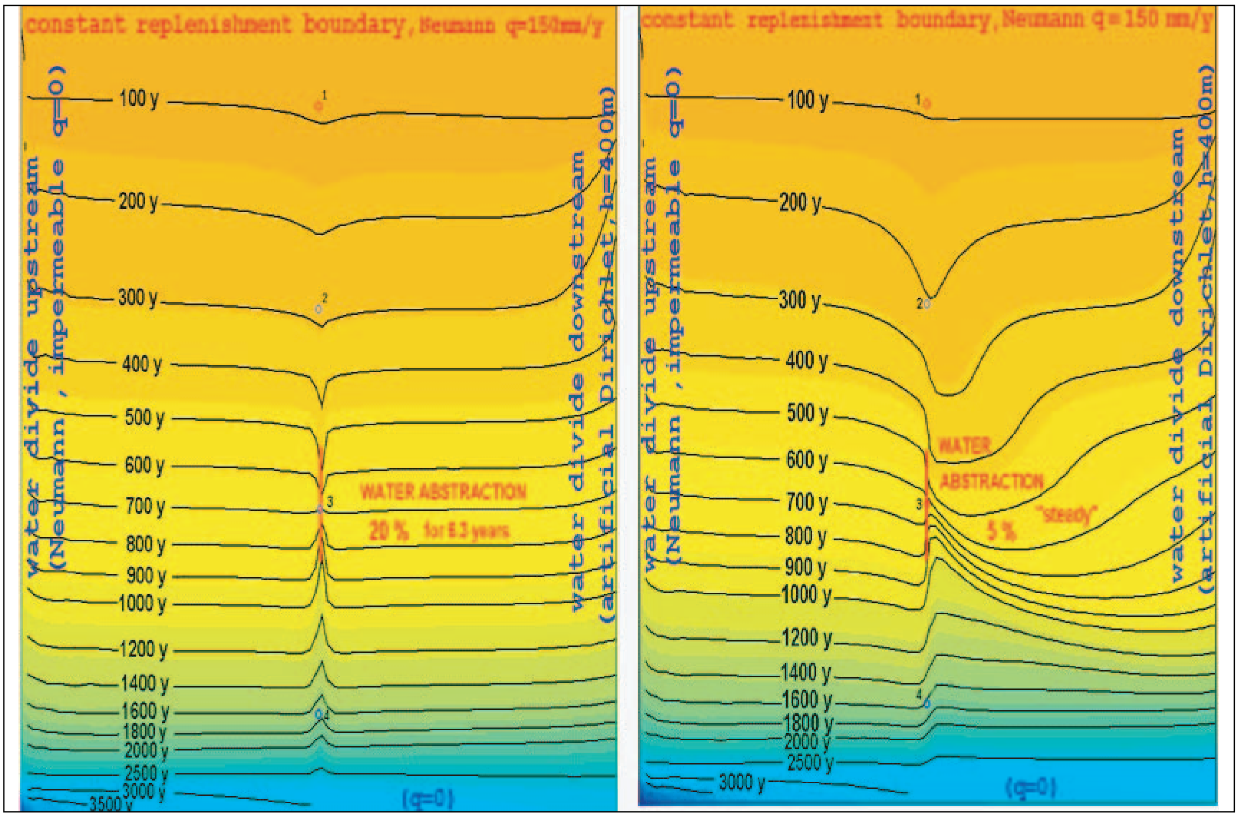
- the active recharge zone is young (<50 years), quite susceptible to contaminants and reaches steady state conditions fairly rapidly if extraction does not exceed groundwater recharge;
- the passive recharge zone is always older (>100 years), the longer time scales ensuring better protection against contaminants, provided that groundwater management takes account of depth related groundwater recharge; otherwise a transient hydraulic response results (delayed mass transfer; Fig. 3.4), which may last decades or hundreds of years. This delayed mass transfer can be monitored through early warning systems;
- the passive recharge zone could be more mineralized (higher ionic concentration) than in the active recharge zone, and sometimes is characterized by rare dissolved elements (e.g. As, I, F), because of high mean turn-over times, resulting in slower leaching than in the active recharge zone.

The thickness of the active recharge zone varies according to the rate of groundwater recharge and the storage properties of the sub-surface. In temperate climates it may reach a maximum of 100 m in consolidated fissured rocks, 50 m in unconsolidated materials and decreases in semiarid and cold climates to less than 10 m; in arid areas it is patchy. The interface between the passive and active groundwater recharge zone can be located by applying environmental radioactive isotopes with a short half life, such as ^{3}H.

The passive recharge zone attains much greater thickness than the active recharge zone. Therefore dilution (of e.g. contaminants) in deep aquifers is more pronounced than in shallow aquifers.

In the long term, groundwater recharge is a cheap and energy-saving regulating factor in the welfare and economic development of a region. The world is close to or already in a situation of water scarcity. In critical situations, following serious accidents or natural disasters in water scarce areas, the only source of water supply is the passive recharge zone, which can be exploited in the short term, without producing irreversible quality changes of groundwater (Fig. 3.4). Such measures, however, should be controlled by an early warning systems (section 10.2).

Figure 3.4 Groundwater abstraction from 150 m depth triggers a transient response of vertical mass transfer over decades or centuries



Abstraction at 20% of groundwater recharge, produces only minor changes in the isochrone field after 6.3 years of continuous pumping, as the transient response is slow.

At 5% abstraction of groundwater recharge the isochrone field changes significantly after reaching steady state.

4. Risk management of groundwater resources in emergency situations

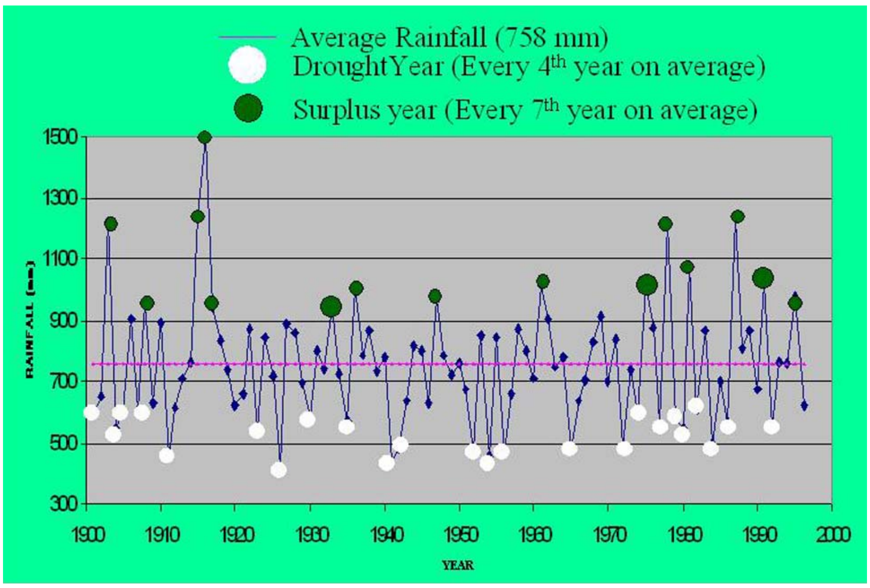
Natural catastrophic/emergency situations caused by devastating geological or climatic events may result in total dependence on groundwater resources for the sustenance of affected communities. Therefore such groundwater resources need to be identified, where possible replenished artificially, safeguarded and developed as a supply source and its sustainability during emergency situations ensured.

Hazardous geological and climatic events tend to be recurrent. Thus it is important to determine from the historical records the frequency of hazardous events of a given magnitude in a particular period of time, which facilitates the estimation of a recurrence interval.

Catastrophic events causing the greatest havoc are much less frequent than events with lesser impact. Another important aspect is that certain areas of the globe are more susceptible than others to geological and climatic hazards. For example it is known that geological plate boundaries are most at risk from earthquake recurrence and volcanism. It is well known that countries like Japan, Iran, Western USA, Italy, Northeast India, New Zealand are prone to earthquakes. Volcanic activity is quite common in countries like Japan, Indonesia, New Zealand, Philippines, Italy, Iceland etc. Similarly, meteorological and topographical factors make certain areas of the globe prone to climatic hazards. For example countries like Bangladesh, NE India, the southern USA, are often ravaged by floods and hurricanes. Similarly there are areas prone to tsunami. Recently, the 26 December 2004 earthquake of magnitude 9.1 in Sumatra resulted in large scale destruction involving about 300,000 deaths throughout Southeast Asia (Indonesia, Sri Lanka and India).

The time series of rainfall data in a semi-arid region of India (Fig. 4.1) shows that every 4th year is

Figure 4.1 Time series of rainfall data 1901–96, Nalgonda hard rock area, Andhra Pradesh, India



a drought year and every 7th year produces floods. Thus it becomes imperative in water risk management to delineate risk zones for climatic and geological hazards in each country or region. This requires prior knowledge of the minimum water requirement per capita and affected population in the event of a natural calamity. The task of water risk management is to compare such data with groundwater resources available for emergency situations, to assess these resources in quantity, quality and durability well in advance of emergency situations, and to sustain water supply schemes.

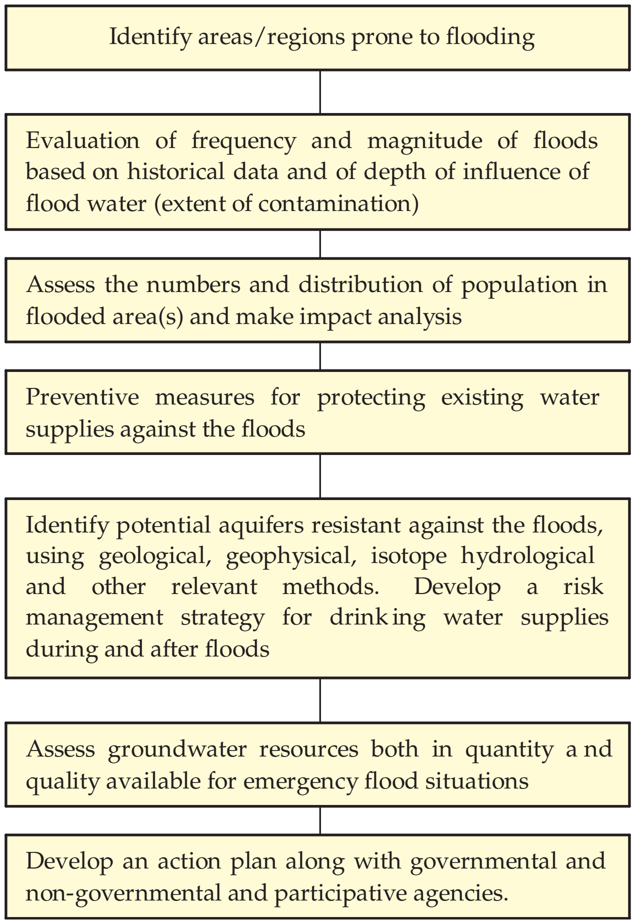
Some basic rules and technical conditions for groundwater exploitation during emergency situations have to be defined, as well as the basic principles of groundwater risk management. Such risk management can be based on **temporary non-sustainable exploitation** of groundwater resources, with the objective of supplying a population **temporarily affected** by climatic or geological disasters and to support rescue activities.

4.1 Groundwater risk management in flood areas

Floods are by far the most common climatic hazard worldwide, affecting more people and property than all the other hazards put together. On the other hand floods are relatively more easily predictable than geological hazards. Floods basically result from excessive rainfall or snowmelt and may be more frequent in certain seasons as well as in certain regions. With respect to drinking water supply management, it is imperative to identify the areas which are likely to be submerged during floods and it may also be important to differentiate between events which flood large areas for considerable lengths of time (weeks or months) as against flash floods, extreme events which last 24 hours or less. During floods, rivers carry not only enormous volumes of water, as shown in Fig. 4.1.1, but also high sediment loads, waste repositories are engulfed and industrial storage and production areas inundated, resulting in contamination of both surface water and shallow groundwater aquifers.

Figure 4.1.1 The flooded Temple of Surat in Gujarat (India)

To counter the effect of floods, water supply risk management plans call for the identification of aquifer(s) which have substantial resources and are not affected by floods, either by their degree of confinement or by their recharge areas being located far beyond the flood ravaged areas. The following is a proposed flow chart for risk management of groundwater during floods.



4.2 Groundwater risk management in regions prone to droughts

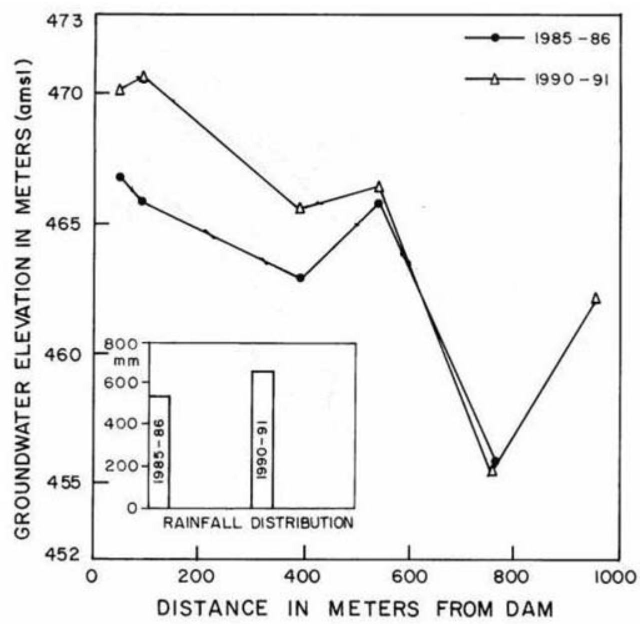
A hazardous drought results in severe shortage of water supply causing famine, starvation, migration of people and livestock. Droughts, like floods, tend to recur in certain areas of the globe due to geographical and atmospheric circulation patterns. One of the better known global drought linkages is the El-Niño-Southern Oscillation (ENSO).

Regions frequented by droughts need to be identified, for example some of the drought prone countries in sub-Saharan Africa, in the Middle East and many South Asian countries where the monsoon periodically fails (Fig. 4.2.1). Drought is responsible for degradation and desertification of nearly a third of the world's arable land.

There can be different solutions to the effects of drought by way of using groundwater. The solution can be preventive as well as mitigating the drought in emergency. Preventive solutions lie in long term integrated management of surface and groundwater resources, such as water conservation, artificial recharge of groundwater through percolation ponds, check dams, roof runoff harvesting, induced recharge, etc. Fig. 4.2.2 shows how artificial recharge structures like percolation ponds constructed

Figure 4.2.1 A scene characterising the severity of a recent drought in Western India: skeletal remains of perished livestock and mitigation measures through supply of drinking water

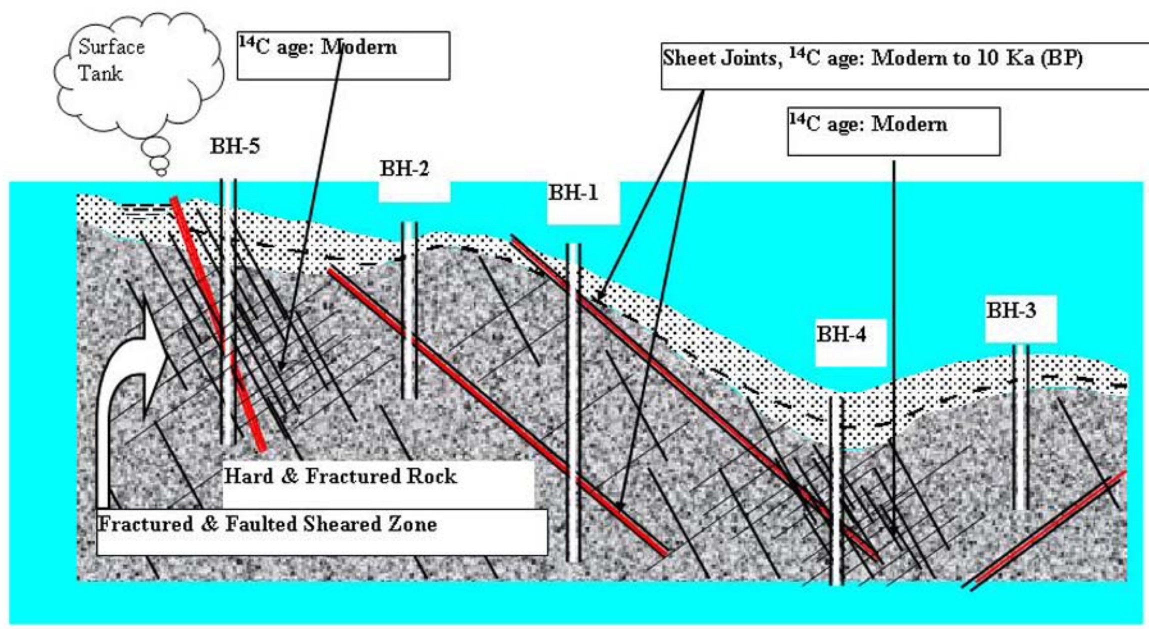
Figure 4.2.2 Spatial and temporal response of groundwater levels downstream from a percolation pond at Kalwakurthy near Hyderabad (India) in granites, before (1985–86) and after (1988–89) its construction. During normal and above normal rainfall years 1989–91, the water levels in the downstream wells increased by 5–6 meters primarily due to the contribution of the percolation pond, the influence of which is observed up to a distance of 500 meters downstream (Sukhija, 2005)



across ephemeral monsoon streams can help to mitigate droughts. In this case, the percolation pond produced a groundwater level rise of 5–6 m through artificial recharge. Crucial too is the use of traditional knowledge and practices of the local population for water conservation like the construction of ridges and water impoundments.

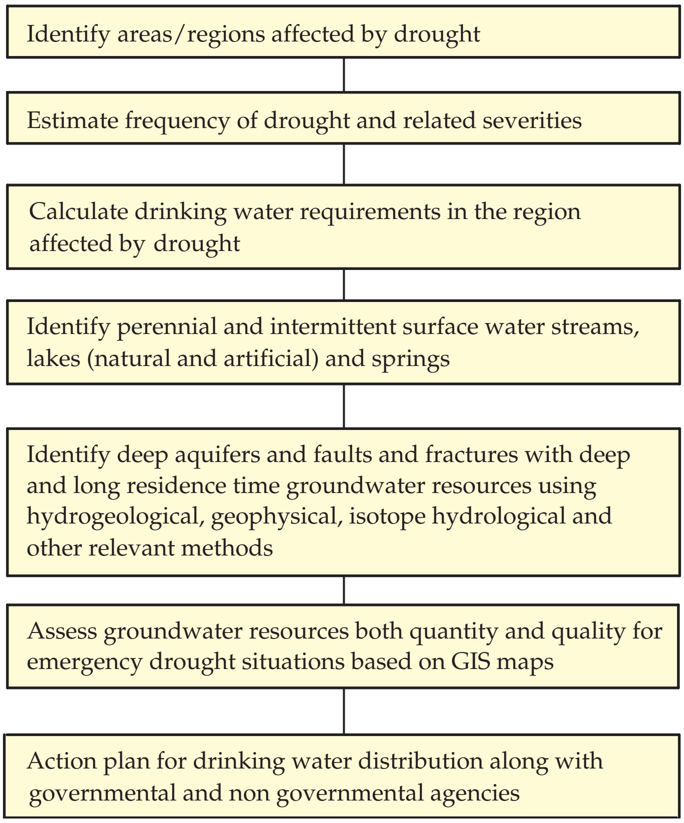
Deep confined renewable or non-renewable groundwater resources, if available in a region, are the most suitable source of safe and usually good quality drinking water in areas affected by drought. However, their development by deeper wells is mostly expensive. Another approach would be to explore water in unconventional aquifer systems such as fractures and faults with deeper circulating groundwater. Such groundwater with high residence time can be delineated by radiocarbon measurements (Fig. 4.2.3). For example boreholes BH-1 and BH-2 drilled in the sheet joints in hard rock aquifers are more suitable for emergency situations such as drought as they encounter groundwater with high residence time. Many faults have associated fracture zones which are porous and permeable structures up to tens of meters wide, thousands of meters long and quite deep. Exploiting groundwater from such aquifers has proven effective in many places in the Middle East, Africa and elsewhere.

Figure 4.2.3 Conceptual hydrogeological model based on radiocarbon data for the delineation of deeper zones with high residence time suitable for use in emergency situations such as droughts (Sukhija et al., 2005)



Risk management of groundwater is part of a framework of multi-disciplinary and integrated plans for drought management. A variety of governmental activities at all levels (local, regional, national) reduce population risk and vulnerability to drought (Dooge, 2004). Formulation of national drought policy, drought planning focused on the improvement of governmental response to drought emergencies and on reducing risks associated with drought occurrence, integration of all sectors impacted by drought, people-centred drought policy, focus on the protection of livelihoods and on community education and capacity building and cooperation of the international community – these are the most important measures of integrated drought management. The following diagram enumerates the step towards risk management of groundwater during a drought.

For example in India, the states of Rajastan and Gujarat which frequently experience drought conditions, the severity and impact of drought has been minimised by identification of deep (100–500 m)



aquifers like the Lathi Sandstone (3,270 km^2) with a ^{14}C age water between 7,000–10,000 years. About 30 successful wells were constructed after the assessment of groundwater resources using hydrogeological, geophysical and isotope hydrological methods (CGWB, India).

4.3 Groundwater risk management in regions affected by earthquakes

One of the major concerns associated with the earthquakes is damage to and destruction of the infrastructure, inclusive of water supply and sanitary systems (Fig. 4.3.1). The 1995 Kobe (Japan) earthquake resulted in large fires that raged out of control, the occurrence of significant numbers of slope failures and landslides, large scale liquefaction, and disruption of water supply lines constituting conditions of extreme water scarcity and famine. Knowing what can be done during or immediately after an earthquake in addition to preventive actions can save thousands of lives.

During several earthquakes drastic changes in the groundwater level were observed (Tokunaga, 1999). Several examples suggest that a significant drop of water table can occur at topographically isolated hills or highlands where shallow, local groundwater flow systems are developed isolated hydrologically from aquifers of regional extent. The drop of water table may continue for more than one year in some cases, which poses a significant problem for local people relying on this shallow groundwater. This phenomenon is often associated with the drastic increase in the flow of springs and streams, constituting small scale floods in the valley and lowland areas surrounding the isolated hills/highlands, which might also damage local structures.

Deeper groundwater is also affected by earthquakes. It is well known that the deeper groundwater level in confined aquifers fluctuates due to earthquake-induced changes in crustal volumetric strain.

Figure 4.3.1 Devastation of a building in an urban area during the Bhuj (India) earthquake of 26 January 2001. The earthquake caused complete failure of basic amenities, including the water supply system

The magnitude of the change of groundwater level depends on the earthquake magnitude, distance from the epicentre, and earthquake source mechanisms (Box 4.3.1). In some cases, the drop of groundwater level due to the change of crustal strain results in the stoppage of hot springs – a situation which may continue for several months. The appearance of new springs related to this effect were also reported, suggesting the possibility of using these as temporary water supply resources.

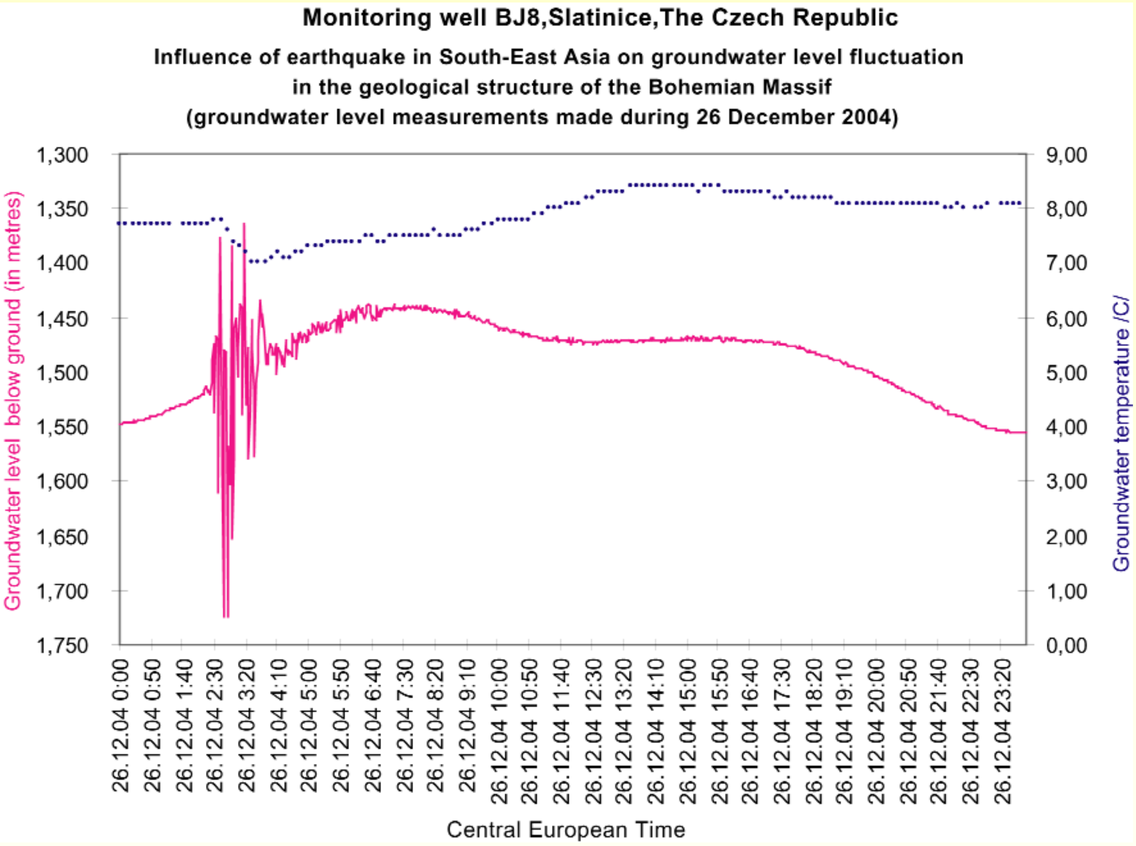
In any case, it is imperative to study the regional geology, hydrogeology, and hydrochemistry to localize and investigate aquifers of low vulnerability, especially with reference to likely changes during earthquakes. Also, the characteristics of expected earthquakes (strike slip, normal, or reverse faults and their magnitudes) help us to predict the spatial distribution of water level change in deeper aquifers. As in other emergency events, low vulnerability groundwater from deeper aquifers may be exploited if available. However, diesel/petrol-driven pumps have to be prepared as part of risk water management, because the required electricity supply may not be available after an earthquake. A high potential aquifer was identified, e.g. in the Bhuj region (India) affected by the earthquake in January 2001 (Fig. 4.3.1). A hydrogeological and geophysical survey aided by exploratory drilling found the aquifer at 150 – 170 m below surface in sandstone of Cretaceous age, which could be relied upon and could be used as an emergency resource.

Box 4.3.1

Relation between groundwater regime in Central Europe and earthquake in South-East Asia (Pospíšil, 2005)

Ongoing groundwater level observations have been conducted since 1974 on a 33 m deep monitoring well in the Czech Republic. The well is located on the contact (lineament) between the Bohemian Massif (European Hercynides, Meso-Europe) and Alpine-Carpathian system (Neo-Europe) in the tectonic structure known as the Carpathian foredeep. The aquifer being monitored is in heavily fissured limestones, connected through a tectonic fault system (fault belt?) to a deep, confined groundwater regime (age of water is more than 10,000 years). The original aim of monitoring the groundwater regime of a regionally important aquifer, was extended to observing the influence of earth tides and earthquake activities on groundwater levels. The figure shows the reaction of the groundwater level in the monitoring well to an earthquake that occurred in South-East Asia on 26 December 2004. The considerable and rapid reaction (a delay of 12 minutes) over a distance of more than 10,000 km indicates the remarkable sensitivity of the groundwater regime to earth seismic activitiy. Similar reactions of groundwater level to earthquakes since 1974 were also registered on the monitoring well.

Groundwater monitoring wells situated in deep tectonic structures between geological units (orogenic belts) could serve as a significant indicator of the vulnerability of groundwater systems to seismic activity and support groundwater risk management in areas repeatedly affected by earthquakes.



4.4 Groundwater risk management in areas affected by volcanic activities

As with earthquakes, volcanic eruptions are located on geological plate boundaries, in particular extensional plate boundaries such as the East African rift valley, and convergent plate boundaries, i.e., Pacific belts. Very hazardous volcanoes tend to be associated with convergent plate boundaries. Fig. 4.4.1 shows such a volcano, the Mahameru in Jawa, Indonesia. The hazards in volcanic areas are eruptions of molten rock, called lava, pyroclastic flow, mud flow, floods and debris avalanches, earthquakes and tsunamis. Ash and gas, sometimes poisonous, can rise into the atmosphere up to thousands of meters, producing not only an immediate hazard but can have long term climatic and atmospheric effects. In order to reduce the hazard, one has to know which areas are most prone to volcanic activities. This objective can be at least partly achieved through detailed geological and geophysical surveys of the areas where active volcanoes are situated. The historical records of volcanic activities will throw light on their eruption recurrence and other volcanic impacts. Precursory phenomena may help in forecasting volcanic activity.

Water quality needs to be monitored not only in open lakes, dams and reservoirs, but also in shallow and deep groundwater wells. In areas of heavier ash fall, roof harvesting supplies should be disconnected from house roofs and the tank protected. Open lakes and dams can become turbid and water quality can deteriorate, (e.g. become acidic) through ash fallout and dissolution of volcanic gas. Thus, surface water supplies have to be replaced by groundwater, if available. Groundwater supplies may be required to tide over the period of hazard, also in areas to which populations may have to be evacuated. Identification, investigation and development of less vulnerable aquifers seem to be most suitable mode of supplying drinking water in emergency situations. Shallow aquifers seem to fulfil the requirements for an emergency water resource because their flow regime is largely separated from active volcanism involving deep magma-related activities and structures. However, the quality of shallow groundwater may also be affected by volcanic activity. Volcanic ash tends to react with acidic rain rather rapidly, and there are plenty of fractures, lava tubes, and other preferential water pathways in volcanic terrain. Thus, once rainfall occurs, shallow groundwater quality is affected by the

Figure 4.4.1 Smoking Mahameru Volcano Jawa of Indonesia. Photo by Jan-Pieter Nap (July 11 2004)

infiltration of precipitated water which reacts with newly deposited ashes. Deep groundwater can also be vulnerable to volcanic activities because volatiles in magma can dissolve into groundwater and an increase of temperature may enhance water-rock interaction and cause groundwater quality degradation. The creation of new fractures may produce sea water intrusion especially on volcanic islands. Therefore, the intensive monitoring of both quantity and quality of groundwater and proper choice of less vulnerable groundwater resources are desirable for reducing the impact on drinking water supplies in areas prone to volcanic activity.

4.5 Groundwater risk management in areas affected by landslide disasters

Landslides and other huge mass earth movements pose major hazards especially in hilly or mountainous terrain. Landslides, as compared with earthquakes, are mostly of local extent only and have both natural and man-made causes. Natural causes include continuous rainfall, earthquakes, steep and unstable slopes (natural topography) etc.; anthropogenic causes are e.g. road building, construction of dams, exploitation of natural resources such as deforestation. Landslides cause extensive damage to infrastructure (roads, bridges, water distribution systems, human dwellings, orchards, forests etc., (Fig. 4.5.1), often resulting in major loss of life and property. Landslides disrupt normal activity, including local water supply which needs to be restored during the emergency. Some springs may stop flowing and new springs may appear. The groundwater regime in shallow aquifers is locally affected too.

Figure 4.5.1 Landslide in Jiangxi Province of south-eastern China in September 29, 2004

To apply a risk management of water supplies potentially affected by landslides, the following steps are required:

1/ Preparation of a comprehensive landslide hazard zonation map based on lithology, geology, geomorphology, rock weathering, structural discontinuity and slope angles, drainage density, land use and distance from major faults or other geological attributes sensitive to landslide events. This is the task of the engineering geologist and serves as a first generation map onto which subsequent information can be entered.
2/ Compilation of hydrogeological and groundwater vulnerability maps, focused particularly on the identification of deeper aquifers present below the weathered zone and not affected by the impact of landslides.
3/ Investigation of such aquifers and assessment of their groundwater resources. Such resources can be developed when the existing water supply system has been affected or even destroyed by landslides.

4.6 Tsunami groundwater risk management

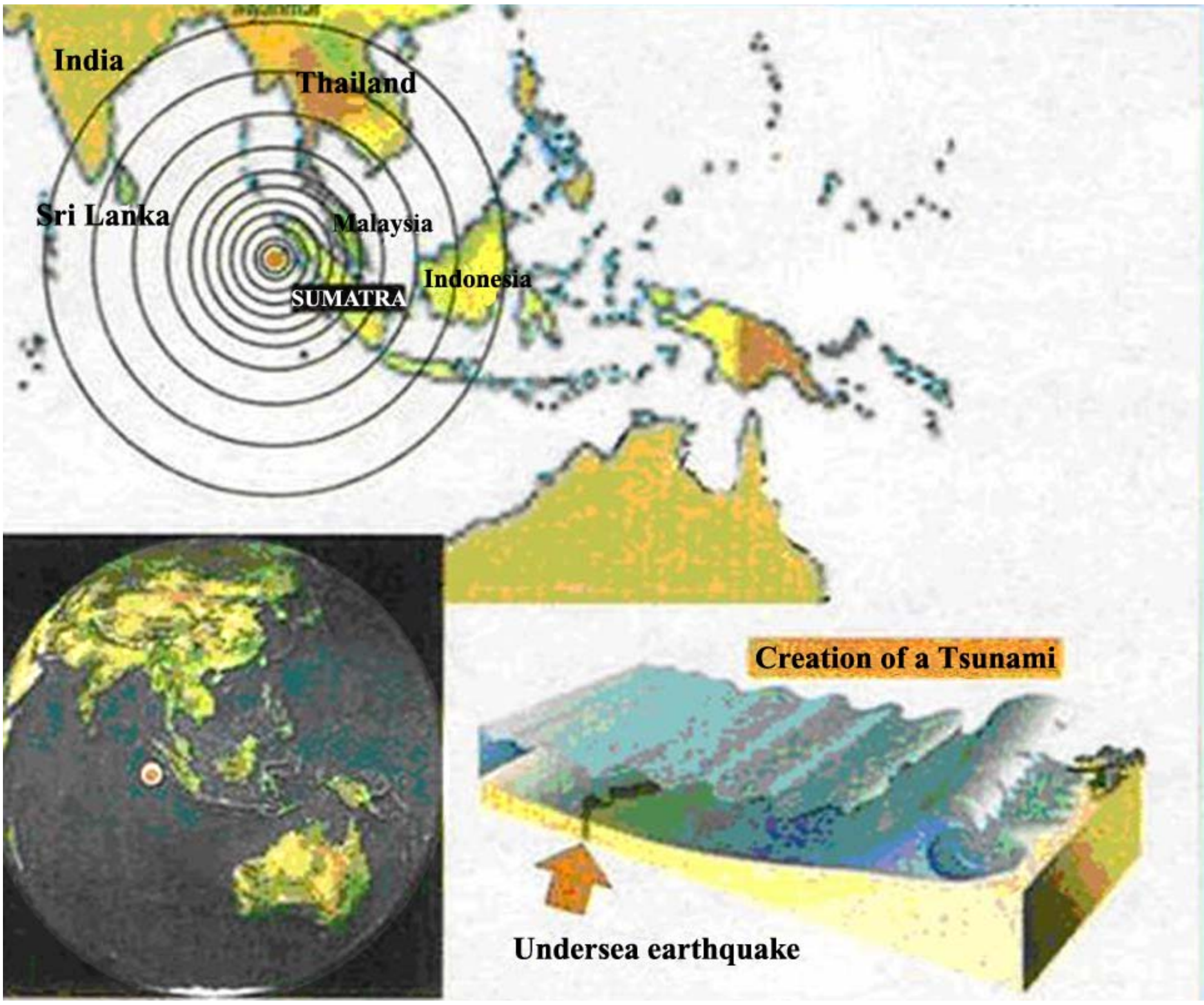
Tsunamis are large waves that are generated in the sea/ocean by any disturbance that suddenly displaces a large mass of water. Such a disturbance may be a massive submarine earthquake (magnitude greater than 7.0 on the Richter Scale and shallow focus of <30 km depth), landslides or volcanic eruptions. Tsunami waves move at high speed and large energy to engulf coastal settlements, scour cultivated land, carry vessels inland or out to sea. They partially or completely destroy infrastructure, including water supply which is often completely paralysed (Fig. 4.6.1). Such a devastating tsunami hit

Figure 4.6.1 The devastating Tsunami that hit the coastal areas of South-East Asia on 26 December 2004 left in its wake a wide swath of death and destruction. A scene shows destruction due to tsunami event in Tamilnadu (India)

the coastal areas of south East Asia on 26 December 2004 (Fig. 4.6.2), triggered by a 9.1 magnitude earthquake off Indonesia. It is estimated that there was a death toll of about 300,000 in Indonesia, Sri Lanka and India. Tsunamis are quite frequent in the Pacific and Indian ocean regions comprising Japan, Taiwan, China, Philippines, Indonesia, and also have been recorded in Chile and Peru. In Europe tsunami were registered in Italy and Portugal. As with floods, the water supply is severely affected, coastal wells are submerged, surface water in tanks and shallow ground water is heavily polluted and rendered impotable, electricity installations are uprooted, affecting water pumping facilities and coastal reverse-osmosis desalination plants.

As with any other risk management of geological and climatic hazards, it is appropriate to have an analysis of historical records, which involves: study of seismicity of a region to establish a recurrence period of earthquakes, spatial differences in earthquake destructiveness, implementation of computer models to estimate the extent of potential tsunami inundation, and ultimately the production of tsunami risk maps which assist in land use planning to mitigate future tsunami impact. Another important management policy is to have tsunami warning systems – such as the Pacific Warning System in place since the 1940s, with another being implemented for the Indian Ocean. However, even such a warning system is of limited value as it concerns mainly the safety of populations and leaves little time for safeguarding infrastructure such as water supply systems.

Figure 4.6.2 The epicentre of the great earthquake of 26th December, 2004, which generated devasting tsunami



The shallow fresh groundwater along the coast becomes saline during tsunami, and it takes several weeks of pumping the degraded (polluted) ground water to restore its quality to drinking water standards. The percolation of sea water which remains behind in pools, lakes etc. leads to further deterioration of groundwater quality of shallow vulnerable aquifers. The hydraulic pressure of a tsunami transgression can disturb the fresh/salt water equilibrium which results in mixing, the deterioration of fresh water quality and the displacement inland of the fresh/saline water interface. Further, there could be pollution of shallow aquifers due to infiltration of chemicals, fuel, pesticides and pharmaceuticals, as storage facilities in coastal areas are often damaged by tsunami.

Deep coastal aquifers which have recharge areas quite far from the coast (if available) will remain unaffected by tsunami and can serve as suitable emergency sources of drinking water. Such aquifers need to be identified, investigated and their groundwater resources assessed or even developed for emergency situations. For example the Cuddalore area of Tamil Nadu, South India, which was devastated during the 2004 tsunami, could utilise the Cuddalore sandstone aquifer having a recharge area about 30–40 km away from the coast. The aquifer extends up to the coast, has high permeability and recharge rate and can be utilized for a considerable time during an emergency (Sukhija et al., 1996).

Islands need special attention as fresh water is limited to the top 4 to 5 meters in sand aquifers or coral limestones. Generally their yields are low and water often does not fulfil drinking water standards. As a preventive measure, it is advisable to locate open well sources on high ground where fresh water lenses are thicker and surround them by a high strong parapet wall and cover slab which will limit the intrusion of sea water into the well. Pumping out or 'skimming' the sea water which entered the well may improve the quality of water produced. Portable desalination plants which source moderately degraded water from open wells are also useful during emergencies. Springs may prove to be an additional source of drinking water.

4.7 Groundwater risk management in regions affected by storm events

Amongst atmospheric phenomena or storms, cyclones, hurricanes and tornadoes are the most destructive. Tropical cyclones are quite common in India, Bangladesh, Philippines whilst hurricanes and tornadoes are frequent in Japan and USA. The impact of such storms (Fig 4.7.1) is felt in various ways. Tidal surges three to fifteen meters higher than normal invade low lying areas 15 to 25 km inland with devastation resembling tsunami. Gale force winds with speeds ranging from 80 to 250 km per hour cause severe damage to trees, crops, homes and infrastructure. Heavy rains before and after the storm event produce damaging floods.

The tracks of 21 historical cyclones from 1876 to 1993 which hit the Indian coast as well Bangladesh reveal that 10 out of 13 storms originating in the Bay of Bengal occur between latitude 8 to 16 degree North and longitude 88 to 98 degrees East. This suggests high recurrence in this region and the need to implement precautionary measures described elsewhere in this work.

An extreme example is the Super Tropical cyclone which struck the Orissa coast of India on 29 October 1999 with wind speeds up to 250 km per hour. It paralyzed the entire state killing 9,887 people. A huge storm surge travelled 15 km inland. Cumulative rainfall of some 60 cm was recorded at some places. Field monitoring by the Indian Central Ground Water Board (CGWB) revealed that most of the dug wells inundated by sea water showed marked quality deterioration, whereas in areas 20 km inland there was no appreciable change in ground water quality. Deeper aquifers were not affected by the salinity problem. Based on hydrogeological surveys and groundwater exploration carried out by CGWB, fresh water aquifers were identified in the affected area and 10 deep bore wells constructed for cyclone relief.

Figure. 4.7.1 A photograph of a hurricane in Florida (USA) which produced natural calamity resulting in an emergency situation

5. Identification and investigation of groundwater resources for emergency situations

This chapter is focused primarily on the identification and investigation groundwater resources naturally protected against harmful natural and man-induced external impacts. Within the objectives of GWES the development of such resources of low vulnerability is seen mainly in deep-seated, mostly confined, aquifers with renewable or non-renewable groundwater. The identification and investigation of such groundwater resources is very exacting and requires an interdisciplinary approach. It also involves the implementation of more sophisticated methods directed towards an understanding of the geological environment and structures which form aquifers.

The more classical methods of groundwater investigation like geology, hydrogeology and hydrochemistry are complemented with the methods of geophysics, isotope hydrology, remote sensing and mathematical modelling. Integrating these methods facilitates establishing a conceptual model of a groundwater system, identifying the groundwater flow regime and origin and assessing residence time – all needed to define conditions for the exploitation of groundwater for emergency situations. Hydrogeological maps depicting the occurrence of aquifers containing potable water and groundwater vulnerability maps are both important means by which to present the outcomes of such complex investigations of groundwater resources. The following sections describe methods applied in the identification, investigation and development, mainly of deep groundwater of low vulnerability for emergency situations.

5.1 Geology

The geological setting controls the occurrence and flow of groundwater as well as geological hazards (earthquakes, volcanic activities, landslides), which in some way affect the environment, which includes groundwater resources, thereby impacting on human lives. The earth is a dynamic, evolving system. The outer layer of the lithosphere consists of several plates that move relative to one another.

Geological hazards

Most **earthquakes** occur in tectonically active areas where lithospheric plates, on which the continents and ocean basins are superimposed, interact – such as along the circum-Pacific belt, the mountainous zone extending from the western Mediterranean to Asia Minor, the Himalayas to Indonesia and central Asia. Amongst the primary effects of earthquakes is the collapse of structures, with secondary effects such as fires, tsunamis, floods, subsidence, uplift, landslides and changes in groundwater levels (Keller, 1976). An important focus for the proposed GWES rescue activities should therefore be on geologically unstable zones where earthquakes are known to recur. The tsunamis in the northern Indian Ocean triggered by submarine earthquakes off Sumatra in December 2004 left in their wake water supply and sanitation problems of monumental proportions. As the damage was restricted largely to low-lying areas along the seaboard, they have focused attention on emergency groundwater supplies which should be sought and established mainly in coastal and adjacent aquifers.

Volcanic activity is another manifestation of geological processes. Volcanic activity is related to plate tectonics. Approximately 80% of all active volcanoes are located in the 'ring of fire' slung around the Pacific Ocean (Keller, 1976), a smaller percentage in the Atlantic, in the Mediterranean, Indian Ocean, and elsewhere. Volcanic events cause loss of life, destroy the environment and crops, contaminate and increase the acidity of surface water; destroy infrastructure and always damage drinking water supplies which require rapid substitution.

Landslides may disrupt infrastructure, including water supply systems. To a certain degree, they can be forecast according to their geological and geomorphological setting. Landslides occur mainly on slopes and in areas where the stability of earth masses is disturbed. They are usually triggered by secondary factors such as heavy rains, earthquakes and human interference, often in regions marked by previous or 'fossil' landslides. Municipalities in Guatemala, Nicaragua and other countries in the Caribbean region affected by landslides which followed the hurricanes and heavy rains during the past decade, have recognised the need for timeously installing substitutes for damaged water supply systems.

Geological investigation and mapping

The occurrence, movement and properties of groundwater depend to a considerable extent on the petrological composition of the aquifer rocks and geological structure of the earth´s crust. **The petrological composition** of rocks influences their physical and mechanical properties, including their porosity and permeability. It also affects geochemical processes and the chemical composition of groundwater. **Geological structure and surface morphology** influence the spatial distribution of the ground-water flow system. Both factors have to be investigated to determine the specific features of the sub-terranean part of the hydrological cycle. In comparison with surface hydrology, groundwater moves slowly and exhibits long residence times.

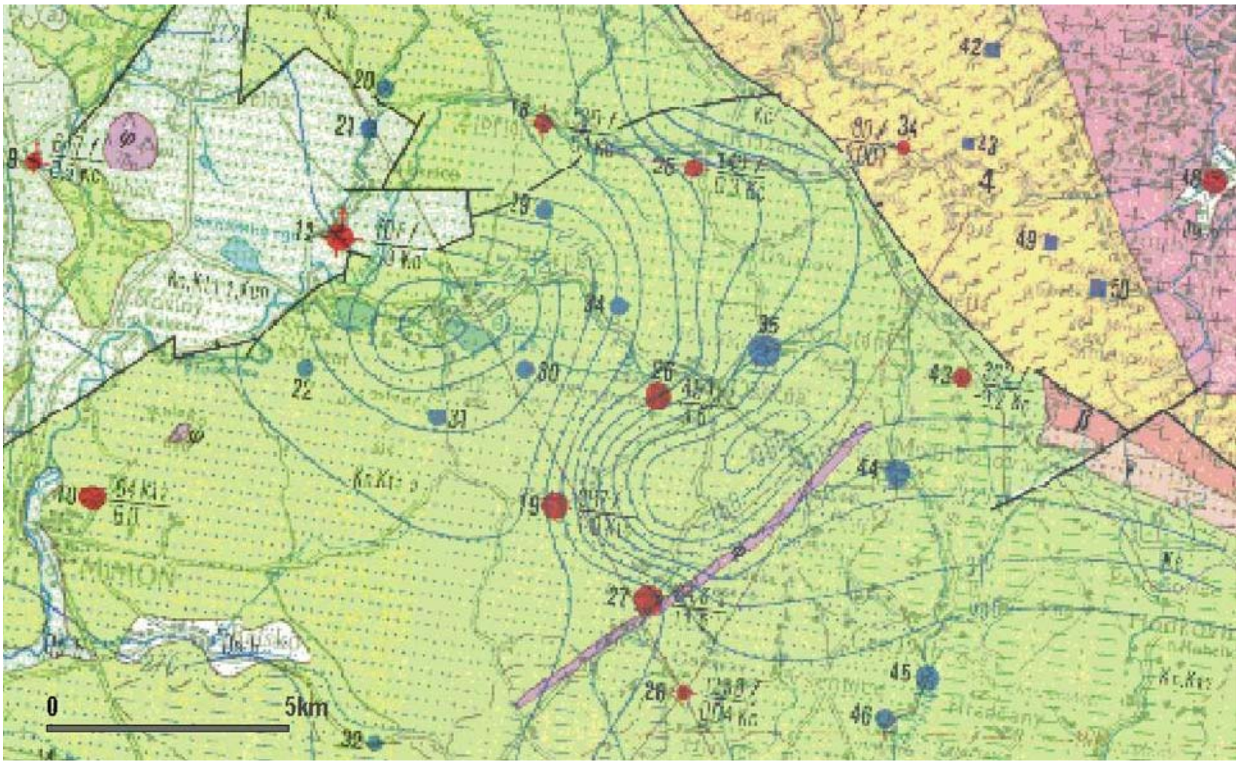
Analysis of the geological structure is particularly needed to obtain an overview of the tectonic setting and development (tectonic phases) of the studied region. Fissures in hard rocks which originate in early orogenic phases are often indurated by secondary minerals and thus impermeable, while the fissures of the post-orogenic age are mostly open and permeable. A further important factor is whether the fracture systems find themselves in a compressional or tensional regional stress field.

Geological maps and sections and satellite and aerial photographs illustrate the geological features of a region. They are useful in support of an investigation of groundwater resources and of rescue activities in regions prone to geological disturbances.

A geological map should show the composition of the rocks and the geological structure of the investigated area. These have a decisive influence on groundwater occurrence and flow system and its evolution in the geological past. A geological map should also show features such as springs, marshes, wet spots, covering formations; indicate sites of fossil landslides and thus their potential of recurrence. Geological maps are also a very useful tool in assessing impacts of geological events on the environment and, in combination with tectonic structure analysis and historical records, indicate areas prone to geological hazards. It should be noted, however, that earthquakes and volcanism are phenomena produced by processes in the earth's interior, while a landslide, though sometimes triggered by the former, is a process affected by the forces acting on the earth's surface, mainly the weathered zone.

Geological maps are drawn to different scales. Maps showing tectonic zones with earthquake activities are at small scale as they represent large regions and continents, while maps designed to indicate specific phenomena like landslides, are at large scale to present greater geological detail. Maps should be illustrative, comprehensible and suited to specific requirements. Geological maps tend be universal, however, and may have to be supplemented with special maps focused on the specific hydrogeological (Fig. 5.1.1), geotechnical or environmental problem.

Figure 5.1.1. Part of the hydrogeological map 1:200,000 (original scale) of a region in northern Bohemia, Czech Republic



The preponderant Cretaceous strata in the basin are shown in different shades of green. The aquifers in the Cretaceous groundwater basin, specified by stratigraphic symbols, are the more productive aquifers in the Czech Republic. Crystalline and volcanic rocks, represented by granite and phyllite, are shown in violet and yellow respectively; upper Paleozoic rocks – sandstones and melaphyres as two brown strips; Tertiary neo-volcanites as violet patches; alluvial plains in grey; ranges of aquifer transmissivity in different colours of hatching, and isopiestic (equal pressure) lines in blue including the depression cone caused by dewatering a uranium mine. Red circles are boreholes and blue circles springs.

5.2 Hydrogeology

Groundwater occurs and circulates in the lithosphere and represents contemporaneous and past hydrological cycles. The study of groundwater requires an interdisciplinary approach to better understand the regime especially of renewable and non-renewable groundwater in deep aquifers. However, knowledge of the geological environment and tectonic structure is the key element in groundwater resources investigation and development.

Occurrence and movement of groundwater in the rock environment

Groundwater occurs in rocks in interstices of various shape, size and origin. The occurrence of groundwater, its amount and movement, therefore depend on the composition of rocks and their hydraulic properties. The ability of the rock to transmit water through its interstices is called permeability. The potential content of water and the permeability of rocks depend mainly on the porosity of the rocks. Both the permeability and the porosity are affected by geological factors and processes, which have to be always considered when studying a groundwater flow system (Box 5.2.1).

The type of interstice in a rock controls the physical behaviour of water, especially its movement. However, only in homogeneous (e.g. sedimentary) porous rock environments do the laws of groundwater movement apply.

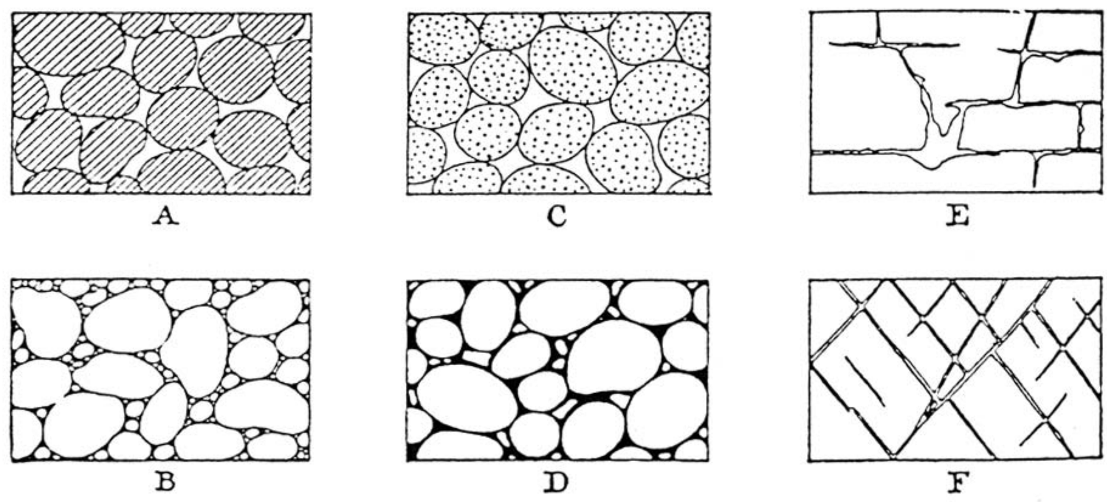
Box 5.2.1

Basic types of interstices in the rocks

According to their hydraulic properties and geological origin, the following basic types of interstices in the rocks become pathways of groundwater flow and circulation (see the Fig. 5.2.1):

- **Pores**, i.e. interstices between the grains of unconsolidated as well as of consolidated clastic sediments (i.e. sediments composed of fragments that derived from older rocks), or of loose volcanic tuff.
- **Fissures.** The term fissure is used here as a fracture or crack where there is a distinct separation between the surfaces.
- **Cavities,** i.e. karst cavities originating in soluble rocks formed by chemical solution or leaching by percolating water; and lava tubes (hollow spaces beneath the surface of a solidifying lava flow, formed by the withdrawal of molten lava after the formation of the surficial crust (*Glossary of Geology,* 1980). Karst cavities are common in soluble carbonate rocks while lava channels are confined to volcanic formations.

Figure. 5.2.1 Diagram showing several types of rock interstices and the relation of texture to porosity (after Meinzer, 1942)



(A) Well-sorted sedimentary deposit having high *(primary)* porosity, (B) poorly sorted sedimentary deposit having low porosity, (C) well-sorted sedimentary deposit consisting of pebbles that are themselves porous so that the deposit as a whole has a very high porosity, (D) poorly-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices, (E) rock rendered porous by solution, or karstified – *secondary* porosity, (F) rock rendered porous by fissures.

Permeability of the principal rock types

Igneous rocks (plutonic as well as volcanic) and *metamorphic rocks* are permeable along fissures. With increasing depth, the fissures close and the rocks become less permeable. By chemical/mechanical weathering, the quartz-rich rocks produce sandy elluvia at the surface which are permeable. Rocks poor in quartz may disintegrate by chemical weathering to clay minerals, which form less permeable soils and clog the fissures in the underlying bedrock. Deeper groundwater circulation occurs along deep faulting in tectonic zones as indicated by thermal springs.

Sedimentary rocks vary considerably in their composition. They exhibit all types of interstices (pores, fissures and karst cavities), as well as all types of permeability. 'Double, or dual (e.g. primary and secondary) porosity' has to be considered when evaluating ground water flow and the behaviour of pollutants and tracers in such a rock medium. The most significant aquifers and groundwater basins are developed in sedimentary rocks. Carbonate rocks are often karstified.

Recent *unconsolidated and incoherent sediments* include various kinds of gravel, sand and clay, sometimes containing organic matter. They occur as alluvia; lacustrine, marine and delta sediments; sediments of alluvial cones of inter-mountain depressions; and glaciofluvial sediments washed out from moraines. Incoherent and thick sediments are prone to compression and to subsidence of the surface in cases where the pore pressure is lowered by groundwater extraction.

On a regional scale, hydrogeology has to consider the principal tectonic structures and discontinuities. In investigating and modelling regional groundwater flow attention should be focused on, and incorporate the irregularities of, such structures which may be significant as either groundwater pathways or barriers.

Hydrogeological system

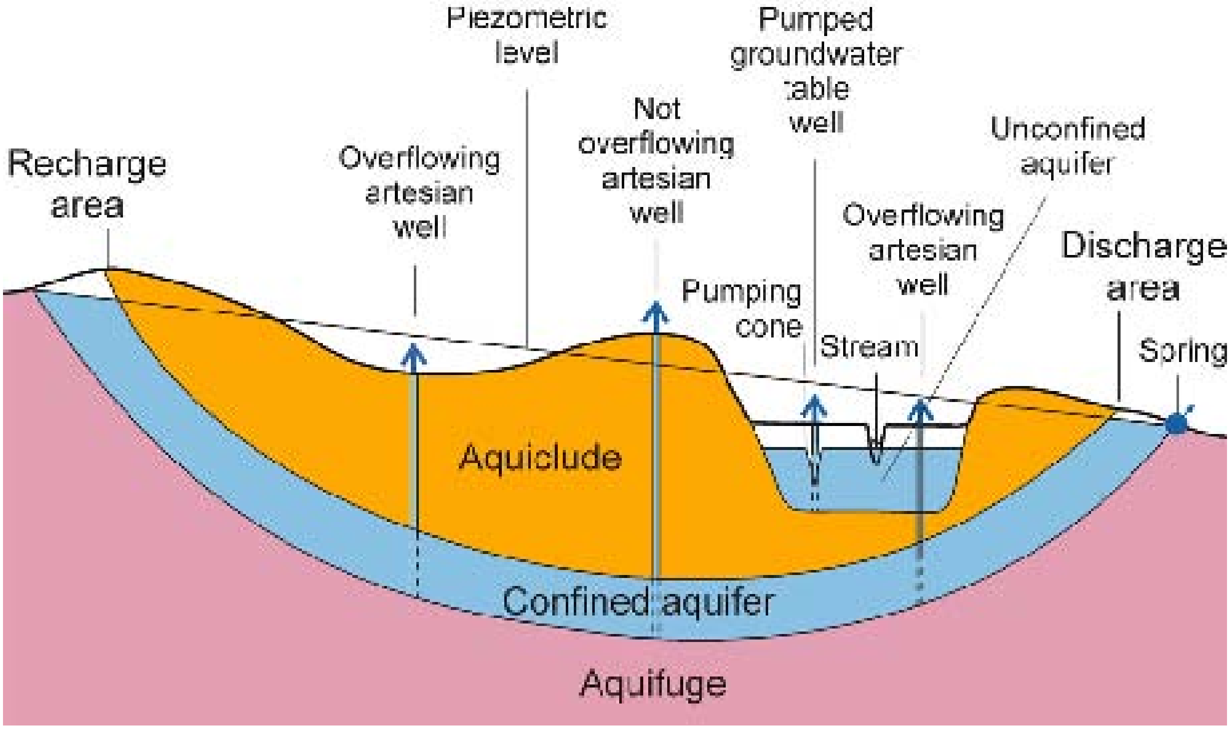
A hydrogeological system consists of an unsaturated zone (pores partially filled) and a saturated zone (pores completely filled) with continuous groundwater movement in permeable material. An aquifer is defined as a saturated water bearing formation capable of yielding exploitable quantities of water. A completely saturated aquifer overlain and underlain by an impervious aquiclude is called confined; it is called artesian when the piezometric (pressure) level lies above the land surface. An aquifer containing groundwater with a free surface, or a water table, and receiving recharge through the unsaturated zone is called unconfined or phreatic. Unconfined, or water table, aquifers are highly vulnerable to natural and human impacts and are often polluted. The vulnerability of deep confined aquifers is generally low. Such aquifers are a significant source of safe water suitable eg. to fulfil the GWES objectives. Groundwater basins are composed of aquifers, the geometry (dimensions) and complexity of which depend on the geological environment and tectonic structure. An example of unconfined and confined aquifers (artesian groundwater basin) is shown in Fig. 5.2.2.

In searching for groundwater as an emergency resource, the essential aspect is groundwater quality. In this respect, a rough rock classification into three groups seems practical (Mazor, 1991): 1) rocks in which fresh groundwater is common, that is, rocks that contribute extremely small amounts of salts to the water (fractured crystalline; leached sandstone), 2) carbonate rocks that contribute dissolved matter but maintain good potable quality, and 3) rocks that enrich the water with significant amounts of dissolved salts, often making it non- potable (marine deposited; containing evaporites).

Groundwater vulnerability

It is generally assumed that the subsurface environment provides some degree of protection to groundwater against natural and human impacts. The degree to which this does not hold is referred to as groundwater vulnerability, which is an intrinsic property of a groundwater system. It depends on the interaction of the system with its environs and human and natural influences. It is obvious that vulnerability should be the first consideration of groundwater to be used for emergency situations. We should consider two indicators of groundwater vulnerability: the groundwater flow system and groundwater residence time.

Figure 5.2.2 Simplified example of an artesian groundwater basin



Two aquifers are shown (both in blue): The upper is unconfined, with a water table in the alluvial plain. The deeper aquifer is confined, its piezometric level inclined from the recharge area to the discharge area. Boreholes are indicated by arrows showing upwards (symbol of a drilling rig). The spring provides natural discharge of the groundwater system. Boreholes tapping the confined aquifer are artesian, or free flowing, where the piezometric level lies above the surface. Not overflowing wells are also called subartesian.

The vulnerability and flow regime of groundwater can be analysed by means of groundwater hydraulics and isotope techniques (section 5.4). These techniques assess flow rate and residence time, and introduce complementary aspects into the classic hydrological approach to groundwater resource assessment and protection such as contaminant transport pathways and addition through mixing. When prospecting for groundwater resources for emergency situations attention is focused particularly on deep aquifers where isotope techniques can prove to be very useful.

5.3 Hydrochemistry

Groundwater contains a broad range of dissolved solids at concentrations usually so low that they are dissociated into ions. Groundwater also contains a small amount of dissolved organic matter and gases. The development of groundwater chemical composition is the result of very complex hydrogeochemical and biological processes occurring in the soil-groundwater-rock system. The ionic composition of groundwater is controlled in particular by: 1) the chemical composition of rain, snowmelt and surface water infiltrating into the subsurface, 2) the properties of the soil and rock environment in which groundwater moves, 3) contact time and contact surface between groundwater and the geological materials along its flow path, 4) the rate of geochemical (dissolution, precipitation, hydrolysis, adsorption/desorption, ion exchange, oxidation/reduction), physical processes (dispersion, advection, filtration, thermal), and microbiological processes (microbial metabolism and decomposition, cell synthesis) which occur in the subsurface, 5) the concentration of dissolved gases, particularly oxygen and carbon dioxide.

There are scale differences in the chemical composition of groundwater both laterally (recharge/ discharge areas) and vertically (shallow oxidation/deep reduction zones), which are typical particularly for groundwater in sedimentary basins. Generally, groundwater in recharge areas and shallow aquifers has a lower dissolved solids content than groundwater in discharge areas and in deeper aquifers. The increase in total dissolved solids and the anion evolution sequence $HCO_3^- \rightarrow SO_4^{2-} \rightarrow Cl^-$, reflecting the change from oxidising conditions (shallow zone) into reducing conditions (deep zone), are to be seen in the vertical/age profile of a groundwater system expressed by Chebotarev (1955):

Travel along flow path ⟶

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

Increasing age ⟶

In crystalline or pure siliceous sedimentary terrain, the Chebotarev sequence might hold for ionic ratios with depth, but the dissolved solids concentrations might even be reversed (Verhagen, 1992).

Based on the Chebotarev anion evolution sequence, Domenico (1972) identified three main zones in large and deep groundwater basins, which correlate in a general way with depth. Mineral availability and molecular diffusion control in particular the gradual changes in anion composition in groundwater.

Active groundwater circulation, lower temperature and short time contact of groundwater with leached rock materials are typical for recharge zones and near-surface highly vulnerable inland aquifers. Groundwater is low in total dissolved solids and HCO_3^- is the major anion. In deeper intermediate zones temperature, pressure, contact time and surface with reactive rock minerals gradually increase as groundwater flow velocity decreases. This leads to increases in dissolved solids with depth and sulphate ion dominance. In deep groundwater systems of negligible vulnerability, where flushing by groundwater is minimal, chloride gradually becomes the dominant anion and groundwater is often high in total dissolved solids. However, the groundwater chemical zonation described above can not be applied to shallow coastal aquifers where groundwater composition is under the influence of saline water.

Both intermediate depth and deep aquifers are important sources of groundwater for emergency situations.

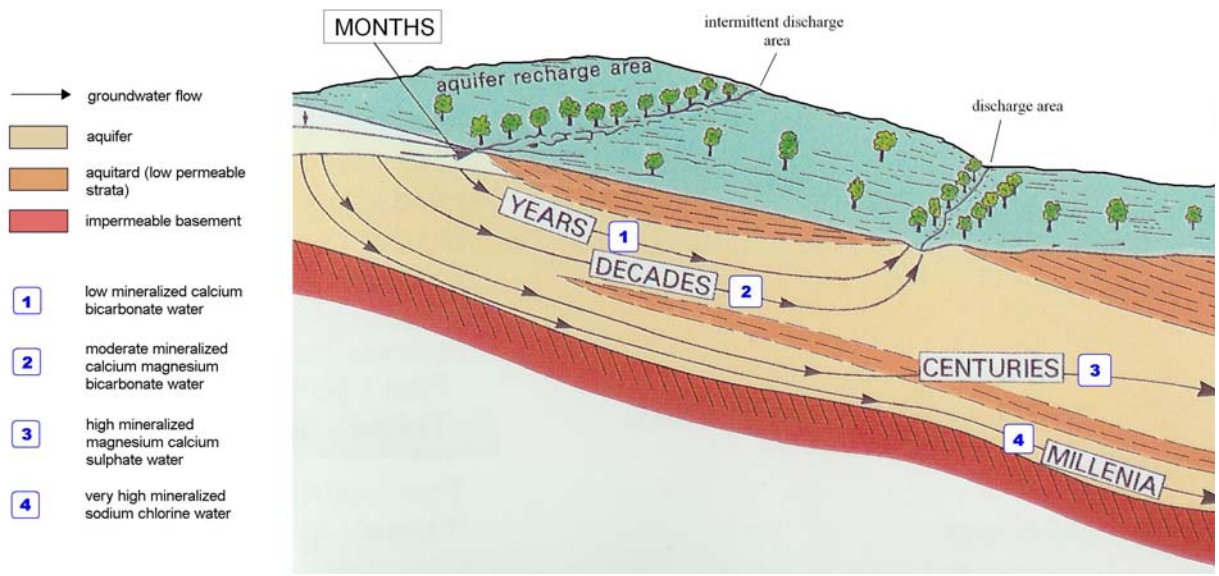
The sequence depicting a gradual transition along the flow paths from fresh bicarbonate groundwater through sulphate water to mineralised chloride water at the downstream end is shown in Fig. 5.3.1.

The mobility of ground water in the different zones can be roughly classified in terms of groundwater ages. According Freeze and Cherry (1979) in some sedimentary basins, groundwater in the upper zone may be years to tens of years old, whereas in deep basins ages of hundreds to thousands of years are common. Saline, chloride-rich connate water in the deep zone is usually very old, the ages varying from thousands to millions of years.

The HCO_3^- content in groundwater is mostly derived from biogenic CO_2 in the soil zone and dissolution of calcite and dolomite, or decomposition of igneous feldspars, depending on the rock environment. The origin of sulphate in groundwater depends on the presence of soluble sulphate bearing minerals (gypsum $CaSO_4 . 2H_2O$, anhydrite $CaSO_4$ and potash salt deposits), metallic sulphide minerals and the deposition of marine aerosols. High chloride contents in deep groundwater depends primarily on the presence of chloride-bearing sedimentary rocks and their soluble halite (NaCl) and sylvite (KCl).contents, and quite strongly on contact surface and time.

A cation evolution sequence in the groundwater system similar to the Chebotarev anion sequence is difficult to identify because there is a larger variation in cation content. The presence of major cations (Ca^{2+}, Mg^{2+}, Na^+ + K^+) strongly depends on the solubility of the source minerals and on the type,

Figure 5.3.1 Example of flow, age and hydrochemical patterns in groundwater (not to scale, adapted from British Geological Survey Documents)



extent and velocity of cation exchange processes. Matthess (1982) identified the following vertical hydro-geochemical zonation based on the characteristic cation:

$$Ca^{2+} \longrightarrow Ca^{2+} + Mg^{2+} \longrightarrow Na^{+}$$

Biological processes enhance the extent and rate of geochemical processes. They are particularly intensive in the uppermost soil and root domain of the unsaturated zone, where dissolved oxygen is usually available supporting organisms which break down organic matter. The biochemical processes in the soil produce large amounts of inorganic and organic acids which render the groundwater aggressive, initiating the hydrochemical process.

The identification and development of groundwater with low vulnerability for emergency situations should be focused mainly on the deeper intermediate groundwater zones. Groundwater in shallow aquifers is usually highly vulnerable to impacts, both natural (floods, droughts, saline intrusion) and human (pollution) and is far from being a safe source of drinking water in regions exposed to natural hazards. The vulnerability of deeper groundwater is mostly negligible, and the resource is resistant to natural and human impacts. It usually is of good quality and suitable to be used untreated or after treatment demanding low technology e.g. aeration, filtration, adjusting alkalinity, to serve as drinking water source. However, in some cases deep groundwater could contain high concentrations of chloride, sulphate, or other components and not fulfil drinking water standards.

Hydrochemical investigations, combined with multiple environmental radioisotope analyses (e.g. ^{3}H, ^{14}C, ^{36}Cl), allow for the identification of age-related groundwater processes. Non-radioactive isotopes assist in defining the origin of groundwater. The groundwater evolution sequence and groundwater zoning could be disturbed in geological structures affected by tectonics, interconnecting aquifers carrying water of different origin and age. In such and other cases Phillips et al. (1989) and Verhagen et al. (1991) proposed more extensive use of isotope techniques to better understand aquifer systems composed of more than one groundwater component and to calibrate the groundwater time scale. Isotope methods and techniques applied in groundwater hydrology are described in the section 5.4.

5.4 Isotope hydrology

In order to understand the behaviour of a ground water resource, classical hydrogeology studies the hydraulic response, or inferred flow in an aquifer under the influence of a natural or induced hydraulic gradient. Such flow can be measured by injecting tracers.

In the single borehole dilution technique the tracer (e.g. a bromide or chloride salt) is mixed uniformly into the borehole standing water column and the concentration then measured by lowering an appropriate probe. The rate at which fluid is diluted or flushed out of the water column allows for the assessment of aquifer permeability and flow profiles with depth in the vicinity of boreholes.

In order to investigate the transport of water in the aquifer, salt or a radioactive tracer injected at point A can be detected at a sampling point B downstream. Such tracing is feasible only over relatively small distances; may involve inordinately long break-through times; the tracer may be absorbed by the aquifer; be excessively diluted or may entirely miss the sampling point.

The relatively modern tool of environmental isotope hydrology overcomes most, if not all, of these disadvantages.

Why environmental isotopes ?

Environmental isotopes label ground water on an ongoing basis, through either natural or anthropogenic processes. It is often necessary only to analyse one suite of samples taken from a number of points in the system – an 'isotope snapshot' – in order to gain an initial understanding of the hydrology. This may apply to a small basin or to an entire catchment. The transport approach, which differs from the classical hydraulic approach, can produce an independent assessment of an existing conceptual hydrogeological model (Box 5.4.1), suggest a model where none existed or produce data such as recharge rate and flow continuity, essential in a numerical model. Environmental isotopes are particularly useful in assessing systems intended for emergency supply, especially where these are often deep-seated; they supply unique information on the dynamics (movement), the origins and environmental conditions of recharge, including palaeo-conditions, and mixing of ground water. Environmental isotope hydrology is increasingly seen as indispensable in understanding and quantifying ground water systems, their vulnerability and sustainability.

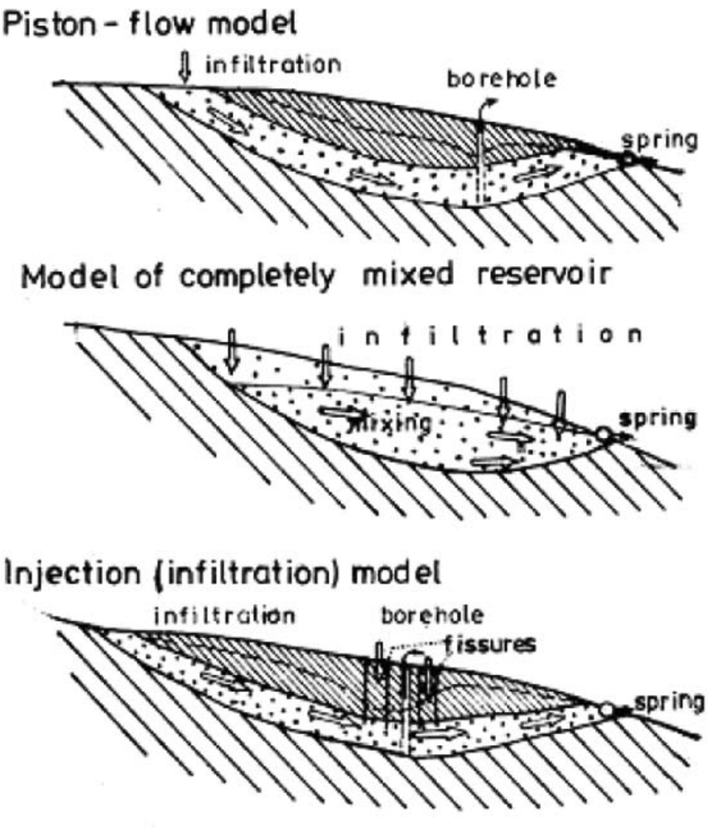
Box 5.4.1

Hydrodynamic models

To interpret isotope data, hydrodynamic models of groundwater flow have to be considered. Three such (idealised) models are shown (Fig. 5.4.1).

For a **confined aquifer** with limited recharge area, it is assumed that particles or volume elements move with the same travel time along parallel flow lines to the sampling point – the **piston-flow model.** The output concentration of the radionuclide is determined only by radioactive decay. The groundwater residence time is identical with the groundwater transit time through the system and with the radiometric age of the groundwater sample. When the distance from the recharge area is known, a flow velocity can be estimated. For a **phreatic aquifer** the **completely mixed reservoir model** is appropriate. The output concentration of the radionuclide at the outflow of the system is determined by the mixture of different flow paths with different delays which can be represented as a mean residence time (MRT). This in turn depends on an exponential, diffusive etc. transit time function. When a confined aquifer is heavily exploited, the piezometric pressure is reduced locally, allowing water from a shallow aquifer or the surface, containing tritium, to be drawn in – the **injection model.** The proportion of the injected component can be calculated from the mass balance of two radionuclides (e.g. long-lived radiocarbon and short-lived tritium).

Figure 5.4.1 Schematic sections depicting three different hydrodynamic models of groundwater flow: piston-flow (confined aquifer) model; completely mixed reservoir model and the injection (leakage) model



In this brief discussion, only isotopes of the light elements: H, C and O are considered – the more commonly-used or 'workhorse' isotopes. Other isotopes employed in hydrology include non-radioactive or stable species $^{15}N/^{14}N$, $^{34}S/^{32}S$, $^{87}Sr/^{86}Sr$ and radioactive species ^{36}Cl, ^{85}Kr, ^{222}Rn for widely differing time-scales from days to hundreds of millennia.

Radioactive isotopes

Unstable, or radioactive, nuclides emit spontaneously one or more particles or quanta to reach stability. This process is random, the emission rate being proportional to the number of radioactive atoms. The equation governing such decay is:

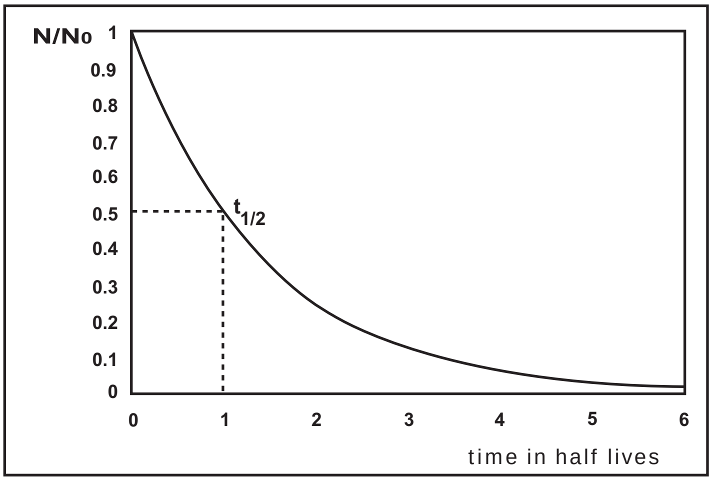
$$N = N_0 e^{-\lambda t} \qquad \text{[eqn. 5.4.1]}$$

where N is number of radioactive atoms at time = t; N_0 is the number of radioactive atoms at time t = 0; λ is the decay constant. The function is plotted in Figure 5.4.2. When only half of the radioactive atoms remain, i.e. $N/N_0 = 1/2$, the time elapsed is called the **half-life, $t_{1/2}$** .

Tritium ^3H. Tritium, or radioactive hydrogen, is produced in the atmosphere by cosmic ray reactions, oxidised to $^3H^1HO$ and becomes a conservative tracer of rain water with a natural $^3H/^1H$ ratio of about 5×10^{-18} or 5 TU (tritium units). Isolated from the atmospheric source following rain recharge, no new tritium is added to an imaginary 'parcel' of groundwater and the concentration of tritium decreases with its characteristic half-life of 12.32 years, giving time-dependent information on fairly recently recharged or 'young' groundwater

Radiocarbon ^{14}C. Radiocarbon also is produced in atmospheric cosmic ray reactions. Oxidised to $^{14}CO_2$ radiocarbon becomes part of atmospheric carbon dioxide, its concentration expressed as 100 pMC - per cent of modern carbon. Atmospheric carbon dioxide, assimilated by plants, liberated by humus and roots and dissolved in infiltrating ground water, leads to ^{14}C-labelled dissolved inorganic carbon (DIC). As for tritium, reduction in concentration due to ^{14}C decay after recharge gives time-dependent information. The biogenic $^{14}C/^{12}C$ ratio can be altered chemically during recharge, but subsequently may be taken as conservative (Verhagen et al., 1991). With its much longer half-life of 5,730 years radiocarbon is the principal radioactive environmental tracer of older groundwater and makes it particularly relevant to studies of usually deeper-seated emergency supplies.

Figure 5.4.2 Exponential decay curve showing the ratio of the number of remaining (N) to the original number (N_0) of radioactive atoms plotted against time in multiples of the half-life $t_{1/2}$



Mean residence time and recharge

Mean residence time (MRT) is an indicator of ground water mobility, or recharge/storage ratio, and is based on a (conceptual) lumped-parameter model of flow through an aquifer, using tritium and/or radiocarbon data (Malozsewski and Zuber, 1996) – see Box 5.1.1. Once a MRT has been evaluated, the important parameters such as recharge R can be assessed:

$$R = \frac{(n \times HR)}{MRT} \quad \text{[eqn. 5.4.2]}$$

where H = the depth of the saturated zone sampled and n = the porosity of the aquifer.

Non-radioactive or stable isotopes

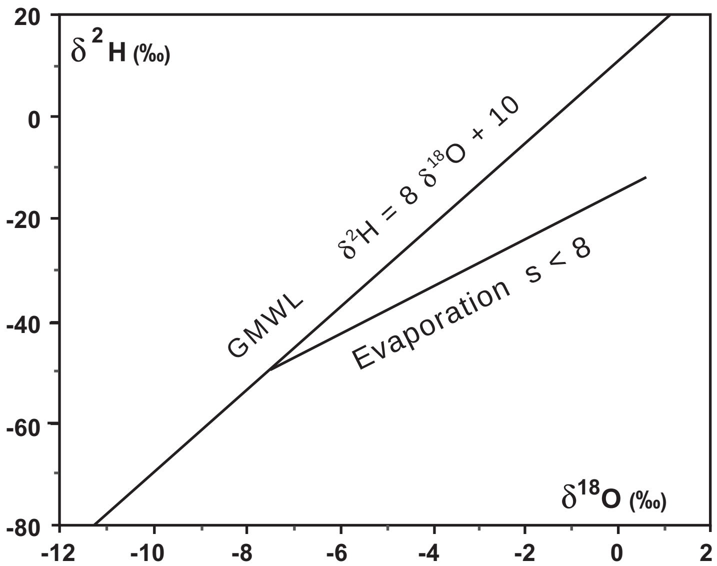
The mass difference of the isotopes, or of molecules made up of different isotopic species, affect chemical and physical processes resulting in small differences in their concentration, or abundance. These can be expressed as relative differences δ in per mille (‰) from a reference standard (Clark and Fritz, 1997): and traced through groundwater systems:

$$\delta = [(R_S / R_r) - 1] \times 1{,}000 \ (‰) \quad \text{[eqn. 5.4.3]}$$

where R_s and R_r are isotope abundance ratios in sample and reference standard respectively. In the case of isotopes in the water molecule, R refers to $^{18}O/^{16}O$; $^{2}H/^{1}H$ and the reference standard is SMOW (Standard Mean Ocean Water).

The δ values for the heavy isotopes of hydrogen ^{2}H and oxygen ^{18}O with respect to the SMOW standard in vapour rising from the ocean are more negative w.r.t. ocean water. Rainout from a vapour mass moving inland leaves it even more depleted, plotting on the so-called 'global meteoric water line' (GMWL; Figure 5.4.3). Evaporation from a lake or river leaves the remaining water enriched in the heavy isotopes, the δ values plotting on a line with slope < 8 – an evaporation line. These signals are retained during infiltration into the sub-surface. The stable isotopic signature on (ground) water therefore gives information on its origin and allows for the distinction between water from different sources in an aquifer, of palaeo-recharge, and to study mixing, flow continuity etc.

***Figure 5.4.3** A $\delta^{2}H$ – $\delta^{18}O$ (‰ SMOW) diagram, showing the global meteoric water line (GMWL), slope 8 and an evaporation line, slope < 8*



The ratio of the stable isotopes of carbon $^{13}C/^{12}C$ undergoes fractionation in biological and hydrochemical processes, and is expressed as relative differences δ (eqn. 5.4.3) from the PDB reference standard. This provides further information on the origins of recharge, on the interpretation of radiocarbon data and the identification of sources of organic pollutants.

See example of the application of environmental isotopes: case study, section 10.

5.5 Geophysics

Geophysical techniques provide clues to subsurface geological formations, which need to be interpreted in terms of the existence of groundwater. Yet for better visualization of the subsurface hydrologic regime, interpretation of complementary data from geological investigations should also be made use of. Geophysical exploration for groundwater is based on the measurement of differences between or anomalies in physical properties (e.g. density, electrical resistivity, magnetism etc.) of the earth's crust. The use of geophysical methods in groundwater exploration becomes all the more important during emergency situations like drought when the shallow groundwater is exhausted or during floods when surface water is polluted. Geophysical methods employed from the surface can rapidly provide not only the information about the existence of groundwater but also provide an estimate of the depth of occurrence. Geophysical methods commonly employed in groundwater exploration include electrical resistivity, seismic refraction, gravity, magnetic, and well logging. Multichannel analysis of surface waves (MASW) and proton magnetic resonance (PMR) are new methods still being evaluated for groundwater investigations. During emergency situations efforts tend to be focussed on deep ground water with the help of the most common methods such as electrical resistivity.

It should be borne in mind that geophysical methods provide information about the geological structures/strata suitable for ground water. In locating groundwater, the success to failure ratio increases considerably when geophysical methods are employed. However, these methods yield no direct information about the ground water occurrence except for the PMR method, which is still under development.

Electrical resistivity method

This technique is the most commonly applied method among all the geophysical methods for groundwater exploration, because of the large variation of resistivity for different formations and different degrees of water saturation. Resistivity is defined as the resistance offered by a unit cube of material to the flow of current normal to a surface. If L is the length of the conductor, and A is its cross-sectional area, then the resistance R is defined as:

$$R = \rho L/A$$

where ρ is the constant of proportionality and is called as resistivity. In the MKS system the unit of resistivity is ohm-metre (Ωm). The reciprocal of resistivity is called conductivity, denoted by σ, with the unit mho/metre.

In general resistivity measurements are carried out using the Wenner or Schlumberger arrangement of electrodes driven into the soil. In the case of an inhomogeneous medium the resistivity measured is called as the apparent resistivity. The apparent resistivity of a geologic formation is equal to the true resistivity of a fictitious homogeneous and isotropic medium. The resistivity of rock formations varies over a wide range; depending on the material, density, porosity, pore size and shape, water content and quality, and temperature. There are no fixed limits for resistivities of various rocks; igneous and metamorphic rocks yield values in the range 10^2 to 10^8 ohm-m; sedimentary and unconsolidated rocks, 1 to 10^4 ohm-m. The apparent resistivity when plotted against electrode separation provides information about a layer of low resistance which needs to be interpreted in terms of the depth of occurrence of groundwater in the aquifer.

Deep resistivity measurement is a well-established tool for delineating deeper aquifers in sedimentary terrains, identified by zones of low resistivity. Based on deep resistivity data of the drought prone Barmer District, Rajasthan (India), drilling at six sites was successful with yields ranging from 2,000 to 10,000 gallons per hour of potable water (Singh et al., 1990).

Electrical imaging. The improvement of resistivity methods using multielectrode arrays has led to an important development of electrical imaging for subsurface surveys (Griffiths and Turnbull, 1985; Griffiths et al., 1990; Barker, 1992; Griffiths and Barker, 1993). Such surveys are usually carried out using a large number of electrodes, 24 or more, connected to a multi-core cable. Apparent resistivity measurements are recorded sequentially sweeping any quadruple (current and potential electrodes) within the multi-electrode array. Two-dimensional multi electrode resistivity (MER2D) data can be interpreted with the help of RES2D inversion software and finally a true resistivity cross-section can be obtained. As a result, high-definition pseudo sections with dense sampling of apparent resistivity variation up to a depth of 100 m are obtained in a short time. It allows the detailed interpretation of 2D resistivity distribution in the ground (Loke and Barker, 1996). Fig. 5.5.1 shows the set-up of the multielectrode resistivity technique in the field.

Although resistivity methods are the most popular methods for ground water exploration, they have certain limitations. In the resistivity sounding method the vertical resolution is limited, it decreases with depth, and requires very high currents for investigating greater depths. Also the

Figure 5.5.1 Field arrangement of a multielectrode system for 2D resistivity imaging

increased salinity of ground water itself results in the decrease of rock resistivity whilst the degree of saturation has a profound effect on resistivity.

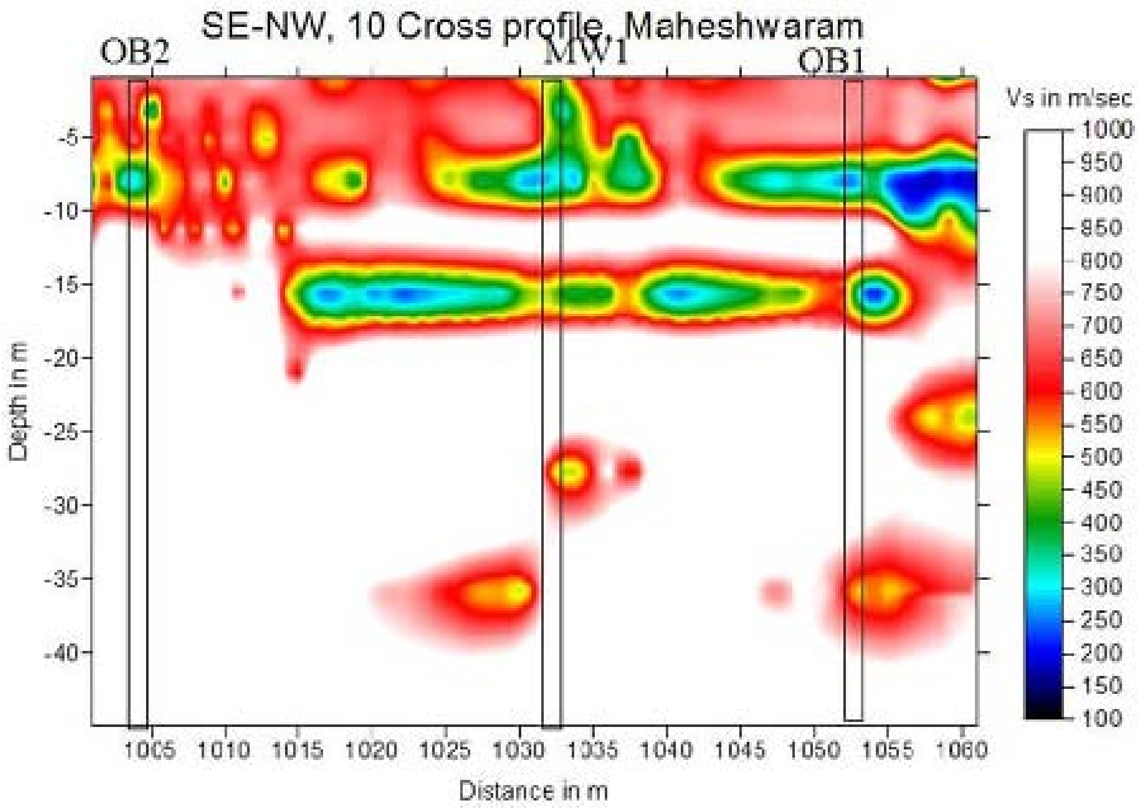
Seismic method

Seismic refraction methods are very useful and accurate for shallow investigations in hard rock areas. This technique is based on the velocity contrast of the acoustic waves between the water bearing zone and the adjacent strata. In this method, sound waves are produced either mechanically or by explosion. Sensors called geophones are placed at regular intervals in line with the shot point, and receive the primary waves after being refracted from layer boundaries. The time of arrival of these waves at different distances from the source produces a distance versus travel time curve, which can be quantitatively interpreted in terms of layers of various velocities, in turn yielding the disposition of water bearing layers. Seismic methods find their application in locating groundwater, determining depth to bed rock or impermeable layer and configuration, locating a buried stream channel and locating faults that could act as ground water barriers.

Multichannel Analysis of Surface Waves (MASW)

MASW (seismic method) has been widely used in geo-technical investigations, but so far no attempt has been made to map the sub-surface, which would indicate low velocity zones of high permeability that can be exploited for groundwater. The exploratory experiments using MASW in a hard rock watershed in Andhra Pradesh (India), revealed the potential of using seismic wave velocity in delineating fracture zones. The seismic velocity in deep fractured zones – potential sources of groundwater – is much lower than in compact solid rock. Fig. 5.5.2 shows the delineation of fracture zones by the MASW method.

Figure 5.5.2 The MASW method applied to the delineation of fracture zones. The green and yellow colours correspond to low velocity layers (weathered and fractured zone), white indicates a high velocity layer (massive granite). Drilling confirmed the presence of fracture zones at MW-1 and OB-1 boreholes and a shallow weathered and compact hard rock zone in OB-2 borehole



Multichannel analysis of surface waves (MASW) has been widely used in geo-technical investigations, but so far no attempt has been made to map the sub-surface, which would indicate the location of zones/fractures of high permeability (low velocity zones) that can be exploited for groundwater. The exploratory experiments using this new geophysical tool at Maheshwaram watershed, one of the hard rock regions of Andhra Pradesh (India), revealed its potential in identifying deep fracture zones. Deep fractured zones have much lower seismic velocity than compact solid rock, and hence represent potential sources for groundwater. The exploratory experiments carried out in the hard rock watershed in Andhra Pradesh have shown the promise of this technique.

Gravity method

The gravity method, which essentially is confined to the study of geological structures, finds applications in the following hydrogeological studies: (a) depth to the basement and its relief, (b) deciphering large sedimentary basin structures having thick permeable zones (c) the location and delineation of ancient, buried river valleys, and permeable channels in alluvial formations.

The limitation of the gravity method is in the ambiguity in interpretation. The same gravity effect can be produced on the surface by an infinite number of combinations of density and volume of the causative body. This can be minimized only by suitably assuming the shape or the physical property of the causative body.

Using gravity prospecting, a buried river valley in Saskatchewan, Canada, was delineated (Hall and Hajnal, 1962). The gravity anomalies on the plotted map appeared as elongated highs and lows giving the appearance of a river system.

Magnetic method

Magnetic methods are based on the observation of anomalies in the magnetic field of the earth that are caused by the magnetic susceptibility of different rocks. As dolerite (diabase) dykes are a very common feature in hard rock terrain and important for groundwater flow, these methods are very useful in granitic areas where vertical or nearly vertical dykes are common and are also useful to delineate even buried dykes. Different types of instruments are available for magnetic surveys e.g. Schmidt type or by compensation as in the torsion magnetometer; induction types of instrument; Fluxgate magnetometer; proton precession magnetometer; optical absorption magnetometer; or the high sensitivity atomic resonance magnetometer.

The main advantage of the surface proton magnetic resonance (PMR) method, compared with other geophysical methods is that the surface measurement of the PMR signal from water molecules ensures that this method only responds to subsurface water. The initial idea of transforming the well-known proton magnetometer into a tool for water prospecting from the surface is ascribed to R.H. Varian (Varian, 1962). This idea was further developed and put into practice much later by a team of Russian scientists under the guidance of A.G. Semen. The basic principle of operation of magnetic resonance sounding or the aforementioned surface PMR method for groundwater investigation is similar to that of the proton magnetometer. They both are based on the magnetic resonance signal from a proton-containing liquid - for example, water or hydrocarbons. In the proton magnetometer, a sample of liquid is placed into the receiving coil and only the signal frequency is a matter of interest. In the PMR, a wire loop 100-m diameter is used as a transmitting/receiving antenna and the water in the subsurface behaves as the sample. The method was tested in sedimentary areas but still is under development for hard rock aquifers.

Spontaneous Polarization (SP) method

The SP method is based upon local electrical fields which arise in geological formations due to oxidation-reduction, diffusion-adsorption and filtration phenomena. The SP values increase in the direction of groundwater flow (Patangay et al., 1981). In rugged regions where the filtration potentials are quite large, negative anomalies are observed. In recharge areas and in places like valleys (discharge areas) positive potentials are observed (Oglivi, 1967).

The limitations in SP surveys are that the high noise levels from telluric currents, topography, electrode polarization, drift caused due to variation in temperature, soil chemistry and moisture content can mask the anomalies. With non-polarisable electrodes short duration measurements can minimize noise due to electrode polarization. The other important factor is that there is no depth control in the interpretation of SP measurements.

Induced polarization method

This method is based on the potentials observed in geological formations when direct current is sent into them. If the current is suddenly switched off the potential difference observed between the measuring electrodes does not vanish instantaneously but will gradually die down in the course of a few seconds or minutes. The field procedure is similar to the resistivity method. Primarily the IP method is used in prospecting for sulphide ores, graphite and coal. The IP method has some advantages in prospecting for water-saturated rocks containing fresh or mineralized water, water table determination, aquifer hydraulic conductivity estimation etc.

Well logging method

For the precise construction of wells and understanding of subsurface conditions for further drilling of bore wells to counter drought situations, geophysical well logging techniques can be used. In this technique, sensors are lowered into the boreholes directly to study some variation of physical, chemical and mechanical parameters with depth. This gives more accurate information than that of surface methods since the measuring probes are in direct contact with the beds being studied. The most important and useful logs are electrical logs (spontaneous potential, point resistance, resistivity) natural gamma and calliper logs.

Electrical logs are generally used qualitatively in water wells for inter borehole correlation, separation of strata type, bed thickness determination and separation of fresh and salt water strata. Nuclear gamma logs based on detection of radioactive minerals, locate useful marker beds and are suitable for differentiating between sand (aquifer) and clay beds (aquiclude). Neutron logs provide measurements of moisture contents above the water table and total porosity below the water table. Fluid column logs are primarily used for investigating the source and movement of water in the fluid column. Caliper logs are used to study the variation of diameter of the borehole due to the variable hardness of the penetrated beds and the location of fractures and fissures. They also aid in correcting other logs.

5.6 Remote sensing methods

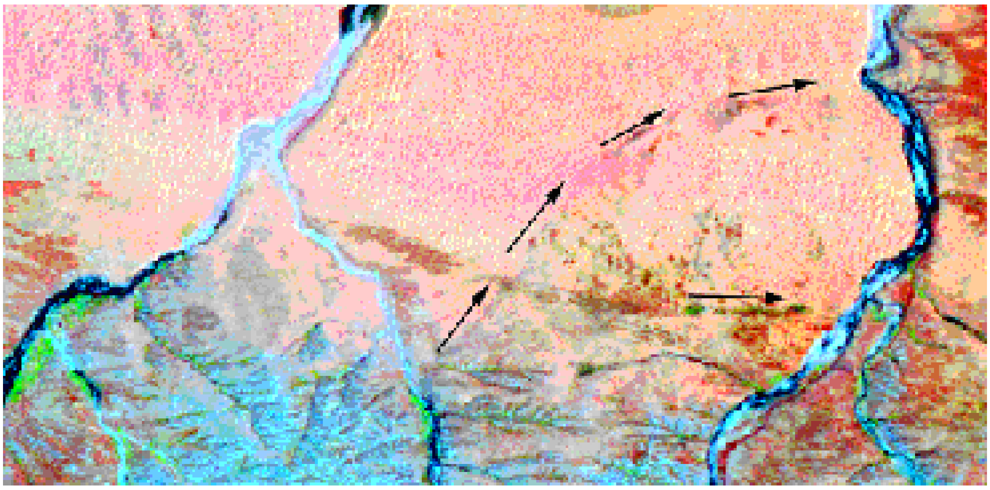
Remote sensing, with its advantages of providing spatial, spectral and temporal data and rapid coverage of large as well as inaccessible areas, has become a very effective tool in groundwater resources identification, assessment and monitoring. Satellite data provides quick and useful baseline information on the hydrological parameters controlling the occurrence and movement of groundwater (Kumar, Tomar, 2002). Visible and infrared imagery is used to map lithologies, soils, vegetation and structure. Radar is used to map structure and soil moisture. Remote sensing technologies have been applied successfully to groundwater resource investigations in various geological environments.

In **unconsolidated sediments,** it has been possible to locate groundwater seepage patterns, and buried river and stream channels. Remote sensing is able to locate palaeochannels based on the moisture content in the soils which cover, and also on vegetation patterns observed above, buried channels (Fig. 5.6.1). Many hydrogeological parameters that may reflect the groundwater regime can be interpreted, such as drainage patterns, soil types, soil moisture, fracture systems, geological structure, relief, and anomalous zones of vegetation. It is also possible to distinguish facies of alluvial fill, such as point bars, channels and flood plains. The airborne electro-magnetics (AEM) technique is suited to establish fault topography and is valuable in detecting, and locating accurately, saline and other palaeochannels (Ackland, Hunter, 2002). Zones of groundwater movement in alluvium-covered semi-arid areas can be detected through infrared imagery of soil moisture which is at lower temperature. Zones of groundwater recharge, run-off and discharge can be detected using composite visible and infrared imagery.

Desert regions usually have hosted many humid phases. Surface water was channeled by drainages, the patterns of some of which are now exposed, and others covered by aeolian sand. The penetrability of radar is helpful in directly identifying shallow groundwater reservoirs in buried stream channels and foot plains of mountains. Remote sensing mapping of these drainage patterns is essential to the evaluation of the groundwater potential of such regions. The **ERS** (Earth Resource Satellite) and **Radarsat** missions provide suitable radar images (Drury, Deller, 2002).

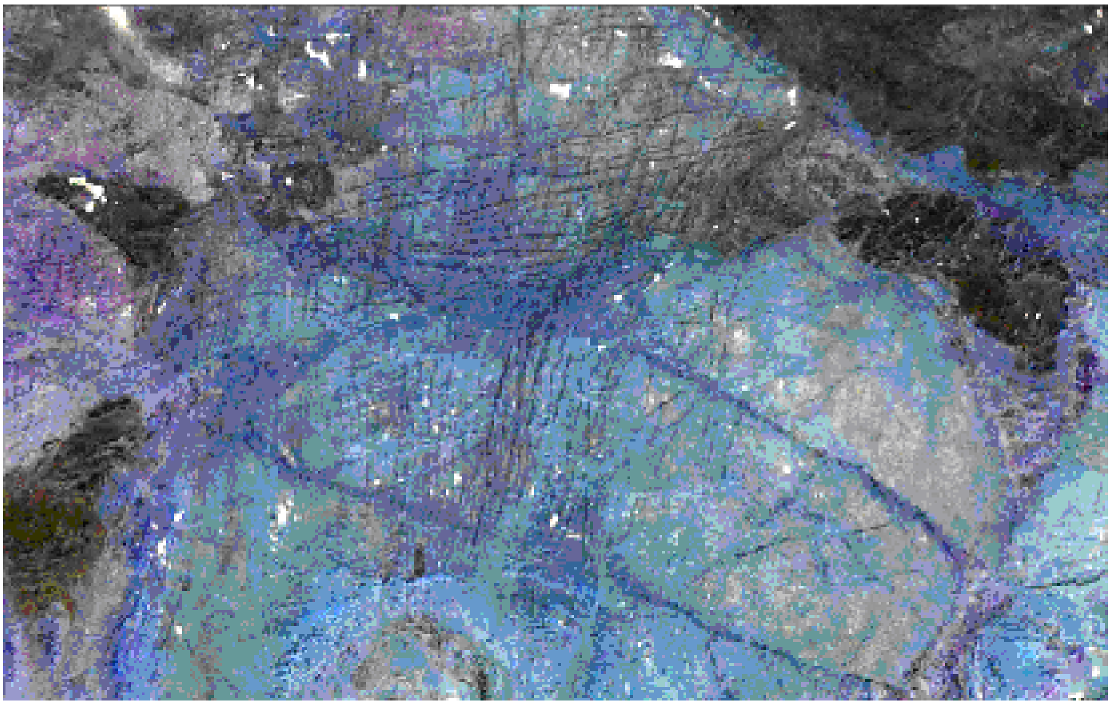
In **hard-rock environments,** digitized aerial photographs and satellite images have been used to

Figure 5.6.1 ***Landsat TM Band 641 RGB composite shows surface channels and palaeochannels in the north of the Erdos Plateau, China. The dark blue is surface water and the light blue shows underground streams. The arrows indicate the location of interpreted buried palaeochannels***



compile maps of lineaments and fracture zones (Fig. 5.6.2). They have been used to locate fracture zones and lineaments that may store and transmit groundwater in fracture reservoirs. The relationship between drainage lines and fracture patterns is important to evaluating the potential concentration of water in fracture zone aquifers (Saint-Jean and Singhroy, 2000). Geostatistical maps (such as for lineaments and lineament intersection densities) are easily extracted by processing remote sensing images (Elfouly, 2000).

Figure 5.6.2 ***Fracture patterns of igneous terrain are recognized in a TM 741 bands composite in the south of Tuha Basin, Xinjiang China. The dark blue/grey areas are rich in groundwater***



Suitable lithological types and the stratigraphic position for potential large groundwater reserves can be identified from multi-spectral remote sensing data. Vegetation is responsive to soil-lithology characteristics. Remote sensing technology is useful in highly vegetated areas because the vegetation gives clues from which to identify the underlying rock types, potential lineaments, faults and folds in the subsurface (Drury, Deller, 2002). Lineament and Karst target areas can be investigated subsequently in the field using geophysical techniques followed by exploratory drilling to assess the groundwater potential reserves.

Delineation of the intersections of faults and fractures is used as a tool for **deeper groundwater** detection by using remote sensing and ground penetrating radar techniques (Elfouly, 2000, Mahmood, 1996). Lineaments represent fundamental zones of weakness in the lithosphere, and offer high permeability pathways which may persist over long periods of geological time, especially in tensional fracture environments. The mapping of linear features associated with fractures (faults and joints) can be performed from multi-spectral images at almost any wavelength. This type of mapping is an important ground water exploration tool for metamorphic and igneous terrain, because the greatest amount of water will be found near fractures, which may constitute the only available porosity and permeability. Satisfactory results are obtained with the ground penetrating radar technique in detecting water which again can be confirmed in nearby local wells.

Remote sensing data is used to focus on promising areas for further exploration. It can help reduce costs by prioritizing areas to be surveyed based on social needs (eliminating the regions where there are no shortages of water, or mostly unpopulated) and on groundwater potential indicators. The priority area can be outlined by processing remote sensing images followed by detailed hydrogeological studies, geophysical prospecting and test drilling. Ideally, remote sensing can be adopted as the first step in exploration procedures. Earth scientists can then use the data to assess potential water resources and suggest the best sites for extraction, storage and distribution.

5.7 Establishing a conceptual model of a groundwater system

> An important stage in the development and management of a ground water system is the initial understanding of the behaviour of the system: setting up a conceptual model. The conceptual model must identify the crucial factors influencing the system (natural and anthropogenic); whether the observed behaviour appears to be predictable and whether mathematical approximations can be used to describe its behaviour (McMahon et al 2001). This is equally important for current water supply systems and for those to be reserved for emergencies only.

Confidence in any conceptual model increases via testing. Hence a conceptual model must be more than simply a qualitative description of our understanding of the system; it should cover the uncertainties in defining the system behaviour and provide the basis for determining further data requirements and the type of mathematical model that is appropriate. Preliminary testing should be carried out by using lumped water balance and mass balance calculations, and simple analytical relationships. Here it is important to realise that emergency supplies will usually be drawn from deeper-seated ground water bodies, where attempts at such calculations often may be complicated by the lack of suitable data.

Developing a conceptual model

Ideally, the development of the conceptual model must be an iterative process, involving continual updating as new data become available. This will usually not be possible for an emergency supply, as it is not continuously exploited, or monitored. Extra care and planning are therefore needed in this step.

It is important to avoid both *over-simplification,* which results in a model which is incapable of simulating observed groundwater conditions adequately, and *under-simplification,* which results in a model which is too complex to be a useful tool for a relatively simple problem.

Data collection

Geological and hydrogeological information can be gathered from maps or existing borehole logs through e.g. the local geological survey department; water authorities; NGO's; aid agencies, and GIS data. More detailed information may require further field investigation to determine the geometry of the different lithologies and the stratigraphy of the aquifer system by targeted drilling. This will help to establish their lateral extent, outcrop and geological boundaries and structures, e.g. faults and dykes. The location, yield and condition of all existing dug wells, boreholes and springs should be established in a hydro-census. A monitoring programme for e.g. groundwater level, hydrochemistry, environmental isotope measurements and observations should be instituted. For an emergency supply, this would be from standby boreholes. Suitable existing and newly-drilled boreholes should be pump tested to obtain preliminary groundwater transmissivity and storage values.

Initial simulation

The available geological and geohydrological information may be used to set up a preliminary test model. User-friendly software is commercially available for depicting the aquifer and to perform rough simulations of aquifer behaviour. Such software is often suited to trace and predict the path of potential contaminants from known or suspected pollution sources.

Isotope hydrology

Environmental isotope hydrology (see section 5.4) is an important tool with which to assess the validity of a conceptual ground water model. Especially for deep ground water structures, which are likely to be targeted for emergency supply, isotope data can suggest a model where little geohydrological information exists and provide parameters useful in simulation.

If there is broad agreement between the outcomes of the conceptual model and features such as flow, hydraulic continuity, residence time and recharge derived from isotope data, confidence in the conceptual model is strengthened. Should the comparison reveal major contradictions, the premises underlying the conceptual model need to be further investigated.

Sustainability

Ground water modelling is usually aimed at establishing long-term sustainable exploitation. The criteria for the development of a conceptual model for emergency supply do not differ radically from those of a long-term, managed supply. However, an emergency supply would typically not be a regularly and significantly exploited water source. The conceptual model should address the ability of the aquifer to deliver the required yield for a period determined by the type of emergency that is likely to occur – even be over-exploited – and provide an assessment of the rate of recovery.

Vulnerability

An emergency supply has to be able to produce water of an expected quality when required. A ground water conceptual model should encompass aquifer vulnerability - factors that will degrade the quality of ground water. These could be the drawing-in of highly-mineralised water from adjacent, overlying or underlying aquifers during heavy exploitation. A guiding parameter for anthropogenic pollution is rain recharge, as surface pollutant ingress often mimics natural recharge. Vulnerability could also refer to the degradation of the aquifer due to collapse or compaction under heavy exploitation of the aquifer's porous skeleton, which can often be irreversible.

5.8 Mathematical modelling

Using groundwater resources in emergency situations requires detailed knowledge on groundwater availability, both in the short and medium term, as well as a control of mass exchanges between adjacent (mostly overlying) aquifers; this assessment requires

- Mathematical modelling to study scenario situations,
- Developing appropriate management and protection strategies and
- Developing an early warning system to better control hydraulic changes caused by groundwater abstraction in emergency situations.

Basically all mathematical models start with a conceptual hydrological model (see section 5.7), defining geometric characteristics, the interaction between reservoirs, groundwater recharge/discharge mechanisms and intrinsic hydraulic parameters.

Since the quality of the model output depends on a number of factors – the conceptual model, input data, the degree of abstraction from the conceptual to the mathematical model and the chosen algorithm – uncertainty considerations are necessary to better assess the reliability of the model output. To do so, the means and the variation range of data and Monte Carlo approaches apply to better assess secure and probabilistic ranges of results.

All mathematical models dealing with water *quantity* are based on a bulk or multi node flux and energy balance according to the Laplace stream and potential functions

Stream function $$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \cdot \text{or} \cdot S_0 \frac{\partial H}{\partial t}$$ *(steady state or transient)*

Potential function $$k_x \frac{\partial^2 H}{\partial x^2} + k_y \frac{\partial^2 H}{\partial y^2} + k_z \frac{\partial^2 H}{\partial z^2} = 0 \cdot \text{ or} \cdot S_0 \frac{\partial H}{\partial t}$$ *(steady state or transient)*

where H = hydraulic head, k = hydraulic conductivity, S_0 = specific storage coefficient.

In an upgrade, the mathematical model is combined with hydrodynamic dispersion, physical, chemical and microbial reactions of specific solutes and the respective kinetics to simulate groundwater *quality.*

$$D_L \frac{\partial^2 C}{\partial x^2} + D_{Ty} \frac{\partial^2 C}{\partial y^2} + D_{Tz} \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial x} \pm R \pm a \frac{\partial S}{\partial t} \pm b \frac{\partial Re}{\partial t} = \frac{\partial C}{\partial t}$$

where D = dispersion coefficient, C = concentration, R = retardation, S = sink or source term, Re = reactivity.

Mathematical models are used

- **For sensitivity analysis as a guide to the frequency and precision of data compilation in field investigations,**
- **To steer field investigations in the development of a reliable conceptual hydrologic model,**
- **As a check on how homogeneous and consistent the data set was.**
- **For the development of water management and protection strategies, following model validation and calibration**
- **To estimate also the future behaviour of the investigated system under changed conditions and**
- **As an early warning tool when the model has been optimally calibrated.**

Water quantity models

According to the scale and the available data set, three general types of mathematical models apply:

- Lump sum parameter models (Maloszewski and Zuber, 1996),
- Compartment models and
- Discretizing models (Kinzelbach, 1986).

Lump sum parameter models have fewest parameters, discretizing models the most. For each of the models a variety of sub-models exists according to special tasks and the applied mathematical algorithm.

The development of mathematical models of water quantity is quite advanced; however, data sets often do not adequately satisfy model requirements; therefore mathematical modelling is often linked with a Monte Carlo approach the better to differentiate between most probable and random results. Because of the above-mentioned problem mathematical modelling is often applied in an inverse instead of a direct mode, in order to obtain reliable data sets.

Water quality models

Quantitative models have been extended to model groundwater quality by coupling the solution for the Laplace equation with

- Hydrodynamic dispersion (Fried, 1975),
- Partition coefficients with and without kinetics (Merkel and Planer-Friedrich, 2002),
- Chemical reaction parameters with and without kinetics (Merkel And Planer-Friedrich, 2002),
- Microbial reactions and
- The development of the microbial habitat (Naumann et al., 2004).

Taking into account the uncertainties of results from field and laboratory studies, it is apparent that in practice the lower the number of model parameters the better is the applicability of model results. For more fundamental applications, however, multi-parameter models can be an outstanding tool to sharpen the direction of and to accelerate investigations.

5.9 Geographical Information System

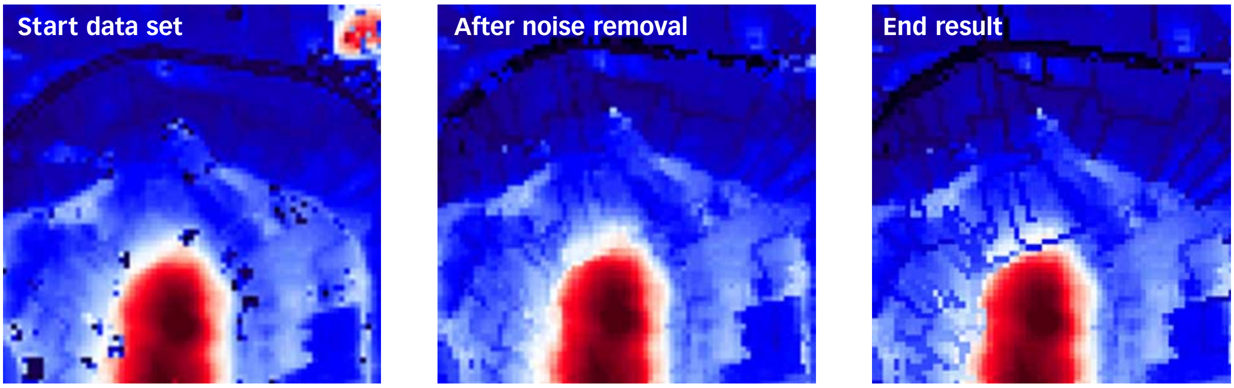
Geographical Information Systems (GIS) have become indispensable in processing and analyzing hydrogeological data. These days the execution of hydrogeological investigations without the use of a GIS has become almost unthinkable. This applies equally to investigations into groundwater resources for emergency situations in which GIS can play an important role.

A GIS usually incorporates or is connected to a database containing the basic data the features of which can be displayed on maps or which can be processed to derive the required hydrogeological information. An example is the combination of borehole data with geophysical data to construct a map indicating the depth or thickness of an aquifer targeted for use in emergency situations. The data is managed using specific database functions or using data management functions of the GIS. Changes to the data such as new boreholes are directly available in the GIS.

Another strong feature of a GIS is the possibility to combine maps from different origins to derive a new thematical map. An example is the combination of maps on land use, pollution sources, soil, geology, and groundwater depth to derive a groundwater vulnerability map. Such map overlays can be done using polygon or raster data types.

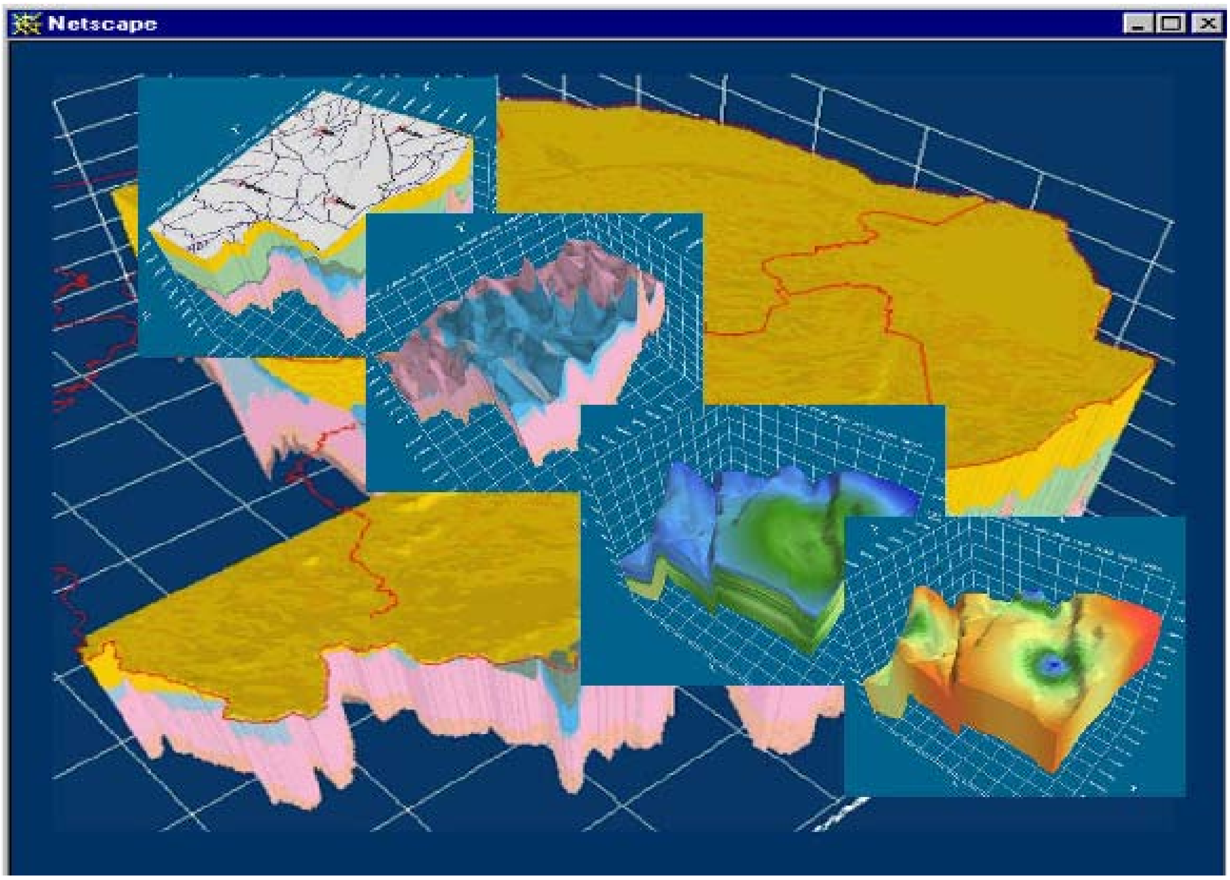
One of the strengths of GIS is the capability to process huge amounts of geo-referenced data (Fig. 5.9.1) – data from thousands of point locations can easily be processed. Statistical methods, like Kriging, are a feature of most GIS and can be applied to interpolate hydrogeological parameters, such as the surface elevation or aquifer thickness. In case of limited numbers of basic data, extrapolation of hydrogeological parameters is also possible.

Figure 5.9.1 Example of a surface raster elevation data set derived from high density point information acquired using radar technology and processed using GIS and dedicated statistical routines to remove noise (artificial objects like buildings) and to add surface water location and water levels (using surface water lines data set)



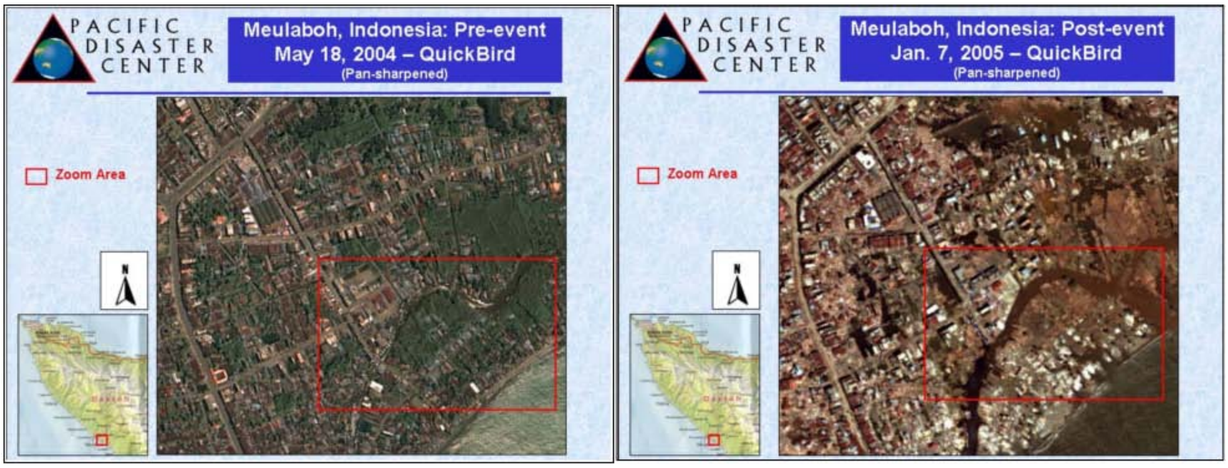
A hydrogeological information system based on a GIS with database, today is an open system tailor-made for the storage and processing of data (Fig. 5.9.2). Routines for e.g. data exchange, data verification or data presentation in graphs or tables are added to the information system using

Figure 5.9.2 Example of a 3D-viewer using GIS derived datasets, showing topography, sub-surface layers and reservoir properties



standard software. This has improved the accessibility to and exchangeability of hydrogeological data tremendously.
Nowadays the use of GIS is not restricted to the geographical information stored on local servers. The GIS which normally runs on an office PC can be connected to a data server anywhere in the world. This gives access to the most recent maps and (remote sensing) images which can be used to display up-to-date field conditions. Following the tsunami in December 2004, for example, maps were available within days indicating damaged areas derived from an analysis of altitude data sets and satellite images (Fig. 5.9.3).

Figure. 5.9.3 Example of satellite images showing effect of tsunami (courtesy of Pacific Disaster Centre)

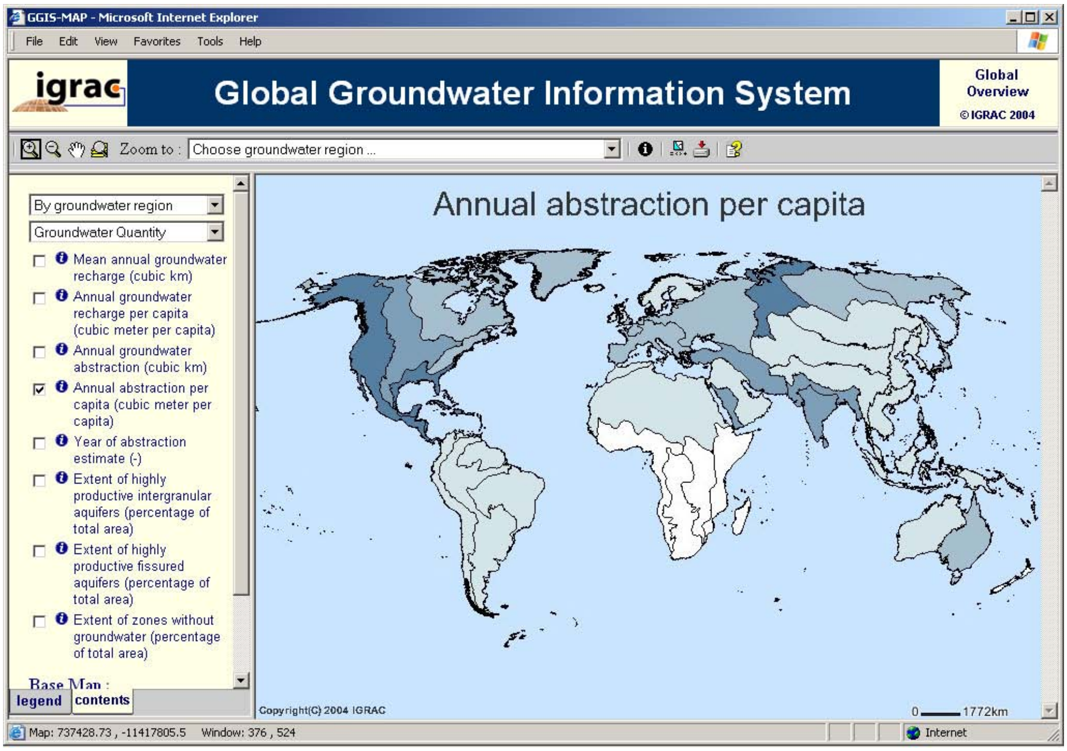


The development of GIS-technology allows users to access the hydrogeological data at different levels. Users who only want to view and combine data, like managers, use the GIS through a browser. They may have only simple functionalities at their disposal, and do not need a GIS-license to access the information from any PC. This technology is applied for the dissemination of data from national databases or of maps for international relief operations (Fig. 5.9.4).
Users who need more advanced tools use the GIS and database as their main source of basic information to process data, e.g. for the pre- and post-processing of groundwater model data. Tools for data handling can be added easily to the GIS as plug-ins, using standard software.

A multitude of GIS applications is imaginable. GIS forms an important part of the tools at the disposal of the modern hydrogeologist and other geoscientists and therefore will be part of any investigation into the availability of groundwater resources in emergency situations.

GIS has particular advantages in the handling of specific disaster issues. It can offer support for the management of various flood disaster scenarios and related flood models; for mapping and enhanced understanding of the impact of earthquakes on groundwater resources; the mapping of land slides and their impact on land use and water supplies and for a variety of other studies concerning groundwater resources used for emergency situations.

Figure. 5.9.4 Example of Internet map viewer (courtesy of IGRAC)



6. Requirements for institutional and technical capacities

The establishment of disaster mitigation and water management plans is a complex process, the implementation of which strongly depends on all the dimensions of a country's institutional and technical capacity building, and whether such capacities are applied in a coherent manner. The importance of national and local institutional and technical capacity building to effectively address disaster prevention, preparedness, emergency response, recovery and mitigation. was discussed at the World Conference on Disaster Reduction (Kobe, Hyogo, Japan, 2005). It is emphasized in the common statement of the special session of the conference focused on the Indian Ocean Disaster: risk reduction for a safer future.

6.1 Institutional capacities building

Institutional capacity building refers to governmental authorities, the legal framework, control mechanisms, the availability of human resources and public participation, information and education. An institutional and legislative framework is a key element in the building of institutional capacities for disaster prevention and mitigation.

Governmental authorities at all levels are responsible for the coordination and implementation of water risk management and disaster mitigation plans, for preparedness strategy and timely warning – as well as for communication with all sectors of society in particular policy and decision makers, civil society, water stakeholders, the scientific community and the general public. Many countries have established multi-sectoral national disaster risk reduction mechanisms and special aid teams with representatives of governmental authorities, firefighting, the army and civil protection forces to enhance governance for disaster risk reduction and to manage post disaster rescue activities including the distribution of drinking water during and after disaster events.

The establishment of a legal framework and regulatory status to support disaster risk reduction is essential for the implementation of effective environmental and water protection policy. The preventive protection of water resources through the establishment of water supply protection zones, early warning monitoring systems as well as the public right to information are part of the legal framework in many countries. The French Environment Law of 1987, for example, established the right of citizens to receive information on hazards and disasters affecting or likely to affect them, and on existing means and measures to reduce vulnerability to these hazards or to reduce disaster impacts. As far as back as 1792 BC Hummurapi, King of Babylon, ruled that the farmers in the valley of Tigris and Euphrates rivers are obliged to maintain their irrigation system in good repair to protect the land against flooding (Hassan, 2004).

Control mechanisms established by environmental and water governmental authorities are focussed primarily on the protection of water resources against man-made hazards. Regular control over industrial and agricultural facilities producing liquid and solid wastes, waste water treatment plants and waste disposal installations is an important element in the water protection policy of many countries, based on the 'polluter pays' principle and 'prevent pollution at source' approach. Monitoring and warning systems feed data on natural and man-induced hazards to the effective governmental control security mechanisms. The maintenance of stream networks, river regulation works, and control of land use in flood-prone areas and groundwater recharge areas are important structural measures in reducing the vulnerability of populations to natural disasters and have to be controlled by relevant state or municipal authorities.

Human resources, properly qualified, experienced, trained and motivated, are a crucial non-structural component in all phases of coping with the impact of disasters on water resources. In the anticipatory and warning phase engineering services prevail e.g. hydrologists, hydrogeologists, water managers, land use planners, legal experts, policy makers. During the impact phase the main role is played by special aid teams, civil protection forces and disaster experts, physicians and other medical personnel, psychologists, water quality advisers and NGO volunteers. In the rehabilitation phase building and structural technicians, land use planners, water managers, hydro(geo)logists and policy makers are the key specialists in the implementation of reconstruction work, the restoration of damaged drinking water supplies and water and sanitary distribution networks. Many less developed countries lack the human resources to implement prevention and reconstruction programmes, and to apply relevant measures following disastrous events. Therefore, as proposed in the Hyogo Declaration, a very urgent task in the building the resilience of developing countries to disaster is to establish training and learning programmes in disaster risk reduction targeted on specific sectors such as planners, emergency managers and governmental authorities.

Active public participation, information and education in the prevention and mitigation of natural and man induced impacts are further extremely important non-structural measures in governmental disaster mitigation policy. The role of communities and local authorities in actions and plans for disaster preparedness measures and rapid and effective disaster response is critical. Democratic countries place public participation in environmental impact and disaster mitigation procedures, land use planning, risk water management, public education and other attributes of public communication policy, on a legal basis. However, in some countries there is a communications gap between managers and decision makers and the public. Developing countries may face low literacy levels and have to introduce specific measures to inform, educate, motivate and involve the local population in all aspects of reduction of disaster risk and disaster impacts. Another important task in disaster-prone developed countries is to develop knowledge: training programmes and information systems focused on disaster prevention and mitigation. According to the World Health Organization (WHO) disaster related fundamental information to the local community should include: knowledge of risk (information on the causes and dynamics of disasters), forecast and warning information, disaster mitigation (information on preparedness measures e.g. protection of drinking water supplies), disaster impact (safety instructions to alleviate injuries and lives) and post-disaster instructions. Several UNESCO publications produced within the International Hydrological Programme are focused on the role of the public in policy and strategy of disaster mitigation and water resources protection (Affeltranger, 2001, Dooge, 2004, and others).

6.2 Building technical and scientific capacity

Technical and scientific capacity building refers particularly to groundwater systems analysis, the identification of potential and existing pollution sources and natural hazards, establishment and operation of early warning monitoring systems, to interdisciplinary research and knowledge transfer.

Groundwater systems analysis is an important part of the technical capacity building process. The study of groundwater systems has to refer to both recent and earlier hydrological cycles. Setting up a conceptual model of the studied area (see chapter 5.7) is based on the identification and investigation of groundwater for emergency situations and on the vulnerability assessment and risk management of groundwater resources in disaster-prone regions. The scientific and technical inputs required for groundwater system analysis are described in detail in chapter 5.

Identifying and inventorising natural disasters and groundwater pollution sources. Compiling an inventory of and evaluating historical data about the nature, extent, frequency and impact of natural disasters in regions prone to natural events are important components of disaster prevention and mitigation policy. Investigation of existing groundwater pollution sources (origin and extent) and assessment and mapping of groundwater intrinsic vulnerability to potential pollution problems both support groundwater protection policy and management. However, attention is mostly focused on existing pollution sources; less so on potential pollution problems. Identification, mapping and monitoring of areas prone to flood, drought, land slides, earthquakes and volcanic activity are important activities supporting the formulation and implementation of disaster prevention and mitigation policy and management at all governmental levels..

Establishment and operation of early warning monitoring systems focused on observation of natural and man induced impacts support disaster prevention policy and disaster mitigation activities. The frequency and magnitude of disastrous events is increasing worldwide. Therefore, the operation of integrated early warning monitoring systems to collect and disseminate data required for the timeous identification and better understanding of potential disaster risk and impact on the population and environment is strongly recommended. However, the operation of such monitoring systems is scare at present. Relatively well developed are surface water monitoring networks established in many national and international river basins and early warning monitoring systems in areas affected by earthquakes and volcanic activities. Groundwater monitoring networks are less well developed. Local monitoring systems around pollution sources to observe pollution plume movement and the effectiveness of remedial activities have been established mainly in industrialized countries. At the global scale, early warning environmental monitoring systems are underdeveloped and coordination is often lacking.

The Dublin Conference on Water and Environment (1992) pointed out the responsibility of governments to promote awareness and provide conditions for the establishment and operation of systems for early warning monitoring and disaster preparedness to prevent or reduce impacts on human life and ecological systems. The outcomes from the second UN International Conference on Early Warning held in Bonn, Germany (2003) stressed coordination and cooperation among all relevant sectors integrated in the early warning monitoring systems and programmes. Establishment of early warning monitoring systems with a view to ensuring that rapid and coordinated action is taken in cases of alert/emergency is introduced among the priorities for action 2005–2015 of the World Conference on Disaster Reduction (2005). The conference supported the agreement of the Association of South-East Asian Nations made in the meeting in Jakarta (2005) to establish a regional early warning system such as a Regional Tsunami Early Warning Centre for the Indian Ocean and the South-East Asia region.

Interdisciplinary research and the transfer of knowledge and expertise are needed for the innovation, improvement and development of methods of early warning monitoring and methods of forecasting and evaluating the risk of natural disasters. Both permit better understanding of the processes related to the occurrence and prediction of disasters and make water resources risk management more effective. The establishment and operation of global early warning environmental monitoring networks and disaster preparedness systems and data exchange and dissemination on the global hydrological cycle are important scientific tools in the policy and strategy for disaster forecasting and mitigation. The 'Declaration on Science and the Use of Scientific Knowledge' produced by UNESCO/ICSU World Conference on Science (1999) emphasized the importance of interdisciplinary research, the application of which may yield significant returns towards economic growth and sustainable human development, including poverty alleviation and disaster mitigation.

Several other UN Organizations support scientific activities related to emergency water resources. The World Conference on Disaster Reduction (2005) and especially the agreed expected outcomes and strategic goals, pointed out the transfer of knowledge, technology and expertise to enhance capacity building for disaster risk reduction and the sharing of research findings, lessons learned and best practices.

7. Prevention and mitigation of natural and man induced disasters

Dooge (2004) formulated five phases of disaster – anticipatory, warning, impact, relief and rehabilitation – in areas repeatedly affected by sudden cataclysmic water (floods) and geological (earthquakes, volcanic activity) disasters or by the effect of both like tsunami, land slides and mud flows. Episodes of hydrological drought, el Niño phenomena, sudden rain and wind storm surges are also classified as repeatedly occurring disaster events. Climatological drought could constitute a long term disaster, leading to hydrological drought, or even to water war or regional armed conflicts. These could last several years e.g. the Sahel drought events. Both types of disasters have serious social, health and economic impacts on the local population. The following activities related to public and domestic drinking water supplies have to be implemented within the specific phases of disaster prevention and mitigation.

7.1 The anticipatory phase

The most important activities of the anticipatory phase in drinking water services are the identification and assessment of the potential risk to and vulnerability of existing public and domestic water supply systems – both surface and groundwater – and the identification, delineation and evaluation of groundwater resources resistant to natural hazards. These steps require interdisciplinary cooperation between hydrologists, hydrogeologists, water managers, land use planners, legal experts, emergency specialists, decision and policy makers and in particular the participation of local governmental authorities and communities. Land use and especially urban and rural planning are important preventive protective issues in emergency situations. In developing countries people often live in unplanned urban settlements below a flood linear or on foot-hills of volcanic cones. Poor, unsustainable land use practices (e.g. deforestation) have led to soil erosion and microclimate deterioration in many regions worldwide and increased their vulnerability to droughts, floods and land slides. Maps depicting geology, hydrogeology, water vulnerability, water management and land use, combined with disaster risk and disaster vulnerability maps are important tools for the identification and location of groundwater resources resistant to natural hazards and human impacts. However, such maps of suitable scale and content are often not available. Therefore, geological, hydrogeological, isotope hydrological and other relevant activities (see chapter 5) have to be projected and applied, as well as an assessment of implementation costs. Such precautionary policies do not yet exist in many hazard-prone regions. Neither do risk water management plans nor the identification of naturally well protected groundwater resources.

7.2 The warning phase

Strongly related to the activities described above is the establishment and operation of early warning monitoring systems for the different hazards posed by climate, hydrology or geology. Geological monitoring systems are developed in many areas affected by earthquakes and volcanic activity and help to forecast and mitigate the impact of hazardous events, reduce human social and economic vulnerability and give early warning to local populations for timely evacuation. Often absent, however, are integrated hydro-climatological monitoring systems and flood and drought early warning systems. Groundwater monitoring systems geared to observing regimes of low vulnerability in particular are at present scarce, as is data on deep groundwater aquifers, especially in developing countries. The formulation of suitable indicators of disaster risk and vulnerability and relevant groundwater indicators and operation of early warning monitoring systems are both important elements of the warning phase focused on disaster preventive protection and mitigation policy.

7.3 The impact and relief phase

The impact and relief phase is mainly focused on rescue efforts during and after disastrous events and on immediate external help. Among the first priorities is the distribution of drinking water because existing water supply systems are usually out of operation and surface water and shallow groundwater aquifers are polluted. Where safe and physically protected emergency water resources have already been identified, developed and set aside rescue activities for the immediate emergency, related to the distribution of drinking water, will be rapid and effective. Such a conceptual approach has been implemented in only a few countries. Affected populations are mostly supplied by importing bottled water or by water from tankers. These are at best temporary measures, are expensive, and emphasize the population´s dependency on outside help. For short term survival, 30 l water per day/person is needed: 10 l for drinking and 20 l for cooking (WHO, 2005). The rehabilitation and cleaning of damaged wells is often a long term process. Water may be polluted by chemicals or effluents and well cleaning and water pollution remediation are costly and technologically demanding. Where aquifers resistant to natural disasters are already known and drilling facilities and emergency financial funds available new water wells can be drilled rapidly to develop ground water resources for emergency situation. However, in the absence of such knowledge and preparedness rescue activities can be severely delayed.

7.4 The rehabilitation phase

The rehabilitation phase of drinking water distribution is usually long term. Reconstruction of water supply systems and water distribution infrastructure may take weeks or months, remediation of polluted water could take years. One effective and often rapid solution mentioned above is intensive pumping of existing deep wells tapping water from deep aquifers resistant to natural and human impacts or to develop deeper aquifers of low vulnerability in areas where their occurrence and properties are known. That is not usually the case in developing countries; not even in many developed countries. Another important activity is a post-evaluation of all phases of the rescue process, the preparation of plans for rehabilitation, including water management plans, and assessment of emergency costs. Developing a more effective policy to reduce disaster risks and social and economic vulnerability of the population, based on an evaluation of past disasters, remains a significant challenge – as was pointed out in the Hyogo framework for action 2005–2015: Building the Resilience of Nations and Communities to Disasters. Here, involving local governments and communities in the disaster prevention, reduction and rehabilitation process and planning of future drinking water protection policy and formulation of risk water management plans is of extreme importance in view of reducing human suffering in future disasters.

7.5 Disaster risk reduction plans and water risk management plans

Disaster risk water management plans are part of the complex strategy for establishing disaster risk reduction plans, which principles include the obligations of governmental authorities, local communities, social groups and individuals in the effort to mitigate disaster risk. The assessment of disaster risk, evaluation of physical, social and economic vulnerability of a population and disaster preparedness, are important elements of disaster prevention and mitigation plans and policy. The principles of disaster management policy are described among others by Dooge (2004), Plate (2003), Affeltranger (2001), Young at al. (1994), and Blaikie at al. (1994) and specified in the documents of various UN Organizations. The responsibility of governments to protect their citizens from natural disasters with special regard to disaster risk management of water resources has been highlighted in the Rio UN Conference on Environment and Development (1992), the Dublin Conference on Water and the Environment (1992), Agenda 21 and in other UN documents and General Assembly Resolutions. The Yokohama Strategy for a Safer World: Guidelines for natural disaster prevention, preparedness and mitigation and the Plan of Action adopted at the World Conference on Natural Disaster Reduction (Yokohama, 1994) are both important steps in the effort to establish practices and policy for disaster prevention and disaster risk mitigation.

During the International Decade for Natural Disaster Reduction (1990–2000) many UN activities were implemented to increase community protection against disastrous events and public active participation in disaster prevention and mitigation processes. Among its key objectives the Millennium Declaration (2000) proposed the intensification of international cooperation to reduce the number and effects of natural and man-made disasters. The World Summit on Sustainable Development held in Johannesburg (2002) in its Plan of Implementation pointed out the following actions: 'An integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the 21st century'. The World Conference on Disaster Reduction held in Kobe (Hyogo Prefecture, Japan) in January 2005, followed very soon after the devastating tsunami disaster in the South-East Asian region (December 2004). In the Conference Declaration (Hyogo Declaration) the vital role of the UN system in disaster reduction was reaffirmed. The strategic goals were formulated in the Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters will be translated into concrete actions at all levels in order to reduce disaster risks and vulnerabilities, inclusive water resources. Reduction of the vulnerability to natural disasters of developing countries on small islands, as part of the Programme of Action for the Sustainable Development of Small Islands Developing States, was discussed on the international meeting held in Mauritius (2005).

Several projects implemented within the sixth phase (2002–2007) of the International Hydrological Programme (IHP) coordinated by UNESCO are focused on extreme events in land and water resources management. Particularly under Theme 2: Integrated Watershed and Aquifer Dynamics several projects are implemented with the objective to 1) develop a framework for reducing ecological and socio-economic vulnerability to hydrological events and 2) analyze extreme events by integrating various sources of data (historical, instrumental, satellite) to secure an improved understanding over large scales in time and space. The project 'Groundwater for Emergency Situations' is one of the key IHP projects supporting the International Decade for Natural Disaster Reduction and the Johannesburg Plan of Implementation of the World Summit on Sustainable Development.

8. Concluding remarks and the future of GWES

The GWES Framework Document stresses the role of groundwater for emergency situations following climatic, hydrologic and geological disasters, which affect hundreds of millions of people annually. Particularly in developing countries the physical, social and economic vulnerability of populations to natural disasters is enormous. The Yokohama Strategy and Plan of Action for a Safer World proposed in 1994 the establishment of practices for more effective disaster risk reduction. This was again emphasized in the Hyogo Framework for Action 2005–2015 adopted at the World Conference on Disaster Reduction held in Japan 2005. Likewise, the development of a framework for reducing ecological and socio-economic vulnerability to natural disasters is part of the activities and specific projects of the sixth phase of the International Hydrological Programme (IHP).

Secure drinking water for endangered populations is one of the highest priorities during and immediately after disasters. This lies at the core of the UNESCO/IHP project Groundwater for Emergency Situations, its main objective being the analysis of methods for the identification, investigation, assessment and risk management of safe groundwater resources. Such methods are summarised in this framework document as well as the role of institutional and technical capacity building in risk reduction and mitigation of calamities with respect to drinking water sources. This is but the first step of the project. Organising workshops and seminars focused on groundwater in various types of emergency situations is another important topic of the GWES project activities.

A series of such workshops is already underway. The first, on groundwater for emergency in the region of Central America, was organized in Mexico (2004) in the framework of the Congress of the International Association of Hydrogeologists. During the GWES Working Group meeting held in New Delhi (2005) there was a very effective discussion on tsunami impacts and related groundwater issues with local experts. Other workshops are in the pipeline following the publication of the GWES Framework Document that will serve as a basic teaching and training document. The core outcome of the GWES project will be the publication of methodological guidelines complemented by case studies and an inventory of groundwater bodies resistant to natural and human impacts. These will be identified in selected pilot regions, preferably those repeatedly affected by disasters, such as South-East Asia. Of value here is the close and ongoing cooperation established with the International Groundwater Assessment Centre (IGRAC). The final stage of the GWES project activities will be the organization of an international symposium to disseminate and summarize in its proceedings the existing knowledge and experience in the identification, investigation and management of groundwater bodies suitable as a source of drinking water for emergency situations.

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10. Case studies

10.1 Isotope hydrology assists in identifying a safe groundwater resource in South Africa

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Introduction

A shallow basalt aquifer was investigated for its sustainability as a ground water supply to 26 rural villages in Limpopo Province, South Africa (Fig. 10.1.1). The initial approach was directed by a conceptual semi-quantitative hydrological model, proposed ten years earlier. According to the model, rain recharges a shallow, phreatic basalt aquifer, underlying a plain of ~600 km^2 in extent. Groundwater drains northwards, away from the mountain watershed in the south to the major Tshipise fault fracture zone which would act as both a sink and a drain of ground water out of the area (Fig. 10.1.2). The underlying consolidated sediments, mostly sandstone, encountered mainly in test drilling along the

Figure 10.1.1 Location map of study area

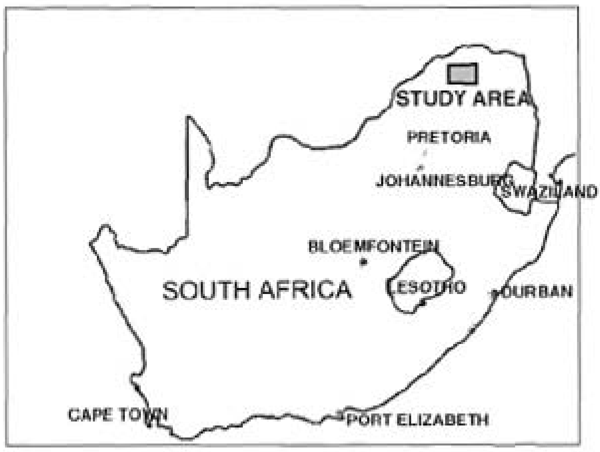
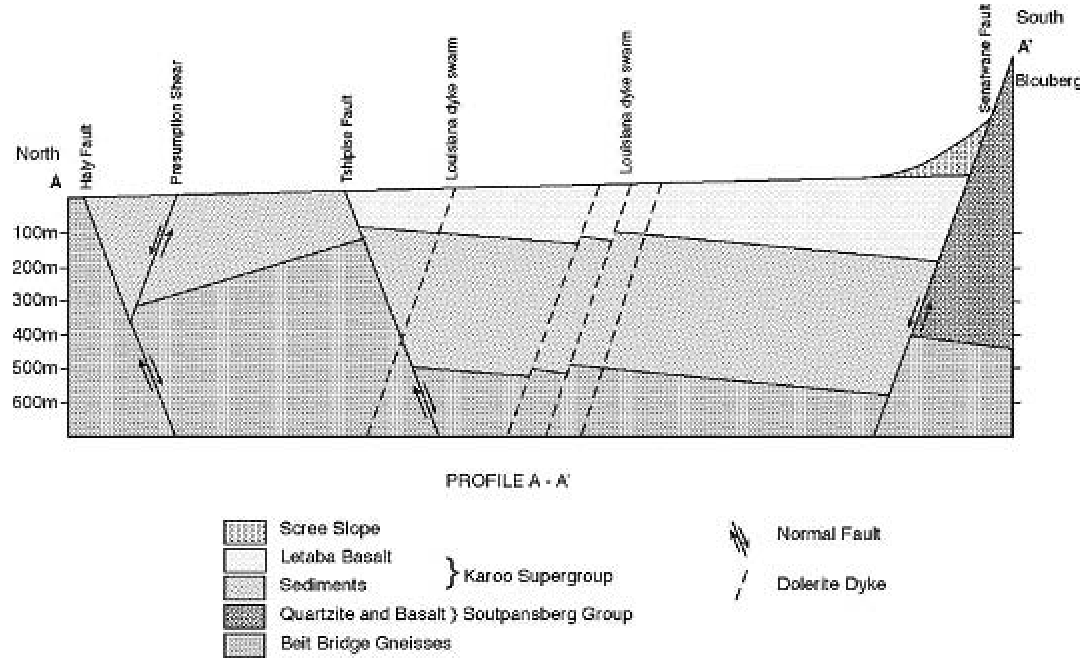


Figure 10.1.2 Geological N – S section of the study area. Note mountains in south and Tshipise in the north



fault zone, were found usually to be a poorly yielding aquifer at outcrop. Therefore regional supply was drawn mainly from the fractured fault zone, and the abstraction potential estimated at some 1 x 10^6 m^3 per kilometre of the fault strike per annum.

A renewed investigation (Verhagen et al. 2003) initially focussed on the fault zone. Production boreholes and exploration boreholes, mostly in the basalt, were sampled for the analysis of environmental isotopes and hydrochemistry. Subsequently, numerous boreholes on the plain were also sampled. Stimulated by the isotope investigation, exploration drilling both on the west and east side of the fault began to reveal greater complexity of the fault structure than initially believed.

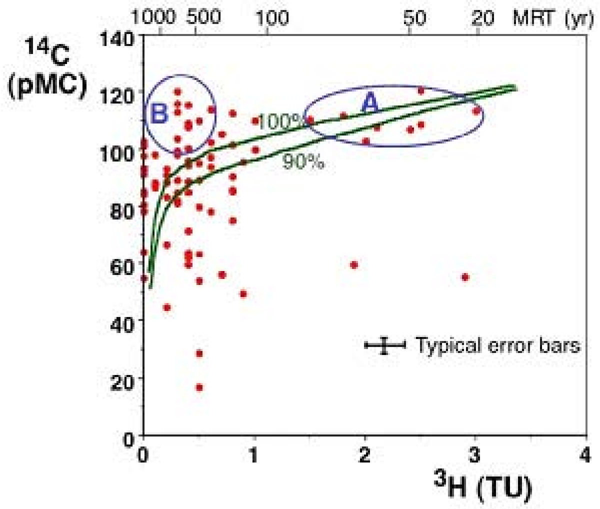
Isotope data: modification of conceptual model

Stable isotope values cluster in a narrow range around $\delta^{18}O \sim -5‰$ with a regression slope of 5.5. Rainwater $\delta^{18}O$ shows a spread of –12‰ to –2‰. Recharge conditions in the area are therefore fairly uniform, with surface ponding on the flat plain before infiltration producing an evaporation imprint on the groundwater stable isotope data. The basalt aquifer shows a pattern of high radiocarbon values, generally in the range of 80–100 pMC, with accompanying tritium in the range 0–3 TU (Fig. 10.1.3).

Recharge can be assessed on the basis of isotope-based mean residence times (MRT), and the depth and porosity of the saturated zone. Scant hydrogeological information was available on the basalt aquifer. The important parameter of porosity had to be based on inspired guesses, in view of the heterogeneity of the aquifer matrix. However, it became obvious that even optimistic residence time-based recharge figures amounted to at most 10% of those arrived at during the earlier investigation. Furthermore, the variability of isotopic and hydrochemical parameters found along the strike of the fault zone cast doubt on the concept of a continuous regional drainage zone. Down-the-hole video observations demonstrated the highly anisotropic nature of the void space in the basalt.

Samples from part of the area show a ^{14}C and ^{3}H relationship (zone A, Fig. 10.1.3) fitting the predictions of the exponential mixing model (Zuber, 1993). Elsewhere, $^{14}C > 100$ pMC with near-zero tritium values, place the data points in the 'forbidden' zone of the model (zone B). Such a combination requires the introduction of biogenic CO_2 near to or in the saturated zone, a process that can only be visualised as transport through phreatophyte roots.

Figure 10.1.3 ***^{14}C–^{3}H diagram for Taaibosch ground water, showing exponential model plots and corresponding mean residence times.***
A: values conforming to model; B 'forbidden' values



High nitrate values are a general characteristic of the basalt aquifer ground water in this region. The inferred deep liberation of root CO_2, along with various hydrochemical and isotope correlations, such as between Si and NO_3, and between both these solutes and ^{14}C, suggest functional root decay and nitrogen mineralization as a nitrate source (Verhagen and Butler, 2004).

The isotope and hydrochemical data led to a realisation that the area is (hydro)geologically far more complex than believed in the original conceptual model. An airborne magnetic survey of the area showed numerous previously poorly known features, such as lineaments that intersect fault structures, that could well partially compartmentalise the basalt aquifer (Fig. 10.1.2). This information is guiding a new exploratory drilling programme to investigate in particular the lithology below the basalt.

Identification of a new resource

The new drilling programme is revealing that the semi-confined sandstone below the basalt is a consistent, regional dual porosity aquifer, producing good quality ground water, high-yielding in places, in contrast to the poor sandstone characteristics at outcrop along the fault. Radiocarbon values up to 50 pMC for sandstone ground water prove economically significant recharge. Stable isotope values, which do not show the evaporation imprint seen in the basalt, show that recharge to the sandstone is derived mainly from mountain run-off infiltrating the scree slopes in the south of the area. Extensive calcretes along the western part of the fault zone suggest a discharge area, confirmed by low radiocarbon values (older water) and more negative stable isotope signature. It would appear that a significant, potentially sustainable, ground water resource has been identified in the sandstone of which the overlying basalt, that had been targeted for supply thusfar, only represents a fraction. The exploitation of this resource will have to be carefully managed, possibly through conjunctive exploitation of both aquifers, and guided by isotope, chemical and hydrogeological monitoring.

Conclusions

An investigation with environmental isotopes and hydrochemistry showed that a shallow basalt aquifer that had been virtually the exclusive target for exploitation for regional supply, has limited sustainability, variable quality and is vulnerable to changes in land use. This led to further exploration and the discovery of a highly productive sandstone aquifer containing good quality ground water. This aquifer is renewable, actively recharged mainly along the mountain scree slopes in the south. These features identify the sandstone as most suitable as an emergency regional water supply. However, its exploitation would have to be carefully managed in order to limit ingress of overlying poorer quality basalt ground water and possible future pollution. In a recent emergency, a nearby town is threatened with growing population and a severe shortfall in water supply due to protracted drought. A few test boreholes are being sunk into the newly-identified sandstone aquifer for short-term relief.

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10.2 Developing an early warning system for river bank infiltration

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Traditional groundwater monitoring focuses on quality analyses in exploitation wells. If any chemical component exceeds threshold values in the extraction well, additional prevention, *in situ/ex situ* remediation or water treatment measures are taken or exploitation must be abandoned. Instead of monitoring the arrival of contaminants, the hydraulic changes between the source and sink area can also be monitored, using non-reactive environmental tracers, to re-calibrate mathematical predictive models and to achieve a reliable prediction.

All exploitation causes changes in the natural hydraulic equilibrium. Basic hydraulic information refers mostly to a single point rather than integrated over time and space. Therefore any mathematical model used to predict hydraulic changes has some degree of uncertainty. This could be overcome by re-calibrating the mathematical model with data integrated over time and space, such as provided by environmental tracer results. Hence it is proposed that for contaminant monitoring one should also analyse non-reactive environmental trace elements in groundwater, which allow for a better assessment of hydraulic changes, delay times or dilution along the flow path from the source to the sink area of contaminants. To reach this goal, the analytic results of repeated environmental tracer monitoring are used to re-calibrate numerical models, thus to achieve a more reliable prediction of the hydraulic fate of contaminants along the flow path from the source area to the exploitation well. This acts as the basis for proposing groundwater management changes to guarantee a safe water supply and to avoid contaminant access to aquifers, which under natural conditions are well protected, such as deep groundwater.

There are two principal ways of natural groundwater tracing:

- Tracing from the river bank which occurs parallel to potential lines; thus a dispersion plume is directed along flow lines from the source to the sink area. This propagation plume can be characterized by a mean transit time and by dilution.
- Natural, or environmental tracing through groundwater recharge, which is perpendicular to potential lines and thus creates a horizontal tracer stratification in aquifer systems. Any change in the groundwater flow direction, induced by groundwater extraction in disequilibrium with the natural flow field, progressively disturbs this horizontal stratification, which can be monitored to re-calibrate numerical models.

^{3}H, ^{39}Ar, ^{14}C, ^{2}H, ^{18}O, Cl or the salt-/fresh-water interface have been shown to be useful environmental indicators for developing an early warning system; this allows for predicting timeously the access of pollutants to any exploitation site. Such early warning systems have been developed for the control of deep groundwater extraction (Gehrgut et al., 2001) as well as river bank infiltration, which is referred to below.

Depending on the piezometric head differences between the river and groundwater, river water either infiltrates to groundwater (river bank infiltration) or groundwater exfiltrates to the surface water (Fig. 10.2.1); both processes are referred to as leakage.

Any use of river bank infiltration for water supply requires a minimum thickness of the aquifer of 5 m in gravels and more in sands to achieve a good yield with a reasonable draw down. For this reason, most river bank infiltration installations are located in major valleys with a quaternary, coarse grained valley fill.

The use of environmental isotope methods in assessing forced river bank infiltration are based on:

- The damping and phase shift of the variable isotope signal with time in the river as compared to the signal in the groundwater observation well (Fig. 10.2.2) from which the flow or mean residence times between the river and any monitoring well can be determined
- The average isotope concentration in the river, the local groundwater and the river/groundwater mixture, respectively (Fig. 10.2.3), to assess dilution and river water input.

Figure 10.2.1 River bank infiltration under normal, flood, forced bank filtration conditions and in the upper reach of rivers without direct contact with groundwater

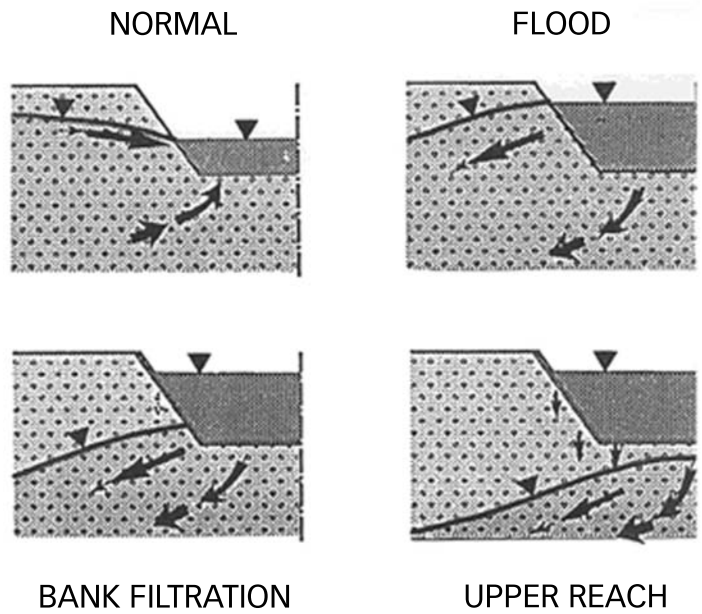


Figure 10.2.2 $\delta^{18}O$ in river water and the $\delta^{18}O$ response in nearby groundwater; depleted $\delta^{18}O$ values are due to the snow melt in the summer season

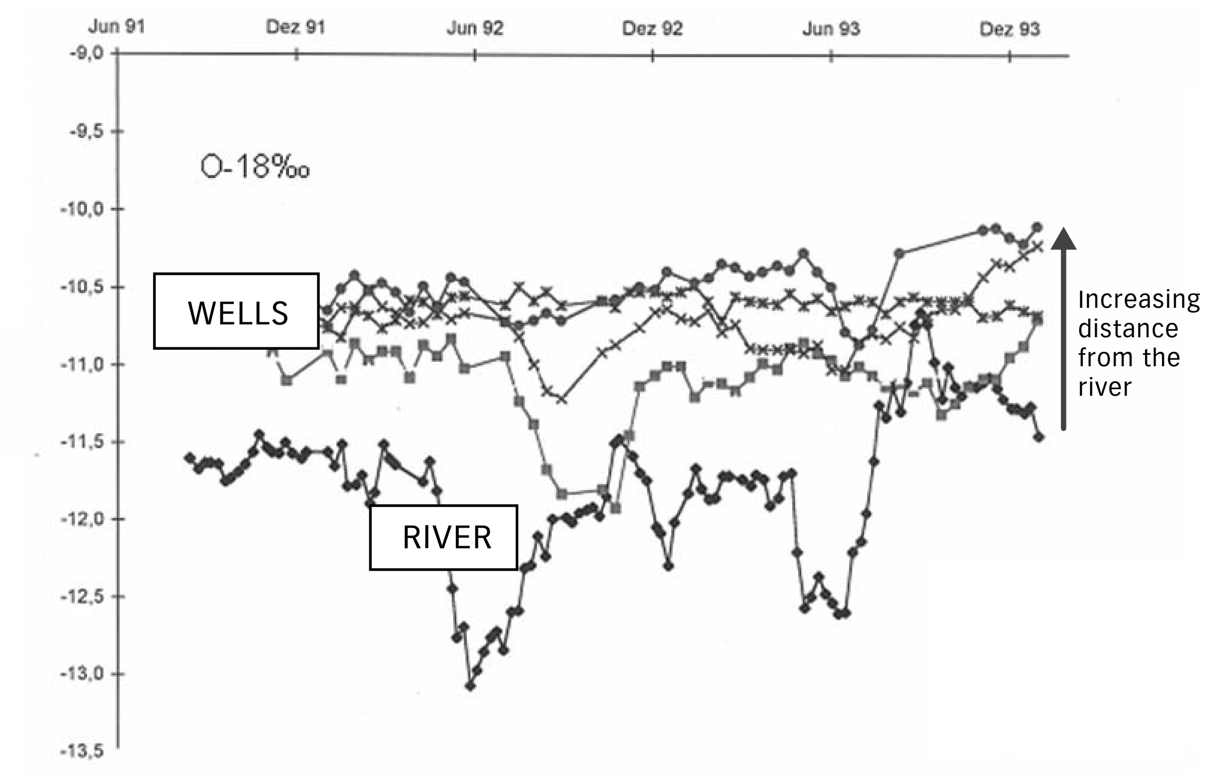
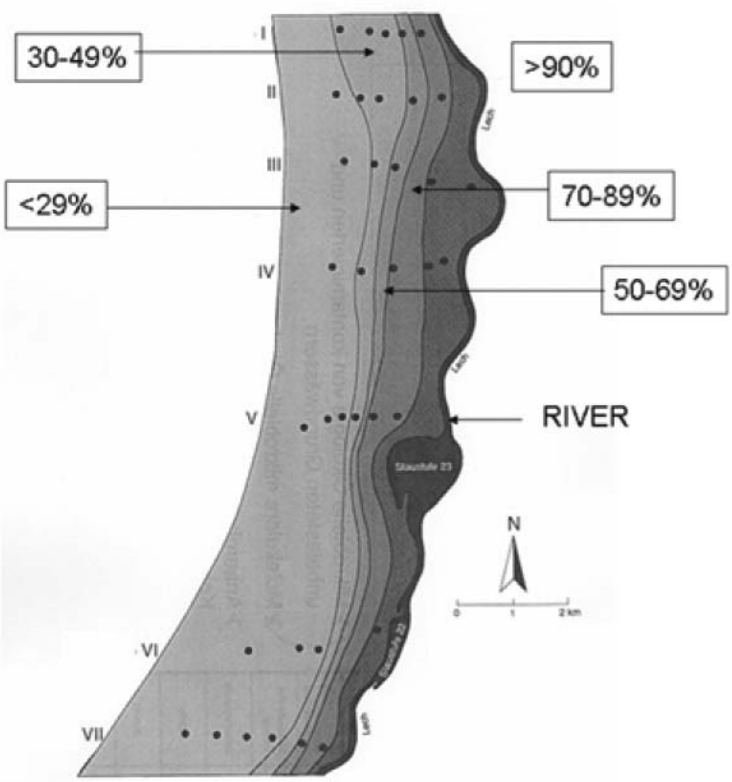


Figure 10.2.3 Percentages of river water contribution to groundwater under undisturbed (southern part) und forced conditions (northern part)



The determination of the mean residence times and dilution of water along the flow path from the river to the groundwater sampling site is based on isotope variations, relating to lumped parameter models, which have been developed by Maloszewski and Zuber (1996).

$$C_{out} = C_{in}\, g(t')$$

The mixing between river and groundwater is calculated using the mixing equation

$$(CQ)_{river} + (CQ)_{groundwater} = C_{mixedwater}\left(C_{river} + Q_{groundwater}\right)$$

where C is the tracer concentration and Q the flow rate.

Once the lump sum parameter model has been calibrated by determining the function g(t′), it can be used to define the threshold input concentration into the river ($C_{in,\ threshold}$), which dilutes a pollutant entering from the river to a maximum permissible concentration at the extraction well ($C_{out,\ permissible}$) according to health standards of the WHO (1996). Since in general there exists a dilution and retardation time of flow from the river to the extraction facility, which both depend on the extraction rate, in emergency cases (floods, accidents) there is sufficient time to reduce or shut down groundwater extraction to avoid harm to health and life.

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10.3 Emergency situations in delta areas: the case of the Netherlands

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Emergency situations in delta areas may result in groundwater resources temporarily not available or recharged. There are effectively no unexplored groundwater resources in the Netherlands. Fresh groundwater is at relatively shallow depth whilst saline groundwater underlies fresh groundwater. Emergency groundwater supplies can be found only where groundwater resources are unused or by allowing over-abstraction of (nearby) resources provided salinization of aquifers is avoided and future recharge of groundwater is ensured. The case of the Netherlands is a good example of a delta area.

Groundwater in the Netherlands

In the Netherlands, groundwater for drinking water supply is primarily abstracted from the generally sandy sediments in the dunes, in the high-lying Pleistocene and Pleistocene/Holocene deposits in the east of the country and from river bank deposits. An estimate of the available volume of fresh groundwater, approximately 2 billion m^3 per year, was made on the basis of a division of the Netherlands into hydrological units (Figure 10.3.1). The total net recharge or infiltration replenishing the groundwater in the aquifers for the entire country was estimated to be about 2.6 billion m^3 per year (Dufour, 2000).

Figure 10.3.1 Estimated volume of fresh groundwater in the Netherlands available per region per year (Source: Ministerie van Verkeer en Waterstaat, 1985)

Volume fresh groundwater available in million m^3 per year

In 2003, 61% of the demand for drinking water in the Netherlands or 0.98 billion m^3 (Ministerie van VROM, 2004) was supplied from groundwater,including bank infiltration of surface water; the remainder was obtained from surface water – primarily from the Meuse and Rhine rivers. The volumes of groundwater used for industrial or agricultural purposes are not accurately known in the absence of detailed monitoring and compulsory national registration of agricultural and private abstractions. Dufour (2000) estimated the total abstraction of groundwater by industries and agriculture at approximately 0.5 and 0.3 billion m^3 resp. The figures show that the total abstraction of 1.8 billion m^3 is not much less than the estimate of the total available volume of fresh groundwater.

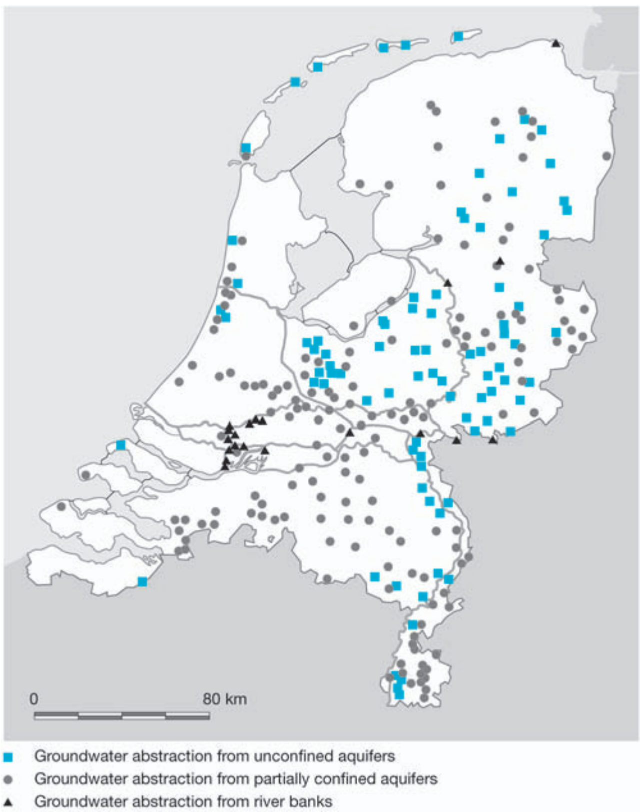
In a dry year, groundwater abstractions by water companies and the agricultural sector will increase and may reach volumes near or more than the available volume. Problems will arise from over-abstraction, especially in such dry summers with a relatively large rainfall deficit and may result in local declines of the water table and hydraulic head, intensifying the negative effects of groundwater abstractions in conservation areas with wet habitats (Dufour, 2000). Recovery of groundwater volumes however is quick and normally volumes and groundwater tables are restored by recharge during the winter.

Emergency situations

In the Netherlands emergency situations in which the supply from groundwater sources may be hampered or forced to be interrupted, are related to floods, droughts or contamination:

- Centuries ago flooding by failing river or sea dykes was a common event in the low lying areas but in recent times this has become rare. The last time extensive flooding by sea water occurred in the Netherlands was in 1944 when dykes were bombed during the war and in 1953, when dykes collapsed during a big storm. In general groundwater resources are not or are only slightly reduced during floods because fresh groundwater resources used for water supply are situated in areas with a higher elevation (e.g. the dunes) which are not flooded. These resources are available more or less directly after the retreat of the flooding. The supply of fresh water during floods will be interrupted mainly because of damages to the supply infrastructure.
- Droughts occur during summers with large rainfall deficits. Groundwater abstractions from deep confined aquifers are generally not affected in this situation and will be able to continue, but groundwater abstractions from shallow unconfined aquifers may have to be reduced (Figure 10.3.2). Abstractions for agricultural purposes, generally from shallow resources also, often have to be reduced or stopped because of regulations protecting the environment. This will cause a reduction in agricultural production because water is not available for irrigation in the months with the highest water demand.
- Low flows in rivers during droughts or pollution of the surface water may force water supply companies to interrupt the intake of surface water used for infiltration (e.g. Amsterdam Water Supply infiltrates water pumped from the river Rhine in the dunes). The available groundwater resources however in general are sufficient to last a period of at least two months without infiltration.

Figure 10.3.2 Locations in the Netherlands of groundwater abstraction for public water supply, classified by type of abstraction (Source: RIVM, 1992)



- Contamination of groundwater by industrial spills may render groundwater resources unfit for water supply. The risk involved is reduced to a minimum by precautions taken around groundwater abstractions by declaring protection zones in which activities are prohibited which may lead to pollution.
- Contamination of groundwater due to big disasters like a nuclear accident requires a different approach. The National Plan for Nuclear Emergency Response (Ministerie van VROM, 2002) describes the actions to be taken to protect and restore water supplies. In general groundwater resources are not expected to be affected directly, but infiltration of radioactive material especially requires measures to monitor and control the shallow groundwater. Contamination of surface water is more likely to occur and groundwater abstractions using bank infiltration may have to cease operation temporarily.

Measures

The types of emergencies in the Netherlands do not require a search for new additional resources. Most emergencies last a few months only and either groundwater resources have sufficient volume to continue abstraction or water supply can be organized from nearby areas with un- or under-used resources. In the situation of a big disaster like a nuclear accident plans are prepared to monitor and remedy the contamination. The measures focus on surface water and water supply systems and less on groundwater.

Some water supply companies maintain emergency facilities to be used in emergency situations. For example in the city of The Hague emergency wells are maintained for use in situations where the normal water distribution stops functioning. The wells tap groundwater below the city normally not used for drinking water production. This may solve problems with the supply of water, but water quality is a concern because like in other cities, pollution of groundwater occurs at many locations.

Groundwater models are an important tool during emergency situations to assess the effect on groundwater conditions of increased pumping or the transport of contaminants. Regional effects on groundwater flows may be assessed using a national groundwater model maintained by RIZA (Institute for Inland Water Management and Waste Water Treatment) or regional models maintained by TNO (Netherlands Institute of Applied Geoscience TNO – Geological Survey) or others. Local effects e.g. around pumping stations may be assessed using groundwater models maintained by water supply companies.

Strategic groundwater resources

The national government introduced in 1988 the concept of strategic water resources and a study was carried out by Engelen (1990) to investigate the availability of strategic groundwater resources. The study concluded that such a concept could be elaborated only in an integrated approach of the requirements of (public) water supply, spatial planning and environmental conditions. Groundwater resources reserved for strategic purposes were not identified in this study, but recommendations were made to reserve deep groundwater resources by increasing the use of surface water and to improve the administrative, legal and financial instruments to facilitate the establishment of strategic water use. The recommendations of the study were not implemented by the authorities due to objections made by groundwater users and at present only the surface water of the Ijsselmeer in the centre of the country is considered as a strategic water source.

Conclusions

The search for additional sources of groundwater in the Netherlands does not involve investigations into unexplored aquifers, because such aquifers do not exist. The available fresh groundwater resources are known and drilling wells deeper does not yield more fresh water as groundwater is saline below a depth of about 50 meter in the west to about 300 meter in the east of the country. Sufficient volumes of unexploited groundwater are available to cover relatively short periods with shortages in recharge or problems with contamination. Also, transport facilities are generally adequate to provide areas without water supply with potable water from nearby areas. Only in worst-case scenarios would water be supplied for drinking purposes only employing tankers or other temporary measures.

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10.4 Ground water risk management during Bhuj earthquake (26th January 2001)

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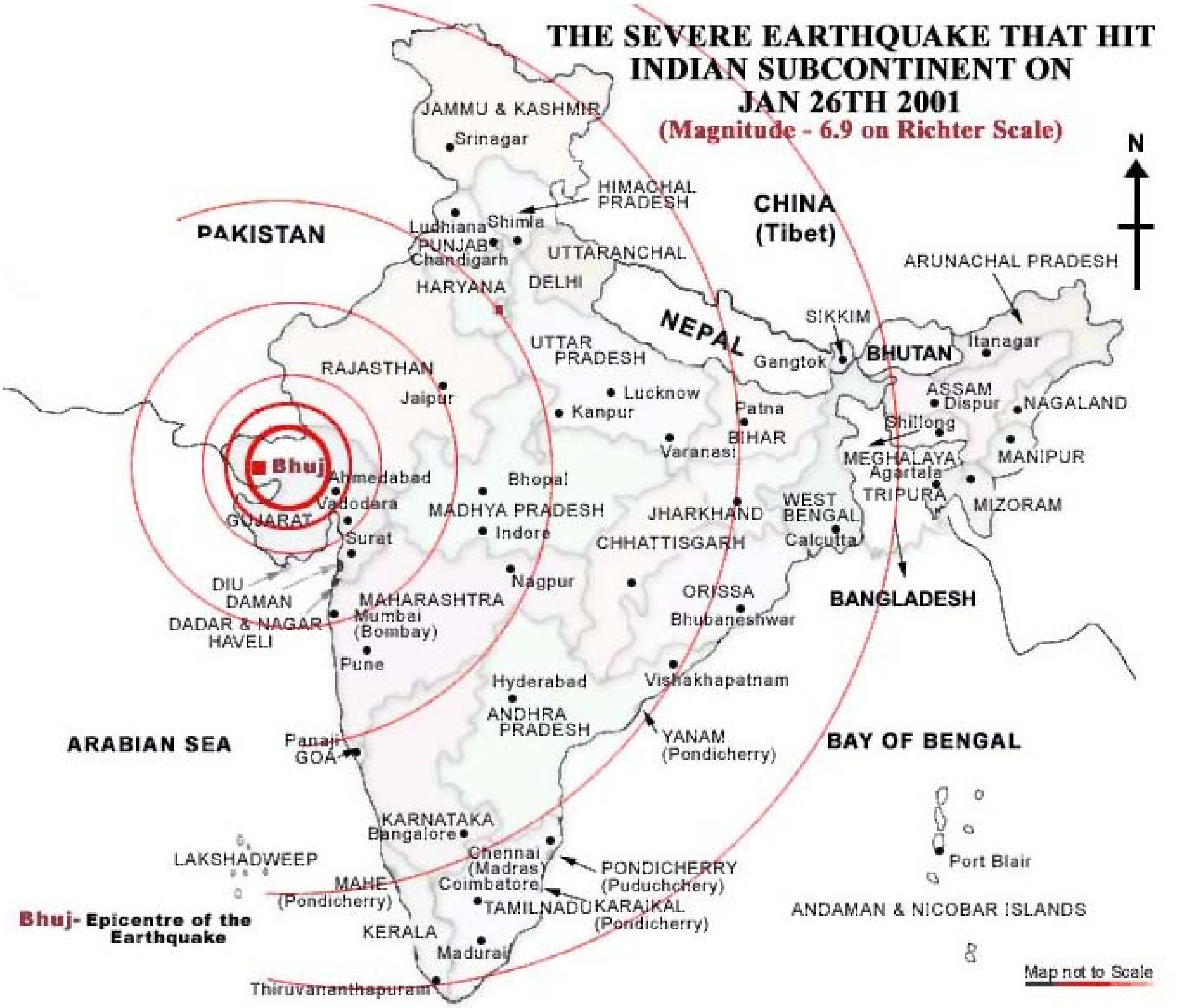
Introduction

The Indian continent witnessed an earthquake of magnitude 6.9 on Richter Scale as per IMD and 7.9 assessed by USGS with its epicentre North East of Bhuj near Amrasar (Latitude N 23°4′ and Longitude E 70°28′) in Kutch district of Gujarat on 26th January, 2001. The effect of this earthquake was observed in different parts of the country (Figure 10.4.1). Kutch has a mainly arid climate characterized by extremely high temperatures, rising up to 50°C with high evapo-transpiration losses. The rainfall is unpredictable, with an annual average of 350 mm. The area is categorised as drought prone, drinking water requirements are mostly met through ground water and rainwater stored in tanks and ponds for all domestic purposes.

Geologically, the area is represented by rocks of both marine and fresh water formations ranging in age from Jurassic to Recent. The prominent rocks are coarse-grained sandstones (Middle to Lower Cretaceous), Deccan traps (Upper Cretaceous to Eocene basalts) and sandstone of the Lower Tertiary. The area is marked by a number of faults displacing different rock formations.

Groundwater in the area is mostly saline to brackish in almost all geological formations except for the Bhuj and Kankote Mesozoic sandstones and Tertiary Manchar Formation. Further, Kutch falls in active seismic zone V and witnessed several earthquakes of different magnitude levels (ML). Under these environmental vagaries the area requires special scientific planning for its overall development, including the survey and exploration of sweet ground water for sustainable development and management of the district.

Figure 10.4.1 Location of epicentre and the areas affected by earthquake



The 2001 earthquake destroyed the entire old walled city and most of the multi-storey buildings of Bhuj City and towns like Anjar, Adhoee, Bhuj, Bhachau, Chaubari, Dudhaee, Kabrai, Rapar, Ratnal were almost completely destroyed. Prior to this earthquake the area had witnessed several earthquakes ranging in magnitude from 4 to 8 levels on Richter scale. The 'Allah Bund' earthquake of 1819 was highly devastating and resulted in the formation of an important palaeo – seismic landform feature, known as Allah Bund, and truncated the Nara stream, a tributary of the Indus, which flooded the area (Fig. 10.4.2). In subsequent years, a number of earthquakes have been recorded, the most notable being the Anjar earthquakes of 1940, 1956 and 1991 and Bhuj earthquake of 1996.

Impacts of earthquake

(a) Emergence of groundwater

The maximum impact of the earthquake was observed in the Banni area, where a series of fractures have been developed. Subsurface water was found oozing even after 20 to 25 days at certain places e.g. near India Bridge north of Patcham Island (Fig. 10.4.3), at Dharampur and Umedpur in the Banni area, through large craters formed along the fractures. Another set of fractures show micro-cratonic vents in series, in the Quaternary Formation of Banni, which lies between the mainland and northern Islands.

Figure 10.4.2 Modified geomorphology of the Kutch area after Earthquake, 1819

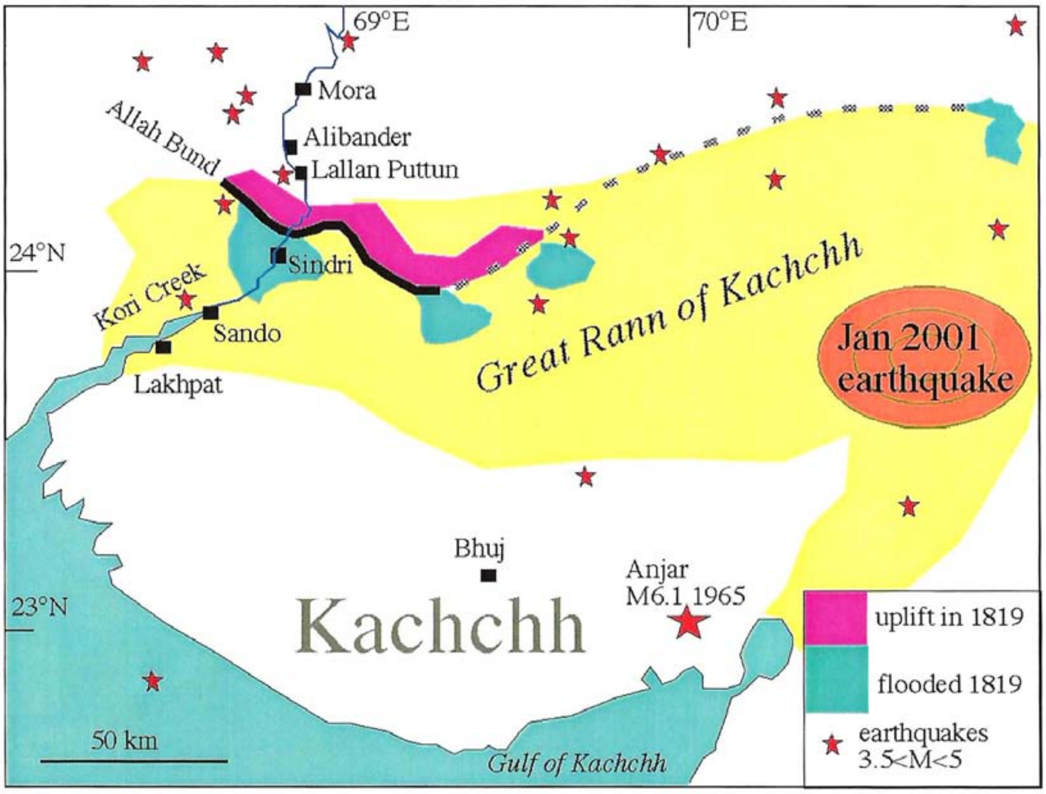


Figure 10.4.3 Emergence of coloured groundwater through craters, vents and fractures near India Bridge

About 2 km west of Amrasar in Bhachau taluka, a series of elliptical fractures (measuring 75 m in width and 125 m in length) with a displacement of 2 to 3 cm in successive inner fractures, are highly conspicuous in nature. Similar major fractures have been observed about 8 km west of Chaubari village. The emergence of ground water through small rounded to elliptical vents was recorded at a few places (Fig. 10.4.4). No damage was recorded in the wells, bored wells and tube wells. However, in some cases where cement assemblies were used, they were found dislocated. The water supply lines were damaged and disrupted in certain places, besides failure of electricity lines and damage to pump houses.

Figure 10.4.4 Groundwater oozing through a series of rounded elliptical vents

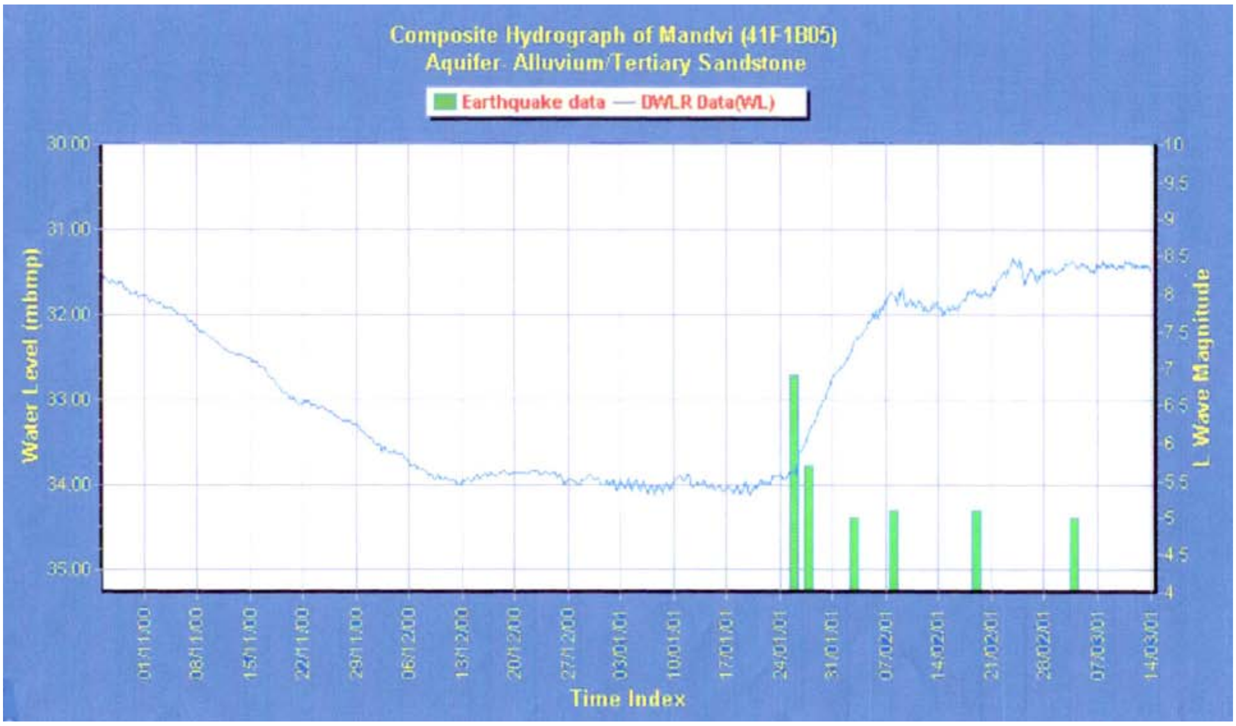
(b) Rise / fall of the groundwater table

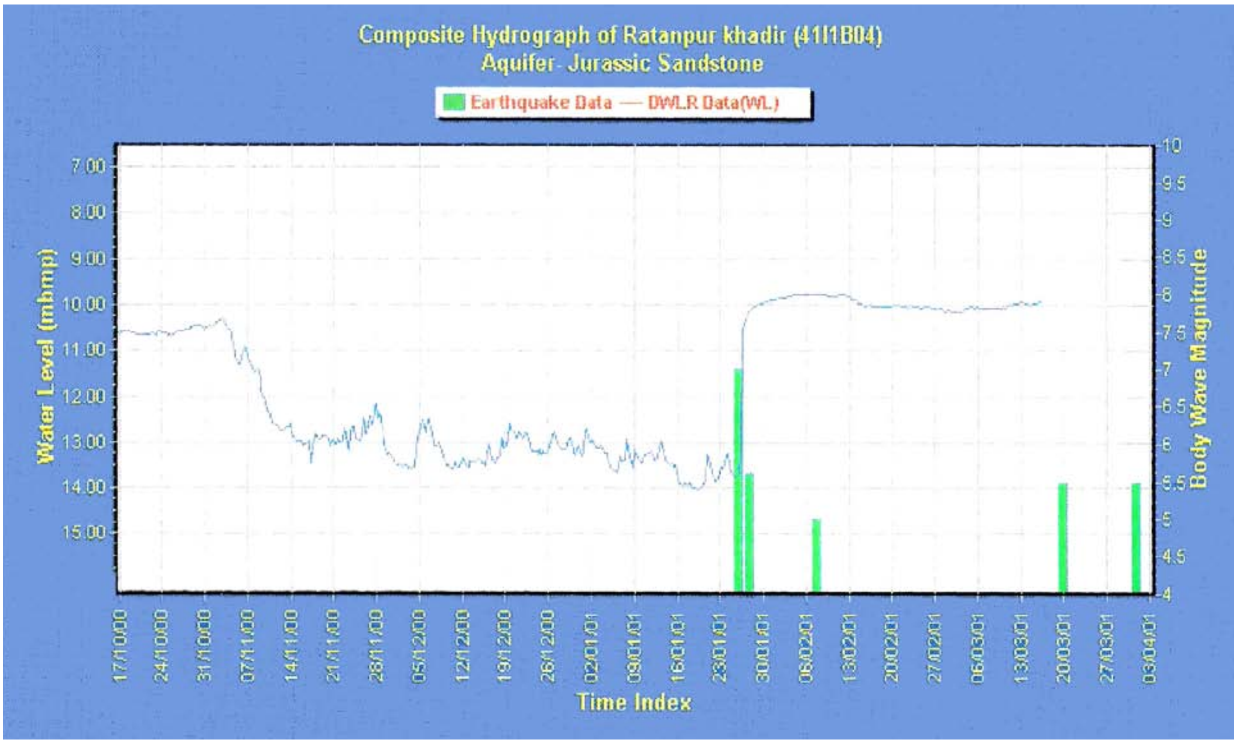
Digital water level recorders had been installed in piezometers to continuously record normal fluctuations of ground water levels at time interval of 6 hours. The digital water level recorders recorded the rise/fall in ground water levels before, during and after the earthquake. The recording in two of the DWLR is given in Figs. 10.4.5 and 10.4.6

(c) Change in ground water quality

The quality of water that erupted on the surface from the craters and fractures in the Rann and Banni plains was highly saline. However, there had been no significant change in the water quality of samples drawn from dug wells and tube wells located in different geological formations.

Figure 10.4.5 and 10.4.6 Impact of earthquake on ground water levels





Identification and development of new aquifers

In order to identify new aquifer systems from which to restore the water supply, a massive drilling operation and chemical quality checks of water samples was organized. The area was scanned with remote sensing, geological mapping and a detailed geophysical survey to identify sites for drilling tube wells. To rapidly restore water supply, 9 deep drilling rotary/reverse rotary rigs were diverted on emergency basis to Kutch district for construction of tube wells. The construction of wells was confined mainly to areas underlain by Bhuj Cretaceous (Mesozoic) sandstone. In general, the ground water quality in this aquifer is good down to 150 to 170 m but saline at greater depth. In all 55 tube wells were constructed in the depth range of 70 m to 156 m. Only 45 tube wells were equiped as others were not of required water quality or of sufficient yield. It was thus possible to supply 20,000 m^3/day through water tankers initially. Subsequently the other tube wells were also rehabilitated and water supply restored.

Conclusions

The devastating earthquake of 26th January destroyed the entire city of Bhuj and 800 villages around the area disrupting the entire water supply system. For the relief operation to supply drinking water, nine deep drilling machines were put into operation, 55 tube wells were sunk out of which 45 were equiped supplying 20,000 m^3/day. This ensured the water supply as interim relief and restoration of the entire water supply system in due course. The prompt and well-planned action proved the importance of ground water in emergency situations.

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10.5 Impact of the 26-12-2004 Tsunami on the Indian coastal groundwater and emergency remediation strategy

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Introduction

Tsunami is a wave of high energy, which is generated by an earthquake or landslide in the sea. The tsunami wavelengths and their periods depend on the generating mechanism and the magnitude of the source event. The period of the tsunami waves may range from 5 to 90 minutes. Length of the wave crests of a tsunami can be more than thousand km and the waves may be from a few kilometres to more than a hundred kilometres apart as they travel across the ocean. The speed of tsunami waves increases with the depth of the sea and may exceed 800 km/hr.

The areas within 1.6 km of the shoreline and about 15 m above the sea level face the greatest risk during a tsunami. Seawater can intrude over land filling wells and ponds, and percolate into the subsurface. Conditions can get worse if seawater penetrates the aquifer. It may take years or decades for the seasonal rainfall to wash the soil/aquifer/rocks clean, or much longer. In some cases, a river channel can provide a passage for a tsunami bore to rush through, allowing it to flood tremendous tracts of land far inside from the shoreline.

This paper examines the adverse consequences of the December 26, 2004 tsunami on the groundwater resources of the Indian coast and proposes a remediation framework for similar emergency situations. The specific interest within the objective of this study has been also to carry out an assessment of hydrogeological characteristics and risk to coastal aquifers in the districts of Tamilnadu in southeastern India.

The 26-12-2004 Tsunami

On December 26, 2004, an earthquake of 9.3 magnitude on the Richter scale struck the active subduction corridor along the eastern margin of the Indian lithosphere off the coast of Sumatra in Indonesia. It took the tsunami waves about 2 hours to reach the Indian coast. The wave reached Andaman, on the east coast of Sri Lanka and Tamilnadu and up to Orissa, further north along the east coast. On reaching shallow waters along the coastline, the energy of the deep sea waves is transformed into very forceful tidal waves of great height (10–30 m) causing vast devastation.

Description of the study area

The Indian coastline spans some 7,500 km (5,700 kms on mainland) shared by nine coastal states, two groups of islands and four union territories. The coastal belt comprises a wide range of ecosystems, from sandy beaches and mangroves to coral reefs and rocky shores. Roughly, one-fifth of the population of India live along the coast. The south-eastern Tamilnadu coast, from Pulicate lake to Cape Comorin, covering a total coastline of 992 km, was damaged by the 26 December 2004 tsunami flood.

This study investigates the consequences of the tsunami on the groundwater regime in terms of hydrogeological characteristics and groundwater quantity and quality. A reconnaissance visit was undertaken and analyses of groundwater and hydrochemical data were carried out as well as groundwater monitoring. GPS (Global Positioning System) was used for geo-referencing of the collected data. The salinity condition of aquifers in Tamilnadu was described by Ramanathan et al. (1997). An assessment of groundwater resources focused on the salinity condition in shallow fluvial aquifers and its extent for the Pondicherry and Cuddalore (district within Tamilnadu State) is available in the studies of Thondimuthu (1994), Keshavan (1996) and Keshari (2005). These studies provide a very good baseline with which to compare conditions after of the tsunami event.

Impact on groundwater quality

The tsunami has affected groundwater systems in the low-lying coastal areas as well as along the coastal areas with weaker bunds, creeks and inadequate vegetation. Fig. 10.5.1 shows one of such area through which the tsunami flood breached the Tamilnadu coast. The signature of the tsunami flood is clearly visible as a watermark on the wall (Fig. 10.5.2), which indicates that the tsunami flood reached more than 1.5 m above ground level. The extent of groundwater quality deterioration depends on the local hydrogeology, soil characteristics, rate of infiltration, duration of sea water ponding and weather conditions during the event.

The study monitored groundwater levels at some locations and compared them with the data obtained for the pre-tsunami period. Fig. 10.5.3 shows that depth below ground level at many locations

Figure 10.5.1 Inland intrusion of tsunami water through weaker zones in coastal dunes

Figure 10.5.2 Water level mark showing height of tsunami intrusion

has decreased between 0.5 and 5.5 m after the event. This rise in level is clearly linked to the groundwater flow pattern and groundwater salinity. The inland intrusion of tsunami water along the most affected southeast Indian coast is shown in Fig. 10.5.4. It is evident that the tsunami waves resulted in the intrusion of saline water up to 2 km inland at some places. It has damaged many water supply infrastructure facilities along the southeast coast including hand pumps in rural areas.

Figure 10.5.3 Groundwater levels before and after the tsunami

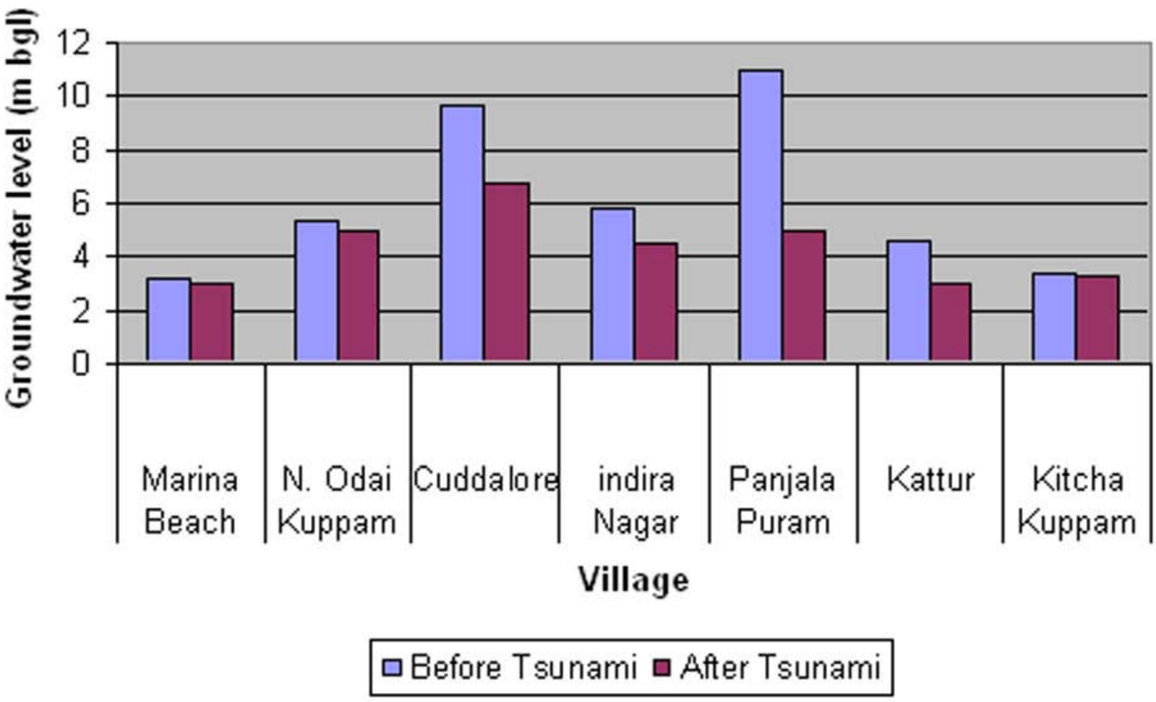
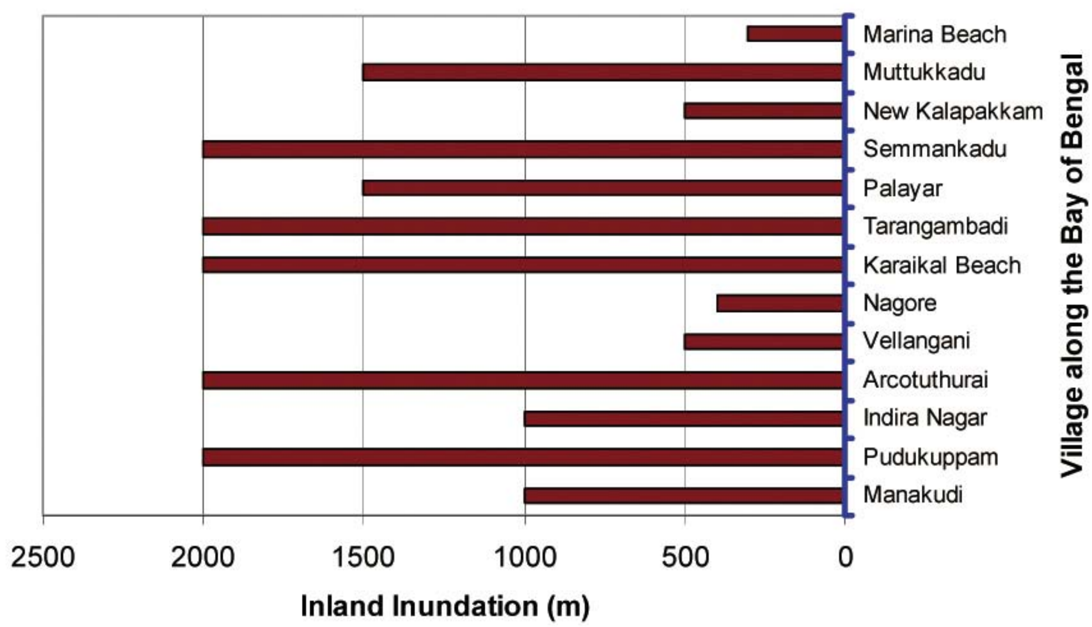
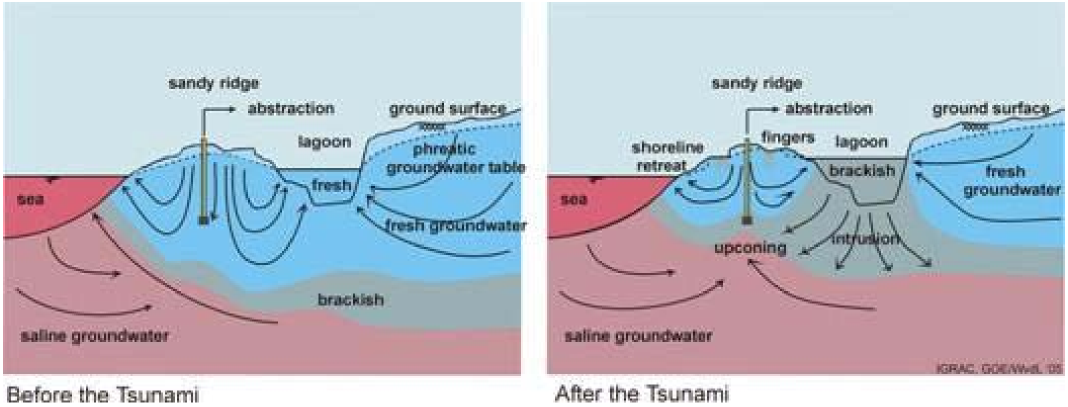


Figure 10.5.4 Inland intrusion of the tsunami flood along the southeast Indian coast



However, there are some wells that have remained fresh even after the tsunami. Such a phenomenon is clearly linked to the hydrogeology, topography and soil and vegetative conditions around the well that influenced the percolation of saline/brackish water and the dynamics of saltwater-freshwater interface. Fig. 10.5.5 shows a possible mechanism of the salinisation of the coastal groundwater system (Source: http://igrac.nitg.tno.nl/tsunami2-i.html).

Figure 10.5.5 Schematic representation of a possible mechanism of a tsunami affecting a coastal groundwater system



Overland intrusion of sea water spilled into open wells and depressions resulting in percolation of saline water to shallow aquifers even after the tsunami event. The inundation of the coastal areas has also led to the spread of pollutants from various anthropogenic sources. These effects have made groundwater unfit for human consumption and also affected the agricultural productivity in the coastal belts of southern India.

Emergency remediation strategy

There is a clear need to devise and implement remediation strategies as the brackish water has contaminated open wells and ponds making them unfit for drinking purposes. However, the event has induced also other processes such as dispersion and diffusion of salts, as well as free convection salinisation due to differences in density. To rehabilitate and control the salinisation process, the saltwater needs to be pumped out to reduce intrusion of brackish water into adjacent freshwater bodies.

A well located 23 m away from the sea in Chennai City was originally a freshwater well but became saline after the tsunami. Local residents report that the contaminated well water was pumped continuously for 1 month with an average running time of 8 hrs/day. As a result, the TDS value of the well has gone down to 990 mg/L. Although this well is still not being used for drinking, the water is being sourced for irrigating a nearby plantation and agriculture. Pumping has positively contributed to control the salinisation process in many nearby wells.

Conclusions

The seawater intrusion due to the tsunami has adversely affected the groundwater quality and quantity. Apart from the immediate impact on drinking water, agricultural land was also degraded due to salt water intrusion. The impact on the latter can be expected to become worse because of high evapotranspiration rates in the area. Natural recharge will account for some flushing of the saline water, but this might take several monsoon seasons.

Unaffected groundwater has played a very important role to meet the immediate drinking water needs of the local population. However, a more managed approach is needed to identify groundwater resources resistant to tsunami and similar events and utilise them as emergency drinking water sources. This is the very purpose of GWES: investigating safe aquifers, development of guidelines for community well installation, awareness campaigns, and emergency strategic measures to rehabilitate wells and control salinisation. There is a need to design a groundwater quality monitoring system, establish proper geochemical characteristics of the affected region and evaluate long-term impacts on the groundwater quality of the coastal aquifers. Notably, this will also help monitor fluxes of remobilised nitrate and fluoride into freshwater.

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11. Glossary

The following list of technical terms was compiled mostly from the International Glossary of Hydrology (UNESCO-WMO, 1992), Bates and Jackson (1980) and Fetter (1980).More specific definitions related to natural disasters are given in World Water Development Report I (2003).

Abstraction: Removal of water from any source, either permanently or temporarily

Alluvial plain (also flood plain): The plain on the valley bottom occasionally flooded by a stream.

Aquiclude: Saturated formation of low hydraulic conductivity, which yields inappreciable quantities of water to drains, wells, springs and seeps.

Aquifer: Permeable water-bearing formation capable of yielding exploitable quantities of water.

Aquitard: Formation of low hydraulic conductivity, which transmits water at a very slow rate as compared with an aquifer.

Area of influence (syn. Zone of influence): Area around a pumping or a recharging well in which the water table (unconfined aquifer) or the piezometric surface (confined aquifer) is lowered or raised to a significant degree by pumping or recharging.

Artesian aquifer (see also confined aquifer): Aquifer whose piezometric surface lies above the ground surface.

Artesian well: Well tapping a confined or artesian aquifer in which the static water level stands above the surface of the ground.

Attenuation: The intrinsic ability of earth materials and groundwater to reduce, remove, dilute or retard contaminants by the complex of physical, chemical and biological processes acting in the soil-rock-groundwater system.

Base flow (syn. Base runoff): Part of the discharge which enters a stream channel mainly from groundwater, but also from lakes and glaciers during long periods when no precipitation or snowmelt occurs.

Blue water: Water with natural physical, chemical and microbial properties.

Boundary conditions: Set of conditions to the solution of a differential equation at the boundary (including fluid boundary) of the region in which the solution is sought.

Brackish water (syn. Saline water): Water containing salts at a concentration significantly less than that of sea water. The concentration of total dissolved salts is usually in the range 1,000 – 10,000 mg/L.

Capillary fringe: Zone immediately above the water table in which all of the interstices are filled with water that is under pressure less than atmospheric.

Climatic change: Significant change observed in the climate of a region with respect to a reference period.

Cone of depression: Depression of the piezometric groundwater surface, in the shape of a cone with concave surface upwards , which defines the area of influence of a well.

Confined aquifer (see also artesian aquifer): Aquifer overlain by an impervious or almost impervious formation.

Confined groundwater (sub-artesian groundwater) Water completely filling a confined aquifer of which the piezometric level lies higher than the interface with the confining layer.

Connate water: Water entrapped in the interstices of a sedimentary rock at the time the rock was formed and which did not show up in the biosphere since.

Contamination (see also pollution): Introduction into a water of any undesirable substance not normally present in water, e.g. micro-organisms, chemicals, waste or sewage, which may render the water unfit for its intended use.

Darcy's law: Law expressing the proportionality of the specific discharge of an incompressible liquid flowing through a porous medium under laminar flow conditions.

Data bank: Comprehensive set of related data files for a specific application, usually on a direct access storage device.

Data collection system: Coordinated system for collecting observations from a hydrological network and the transmission of the observations to a data-processing facility.

Data processing: Handling of observational data until they are in a form ready to be used for a specific purpose.

Disaster: A serious disruption to the normal functioning of a community or a society, which causes widespread human, material, economic or environmental losses that exceeds the ability of the affected community/society to cope using their own resources. Disasters are often classified according to their speed of onset (sudden or slow), or according to their cause (natural or man-induced).

Discharge (syn. Rate of flow): Volume of water flowing through a unit cross-section in unit time.

Divide (surface water of groundwater): A line along which water levels are at their highest and decline to both sides of it.

Drainage basin (syn. Catchment area, River basin, Watershed): Area having a common outlet for its surface runoff.

Drawdown: Lowering of the water table or piezometric surface caused by the extraction of groundwater by pumping, by artesian flow from a bore hole, or by a spring emerging from an aquifer.

Drought: Prolonged absence or marked deficiency of precipitation.

Dry year: Year of drought during which precipitation or stream flow is significantly less than usual.

Earthquake magnitude: A measure of the strength of an earthquake, or the strain energy released by it, as determined by seismographic observations.

Ecosystem: System in which, by the interaction between the different organisms present and their environment, there is a cyclic interchange of materials and energy.

Effective porosity: Amount of interconnected pore space available for fluid transmission. It is expressed as the ratio of the volume of interconnecting interstices to the gross volume of the porous medium, inclusive of voids.

Endorheic basin: Basins with evapo(transpi)rative water losses, but without run-off to the oceans.

Environment: Generalising reference to the surroundings, either in the natural state or influenced by man, both above the earth's surface and to depths where there could be finite interaction with the surface.

Erosion: Wearing away and transport of soils, sediments and hard rocks by water, glaciers, wind or waves.

Evaporation: Emission of vapour by a free liquid surface at a temperature below the boiling point.

Evapotranspiration: Water transferred from the subsurface to the atmosphere by evaporation and plant transpiration.

Exorheic basin: Basin with run-off to the oceans.

Flood: Rise, usually brief, in the water level of a stream to a peak from which the water level recedes at a slower rate.

Flood plain: Nearly level land along a stream flooded only when the streamflow exceeds the water carrying capacity of the channel.

Fossil water: Water that infiltrated into an aquifer during an earlier geological period (>10,000years) under climatic and morphological conditions sometimes different from the present and stored or flowing since that time.

Fracture porosity : Porosity resulting from the presence of openings produced by the fracturing or shattering of rocks.

Fresh/salt water interface: Surface separating a body of fresh water and one of brackish or salt water, taken to lie somewhere within the transition zone between the two fluids.

Fresh water: Naturally occuring water having a low concentration of salts, or generally accepted as suitable for abstraction and treatment to produce potable water (ISO/6107).

Gaining stream: Stream gaining water from the sub-surface through contributions from the saturated zone or perched aquifers.

Green water: Water, which is naturally available for vegetation.

Grey Water: Waste water.

Groundwater: Subsurface water occupying the saturated zone.

Global water balance: Water balance for the combined land and sea areas of the Earth.

Groundwater basin: Physiographic unit containing one large or several connected or interrelated aquifers, whose waters are flowing to a common outlet, and which is delimited by a groundwater divide.

Groundwater dating: Determination of the time between the recharge of groundwater and its sampling.

Groundwater flow: Movement of water in an aquifer.

Groundwater level: Elevation, at a certain location and time, of the water table or pressure head of an aquifer.

Groundwater mining: (Strict) – Groundwater persistently withdrawn at a rate exceeding interannual recharge, (Extended) – Groundwater storage continuously depleted by withdrawal.

Groundwater overexploitation: Withdrawal from a groundwater reservoir in excess of the average rate of replenishment (see also: Groundwater mining).

Groundwater preservation (syn. Groundwater Conservation): Maintaining the hydraulic and hydrochemical integrity of the groundwater system.

Groundwater protection: Measures to protect groundwater from adverse human and natural impacts (e.g. depletion, pollution) above and within aquifers.

Groundwater runoff: That part of the runoff which has passed into the ground, becomes groundwater, and is discharged into a stream channel as spring or seepage water.

Groundwater storage: Quantity of water in the saturated zone of an aquifer.

Groundwater vulnerability: An intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts.

Hard rock aquifer: Consolidated rocks permeable mainly along fissures.

Hazard: A potentially damaging physical event or phenomenon that can harm people and their welfare. Hazards can be latent conditions that may represent future trends, as well as being natural or induced by human processes.

Hydraulic conductivity: Property of a saturated porous medium which determines the relationship between the specific discharge and the hydraulic gradient sustaining it.

Hydraulic gradient: In porous media: the decrease in piezometric head per unit distance in the direction of flow.

Hydrogeological boundary: Discontinuity in geological material, marking the transition from the permeable material of an aquifer to a material of significantly different hydrogeological properties.

Hydrogeology: The branch of geology which deals with groundwater and especially its occurrence.

Hydrological cycle: Succession of stages through which water passes from the atmosphere to the earth and returns to the atmosphere.

Hydrological network: Aggregate of hydrological stations and observing posts situated within any given area (basin, aquifer, administrative unit) in such a way as to provide the means of studying the hydrological regime.

Hydrological regime: Variations in the state and characteristics of a water body which are regularly repeated in time and space and which pass through phases, e.g. seasonal.

Hydrological year: Continuous 12-month period selected in such a way that overall changes in storage are minimal so that carryover is reduced to a minimum.

Induced recharge: Withdrawal of groundwater at a location adjacent to a stream or body of surface water so that lowering of the groundwater level will induce water to enter the ground from the stream or surface source.

Infiltration: Flow of water from the land surface into a porous medium.

Influent seepage: Movement of gravity water in the zone of aeration from the ground surface toward the water table.

Intake area (syn. Recharge area): Area which contributes water to an aquifer, either by direct infiltration or by runoff and subsequent infiltration.

International groundwater (cross-boundary basins) **:** Groundwater which is either intersected by an international boundary or that part of a flow system of surface water and groundwater, parts of which are situated in different States.

Isotopes: Atoms of a single element, either radioactive or stable, with differing atomic or nuclear mass.

Isotopic fractionation: Change in the ratio of the isotopes of an element caused by rate-sensitive processes, such as change of phase, diffusion or chemical reaction.

Isotopic tracer: Artificial (added to water) or natural (present in water) tracer which is an isotope of one of the elements present in water.

Karst hydrology: That branch of hydrology which deals with soluble geological formations having fractures and solution channels, which enable underground movement of large quantities of water.

Laminar flow: Flow of a fluid in which the viscous forces are predominant (non-turbulent).

Landslide: A general term covering a wide variety of mass-movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock material in masse.

Leakage: Flow of water from or into an aquifer through underlying or overlying semi-pervious layers.

Losing stream: Stream losing water to the subsurface, and contributing water to the saturated zone.

Mineral water: Water which contains significant quantities of mineral salts (>1g/L).

Monitoring: Continuous or frequent standardized measurement and observation of the environment, often used for warning and control.

Mudflow: Flow of water so heavily charged with earth and debris that the flowing mass is thick or viscous.

Observation well: Well used for measuring physical or chemical parameters of groundwater.

Outflow: Flow of water out of stream, lake, basin, aquifer, etc.

Overdraft: Amount of water withdrawn from a water resource system in excess of the optimal yield.

Permeability: The property or capacity of a porous rock, sediment, or soil for transmitting a fluid: it is a measure of the relative ease of fluid flow under unequal pressure.

Perched groundwater: Groundwater body, generally of moderate dimensions, supported by an aquitard or aquiclude and which is located between regional phreatic groundwater and the land surface.

Phreatic water (syn. unconfined groundwater): Groundwater occurring in the zone of saturation and having a water table.

Piezometer (litt. pressure gauge) A borehole sunk into a (confined) aquifer, the water level in which being a measure of the pressure in the aquifer.

Piezometric head (syn. hydraulic head): Elevation to which water will rise in a piezometer connected to a point in an aquifer.

Pollutant: A substance which impairs the suitability of water for a considered purpose.

Porosity: Ratio of the volume of the interstices in a given sample of a porous medium to the gross volume.

Radioactive dating: Method of age determination based on the property of radioactive decay of isotopes.

Radioactivity: Process through which an unstable (radioactive) atom of an element emits a sub-atomic particle or quantum to achieve a more stable configuration, which might be another element.

Recharge (syn. Groundwater recharge): Process by which water is added from outside to an aquifer, either directly into a formation or indirectly by way of another formation.

Remote sensing: Measurement of, or acquisition of information on, some properties of an object, area or phenomenon by a recording device that is not in physical or intimate contact with the object or phenomenon under study.

Residence time: (see also age) Period during which water or a substance remains in a component part of the hydrological cycle.

Runoff: That part of precipitation that appears as streamflow.

Risk: The probability of harmful consequences or the expected loss (of lives, through injuries, damage to property or environment, livelihoods or economic activity disrupted) resulting from interactions between natural or human events and vulnerable systems. Conventionally, risk is expressed by the equation: Risk = Hazard x Vulnerability.

Risk assessment: Investigations of the potential damage that could be caused by a specific natural or human induced hazard to people, the environment and infrastructure. The assessment includes hazard or multi-hazard analysis, probability and scenario; vulnerability analysis (physical, functional and socio-economic); and the analysis of coping capacities and mechanisms. Risk assessment forms the necessary basis for the development of disaster mitigation and preparedness measures.

Salinity: Measure of concentration of dissolved salts, mainly sodium chloride, in saline water and sea water.

Salt water: Water in which the concentration of salts is relatively high (over 10,000 mg/L.)

Salt-water intrusion: Phenomenon occurring when a body of salt water invades a body of fresh water. It can occur either in surface water or groundwater bodies.

Saturated zone: Part of the water-bearing material in which all voids are filled with water.

Specific groundwater runoff: The average groundwater runoff per unit area of an aquifer or groundwater basin.

Specific discharge. The yield of a well per unit drawdown of the water level in the well.

Spring: Place where water flows naturally from a rock or sediment onto the land surface or into a body of surface water.

Stable isotope(s): Isotope(s) of an element which do not undergo change through radioactive decay.

Storage: Volume of water stored in the interstices of a water-bearing unit.

Storm: Heavy fall of rain, snow or hail, whether accompanied by wind or not, associated with a separable meteorological event.

Stratigraphy: The science of rock strata.

Stream flow: General term for water flowing in a stream or river channel.

Sustainability: Ability to meet the needs of the present generations without compromising the ability of future generations to meet their needs.

Tracer: Easily detectable material which may be added in small quantities to flowing surface water or groundwater to depict the path lines or to serve in the measurement of characteristics of flow, e.g. velocity, transit times, age, dilution, etc.

Transmissivity: Rate at which water is transferred through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the hydraulic conductivity and the thickness of the saturated portion of an aquifer.

Travel time: Time elapsing between the passage of a water parcel or packet between a given point and another point downstream.

Tsunami: Great sea wave produced by a submarine earthquake or volcanic eruption.

Unconfined aquifer: Aquifer containing groundwater with a groundwater surface identical with the piezometric head.

Unsaturated zone: The zone between the land surface and the water table. It includes the root zone, intermediate zone and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases.

Vulnerability (to hazard events)**:** A function of human actions and behaviour that describes the degree to which a socio-economic system is susceptible to the impact of hazards.

Wadi: Erosion channel which is dry except in the rainy season.

Waste water: Water containing waste, i.e. liquid or solid matter discharged as useless from a manufacturing process.

Water conservation: Measures introduced to reduce the amount of water used for any purpose, and/or to protect it from pollution.

Water management: Planned development, distribution and use of water resources.

Water policy: Collection of legislation, legal interpretations, governmental decisions, agency rules and regulations, and cultural responses which guide a country's actions concerning the quantity and quality of water.

Water resources: Water available, or capable of being made available, for use in sufficient quantity and quality at a location and over a period of time appropriate for an identifiable demand.

Water table: The imaginary plane in the saturated zone of a phreatic aquifer at which the pressure equals that of the atmosphere (approximated by the standing water level in a borehole).

Watercourse: System of surface water and groundwater constituting a unitary whole and normally flowing into a common terminus by virtue of their physical relationship.