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GROUNDWATER FOR EMERGENCY SITUATIONS

A Methodological Guide

Edited by Jaroslav Vrba and Balthazar Verhagen

IHP-VII Series on Groundwater No. 3

International Hydrological Programme

Division of Water Sciences

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This book is dedicated to the memory of

Jan Šilar

a long-time member of the
International Association of Hydrogeologists
and one of initiators of the project
Groundwater for Emergency Situations.

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Preface

The precipitate growth of disasters that affect ever-increasing numbers of humanity in recent decades and the inevitable attendant crisis in the supply of drinking water has prompted UNESCO IHP to undertake a project entitled 'Groundwater for Emergency Situations' (GWES).

The aim of the GWES project is to consider natural catastrophic events that could adversely influence human health and life and to identify in advance emergency groundwater resources resistant to natural and man-made disasters that could replace damaged public and domestic drinking water supplies. The project was approved at the 15th session of the Intergovernmental Council of the International Hydrological Programme (IHP) and included in the Implementation Plan of the Sixth Phase of the IHP (2002–2007), Theme 2: 'Integrated watershed and aquifer dynamics', under the title 'Identification and management of strategic groundwater bodies to be used for emergency situations that result from extreme events or in case of conflicts'. 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 evens by integrating various sources of data (historical, instrumental, satellite) to secure an improved understanding over large scales in time and space.

Considering the increasing frequency and impact of natural disasters on populations the Intergovernmental Council of the IHP approved the prolongation of the GWES project and implementation of its second phase within IHP-VII (2008–2013), Theme 1: Adapting to the impacts of global changes on river basins and aquifer systems, Focal area 1.3: Hydro-hazards, hydrological extremes and water related disasters.

The GWES project is implemented by an International Working Group composed by experts from UNESCO, International Association of Hydrogeologists (IAH) and other experts from different countries and regions. The activities and objectives of the GWES project were formulated at the first meeting of the Working Group held at UNESCO Headquarters, Paris (February, 2004). The preparation of a framework document was proposed by UNESCO as one of the first outcomes of the GWES project. The content of the document was discussed and approved at the above-mentioned Paris meeting. The second meeting of the Working Group took place at the UNESCO Offices in New Delhi, India (April, 2005). During this meeting the first draft of the document was evaluated and its final version agreed on. Groundwater for Emergency Situations – A Framework Document, edited by J. Vrba and B. Verhagen, was published by UNESCO in the IHP-VI Series on Groundwater No. 12 in the year 2006. It is available also on CD format.

Several workshops were organised in the first phase of the GWES project: Mexico (2004), India (2005) and Islamic Republic of Iran (2006). For the latter the Proceedings of the International Workshop, Tehran, 29–31 October 2006 are available as IHP-VI Series on Groundwater No. 15, published by UNESCO. A GWES project presentation has been organised on the seminar of the International Association of Hydrogeologists (IAH) Congress held in Toyama, Japan, in 2008.

The second phase of the GWES project sees implementation in the years 2008 –2013. Beneficiaries of the project will be governmental, water management and rescue authorities at all administrative levels (local, national, international) as well as local communities in the areas repeatedly affected by natural disasters. In such areas a timely investigation of emergency groundwater resources is essential in developing emergency drinking water supply policy and becomes imperative in risk management of groundwater resources resistant to natural disasters. This Methodological Guide supports the scope of the GWES project: Identifying, investigating, assessing, managing and mapping groundwater resources resistant to natural disasters that could be used in emergencies resulting from different extreme climatic and geological disaster events.

A very important aspect of the GWES project, 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 rendered helpless following a disaster, cut off from its traditional water supplies and faced with delays in aid from outside. This may lead to destabilization and demoralization at a time when people need to rebuild their lives. The empowerment inherent in the GWES approach enables people to take charge immediately, with ownership of knowledge and infrastructural means, to restore water supply from their own groundwater resources, thus forestalling lengthy deprivation and illness and releasing energies for general reconstruction.

This Methodological Guide provides background information on groundwater protection with particular reference to its use in emergency situations as result of natural hazards and hydrological extremes. It also outlines the governance policy framework in which groundwater as an emergency resource may be integrated into overall emergency management and service provision. To illustrate the principles and techniques presented in the Guide, a varied number of real world case studies from widely differing regions is presented.

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Coordinator of the GWES project

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Jaroslav Vrba and Balt Verhagen

1. Introduction

The aim of the UNESCO IHP project 'Groundwater for Emergency Situations' (GWES) is to consider natural catastrophic events that could adversely influence human health and life and to identify in advance emergency groundwater resources resistant to natural disasters that could replace damaged public and domestic drinking water supplies.

The GWES project was approved during the 15th session of the Intergovernmental Council of the International Hydrological Programme (IHP). It was included in the Implementation Plan of the Sixth Phase of the IHP (2002–2007), Theme 2: 'Integrated watershed and aquifer dynamics', 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 Second phase of the GWES project is implemented within IHP VII (2008–2013) by an International Working Group composed of UNESCO, and IAH representatives and experts from different regions of the world.

2. Groundwater: origin, occurrence and recharge

Fresh water on earth is a product of the hydrological cycle that links the huge reservoirs of the ocean with the atmosphere, the earth's surface and the lithosphere. In between these reservoirs the lithosphere acts as a retarding and storage link, smoothing the natural variations of the precipitation input, thereby enhancing the longer-term availability of renewable water.

On continents, liquid fresh water occurs predominantly as groundwater, which amounts globally to about 8,300,000 km^3 and may occur to depths up to some kilometres beneath the earth's surface. Groundwater reflects both present and past replenishment by rainfall (recharge) and some groundwater is trapped in aquifers since the formation of the sediments (connate water). However, the present water cycle provides only 44,800 km^3 of yearly excess discharge from exorheic, or externally draining, continental catchments, which is equivalent to the contribution of the oceans to the continental water cycle. This excess recharge is low as compared to 8,300,000 km^3 of groundwater stored beneath continents. As a consequence, fresh water resources are limited in quantity and, when considering the interference of human activities, also in quality.

For the development of groundwater management and protection strategies it is important that groundwater recharge rates as well as the structure, geometry and hydraulic properties of aquifer systems should be known. The determination of the groundwater recharge rate is both scale and time dependent and should therefore be based on the simultaneous application of independent methods of investigation. Recharge can be approximated by water balance methods, which however do not apply successfully in all climate zones. An exception is the chloride balance method, in principle applicable in all climates, provided that there are no chloride sources other than precipitation, that groundwater is sufficiently mobile and that surface runoff can be adequately accounted for. The distribution of groundwater recharge also varies with depth. The variability is enhanced by differing hydraulic properties of the aquifer system. Numerical modeling for typical sequences of hydraulic conductivities in aquifer systems shows that on average more than 85% of the recharged groundwater discharges through the near-surface, the so-called active recharge zone, that may reach a depth of some 100 m. Less than 15% discharges through deep aquifers – the passive recharge zone that may extend to much greater depths. In critical situations, following natural disasters or serious pollution events in water-scarce areas, water supply is sought mostly in the passive recharge zone, which can be exploited in the short term, without producing irreversible quality changes of groundwater. Such measures, however, should be controlled by an early warning monitoring system.

3. Groundwater: an emergency source for drinking water supply

The uneven distribution of groundwater recharge with depth results in 'young' and 'old' groundwater in the active and passive groundwater recharge zone, respectively. Groundwater extraction produces quite different hydraulic stresses in each of these zones. Shallow groundwater reacts more or less instantaneously to stress in as far as no overexploitation occurs; whereas in deep groundwater the hydraulic reaction to stress is considerably dampened, the hydraulic response becoming apparent only after years, decades or even centuries.

Emergency water resources may be sought in shallow aquifers in catchments away from flood plains and the influence of extreme natural events. However, shallow water table aquifers are highly vulnerable to drought and human impact, particularly to pollution. To operate such an emergency resource for drinking water supplies requires moreover, the construction of costly water distribution networks and involves long construction times. Such solutions are preferable for areas affected by foreseeable disasters such as floods and hard-to-control instances of water quality degradation.

Deep groundwater is often confined, protected from downward influx of pollutants and impact of natural disasters (floods, droughts, tsunamis) and therefore, a favourable emergency resource. Its recharge and hydraulic response differs from those of more vulnerable shallow water resources. However, the exploitation of deep groundwater involves special drilling, exploration and management measures. As deep aquifers tend to be more extensive, wells can be located closer to the point of consumption, with shorter and lower cost connections to existing distribution networks and also closer to or even inside the area affected by natural disaster events.

4. Tools for identifying and exploring emergency groundwater resources

Within the objectives of the GWES project, the identification of groundwater resources of low vulnerability – naturally protected against harmful natural and man-induced impacts – is seen mainly in deep-seated, mostly confined aquifers with renewable or even non-renewable groundwater. The investigation of such groundwater resources requires an interdisciplinary approach and involves the implementation of more sophisticated methods directed towards an understanding of the geological environment in which groundwater aquifers are formed.

The more classical disciplines of groundwater investigation such as geology, hydrogeology and hydrochemistry are complemented with the methods of geophysics, isotope hydrology, remote sensing and mathematical modeling. Integrating these methods facilitates establishing a conceptual model of a groundwater system and identifying the aquifer geometry and boundaries as well as the flow paths, residence time and origin of groundwater. Hydrogeological maps and groundwater vulnerability maps are both important means by which to present the outcomes of such complex investigations. The following sections describe methods applied in the identification, investigation, assessment and management of groundwater resources with low vulnerability, resistant to natural disasters and suitable as a source of drinking water for emergency situations.

4.1 Geology

The geological setting generally controls the occurrence, movement and properties of groundwater as well as geological hazards such as earthquakes, volcanic activities, and landslides. The petrological composition of rocks influences their physical and mechanical properties, including their porosity and permeability. It also affects geochemical processes and thus the chemical composition of groundwater. Geological structure and surface morphology influence aquifer geometry and the spatial distribution of the groundwater flow system. Analysis of the geological structure is particularly needed to obtain an overview of the tectonic setting and development of tectonic phases of the studied region.

Geological maps and sections and satellite and aerial photographs illustrate the geological features of regions studied. They are useful in support of both an investigation of groundwater resources and delineation of areas prone to geological disturbances. A geological map should show the composition of the rocks and the geological structure of the investigated area. 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 drawn to different scales. Maps showing tectonic zones with earthquake activity are usually at small scale as they represent large regions and continents, while maps designed to indicate specific local 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 specific local geotechnical, environmental or other relevant issues.

4.2 Hydrogeology

Groundwater occurs within the broad context of the global hydrological system. In nature, groundwater drives many geological, geochemical and biochemical processes. Groundwater also maintains critical ecological services , sustaining springs, river base-flow, lakes and wetlands. The study of groundwater requires an interdisciplinary approach the better to understand its occurrence and movement in the physical environment, its chemical properties and growing human influences on its regime. The ability of the rock to transmit water through its interstices of various shape, size and origin is expressed as rock permeability. In permeable rocks groundwater forms aquifers and aquifer systems. On a regional scale, the occurrence of groundwater aquifers is controlled by structural tectonic features (fractures, faults, fissures, folds, cleavages) and discontinuities. The extent and geometry of many aquifers and groundwater flow direction and storage within them are constrained by faults or folds which may be significant as either groundwater pathways or groundwater barriers (impermeable boundaries).

Within the scope of the GWES project, attention is focused on the identification and description of aquifers of low vulnerability to natural and human impacts. The thickness, lithology and permeability of the unsaturated zone, groundwater level below surface, the physical and hydraulic conditions of the aquifer (confined, semi-confined, unconfined) and origin and age of groundwater are decisive in groundwater vulnerability assessment. General and thematic hydrogeological maps and groundwater vulnerability maps are very useful means for visual presentation of groundwater conditions and aquifer vulnerability and assist in delineating and depicting groundwater resources resistant to natural disasters.

When prospecting groundwater resources for emergency situations attention should ideally be given to deep confined aquifers in sedimentary basins; deep unconfined aquifers with a thick unsaturated zone inter-bedded with layers of low permeability and local extent, and deep aquifers with limited replenishment, containing essentially fossil water recharged during past pluvial periods.

4.3 Hydrochemistry

Groundwater chemical composition and age, or residence time, are significant indicators for identifying emergency groundwater resources. The chemical composition of groundwater is the result of the combined effect of hydrogeochemical and biochemical processes occurring in the soil groundwater-rock system. 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 with residence times of years to a few decades has a lower dissolved solids content than groundwater in discharge areas and in deep aquifers hundreds to thousands of years old. The anion dominance evolution sequence $HCO_3^- - SO_4^{2-} - Cl^-$ reflects the change from oxidising conditions with HCO_3^- as the major anion (shallow zone) into reducing conditions where chloride gradually becomes the dominant anion (deep zone). Saline, chloride-rich connate water in the deep zone is usually very old, the ages varying from thousands to millions of years. However, high salinity groundwater is found also in arid and semi-arid regions, even in shallow aquifers. Inverse and forward geochemical modeling helps to clarify the chemical evolution and thereby the origin, or recharge pathway, of groundwater.

The chemical evolution and zoning of groundwater described above could be disturbed in geological structures affected by tectonic faults interconnecting aquifers carrying water of different origin and age. The same applies to coastal aquifers where the chemical composition of fresh groundwater is influenced by the intrusion of saline water. The impact of natural disasters particularly floods, earthquakes and volcanic eruptions on the quality of groundwater has been reported in many parts of the world.

Biological activity enhances the extent and rate of geochemical processes. It is particularly intensive in the uppermost soil and root domain of the unsaturated zone, where dissolved oxygen is usually available to organisms which break down organic matter.

4.4 Isotope hydrology

Groundwater movement can be studied by injecting tracers and following their pathway. Such tracing is subject to severe spatial limitations. Environmental isotopes continuously label groundwater during recharge and therefore trace the entire system. Conventional geohydrology studies the movement of water under the influence of pressure changes. Implicit in isotope hydrology is the transport approach. These two approaches complement each other: when the results converge, a viable conceptual model is indicated. Often an 'isotope snapshot', the data from a single survey sampling of a groundwater system, can provide a tentative conceptual model. Environmental isotope hydrology is increasingly seen as indispensable in understanding and quantifying groundwater systems and is particularly suited to assessing deep-seated emergency groundwater resources.

There is a large range of isotopic species that can be applied to hydrology, mainly of the light elements H, He, C, N, O, but some heavier elements can also be employed. Radioactive species provide information on the dynamics of groundwater. The non-radioactive, or stable, species give information on the origin and pathway through hydrogeological systems, their abundance established by fractionation processes prior to or during recharge. The decay of cosmic radiation-produced radioactive species, e.g. ^{3}H, ^{14}C and ^{39}Ar, allows for the assessment of the residence time of groundwater in the range of decades up to millennia.

In order to interpret radioactive isotope data, hydrodynamic models are employed. These are usually lumped-parameter models, in which the system is divided into one or more 'boxes', each with uniform parameters. This underlines the ability of environmental isotopes to integrate changes in input and flow over time. Two of such models are the exponential model, that idealises a water table system and the piston flow model, characterising a confined aquifer. Such models also apply to dissolved fluorocarbons that, although not radioactive, can be used as short-term 'dating' tools on account of their increase in the atmosphere over the past 60 years.

Non-radioactive, or stable, isotopes act as tracers on account of fractionation (change of concentration) occurring during phase changes, and other physical and chemical processes. Thus the isotope ratios of hydrogen and oxygen can be followed through the hydrological cycle and characterise rain and infiltration into the sub-surface. The global meteoric water line, depicting the relationship between these isotopes in rainfall, acts as a benchmark for interpreting analytical data in terms of (ground)water provenance. In similar ways, the abundance of ^{13}C can be interpreted in terms of the origins of dissolved inorganic carbon, a basic constituent of groundwater and important in understanding hydrological and hydrochemical processes. Isotopic species such as ^{15}N and ^{34}S are useful in pollution source tracing.

4.5 Geophysical methods

In order to investigate strategic groundwater resources for emergency situations, geophysical methods have been proven both rapid and reliable. Geophysical methods detect anomalies caused by the contrast in the physical properties of geological strata such as resistivity, magnetic susceptibility, density, seismic wave velocity or radioactivity which in turn may be related to the occurrence of groundwater.

The application of geophysical methods in groundwater exploration has several advantages as these methods are generally low cost and time effective. Further, the methods can provide quantitative data regarding hydrogeological properties, geometry and depth of aquifers, groundwater quality, freshwater/salt water interface, delineation of structural and tectonic features controlling groundwater movement. The methods even provide guidelines for proper well construction after drilling. However, geophysical methods are not free from limitations. Since geophysical methods are indirect and utilise matrix phenomena of the subsurface, different strata may present similar anomalies. A combination of two or more methods therefore may be required such as electrical, seismic, magnetic, gravity, radiometric methods and well logging. Electrical Resistivity Methods (ERM) are most commonly employed, because of the simplicity of the techniques used in the field, and relatively low cost of equipment. In addition, quantitative data on the depth of occurrence of groundwater is obtainable through ERM in the field. Newly developed methods like MASW (Multi-channel Analysis of Surface Waves), GPR (Ground Penetrating Radar), Radon Emanometry and PMR (Proton Magnetic Resonance) may also prove valuable in the exploration of deep emergency groundwater resources.

4.6 Remote sensing

Remote sensing, with its advantages of rapid availability of spatial, spectral and temporal data covering large and inaccessible areas, has become a very effective tool in the identification of groundwater resources in various geological environments which can be used in emergency situations. Satellite data provides quick and useful baseline information on the hydrological parameters controlling the occurrence and movement of groundwater. Visible and infrared imagery is used to map rock lithology, soils, vegetation and tectonic structures. Radar is used to map tectonic structures and soil moisture.

In unconsolidated sediments, it has been possible to locate groundwater seepage patterns, as well as buried river and stream channels. It is possible to locate paleochannels based on the moisture content in the soils and also on vegetation patterns observed above buried channels. Desert regions have hosted many humid phases in the past. Surface water was channeled by drainage patterns, some of which are now exposed, and others covered by aeolian sand. The penetrability of radar is helpful to directly identify shallow groundwater bodies in buried stream channels and mountain peneplains. In hard-rock environments, digitalised aerial photographs and satellite images have been used to locate fracture zones and lineaments that may store and transmit groundwater. Delineation of faults and fracture intersections is used as a tool for deeper groundwater detection using remote sensing and ground penetrating radar techniques. Lineament analysis has provided useful information on the fracture permeability of aquifers.

4.7 Conceptual and mathematical modeling of groundwater systems

Setting up a conceptual model is a critical step towards a more quantitative representation of sub-surface hydrology, such as a numerical groundwater flow model for predicting groundwater behaviour under various stresses. The conceptual model allows for more general conclusions and identifying gaps in the data required for more quantitative analysis.

Groundwater flow models, whether conceptual or numerical, are a form of water balance calculation, of inputs and outputs and the change of storage, and are useful in assessing deeper groundwater bodies as emergency resources. Confidence in a model is increased through testing, using lumped parameter and mass balance calculations.

The development of a conceptual model is ideally iterative, involving the continual updating of monitoring data. The model must identify crucial factors influencing the system. It is important not to over-simplify, thereby losing valuable structure, or under-simplify, resulting in excessive complexity.

The required base data can be collected from a variety of documented sources. More detailed information usually requires a hydrocensus, field investigations and borehole drilling that will define the geometry and geological structure of the aquifer system. Isotope hydrology can suggest a conceptual model when none is available, can test the outcomes of existing models and provide quantitative parameters for numerical models. An isotope-based residence time can define monitoring frequency, and rough simulations guide further data gathering efforts. The conceptual model should anticipate the ability of an aquifer to deliver the required yield for a specified period and rate of recovery after groundwater emergency over-exploitation.

Mathematical models, based on mass and energy balances of the natural hydraulic system, are useful in steering field investigations, checking data consistency, and predicting the future behaviour of the investigated system under hydraulic stress. They can also be employed in developing water management and resource protection and in providing an early warning tool for hydraulic systems with a transient response to stress in emergency situations.

Mathematical models are often based on the bulk (lump-sum) parameter approach but also on detailed parameter distribution in the hydraulic system (numerical models) with a variety of intermediate transient models. Lump-sum models, such as piston flow, exponential and dispersion parameter models were developed in the early stages of hydrogeology. In contrast, numerical models are based on a grid of nodes with known hydraulic conductivity and hydraulic head and recharge along system boundaries, and often linked to a Monte Carlo approach to better differentiate between most probable and random results.

4.8 Geographical Information Systems (GIS)

Geographical Information Systems (GIS) are indispensable in presenting, processing and analysing groundwater data. These days most hydrogeological investigations use GIS-tools in combination with a groundwater database. Different types of data can be plotted on a map and then processed to prepare input for groundwater resources calculations such as simulation models. One of the strengths of GIS is the capability to process huge amounts of geo-referenced data. Spatial statistical methods such as Kriging are a feature of most GIS systems and can be applied to interpolate hydrogeological parameters. With GIS it is also possible to derive new thematic maps from overlays of existing maps or a combination of topographical or geological data with remote sensing images.

GIS has particular advantages in the handling of specific natural disaster issues and therefore will be part of any investigation into the availability of groundwater resources in emergency situations. It can offer support through web-based applications enabling dissemination of urgently needed geographical information through the internet.

GIS-technology allows advanced users as well as novices to access groundwater data at different levels. Today, a groundwater information system based on the combination of GIS and a groundwater database is an open system tailor-made for the storage and processing of data and forms an important component of the tools at the disposal of modern hydrogeologists and other geoscientists.

5. Risk assessment and management of groundwater resources in emergency situations

Natural hazards, be they climatic and hydrological (droughts, floods, storms) or geologic (earthquakes, volcanoes) or a combination of these such as tsunami and landslides, invariably result in huge numbers of casualties, damage to infrastructure and a shortage or unavailability of drinking water. This chapter deals with the main characteristics of different natural hazards and of the risk mitigation, assessment and management methods which may be considered in the formulation of water policy in emergency situations. Such policy should produce strategies or guidelines for solving problems related to drinking water supplies, particularly to the identification, investigation, assessment and management of groundwater resources resistant to natural hazards. Natural hazards are known to recur, historical records often providing vital information from which to estimate their recurrence period. Such data would be very useful in preparing various types of geological, hydrogeological, hazard and vulnerability maps that depict areas or regions prone to a particular type of hazard and show various groundwater aquifers resistant to such hazards. Suitable aquifers ideally should be of large areal extent, with favourable hydraulic properties, storing groundwater of reasonably good quality, with large residence or turnover time ensuring low vulnerability to both natural and human impacts and able temporarily to be overexploited during a period of emergency.

Each emergency situation calls for a specific approach and management strategy. The delineation of protection and risk zones for hydrological, climatic and geological hazards, imperative in drinking water risk management, requires prior knowledge of the minimum water requirement per capita and numbers of affected population in the event of a natural calamity. The task of risk management is to compare such data with emergency groundwater resources, to assess these resources in quantity, quality and vulnerability well in advance of emergency situations, and to sustain these water supply schemes.

5.1 Groundwater risk assessment and management in flood-prone areas

Amongst the natural catastrophies mankind has to face, floods are the most common. They are caused most frequently by a coincidence of meteorological and hydrological circumstances; however, flooding might also have geological and man-made causes. The circumstances leading to floods change with time due to the natural evolution or human alteration of the landscape of catchments and river beds. Even in arid regions, communities residing in or near wadis may be devastated by floods.

Resistant groundwater resources for substituting flood damaged public and domestic water supplies can be found mainly in e.g. confined aquifers with a piezometric surface well above the confining layer; in aquifers overlain by rock formations of low hydraulic conductivity which attenuate infiltration from the surface, and in groundwater systems with a hydraulic potential increasing with depth, i.e. with a natural upward flow. In mountainous regions springs located on the slopes well above alluvial plains may also be used for emergency water supply.

Streams interact with groundwater, along either gaining or losing sections. These should be identified, and the fluxes involved assessed through flow data obtained by calculation, by qualified estimation or more precisely through e.g. isotope data. Losses or gains of groundwater to or from streams have to be known in terms of the available amount of emergency groundwater and its vulnerability. Maps showing stream flow networks and surface water bodies, land use, inundation and vulnerability are other valuable documents in the process of delineating and assessing aquifers resistant to floods. Sources of potential pollution, both natural and man-made, in flood-plains have to be identified and evaluated with respect to their origin, chemical composition and physical type, and the mode and extent of their discharge.

In regions repeatedly affected by floods the following managerial measures should be adopted: 1/identification and assessment of flood risk considering particularly the vulnerability of existing public and domestic water supplies; 2/ calculation of water demand for the population living in flood plain areas; 3/ construction of hydrogeological, vulnerability and inundation maps; 4/ ground-truth and inventorise existing wells and springs vulnerable to floods; 5/ establishment and operation of early warning monitoring systems for both surface water and groundwater; 6/ identification and evaluation of safe groundwater resources resistant to flood events; 7/ drilling, appropriately equipping and testing of new emergency wells in aquifers proved to be resistant to flood impact; 8/ informing the population about the location of emergency drinking water sources, the rules governing their use and water distribution during and after flood.

Where local emergency drinking water resources cannot be developed, an emergency system of water supply by mobile cisterns and related water distribution network has to be secured.

The rehabilitation of flood-damaged water supplies and drinking water distribution networks has to be prioritised considering not only the importance of water sources for human survival, available manpower and technological and financial resources but also the time needed for the physical reconstruction of water supply facilities and water quality remediation. The responsibility for assessing and mitigating flood risk, and the establishment of drinking water supply emergency plans both rest on governmental authorities as well for education, information and building the resilience of the local population to flood disasters. Floods cannot be prevented but their detrimental effects can be controlled and managed.

5.2 Drought: identification, investigation and risk management of emergency groundwater resources

Drought is a recurrent phenomenon and ranks about equally amongst other natural phenomena that may constitute disasters in all environments and climates. Droughts differ from phenomena such as floods and earthquakes in their rate of onset, duration and knock-on effects. Drought should not be confused with aridity. It is a region-specific concept and can be difficult to define. Operational definitions identify meteorological drought – the lack of precipitation; agricultural drought, when root-zone moisture cannot sustain crops; and hydrological drought, where the impact on hydrological systems becomes marked. Groundwater drought is a consequent hazard, with delayed and complex responses.

The impact of meteorological drought on groundwater may depend on factors such as the severity and length of the episode; design and location of wells and boreholes; hydraulic characteristics of the aquifer tapped; excessive demand and consequent source failure, exacerbated by poor maintenance; long-term increases in demand and long-term climate changes. Criteria for drought emergency groundwater supplies have features in common with normal supplies as their function is not immediately threatened. The usually gradual onset of drought can set off pre-determined thresholds or 'triggers' for engaging various emergency supplies and measures to be activated. Groundwater protection is of secondary importance where there are no anthropogenic threats, and all sources, shallow and deep should be considered. Sustained exploitation or timely limited groundwater overexploitation at predicted rates should be assured, as well as the maintenance of quality against drawing-in of saline water.

Drought vulnerability maps can be useful management tools. These would be based on two major components: a physical data set such as aquifer type, groundwater level depth, yield and recharge, and a sociological data set, such as population density, supply coverage and access, and traditional sources. Superimposing these sets can identify the geographic spread of risk, facilitating management planning.

Early warning systems are not un-common for meteorological drought but still rare for groundwater drought. Both global and regional scale monitoring can be employed, especially long-term trends in groundwater observational networks with the scope to identify drought management areas.

Mitigation triggers can be activated when supply and demand begin to be imbalanced, or on the basis of rainfall and soil moisture indices. Responses can be applied in stages: curtailing demand when supply falters; deepening of existing wells and activation of reserve wells; tapping un-conventional sources such as roof-top rain harvesting; construction of artificial recharge installations. The fundamental requirement is a well-conceived drought emergency management plan.

Drought risk management for groundwater is part of an overall drought management strategy, involving governmental activities at all levels. Basic is a national people-centered drought policy, integrating all sectors, community education and capacity building, protection of livelihoods and cooperation with the international community. Specific management steps could include the consideration of the actual and potential effects of climate change; groundwater monitoring; ongoing testing and maintenance of supply systems; identifying aquifers for emergency supply using standard modern techniques as enumerated above such as hydrogeological and isotope techniques to establish supply sustainability, and modeling groundwater systems; establishing control of emergency drinking water supplies and developing integrated risk management strategies, considering the demographic situation and agricultural practices. Regional management can be of vital importance as groundwater systems and catchments often straddle international boundaries, and is essential in identifying capacity needs in the relevant countries. As groundwater is the only dependable source in the extensive arid areas of the world, careful management is needed to achieve the Millennium Development Goals.

5.3 Groundwater risk assessment and management in regions affected by earthquakes

The theory of tectonic plates has firmly established that certain regions of the earth, both terrestrial and submarine, are more vulnerable to earthquakes. Earthquakes are recurrent in plate boundary areas such as Japan, Iran, western Americas, Italy, India, New Zealand, Indonesia and the Philippines. Earthquakes cause not only huge destruction or devastation of infrastructure and very high rates of mortality, but also cause surface geomorphologic deformation, tilting, liquefaction of sediments due to increased pore pressure, slope failures, landslides and tsunamis. In the immediate aftermath of an earthquake, the disruption of drinking water supplies and other daily needs may assume catastrophic proportions.

During several earthquakes, a drastic change in groundwater level has been observed. Water tables may decline for more than a year in some cases, which poses a significant problem for inhabitants relying on shallow wells. On the other hand a drastic increase in the discharge of springs and flow of streams may occur, constituting small scale floods in valleys and low-lying land areas.

It is well known that the groundwater level in confined aquifers fluctuates due to earthquake induced crustal volumetric strain changes and depends on the magnitude, distance from the epicentre and source mechanism of an earthquake. In some cases a drop of groundwater level due to changes in crustal strain results in the loss of discharge of hot springs – a situation which may continue for several months (e.g. Kobe earthquake, Japan, 1995). On the other hand, the emergence of new springs could opportunistically be used as a temporary water supply resource. A drop in groundwater level was observed on one side of a fault, and a groundwater level rise on its other side (Chuetsu earthquake, Japan, 2004).

It is generally observed that urban areas are more severely affected by earthquakes, as major infrastructure collapses. In the Kobe earthquake, 80% of the households of the city were cut off from water supply due to ruptured water mains. Developing better methods for quake-proofing pipelines, installing shallow wells with hand pumps, small-scale water supply systems with membrane filtration and facilities for rain water harvesting and conservation are amongst important managerial measures with which to tackle water supply failure due to earthquakes. Minimum total water demand (for fire fighting, medical activities, daily drinking, washing and sanitation etc.) needs to be estimated. Various water sources, particularly existing wells, should be identified and characterised according to quality for different usages, e.g. high water quality for medical and drinking purposes. An emergency plan is to be developed for securing water from different sources and activated using governmental mechanisms and volunteers to mitigate the emergency situation after an earthquake. A system for groundwater level and quality monitoring data collection and the evaluation and mapping of existing public and domestic wells are further important managerial measures to secure groundwater sources for an earthquake emergency.

5.4 Groundwater risk assessment and management in areas affected by volcanic activity

Volcanic eruptions pose a formidable hazard to people living in volcanic areas. In common with earthquakes, volcanic activity is related to plate tectonics, in particular to extensional and convergent plate boundaries. Approximately 80% of all active volcanoes are located in 'the ring of fire' slung around the Pacific Ocean, a smaller percentage in the Atlantic Ocean, around the Mediterranean Sea, in the Indian Ocean and elsewhere. A volcanic eruption is generally quite damaging to the environment, involving the emission of lava, pyroclastic material, ash and water vapour, as well as the emission of a number of toxic gases. Chemical reactions may on occasion convert sulphur compounds into sulphuric acid that is precipitated as acid rain. The products of volcanoes pose not only such immediate hazards but can as well cause long-term climatic and atmospheric perturbations.

Volcanic eruptions can have a dramatic impact on both surface water and groundwater, though surface water will clearly be at far greater risk. Explosive eruptions which expel great quantities of gravel and sand can obliterate watershed divides, disrupt drainage patterns, modify river channel size and the shape and pattern of water structures, thereby affecting runoff, erosion, sediment transport as well as water supply and sanitation facilities.

The impact of volcanic eruptions on the chemical quality of water resources obviously will depend on the magnitude of the eruption and also on the varying amounts of eruption products such as pyroclastic material, volcanic ash, lahars, or volcanic gases. Ash fallout may affect the landscape and groundwater recharge for hundreds of square kilometres surrounding the volcano. The local surface water could become heavily ash laden. An obvious immediate response would be to disconnect all roof top rain water harvesting supplies.

An early warning system would ensure that a volcano be monitored regularly at a level commensurate with the threat it poses. A state of the art warning system would include satellite imagery, remote sensing of eruption clouds, of gases such as sulphur dioxide, escalated heating of the ground, and real time data on seismicity and ground deformation. Sudden changes in groundwater level and in the discharge rate of springs and their chemistry may also be precursors, and act as indicators of, growing volcanic activity and should be part of an early warning monitoring system. Also, for preparedness and risk management plans, it is important to have knowledge of the recurrence period of volcanic eruptions obtained from historical and geological records, the geographical distribution of inhabitants whose lives are at risk and an estimate of their water requirements.

For addressing the problem of water supply, suitable aquifers which could produce groundwater of acceptable quality even in the event of volcanic eruption need to be identified and investigated and accessible groundwater resources assessed. The geometry of cold aquifers formed in the close vicinity of a hydrothermal system needs to be delineated. Recent studies have shown that springs whose recharge area can be shown to lie outside the probable sphere of influence of volcanic activity can prove to be a valuable resource in an emergency situation. Isotope and hydrochemical measurements provide invaluable information about the origin and recharge area of such, sometimes high yielding, springs that may constitute a source of safe drinking water for a population living within the volcanic impact territory. Isotope studies in the volcanic area may also help to identify groundwater of meteoric origin in certain aquifers which at depth may contain a certain proportion of thermal water. The origin of groundwater, its residence time and flow path can therefore become an integral part of groundwater risk management in volcanic emergency situations.

Another management strategy to be adopted for mitigating the drinking water problem for volcanic emergencies is to identify and map potential water supply bore-wells and raising their casings sufficiently for them not be buried below ash or other volcanic ejecta.

5.5 Groundwater risk management in areas affected by landslides

Amongst the examples of environmental emergencies discussed in this volume, landslides are arguably the only hazard which may be triggered, or exacerbated, by groundwater itself. A landslide is a common geological calamity in hilly or mountainous terrain in which a large volume of soil, clay, rock and other clastics accumulated through erosion on a slope becomes unstable and may slide down along a failure plane under the influence of gravity and water. Landslides frequently occur in regolith, sliding down along a contact interface with bedrock or moving along a bedding or a fault plane. The main factors inducing landslides are rainfall, earthquakes, scouring and soaking by surface water and also human intervention e.g. deforestation, construction of roads and dams. Generally the velocity of a landslide is very slow, several centimetres per day. Under extreme conditions such as storms or earthquakes, triggering earth or mud flows, rates of movement may reach 20 km/h. Large-scale landslides often claim human lives, may bury villages, destroy infrastructure inclusive of water supply and sanitation facilities, blockade rail and road traffic, temporarily impound rivers causing flash floods and debris flows on subsequent failure and severe damage on flood plains.

Water is the principal factor in the onset of landslides. Comprehensive groundwater studies, especially on changes produced by natural events and human activities have proven very useful for eliminating or reducing risks of water-induced edge slope destruction and for protecting water supply and sanitary facilities.

5.6 Tsunamis: risk assessment and management of groundwater resources

Tsunami are exceptionally large waves involving huge masses of sea water which move inland with destructive effect. The large energy represented by such waves may be developed from submarine seismic activity ($M \geq 6.5$ on the Richter scale) caused by fault displacement, by explosive volcanism, sub-marine land slides and exceptionally by major meteorite impact. Tsunami can be more violent and disastrous than the quake itself, a very important feature being the suddenness with which they engulf coastal areas. Therefore, tsunami hazard assessment has to take into account the huge and destructive wave energy imparted to the environment including groundwater in coastal aquifers as well as water supply facilities, water distribution networks or water treatment plants. Another important aspect is the transport of sediments, debris (chemicals, medicines, carcasses etc.) and of course salt water as far as several kilometres inland, which contaminate shallow fresh groundwater resources often used for drinking water supply. The most recent major tsunami experience in South-East Asia (2004) has starkly underlined the need for the installation and proper operation of tsunami warning systems and for the preparation of various kinds of vulnerability maps. Groundwater maps depict aquifer distribution and type, distance from the sea shore, depth of groundwater level below surface, groundwater quality, physical and environmental susceptibility of the affected area to tsunami impact, the presence of natural shields such as clay layers, and the availability of potentially safe water resources. Demographic information could also be of vital importance to highlight intervention priorities where populations may be disrupted and scattered in the immediate aftermath of a tsunami.

Considering water requirements for the tsunami-affected regions, the identification of possible freshwater resources resistant to tsunami events and evaluation of damage to water supply structures is a priority task. The most direct and notable impact is saline intrusion and pollution of groundwater in shallow public or domestic water supply wells. Desalinisation plants brought in to cope with the emergency may run into problems because of the lack of technical and financial resources to maintain the equipment. Attempts at rehabilitating wells invaded by salt water through controlled pumping are usually successful. Poorly controlled pumping often disrupts the freshwater/seawater interface common in coastal areas and may disturb groundwater quality for a very long time.

The development of new community wells to replace those polluted; cleaning of existing wells; active public participation in disaster mitigation procedures; identification and development of aquifers resistant to tsunami impact; and rainwater harvesting – these can be important measures for mitigating drinking water supply problems thereby reducing human suffering in regions affected by tsunami disasters.

5.7 Groundwater risk assessment and management in regions affected by storms

Storms are high velocity pressure disturbances in the earth's atmosphere designated as tropical and extra-tropical cyclones, hurricanes, tornados, or typhoons depending upon their strength and geographical location. These events are often destructive of the environment and infrastructure and may inflict human suffering and death. Historical records show that certain geographical regions, such as Asia and Northern and Central America are repeatedly affected by storm disasters. Hazards commonly associated with storms include storm (tidal) surge, high wind speed and intense precipitation. Early warning systems based on satellite observations and tracking of atmospheric pressure systems, computer models and tele-communication links are very useful tools in forecasting, managing and mitigating the impact of storm calamity.

Storms may damage water supplies and related water infrastructure and produce flooding that contaminates water supply systems as do frequently reported storm-associated flash floods, landslides and subsidences. Experience gained from extreme storm events in India clearly demonstrated, as in the case of tsunami, that most of the dug domestic wells up to 30 kilometres distance from the coast line were inundated by tidal waves, resulting in the marked deterioration in the groundwater quality of shallow aquifers. In regions prone to major storms drinking water supplies should therefore be identified, assessed and developed in deeper aquifers with good quality groundwater resources and resistant to storm impacts.

Such a management strategy for groundwater use in storm emergency situations applies in particular to coastal areas where saline groundwater generally prevails. The areal extent of the freshwater/saltwater interface can be delineated by implementing geophysical, isotope and/or geochemical methods. Locating water well sites on the basis of such activities will enhance the understanding and management of aquifers utilised during an emergency.

6. Protection of emergency groundwater resources

Many countries have a long tradition of groundwater protection responding to two challenges:

- general protection of groundwater recharge areas and other vulnerable sections of aquifers, which often extend over hundreds of square kilometres and
- special comprehensive protection of production wells based usually on two degree protection zones to guarantee high level water quality for drinking water supplies (see page 174).

Establishing a conceptual model of a groundwater system is the basis for both general and special groundwater resources protection and the delineation of protection zones. In many countries efficient protection of groundwater supply installations has been introduced more recently.

Protection of groundwater resources for emergency situations has to be based on knowledge of the entire aquifer system. Designs of groundwater protection zones and subsequent monitoring activities differ for shallow and for deep aquifers because of differences in groundwater behaviour and thus vulnerability to natural disasters and human impacts. The delineation and protection of the recharge area of a deep, usually resistant aquifer is of particular importance, as it may lie well outside the disaster prone area. There are also hydraulic differences in the magnitude of reactions of stressed shallow groundwater as compared to deep groundwater flow fields and of the reaction times during hydraulic stress situations. The hydraulic reaction of shallow groundwater is instantaneous, whereas deep groundwater shows a transient or delayed response. Furthermore, the ground water flow field, contributing to deep aquifers, differs significantly from that of shallow groundwater bodies, hence the protection zone cannot be designed in the same way.

Monitoring of both the quantity and quality of exploited groundwater is an important component of protection policy. Such monitoring is oriented to the specifics of different natural disasters and supports efficient groundwater protection measures and policy for emergency groundwater resources. Early warning systems in combination with conventional monitoring improve the prediction of pollution or other disaster impacts on the groundwater system. Early warning monitoring makes use of proxy indicators such as environmental tracers, which allow for recalibrating mathematical models thus refining the prediction probability of pollution. Numerous runs of numerical models with different initial and boundary conditions as well as intrinsic parameters, have shown that the transient hydraulic behaviour of deep groundwater may retard pollutants by years, decades and even centuries. Results of early warning monitoring may compensate for uncertainties in model parameters and allow timeous modification of groundwater management strategies in favour of efficient groundwater protection.

Data collection in early warning and groundwater monitoring is technically demanding, time consuming, and costly. However, threats to groundwater resources are increasing and implementation of relevant groundwater monitoring strategies is justified from social, economical and environmental points of view. Governmental institutions, water managers and other water stakeholders worldwide may not yet be prepared to accept the need of a groundwater monitoring and early warning strategy. However, reality on the ground and rehabilitation costs of affected aquifers suggest that groundwater monitoring may be an important cost-benefit approach for mitigating disaster risk and impact.

7. Groundwater governance policy in emergency situations

Developing effective governance policy to reduce disaster risks and social and economic vulnerability of the population and building the resilience of nations and communities to disasters were highlighted at the World Conference on Disaster Reduction (Kobe, Hyogo, Japan, 2005) and formulated in the Hyogo framework for action 2005–2015. These could be achieved through proactive, integrated, multi-hazard, and multi-sector approaches and activities in the context of various disaster phases - prevention, preparedness, emergency response, recovery and rehabilitation. All actors in water governance policy should actively participate in the protection of the population in regions repeatedly affected by disasters and take responsibility in all disaster phases. It needs to be acknowledged that there is a significant difference between developed and developing countries in both the economic potential to manage and mitigate emergency situations and the present status of water governance policy with respect to emergency drinking water supplies.

7.1 Emergency drinking water supply governance policy and related activities in different phases of a disaster

In the anticipatory phase the most important activities to ensure drinking water services in case of emergency are the identification and assessment of the potential disaster risk to and vulnerability of existing public and domestic water supply systems; also, the delineation and quantitative and qualitative evaluation of groundwater resources resistant to natural hazards. The exploitable volume of groundwater resources resistant to natural hazards has to be compared to the drinking water requirements of an endangered population. Maps depicting geology, hydrogeology and water resources vulnerability, combined with maps of disaster risk and inundation are also important activities in the anticipatory phase.

The warning phase involves the establishment and operation of specific and early warning monitoring groundwater systems for the different natural hazards. Geological monitoring systems are developed in many areas affected by earthquakes, tsunamis and volcanic activities. Both monitoring systems help to forecast and mitigate the impact of hazardous events, reduce human vulnerability and give early warning to local populations for timely evacuation.

The impact and relief phases are mainly focused on rescue efforts during and after disastrous events and on the prompt reaction of affected local communities and external help. Among the first priorities is the distribution of drinking water. However, existing water supplies are usually impaired and surface water and shallow groundwater is often polluted. Water supplies then frequently depend on importing bottled water or by tankers from surrounding areas outside the disaster's influence. This often involves serious and painful delays. Where safe emergency groundwater resources have already been identified and developed, the distribution of drinking water will be more rapid and effective and the impact on the social and health conditions of the population will be significantly reduced.

The rehabilitation phase with respect to drinking water distribution is usually long-term. Reconstruction of water supply systems and water distribution infrastructure may take weeks or months, remediation of polluted groundwater even years. One effective and rapid solution is cleaning, purging and disinfecting existing domestic wells and small rural water supply systems. The other is tapping aquifers resistant to natural impacts. In cases of drought, well deepening can be both straightforward and effective. In the case of floods, inundation and land use maps and water management and rehabilitation plans usually need updating. Systems for groundwater monitoring, and particularly for early warning, could be improved as well as drinking water supply protection and emergency policy. Governance experience gained should flow into education and training of human resources concerned with rescue and aid, and of public awareness campaigns, with the necessary sensitivity towards the ethical, religious and cultural background of the affected population.

7.2 Institutional and technical capacity building for groundwater governance policy in emergencies

The establishment of a water governance framework 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.

Institutional capacity building refers to governmental and water authorities, emergency water policy, the legal framework, disaster risk reduction and rescue systems, the availability and capacity of rescue teams composed of professionals and volunteers, as well as public participation, information and education.

Technical capacity building includes groundwater system analysis, inventorising and evaluating climatic and hydrological data and historical data on earlier disasters, groundwater specific and early warning monitoring, interdisciplinary research, and transfer of knowledge and expertise.

8. Concluding remarks

Secure drinking water for endangered populations is one of the highest priorities during and after natural disasters. This lies at the core of the UNESCO-IHP project Groundwater for Emergency Situations (GWES). The GWES Framework Document was published in the year 2006. The main outcome and publication of the GWES project is this Methodological Guide complemented by case studies.

Another significant aspect of GWES project activities is organising workshops and seminars focused on groundwater in various types of emergency situations in different regions of the world. A series of such workshops has been held, e.g. in Mexico (2004), in India (2005), in Iran (2006), and others are planned. The GWES project was also introduced to the World Water Forum in Mexico in 2006.

The second phase of the GWES project was approved by the Intergovernmental Council of IHP and included in the Implementation Plan of the IHP-VII (2008–2013). Project activities during the second phase will be focused mainly on an inventory of groundwater bodies resistant to natural and human impacts in selected pilot regions; the development of methodology and legend of a groundwater vulnerability map depicting emergency groundwater resources; implementation of pilot studies (Orissa State in India affected regularly by storms and floods has been selected) and publication of the (present) GWES Methodological Guide. Cooperation with the UNESCO International Centre for Water Hazard and Risk Management (ICHARM) established in Tsukuba, Japan, and with UNISDR and UNU-EHS will be developed further within IHP-VII.

1. Introduction

Balt Verhagen and Jaroslav Vrba

Groundwater is a vast global resource and a significant component of the hydrology of watersheds and river basins. Its occurrence, flow and storage depend upon climate, physiography and geological conditions. Groundwater is a key component of many geological and hydrogeochemical processes, and geotechnical conditions, such as soil and rock behaviour. Groundwater also has important ecological functions, sustaining spring discharges, river-base flows, lakes and wetlands. Mankind has depended on groundwater since times immemorial, accessing the resource through springs and wells. As awareness grew of the value and widespread occurrence of groundwater, its mostly good quality and low vulnerability to environmental influences, its reliability during droughts and other natural disasters and its generally modest development costs, its use has increased significantly in recent decades. In many developing countries groundwater resources support sustainable living and poverty alleviation of rural populations. In arid and semi-arid regions and on islands, groundwater is the most important and safest, if not the only, source of drinking water.

Historically, even up to the present, people have had to face severe drinking water shortages in the immediate aftermath of natural or man-induced catastrophic events - even in highly developed communities. When rescue operations have physically secured an endangered population, the most pressing priority is the supply and distribution of potable water. Emergency situations in drinking water supply of varying severity are reported from many parts of the world following floods, droughts, rain-induced landslides, earthquakes or pollution accidents. However, it is often difficult to organise and construct at short notice a replacement water supply when a regular drinking water source has been damaged or even destroyed. The restoration of a supply may take weeks or months.. Where groundwater has become polluted, its remediation may require years. In order to prevent epidemics and mitigate individual deprivation in the short term, drinking water is often transported to the affected regions in tankers, or imported in large quantities as bottled water. These measures take time to implement, they are expensive and cannot be sustained. As a result, the affected population temporarily is left deprived and disempowered. Access to local groundwater resources that – ideally - have been proven safe and protected by geological and environmental features, and with long residence times makes rescue activities during and after an emergency more rapid and effective. Such emergency resources have to be identified, evaluated and developed as substitutes for drinking water supplies by installing the necessary infrastructure with which to implement promptly their exploitation. They are essential for drinking water security in disaster-prone regions repeatedly affected by destructive events such as flood plains, tectonically active, volcanic or coastal areas, mountain slopes and/or arid zones.

The impact of natural disasters on drinking water sources is felt far more severely in developing countries than by developed, industrial states. The rural populations of developing countries depend particularly on shallow dug wells for their drinking water. These sources are highly vulnerable to drought, floods and related pollution, and to saline intrusion in coastal aquifers. The loss of such basic and low-cost sources of water for drinking and other purposes affects significantly the social conditions and economic activities of local populations.

Ongoing global climate variability and change manifest themselves in the increasing frequency of floods, droughts and other water-related natural disasters, such as landslides and mudflows. There is a growing trend in the occurrence of major natural disasters globally and increasing numbers of people are affected or killed in such events, with the concomitant physical devastation and /or chemical and biological pollution of drinking water supplies. Developing an effective governance policy to reduce risks associated with disasters and the socio-economic vulnerability of populations is therefore needed on both international and national levels. Particularly in regions regularly affected by natural disasters the establishment and implementation of *disaster mitigation policy* and *drinking water risk management plans* significantly reduce or may even eliminate drinking water services failure following catastrophic events. Both these measures support the formulation of *effective water governance policy* for emergency situations to manage water resources during and after disasters in an equitable manner.

2. Groundwater: origin, occurrence and recharge

Klaus-Peter Seiler

Introduction

The terrestrial water inventory amounts to about 1.386 x 10^9 km^3. Ocean water constitutes about 97.5 vol.% and fresh water the remaining 2.5 vol.%.

Fresh water occurs only because of the water cycle, which links the three big reservoirs on earth, the atmosphere with the lithosphere and the oceans. Solar radiation is the driving force of the water cycle, transformed into heat in the atmosphere and the earth's surface thus driving evapo-transpiration.

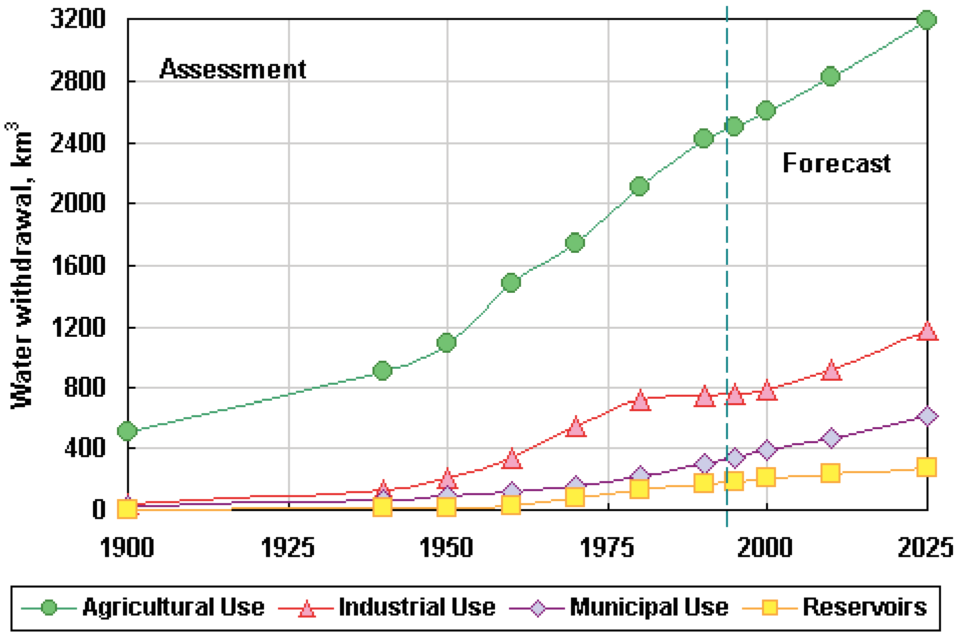
Except for sea-ice at the North Pole, all fresh-water is found on the continents:

- 68.9 vol.% is fixed in ice shields, glaciers (27,000,000 km^3) and about 300,000 km^3 in permafrost (Shiklomanov, 1990),
- 29.9 vol.% is groundwater,
- 0.9 vol.% is soil moisture and atmospheric water vapour and
- 0.3 vol.% appears as surface water. The average groundwater contribution to surface run-off amounts to about 50%; 5 to 10% of subsurface fluxes discharge directly to the oceans. As compared to the water cycle and the mean groundwater recharge on earth, less than 50% of the existing groundwater was recharged within the last 100 years through the present water cycle, the rest was renewed in the historic or geological past under climate conditions which are not known in every detail; hence, groundwater resources evaluation is faced with a variety of water storage forms and run-off systems, changing with time.

At present, more than 40% of the world's population uses groundwater and about 50% of the world's food production depends on irrigated agriculture linked to groundwater. Apart from human and ecosystem needs, water plays an important role in distributing and storing energy and matter over the globe and in natural attenuation processes. Fortunately, and in contrast to other geological deposits of economic value, the water cycle drives the renewal of water resources and groundwater flow at various time scales, governed by local or regional orography, tectonics and ocean levels. In temperate and tropical humid climates, groundwater flow is usually at steady state, hence, in balance with present groundwater recharge; in permafrost and arid areas (Loyd, 1980), however, its motion is often transient, or not in balance with the present water cycle. Groundwater management and land use may add a man-made transient behaviour to groundwater flow, which, however, is often not immediately discernible.

Human water demand (Fig. 2.1) and the transformation of blue into grey water are approaching some 10% of the presently recharged fresh water on continents on average. In certain areas this percentage is much higher. Future social and economic welfare will have to rely ever more on this rechargeable groundwater, assuming a stable ecosystem. In recent years, the attention of water managers is increasingly focused on the possible diminution of usable water resources as a consequence of man-made global changes. Although the extent of such changes is still difficult to estimate, new strategic approaches have to be developed to provide more flexible water demand management and protection solutions.

Figure 2.1. Water withdrawal in the 20th century and the extrapolated development into the 21st century, detailed according to the main sectors of water use (UNESCO 1999)



Groundwater resource development is based on the concept of sustainable groundwater yield, which has to meet a set of hydrologic, ecologic, social and economic objectives. In this concept, groundwater recharge is an important component, which is mostly determined under special steady-state initial and boundary conditions. However, groundwater development may change these conditions throughout the recharge-discharge regime with time. Therefore, the development of sustainable groundwater management strategies cannot rely on single data sets, but needs an integrated concept within a specific time frame.

The global water cycle

The main link between the lithosphere, oceans and the atmosphere is the water cycle (Fig. 2.2), which provides fresh water to sustain life, continental ecosystem functions, weathering and sediment transport and temperature equilibration on earth. On the time scale of a century, the hydrologic water cycle (Fig. 2.2) is to a first approximation balanced; however, on extended time scales it appears imbalanced. To better understand the importance of reservoirs to the fresh-water balance, mean turnover times (MTT), or mean residence times (MRT) are considered (Table 2.1). In contrast, atmospheric water vapour, lakes and rivers and shallow, mostly unconfined groundwater are significantly recharged within the present water cycle. In between presently renewable and non-renewable groundwater there

Figure 2.2. Schematic representation of the water cycle. All numbers in km³ (exorheic: system discharges to the oceans; endorheic: evapo-transpiration is the only form of discharge)

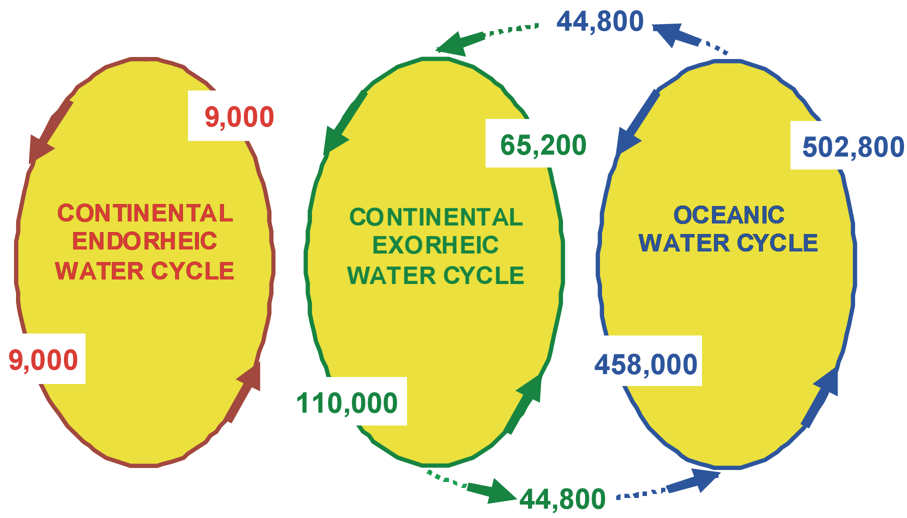


Table 2.1. Average mean turn-over times (MTT) or mean residence times (MRT) for water in different reservoirs

Ocean	~2,500	years
Polar glaciers	>100,000	years
Temperate glaciers	< 500	years
Connate water	>1,000,000	years
Deep groundwater	>>100	years
Shallow groundwater	<100	years
Lakes	~15	years
Rivers	~16	days
Atmospheric water vapour	~10	days

is an intermediate zone, designated by Seiler and Lindner (1995) as deep, mostly confined groundwater, recharged on geologic or historical time scales with minor contributions of present-day groundwater recharge.

Continental water resources are distributed unequally with latitude. This is due to the uneven distribution of solar radiation and evaporation on earth, the global atmospheric circulation pattern and its modifications by heat capacities, the albedo of surfaces, the size and topography of continental masses and interactions between the atmosphere and warm or cold ocean currents.

According to the most recent world water balance estimate (UNESCO, 1999) the average yearly discharge from continents amounts to 44,800 km^3. In the time span 1921-1985 discharge trends did not show any marked increase or decrease (UNESCO, 1999); this may be interpreted in terms of either:

- steady state conditions in the water cycle over this time span, or
- changes in temperature, precipitation and evapo-transpiration do not show up instantaneously, because of the transient or delayed character of discharge governed by long mean residence times in the respective reservoirs.

One can distinguish between a continental and oceanic branch of the water cycle (Fig. 2.2), which are interconnected. Most of the water evaporating from oceans falls back as precipitation over the ocean; however, 9% (44,800 out of 502,800km³, Fig. 2.2) of the water of oceanic vapour is added to the air humidity of continental evaporation, precipitates on continents and returns as run-off to the oceans (exorheic areas). There is also an endorheic water cycle branch on continents, which has no outflow to the oceans, but operates static intra-continental run-off/evaporation mechanisms (such as the catchments of the Aral Lake, Baikal Lake or the Dead Sea).

Strictly speaking, any sustainable, long-term groundwater yield in equilibrium with the present water cycle is limited to the present-day run-off, discharging from continents to the ocean. Any potential use of older water, stored in deep aquifers, beneath permafrost or retained by glaciers (Table 2.1) as well as of water which is unproductively consumed by evaporation in endorheic areas, must be approached with caution. The resulting negative feedback could affect delicately balanced ecosystem functions and may lead to severe water supply and ecological problems in the long term.

Traditionally, the concept of water balance refers to precipitation and river discharge on the scale of a catchment and on time scales of more than 15 years. To gather reliable water balance data a minimum of a decade or more of meteorological and hydrologic observations is required. Such long-term observations:

- smooth the short-term variability of precipitation and evapo-transpiration, which govern the input function of discharge, and
- reduce errors related to delayed responses of the subsurface system in connection with water storage and release and slow percolation velocities between the land surface and groundwater.

In developed countries, such long-term observations on precipitation and surface water have been conducted continuously since the late 19th or early 20th century and many of them are still operating. Systematic groundwater level observation schemes on regional or national networks date from the first half of the 20th century. In many developing countries such observations were initiated mainly in the second half of the 20th century through the initiative of various agencies, i.a. the WMO. Natermann (1951) analysed the hydraulic response in rivers. However, these observations were often discontinued after some years or a few decades, on account of logistic and financial problems. Therefore, it is important to develop and apply additional complementary water balance methods, to supplement long-term meteorological and hydrologic observations, and obtain information on groundwater recharge integrated over time and space. For the last 60 years this was achieved step by step with artificial and environmental tracer techniques that have been developed since the 1940's using chloride (Schoeller, 1941), environmental isotopes (Münnich, 1968), environmental tracer response (Sklash et al., 1976) to storm events, or using CFCs as tracers (Busenberg and Plummer, 1992, Oster et al., 1996).

The determination of groundwater recharge

Groundwater recharge is a most important factor for any safe yield concept of fresh water exploitation. Recharge occurs in all climate zones, albeit at different rates, e.g.:

- < 5 mm/a in arid regions with low and very irregular groundwater recharge (Verhagen et al., 1979),
- < 25 mm/a in semi-arid regions with large annual fluctuations,
- <100 mm/a in humid tropical regions, again with considerable annual variations,
- >300 mm/a in many humid temperate regions
- very slow groundwater recharge also occurs through (probably wet) permafrost (Michel and Fritz, 1978).

Knowledge of groundwater recharge is the base parameter in developing groundwater management and protection strategies to satisfy human and ecosystem water demand and conservation. Groundwater recharge is also a critical parameter for assessing emergency groundwater resources. Additional parameters are storage, conductivity and geometric parameters of the water bearing and conducting strata – the aquifer.

Depending on the aim of the investigation, groundwater recharge studies contribute to the development of long or short-term strategies on water use and also groundwater use in emergency situations. As a first step it must be clarified to what extent the studied hydro-geologic system discharges under either steady state or transient hydraulic conditions. Both conditions occur naturally world wide. As a second step the scale to which results on groundwater recharge refer has to be assessed. Finally, it should be kept in mind that virgin conditions may significantly differ from managed conditions, because groundwater recharge is not a fixed number, but may vary with the boundary conditions of the recharge system. There are six general approaches to estimate groundwater recharge:

- mass balance methods,
- mixing methods,
- hydraulic approaches,
- flux measurements,
- methods based on outflow analysis,
- turn-over time methods.

The results of various methods for determining groundwater recharge have different scale relations (Seiler and Gat, 2007). Flux methods, based on tracing, refer to the smallest scale; bulk mass balance methods to the largest scale and inverse calculations of groundwater recharge as well as many discharge analyses often deal with an intermediate scale. Long-term recharge estimates allow for the development of appropriate exploration and exploitation strategies for periods of water scarcity and water excess. In contrast, short-term information on groundwater recharge is needed to better assess the impact of floods and accidental pollution spills on groundwater resources and to optimise irrigation.

All these methods have in the past undergone modifications according to the available investigation tools, the local or regional climate, and orographic, plant cover and hydro-geologic conditions. The earth's crust is composed of 95 vol.% crystalline and 5 vol.% sedimentary rocks. In contrast, 75% of sedimentary rocks and 25% of crystalline rocks crop out at the continental surface. Since sediments favour groundwater recharge and have much greater storage than crystalline rocks, there appears to be a pretty high average potential of infiltration and safe or sustainable yield on the continents. This needs to be assessed. The most common method is through meteorological mass balance studies, that produce bulk information on run-off, but mostly not on groundwater recharge. Methods of outflow analysis as well as groundwater hydraulic approaches, based on numerical modeling of groundwater flow (Sanford, 2002), deliver approximate results on groundwater recharge. The results of all these studies always refer to the catchment scale and depend on observations of precipitation, the energy balance, land use, river discharge and groundwater level fluctuations and must be based on a reliable conceptual hydrogeologic model of discharge generation and the transformation of infiltration into groundwater recharge.

In contrast, lysimeter mass balance studies, soil hydraulic and injeccted tracer based methods always provide small-scale and instantaneous information on recharge, referring to local singularities, requiring an often poorly known weighting factor to determine groundwater recharge.

The above mentioned methods frequently apply in all humid climates but suffer from limitations in arid/semi-arid and frigid areas, because:

- input data for meteorological mass balance vary considerably in time and space and are not always adequately known over large time and spatial scales,
- intrinsic hydraulic parameters, the boundary conditions of aquifer systems and time-dependent parameters such as groundwater level fluctuations are often neither precise nor representative for the entire catchment,
- semi-arid/arid and frigid zones tend to receive point-source rather than diffuse infiltration,
- where groundwater discharges in arid environments it is often old and therefore does not really correlate with present meteorological data sets.

Tracer methods, using environmental elements such as chloride and stable and radioactive isotopes have been developed to determine groundwater recharge. Such tracer methods represent an integrating tool in time and space, as far as these tracers do not interact with the aquifer and do not change species in changing chemical environments. These tracers are called ideal or non-reactive or conservative with respect to water motion (Seiler and Gat, 2007) and are proving particularly useful in semi-arid/arid and frigid climates.

Traditional mass balance calculations

Traditional mass balance calculations require steady-state conditions and refer to average annual averages of precipitation and evapotranspiration, smoothing areal variations and time dependent effects:

Run-off = (precipitation) - (evapo-transpiration)

This water balance depends primarily on the precision of the estimate of the present evapo-transpiration, which undoubtedly is the most difficult parameter to determine. In addition such water balance calculations can rarely differentiate between the specific run-off components of over-land-flow, inter-flow and groundwater recharge.

Under dry weather conditions the discharge of springs or rivers is fed by either perched or regional groundwater, called dry weather discharge, base-flow or groundwater run-off. Where perched groundwater dominates base-flow, any base-flow analysis calculation of groundwater recharge rates tends to either underestimate or overestimate recharge, to the extent that the discharge from perched groundwater is based on either an over- or underestimate of the orographic catchment size (Seiler and Gat, 2007). In the case of base-flow from regional groundwater, the groundwater recharge rate is often underestimated since base-flow analysis refers to a threshold altitude, which is usually higher than the base of the aquifer or aquifer-system; hence, subsurface discharge beneath the threshold level is not considered in the base-flow analysis. Only at gauging stations of extended catchments with a very small subsurface through-flow section and with the same surface and subsurface catchment size, does the base-flow analysis produce a reasonable value of available groundwater recharge.

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Hydrograph analysis

Hydrograph analysis separates direct (overland flow plus inter-flow) and indirect (base-flow) run-off, whereas chemical/isotope discharge separation distinguishes between pre-event and event water. Only a combination of these methods allows for a good estimate of the main discharge components such as base-flow, inter-flow and overland-flow. Hydrograph analysis of base-flow always refers to a threshold discharge level of the gauging station. In contrast, environmental tracer studies of base-flow refer to a 'trench' of the groundwater flow field, which penetrates below the aforementioned threshold altitude in the upper reaches of the catchment. Therefore these methods result in somewhat different values for base-flow: environmental isotope methods often overestimate, whilst hydrograph analysis tends to underestimate, the groundwater contribution to run-off.

Hydrograph analysis based on environmental tracers

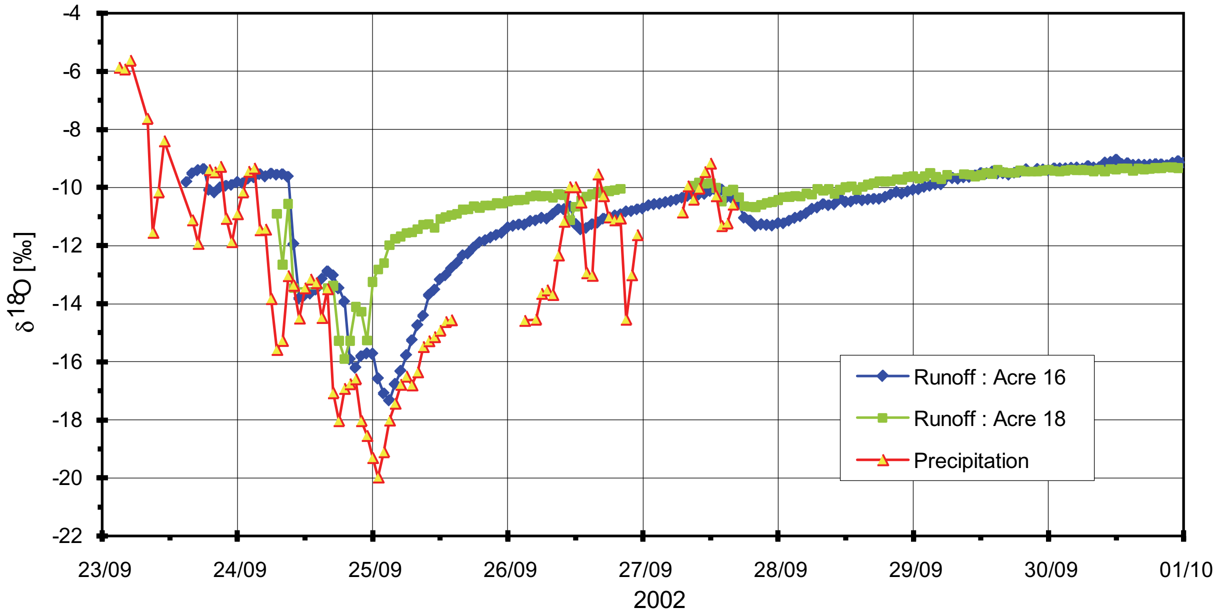
Hydrograph analysis based on environmental tracers is also called the 'end member mixing method (EMMM)'. Surface (stream) flow is analysed as a mixture of two end members: direct and indirect run-off. As far as these end members are characterised by different concentrations of a non-reactive tracer, their mass balance partitioning in surface run-off is proportional to the respective discharge components:

$$\begin{aligned} Q_1 C_1 + Q_2 C_2 &= (Q_1 + Q_2) C \\ \frac{Q_1}{Q_1 + Q_2} &= \frac{C - C_2}{C_1 - C_2} \end{aligned} \qquad (2.1)$$

where Q= discharge; C=concentration; subscripts 1, 2 - pre-event and event water resp.

A typical example for such an EMMM is shown in Fig. 2.3 for an area without base-flow, but with overland- and interflow; the example shows that at the beginning of the discharge event, pre-event water does not measurably contribute to the discharge of the two agricultural plots (acres 18 and 16). Infiltration capacities are still low, hence overland-flow with the same ^{18}O fingerprint as precipitation dominates. From 25.09.2002 inter-flow with pre-event water intervenes, but at different proportions for each plot. The environmental isotope tracers ^{18}O, ^{2}H, (^{3}H) and the weathering products $Si(OH)_4$ and DOC are often applied in EMMM.

Figure 2.3. ***Direct run-off from two cultivated fields (acre 16 and 18) produced by a precipitation event in the area of Scheyern, Germany. The figure shows the variations of $\delta^{18}O$ in precipitation (orange) and direct run-off (blue and green). The response function is similar at the beginning of the rain event and differs at a more advanced stage of the event.***



Groundwater recharge determination with tritium

Tritium has been used widely to determine groundwater recharge qualitatively and quantitatively.

In areas with a huge deficit in precipitation as compared to potential evapotranspiration (semi-arid/arid and frigid climates), it is often doubtful if groundwater recharge occurred or not. In such areas, however, heavy rainfall can produce groundwater recharge within a short period of time, which is qualitatively documented by measurable ^3H-concentrations in the percolation zone or the upper layer of shallow groundwater. The assessment of such ^3H evidence in groundwater of arid (Sinai, Kalahari, Djibouti, Oman, Saudi Arabia, Sahara, Gobi), semi-arid areas (Sahel) and frigid climates (permafrost areas) is generally attributed to exceptional rain events, but it does not necessarily prove net recharge over long periods of time. In such areas, recharge may be balanced by evapo-transpiration. Similar observations were made in permafrost areas, where ^3H was found in groundwater beneath ground-ice (Michel and Fritz,1978).

Following tritium on its flow path from infiltration through the vadose zone to the groundwater, it can also be used to quantify groundwater recharge employing the thermonuclear peak, mass balance or mean transit time/mean residence time methods (Seiler and Gat, 2007).

Today the environmental tritium peak and mass balance methods (see chapter 4.4) are of little use, because no new ^3H signal was produced since the nuclear weapon moratorium (1963/1964). Longer-lived radiocarbon has been employed in assessing recharge to deep groundwater in the Kalahari (e.g. Verhagen, 1990). Artificial tritium has been applied to replace the bomb peak in determining unsaturated zone transport in India (Gupta and Sharma, 1984, Sukhija et al., 1996), Africa and Australia (Sharma, 1989).

Groundwater recharge determination with chloride

Under natural conditions, chloride in recharge/percolation is of atmospheric origin; other sources contribute only under special climate, land use, geologic or hydrogeologic conditions (Seiler and Gat, 2007).

As compared to many other solutes, chloride is a non-reactive tracer. It is not affected by transport along the different flow paths within the water cycle, except where the water comes into contact with other Cl sources. Chloride does undergo concentration changes in the water cycle through water volume reduction by evapotranspiration along the atmosphere/lithosphere/biosphere interface . This was recognised by H. Schoeller (1941), Ericsson (1952) and M. Schoeller (1963), who were the first to study chlorides in the water cycle for determining groundwater recharge. In the following decades, this method was further elaborated (e.g. Edmunds & Walton 1980, Edmunds 2001) and may be considered a standard application at present.

Applying the law of mass conservation (eq. 2.2), the non-reactive chloride input equals the chloride output, both in mass/(unit time).

$$
\begin{aligned}
Cl_{input} &= Cl_{ouput} \\
Cl_P * P &= Cl_{R'} * R' \\
\frac{Cl_P * P}{Cl_{R'}} &= R'
\end{aligned}
\qquad (2.2)
$$

where Cl – chloride (g/L), P – precipitation (L/m² year), R´- groundwater recharge (L/m² year)

This expression is based on the principle that during transport through the unsaturated zone water is lost only through evapo-transpiration. It shows that recharge can be determined by comparing the chloride concentration in groundwater with that of local rainfall, the concentration in groundwater increasing with decreasing recharge rates.

Further requirements for applying eq. 2.2 are: 1) there is no net run-off from the area under consideration, or that runoff can be adequately be accounted for, and 2) there is significant lateral transport in the saturated zone (area is exorheic).

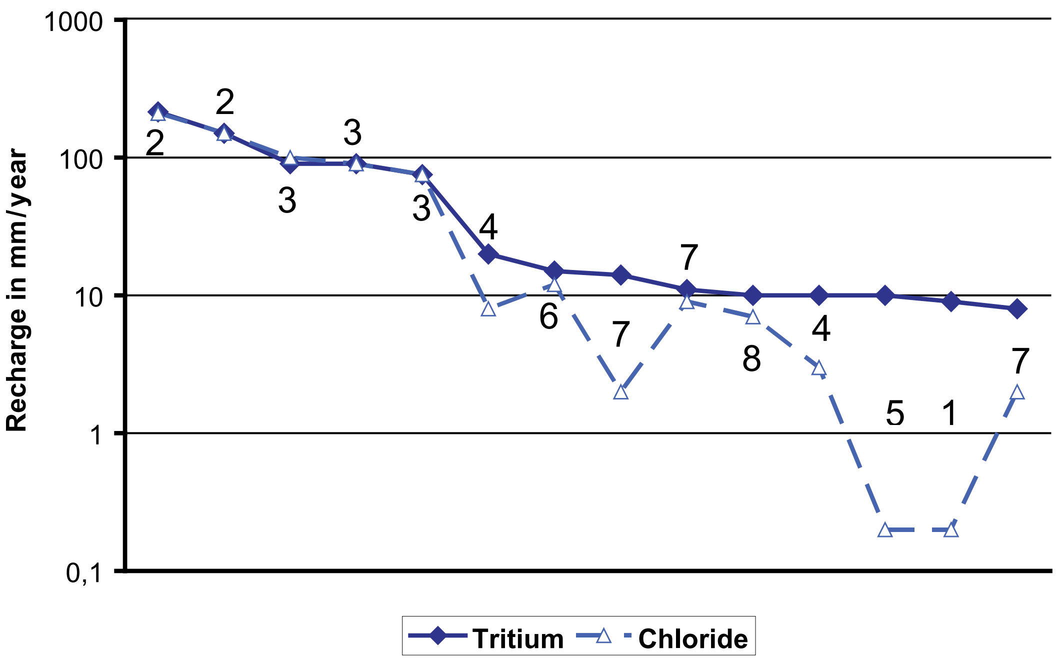
In areas such as the Kalahari (Verhagen et al., 2002) phreatophyte demand from the saturated zone to depths of tens of metres leads to an underestimate of recharge based on the chloride method. This is noticeable in Fig. 2.4 where for low recharge rates (~10 mm/a) the chloride methods tends to underestimate recharge. On a global scale, the comparison of the chloride with the tritium method (Fig. 2.4) shows good agreement when recharge exceeds 25 mm/year.

To differentiate between natural Cl-inputs by precipitation, anthropogenic or geogenic emissions, the atmospheric $^{36}Cl/^{34}Cl$-ratio in precipitation has been used (Magaritz et al., 1990).

Furthermore:

- the chloride input function is mostly not as well known as the tritium input function,
- the tritium method provides time-related information to calculate recharge, but the chloride method delivers process information,
- in areas of pronounced topography with enhanced run-off, the chloride method often over-estimates recharge (see above),
- apart from precipitation, aeolian dust (aerosols) often imports chlorides to the infiltration interface.

Figure 2.4. Comparison between groundwater recharge determined with the chloride and the tritium method. The numbers refer to: 1. Tyler and Walker (1994), 2. Allison and Hughes (1978), 3. Edmunds et al. (1988), 4. Allison and Hughes (1983), 5. Phillips et al.(1988), 6. Gieske et al. (1990), 7. Foster et al. (1982), 8. Cook et al.(1992).



Mean residence time (MRT) to determine groundwater recharge

Another application to determine groundwater recharge with radioactive environmental tracers refers to the mean residence time (MRT), or mean transit time (MTT) (see chapter 4.4).

An example is the Molasse basin of south Germany. The active groundwater recharge zone has a saturated depth of 50 m, porosity about 0.25 and the tritium content represents an MRT of 70 years. From this data groundwater recharge was calculated to amount to 180 mm/year, which is in good agreement with hydrograph analysis (163 to 173 mm/year).

In determining the MRT with ^3H, groundwater should be sampled from steady phreatic flow (diffuse recharge), i.e. not beneath receiving rivers or subsurface water divides. Another limitation in applying this method may arise when:

- shallow groundwater is overexploited (chapter 3.2) The groundwater level decline will cause up-coning of deep, ^3H-free groundwater;
- groundwater is exploited from the deep, passive groundwater recharge zone, causing down-coning of the active recharge zone (Fig. 3.2 left; chapter 3).

The determination of groundwater recharge through MRT and the geometry of the active groundwater recharge zone should be applied cautiously in dual porosity aquifers.

MRT can also be determined with the stable isotopes of the water molecule. These isotopes undergo seasonal variations in precipitation, which can be used for short-term groundwater dating in as far as damping through hydrodynamic dispersion has not reduced input variations to near zero in the subsurface. This method provides MRTs of months to < 6 years according to the measuring precision and the extent of the existing seasonal variations of the stable isotope content and implies that age distributions always start from zero.

Mean residence times can also be determined using environmental chloride as a tracer in the unsaturated zone. Where the long term chloride input function is known, the chloride distribution in the unsaturated zone is given by (eq. 2.3):

$$MRT = \frac{1}{PC_{Cl,P}} \int_0^z \theta(z)\, C_{Cl}(z)\, dz \qquad (2.3)$$

where P = precipitation (L/m² year), C=concentration (g/L), θ =water content (-), Cl=chloride

In view of preferential flow, the studied profile should be thick enough (>5 m) to produce reliable results. Even so, preferential flow was shown to be an important, even dominant factor in pure sand unsaturated zones many tens of metres thick in the Kalahari (Gieske, 1990).

Groundwater recharge and groundwater level fluctuations

Groundwater levels fluctuate according to atmospheric pressure, the compression of rocks during earthquakes and tides and as a response to groundwater recharge/discharge. Atmospheric pressure and rock compressibility produce measurable groundwater level fluctuations only where the porosity is low and the groundwater is confined.

Regionally, groundwater levels rise where recharge exceeds consumption plus natural losses of evapo-transpiration and horizontal fluxes. They decline where recharge falls short of discharge. Where groundwater fluxes are essentially constant, groundwater level fluctuations essentially reflect groundwater recharge (Healy and Cook, 2002). Observing average monthly groundwater levels over a time span of many years results in an average amplitude of groundwater fluctuations, high groundwater levels following recharge periods and low groundwater levels following dry weather conditions. This range defines the vertical recharge space in an aquifer of amplitude Δh. Recharge R' is then, assuming constant flux:

$$R' = \Delta h p' \qquad (2.4)$$

The porosity p' is not necessarily constant, because it might be reduced by entrapped air in the groundwater fluctuation zone.

This method of mean groundwater level fluctuations may underestimate groundwater recharge, because it does not consider recharge driven variations in groundwater fluxes.

Groundwater recharge from lysimeter studies

Lysimeter studies are known to have been conducted since the end of the 17th century. The prime concept in using this tool was to better estimate evapo-transpiration and through-percolation; through-percolation and precipitation have been volumetrically measured in lysimeters and the difference ascribed to evaporation or evapo-transpiration. Later lysimeter studies were used to investigate solute transport as well as physical, chemical and microbial transformation processes of pollutants in the vadose zone. When compared to the bulk determination of groundwater recharge by water balance or discharge analysis, lysimeter studies undoubtedly produce more detailed insights into the role of factors such as geology, soil, vegetation and climate on recharge mechanisms.

Lysimeters have distinct limitations: their construction and maintenance costs are high; their small scale as compared to inhomogeneities in soil/sediment texture; problems in reliably translating lysimeter results to catchment scale (Blöschl and Sivapalan, 1995); their mostly non-representative vegetation cover.

Concluding remarks

Groundwater, surface water, the oceans – the largest water reservoirs on earth – and the atmosphere are linked through the water cycle, which provides renewable water for humans and ecosystems. The groundwater reservoir amounts to about 8,300,000 km^3; it is known to occur to depths up to some kilometers beneath the surface of continents; its origin refers to present-day, as well as past, replenishment by rainfall (recharge) and some groundwater is trapped in aquifers since the formation of sediments (connate water).

Groundwater is the dominant component of fresh water resources on continents. Recharge renews less than 50% of groundwater storage in the time span of a century. Managed extraction and protection measures of this limited resource require detailed knowledge of the present-day groundwater recharge rate under the given meteorological, geologic and ecologic boundary conditions.

There is no generally applicable method to determine groundwater recharge in all climate zones on earth. Therefore mass-balance and tracer methods as well as numerical and analogue methods (lysimeters) have been developed to calculate groundwater recharge. Where the only input source of chloride is precipitation, chloride balance is often favoured. Its limitations (such as run-off estimates) are, however, not always taken into account. It is recommended to always apply various approaches to better guarantee a good estimate of groundwater recharge. Estimation of groundwater recharge is particularly important for the evaluation of groundwater resources of low vulnerability stored in aquifers which should be developed and used in emergency situations. Groundwater recharge is not a fixed number, it is scale and time dependent and is also influenced by the mode of groundwater management and in more recent times by global changes. Therefore thorough and ongoing monitoring of groundwater recharge is strongly recommended.

3. Groundwater: An emergency source for drinking water supply

Klaus-Peter Seiler

Introduction

A water supply based on groundwater traditionally relies on high yielding wells, capable of long-term production of water of good quality. In contrast, emergency water supply is needed for a period short enough (usually weeks or months, possibly up to a year) for the exploitation and hydraulic boundary conditions to adjust without seriously harming the quantity and quality of the water resource, nor groundwater dependent ecosystems.

Emergency water resources should be protected from hazardous and natural events. This can be realised by:

- the exploration for and exploitation of water resources sufficiently distant from the (potentially) endangered area,
- the exploration and exploitation of deep groundwater.

The emergency water supply must guarantee easy access to the resource, and a continuous supply over a limited period. Further requirements are:

- protection measures that ensure safe groundwater of good quality (chapter 6) and
- sound risk (or emergency) management measures.

Groundwater in shallow and generally unconfined aquifers should be exploited as an emergency water resource only in catchments unlikely to be affected by natural disasters such as floods and storms. However, shallow water table aquifers are mostly vulnerable to human impacts (particularly to pollution) and have to be comprehensively protected. To operate such a spread of local water resources involves long construction lead times and requires the construction of a water distribution network which itself is vulnerable to disaster.

Deep, mostly confined, groundwater is considered a favourable emergency water resource, granted that the exploitation of deep aquifers often requires specialised drilling, exploration and management measures. As such deep systems are usually extensive, the placement of exploitation wells is less restricted, and can often be located close to the user community.

Groundwater flow in aquifer systems

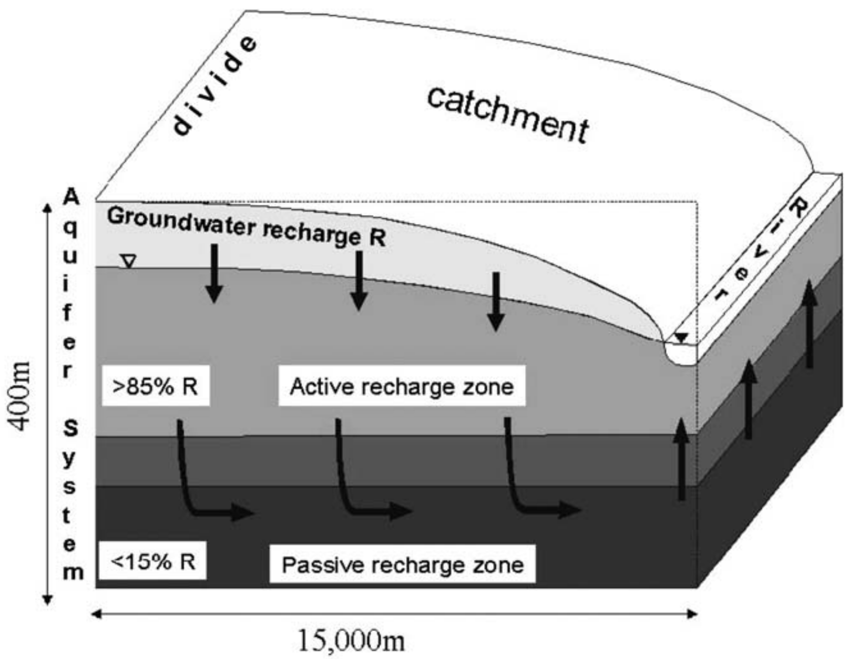
Groundwater is stored and flows in an aquifer, or a system of aquifers, each with particular hydraulic properties. In unconsolidated intergranular aquifers the hydraulic conductivity and porosity are generally higher than in crystalline, fissured rocks, but decrease with depth at much the same rate. Since groundwater through-flow is linked to groundwater recharge, groundwater recharge cannot be distributed equally among all units of a layered aquifer. To investigate this assumption more quantitatively, numerical modeling was performed:

- with aquifer sequences of different hydraulic conductivities,
- for groundwater movement between an underground water divide (Fig. 3.1) and a river receiving groundwater which collects all subsurface discharge.

This extended modeling exercise has shown that generally more than 85% of the recharged groundwater discharges through near-surface layers (active groundwater recharge zone, mostly unconfined) and less than 15% of the groundwater recharge reaches and is discharged through, the more extensive deep lying aquifers (passive groundwater recharge zone, often confined groundwater) (Seiler and Lindner, 1995). Groundwater in near-surface aquifers therefore tends to be young ($<10^2$ years) and old in deep aquifers ($> 10^2$ years). In all climate zones older groundwater ($>10^3$ years) is more abundant than presently recharged groundwater. Such old groundwater should be conserved in selected areas, in order to maintain a buffer system for emergency exploitation and for the gradual adaptation of ecosystem functions to changing boundary conditions.

This vertical differentiation into recharge zones with different mean residence times and water turnover exists for both homogeneous and inhomogeneous aquifer systems; however, in the more common

Figure 3.1. A modeling section representing the influence of hydraulic conductivity distributions in rocks upon the distribution of groundwater recharge in the individual layers. Groundwater recharge of 150 mm/a and complete flow cut-off by the receiving stream were assumed



inhomogeneous (layered) aquifer systems, the differentiation into high and low turn-over quantities is much more pronounced. Very permeable deep aquifers often receive attenuated groundwater recharge from overlying strata with low permeability and exploitation therefore is balanced rather by lateral drainage from adjacent or upwards from underlying aquifer systems (Seiler and Lindner, 1995).

The thickness of saturation in shallow aquifers depends upon the effective groundwater recharge as well as the storage and drainage properties of the aquifer system. In semi-arid regions, the active groundwater recharge zone approaches a thickness of a few metres to some tens of metres; in warm humid climates it is typically many tens of metres and in temperate humid climates up to 100 m. Water table aquifers in fluvial deposits in e.g. the Danube river in Slovakia, which does not have a humid climate, attains several hundreds of metres – the thickness of the aquifer.

Groundwater in the active and passive recharge zones is always of fairly recent meteoric origin and by nature of good quality – in as far as geologic and surface conditions are favourable. When these systems become stressed by deep exploitation or by tectonic, eustatic and/or climate changes (Seiler et al., 2007), transient hydraulic conditions do not play a significant role in the active groundwater recharge zone, but do so in the passive groundwater recharge zone.

The low flow velocities in the passive groundwater recharge zone (< 10 m/year) result in long contact time with the aquifer matrix and consequently higher solute concentrations than in the active groundwater recharge zone. Therefore, the chemical composition and ionic concentration of deep groundwater often differs from that in shallow groundwater.

According to a concept developed by an international working group within UNESCO IHP (Foster and Loucks, 2006), deep groundwater can be termed either non-renewable or fossil, but of meteoric origin. The term non-renewable is used for groundwater that is available for extraction, of necessity over a finite period, from the reserves of an aquifer which has a very low current rate of average annual renewal but a large storage capacity. This storage can be used for a long period in emergency situations. The term fossil is used for generally confined groundwater that infiltrated mostly many millennia ago and often under climatic conditions that differed from the present, and stored underground since that time.

Below the passive groundwater recharge zone connate or formation water (Engelhardt, 1960) occurs, which was deposited along with the sediment in either a marine or continental environment and remained isolated from the biosphere since the time of sedimentation. Connate groundwater can be found at shallow depth in desert areas and at depths of several hundreds of metres in humid areas (see case study 11. 3, Fig. 11.3.6). Hydrocarbon resources, entrapped in sediment structures, are always associated with connate water. The quality of connate water is usually not favourable for use and can not be considered as a suitable emergency drinking water resource.

As a consequence of the above considerations, which have been confirmed by field investigations in various climate zones, effective groundwater recharge diminishes with depth and groundwater management strategies have to consider a depth-related distribution of groundwater recharge. If this is not taken into account in exploitation, significant and long term transient changes in the groundwater flow field and in quality are likely to appear (Einsele et al., 1987, Seiler and Lindner, 1995, Vrba and Verhagen, 2005) (Fig. 3.3).

The interface between the active and passive groundwater recharge zone can be identified (Seiler and Lindner, 1995, Vrba and Verhagen, 2005) by very sudden changes with depth in:

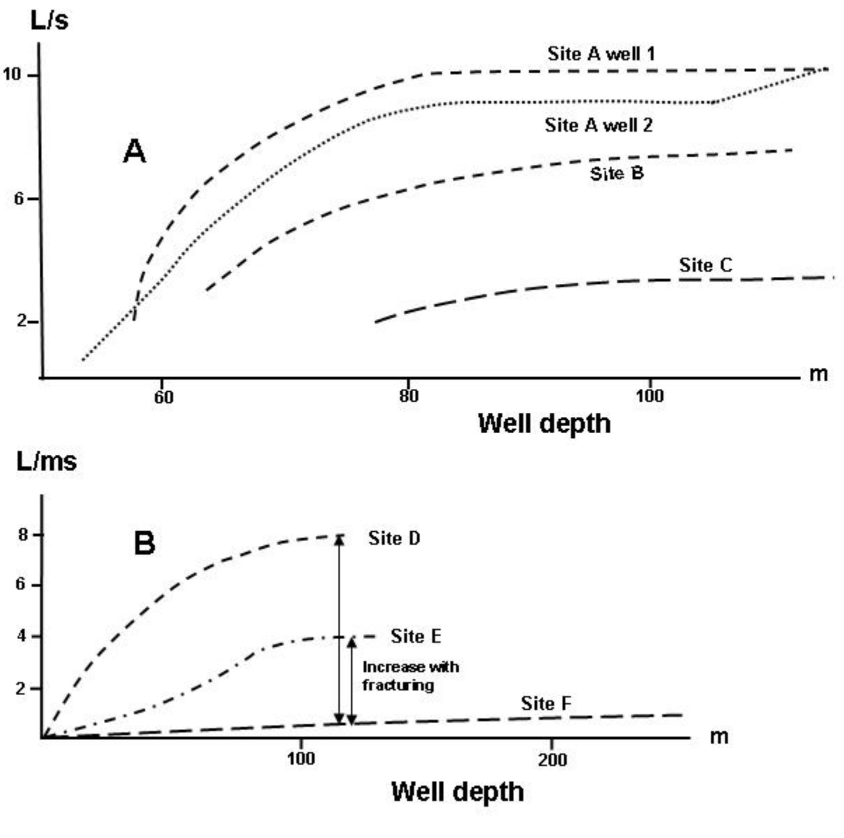
- water ages, as indicated by the concentrations of the radioactive environmental isotopes ^{3}H, ^{39}Ar and ^{14}C, and
- less commonly the chemical composition of groundwater (Fig. 11.3.6).

Groundwater of the active recharge zone (containing ^3H) stands for water younger than 100 years (a century) and deep groundwater (containing no detectable ^3H) for water much older than this (millennia). The transition between tritium bearing and tritium free groundwater often coincides with an abrupt change in ^{14}C- and ^{39}Ar-concentrations and in the chemical composition of groundwater. Here it should be pointed out that there is a major quantitative difference in both the present and historical tritium levels in precipitation between the southern and northern Hemispheres (see Chapter 4.4). Analytical considerations as well as the relationship between ^3H and ^{14}C imply that this approach has to be treated with caution in the southern Hemisphere, where fractured hard rock aquifer conditions often prevail. Fig. 3.2 shows the increase of artesian outflow with depth in fissured hard rock measured during drilling of a well. This indicates that the bulk of the available flow occurs at relatively shallow depths. Further examples are given in a case study (11.3) focused on the Mollase Basin of South Germany.

Transient flow in deep aquifers

Flow through vertical short cuts, induced in deep aquifers during exploitation at depth, compensates the resulting deep groundwater deficits in the low recharge zone. Depending on the exploitation rate, hydraulic equilibrium is reached only after years, decades or even centuries, during which transient conditions prevail in the hydrodynamic system.

Figure 3.2. The increase of artesian outflow (A) and specific yield (B) with depth during drilling of a well in fissured, consolidated rocks

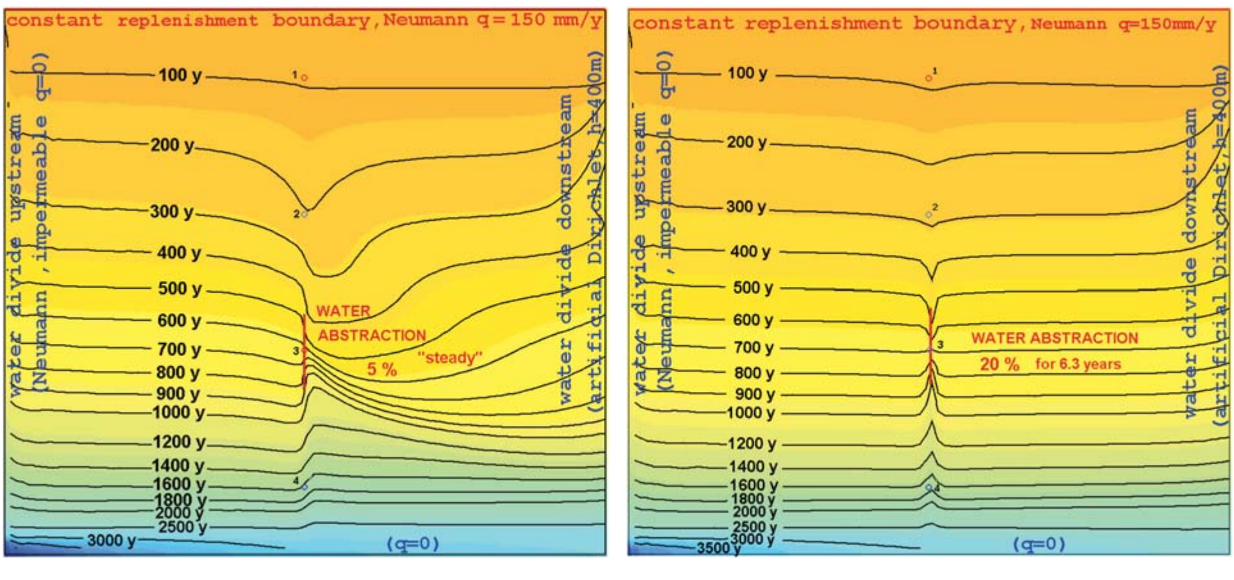


An example is the Czech Cretaceous basin receiving active groundwater recharge in marginal flanks of the basin where groundwater several thousands years old from thick aquifers 150–300 m below ground has been exploited as a permanent source for drinking water supplies since 1930. Integrated water resources management based on an assessment of groundwater reserves has been applied for many years. No significant changes in groundwater flow have been observed even though hydraulic equilibrium has not yet been reached.

The modeling results in Fig. 3.3 show the transient character of the hydraulic response of deep groundwater exploitation by a change of the isochrone field (lines of equal groundwater age), which may persist for decades or centuries after the beginning of deep groundwater abstraction. The magnitude of this transient response increases with the depth at which exploitation occurs. The impact will therefore be limited with emergency groundwater abstraction that usually lasts for at most a couple of years. It should, however, be considered that the response time after the end of groundwater abstraction is as long as the response time after the beginning of abstraction; hence, once groundwater pollution has migrated from the shallow to the deep aquifer it will take a very long time for the deep aquifer to recover its former water quality. What has been said for abstraction and recovery of the flow field is equally valid for remediation, in other words, once a deep aquifer has been polluted it will remain so for a very long time.

The response time depends on the hydraulic properties of the aquifer system, groundwater storage and the depth and quantity of groundwater abstraction. In any case it is recommended that deep groundwater emergency abstraction be spread over many production wells, more than would be employed for the same total abstraction from shallow groundwater. Local hydraulic head changes would thereby be minimised, thus avoiding rapid access of potential pollutants to depth and extending the period of abstraction.

Figure 3.3. ***Water age (isochrone) alteration in two deep abstraction scenarios. Left, abstraction at 5% of groundwater recharge up to approximately steady state hydraulic conditions (long-term abstraction). Right, abstraction at 20% of groundwater recharge over 6.3 years. Groundwater flow from left to right.***



Conclusions

Emergency water supply can be found in shallow aquifers but more particularly in deep groundwater resources. However, development of shallow aquifers in catchments away from the disaster affected sites is often costly and time consuming as new wells have to be connected to the existing water distribution network, which in turn can be vulnerable to disasters. On the other hand, exploiting more extensive deep aquifers resistant to natural disasters allows for shorter connections to existing water supply distribution networks. Increased costs for drilling deep production wells can be offset in that such wells can be drilled near traditional and existing shallow water supply wells where a deep aquifer has been identified by hydrogeological investigations.

4. Tools for identifying and exploring emergency groundwater resources

In the identification and investigation of groundwater resources naturally protected against harmful natural and man-induced impacts the GWES project focuses particularly on deep-seated, mostly confined aquifers with either renewable or non-renewable groundwater. The investigation of such groundwater resources requires an interdisciplinary approach and involves implementation of more sophisticated methods.

The more classical disciplines of groundwater investigation such as geology, hydrogeology and hydrochemistry are complemented with the methods of geophysics, isotope hydrology, remote sensing and mathematical modeling. Integrating these methods facilitates establishing a conceptual model of a groundwater system and identifying the aquifer geometry and boundaries as well as the flow paths, regime, residence time and origin of groundwater. Hydrogeological maps and groundwater vulnerability maps are both important means by which to present the outcomes of such complex investigations. The following sections describe methods applied in identifying and investigating groundwater resources of low vulnerability resistant to natural disasters and suitable as a source of drinking water for emergency situations.

4.1 Geology

Wenbin Zhou

The geological setting controls the occurrence and flow of groundwater as well as geological hazards (earthquakes, volcanic activities, landslides), which in various ways affect the environment, thereby impacting on human lives. This also includes groundwater resources. Underlying these hazards is that the earth is a dynamic, evolving system, the outer layer of the lithosphere consisting of several tectonic plates that are in constant motion relative to one another.

Geological settings

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 intrinsic porosity and permeability. Geological structure influences and may enhance these properties. These factors also influence geochemical processes and thus the chemical composition of groundwater.

There are three main rock types: igneous, sedimentary, and metamorphic. Although rocks are primarily classified according to both mineralogy and texture, it is texture which is most significant in groundwater hydrology. Rock texture – the size, shape, and arrangement, along with fractures, shear zones, and faults determines the strength, water content and conductivity of rock.

Igneous rocks have crystallised from a naturally occurring, mobile mass of quasi-liquid earth material known as magma. If magma crystallises below the surface of the earth, the resulting igneous rock is called intrusive, such as e.g. granite. Extrusive igneous rocks form when magma reaches the surface, blown out of a volcano as pyroclastic debris or else flows out as lava. After cooling, and solidifying, lava flows often exhibit extensive columnar joints as in basalt (Fig. 4.1.1) which may enhance the bulk porosity and permeability of the rock. Solidified lava flows may also contain large subterranean voids known as lava tubes, which may collapse under the weight of the overlying material or carry large amounts of groundwater.

Figure 4.1.1. Columnar jointed basalt in Tengchong Volcanic area, China

Sedimentary rocks form when material eroded from igneous rocks, or sediment is transported, deposited, and then consolidated by natural cementation, compression, or other mechanisms. There are different types of sedimentary rocks: detrital sedimentary rocks, which form from clastic fragments; and chemical sedimentary rocks, which form from chemical or biochemical processes that precipitate material carried in chemical solution. Detrital sedimentary rocks include shale, sandstone, and conglomerate. Shale, argillaceous and fine-grained and usually very low in permeability, is the most abundant sedimentary rock. Sandstones and conglomerates are relatively coarse-grained and porous, high in permeability, and make up about 25 percent of all sedimentary rocks. Unconsolidated and shallow sediments, gravel, sand, silt, or clay, of fluvial glacial, aeolian origin are also significant. Particularly widely developed fluvial sediments in flood plains are characterised by excellent porosity and highly variable hydraulic properties. Carbonate rocks (mostly limestone to a lesser extent dolomites) make up about 25 percent, of all sedimentary rocks and are by far the most abundant, of chemical sedimentary rocks. Limestone is composed almost entirely of mineral calcite. Although it may have considerable mechanical strength, it weathers easily, along with dolomite, to form subsurface caverns and solution pits called sinkholes and can constitute a significant aquifer. Fig. 4.1.2 shows a typical karst landscape in the famous Guilin area of China.

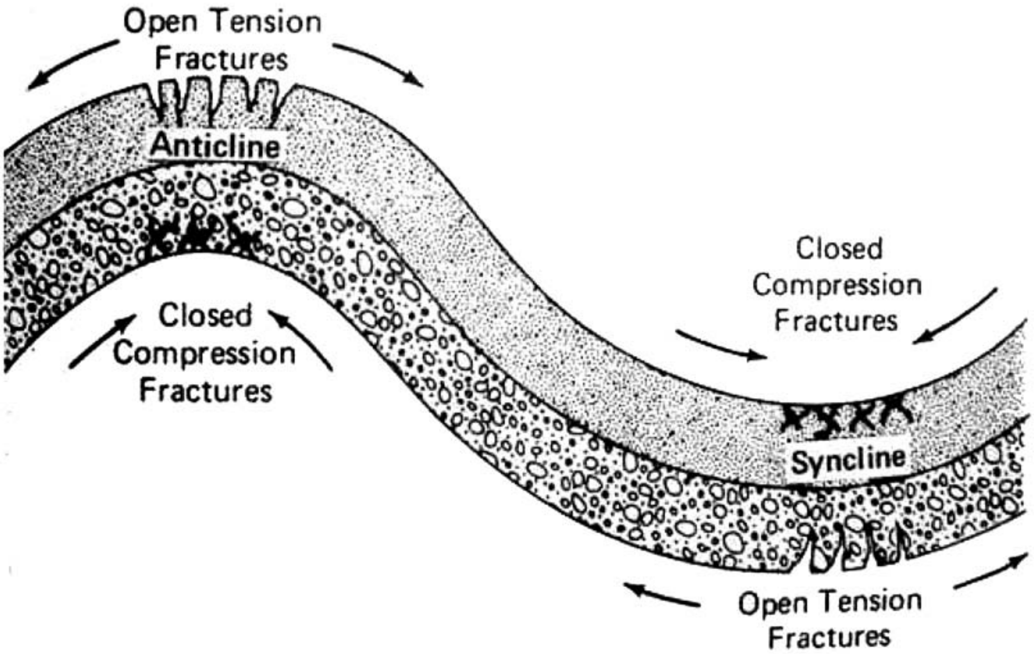
Groundwater shows a close relation to structures such as folds and unconformities in sedimentary rocks. Firstly, structures influence the flow of groundwater in the rocks; that is, water usually migrates

Figure 4.1.2. Typical karst landscape in Guilin, China. Karstic limestone was eroded away to the extent that only the solid limestone remains as isolated hills above the alluvial/colluvial flood plain

down the limbs of folds and along unconformities. Secondly, folding produces typical fracture systems characterised by open tension fractures on the crest of anticlines and closed compression fractures in the troughs (Fig. 4.1.3). This may be significant in the occurrence of groundwater reservoirs in folded sedimentary rocks such as limestone where solution weathering enlarges fractures. At depth, synclines retain water better than anticlines and, therefore, are hydrogeologically favourable sites.

Metamorphic (crystalline) rocks were altered by heat, pressure, and chemically active fluids produced in the tectonic cycle that may change their mineralogy and texture - in effect producing new rock types. There are two types of metamorphic rock: foliated, such as slate, schist, and gneiss, those in which the elongated or flat mineral grains have a preferential parallel alignment or banding of different minerals; and non-foliated, those without preferential alignment or segregation. The foliation planes of metamorphic rocks are potential planes of weakness. The strength of a rock, its potential to slip, and the movement of water through the rock, all vary with the orientation of the foliation.

Figure 4.1.3. Schematic diagram showing an anticline and a syncline and the accompanying tension and compression fractures formed during folding.



Geological structure and surface morphology influence the spatial distribution of the groundwater flow system. Both factors have to be investigated to determine the specific features of the sub-terranean part of the hydrological cycle. Geomorphological investigation, specifically land form and relief evaluation, and of rock resistance to erosion and drainage characteristics (pattern and density), are hydro-geologically significant because of their influence on groundwater recharge and infiltration capacity. In comparison with surface hydrology, groundwater in the rock environment moves slowly and exhibits long residence times. Therefore, it is necessary to analyse the geological structure to obtain an overview of the tectonic setting and development (tectonic phases) of the studied region. This applies in particular to the orientation and density of fractures which influence rock permeability. Fissures in hard rocks which originate in early orogenic phases are often indurated by secondary minerals and thus impermeable, while the fissures of 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 investigation and mapping

Geological maps and sections, as well as satellite images and areal photos, illustrate the geological features of a region. They are useful in support of an investigation of groundwater resources in regions prone to geological disturbances. A geological map should show the composition of the rocks and the geological and tectonic structure of the investigated area. These have a decisive influence on groundwater occurrence and the groundwater flow system. Geologic mapping provides the basis for determining the size and location of aquifers, the variability of aquifer properties, and the composition of covering materials which protect them. A geological map should also show various features such as springs, marshes, wet spots, and covering formations; indicate fossil landslides and thus sites of 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 often deep in the earth's crust, while a landslide, though sometimes triggered by the former, is a process affected by the forces acting near the earth's surface, mainly the weathered zone.

Geological maps are drawn to different scales. Maps showing tectonic zones with earthquake activities are usually at small scale as they represent large regions and continents, while maps designed to indicate specific phenomena such as 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, and may have to be supplemented with special maps focused on the specific hydrogeological, geotechnical or environmental issue.

4.2 Hydrogeology

Jaroslav Vrba and Jan Šilar

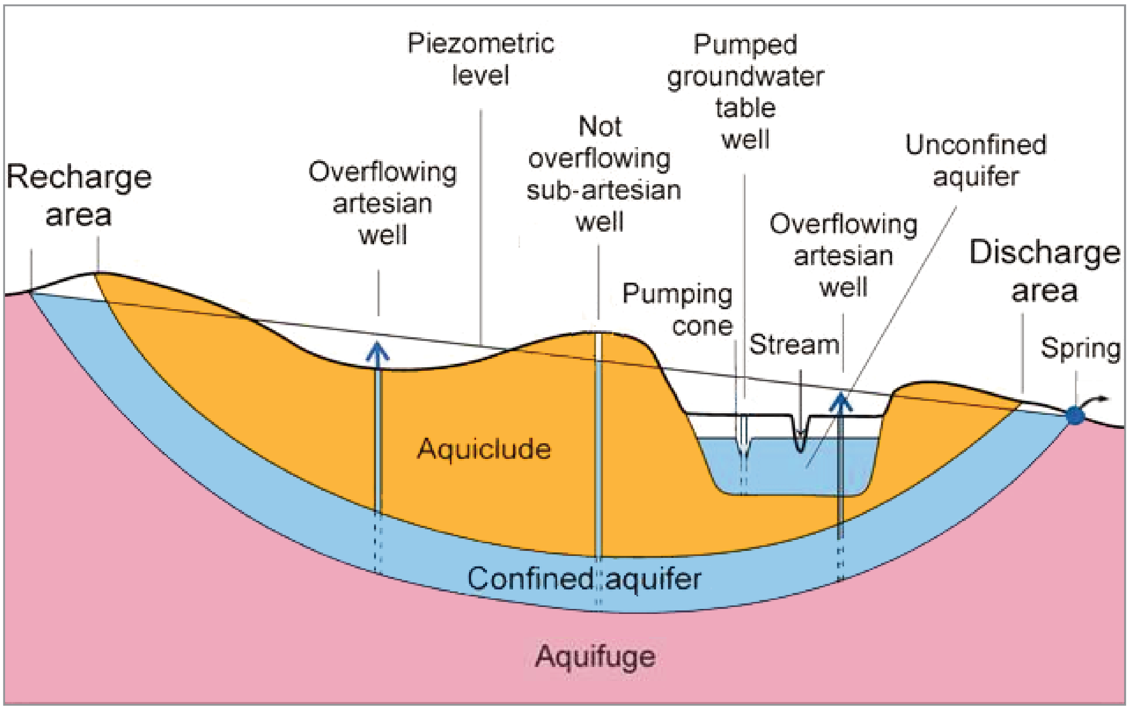
Groundwater is a vast resource, occurs within the broad context of the global hydrological system, and infiltrates into subsurface during current and past hydrological cycles. Groundwater drives many geological and geochemical processes such as the generation of land slides, ore deposit formation, the transfer of chemical constituents, karst development, weathering, and erosion. Groundwater also has an ecological function which sustains spring discharges, river base-flow, many lakes, wetlands and other groundwater dependent ecosystems. The study of groundwater requires an interdisciplinary approach to better understand its origin, occurrence and movement in the physical environment, its chemical composition and the growing human influences on its quality and regime.

Characteristics of groundwater systems

In transmissive unconsolidated and consolidated rocks groundwater forms aquifers and aquifer systems. Aquifer consists of an unsaturated zone (pores only partially saturated with water) and a deeper saturated zone with fully saturated pores. An aquifer is defined as a saturated water bearing formation capable of yielding exploitable quantities of water (UNESCO-WMO Glossary, 1992), or 'a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation' (UNESCO, 2008). A saturated aquifer overlain and underlain by a more or less impervious aquiclude is called confined; it is called artesian when the piezometric (pressure) level lies above the land surface. A confined aquifer of which the pressure level lies well above its upper boundary but below the land surface is called sub-artesian. An aquifer containing groundwater with a free surface is called an unconfined or water table aquifer. An example of different types of aquifers is shown in Fig. 4.2.1. The figure also shows three main components of the aquifer, the recharge area, groundwater flow and storage zone and discharge area (seepages and springs). An aquifer therefore, presents both storage and conduit functions.

The source of natural recharge to an aquifer is precipitation (rainfall and snowmelt); however, infiltration from surface water bodies (e.g. streams and lakes) may also be significant. The recharge water penetrates vertically through the unsaturated zone. Once it has reached the water table, it flows according to the pressure gradient and aquifer permeability. Groundwater discharges naturally in springs or seeps into surface water where the groundwater level intersects the land surface. Groundwater recharge and discharge are components of the hydrological regime of a watershed. An

Figure 4.2.1. Simplified example of an artesian basin consisting of an upper unconfined (water table) aquifer in an alluvial plain and a deeper, confined aquifer the piezometric level of which is inclined from the recharge area to the discharge area. Boreholes (indicated by arrows) tapping the confined aquifers, are artesian or overflowing where the piezometric level lies above the ground surface. Apart from leakage and diffusive loss, the spring represents the natural discharge of the groundwater system.



evaluation of this regime can be expressed in a water balance equation which compares precipitation with runoff, evapotranspiration, change in storage of surface water (ΔSW) and groundwater (ΔGW), and external inflow to and outflow from an aquifer over a hydrological, usually an annual, cycle. However, if data are available for a longer period it can be assumed that $\Delta SW = \Delta GW = 0$ and the equation can be written in simplified form (all components in both equations are expressed as the average annual value):

$$\text{Precipitation} = \text{Runoff} + \text{Evapotranspiration} \tag{4.2.1}$$

and water balance equation for the recharge area of an aquifer can be written:

$$\text{Precipitation} = \text{Surface water runoff} + \text{Recharge} + \text{Evapotranspitation} \tag{4.2.2}$$

Several other methods for recharge calculation (e.g. the Darcy numerical flow model, and others, see chapter 2) may be also applied. Both groundwater recharge and discharge can be enhanced and managed. There are several methods for enhancing recharge to aquifers, like e.g. infiltration ponds and dams, rainwater harvesting, bank infiltration, or injection wells. More or less controlled discharge of aquifers usually occurs by exploitation through various types of water supply wells or other supply facilities and irrigation wells. Discharge through the dewatering of mines, underground constructions, building foundations and by irrigation may be significant too.

Occurrence and movement of groundwater in the rock environment

Groundwater occurs and circulates in rock interstices of various shape, size and origin. The amount and movement of groundwater depend on the composition of rocks and their hydraulic properties and is controlled by structural tectonic features and discontinuities (fractures, faults, fissures, folds, cleavages). The spatial distribution of the faults and fissures and their aperture, density, orientation and size have a strong influence on rock permeability and groundwater storage as well as flow direction. Faults and other tectonic structures may be significant as either groundwater pathways

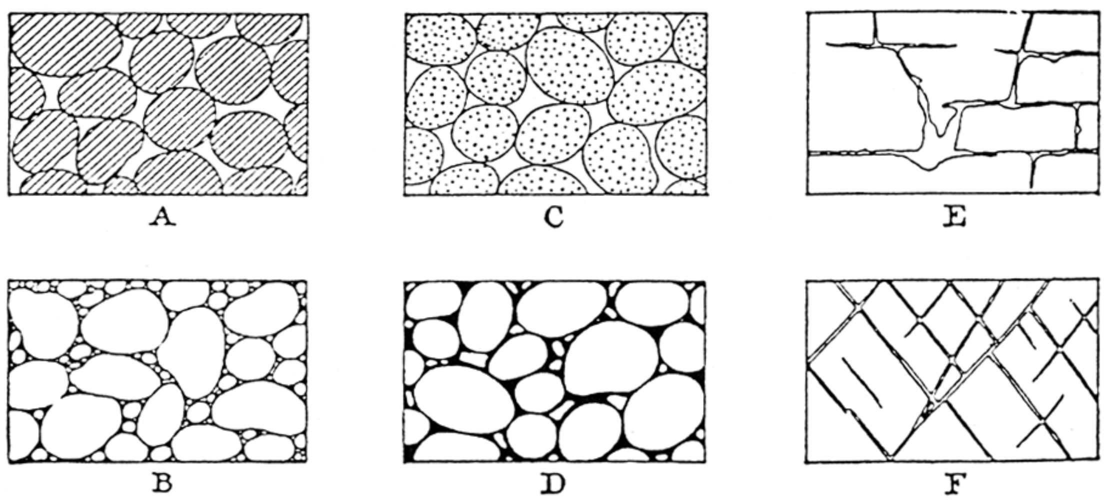
Box 4.2.1

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. 4.2.2):

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



(A) Well-sorted sedimentary deposit with high *(primary)* porosity, (B) poorly sorted sedimentary deposit with 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.

or groundwater barriers (boundaries). The intrinsic ability of the rock to transmit water through its interstices is called **permeability.** The total amount of water which can be stored in an aquifer as a proportion of its volume, expressed as a percentage of the total void space within a rock environment, is called **porosity**. Clay and silt present high porosities (35–55%), with lower values in sand and gravel (10–30%) and sandstones (5–30%) and very low porosities in shale and crystalline rocks (0–10%). Distinctions between primary porosity developed during rock formation and secondary porosity developed subsequently by fracturing, weathering and other geological and chemical processes have to be taken into consideration when water bearing formations are evaluated. (Box 4.2.1 and Figure 4.2.2). Basic hydraulic parameters related to groundwater and the physical environment in which groundwater moves are defined mostly from pumping and recovery tests on boreholes and water supply wells.

Hydraulic conductivity (usually measured in m/day), a basic parameter for groundwater hydraulic calculations, is a property of a saturated porous medium which determines the relationship between the specific discharge and the hydraulic gradient causing it (*International Glossary of Hydrology,* 1992). In Darcy's equation it represents the relationship between the linear velocity of laminar groundwater flow through the rock environment per unit time under a hydraulic gradient of 1 m per metre. Hydraulic conductivity is related to grain size, ranging from coarse grained rock material (10^{-3}m/day–10^{-4} m/day) to lower values in fine grained sediments such as silt and clay (10^{-6} m/day–10^{-8} m/day).

Transmissivity (measured in m^2/day) the product of the hydraulic conductivity and saturated aquifer thickness, expresses the rate at which groundwater is transmitted through a unit width of an aquifer under unit hydraulic gradient; is calculated by multiplying the hydraulic conductivity by the aquifer thickness. A transmissivity greater than 125 m^2/day indicates an aquifer of good productivity that is suitable for emergency exploitation. The rate at which groundwater moves under a hydraulic gradient depends on the type of interstices in the rock environment and their inter-connectedness. However, only in homogeneous (e.g. sedimentary) porous rock environments do the laws of groundwater movement effectively apply.

Storativity is a measure of how much water can be stored in an aquifer. Coefficient of storage is expressed as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head (*International Glossary of Hydrology,* 1992). Storativity is dimensionless. Its value ranges from 0.05 to 0.30 in unconfined aquifers and from 0.005 to 0.00005 in confined aquifers (Freeze and Cherry, 1979). Water is released from storage through gravity in unconfined aquifers and through the compressibility of rock environment (squeezing) in confined aquifers. For unconfined aquifers the storativity term is known as the **specific yield**. It is defined as the volume of water that a unit volume of unconfined aquifer releases by gravity from storage per unit area of the aquifer per unit decline in the groundwater level. Calculation of storage coefficient (amount of groundwater released per 1 m^2 from an aquifer if the water level drops by 1 m) allows one to define the amount of groundwater stored in the aquifer and recommend a reasonable rate of its exploitation (or temporary over-exploitation) in emergency situations. With respect to the scope of GWES project it is important in deciding whether an aquifer resistant to disastrous events is able to supply the required amount of drinking water to the affected population or whether other emergency drinking water sources have to be found.

Drilling of exploration wells and observation boreholes, conducting pumping and recovery tests whilst measuring groundwater level drawdown in the pumped well and radius of influence in observation wells, calculating the yield and specific capacity of the well, groundwater sampling for chemical and environmental isotope analysis and other relevant field and laboratory tests – these are the most common methods and tools for obtaining data for calculating the hydraulic parameters and groundwater quality of an aquifer. Examples of groundwater resources assessment and evaluation of their quality are given in Chapters 4.2, 4.3, 4.4, 4.7, 6 and in some of the case studies.

Permeability and porosity of the principal rock types

Crystalline (igneous and metamorphic) rocks are mostly of negligible primary porosity (usually less than 1%) and permeability and are considered impervious. However, owing the influence of tectonic processes, secondary porosity and permeability are developed along fractures and fissures and other discontinuities. The origin, extent, orientation and widths of the fissures and fractures depend on the intensity and directions of various tectonic movements and stresses that occurred over the geological history of the earth. The study of the nature of tectonic and structural events is therefore fundamental to a better understanding of groundwater flow systems in hard rocks. The orientation of foliation in metamorphic rocks also influence rock permeability. Generally, with increasing depth and temperature, the fissures close, the rocks become less permeable and groundwater flow intensity decreases. However, active groundwater circulation has been observed in deep fractures and folds of crystalline rocks hundreds of meters below ground (Singhal and Gupta, 1999). Groundwater circulation has been observed also in plutonic rocks at depths of more than a thousand meters along deep tectonic structures (lineaments) and may be indicated by the occurrence of thermal springs. The age of fissures also controls rock permeability. Fissures of post-orogenic age are mostly more permeable than old fractures consolidated by orogenic phases and indurated by secondary minerals. The contact between intrusive plutonic bodies and the host permeable sedimentary rocks define boundary conditions for the aquifer. There are also differences in hydraulic properties and groundwater flow between plutonic rocks, e.g. granite (higher transmissivity, yields and groundwater flux rates in weathered and fractured zones) and metamorphic rocks. Foliation, a typical property of metamorphic rocks (e.g. gneiss, schist) has significant influence on groundwater movement. Dissolution (chemical weathering) of siliceous rocks may be observed in the increase of the width of fractures and thus in the increase of fracture permeability.

Volcanic rocks (e.g. basalts, rhyolites, andesites, dacites). Porosity and permeability vary and depend mainly on the age and chemical composition (basic or acidic) of the magma, its viscosity, nature of eruption, gas loss during cooling producing pore spaces, amount of enclosed ash and pyroclastics and susceptibility to weathering. Plateau basalts, composed of a number of low viscosity lava flows covering areas of thousands of square kilometres and attaining a thickness of hundreds of metres contain valuable sources of groundwater due to intensive fracturing, high primary and secondary permeability and horizontal hydraulic conductivity and groundwater flow parallel to the lava flows (David, 1969). Multi-layered aquifers may be formed in permeable volcanic sediments trapped between lava flows as well as in other fractured volcanic rocks, particularly in unconsolidated pyroclastic deposits. Low hydraulic conductivity is observed in dense basalts with fracture porosity less than 2% and in welded tuffs with porosity less than 20%. It has been reported from many parts of the world that porosity and hydraulic conductivity of volcanic rocks tends to decrease with increasing age.

Through chemical and mechanical weathering, **alumino-silicate** and **quartz-rich rocks** produce permeable and sandy elluvia of high porosity (up to 45%) often tens of metres thick, which facilitate groundwater recharge and may constitute locally important aquifers. **Basic rocks** disintegrate into minerals with high clay content through chemical weathering and form less permeable soils, clog the fissures in the underlying bedrock and thus reduce recharge potential and rock permeability. Generally, porosity decreases with depth in zones of weathering. However, permeability and hydraulic conductivity may increase with depth as the rate of weathering and clay mineral reduction declines as one approaches the rock basement.

Groundwater aquifers which occur in granite and young volcanic rocks are a valuable source of drinking water in many parts of the world. Groundwater sources in both types of rocks located away from flood plains and the influence of tsunami and flooding through storm events may be considered as a safe source of water for emergency situations, provided that they are protected from ongoing pollution. Springs discharging from volcanic rocks are also important sources of emergency water supplies.

Sedimentary rocks vary considerably in their composition. They exhibit all types of interstices (pores, fissures and karst cavities), all contributing to their bulk permeability. Double, or dual (e.g. primary plus 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 prominent aquifers are developed in **sandstones and carbonate rocks,** particularly **limestones.** In claystones (mudstones) and siltstones groundwater movement is possible only in layers which contain a proportion of sand and/or open fractures where these are developed. Though groundwater resources in these rocks are often too small to be used for public water emergency supply, they might constitute a valuable domestic drinking water source in areas of water scarcity and also in emergency situations.

The most productive aquifers, aquifer systems and groundwater basins in sedimentary rocks world-wide are developed in coarse porous and fractured **sandstones**. Sedimentary sandstone basins often attain a thickness of several hundreds or even thousands of metres. Changes in basin size may have occurred through transgression and regression or changes in palaeographic setting affecting sedimentary conditions and are reflected in the considerable variability in a complex sedimentary lithology. Examples are the formation of lithofacies represented by sandstones of variable grain size, with layers of marlstones, siltstones, and basal conglomerates of terrestrial, marine or lacustrine origin – and in groundwater occurrence and the formation of aquifers both confined and unconfined, and aquitards. The tectonic structure of sedimentary basins controls aquifer boundary conditions and groundwater pathways. Further tectonic features are fold structures defining groundwater basins with distinctive groundwater circulation and block tectonics that limit individual groundwater structures and may juxtapose aquifers. Aquifers in sandstones containing large groundwater resources, usually exhibit appreciable dual porosity and permeability and are usually characterised by a number of laterally interconnected groundwater flows forming multi-aquifer systems. However, vertical hydraulic inter-aquifer connection commonly also exists. In young sandstones primary porosity dominates; in older sandstones the primary porosity is controlled by the degree of cementation. Cementing minerals, mainly quartz and calcite, reduce sandstone porosity and hydraulic conductivity and compaction increases with depth and sandstone age. Sandstone porosity in the range 30−35% and hydraulic conductivity in the order 10^{-4} – 10^{-6} m/s is observed in many parts of the world.

Large groundwater storage is typical for aquifers in sedimentary basins, implying lower pollution impact that becomes negligible in deep confined aquifers. Many large aquifers in sedimentary basins are shared by two or more countries and referred to as transboundary aquifers. Cooperation among countries is needed to eliminate potential water conflicts by coordinating groundwater extraction and protection based on integrated, sustainable groundwater resources policy and management. Some deep sedimentary basins contain extensive and thick aquifers with limited current replenishment and enormous stored groundwater resources (called non-renewable or fossil), largely from the past hydrological cycles. The absence of significant groundwater renewal is usually the consequence of very low rainfall in the unconfined part of the aquifer. It may also result from hydraulic inaccessibility of some confined aquifers (Foster and Loucks, 2006). In many parts of the world groundwater (both renewable and non-renewable) stored in sedimentary basins is the most important and safe source of drinking water in disaster-prone areas in emergency situations.

Carbonate rocks (limestones and dolomites) are widely developed in many parts of the world. Their primary porosity is low. Groundwater motion and storage occurs in fractures and horizontal bedding planes. Both are enlarged through rock dissolution by chemically aggressive groundwater to form karst cavities and karst landscape features and conduits with groundwater circulation. Folded carbonate rocks, particularly in anticlines, present high secondary permeability owing to their tectonic exposure and enlargement of fractures by weathering and dissolution. High infiltration rates (40% or more of the annual rainfall), rapid groundwater flow (up to several thousands of meters per day) in conduits (channels, caverns), large open fissures and openings, considerable irregularity in karstification and related yield variability are typical for karst aquifers.

Springs, often with substantial discharge, are another typical feature of karst hydrogeology. Terrestrial springs and submarine springs in coastal and off-shore karst regions with discharges up to hundreds of m^3/s are known worldwide. Seasonal groundwater level fluctuations in karst regions are high, often in order of tens metres. This, along with highly variable spring discharge reflects both rapid infiltration of seasonal rains and rapid response of the groundwater system.

The hydraulic conductivity of karstic rocks is highly variable due to their heterogeneity and anisotropy and the intensity of fracturing and solubility of the rock mass. Hydraulic conductivity differs by orders of magnitude between unfractured (10^{-9}–10^{-13} m/s) and fractured (10^{-1}–10^{-6} m/s) carbonate rocks. Generally, hydraulic conductivity decreases with increasing rock age and depth, along with porosity. Productive aquifers are also developed in many coastal areas in young and recent poorly cemented limestones with high primary porosity. Differences in karstification between of dolomites and limestones have been noted and reflect in their hydraulic properties. Although lower well productivity is common in dolomite environments, high-yielding dolomite supplies have been developed e.g. in southern Africa.

Chalks, limestones rich in shell fossils and typically white in colour, present different hydraulic characteristics. Groundwater systems in these rocks were comprehensively studied in England with respect to diffuse nitrate groundwater pollution. Chalk aquifers exhibit considerable variations in porosity and (preferential) groundwater flow, mostly confined to fissures.

Groundwater vulnerability in carbonate rocks and particularly in karst regions is high due to an often thin and permeable soil cover, resulting in rapid infiltration of rainfall, surface streams and pollutants into the aquifer and generally low pollutant attenuation in the unsaturated zone. Groundwater in karst aquifers is not considered a safe source of water for emergency situations because of low resistance to events such as floods and storms and particularly high vulnerability to human impacts. However, deeper aquifers in carbonate rocks and karst springs used for drinking water supplies may serve as suitable emergency sources of drinking water.

Unconsolidated and incoherent sediments of Quaternary and recent age include various kinds of gravel, sand and clay, sometimes containing organic matter. They occur as alluvia; fluvial, lacustrine, marine and delta sediments; sediments of elluvial cones of inter-montane depressions; and glaciofluvial and glaciolacustrine sediments washed out from moraines. Incoherent and thick sediments are prone to compression and to subsidence of the surface, mainly if the pore pressure is lowered by groundwater level decline through pumping. Shallow water table aquifers in coarse grained sediments are characterised by high hydraulic conductivity, interconnected groundwater flow patterns, and interaction with surface water and in coastal aquifers with salt sea water.

Unconsolidated sediments in **fluvial deposits** of flood plains, deltas of big rivers in coastal areas and in river terraces store very large volumes of groundwater widely used for public and domestic water supplies, irrigation and other purposes. Often a hydraulic relationship between a stream and shallow aquifer is observed. Heterogeneous fluvial deposits in deltas of big rivers may be hundreds of metres thick. Productive, usually water table, aquifers with high hydraulic conductivity (in the order of 10^{-3} – 10^{-4} m/s) occur particularly in coarse grained porous and permeable fluvial sands and gravels with thicknesses varying from a few meters to hundreds of meters. The palaeo-morphology and geology in the development of river valleys (shifting, meandering, eroding) have to be studied to identify buried paleochannels and relicts of past river drainage networks (see chapter 4.6). Palaeo-channels filled by thick coarse-grained sands and gravels can serve as reservoirs of natural and artificially recharged water in arid and semi-arid regions and constitute a safe emergency source of drinking water in areas affected by drought.

Productive aquifers occur also in unconsolidated sediments such as **glacial deposits** composed of glacial tills and glaciofluvial and glaciolacustrine sediments. Glacial till is poorly sorted, unstratified and thick material extensively deposited during the Pleistocene period mainly in the northern regions of America, Asia and Europe. Owing to their spatial heterogeneity aquifers and aquitards often alternate in the profile of the till deposits. Porosity of glacial tills lies in the range of 25–45%, hydraulic conductivity is low (10^{-9}–10^{-10} m/s) however, due to deposits weathering and fracturing may acquire 10^{-6}–10^{-9} m/s (Singhal and Gupta, 1999) . Hydraulic conductivity of fine-grained glacial till (sand and silt) and glaciolacustrine deposits is very low, in the order 10^{-10}–10^{-12} m/s (Freeze and Cherry, 1979). Networks of mostly vertical fractures in fine grained glacial deposits of different origin (glacial till, glacio-lacustrine clay) facilitate hydraulic connection between groundwater flows and aquifers (Cherry, 1989). The most important aquifers occur in buried valleys eroded in the bedrock of glacial deposits and filled by glaciofluvial coarse grained sediments (sands and gravels). Such aquifers are from tens up to hundreds meters thick, up to tens of kilometres wide and drain and store large amounts of groundwater, usually of good quality. Groundwater in buried valleys of glacial origin is a valuable source of drinking water which may be used for emergency situations.

Homogenous and isotropic **aeolian deposits** occur mostly as local aquifers in loess composed of fine rounded sand and silt grains, with porosity of 40–50% and hydraulic conductivity on the order of 10^{-5}–10^{-7} m/s. On the other hand thick (up to 300 m) loess deposits are widely distributed in China and contain valuable groundwater resources.

Aquifers in unconsolidated sediments are mostly unconfined, often overlain by sandy soils and with a groundwater table usually close to the surface. Groundwater vulnerability of such aquifers is generally high. Particularly aquifers in fluvial deposits in flood plains are by their nature highly vulnerable to human impacts (pollution) and natural disasters, such as floods, tsunami and storms. However, aquifers in paleo-channels and buried valleys can serve as a safe source of water in emergency situations.

Tectonic structures and discontinuities

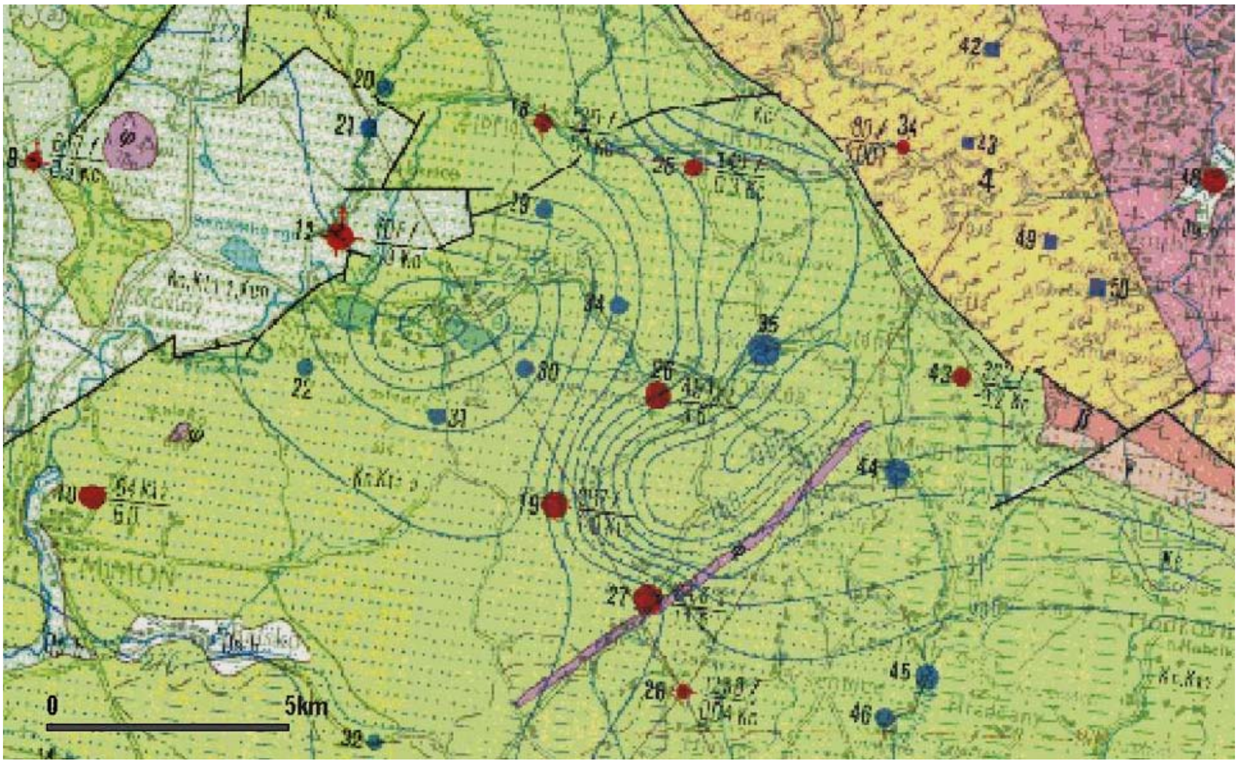
On a regional scale, the influence of the principal tectonic structures and discontinuities (fractures, fissures, folds, flexures, foliation in metamorphic rocks, beddings in sedimentary rocks) on the movement and storage of groundwater have to be carefully investigated and evaluated and relevant structural analysis of the geological setting implemented. Tectonic structures may be significant as either groundwater pathways or barriers to groundwater flow. Folding in anticlines and synclines (Fig. 4.1.3) leads to the formation of well delineated groundwater basins (synclines) and their recharge areas (anticlines). The role of tectonic features on rock bulk permeability in the principal rock types was described in chapter 4.1. The origin of fractures, their geometry, density and aperture control hydraulic conductivity and rate of groundwater flow in igneous and metamorphic rocks. Bedding planes have a decisive influence on groundwater flow and hydraulic conductivity in sedimentary rocks. In both types of rocks tectonic stresses and temperature increase with increasing depth whilst hydraulic conductivity and groundwater flow decrease.

Geological and hydrogeological mapping, field measurements of tectonic features, geophysics, air born remote sensing and satellite based methods and borehole surveys and their hydraulic testing can provide a set of reliable geological and hydrogeological data about the genesis, occurrence, orientation and permeability of tectonic structures and their influence on the formation of aquifers, on groundwater flow and seepage and the origin and discharge of springs. Various classification systems, graphical methods (e.g. rose diagrams, Mohr diagrams) and statistical techniques are applied in evaluating data related to fracture and discontinuity measurements and mapping and help in establishing a conceptual model of a groundwater system. In investigating and modeling groundwater attention should be focused on such tectonic structures as they may influence fracturing and thus rock bulk permeability, aquifer geometry and boundaries and thus both groundwater storage and flow paths as well as groundwater drainage or barriers.

General and thematic hydrogeological maps

Hydrogeological maps are very useful means of visual presentation of groundwater conditions and an indispensable tool for hydrogeologists, land use planners, water managers, decision and policy makers, and the public. The art of hydrogeological mapping has developed historically from geological mapping. A hydrogeological map sheet usually comprises a map, vertical sections and diagrams, a legend and an explanatory booklet and may be published as a single sheet, as part of a map series or as part of an atlas. There are different categories of hydrogeological maps depending on map content and scale. Colour tones and ornaments are combined with symbols and lines depicting groundwater data and information. General hydrogeological maps are synthetic and present the principal groundwater bodies and their productivity, rock lithology and related porosity and permeability, groundwater level contours and flow direction and hydrogeological data (e.g. springs, water wells, areas of saline groundwater amongst others). They are usually constructed on the country or regional level and their scale determined by the size of the country (usually 1:1 000 000 and smaller). Thematic or specialised hydrogeological maps, such as groundwater protection maps, groundwater pollution maps, groundwater vulnerability maps, are constructed for regional and local planning and managerial purposes. Their scale is usually 1:200 000, 1: 500 000 and bigger (Fig. 4.2.3). However, specialised maps may also be produced on a country scale as part of a map series or atlas.

Figure 4.2.3. 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.

Traditional manual techniques for map construction have been replaced by computer generated mapping. The wide coverage of the Geographical Information System (GIS) is used for constructing digitised maps (see chapter 4.8). Data collected within GIS is collected, processed, assessed, and categorised in data layers with a common coordinate system and mapped in a format and at a scale designed to meet specific requirements. The raster format is the best and the most widely used way to enter data and represent remote sensing images and colour-coded thematic maps at small pixel size (Civita, 1994). It is important that disclaimers appear on thematic maps informing the user of the map limitations and of its intended use, and that a map is accompanied by sufficient information to fully describe the assumptions and methodologies used and the level of accuracy of presented information (Vrba and Zaporozec, 1994).

Digitised aerial photographs and satellite images are also very effective in groundwater resources identification and the presentation of parameters controlling e.g. groundwater occurrence, groundwater level variation, soil moisture, tectonic structures, palaeochannels. They are particularly useful in areas where geological maps are not available or available only on small scale as well as for inaccessible areas. In e.g. desert regions ERS (Earth Resource Satellite) and Radarsat missions provide data for the identification of shallow groundwater reservoirs in buried stream channels (Drury and Deller, 2002), which may serve as emergency source of drinking water.

Groundwater vulnerability assessment and mapping

It is obvious that vulnerability should be a primary consideration when groundwater is to be used for emergency situations. The GWES project focuses attention mainly on aquifers of low vulnerability, resistant to natural impacts. It is generally assumed that the subsurface environment provides some degree of protection to groundwater. The degree to which this does not hold is referred to as groundwater vulnerability, which is an intrinsic property of a groundwater system. Groundwater vulnerability is a relative, non-measurable, dimensionless property. Parameter rating and weighting methods are implemented to express the relationship among the parameters used for vulnerability assessment. Groundwater recharge, soil property, lithology, thickness of the unsaturated zone, groundwater level below land surface and aquifer media and hydraulic properties are the standard attributes used in the assessment of groundwater vulnerability (e.g. DRASTIC index). In the assessment of deeper aquifers vulnerability, aquifers with limited replenishment, and aquifers with fossil groundwater, isotope hydrology techniques are often applied (see chapter 5.4). These techniques serve to assess groundwater age and origin, both valuable attributes supporting the isotope hydrology methods applied when assessing the vulnerability of emergency groundwater resources.

The spatial variations in groundwater vulnerability may be depicted on vulnerability maps, classified as interpretive groundwater protection maps. Derived from hydrogeological maps, groundwater vulnerability maps are useful for planning, regulatory, managerial and decision-making purposes. They display, and assist in identifying, areas where groundwater is prone to natural disasters and human impacts, and to pollution. Such maps can help planners make informed, environmentally sound decisions regarding land use and groundwater protection and assist in the formulation of disaster risk assessment and risk mitigation policy. Vulnerability attributes may be selected with respect to the type of natural events presented. Vulnerability maps also create public awareness through publicity about environmental protection because the term ‘vulnerability’ is explicit and readily understood by non specialists.

Methods of groundwater vulnerability assessment and mapping have been described by Vrba and Zaporozec (1994), Witkowski at al. (2007) and others.

Aquifers suitability for emergencies

When prospecting for groundwater resources for emergency situations attention is focused mainly on **confined aquifers** of **low vulnerability** in sedimentary basins, **deep unconfined aquifers** overlain by a thick unsaturated zone interbedded with low permeability layers of local extent and **deep aquifers with limited replenishment and fossil water** recharged during past pluvial periods. The unsaturated zone of these aquifers is often hundreds metres thick consisting of rocks of low to negligible permeability. Their thickness, together with large groundwater storage and long residence time, are the main parameters which control low vulnerability of the deep aquifers to natural disasters and their suitability to be used as a safe source emergency resource of drinking water.

In comparison, **shallow water table aquifers** in fluvial deposits, **coastal aquifers** and **karstic aquifers** are highly vulnerable to natural disasters, particularly to floods, storms, tsunamis, and prone to droughts in semi-arid and arid regions. Such aquifers may be considered as a suitable source of drinking water in emergency situations only under specific hydrogeological or geographical circumstances. In addition, the storage capacity of shallow aquifers in various types of Quaternary deposits is often limited and their potential as a emergency resource has always to be carefully evaluated. However, where shallow aquifers are developed in thick and permeable fluvial or glacial deposits, away from flood plains and coastal areas as well as the influence of pollution sources, they can be considered as a significant emergency resource of drinking water.

4.3 Hydrochemistry

Jaroslav Vrba and Ryuma Yoshioka

The chemical composition of groundwater is the result of the combined effect of hydrogeochemical and biological processes occurring in the atmosphere-soil-groundwater-rock environment. In particular it is controlled by: 1) the chemical composition of rain, snowmelt and surface water infiltrating into the subsurface, 2) vegetation cover and land use, 3) the permeability and chemical composition of the soil and rock environment in which groundwater moves, 4) contact time and contact surface between groundwater and the geological materials along its flow path, 5) the rate of geochemical (dissolution, precipitation, hydrolysis, adsorption/desorption, ion exchange, oxidation/reduction), physical (dispersion, advection, filtration, thermal), and microbiological (microbial metabolism and decomposition, cell synthesis) processes, as well as 6) the concentration of dissolved gases, particularly oxygen and carbon dioxide.

The influence of rocks on groundwater quality can, as proposed by Mazor (1991), be classified roughly into three rock groups: 1) those in which fresh, good quality groundwater is common, that is, rocks that contribute minor amounts of mineralisation to the water (fractured crystalline; leached sandstone), 2) carbonate rocks that contribute a higher dissolved solid load to, but maintain good potable quality of, groundwater, and 3) rocks that enrich the water with significant amounts of dissolved salts, often rendering it non-potable (e.g. marine deposits containing evaporites).

Groundwater chemical zoning

There are scale differences in the chemical composition of groundwater both laterally (recharge/discharge areas) and vertically (shallow oxidation and deep reduction zones), which are typical particularly for groundwater in sedimentary basins. Generally, groundwater in recharge areas and shallow aquifers has a lower total dissolved solids (TDS) content than groundwater in discharge areas and in deeper aquifers. The increase in total dissolved solids and the anion dominance 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 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 ⟶

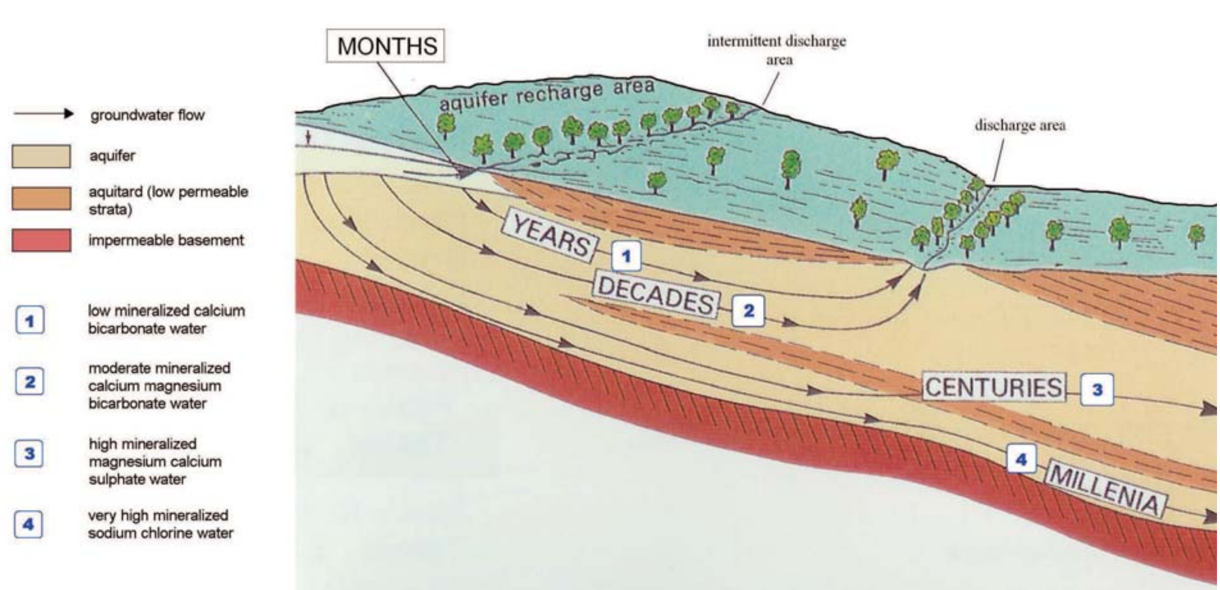
In crystalline or pure siliceous sedimentary terrain, the Chebotarev sequence might hold for ionic ratios with depth, but the dissolved solids concentrations might even be reversed (Verhagen 1992).

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

Recharge zones and near-surface inland aquifers are characterised by active groundwater circulation, lower temperature and brief contact of groundwater with leached rock materials. Groundwater is low in total dissolved solids and HCO_3^- is the dominant anion. In deeper intermediate zones temperature, pressure, contact time and surface with reactive rock minerals gradually increase as groundwater flow velocity decreases. This usually leads to increases in groundwater TDS with depth and sulphate ion dominance. In deep groundwater systems where flushing by groundwater is very low and residence time long, chloride gradually becomes the dominant anion, calcium is replaced by sodium and groundwater is often high in total dissolved solids. At the base of the aquifers in deep basins highly saline brines are found. The sequence of a gradual transition along the flow paths from fresh bicarbonate groundwater through sulphate water to mineralised chloride water many millennia old at the deep downstream end is shown in Fig. 4.3.1.

The HCO_3^- content in groundwater is mostly derived from biogenic CO_2 in the soil zone (soil microorganisms and organic matter), dissolution of calcite and dolomite, or decomposition of igneous feldspars. The origin of sulphate in groundwater depends on the presence of soluble sulphate bearing minerals (gypsum $CaSO_4 . 2H_2O$, anhydrite $CaSO_4$ or potash salt deposits), metallic sulphide minerals and the deposition of marine aerosols. High chloride contents in deep groundwater depends primarily

Figure 4.3.1. Example of flow, age and hydrochemical patterns in groundwater (adapted from British Geological Survey, 2003)



on the presence of chloride-bearing sedimentary rocks and their soluble halite (NaCl) and sylvite (KCl) contents, and quite strongly on groundwater contact surface and time with these rocks.

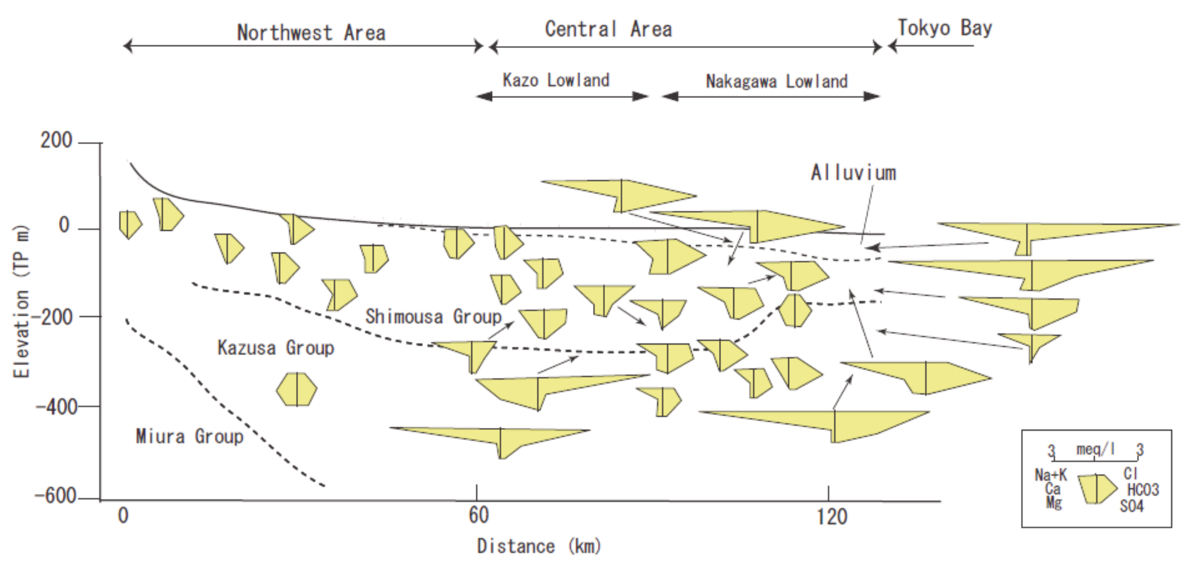
The chemical composition of groundwater in some deep aquifers may be modified by gases - particularly by carbon dioxide (CO_2), originating from volcanic processes and present in high concentrations in deeper parts of aquifers. Dissolved CO_2 is an acid that keeps pH low, hydrolyses silicates, and releases solutes to the groundwater (Bucher and Stober, 2000).

Ground water in the different zones can be roughly classified in terms of its age. In 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 groundwater evolution sequence and groundwater zoning described above could be disturbed in geological structures affected by tectonics that interconnect aquifers carrying water of different age and origin. In coastal regions where groundwater composition is under the influence of saline water intrusion, the chemical zoning of groundwater does not apply as high groundwater salinity in shallow groundwater aquifers is produced by mixing of fresh water with sea water or through salination by evaporation in arid environments.

The potential usefulness of groundwater in emergency situations needs to be carefully studied as it is controlled by its chemistry and quality. This is illustrated by an example from the Kanto Plain, the largest groundwater basin in Japan containing groundwater of different origin, age and chemistry. A distinct vertical hydrochemical zonation is developed in this basin that is clearly visible in the cross section from the Kanto Plain to Tokyo Bay (Fig 4.3.2). In the central part of the Plain groundwater with different dissolved solids content and different chemical type is present at various depths. Most prominent here is shallow groundwater of low dissolved solids and Na-HCO_3 type derived from hills, plains and from shallow aquifers of less than 100 m deep (e.g. sampling sites no. 21, 22, 43, 72 in Table 4.3.1). High groundwater salinisation in shallow aquifers in Tokyo Bay is the result of sea water intrusion. In Tokyo Bay and the deep parts of Kozo lowland electric conductivity (EC) is high and groundwater of Na-SO_4 or Na-Cl type. The chemical composition of high residence time groundwater

Figure 4.3.2. Vertical distribution of groundwater quality in the cross section across the Kanto Plain to Tokyo Bay in Japan displayed in Stiff diagrams



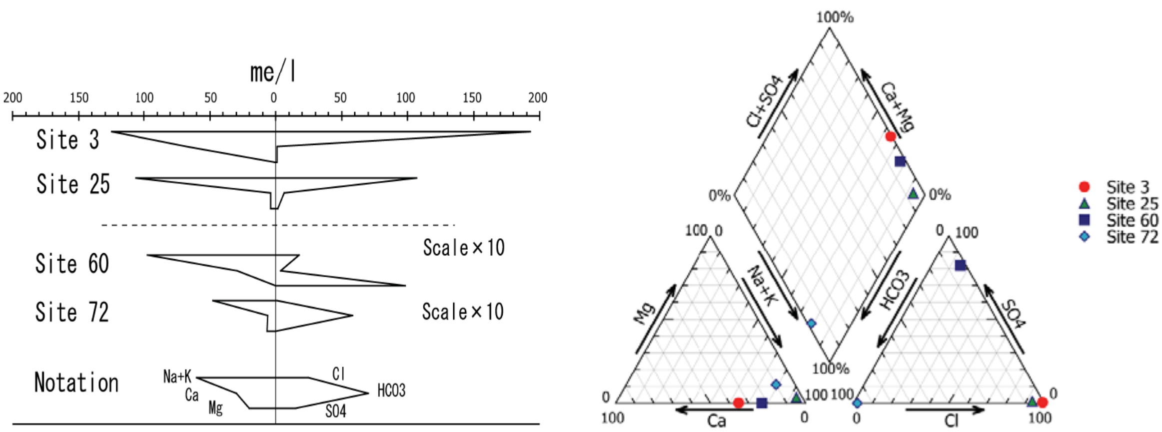
in such deeper aquifers is influenced by intrusion of fossil saltwater that contains gases (mainly methane) or by salts eluted from the sediments. The chemical composition of groundwater in various depths of shallow and deep aquifers and coastal regions of the Kanto Plain and with influence of fossil water is given in the Table 4.3.1. Stiff and Piper diagrams of the four typical groundwater chemistry sites selected in this table can be seen in Fig. 4.3.3.

Table 4.3.1. Chemical composition of groundwater of the Kanto Plain and Tokyo Bay at various depths (compiled by Yoshioka, based on the data of Seki et al., 2001)

Site No.	Site Type	Depth m	pH	EC mS/m	Na ppm	K ppm	Mg ppm	Ca ppm	Cl ppm	SO_4 ppm	HCO_3 ppm	Quality Type
3	C	880	7.8	2,020	2,849	42	4.2	1,358	6844	45	73	NaCl
20	M	150	9.0	100	228	2.0	0.3	1.5	6.0	138	451	$NaHCO_3$
21	M	50	8.6	50	98	0.8	0.5	7.4	7.8	26	222	$NaHCO_3$
22	M	10	8.4	40	107	3.1	0.4	4.3	5.2	14	300	$NaHCO_3$
25	P	250	7.7	1,230	2,378	117	49	72	3,799	66	400	NaCl
31	M	1,200	6.6	3,390	8,663	138	111	104	12,800	106	2,115	NaCl
36	M	600	9.5	40	98	1.7	0.7	2.3	3.1	17	239	$NaHCO_3$
41	P	1,500	7.6	3,090	6,441	77	50	440	11,060	76	127	NaCl
43	M	83	9.1	30	63	1.2	0.7	3.7	2.1	23	142	$NaHCO_3$
45	C	1,066	8.0	3,400	6,674	76	41	1,454	13,150	78	49	NaCl
47	C	100	8.4	160	407	17	3.1	3.0	31	0.0	1,103	$NaHCO_3$
56	P	1,200	7.5	3,170	6,770	91	166	352	11,510	79	317	NaCl*
60	M	1,000	8.4	140	221	3.6	0.0	58	64	472	22	Na_2SO_4
72	P	95	7.4	50	104	8.9	8.2	12	4.2	0.1	356	$NaHCO_3$
78	P	1,500	7.4	3,570	7,308	92	180	364	12,660	156	550	NaCl*
79	P	1,500	7.5	2,370	4,602	95	276	276	8,556	8.1	310	NaCl
80	P	1,500	7.5	3,610	9,989	353	249	880	18,270	181	254	NaCl*
81	P	1,300	7.4	4,710	13,600	623	204	927	23,410	216	204	NaCl*
86	P	200	8.5	100	201	14	2.4	5.9	13	0.0	630	$NaHCO_3$

M: Mountainous P: Plain C: Coastal * Fossil Water

Figure 4.3.3. Stiff and Piper diagram of groundwater chemistry in the 4 typical sites of the Kanto Plain and Tokyo Bay. Position of shallow groundwater of Na – HCO_3 type (site No. 72) in the diagram significantly differs from the other three samples of groundwater from deep aquifers



High salinity groundwater is observed in arid and semi-arid regions. Evapotranspiration at high rates over a long time periods leads to the build up of high groundwater salinity (Chapman, 1992). This is seen in seepages or salt marches with distinctive vegetation, known as Salinas, or in sabkhas or pans mostly without vegetation due to locally endorheic conditions.

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 contents. The presence of major cations (Ca^{2+}, Mg^{2+}, Na^{+} + K^{+}) depends on the solubility of the source minerals and on the type, extent and velocity of cation exchange processes. Matthess (1982) identified the following vertical hydro-geo-chemical zonation based on the characteristic cations:

$$Ca^{2+} \rightarrow Ca^{2+} + Mg^{2+} \rightarrow Na^{-}$$

Influence of biological processes on groundwater chemistry

Biological processes enhance the extent and rate of geochemical processes, stimulate or control many redox processes occurring in groundwater systems, have significant influence on the solubility of salts (particularly in the soil environment), on oxidation processes, and on oxygen and carbon dioxide content. The occurrence of the latter involves the active participation of bacteria and fungi. According to Fairbridge (1967) the subsurface environment is always modified to some degree by organic metabolic processes. Biological processes are particularly intensive in regions with warm and humid climates in the uppermost soil and root domain of the unsaturated zone, where dissolved oxygen is usually available supporting organisms which break down organic matter. Organic material often present in these sediments may produce reducing conditions favourable for the mobilization of iron and manganese and their higher content in groundwater. Biochemical processes in the soil produce large amounts of inorganic and organic acids which render the groundwater aggressive, initiating the hydrochemical process. Biological processes affect groundwater composition and quality particularly in shallow aquifers which are usually not considered as a safe source of groundwater in emergency situations. However, living bacteria were identified also in deep groundwater hundreds of meters below ground (Gurewisch, 1962, Davis 1967, and others). Their occurrence is controlled mainly by nutrient supply, pH, Eh, salt content, groundwater temperature, and permeability of the aquifer (Matthess, 1982). It should be stressed that such bacteria as are part of natural evolutionary processes of mineralisation and purification of groundwater, are not in themselves harmful or pathogenic.

Modeling of hydrogeochemical processes

Geochemical modeling may be applied to study the chemical and isotopic evolution of groundwater and helps in evaluating the suitability of groundwater as a source of drinking water in emergency situations. The implementation of inverse modeling requires the identification of the extent of specific chemical reactions that control groundwater chemical evolution. In addition one needs to know the hydrogeological conditions, i.e. the minerals which can be dissolved or precipitate, to define processes which may occur in the groundwater system and which are kinetically and thermo-dynamically possible. Furthermore a conceptual groundwater flow model is desirable with which to calculate travel time and to support the establishment of a relation between initial and final chemical composition of the studied groundwater system. Forward modeling is based on a definition of initial conditions in the groundwater system and calculation and quantification of the extent of a series of reactions imposed on that system. Incorporating thermodynamic databases is desirable in order to quantify and predict the extent of reactions (Glynn and Plummer, 2005).

The further development of geochemical modeling strongly depends on the quality and consistency of groundwater chemical and isotopic data. The use of statistical methods – particularly factor and cluster analysis – can provide reliable data needed for geochemical modeling and groundwater chemistry studies. According to Griffionen (2004) present-day hydrochemical modeling of a groundwater system has to deal with mineralogical constraints, limitations in the knowledge of thermodynamic and kinetic reactions and uncertainties in the knowledge of the groundwater system of large aquifers. More details about modeling of geochemical processes can be found in Glynn and Plummer (2005). Some hydrogeochemical models are freely available from the U.S. Geological Survey.

Impact of natural disasters on the chemistry and quality of groundwater

Shallow, water-table aquifers worldwide have been shown to be highly vulnerable to the ingress of surface water which may carry significant loads of biological and chemical pollutants or salinity. Such surface water may be deposited by floods, storms and tsunamis, often covering the aquifer temporarily with considerable thickness of water, which in a short time can produce significant amounts of recharge, especially to unconsolidated or semi-consolidated coastal aquifers. Increasing sea water levels will not only encroach on shorelines but allow the salt water-fresh water interface to penetrate further inland. These factors have to be taken into account when planning emergency groundwater supplies in such areas.

Natural disasters of geological origin such as earthquakes and volcanic eruptions have been widely reported to impact on both the availability and the chemistry, or quality, of groundwater. Several observed chemical and physical groundwater variables may act as early warning indicators of an impending volcanic and earthquake activities.

Volcanic activity has been observed to affect the temperature, TDS, chloride and sulphate content, and produce changes in the composition of dissolved volcanic gases and in the isotopic composition of groundwater. An increase of fluorine content has been registered in regions affected by volcanic activity in Japan and elsewhere. The concentrations and proportions of dissolved volcanic gases (e.g. CO_2, H_2S, HCl) and temperature control groundwater TDS content, pH and chemical type. The acid gases produced by rhyolitic volcanoes are highly reactive with the rock environment. Changes in groundwater chemistry and quality are often registered several days prior to a volcanic eruption, may continue during the eruption and often in the post-eruption period.

Earthquakes are also known to significantly alter groundwater chemistry, with changes observed in pH, electric conductivity or TDS, sulphate, chloride, isotopic composition as well as an increase of turbidity and radon concentration both before and after seismic events in many parts of the world. Such changes, e.g. in radon, are investigated as possible early warning signals of impending earthquakes.

Particularly threatened in earthquakes are water supplies to hospitals, which are placed under great stress in such emergencies, and need well-designed alternatives in case of failure or serious deterioration of water supply quality. Whereas disasters of meteoric origin principally threaten shallow coastal and flood-plain aquifers, geologic events such as earthquakes and volcanism may influence the quality of groundwater in both shallow and deep aquifers.

Importance of groundwater quality assurance for emergency supplies

Potable water quality needs to be assured at the time an emergency water supply is established as well as sustained into the future. Detailed hydrochemical analysis allows for the assessment of the source itself and of possible adjacent water bodies that, in time, might cause a deterioration of the potability of the source. Environmental isotope (chapter 4.4) data indicate the dynamics of the water source and enable an assessment of its vulnerability to surface pollution due to catastrophic events. The aquifer being exploited is placed in hydrological context with its geological environment, allowing for estimates of its sub-surface vulnerability to e.g. pollution over time from highly mineralised or polluted adjacent water bodies.

Confined aquifers in sedimentary basins with large groundwater storage capacity are recommended in this Guide as a target for safe emergency supply. They usually contain groundwater of good quality and suitable for use untreated or after simple treatment (e.g. aeration, filtration, dilution). However, even in such favourable conditions, a thorough study is recommended. Detailed chemical analysis during long-term pumping tests may reveal that water initially potable shows trends towards higher mineralisation or show measurable traces of toxic elements, such as As. Changes in isotopic parameters may give an early warning of hydrological changes in the aquifer and clues to the origins of pollutants. The same applies to the, very essential, long-term monitoring of emergency supply boreholes.

Groundwater in deep aquifers with high residence time, and thus little replenishment and regarded as non-renewable, may be highly mineralised. Only in cases of extreme need should desalination be considered. Generally, further exploration, guided by geophysics, hydrochemistry and environmental isotopes should identify potable sections of the aquifer. Here in particular, development and exploitation would need careful study and rigorous monitoring. However, potable quality water has been found in many deep aquifers e.g. the Nubian, North Western Sahara, Iullemeden, the Chad, Australian Great Artesian and Kalahari Karoo basins.

Coastal aquifers and shallow water table aquifers present quite different problems where emergency water supplies need to be developed. Such aquifers are extremely prone to quality degradation from both human and natural sources. High salinity, high concentrations of iron and manganese, nitrate and anthropogenic chemicals are encountered worldwide, especially in areas prone to flooding. Treatment of such polluted water for emergencies would mostly be prohibitive. Groundwater could be developed well above reasonably foreseeable flood lines, even for tsunami. Flow patterns should be properly evaluated with the various available methods and the area of exploitation rigorously protected against all activities that might produce surface and upstream pollution. Such emergency supplies, rigorously monitored, could be available in reasonable proximity, if not at the site of the disaster itself, as short-term emergency water relief.

4.4 Isotope hydrology

Balt Verhagen

Artificial vs. environmental tracers

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 measured. The rate at which fluid is flushed out of the water column allows for the assessment of aquifer permeability and flow profiles with depth. For larger-scale aquifer evaluation, salt or a radioactive tracer injected at an upstream point is detected at a sampling point downstream. However, 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 the ‘plume’ may entirely miss the sampling point. The relatively modern tool of environmental isotope hydrology overcomes most, if not all, of these disadvantages (Box 4.4.1).

Box 4.4.1

Why environmental isotopes?

The term 'environmental isotopes' is employed to refer to isotopic ratios of elements making up substances in the environment, such as oxygen and hydrogen in water. Environmental isotopes label ground water on an ongoing basis, through either natural or anthropogenic processes. Isotope ratios are established largely during the recharge process. It is often necessary only to analyse one suite of samples taken from a number of points in the (groundwater) system – an 'isotope snapshot' – in order to gain an initial understanding of the hydrology, i.e. set up a tentative conceptual model. This may apply to a small basin or to an entire catchment. The complexity of the system will determine the extent to which more detailed information is required.

Underlying the application of environmental isotopes is the *transport approach*, which differs from the classical *hydraulic approach*, can produce an independent assessment of an existing conceptual hydrogeological model, suggest a model where none existed or produce information such as recharge rate and flow continuity, essential information in calibrating a numerical model. Environmental isotopes are particularly useful in assessing groundwater systems intended for emergency supply, especially where these are often deep-seated. Isotopes 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.

Environmental isotopes

Some of the isotope species used in isotope hydrology are shown in Table 4.4.1. In this brief discussion, the isotopes of the light elements: H, C and O are considered mainly – the more commonly-used or 'workhorse' isotopes; ^{3}He, and its relevance to ^{3}H dating; ^{39}Ar on account of its strategic half-life. Other isotopes employed in hydrology include non-radioactive or stable species ^{15}N and ^{34}S (especially for pollution studies), and radioactive species such as ^{36}Cl, ^{85}Kr for residence time measurements at widely differing time-scales up to hundreds of millennia (Clark and Fritz, 1997; Mook, 2004).

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 radioactive decay is:

$$N = N_0\, e^{-\lambda t} \qquad (4.4.1)$$

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 Fig. 4.4.1. When only half of the radioactive atoms remain, i.e. $N/N_0 = 1/2$, the time elapsed is called the half-life, $t_{1/2}$.

When equation 4.4.1 is written in the differential form:

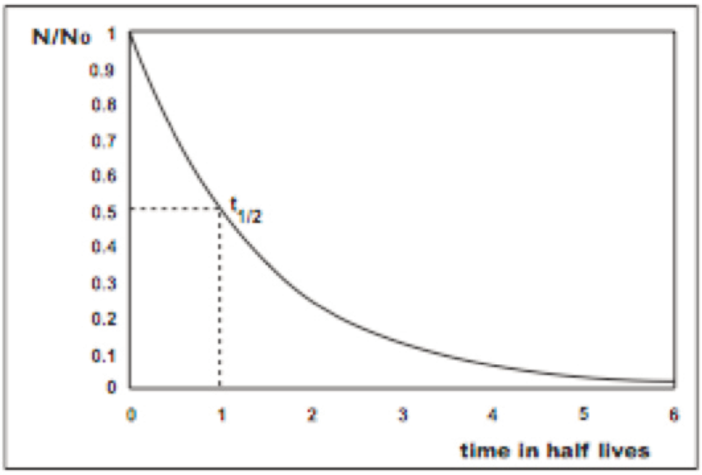
$$dN/dt = -\lambda . N \qquad (4.4.2)$$

it is clear that the rate of decay is proportional to the number of radioactive atoms remaining. When the rate of decay, or particles emitted per unit time, is measured by low level counting techniques, we have a measure of the concentration of the radionuclide.

Table 4.4.1. Some isotopic species used in isotope hydrology

Isotope/ ratio	Half-life [a]	Abundance/ Origin	Measurement technique	'Dating' range [a]	Application
$^{2}H/^{1}H$	stable	0.015%	Isotope ratio mass spectrometry/ laser absorption	–	Origin, pathway and mixing of groundwater
^{3}He	stable	Atmosphere, terrestrial He, tritium decay	Isotope ratio mass spectrometry	–	Direct determination of turnover time
$^{18}O/^{16}O$	stable	0.2%	Isotope ratio mass spectrometry/ laser absorption	–	Origin, pathway and mixing of groundwater
$^{13}C/^{12}C$	stable	1.1%	Isotope ratio mass spectrometry/ laser absorption	–	Hydrochemistry of dissolved inorganic carbon
$^{15}N/^{14}N$	stable	0.37% (air)	Isotope ratio mass spectrometry	–	Tracing of pollutants
^{85}Kr	10.8	Cosmic rays Nuclear industry	Low level beta counting	decades	Indicator of recent recharge
$^{3}H/^{1}H$	12.32	Cosmic rays Nuclear tests	Low level beta counting	decades	Identify recent recharge
^{32}Si	≈100	Cosmic rays Nuclear tests	Low level beta counting	≈1,000	Fills gap between ^{3}H and ^{39}Ar, ^{14}C
^{39}Ar	269	Cosmic rays Crustal	Low level beta counting	≈ 2,000	Fills gap between ^{3}H and ^{14}C
$^{14}C/^{12}C$	5,730	Cosmic rays Thermonuclear tests	Low level counting/ Accelerator mass spectrometry	≈ 3 x 10^{4}/ 7 x 10^{4}	Wide range; needs hydrochemical interpretation
^{81}Kr	2.1 x 10^{5}	Cosmic rays	Low level beta counting	5 x 10^{5}	Old groundwater
^{36}Cl	3.06 x 10^{5}	Cosmic rays Nuclear tests	Accelerator mass spectrometry	2 x 10^{6}	Relatively inert ; 'fossil' water
^{222}Rn	3.85 days	Decay of uranium	Alpha ray counting; laboratory or field	days	Inert gas; groundwater/ surface water relations

Figure 4.4.1. Exponential decay curve showing the ratio of the number of radioactive atoms remaining (N) to the original number (N_0) plotted against time in multiples of 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) at continental sites. 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 as the 'parcel' moves through the system, giving time-dependent information or 'ages' on fairly recently recharged or 'young' groundwater. Routine low level counting techniques (see below) allow for the routine detection of tritium down to about 0.2 TU.

Tritium produced in anthropogenic processes and used commercially and in research escapes readily and adds to the atmospheric hydrogen inventory. During the thermonuclear test series since 1952, atmospheric tritium values rose up to 1,000 x in the northern Hemisphere in the early 1960s. Since the moratorium on testing in 1962 atmospheric concentrations have declined (Figure 4.4.2) and are reflected in rain. In the southern Hemisphere the response to these injections was considerably damped, where present-day rainfall values continue to be lower and closer to natural levels. In both Hemispheres there is a degree of ambiguity when 'dating' groundwater with environmental tritium on account of the rising and falling trends in atmospheric concentrations and thus in groundwater recharge, since 1960.

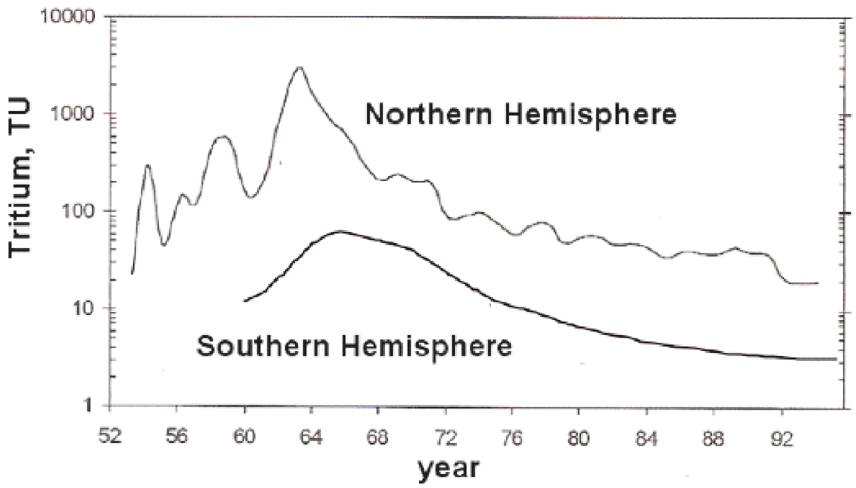
$^3H/^3He$ dating

Very low ^3H abundances, beyond the range of low-level counting, can be measured by thoroughly degassing and storing a water sample gas-tight for a time t, at least half a year. Subsequently, ^3He – the decay product of tritium – is collected and measured by mass spectrometry (see below). The tritium content of the sample is given by:

$$^3H = {^3He}/(1 - e^{-\lambda t}) \qquad (4.4.3)$$

Alternatively, the age of the sample may be determined without knowing the tritium input function (Mook 2004).

Figure 4.4.2. Tritium concentration in rain for the northern and southern Hemispheres since the early 1950s. Note: logarithmic tritium scale (after Clark and Fritz, 1997).



Radiocarbon ^{14}C

Radiocarbon is produced in atmospheric cosmic ray reactions similar to those producing ^{3}H. Oxidised to $^{14}CO_2$ radiocarbon becomes part of atmospheric carbon dioxide, its natural 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 provides time-dependent information on groundwater. The initial biogenic $^{14}C/^{12}C$ ratio can be altered chemically during recharge, and during chemical processes in the aquifer, but subsequently may be taken as conservative when the hydrochemistry has stabilised (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 groundwater emergency supplies.

During the historic atmospheric thermonuclear test series, atmospheric radiocarbon values rose up to more than 200 PMC in the northern Hemisphere in the early 1960s and have since declined (Figure 4.4.3). In the southern Hemisphere the response to these injections was considerably damped. Atmospheric values worldwide at present are similar and tending towards the pre-bomb, natural level.

Argon-39

^{39}Ar is produced in the atmosphere where its natural abundance (8.5×10^{-16}) is effectively constant. Dissolved in rain water along with other gases, it enters ground water. With its half-life of 269 years, ^{39}Ar is suitable to fill the gap in dating range between ^{3}H and ^{14}C with the advantage that it is chemically inert. However, the subsurface production of ^{39}Ar through radiation from thorium and uranium of the rock matrix makes it problematic in certain environments (Mook, 2004).

Hydrodynamic models

To interpret isotope data, hydrodynamic models of groundwater flow have to be considered. The concept of lumped parameter modeling is employed: parcels of water following flow lines through an isotropic aquifer. Three such (idealised) models are shown (Fig. 4.4.4).

Figure 4.4.3. Atmospheric radiocarbon values since 1960. Northern Hemisphere values increased sharply following the thermonuclear tests in the early 1960s showing a marked seasonal effect. Southern Hemisphere increases were delayed and damped. Values in both Hemispheres are trending towards natural values (after Mook, 2004)

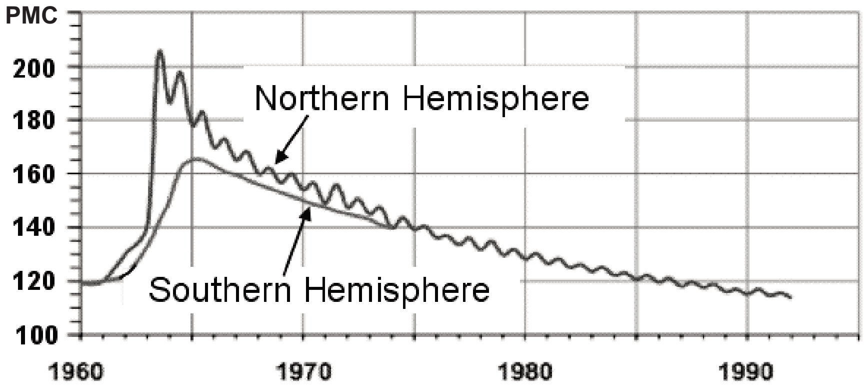
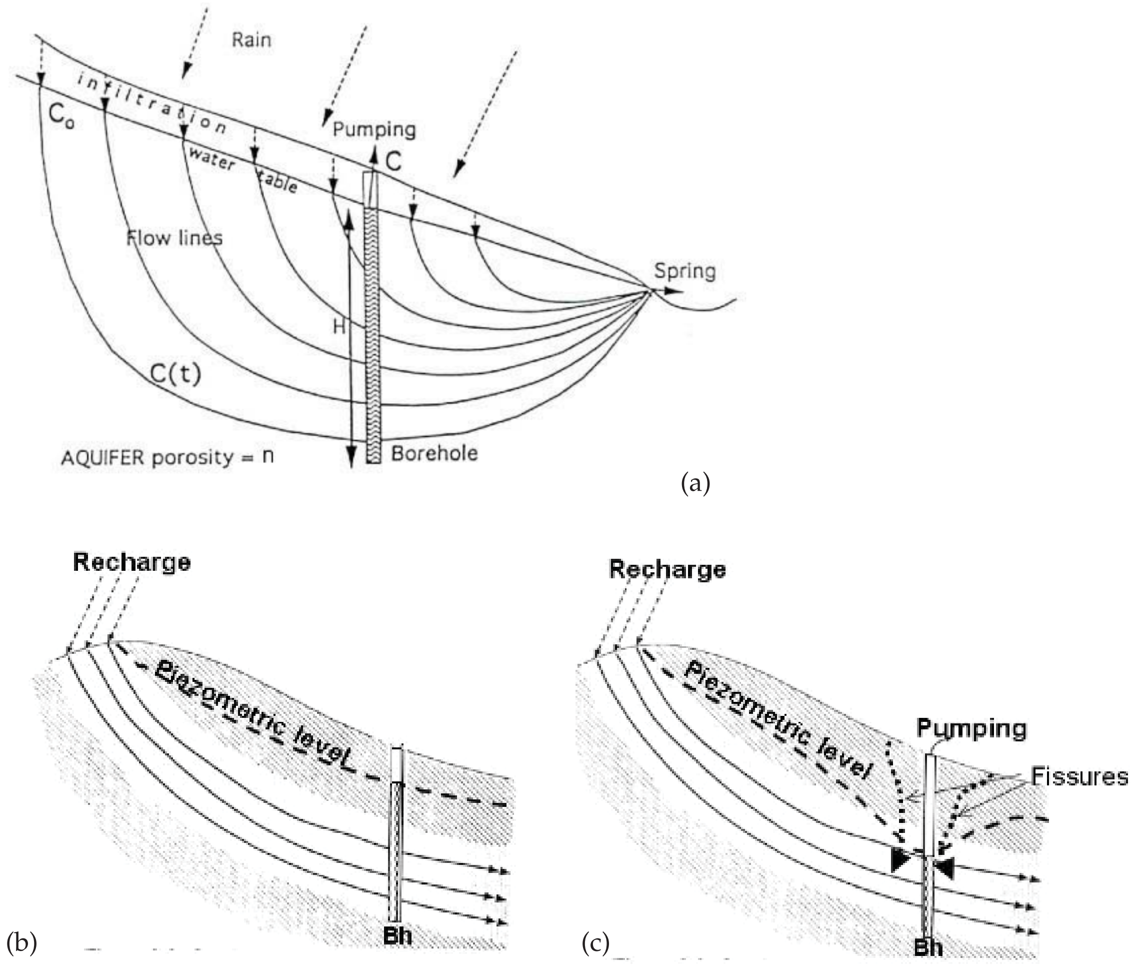


Figure 4.4.4. Schematic sections depicting three different hydrodynamic models of groundwater flow: a) completely mixed reservoir (phreatic) model; b) piston-flow (confined aquifer) model; and c) the injection (leakage) model



For a **confined aquifer** with limited recharge area, it is assumed that 'parcels' or volume elements move with the same travel time along parallel flow lines to the sampling point – the **piston-flow model** (Fig. 4.4.4 b). 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** (Fig. 4.4.4a) 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 that can be represented as a mean residence time (MRT). This can be described by a convolution integral (eqn. 4.4.4):

$$\mathrm{A}(\mathrm{t}) = \int_0^\infty A_0(t-\tau)e^{-\lambda\tau} f(\tau)\,\mathrm{d}\tau \qquad (4.4.4)$$

where A(t) is the measured tracer concentration; A_0 the input concentration, a function of time (thermonuclear peak); τ is the transit time; $e^{-\lambda\tau}$ accounts for radioactive decay. $f(\tau)$ is the transit time function, that describes the flow path through a phreatic aquifer (**exponential** or **diffusive**), or through a confined aquifer (**piston flow**).

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 (Fig. 4.4.4c). The *in situ* tracer (e.g. ^{14}C) concentration, dependent on the transit, or residence, time can be calculated e.g. from the mass balance of two radionuclides (e.g. long-lived radiocarbon and short-lived tritium) in the injected component.

Mean residence time and recharge

Mean residence time (MRT) is an inverse indicator of groundwater mobility, or recharge/storage ratio. It is based on the reverse calculation of the convolution integral for the (conceptual) lumped parameter model of flow through an aquifer, using tritium and/or radiocarbon data (Malozsewski and Zuber, 1996). Once a MRT has been evaluated, the important parameters such as recharge R can be assessed:

$$R = H.n/MRT \qquad (4.4.5)$$

where H = the thickness of the saturated zone sampled and n = the mean *total* porosity of the aquifer.

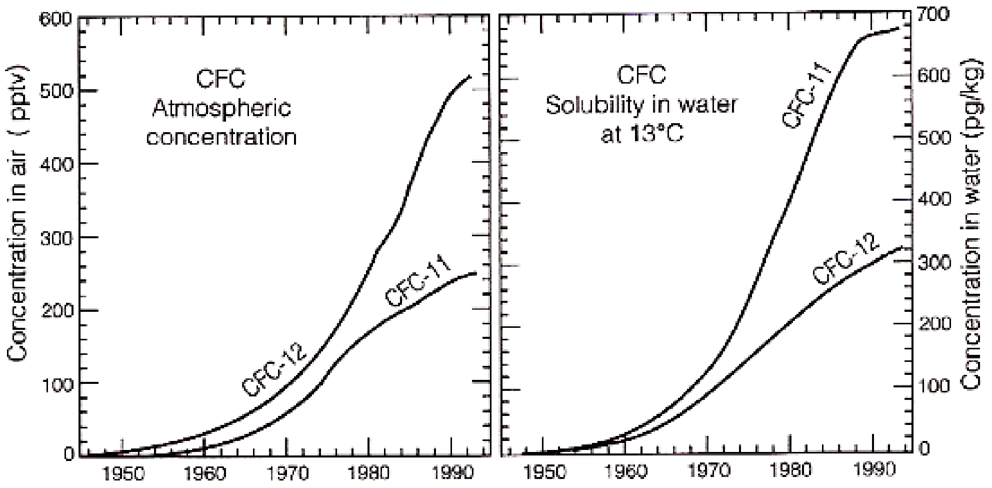
Radon

Uranium and thorium are present in traces in all rocks, especially igneous rocks. One of the decay products is ^{222}Rn ($t_{1/2}$ = 3.85 days), a noble gas that mostly remains trapped in the rock matrix. Through fractures it can escape to the surface, where it can act as an indicator of fault and shear zones. Its very short half-life and α-radiation gives ^{222}Rn a very high specific activity and renders it easily detectable. All groundwater contains some radon that disappears rapidly when exposed to the atmosphere. This makes it distinguishable from surface water and allows for the measurement e.g. of groundwater contributions to streamflow.

Dissolved Chlorofluorocarbons

Groundwater tracers that in the last fifteen years have occupied a place in the dating of young groundwater are dissolved chlorofluorocarbons (CFC). Although not isotopic tracers, the rise of concentration in the atmosphere of these gases due to increased industrial use shows similarities with the rise in atmospheric concentrations of ^{3}H and ^{14}C from thermonuclear tests (Figure 4.4.5).

Figure 4.4.5. Concentrations of two chlorofluorocarbons in the atmosphere and in water as a function of time. Note the rising trend over 50 years (Clark and Fritz, 1997)



Dissolved in infiltrating (rain) water, the concentration of the gases CFC-11, CFC-12 and CFC-113 is assumed to be preserved into the aquifer. The input concentration can be assessed using the solubility of the gas and the temperature of equilibration just before reaching the saturated zone. Water is sampled under strict precautions against any atmospheric contact, the measured concentration being related to the time of last atmospheric contact, assumed to be the time of infiltration (Busenberg, 1996). Any exposure to the atmosphere would almost immediately reset CFC concentrations. Sampling boreholes with considerable drawdown can expose part of the yield to such conditions.

CFC dating came to prominence at a time when tritium levels world-wide began to decline after the bomb peak (Fig. 4.4.2), producing ambiguities in interpretation. CFC concentrations have steadily risen since the 1940s without such ambiguities up to the present. On the other hand, concentrations are now peaking as did tritium in the 1970s, and will decline as their use is being curtailed. It is recommended that CFC measurements should be accompanied by a tritium value for the water in order to support the interpretation i.t.o. a recharge date.

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, a process called fractionation. These small changes can be expressed as relative differences δ in per mille (‰) from a reference standard (Clark and Fritz, 1997) and traced through groundwater systems:

$$\delta = [(R_s/R_r) - 1] \times 1{,}000 \quad (‰) \qquad (4.4.6)$$

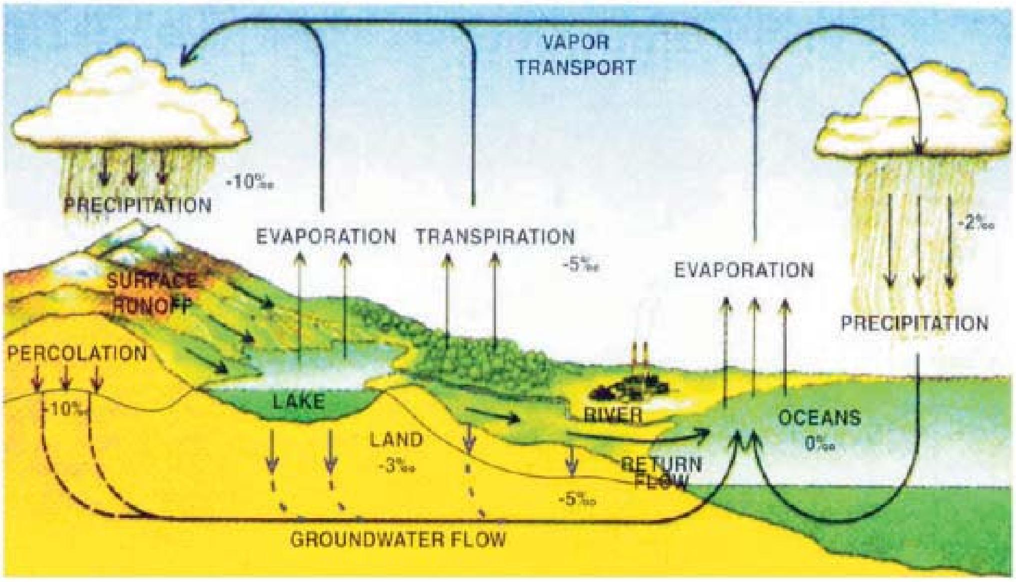
where R_s and R_r are isotope abundance ratios in sample and reference standard respectively.

In the case of isotopes in the water molecule, R refers to either $^{18}O/^{16}O$ or $^{2}H/^{1}H$ and the reference standard is VSMOW (Vienna Standard Mean Ocean Water).

δ^2H and $\delta^{18}O$ in the hydrological cycle

Vapour rising from the ocean is slightly depleted in the heavy isotopes through fractionation. When the vapour condenses, the rainfall precipitating from this vapour mass will, in turn, become slightly enriched but will still be depleted with respect to the oceanic source. On further precipitation along its trajectory inland, the vapour mass, and further precipitation from it, will become increasingly depleted – the continental effect (Fig. 4.4.6). Depletion will occur as well with altitude of precipitation, rainout during intensive storms and other effects.

Figure 4.4.6. Diagrammatic representation of the meteoric water cycle, showing typical values of 2$\delta^{18}O$ for atmospheric vapour and its depletion inland, rainfall, evaporative enrichment and the effect on the isotopic composition of groundwater (IAEA, 1997)



All these are equilibrium processes, the resulting water plotting along the global meteoric water line (Figure 4.4.7) (see e.g. Clark and Fritz 1997)

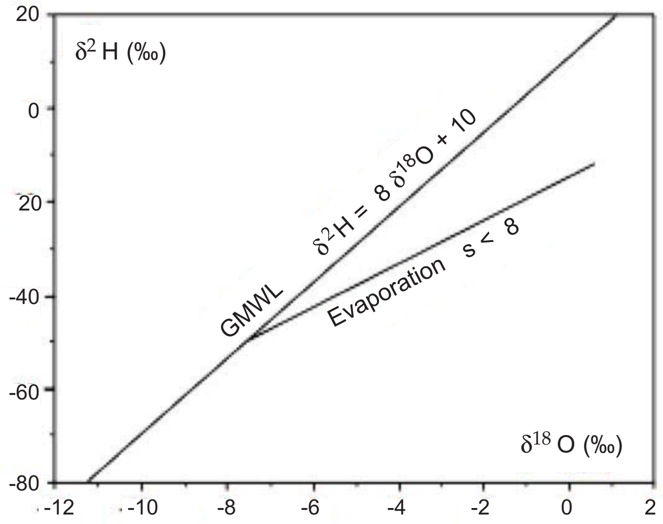
$$\delta^2H = 8\delta^{18}O + 10 \qquad (4.4.7)$$

This relationship holds world-wide, more depleted (more negative) δ^2H and $\delta^{18}O$ occurring in colder climates, more enriched (positive) values in warmer environments.

Loss of water through evaporation from a lake or river leaves the remaining water enriched in the heavy isotopes. The net transport of water implies that this is a diffusive, kinetic process, the δ values now plotting along a line with slope $s < 8$ – a so-called evaporation line. The slope of this line depends on the air moisture content of the environment and tends to 4 for arid conditions. The isotopic composition of the remaining water will plot further away from the original value as the volume of remaining water diminishes.

These signals are retained during infiltration into the sub-surface. The stable isotopic signature on (ground)water therefore gives information on its origin at the land surface and allows for the distinction between water from different sources in an aquifer, of palaeo-recharge, and to study mixing, flow continuity etc.

Figure 4.4.7. A schematic δ^2H – δ^{18}O (‰ SMOW) diagram, showing the global meteoric water line (GMWL), slope 8 and an evaporative enrichment line, slope < 8



Stable isotopes of carbon

An important tracer of groundwater is the isotopic composition of the total dissolved inorganic carbon (TDIC). 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 $\delta^{13}C$ (as for δ^2H and $\delta^{18}O$; cf. eqn. 4.4.6) from the VPDB (limestone) 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.

Analytical methods

The determination of isotope abundances for both stable and radioactive environmental isotopes can, in general, be performed only in specialised laboratories. It is advisable to establish a working relationship with one or more laboratories/research groups in the field of isotope hydrology before undertaking a study involving environmental isotopes. These will be able to give guidance and provide information on sampling, precautions to be taken, analytical facilities, costs etc.

Radioactive isotopes - Low-level counting

The low activity and poorly penetrating β-radiation of isotopes such as ^3H, ^{14}C and ^{39}Ar require highly sensitive, low-background, internal source detection techniques. Most commonly used for ^3H and ^{14}C at present is liquid scintillation spectrometry. The sample is incorporated in a liquid ‘cocktail’ that also constitutes the detection medium.

A form of pre-concentration is usually required to bring the low levels of radioactivity into the measurable range. In the case of tritium, electrolysis is used to increase its concentration by a known factor. Conventional radiocarbon measurement typically requires that the TDIC is precipitated in the field from 50 litre or more of water sample. For the measurement of ^{39}Ar the noble gases are extracted from about 15 m^3 (*15 tons*) of water in the field.

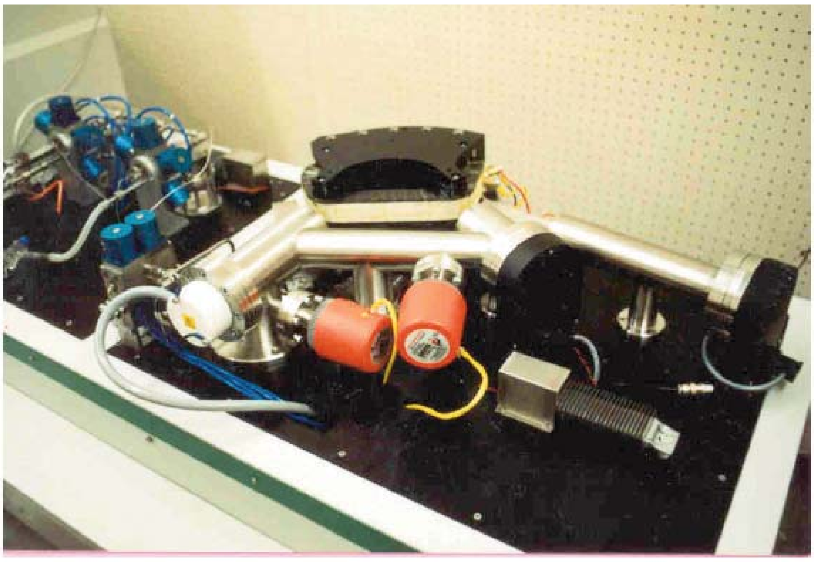
Radioactive isotopes - Accelerator mass spectrometry (AMS)

This technique is employed increasingly for the measurement of radiocarbon and other isotopes in which the actual number of radioactive atoms is measured in the sample, rather than its radioactivity. Advantages of this method are extremely small sample sizes (a few mg) required and the large sample throughput (short counting time). For radiocarbon, the TDIC from a one litre water sample generally suffices. Increasing numbers of dedicated tandem electrostatic accelerators are becoming available world-wide. The technique enables the measurement also of several other, usually long-lived isotopic species used in specialised hydrology studies, such as ^{36}Cl, ^{81}Kr etc.

Non-radioactive or stable isotopes - Isotope ratio mass spectrometry (IRMS)

In this method a gas is produced reflecting the isotope ratio of the original water sample. The measurement is performed in an isotope ratio mass spectrometer (Figure 4.4.8) in which an ionic beam is magnetically separated into different mass components. Comparing the isotope ratio of the sample with that of a reference material, its deviation from that reference is expressed as a δ-value (see above). This reference is then normalised to the value of an international standard (e.g VSMOW, VPDB etc.).

Figure 4.4.8. Layout of an isotope ratio mass spectrometer, showing (from left) gas inlet valves; ion source, flight tubes, magnet and ion collectors



Non-radioactive or stable isotopes - Analysis by laser absorption

Recently, a laser absorption technique has been developed into commercial instrumentation that can determine δ^2H and $\delta^{18}O$ in the water phase to precisions comparable with those attainable with IRMS. Such instruments are simple and compact, cost a fraction of the price of an IRM spectrometer and could even be operated in the field. $\delta^{13}C$ can also be measured with this technique, but requires a separate instrument.

Field water sampling requirements

Water sample volumes and treatment need to be discussed with the isotope analysts/specialists involved. General guidelines are given below.

- **δ^2H and δ^{18}O** : 20 ml, vessel completely filled and tightly stoppered. No pre-treatment.
- **δ^{13}C:** 100 ml to 1 L, depending on TAlk (total alkalinity). Filtered. Can also be measured on an aliquot of CO_2 produced for ^{14}C analysis.
- **^{3}H:** 500 ml to 1L. No pre-treatment.
- **^{14}C:** ~ 50 L or more, depending on TAlk, treated in the field with cleaned alkali and $SrCl_2$ or $BaCl_2$. Precipitate collected and stored in 500 ml to 1 L bottles. For AMS measurement, a 1L water sample for laboratory extraction generally suffices.
- **^{3}He.** Water samples need to be collected with extreme care, avoiding any atmospheric contact and stored in special sealed containers
- **^{39}Ar.** As 15 *tons* of water have to be treated by flash boiling under vacuum in the field, this method is extremely costly and can be employed only where the required major equipment is available and there is a specific need for its unique data
- **^{222}Rn.** Water samples need to be sealed promptly and measured either in the field or within a few days in a laboratory
- **CFC's:** Usually a few tens of millilitres of water, extracted well below the surface of the water body and sealed hermetically
- **General remarks**: Except for dissolved gases, clean PVC sample vessels, with sound stoppers and inserts suffice. Samples can be taken directly from a spring or from the output of a producing borehole. When an equipped borehole is rarely pumped or when a mobile pump is employed to sample a non-equipped borehole, the general rule is to extract two standing water volumes of the borehole before sampling; alternatively when measurements of e.g. electrical conductivity, pH and temperature in the pumped water have stabilised for some time. For more detailed guidelines on sampling see Clark and Fritz (1997).

A brief guide to the application of environmental isotopes

When planning an investigation of a groundwater system as an emergency resource using environmental isotopes, it is useful to have some guidelines as to their application.

At the outset, it is desirable to have available a good coverage of major ion chemical analyses, along with as much hydrogeological information as may be available. These, along with the results of any existing hydraulic and chemical numerical modeling act as an important guide as to the strategy of devising the isotope study.

In the application of environmental isotopes, three broad groups of aquifers could be considered: 1. shallow and karstic, 2. deep renewable and 3. deep non-renewable (fossil) such as are often referred to in this manual. Common to these is the question of the origin of the water. Here, the stable isotopes of the water molecule (^{2}H and ^{18}O) are relevant with additional information obtainable from those of some dissolved constituents, such as inorganic carbon (^{13}C), nitrate (^{15}N) and sulphate (^{34}S).

The measurement of the stable isotopes ^{2}H and ^{18}O in water has become routine and often automated. Laboratory turnaround time is usually rapid (1 to 2 weeks), analytical cost modest and required sample size small (~ 20 ml). This allows for a rapid scan of available sample points. Plotting on a δ^2H/δ^{18}O diagram allows for the characterisation of different input/infiltration sources. Mapping the data may reveal patterns of groundwater movement, flow continuity, stratification of different systems etc. The analysis of the other stable isotope species considered tends to be slower and more expensive, but may add to the overall spatial picture, especially of pollutants.

When considering time-dependent factors ('age' or residence time) the radioactive isotopes come into play. Here, the widely different turnover time scales of the four aquifer groups should be considered.

Shallow and karstic aquifers can be expected to have groundwater residence times in the range of months to decades. Here, tritium is usually employed, as it is a conservative tracer, and its half-life and input level allows for the differentiation of mean residence times up to a 100 years or so. For larger and deeper shallow systems tritium concentrations may be too low to allow differentiation and the much longer lived radiocarbon becomes useful. Radiocarbon measurements are often done in parallel with tritium analysis in order to extend the 'dating' range. Here, one has to take the uncertainty in the initial, or recharge concentration of radiocarbon into consideration. This, in turn, may be 'corrected' for on the basis of $\delta^{13}C$ and chemistry, or calibrated by the associated tritium. It should be kept in mind that the analysis of these isotopes is considerably more expensive with laboratory turnaround times on the order of two months. Chlorofluorocarbon measurements may further narrow down the shorter time constants, but the difficulty in obtaining reliable samples often rules out this tracer. Shallow and karstic aquifers are usually vulnerable to natural and human impacts and only exceptionally may be used as emergency source of groundwater.

Deep aquifers containing renewable groundwater are generally those in which groundwater residence times lie in the range of many thousands of years. Here, tritium has decayed away completely and the tracer of choice is ^{14}C. The uncertain initial concentration can be assessed through concomitant hydrochemical and $\delta^{13}C$ evolution with increasing water age. In this range, even relative residence times or 'ages' may be of value. In comparison with the uncertainties inherent in assessing other hydrogeological parameters, the initial or dilution uncertainty in ^{14}C may not be important. The intermediate half-life of ^{39}Ar seems attractive, but the complexity and cost of analysis makes it prohibitive for all but very specialised studies. Deep aquifers, often confined, are recognised as a safe source of groundwater resistant to the impact of natural disasters.

Deep aquifers containing non-renewable groundwater that is extremely slow moving, often called 'fossil', with residence times in the range of tens of millennia. On this scale the dating range even of radiocarbon may be exceeded. There are long-lived isotopes that can be employed that cover this age range, such as ^{36}Cl and ^{81}Kr. However, their application tends to become academic from a purely hydraulic point of view. Proving stratification in the 10^4–10^5 year age range, along with hydraulic conductivity estimates, may allow for sophisticated modeling of long-term pollution potential under exploitation stress. Provided that the water is potable, the conclusion drawn from such high isotopic ages is that in the short to medium term, the groundwater is safe from pollution for the relatively short periods of exploitation foreseen in emergency situations.

Aquifers containing fossil groundwater are known in particular in the Middle East and North African regions and in Australia where they are often exploited as a 'normal' source of water. Ensuring a population against extended drought, and other hazards, may require sections of such aquifers to be specifically investigated, developed and set aside as safe emergency drinking water supplies.

4.5 Geophysical methods

Balbir Sukhija

Introduction

Geophysical methods are cost and time efficient, and vital in the identification and documentation of emergency groundwater resources. Geophysical exploration for groundwater is based on the measurement of differences between or anomalies in physical properties of geological strata e.g. resistivity, magnetic susceptibility, density, seismic wave velocity, and radioactivity. In general, geophysical methods complement remote sensing, geological and hydrogeological methods and make use of the surface/subsurface information obtained from these methods including that from existing observation wells. Geophysical methods in groundwater exploration have distinct advantages. They can provide quantitative data regarding hydrogeological properties and the geometry and depth of aquifers, groundwater quality, the freshwater/salt water interface, and delineation of structural and tectonic features that control groundwater movement, and even in the delineation of pollutant plumes and providing guidelines for proper well construction after drilling. Geophysical methods are particularly effective in identifying deep seated emergency groundwater resources. However, there are some limitations in their implementation. Since they are indirect and based on various physical and chemical characteristics of subsurface strata, different hydrogeological parameters may lead to the same type of anomalies being interpreted from geophysical measurements. Thus, it is prudent to apply a combination of two or more methods to obtain more precise and reliable data about rocks and the groundwater environment. Geophysical methods generally employed are: electrical resistivity, electromagnetic, seismic, magnetic, gravity, radiometric and well logging.

Electrical methods

Electrical methods include a variety of techniques, each based on some different electrical property or characteristic of subsurface material such as electrical resistivity, electromagnetic, induced polarization, and telluric and magnetically induced currents.

Electrical resistivity method

This method is based on Ohm's law. Electrical resistivity is the resistance offered by a unit cube of a medium when traversed by a unit current at right angles to one face. For material with cross sectional area A and length L:

$$\rho = (R.A)/L \tag{4.5.1}$$

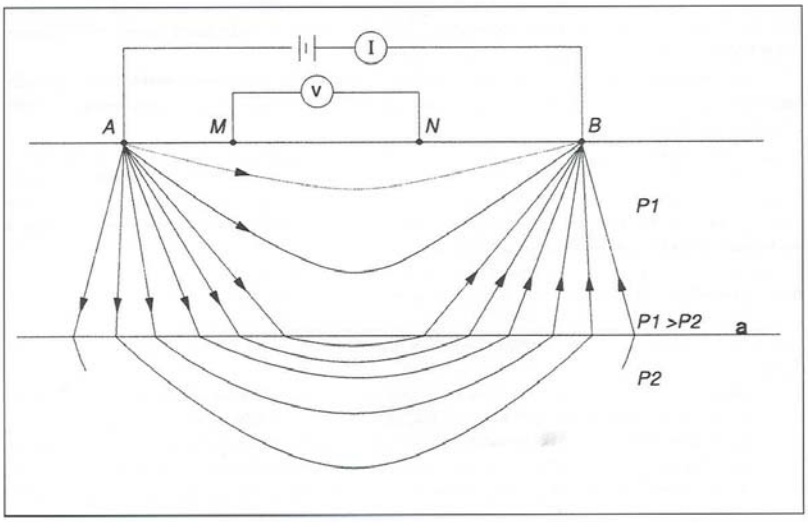
Where ρ = resistivity in Ohm-metre (Ωm)
R = Electrical resistance offered by the cube in Ohms (Ω)
A = cross sectional area (m^2)
L = length (m).

In measuring electrical resistivity of different subsurface layers, a known current is sent through a pair of electrodes thrust into the soil, the resulting potential difference being measured by another pair of electrodes. The objective of such measurements is to locate layers of low resistance which may be associated with groundwater, as the water within the pores of rock renders them more conductive to flow of electric current. The electrical resistivity of the strata is controlled by two components: the solid material and pore fillings. If the pores are filled with water, the rock will have lower resistivity; even lower when the water is mineralised.

In Figure 4.5.1 A and B are two electrodes that are used to send current into the ground and are referred as current electrodes, whereas M and N are used to measure the potential difference and thus referred to as potential electrodes. The potential difference varies with position and geometry of the four electrodes for the given strata segment. The most common electrode configuration is that of Wenner and Schlumberger. In the Wenner configuration all the four electrodes are equally spaced, and are disposed symmetrically; in the case of Schlumberger array the distance between current electrodes is at least 5 times the distance between the potential electrodes.

The different layers of the earth being non-homogeneous cause distortion or refraction of current flow lines and thus of the electric potential field. The measured resistivity is generally called an apparent

Figure 4.5.1. Principle of the resistivity method using two current electrodes and two potential electrodes. Strata with different resistivity affect the current distribution by refraction of the field in the earth (Kovelesky et al. 2004)



resistivity ρ_a. The apparent resistivity may represent the weighted average of true resistivity (10^0 to 10^5 Ohm-m) of formations and that of other underlying features (Karanth, 2001), and also depends upon several variables such as electrode spacing, geometry of the electrode array and anisotropic properties. Resistivity surveys are generally carried out in two different ways 1) resistivity profiling and 2) vertical resistivity soundings (VES). A resistivity profiling survey focuses on the lateral changes in the resistivity characteristics of strata, while in sounding the vertical variations of the electrical parameters of rocks are evaluated. For profiling, the Wenner electrode configuration is most suitable and the apparent resistivity value at a site is obtained by shifting the whole electrode array along a profile. Profiling is particularly useful to locate the vertical contacts of different geological structures such as faults, dykes, a stream channel or the fresh water/sea water interface. Vertical electrical soundings are useful in defining the electrical characteristics in depth section, and particularly useful in delineating low resistive layers indicating the possible presence of groundwater. The depth dependent variation in apparent resistivity is particularly useful for determining the depth of a water bearing formation, its thickness, delineation of different lithological strata, the depth of bedrock and the fresh water/salt water interface. Using VES with Wenner or Schlumberger configuration the thickness of different layers may be calculated.

The newly developed 2D (Barker, 1978 and 1992) resistivity imaging, using 20 or more electrodes (Fig. 4.5.2a) combines sounding and profiling to investigate complicated geological structures with lateral and vertical resistivity changes. The advantages of 2D measurements are their vertical and lateral resolution along the profile, computer based data acquisition and small field crew required. The information regarding an aquifer, its exact depth etc. is obtained through the concept of pseudo sections, which divide the subsurface into a number of rectangular blocks that provide apparent resistivity of the pseudo section that agrees with actual field measurements (Fig. 4.5.2b).

Fig. 4.5.3a shows the application in a basaltic area to identify shallow and deep aquifers. The method is also useful for delineating intrusive lineaments such as dykes or quartz veins. This can be illustrated by an example shown in Fig. 4.5.3b obtained by an ERT (Electrical Resistivity Tomography) survey that was carried out at the Kothur quartz vein (~25 m thick) in the Maheshwaram watershed located in a granitic terrain near Hyderabad, India. The resistivity image reveals the weathering effect at the contact zone, which was confirmed by successful drilling of a bore well.

Figure 4.5.2a Photograph of multi-electrode system being used in the field for 2D resistivity imaging

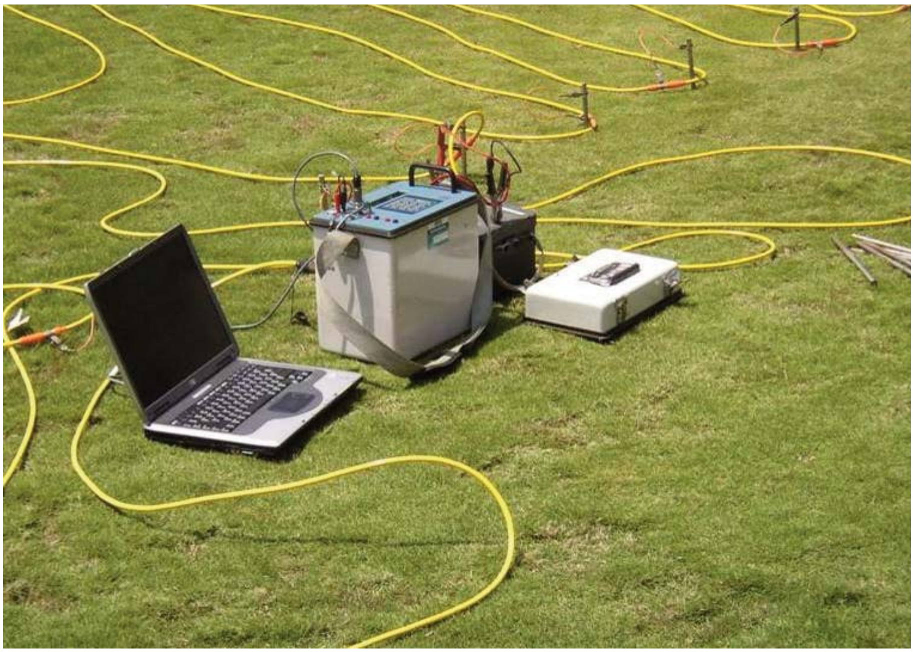
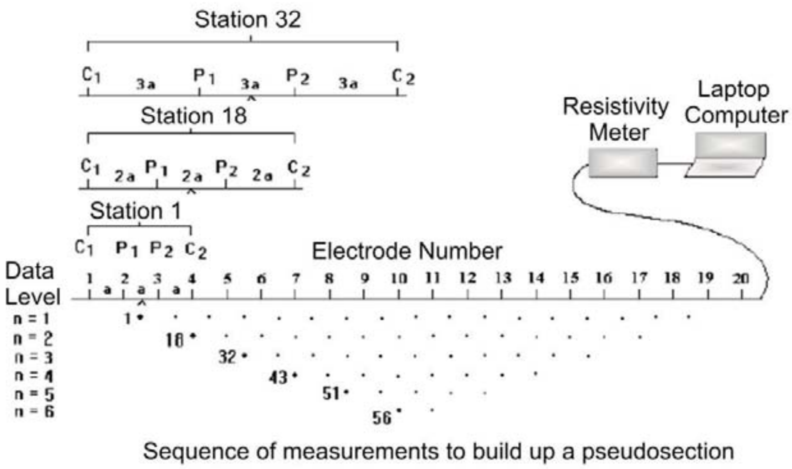


Figure 4.5.2b. A field layout for 2D resistivity imaging



With proper survey design 2D as well as 3D pictures of the subsurface can be obtained. Significant variations in the topography can also be taken into account in a final modeling of the electrical resistivity data providing parameters such as depth of the water bearing strata, stratification, and the fresh water/salt water interface which no other geophysical method can provide. However, there are limitations to electrical methods especially when the depth range exceeds 500 m and further heterogeneity of different strata reduces the resolution. The presence of highly conductive layers at shallow depths (e.g. reactive water) masks the less conductive layers thus making the method less effective.

Figure 4.5.3a. 2D Section obtained with Wenner-Schlumberger array in basaltic terrain (Ghatia watershed, near Ujjain, Madhya Pradesh, India) showing a shallow subsurface and deeper aquifers. Blue – light green indicate zones with resistivity 25-90 Ohm-meters. The arrows indicate the potential sites for drilling successful wells (Anand Rao and Kesri, 2008).

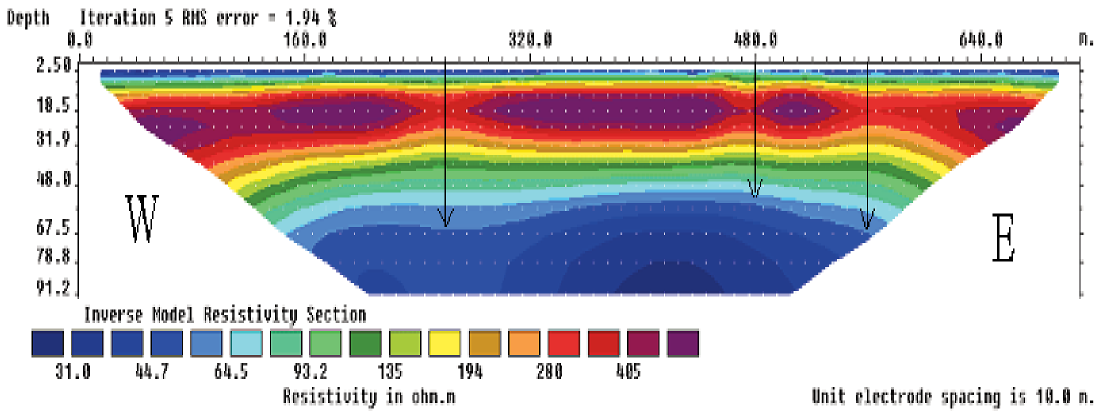
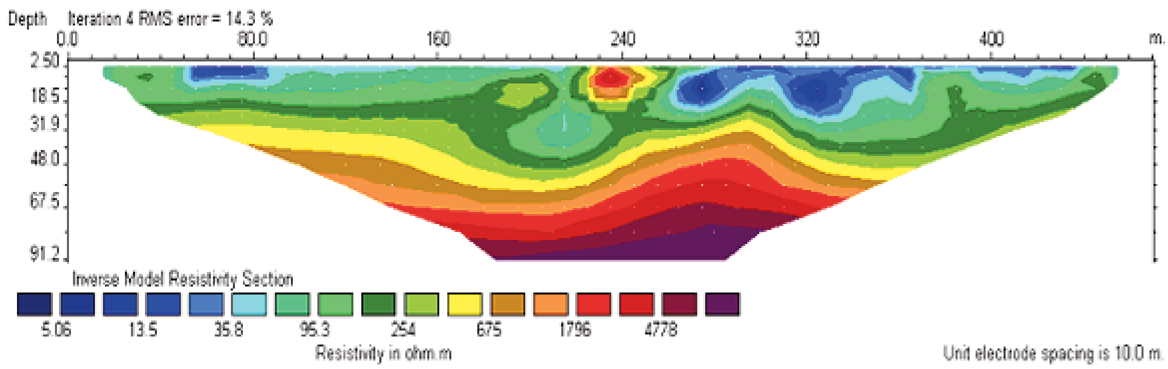


Figure 4.5.3b. ERT across a quartz vein in granites near the Kothur, Maheshwaram watershed about 30 km from Hyderabad, India. (Krishnamurthy et al., 2007).



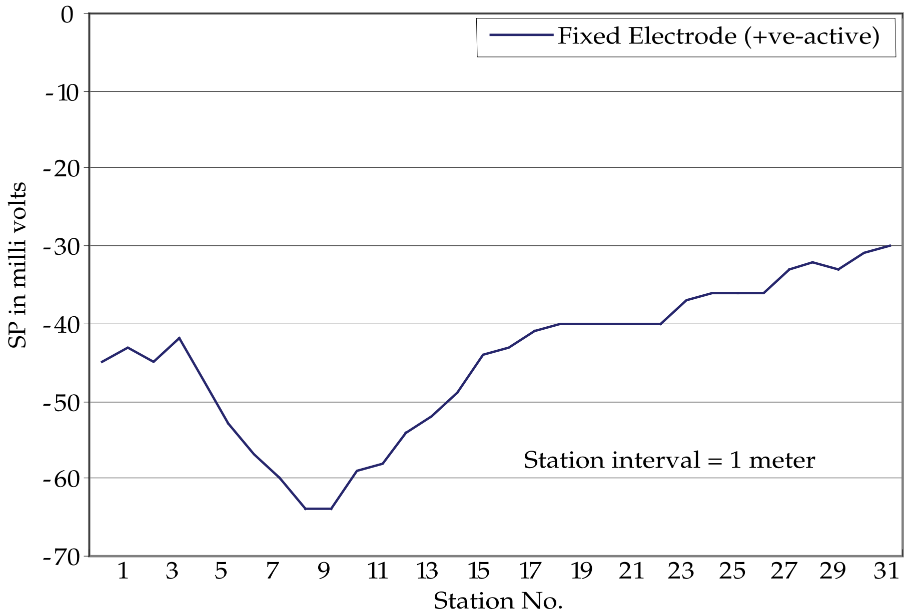
Similarly, if the upper layers are too resistive, the method becomes less effective for delineating conductive layers below.

Deep resistivity measurement is a well-established tool for delineating deeper aquifers in sedimentary terrains, identified by zones of low resistivity. Based on such data, drilling at six sites in the drought prone Barmer district, Rajasthan, was successful in identifying aquifers resistant to drought with yields ranging from 2.5 to 12.5 l s^{-1} of potable water (Singh et al, 1990).

Self Potential (SP) method

The self potential (SP) method complements electrical resistivity methods in identifying potential aquifer zones. Groundwater flow in weathered and fractured zones develops an electrical potential known as streaming potential/self potential (SP). The SP low anomaly (Fig 4.5.4) indicates the presence of a water bearing zone.

Figure 4.5.4. A self–potential (SP) profile exhibiting low anomaly indicating a water-bearing zone



Induced Polarization (IP) method

The time consuming induced polarisation method utilises potential electrodes to measure the decay of the potential difference when a steady current injected into ground is switched off. The induced reaction is based mainly on the membrane and polarization effects. The membrane effect is caused by the presence of an ionic cloud in pore water, which moves under the influence of the applied electrical field neutralised by free positive ions of the electrolyte of pore water. The applied current induces a redistribution of charge and thus a weak current flow which is detected by the potential electrodes when it is removed. The membrane potential is generated particularly by clay particles. Where the resistivity method is not capable of differentiating between clay and a groundwater formation, the IP method can assist in indicating the presence of clay. The IP survey technique employs the same equipment as that for resistivity (current 'on' time) measurement but observes the IP effect during current 'off' time.

Electro-magnetic (EM) method

This method is based on the electrical properties of sub-surface layers. It overcomes the problem of establishing good galvanic (electrical) contact between source of current and (earth) media, such as encountered in resistivity measurements. In an EM survey measurements are carried out by passing an alternating current through a loop of wire, called the transmitter, which generates an electromagnetic (primary) field. This primary field will induce a secondary field in a medium its strength depending on its electrical conductivity. The secondary field, produced by the different properties of the sub-surface, will have the same frequency as that of the primary field. The transmitter and receiver coil assembly with constant separation and orientation will provide the electrical response of sub-surface material and assists in locating conductive material. The depth capability of EM system is dependent on geometry of the transmitter/receiver pair. The different versions of the method are called: frequency domain; VLF (very low frequency i.e. 15 kHz – 3 kHz); and single frequency horizontal loop, the latter being particularly useful in targeting faults, fractures, dykes, and shallow karst features which are conductive (Bromley et al., 1994).

Proton Magnetic Resonance (PMR) / Nuclear Magnetic Resonance (NMR)

PMR/NMR is yet another novel technique developed by Russians Varian (1962) and Schirov et al. (1991) and tested in France by locating groundwater using the electromagnetic field that directly energises the protons in water. The method has shown promise in sedimentary basins but is yet to be proven in fractured hard rock areas. It can, however, be applied in weathered hard rock terrain. The method has limited application as it requires an electrical noise-free environment, which is generally hard to find at present.

Ground Penetrating Radar (GPR)

The GPR method (Fig. 4.5.5) is a special application of electromagnetic waves (frequency 25 to 200 MHz - in the domain of radar waves) to interrogate the interface between layers with contrasting electrical properties. This concept is similar to that of seismic reflection. The receiver antenna registers the reflected waves. Based on the travel time and amplitude in the receiver system, the depth of the reflecting surface is estimated. The method is based on the degree of reflection from the interface, which in turn is dependent on the dielectric constant of materials. The high contrast between dry and water saturated material at the water table is a good reflection interface that can be detected by GPR (Fig. 4.5.6). This applies also to a fresh/saline water interface. The method is generally applicable at

Figure 4.5.5. An example of GPR survey being carried out (Kovelesky et al., 2004)

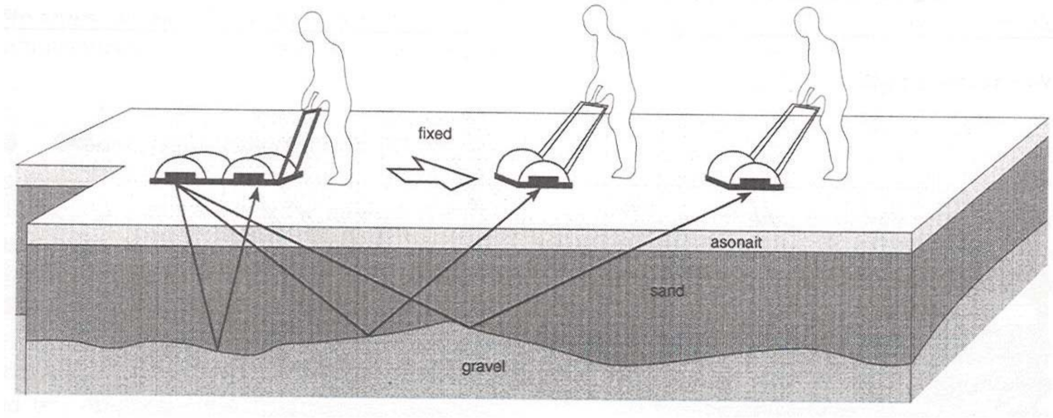
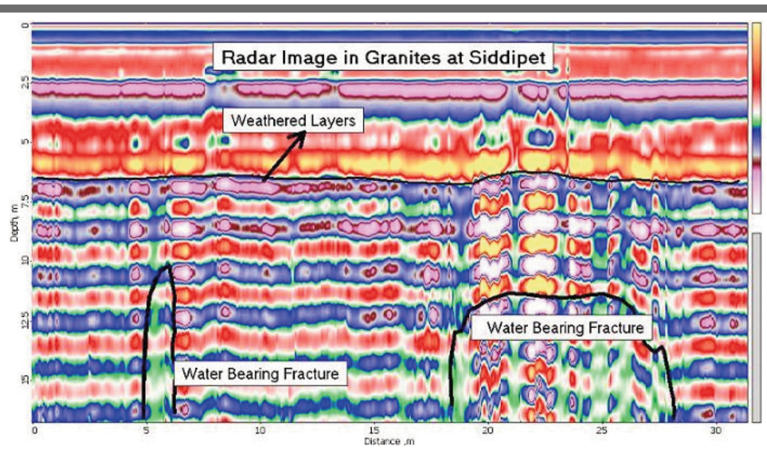


Figure 4.5.6. GPR image with 100 MHz signal frequency in a typical granite terrain of Siddipet (India) shows the weathered zone, compact granite and water bearing fractures. (Source: Rao, NGRI Annual Report, 2006-2007)



shallow depth (van Overmeeren, 1994), up to some 40–45 m as the depth of penetration of radar waves is limited in a low resistance environment.

Magnetic method

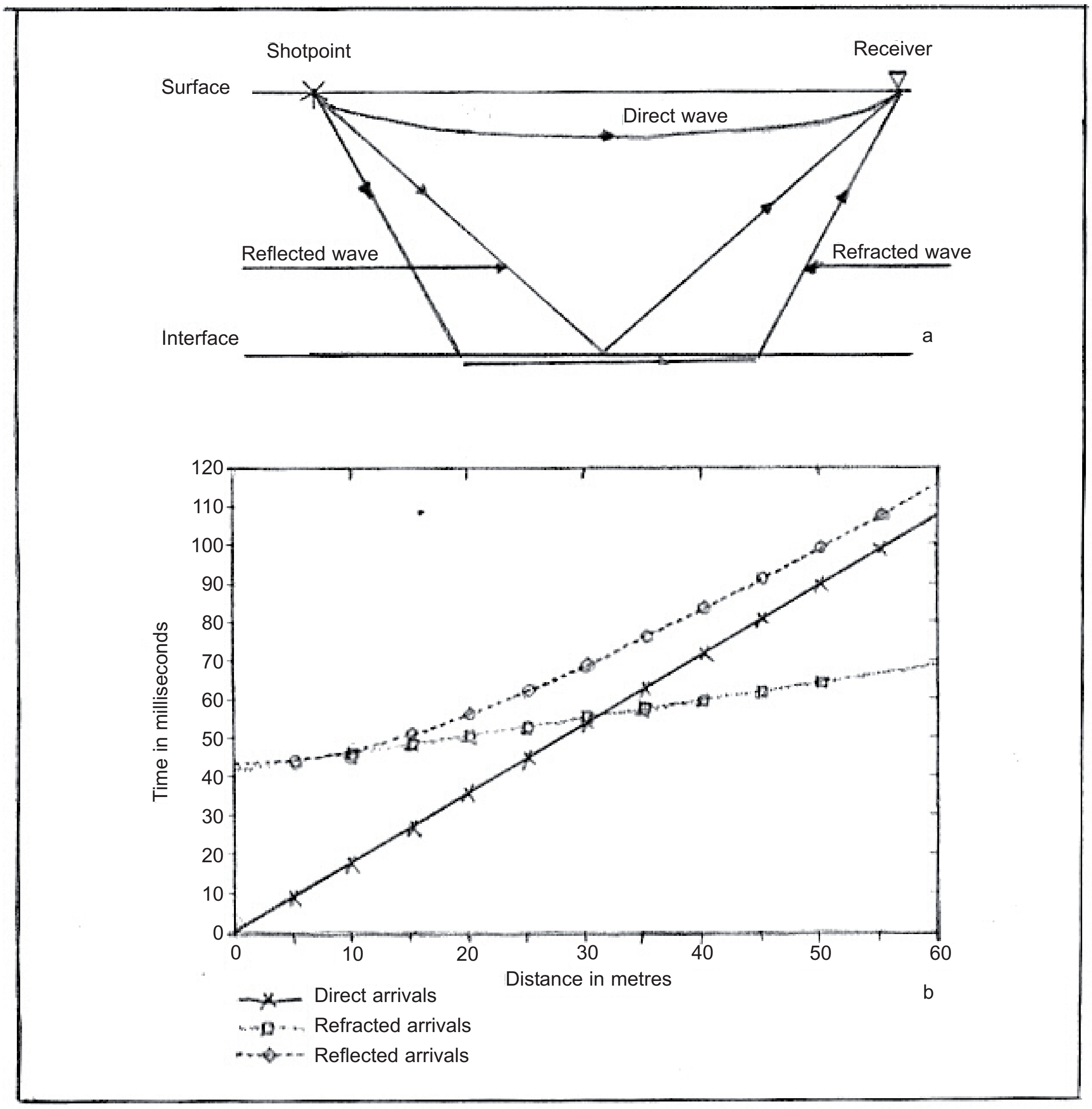
The magnetic method is useful in groundwater investigations in the delineation of structures such as faults and fractures. Surface lineaments are often associated with faults and fractures and thus are preferred locations for groundwater occurrences. Delineating these with magnetic methods has proved successful for siting boreholes (Astier and Paterson, 1987). The method is based on anomalies in the remanent or induced magnetisation of the magnetic fabric of the rock controlled by its magnetic susceptibility. Such anomalies can be mapped by surveys carried out at ground level or using airborne techniques. The magnetic field can be measured by various types of magnetometer. Present-day magnetometers can measure magnetic changes as small as one nano Tesla (nT). The earth's magnetic field ranges from 25,000 to 60,000 nT. Anomalies can generally range upwards from less than 10% of the total magnetic field at a given location. Temporal or short-term changes (50–100 nT) in magnetic field due to solar flares or diurnal variations need to be corrected. Magnetic anomalies can be positive or negative and can be modeled by assuming certain geometric shapes of the body and by adjusting the probable depth of occurrence, which fits the observed data, including anomalies. In fact well-defined anomalies have been interpreted by inversion to produce a reliable estimate of the geological structure (dyke, fault, horizontal plate, down-thrown block etc).

Seismic methods

The seismic method for groundwater investigations is based on the principle that seismic wave velocities are related to the elastic properties and densities of the strata which in turn depend on the porosity. Seismic waves, compressional (P) and shear (S), can be generated by a mechanical impact (hammer) or by an explosion on the ground surface. The P and S waves travel through different strata at different velocities and are also reflected and refracted at the interfaces between layers with different elastic properties. In seismic methods, the velocities ν (m/s) of P and S waves are measured, which are obtained through the distance (D) and time (T) relationship ($\nu = D/T$). The time is measured between the initiating event and the arrival of the seismic waves at the geophones placed at the surface, either directly (near surface) or travelling from the source through the different strata, refracted or reflected at the interfaces. Their first arrival time is computed and plotted on time/distance curve (Fig. 4.5.7). The seismic waves follow the same laws as those of optics (Snell's law).

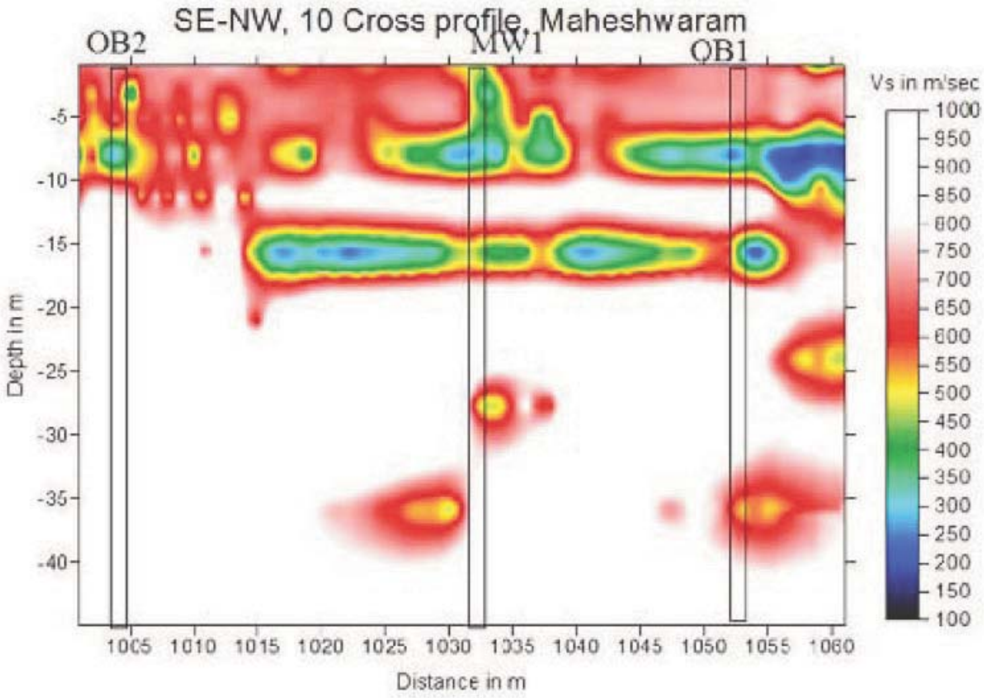
Generally in a refraction seismic survey, 5 to 7 shots are deployed for each spread of a series of geophones (in multiples of 12) and data is processed with a computer. A travel time curve for either direct waves or refracted waves is constructed as mentioned above. Seismic refraction surveys are most commonly useful in determining the thickness of valley fills overlying impervious bedrock and buried bedrock channels especially where the upper portion is weathered. Thus the depth of the water table (wave velocities increase abruptly at the water table, the zone of saturation acting as a refractor) can be determined, as well as lateral facie variations and tectonic structures. A reflection survey can be extremely useful for very high resolution in subsurface mapping. Especially strong reflections are obtained from the top of clay layers overlying sandy aquifers.

*Figure 4.5.7. **Above: Three different waves trajectories: direct, refracted and reflected. Below: Each wave (trajectory) has a different arrival time depending upon the lay-out geometry, depth of interface and the characteristic velocity of each layer (Kovelesky et al., 2004)***



In some recent developments use was made of multi-channel analysis of surface waves (MASW) for the delineation of fractures. Exploratory experiments using MASW in a hard-rock watershed in Maheshwaram, Andhra Pradesh (India) revealed the potential for using seismic shear 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. 4.5.8).

Figure 4.5.8. 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.



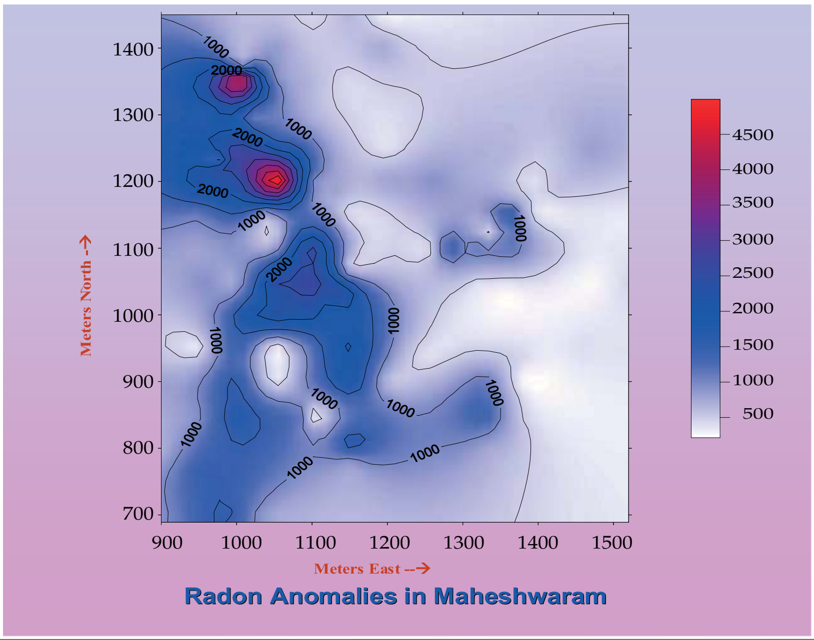
Gravity method

This method utilises changes in density of the geological material in the subsurface to detect structures suitable for groundwater storage. It assesses the depth of basement and could delineate large sedimentary structures, which may have permeable zones. The method may also be applied to delineate and locate buried paleo-channels and alluvial formations and faults, and zones of deformation. In this method, the difference in gravity expressed as acceleration (ms^{-2}) is measured between different points on the surface of the earth which is related to changes in the density of the material. The instrument used is called a gravity meter which can measure differences in the gravity field down to milligal (acceleration of 10^{-8} ms^{-2}) level. However, apart from density there are several other factors which determine the gravity measurements. The gravity anomaly could also be due to elevation difference, terrain, latitude, earth tides and instrumental drift. Thus several corrections are needed to process the observed data to obtain accurate gravity anomalies expressed as Bouger anomalies. Generally Bouger anomaly maps are prepared by contouring the iso-anomalies, interpreted in terms of geological structure. For example a strong gravity gradient may indicate faulted strata with different densities or an intrusive body. Similarly, low gravity may indicate a sedimentary basin. Typical small gravity anomalies of 0.2 to 2 milligals have been successfully applied for the detection of palaeo-channel aquifers (Angelito et al., 1991, Carmichael and Henry, 1977).

Radiometric methods

Radiometric methods employ the radioactive decay of elements such as uranium, thorium, and potassium which emit α, β or γ rays. γ rays are the most penetrating (with a range of 600-800 m in air), whilst in rocks β particles have a range of a few millimeters and α particles a few microns. Different rocks contain varying amounts of radioactivity. Because of the high penetrating power of γ rays, they find application in geological mapping such as the delineation of contacts between different rock formations, faults, shear zones etc. It is known that clay and shale (higher mineral content) have higher radioactivity as compared with sand and sandstones. Among the igneous rocks, the radioactivity is lowest in the ultra-basic rocks. It has been demonstrated that a radiometric survey can help to delineate an aquifer by differentiating non-productive shales from productive shaley sandstones, something that could not be achieved by an electrical resistivity survey. In a recent study, Reddy et al. (2006) demonstrated (Fig. 4.5.9) that radon (a radioactive noble gas) can serve as a useful tool in delineating fractures in granites. As a result of a systematic survey of ^{222}Rn concentration in soil gas (at a depth of 60 cm to 160 cm) in granites of a watershed located in the semi-arid area of Maheshwaram, India they demarcated three high ^{222}Rn anomalies, an observation also supported by ^{4}He measurements.

Figure 4.5.9. Radon anomalies (red) indicate the presence of fracture zones. A well drilled on the anomaly was successful (Reddy et al., 2006)



In order to test the radon emanometry method, drilling was carried out at the sites of high radon anomaly as well as on sites of low radon values. A reasonable correlation was found between radon levels and borehole yield (Table 4.5.1).

The above results suggest that ^{222}Rn concentration in soil is controlled by fracturing of the underlying rock, in addition to its parent uranium concentration. The radon emanometry method may prove to be useful in siting successful boreholes, as radon can even be detected by simple cumulative detectors placed on the ground surface.

Geophysical well logging methods

Geophysical well logging provides data on the sequence and thickness of various rock

Table 4.5.1. Radon emanometry data and corresponding well yields

Village	Radon conc. Bq/l	Well No	Well depth (m)	Discharge during drilling (litre/s)
K.B.Tanda	233	MW 1	91.5	4.5
	83	OB_1-1	45.75	1.0
	50	OB_1-2	45.75	No water
	42	OB_1-3	45.75	No water
	42	OB MW-2	64	0.5
	42	MW-3	55	No water
Siglipuram	183	MW-4	91.5	0.5

formations, through subsurface (down the hole) measurements of various physical parameters such as resistance, self potential, natural radioactivity, temperature, seismic wave velocity, and even borehole diameter which reflect the physical properties of rock formations such as porosity, permeability, salinity, water flow, hardness etc. The most common methods employed are resistivity, self-potential, natural gamma ray activity and caliper (borehole diameter). Well logging measurements also assist in the design of water supply wells, particularly in the placing of well screens in water-bearing formations.

Resistivity logging

The procedure for measuring resistivity in a borehole is essentially the same as for surface logging. The current and potential electrodes are lowered in the (uncased) well to the depth of investigation. There are three electrode arrangements, which are generally used to obtain resistivity logs. In the short normal arrangement, the effective spacing distance between current and potential electrode is small; in the long normal arrangement the distance is large; in the lateral arrangement the potential electrodes are close together and further from the current electrode. This array focuses the current deeper into the formation.

Self-Potential (SP) logs

The phenomenon of self-potential (SP) is the result of two components: electro-chemical potential and streaming potential. The electro-chemical potential is generated when two fluids with different salt concentration are separated by a dry or semi-permeable membrane. Streaming potential is generated by flow of water with dissolved ions through narrow rock formations. The SP level of a clay formation is considered as the base value. Thus it is a relative value, that can be positive across a fresh water bearing formation and negative for saline water. The measurement of SP is used more as a qualitative tool to differentiate layers, delineate boundaries of different formations and/or indicate the presence of saline water.

Nuclear logging

Nuclear logging comprises a host of radioactive logging methods based on the natural radiation of formations, its level determined by the lithology. Most commonly employed is the natural gamma radiation emitted by radioactive minerals such as uranium, thorium and ^{40}K, though α and β particles are also emitted. Generally ^{40}K is more common in shales and clays than in sands. Gamma radiation is detected using a scintillating crystal and amplification by photo multiplier. The logger is moved at only 1 to 2 m/minute so that statistically significant counts of the radiation are obtained. The density of the formation is found by γ-γ logging, in which a gamma ray source is lowered and backscattered γ radiation is measured.

Caliper Logging

This logging method uses a spring-loaded device that transmits changes in the diameter of the well caused during drilling as the material from the borehole wall is washed out. The method provides some information on the location of relatively friable material and thus is very useful for locating fracture zones and consequently in the design of the well.

Sonic Logging

This method utilises the acoustic wave velocity in the formation surrounding the borehole. The velocity is related to the density and the elastic properties of the rock formation. A transmitter and two receivers are placed at different depths and the travel time of the sonic wave is recorded. The method is rarely used, but can prove valuable in locating fracture zones in hard rock aquifers.

Geophysical methods suitable for delineating aquifers resistant to disaster events

Table 4.5.2 and the following text summarises the use of different geophysical methods for delineating groundwater aquifers for emergency situations as well as to study the potential impact that some disaster events may have on them.

- Geophysical methods are the most appropriate first step in identifying emergency groundwater resources as they are rapid and may even provide guidelines for the location and construction of water supply wells.
- Geophysical methods can provide quantitative data regarding aquifers, their location, depth, thickness and lateral extent, groundwater quality, freshwater/salt water interface, delineation of structural and tectonic features controlling groundwater movement and even assist in identifying aquifer pollution.
- As can be seen from the table 4.5.2, the most widely used are geo-electrical methods including resistivity arrays for profiling or electrical soundings or, in combination, are called 2D resistivity, employed along with electromagnetic methods. This is because the presence of water greatly increases the conductivity of most rocks.
- The presence of saline water in coastal aquifers due to sea water intrusion in the geological past or due to contemporaneous sea water surges resulting from storm or tsunami events can be revealed using a combination of electrical resistivity and IP methods. The EM method has been routinely used for identifying saline water bodies (Goldmann et al., 1988).
- Deep seated aquifers, including buried river channels and vertically offset faulted aquifers can be delineated through deep resistivity surveys, seismic reflection and gravity methods. Such aquifers are usually an eminently suitable source of groundwater for drinking water supplies in emergency situations.
- Aquifers in fractured and fissured hard rock environments can be revealed by newly developed methods based on MASW, GPR, radon emanometry in addition to the electrical and electromagnetic methods.
- Karst aquifers can be delineated using resistivity, EM, VLF and radon low anomalies.

- Well logging methods are most useful in vertical geological and hydrogeological profiling of the borehole and in water well design, the identification of water-bearing formations, salt-fresh water interface and groundwater pollution.
- Geophysical methods (especially electrical and electromagnetic) are also useful in identifying an aquifer and estimating its hydraulic properties as well as delineating zones vulnerable to natural (disaster) events and human (pollution) impacts.

Table 4.5.2. A summary of geophysical methods (based on Kirsh, 2006) for delineating groundwater aquifers for emergency situations as well as to study the potential impact of some disaster events on them

Type of aquifers and their characteristics	*Electrical*	*Electro magnetic*	*Seismic*	*Gravity*	*Radiometric/ Geochemical*	*Well logging*
Aquifers in unconsolidated & consolidated porous sediments	Resistivity profiles, VES & SP	GPR (for Shallow aquifers) TEM	Refraction	-	-	Electrical Conductivity
Faulted/ jointed Fractured/ Fissured Aquifers	Resistivity profiles, VES & SP	Electro Magnetic Induction GPR	MASW	Bouger Gravity Profile	Radon	Electrical Conductivity SP & Caliper
Aquifers in volcanic areas	Resistivity profiles, VES & SP	-	-	-	CO_2 emission & stable isotope in spring water	-
Karst aquifers	Resistivity, VES & SP	Electro Magnetic Mapping, & VLF	Refraction, Reflection		Radon	Electrical Conductivity Caliper
Deep seated aquifers including buried valley fills	Deep Resistivity	TEM	Reflection	Micro gravity		SP & Induction Log
Aquifer basic characteristics & estimation of hydraulic conductivity	Resistivity	NMR, IP, & SIP	P-Wave velocity	-	C-14 dating of groundwater	Tracer tests
Identification of protective layers controlling aquifer vulnerability	Electrical, VES	IP, Electro TEM	GPR			Electrical Conductivity, SP & Gamma
Coastal aquifers impacted by seawater intrusion and by tsunami/ storm events	Electrical Conductivity, VES	Electro Magnetic Induction	-		Salinity Studies	Electrical Conductivity

4.6 Remote sensing

Wenbin Zhou

Introduction

Remote sensing refers to instrument-based techniques employed in the acquisition and measurement of geographically distributed land surface data/information on spectral, spatial and physical properties of an array of target points (pixels) within the sensed scene that correspond to features, objects, and materials. This is done by applying one or more recording devices not in intimate physical contact with the items under surveillance. The techniques utilise electromagnetic radiation, force fields, or acoustic energy sensed by a large variety of devices such as recording cameras, radiometers and scanners, lasers, radio frequency receivers, radar systems, sonar, thermal and sound detectors, magnetometers, gravimeters, scintillometers, and other instruments carried by airplane, satellite, spacecraft or space shuttle.

Remote sensing images contain both spectral and spatial information. The spectral information informs on various properties and characteristics of the surface cover at a given location or pixel (image unit) e.g. vegetation and/or soil type. The spatial information informs on the distribution, variation, and topographic relief of the cover types from pixel to pixel. Therefore, the main characteristics that determine a pixel's brightness/reflectance and, consequently, the digital number (DN) assigned to the pixel, are the physical properties of the surface and near surface, the cover type, and the topographic slope. In applications, the ability to detect and map lineaments, especially those related to underlying fractures and faults, is critical. Therefore, the extraction of spatial information from the digital images is of prime interest. The spatial information varies among the different spectral bands available; in particular, a near infrared spectral band is better than a visible band when extracting spatial information in highly vegetated areas.

Remote sensing images and subsequent digital image processing have hitherto been under-utilised in ground water resource evaluation and exploration. Various enhancement and manipulation procedures could be applied to the digital satellite images; the results, in both digital and hardcopy format, are used for detecting and mapping the regional geological structural patterns, including major fracture and fault systems. The wide swath coverage of remotely sensed satellite digital images makes them ideal for regional tectonic analysis as a major requirement for groundwater resource evaluation and exploration; it allows us to stand back (actually up, about 440 miles), to look at, and map the regional structural setting of the studied area. The main focus of the remote sensing and digital image processing component is to use both remotely sensed digital satellite images and a digital elevation model (DEM) to extract spatial information related to the structural and topographic patterns in the studied area.

Satellite techniques have also become an effective tool in monitoring of groundwater level and storage data in countries and regions with a dearth of groundwater monitoring networks and groundwater data. However, the accuracy of satellite based groundwater data is lower in humid regions with unbroken and extensive vegetation canopies and declines with increasing depth of aquifers overlying each other.

Satellite image systems

The data types commonly used are digital satellite images collected by the United States' Landsat Thematic Mapper (TM) and French Systeme Probatoire d'Observation de la Terre (SPOT) imaging systems, along with a DEM of the same region.

The **Landsat TM** imaging system, launched in 1982 by the United States, collects six reflective spectral bands (blue, green, red, near infrared, and two mid infrared), having a spatial resolution of 30 meters, and a thermal band with a 120 meter spatial resolution. The area covered by a single image is approximately 185 by 185 km (115 by 115 miles); the satellite orbits at an altitude of about 700 km (438 miles). A low sun elevation angle is better at enhancing structural features. The digital data can be processed using spatial filters to enhance the structural information at several different frequencies, including both edge and textural enhancements. These types of digital image processing procedures generate image products useful in helping identify both areas that contain individual lineaments and areas with a high density of surface fractures, both important in the study of groundwater system..

The French **SPOT** satellite imaging system, launched in 1986, collects three spectral bands (green, red, and near infrared), with a 20 meter resolution, or a single visible panchromatic band, with a 10 meter resolution. The area covered by a single image is approximately 60 by 60 km (37.5 by 37.5 miles) and the satellite orbits at an altitude of about 830 km (520 miles). The SPOT imaging system can collect stereo image pairs that contain topographic (3-D) information.

A **Digital Elevation Model (DEM)** is a data set that can be used to complement remotely sensed satellite images; it is a representation of the topography/elevation of an area on a pixel by pixel basis in a raster image format. The digital number at a given DEM pixel is equal to the elevation at that location, usually in feet or metres. Therefore, a favourable aspect of working with DEM data is that it 'strips' away both man made features and the effect of vegetation and soil types as it looks at the surface strictly from a topographic/elevation point of view. Part of the digital image processing and interactive analysis done in the Flagstaff area with the USGSMIPS included enhancing and analysing the structural patterns and related topographic information using the 30 meter resolution DEM. The products generated included shaded relief images, stereo pairs created by introducing parallax into the shaded relief and Landsat TM images using the 30 meter DEM, and colour coded DEMs. The real-time interactive colour coding of the DEM data shows both the direction of surface water runoff and the basin that it is related to within the same image. This information helps determine where the surface water runoff from different locations is drained by the various fractures and faults.

Satellite data processing

The digital image processing, manipulation, and interactive analysis can be done by using open or commercial image processing software packages, such as ERDAS IMAGINE, MapInfo and PCI. As mentioned before, the primary information extracted from data processing are lineaments that could be related to fractures, faults, or other geologic structures. The remotely sensed satellite images assist in mapping regional structural patterns and identify areas of localised high density fractures. These results are used both in geologic mapping and identifying areas that need to be investigated in greater detail in the field, including the collection of ground penetrating radar and seismic reflection profiles of selected geological and hydrogeological structures.

Applications

Remote sensing, with its advantages of obtaining spatial, spectral and temporal data covering large and/or inaccessible areas within a short time, has become a very effective tool in identifying and monitoring emergency groundwater resources. Satellite data provides quick and useful baseline information on the hydrological parameters controlling the occurrence and movement of groundwater and fluctuation of groundwater levels (Kumar and Tomar, 2002). Remote sensing is particularly helpful in the detection of tectonic structures that may transmit groundwater from or to deeper aquifers resistant to the impact of disaster events as well as groundwater resources stored in buried paleochannels useful as emergency sources in (arid) regions affected by droughts. 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 successfully applied 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. They are able to locate paleochannels based on the moisture content in the soils above the channels and also on vegetation patterns observed above the buried channels (Fig. 4.6.1). Many hydrogeological parameters that may reflect the groundwater regime can be interpreted by remote sensing, such as drainage patterns, soil types, soil moisture, fracture systems, geological structure, relief, and anomalous zones of vegetation (Fig. 4.6.2). It is also possible to distinguish facies of alluvial fill, such as point bars, channels and flood plains (Fig. 4.6.3). The airborne electro-magnetic (AEM) technique is suited to fault topographies and revealing saline paleochannels and is proving a valuable and accurate method of detection and definition (Ackland and Hunter, 2002). Zones of groundwater movement in soil-covered semi-arid areas can be detected by temperature contrast of moist soil with infrared imagery. Groundwater recharge, run-off and discharge can be detected using composite visible and infrared imagery (Zhu, 2002).

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

In hard-rock environments, digitised aerial photographs and satellite images were used to compile lineament and fracture zone maps (Fig. 4.6.4). 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 in evaluating the potential concentration of water in fracture zone aquifers (Saint-Jean, Singhroy, 2000). Geostatistical maps such as of lineament densities and lineament intersection densities, are easily extracted by processing remote sensing images (Elfouly, 2000). Suitable lithological types and stratigraphic position for potential large groundwater reserves can be identified from multispectral remote sensing data. Vegetation is responsive to soil-lithology characteristics. Remote sensing technology is useful in highly vegetated areas because the vegetation gives clues in identifying the underlying rock types, potential lineaments, faults and folds in the subsurface

Figure 4.6.1. Landsat TM Band 641 RGB composite showing channels and paleochannels in the north of the Erdos Plateau, China. The dark blue is surface water and the light blue shows underground streams and moisture. The arrows indicate the location and trend of interpreted buried paleochannels

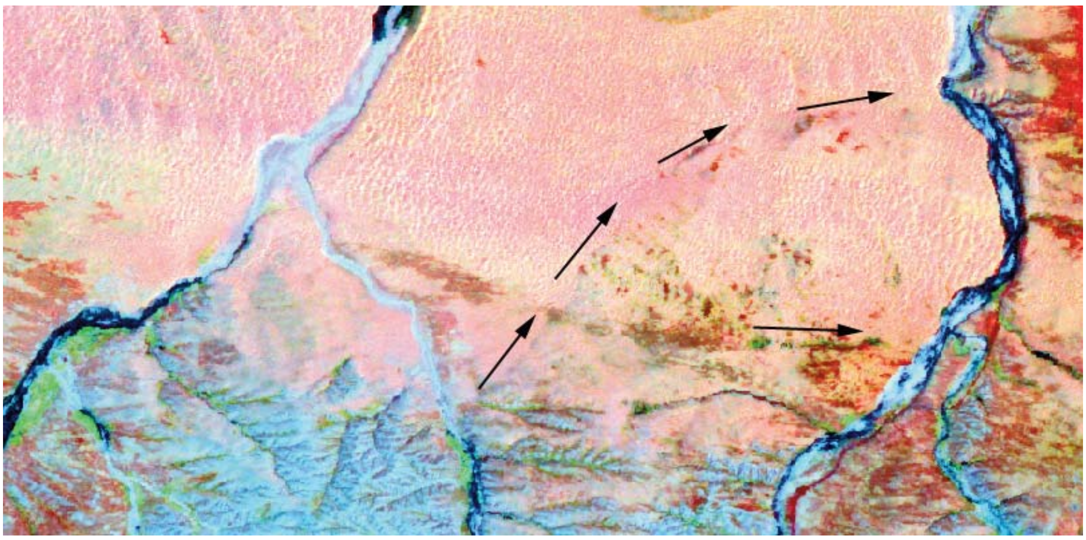


Figure 4.6.2. Anomalous zones of vegetation show recharge and discharge of groundwater, Hami, Xinjiang, China

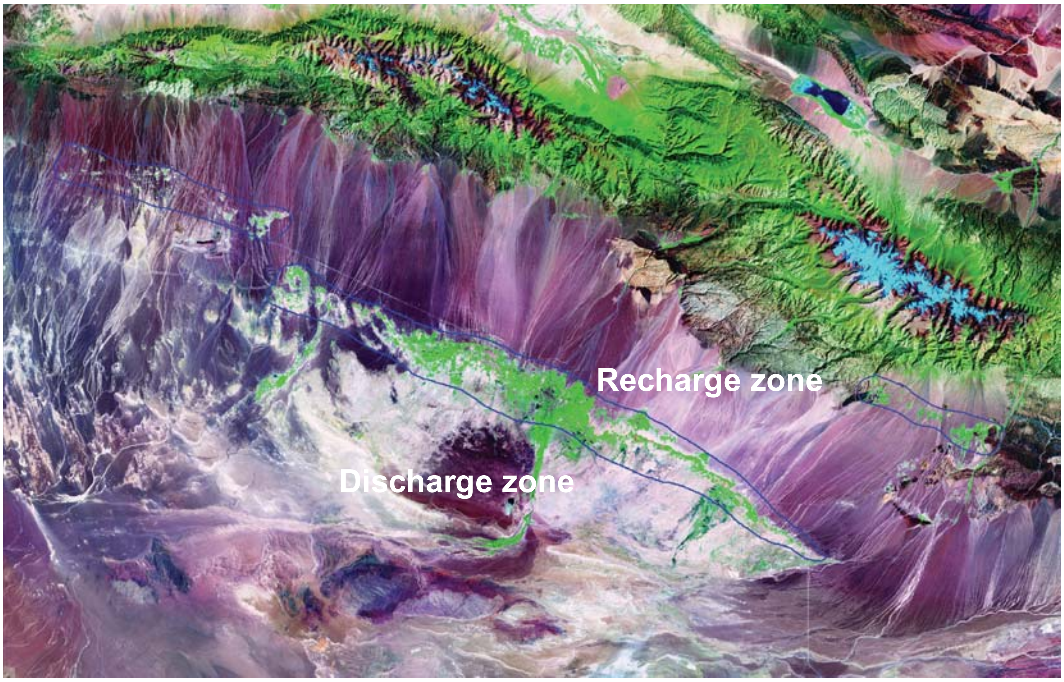


Figure 4.6.3. The TM band 543 RGB composite shows the buried point bars (arcs shown in brown), channels and flood plains of Songhua River, northeast China

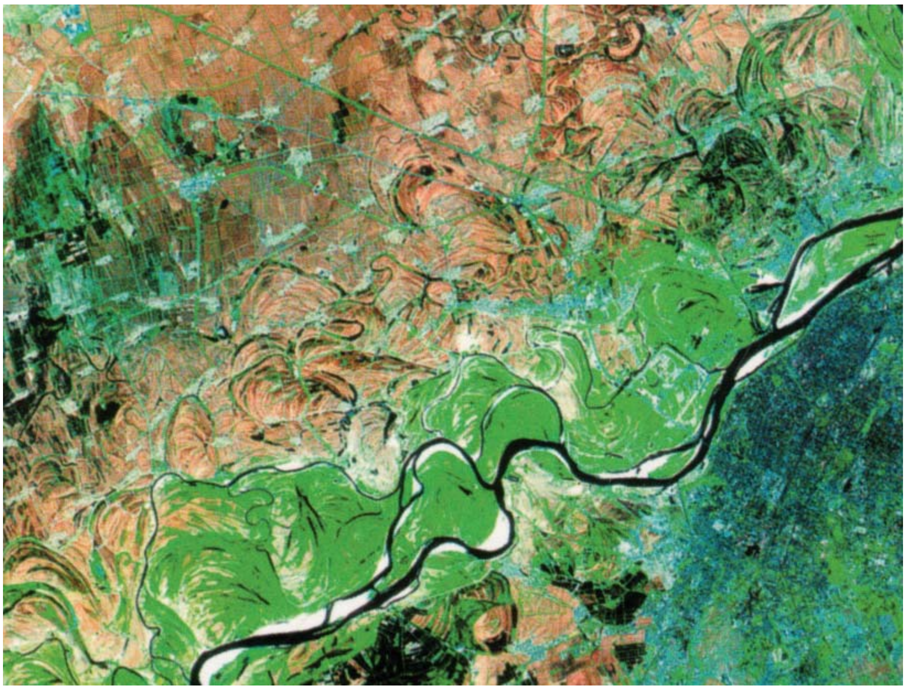
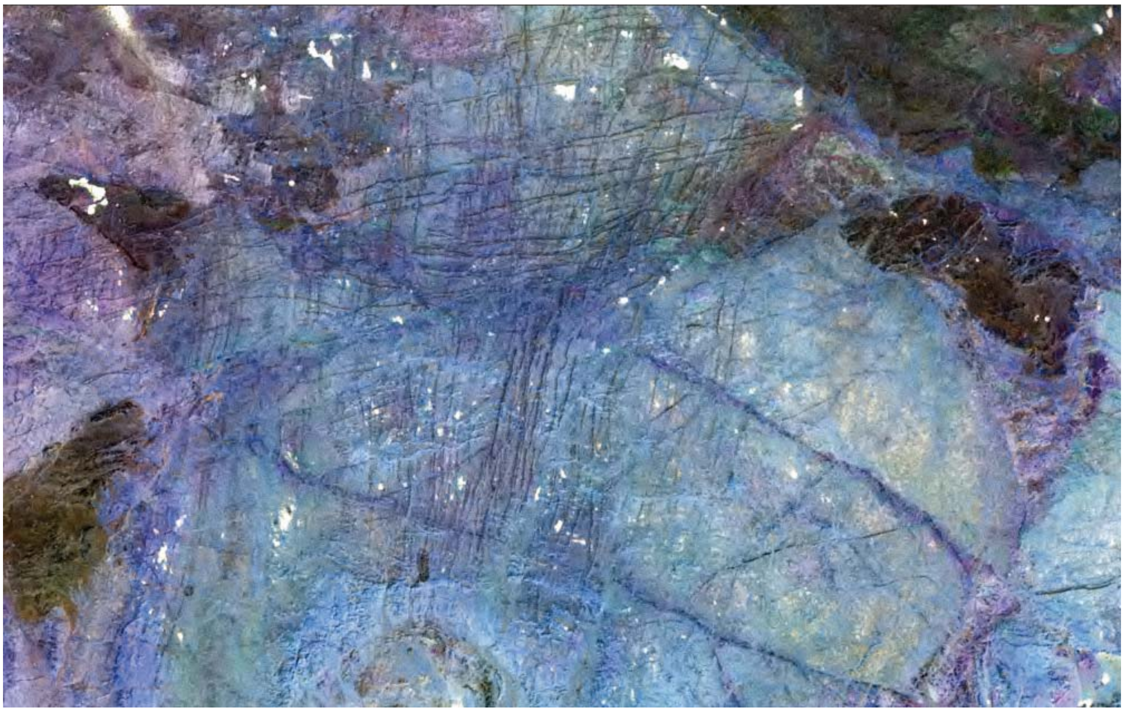


Figure 4.6.4. Fracture patterns of igneous terrain are recognised using a composite of TM 741 bands in the south of Tuha Basin, Xinjiang China. The darker blue grey areas are rich in groundwater.



(Drury and Deller, 2002). The lineament target areas were subsequently investigated in the field using geophysical techniques followed by exploratory drilling to assess potential groundwater reserves.

The delineation of 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, in representing fundamental zones of weakness in the lithosphere, offer such high permeability pathways, and may continue to provide them over long periods of geological time. Lineament analysis has provided useful information on the fracture permeability of aquifers. The mapping of linear features associated with fractures (faults and joints) can be performed multi-spectral images of almost any wavelength region. This type of mapping is an important tool for groundwater exploration in metamorphic and igneous terrain, because the greatest amount of groundwater will be found near fractures, where the only significant porosity and permeability will be located. Underground water detection is accomplished successfully by using the ground penetrating radar technique in showing water table conditions and fluctuations, the results being confirmed in nearby local wells.

Time series gravimetric measurements to assess variations in groundwater level changes and so variations in groundwater mass storage radar altimetry measurements as well as microgravity (satellite and land based) measurements to estimate changes in groundwater storage by use of gravity gradiometer systems (IGOS, 2004) have been applied e.g. within the GRACE gravimetric mission, ESA GOSE mission or in the Tuscon Basin, USA, to estimate groundwater storage changes in the period 1989–1999 (Donnethy, 2007).

Remote sensing data is used to focus on promising areas for further hydrogeological exploration of groundwater resources which can be used in emergency situations. It can help reduce costs and save time in a groundwater terrestrial investigation by prioritising areas to be supplied by groundwater based on social and emergency needs. Detailed hydrogeological studies, geophysical prospecting and test drilling in priority areas can be guided by processing and analysing remote sensing images. Exploration procedures can ideally adopt remote sensing as the first step, whilst earth scientists can use the data to apply geophysical, hydrochemical and other relevant field studies, to assess potential emergency water resources and suggest the best sites for their storage, extraction and distribution. However, space-based groundwater data should always be calibrated and validated according to the available groundwater data acquired from in-situ observations and measurements.

4.7 Conceptual and mathematical modeling of groundwater systems

Balt Verhagen and Klaus-Peter Seiler

Conceptual modeling of a groundwater system

The basic components of a conceptual model are the sources of water to, and sinks of water from the region, the physical boundaries of the region, and the distribution of hydraulic properties within the region (Léon and Ferré, 2003). The formation of a conceptual model is critical to the development of a more quantitative representation of the subsurface hydrology, such as a numerical groundwater flow model. A calibrated, numerical groundwater flow model allows for prediction of the impacts of changes to the hydrologic conditions on subsurface flow. However, this requires precise definitions of the physical boundaries, the water fluxes into and out of the system, and the distributed hydraulic properties. In contrast, a conceptual model allows for more general conclusions regarding the impacts of aspects of the hydrologic conditions on current water flow directions. In addition, a conceptual model is very useful for identifying gaps in knowledge or data that must be filled in before a quantitative model can be constructed.

Any groundwater flow model, whether conceptual or numerical, is a form of a water mass balance calculation. Water is typically added to the system as precipitation. Water can also be added to the system as subsurface flow. Water is lost from the system through streamflow, subsurface flow, evaporation, transpiration, and human withdrawal. If the aquifers are unconfined, the change in water stored can be determined based on changes in the water table elevation through time. More complex groundwater flow models account for the movement of water within the domain. A steady state groundwater flow model requires that the spatial distributions of water inflow and outflow as well as the subsurface hydraulic properties be defined throughout the region. These models can be used to characterise the movement of water through the subsurface if none of the input parameters discussed change in time.

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's behaviour and provide the basis for determining further data requirements and the type of mathematical model that is appropriate (McMahon et al., 2001). Preliminary testing should be carried out by using lumped parameter 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 scarcity 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 always (or should not be) continuously exploited. Extra care and planning are therefore needed in this step, especially with monitoring.

An important stage in the development and management of a groundwater 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.

It is important to avoid both over-simplification, which results in a numerical model that 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; NGOs; 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, or field investigation. As transport is becoming increasingly expensive, this is an opportunity to perform the first well-head observations of basic parameters such as water temperature, pH, EC, TAlk and possibly Eh and BOD; even appearance and taste. Such observations and sampling should, as far as possible, be performed according to standard principles (e.g. IAEA, 2007), and can in themselves reveal a great deal about the groundwater system being investigated. It is good policy to take a well-documented water sample for initial chemical and possibly isotope measurements. Suitable existing and newly-drilled boreholes should be pump tested to obtain preliminary groundwater transmissivity and storage values.

An ongoing monitoring programme for e.g. groundwater level, hydrochemistry, environmental isotope observations and measurements should be instituted. For an emergency supply, this usually would be from standby boreholes. Establishing an efficient monitoring frequency is often difficult, but essential process. There is little point in sampling a borehole on a seasonal basis when the groundwater mean residence (or response) time is several thousands of years. On the other hand, sampling once every few years could miss important but serious contamination trends in rapidly turned-over groundwater systems (e.g. karst aquifers, shallow aquifers in fluvial deposits connected with surface streams). Here, isotope-based residence time estimates could be of great value in designing a monitoring programme (see below).

Initial simulation

The available geological and geohydrological information may be used to set up a preliminary test model. User-friendly software is commercially available (see below) 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. To conduct meaningful simulations, careful scenario-building of the projected demand intensity, duration and geographic spread is necessary in order to obtain realistic feedback on additional development and resource protection requirements. This requires detailed information on actual and projected demography, minimal water requirements and extractive capacity under different projected emergency situations.

Isotope hydrology

Environmental isotope hydrology (see chapter 4.4) is an often indispensable tool with which to assess the validity of a conceptual ground water model. Especially for deep groundwater structures, which are likely to be targeted for emergency supply, isotope data can suggest a model where little geohydrological information exists and provide parameters such as recharge estimates, flow continuity, residence time and mixing that are 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 investigated further. Several examples of the use of environmental isotopes in establishing conceptual models of potential emergency supplies are to be found amongst the case studies presented in chapter 11.

Sustainability

Ground water modeling 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 exploited water source.

The conceptual model should anticipate 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 to be over-exploited – and provide an assessment of the rate of recovery. The results of such potential over-exploitation can be tested through simulation once a reliable numerical model has been established. If such simulation is not possible, it may be necessary to over-design the extraction system i.e. through installing more emergency wells (and also monitoring wells), in order to limit the drawdown in individual wells and/or parts of the groundwater system. Here it should be kept in mind that adequate spacing is allowed between production wells to avoid mutual interference.

Vulnerability

An emergency supply has to be able to produce water of an expected quality when required. A groundwater conceptual model should encompass aquifer vulnerability – factors that will degrade the quality of groundwater. These could be the drawing-in of highly mineralised water from adjacent, overlying or underlying aquifers during heavy exploitation. As most instances of anthropogenic pollution are derived from the land surface, a guiding parameter is rain recharge, as surface pollutant ingress often mimics natural recharge controlled by the thickness, permeability and attenuation capacity of the soil and unsaturated zone. Many examples of conceptual model construction are centered on this problem (e.g. León and Ferré, 2003, Maidment 1997, McMahon et al., 2001, Vrba and Zaporozec, 1994), particularly in highly-developed industrial environments. However, surface pollution is increasing rapidly also in developing states and much can be learned from these methodological developments.

Vulnerability could also refer to the degradation of the aquifer due to collapse or compaction under heavy exploitation of the aquifer's porous skeleton. The result would be lowering of the porosity or specific storage as well as the transmissivity, i.e. aquifer performance, which can often be irreversible. This is particularly important in cases of intense exploitation of poorly-consolidated primary aquifers. The best precaution would be to drill wells sufficiently far apart and moderate individual well delivery. Of great importance too is to ensure that regional drawdown is minimised and the aquifer is allowed to recover after periods of intense exploitation.

Conceptual model software innovations

Groundwater modeling simulations are typically performed according to the following steps:

1. Develop a conceptual model
2. Create a numerical grid
3. Assign model parameters and boundary conditions to the grid
4. Calibrate the model
5. Make predictions from model run results

The development of a conceptual model is often the most important step in the modeling process: a simplified, if high-level representation of the system to be numerically modelled. If not developed sufficiently, steps 2&3 will not lead to proper model calibration in step 4. Often, several conceptual models must be developed before proper calibration is achieved. In groundwater modeling appropriate boundary conditions and stratigraphic representations are often difficult to determine. Most groundwater modeling pre-processing software is designed to automate and enhance steps 2-5, the conceptual model being developed independently of the modeling software. A new approach to model development (Computer Graphics Laboratory, Brigham Young University) features the conceptual model as the primary focus of model generation and data entry process. On a numerical grid or mesh, a conceptual model is set up using GIS objects and boundary conditions and model properties assigned.

The conceptual model is independent of grid type such as finite element or finite difference. The numerical model is automatically generated once the conceptual model is defined at this higher level. The grid or mesh is constructed in a manner that fits or adapts the grid to the conceptual model; the boundary conditions and material properties are then extracted and assigned to the appropriate cells or elements.

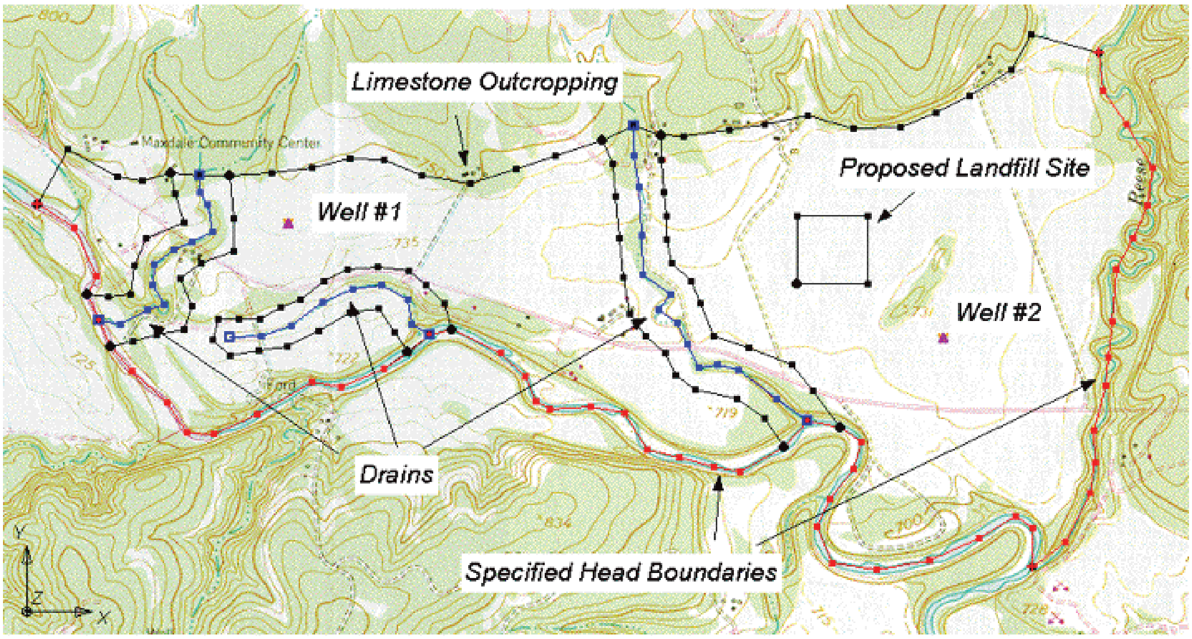
Setting up a conceptual model

Fig. 4.7.1 shows a sample conceptual model constructed in a map module and was installed as an overlay onto a scanned map that was imported and registered to the correct world coordinates. The objects in the conceptual model consist of sets of points, arcs, and polygons organised into coverages or layers.

Once the GIS objects are created, attributes are assigned to the objects. For example, for a drain arc, the conductance of the drain would be assigned to the arc and the elevation of the drain would be assigned to the endpoints (nodes) of the arc. The elevation would then vary linearly along the length of the arc.

This conceptual model approach has numerous advantages. The defining a model using GIS objects is faster and simpler than the cell-based approach, complex models being defined quickly and easily. Changes to the conceptual model can be made by changing or re-arranging the GIS objects and regenerating the grid data. As a result, numerous configurations of the conceptual model can be evaluated in the time normally required to perform a single simulation.

Figure 4.7.1. On a scanned, imported map of the area the various GIS objects are inserted and delineated by segmented contours (after: Maidment, 1997)

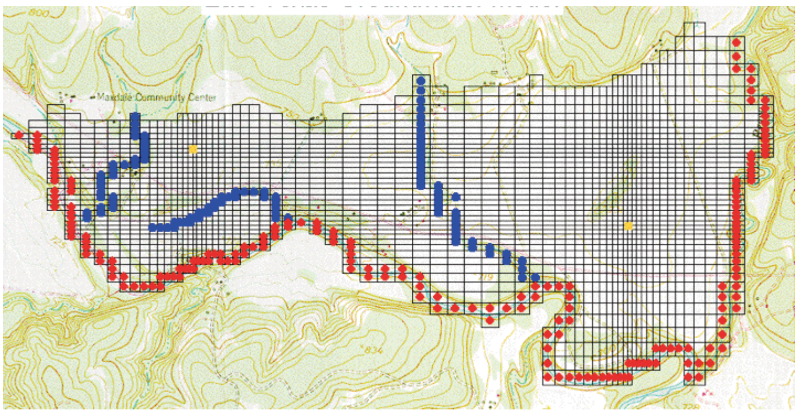


Converting the Conceptual Model

Once the conceptual model is constructed, the software automatically constructs a grid (Fig. 4.7.2). The spacing of the rows and columns in the grid is adjusted around the wells or other points where a large gradient in heads is expected and the cells outside the model domain are inactivated.

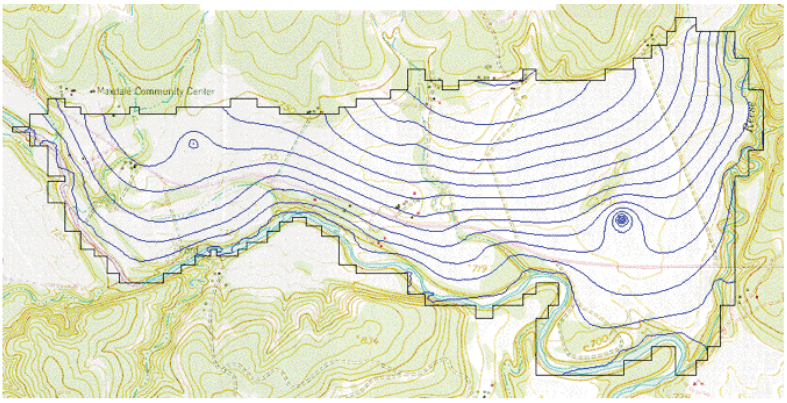
Finally, the GIS objects are overlaid on the computational grid and all stresses (rivers, wells, drains, generated head, constant head), recharge zones, hydraulic conductivity zones, etc. are automatically assigned to the grid cells in the appropriate numerical modeling format.

Figure 4.7.2. The outcome of iterated conceptual model runs, showing the relevant objects - no-flow boundaries (red), drainages (blue), wells (yellow) on a refined grid. This is imported into the simulation software (after: Maidment, 1997).



The conceptual model is converted to a grid-based numerical model. Once the numerical model solution is complete, the solution can be imported to the groundwater modeling system for plotting (Fig. 4.7.3)

Figure 4.7.3. The results of the simulation, in this case for the distribution of hydraulic head contours, are re-imported into the conceptual model software for visualization (after: Maidment, 1997)



Mathematical modeling of a groundwater system

Mathematical models are standard tools in providing a better understanding of the response of groundwater systems under natural or man-made stress conditions. At the base of a mathematical model is an appropriate conceptual model as described in the previous chapter; such conceptual models refer to

- input/output parameters
- physical and hydraulic boundary conditions
- intrinsic parameters of groundwater systems as well as
- natural (seasonal, global) and man-made changes (exploitation) of all these parameters in time and space.

Purpose of mathematical models

Mathematical models are based on mass and energy balances of the natural hydraulic system. They serve to

- steer field investigations for groundwater exploration,
- check the logic of field data sets through a sensitivity analysis,
- predict the future behaviour of the investigated system, undergoing hydraulic stress conditions,
- develop water management and protection strategies for such systems,
- provide an early warning tool for hydraulic systems with a transient response to stress situations, which typically occur during the intensive exploitation of groundwater resources in emergency situations (see chapter 6)

To achieve these objectives, a systematic feed-back between the development of the conceptual and mathematical model is needed to validate the mathematical model and, subsequently, good calibrations of the mathematical model to provide reliable predictions of the system's behaviour.

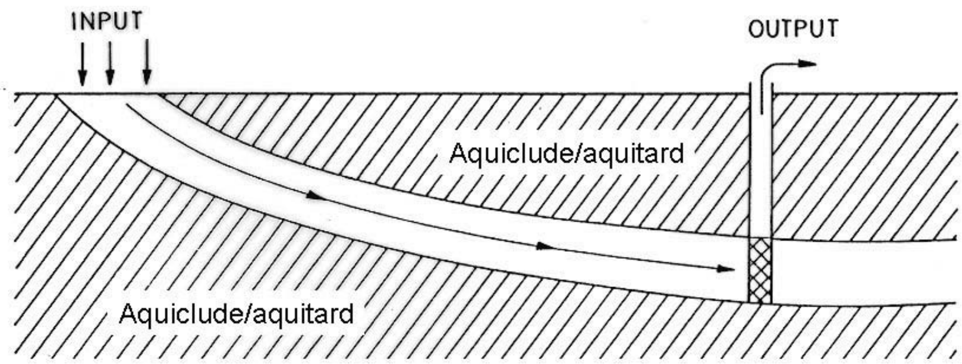
Since during an emergency hydraulic data is mostly scarce for a proper validation and calibration of mathematical models, the resulting predictions will entail considerable uncertainty. Constraints of early warning parameters are therefore needed, which allow overcoming the gaps in basic knowledge by repeated recalibration of the mathematical model with the monitored changes of the early warning parameters.

Types of mathematical models

Mathematical models balance the mass and energy transfer in a hydraulic system. They are based on bulk parameters (lump-sum-parameter models) or on a detailed parameter distribution in the hydraulic system (numerical models). Between both types of models there is a variety of transient models; one of these is compartment models, which do not provide as much detail as numerical models but much more than bulk-parameter models and may therefore be named multi-lump-sum-parameter models. The gap between bulk and detailed knowledge is often bridged by either geo-statistical methods or random parameter distributions (Monte Carlo approach), which both lead to different certainties/uncertainties for different parts of the groundwater system (see below).

- **Lump-sum-parameter models** (also named black-box or bulk-parameter models) have been developed in the early stages of hydrogeology as calculations of water balance or through-flow calculations in combination with water balances. They have been refined by Maloszewski and Zuber (1996) by introducing
- The **piston flow model** (Fig. 4.7.4), a simple or plug flow model, which does not consider any longitudinal or transverse mixing; the boundary conditions of this type of model rarely occur in nature.

Figure 4.7.4. Boundary conditions for the piston flow model (Maloszewski and Zuber, 1996). A thin aquifer occurs between two aquicludes or aquitards.



- The **exponential model** (Fig. 4.7.5), which is based on an exponential age distribution in the groundwater system and on groundwater recharge occurring all along the catchment surface, hence water ages always start with zero. This model may be considered a multi piston flow model, because it does not allow any transverse mixing.
- The **dispersion model** (Fig. 4.7.6), which is an extension of the exponential model, allowing a transverse mixing and starting with water ages older than zero.

All these models have been extended to further boundary conditions, which, however, rarely occur in nature like those of the linear model. Often a combination of different lump-sum-parameter models is used by introducing weighting factors, assigning a weight to each model.

Figure 4.7.5. Boundary conditions for the exponential model (Maloszewski and Zuber, 1996). An unconfined aquifer occurs above an aquitard or aquiclude. Groundwater recharge typically occurs over the entire surface of the aquifer.

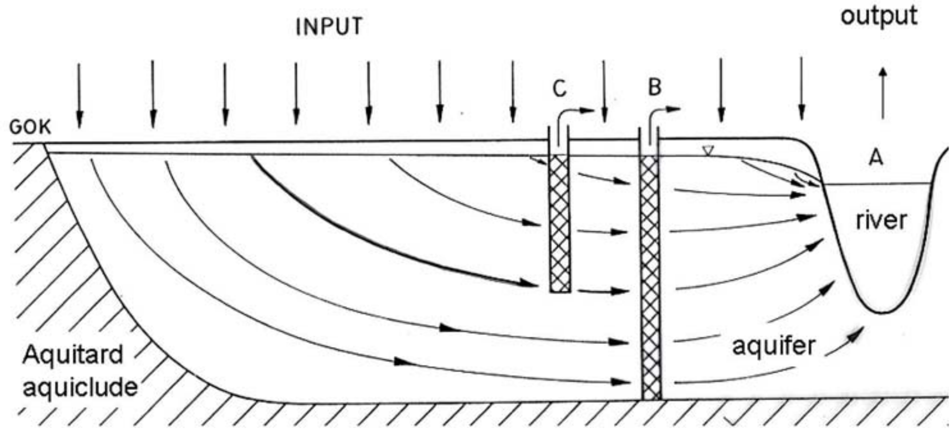
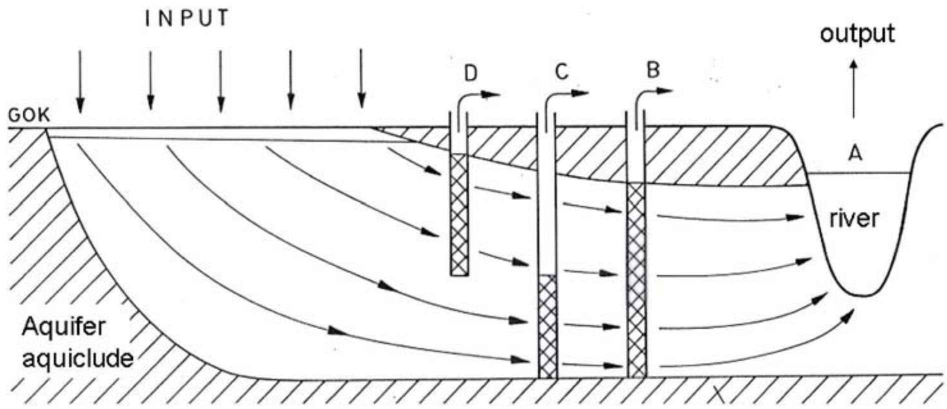


Figure 4.7.6. Boundary conditions for the dispersion model (Maloszewski and Zuber, 1996). An aquifer occurs above an aquitard or aquiclude and is partially overlain by another aquitard or aquiclude. Groundwater recharge occurs only along the outcrop of the aquifer.



All these models converge for low mean residence times (less than about 2 years) and deliver quite different results for aquifers with high mean residence times as is often the case for emergency aquifers.

In contrast, **numerical models** are based on a grid of nodes, each with known hydraulic conductivity and hydraulic head and groundwater recharge along the boundaries of the system. They balance the in- and out-flows at each node applying the

Stream function
$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \cdot or \cdot S_0 \frac{\partial H}{\partial t} \qquad (4.7.1)$$
(steady state or transient)

Potential function
$$k_x \frac{\partial^2 H}{\partial x^2} + k_y \frac{\partial^2 H}{\partial y^2} + k_z \frac{\partial^2 H}{\partial z^2} = 0 \cdot or \cdot S_0 \frac{\partial H}{\partial t} \qquad (4.7.2)$$
(steady state or transient)

where v=flow velocity, k=hydraulic conductivity, H=hydraulic head, S_0=specific storage coefficient. There are two frequently used options to solve these differential equations, either by applying the finite difference or the finite element method. Finite difference methods mostly refer to a node net with fixed separation, in contrast to the finite element method that is more flexible with respect to the distances between the nodes and is usually employed. With the present computer capacities such models can run on PCs.

Groundwater modeling is also often linked to a Monte Carlo approach to better differentiate between most probable and random results. This approach is based on a range of boundary and intrinsic data uncertainties.

In an upgrade, the numerical model may be combined with hydrodynamic dispersion (Fried, 1975), on reactions - physical, chemical (Merkel and Planer-Friedrich, 2002) as well as microbial and the development of microbial habitats of specific solutes and the respective kinetics to simulate groundwater quality

$$D_L \frac{\partial^2 C}{\partial x^2} + D_{Ty} \frac{\partial^2 C}{\partial y^2} + D_{Tz} \frac{\partial^2 C}{\partial z^2} + v \frac{\partial C}{\partial x} \pm R \pm a \frac{\partial Si}{\partial t} \pm b \frac{\partial \mathrm{Re}}{\partial t} = \frac{\partial C}{\partial t} \qquad (4.7.3)$$

where D=hydrodynamic dispersion in x- (L), y- (T_y), z- (T_z) direction, C=concentration, R=retardation, Si=sink-or source term, Re= reactivity.

The mathematical development of water quality models is quite advanced; however, data sets on retardation and chemical reaction kinetics often do not adequately satisfy model requirements. A special problem is posed by microbial kinetics, which differs according to the developed habitat and is highly scale related.

In conclusion, the importance of obtaining in situ observational data for the (ongoing) calibration of a conceptual and mathematical model should once again be stressed. Groundwater monitoring networks need to be established for producing updated data on the hydrological behaviour of the system as well as its evolving hydrochemistry, or quality.

4.8 Geographical information systems (GIS)

Wim van der Linden

The locations of boreholes, water supply wells, rainfall stations, etc. are specified by their geographical coordinates and can be plotted on a map. GIS (Geographical Information System) was developed to present data obtained from such points and to facilitate the analysis and processing of geographically specified data.

A GIS can be considered as a combination of a database and software: the database stores the geographically defined information; the software helps to manage the geographical information and its attributes. Geographical information can be point, line or polygon data (so-called vector data) or can be raster data. The vector data contains the exact location of the connected information. The raster data presents the data in a grid in which each grid cell represents the property of the connected information.

Vector data represents the geographical information more accurately than raster data. The vector data will follow exactly the geographical position of the information, such as the location of rivers, boundaries of forests, etc. Raster data is very useful to store the information on a continuous surface and enables the calculation of e.g. the depth of an observed groundwater table below the ground surface.

Many references exist describing the properties of GIS. Good references to start with can be found on the Internet (see references).

The use of a Geographical Information System (GIS) is indispensable analysing groundwater and other relevant data and presenting it on groundwater, vulnerability and other types of maps. These days the execution of hydrogeological investigations without the use of a GIS has become almost unthinkable. Investigations into groundwater resources for emergency situations are not different and GIS will play an important role.

GIS assists the mapping of hydrogeological variables and enables the analysis or modeling of hydrogeological and other conditions. With a GIS it is possible to combine spatial data from different sources and at different scales, for instance information from field investigations and remote sensing.

An example is the combination of observed groundwater levels with a DEM (digital elevation model) constructed from SRTM ground elevations (see also chapter 4.6) to construct a water table map in areas where elevations of well collars are unknown (Fig. 4.8.1).

Another example is the application of remote sensing radar observations (see also chapter 4.6) to identify lineaments or to estimate differences in soil moisture to map the spatial distribution of groundwater availability (Fig. 4.8.2).

With a GIS it is also possible to derive a new thematic map from existing maps. Such map overlays can be done using polygon or raster data types. An example is the combination of maps on land use, pollution sources, soil, geology, and groundwater depth to derive a groundwater vulnerability map. Another example (Fig. 4.8.3) is the overview made for UNHCR of conditions at existing or proposed locations of refugee settlements (Beaudou, 2003).

A GIS may be 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.

Figure 4.8.1. Example of a DEM constructed from SRTM ground elevations in the Himalaya area (Source: Internet)

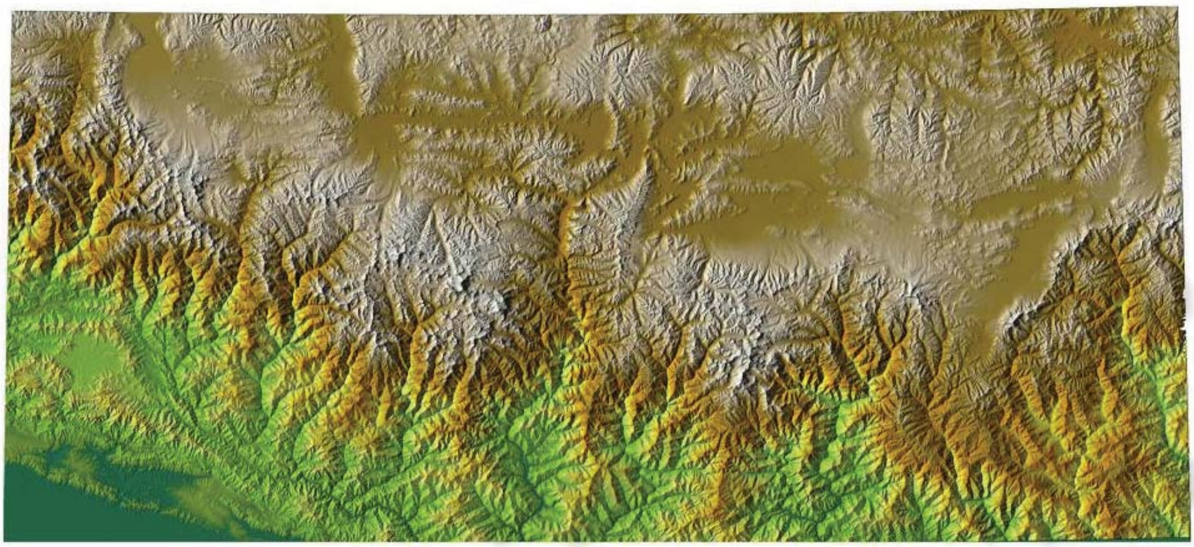


Figure 4.8.2. Example of a map derived with remote sensing radar technology indicating potential groundwater sources (source: UNOSAT)

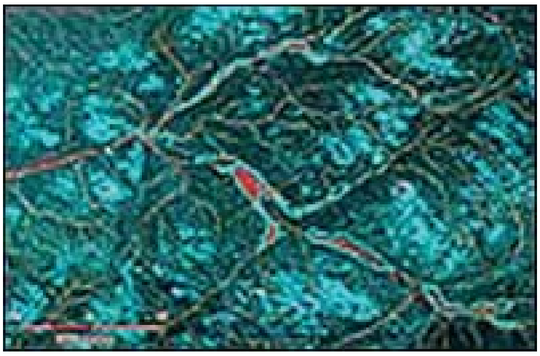
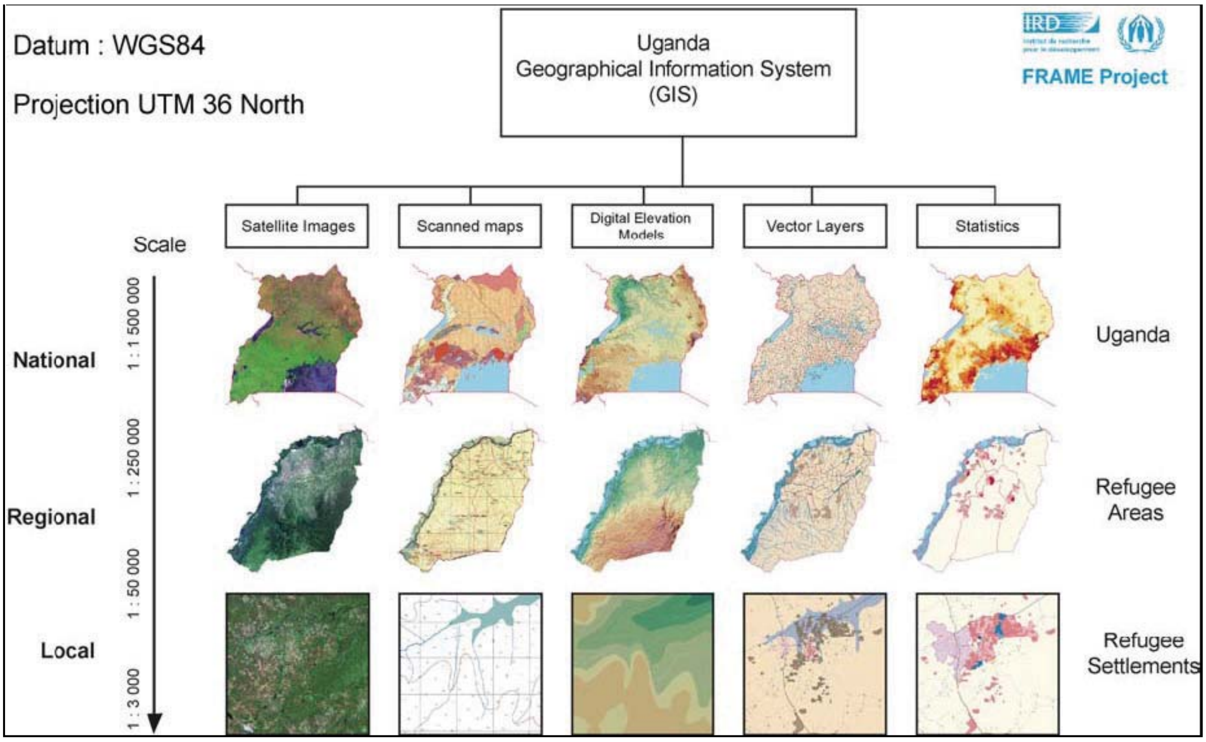


Figure 4.8.3. Example of GIS maps combined to analyse locations for refugee settlements (Source: Beaudou, 2003)

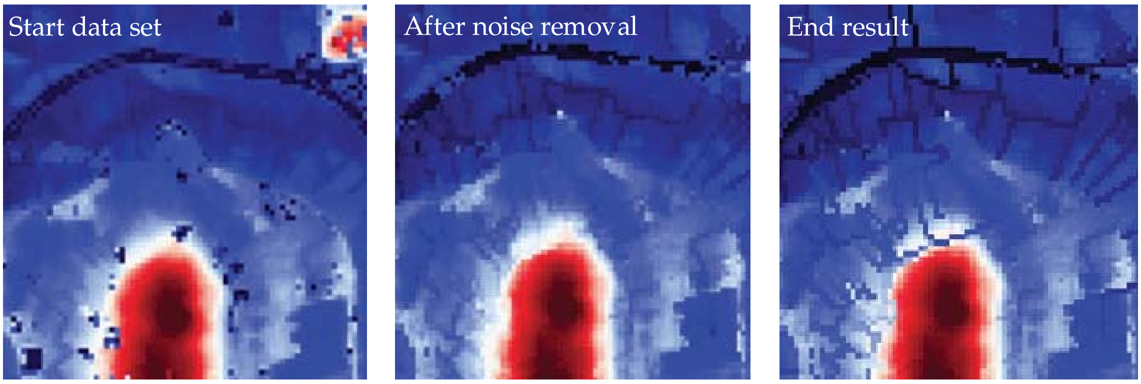


One of the strengths of GIS is the capability to process huge amounts of geo-referenced data – data from thousands of point locations can easily be processed (Fig. 4.8.4). A GIS is very useful too in plotting on a map locations obtained using GPS equipment. Spatial statistical methods, like Kriging, are a feature of most GIS and can be applied to interpolate physical parameters, such as the surface elevation or aquifer thickness

Today a hydrogeological information system based on a GIS with database is an open system tailor-made for the storage and processing of data. Routines for e.g. data exchange, data verification or data presentation in graphs, tables or maps are added to the information system using standard software.

This has improved the accessibility to and exchangeability of hydrogeological data tremendously.

Figure 4.8.4. 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 artificial objects (e.g. buildings) and to correct for the location of surface water (using a surface water lines data set)



The use of a 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 SRTM data and satellite images (Box 4.8.1, Fig. 4.8.5).

Box 4.8.1

Obtaining up-to-date information using GIS and Internet technology. The 2004 tsunami as example

The first information on the tsunami appeared on the USGS internet-site. Within minutes the location and magnitude of the earthquake was published. However information on the extent and size of the tsunami generated by the earthquake only became clear once satellite images of the affected coastal zones became available on the Internet. This was within a few days and provided a detailed overview of the extent of the disaster. Combining the satellite images with data on land elevation from the Shuttle Radar Topography Mission (SRTM) provided early estimates of the coastal zones potentially affected.

The map and image data were disseminated rapidly using Internet-GIS technology making it possible for a worldwide audience to obtain an overview of the extent of the emergency situation. In the meantime authorities on the ground were struggling to contact the areas affected and in many areas it took several days until communication was established. Observations by survivors and aid personnel flown in by helicopters were extremely important to obtain first hand accounts of the situation on the ground.

The UN and donor agencies involved in disaster management and/or humanitarian assistance have organised a Geographic Information Support preparedness and emergency response. GIST members are technical experts, geographic information specialists and information management officers from UN and donor agencies.

The United Nations Office for the Coordination of Humanitarian Affairs (OCHA): http://ochaonline.un.org/index.asp) acts as the GIST secretariat.

Figure 4.8.5. Example of satellite images showing the effect of the tsunami (courtesy of Pacific Disaster Center)

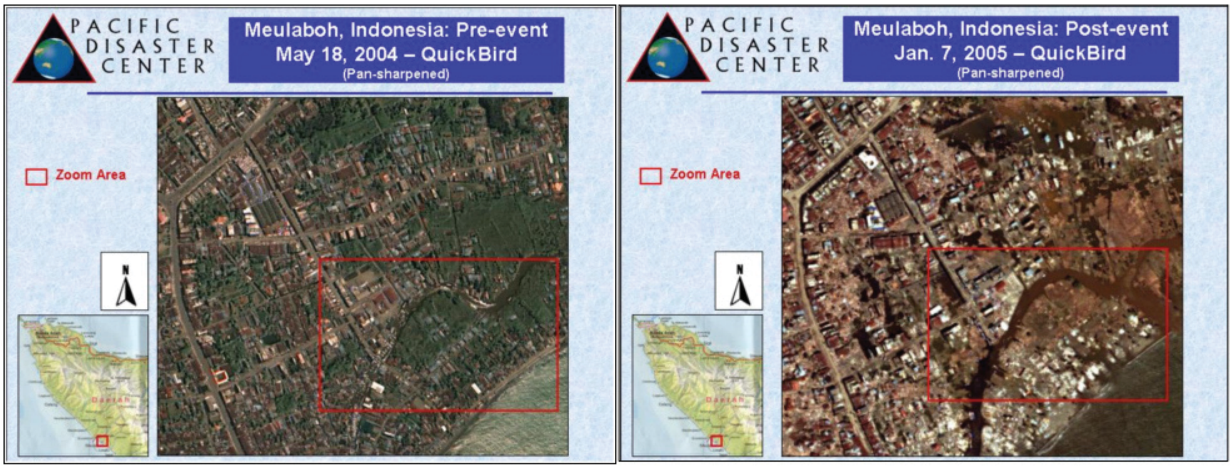
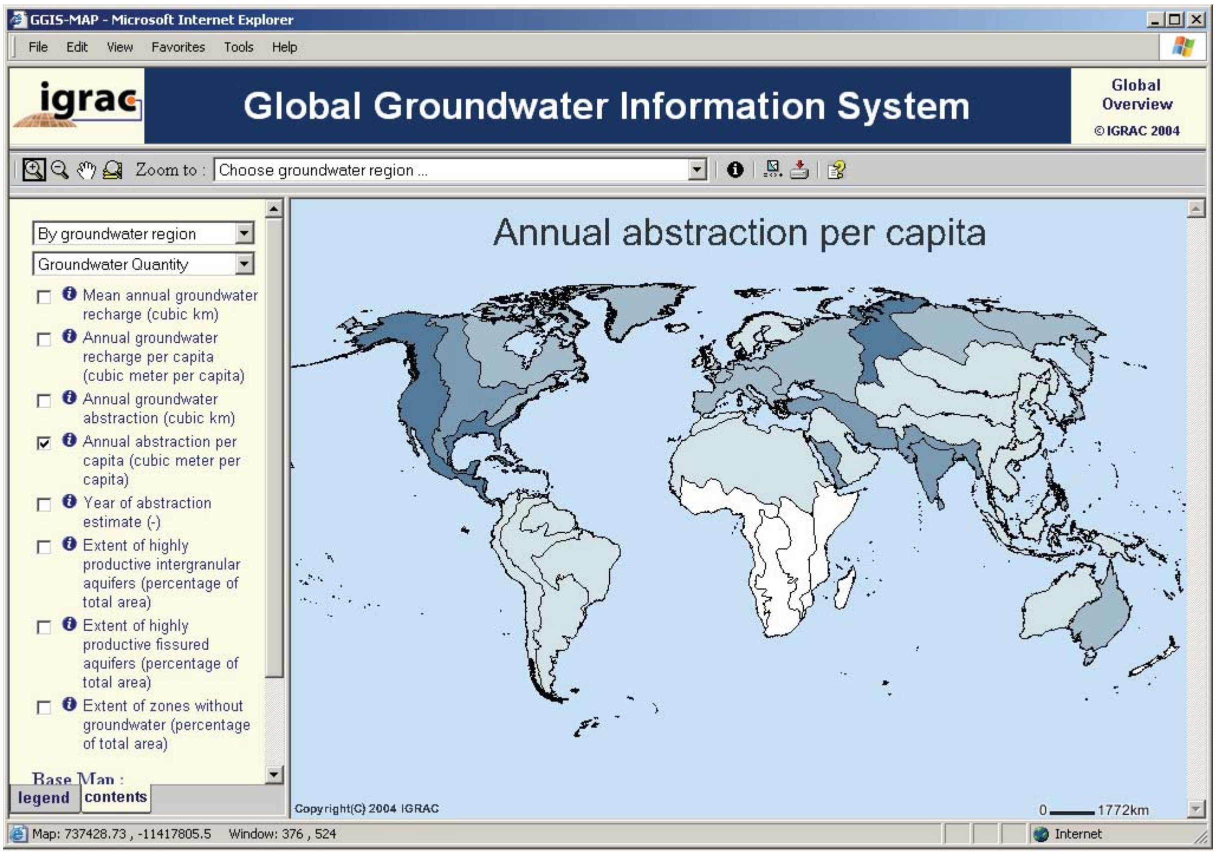


Figure 4.8.6. Example of Internet map viewer – Annual groundwater abstraction per capita (courtesy of IGRAC)



The development of GIS-technology allows users to access hydrogeological data at different levels. Users who only want to view and combine data, such as managers, use the GIS from the Intranet or Internet through a browser (Fig. 4.8.6). These 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 to international relief operations.

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 facilitate any investigation into the availability of groundwater resources in emergency situations.

Google Earth is an example of a successful Internet application available since 2005, which may be combined with a GIS. It comes in three versions: a free version with limited functionalities, Google Earth Plus with additional features and Google Earth Professional for commercial use. Google Earth enables the viewing of topographical and related information anywhere in the world.

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 and volcanic activities on groundwater resources; the mapping of land slides and their impacts on land use and water supplies and for a variety of other studies concerning groundwater resources used for emergency situations.

5. Risk assessment and management of groundwater resources in emergency situations

Introduction

Natural disasters, be they the result of climatic events such as droughts, floods or storms or geologic upheavals such as earthquakes and volcanoes invariably result in huge impacts on a population. These events may combine in landslides or tsunamis. Inevitably, there is loss of human life, and damage to infrastructure including private and public drinking water supplies. Such emergency situations call for the development of risk assessment and risk management water policy. The purpose of this chapter is to describe the main characteristics of different natural disasters, as well as risk assessment and risk mitigation and protective approaches to the management of groundwater resources which may be considered safe sources of drinking water for emergency situations. Such policy should provide for strategies or guidelines based on priorities in solving problems related to emergency drinking water supplies. High on the priority list is the identification, investigation, assessment and management of water resources resistant to natural disasters. The emergency guidelines for drinking water supplies should include preparedness and warning plans as well as short term relief and long term mitigation and rehabilitation measures based on available information or experience obtained during earlier events. It is well known that natural disasters are recurrent. Historical records are therefore an important tool in managing emergency water resources and estimate their recurrence period. Such data would be particularly useful in preparing vulnerability maps of areas or regions prone to particular types of disasters and their potential intensity. For each vulnerability map the boundaries of zones of differing disaster intensity should be demarcated so that such maps can be used even by laymen. A vulnerability map should be based on a hydrogeological map and enhanced by accompanying maps showing surface water/groundwater resources suitable for emergency situations. In addition, monitoring and early warning systems are useful particularly for areas prone to floods, droughts, volcanoes, and of tsunami including earthquakes that generate them. The operation of such systems allows for effective measures to be taken for reducing the vulnerability of water resources and the population, enhance their protection and formulate plans for timely evacuation of people and domestic animals from high risk areas.

The impact of natural disasters remains a significant challenge to sustainable social and economic development. Coping with disasters faces populations in many parts of the world. Building the resilience of nations and communities is the strategic goal set in the Hyogo Framework for action 2005–2015 (Hyogo Declaration, 2005). Securing drinking water for an endangered population is one of the highest priorities during and after disasters.

5.1 Groundwater risk assessment and management in flood-prone areas

Jan Šilar and Jaroslav Vrba

Introduction

Floods are the most frequent of all catastrophic events worldwide. They are caused most frequently by a coincidence of meteorological and hydrological circumstances but may be influenced also by geological and man-made factors. Between the years 1960 and 2005, there has been a significant increase in extreme water-related events, such as floods and storms. Many experts relate this increase in water related disasters to climate variability and change. According to the Centre for Research on the Epidemiology of Disasters in Belgium (CRED) about 80% of all natural disasters were of meteorological or hydrological origin in the ten-year period from 1996–2005. Between 2000–2004 (CRED 2005) 1,942 water-related disasters affected more than 1.5 billion people.

Floods: origin, types and impact on water resources

A flood is a temporary rise of water level in a stream caused by an abrupt increase of discharge, or by a temporary blockage by ice pack or landslide, resulting in flooding of banks and flood plains. Catastrophic floods result from meteorological situations such as floods along river tracts during hurricanes, linked to a geological setting as with tsunamis in unstable tectonic zones, or with landscape geomorphology, such as landslides damming a stream. Urbanisation changes rainfall-runoff relations through river bed re-routing and canalisation and increased runoff owing to decreasing soil retention capacity, expansion of paved areas and storm patterns (Keller, 1976).

Since prehistoric times populations have spread along streams in valleys, their water supply often depending on groundwater in shallow aquifers in flood plains (Fig. 5.1.1). The impact of floods on these aquifers is a phenomenon which depends on the stochastic characteristics of the floods. Water supply should therefore, take account of the probability of flood recurrence and impact. This is why in flood-prone areas the taxonomy and statistics of floods should be considered in groundwater studies and groundwater resources evaluation.

According to their origin, the following types of floods can be distinguished (Jeggle, 2005): marine, riverine, 'run off', low lying, wave and tidal, storm surge, and marine encroachment. The latter may be caused even by land subsidence and erosion along the coast. Floods of a longer duration (weeks or even months) caused by regional rains should be distinguished from flash floods which last 24 hours or less. Both types of floods often produce pollution of surface water and shallow aquifers. Flood impact on groundwater differs in humid and arid regions. In an arid environment, the surface water from a flash flood in a wadi infiltrates fairly rapidly in coarse sediments and can pollute the groundwater; in humid environments, with humic soil covers near field capacity, infiltration of possibly polluted flood water is much slower.

In some climatic zones, floods are a very regular phenomenon linked to heavy precipitation, e.g. in the tropical monsoon regions of South-East Asia. However, a flash flood can occur also due to the collapse of a lake impoundment by a landslide or a mountain glacier. Contemporary geological endogenic energy may also cause floods. Landslides triggered by an earthquake in Kashmir on 8 October 2005, caused damming and flooding of valley bottoms. Many water supply systems were destroyed in five districts in Pakistan and in three districts in India and 3.2 million people were affected (Berger, Olafsdottir, 2005).

Flooding intensified by sudden storm surges has been observed in many coastal regions. Floods can also cause tremendous damage to communities inhabiting dry wadi stream beds in arid regions.

Figure 5.1.1. View of the flood plain of the Labe (Elbe) River during the flood in August 2002 in the northern Czech Republic. Shallow water table aquifers in the fluvial deposits of the flood plain were polluted and several groundwater supply facilities in rural areas were damaged. (Photograph by Raudenský and Dorazil, 2002).

The intensity of changes in the climatic pattern and related influences on hydrological systems has undergone a notable increase. Examples of such changes are case histories of El Niño events which occur with considerable regularity in Peru, along the Pacific coast. The 'Servicio Nacional de Meteorología e Hidrología' in Perú registered 18 heavy El Niño rains events in the 20th century. The most recent in 1997–98 caused damage to water infrastructure, collapsed water supplies and sewage systems causing groundwater pollution, damage to water-supply wells, and silted up reservoirs. However, positive effects were also noted: a large lake was produced in a former desert area in northern Peru which resulted in increased surface water storage and the recharge of aquifers (chapter 11.7, Molina, 2006).

Floods have occurred throughout geological history. Radiocarbon dating of fluvial sediments of the Labe (Elbe) River in the Czech Republic suggests several abrupt changes in temperature and precipitation during major Holocene climatic events. These may be correlated with events globally, as suggested by studies of Holocene floodplains in other regions worldwide (Jílek et al., 1995).

Probability and recurrence of floods

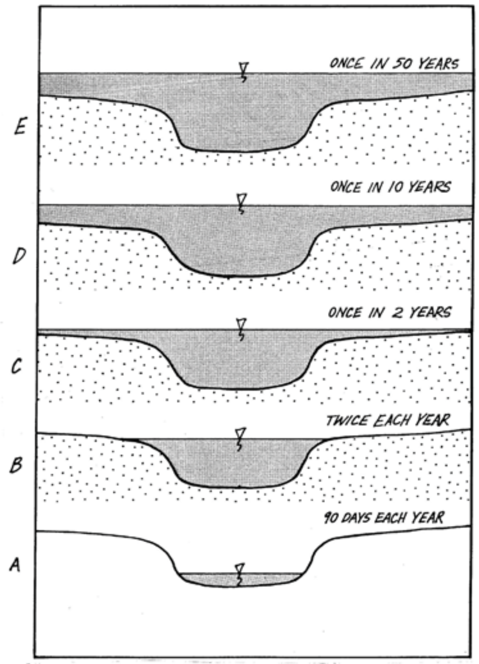
The probability of occurrence of a flood with a certain discharge is expressed as its recurrence interval T in years. This is the average number of years during which an event of a given magnitude may be expected to occur once, and it is computed according to the equation (Butler, 1957)

$$T = \left(\frac{1}{F}\right) \cdot 100 \qquad (5.1.1)$$

where F is the flood recurrence frequency per 100 years. In other words: if the length of the monitoring period is 100 years and the number of occurrences of a certain culminating discharge during floods within this period is 5, then the recurrence interval T in years (or return period) of such a flood is 20 years. This expression, however, does not mean that the flood would repeat only after 20 years. It only denotes its probability. The frequency of hydrological phenomena is a matter of statistics. An introduction to hydrological statistics and calculation of the recurrence intervals may be found in e.g.

Butler (1957), Ven Te Chow (1964), Manning (1987, Fig. 5.1.2). The devastating effects of different flood disasters may be similar, can combine, and may endure from one into the other.

Figure 5.1.2. Water levels of different recurrence intervals in a stream (Manning, 1987)

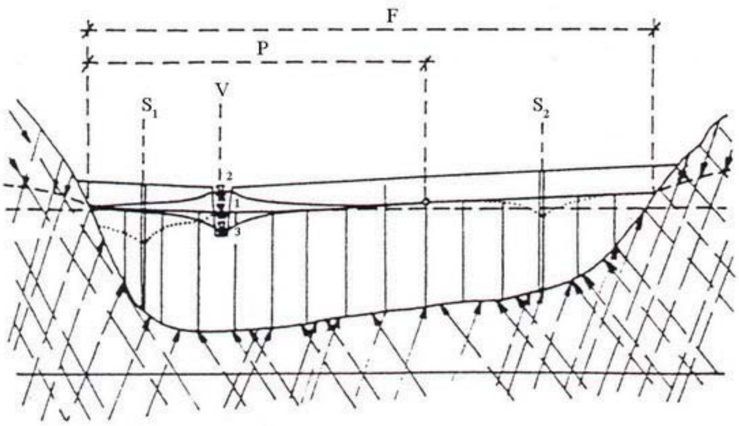


Groundwater emergency resources in regions affected by floods

The search for emergency groundwater resources in regions repeatedly affected by floods requires knowledge of the geological and hydrogeological setting of the affected region. Generally, the deep-seated mostly confined aquifers in sedimentary basins with renewable and non-renewable groundwater are resistant to flood impacts and a safe emergency source of drinking water. Groundwater vulnerability to floods is most pronounced in shallow aquifers which are in hydraulic contact with rivers and other surface water bodies (Fig. 5.1.3). Such shallow aquifers in fluvial deposits of flood plains are often major sources of groundwater for drinking water supplies, irrigation and other purposes. However, they are highly vulnerable to flood events and cannot as a rule act as a safe source of drinking water in emergencies. There have been reports of flooding and pollution of wells situated in shallow aquifers hundreds of metres or even kilometres from river banks. Wells may also physically be damaged by floods along with water distribution pipelines. Nevertheless, shallow aquifers are technically and economically the most accessible sources of drinking water and are often tapped by hand dug wells or shallow drilled wells for domestic or public water supplies of local communities, even where groundwater quality does not quite conform to drinking water standards. Some shallow aquifers could be exploited in emergencies, as they may be protected from pollution by an overlying impermeable clay layer. In the case of the 2004 Indian Ocean tsunami for example, groundwater in the shallowest part of coastal water table aquifers was polluted by infiltration of marine water during the transgression. But groundwater from deeper levels of the same aquifer, when tapped judiciously, could be used as a source of drinking water without producing up-coning of the underlying brackish water (Keshari et al., 2006). Pumping rate has to be carefully controlled, however, and be commensurate to aquifer transmissivity and storage.

Substitute emergency drinking water resources may also be found in springs on slopes beyond alluvial

Figure 5.1.3. The relation of groundwater in fluvial deposits to the water in a stream. Bank infiltration may be induced from the river when pumping rate from the well S_1 is not controlled. The well S_2 pumps groundwater from the water table aquifer. If the surface of the river plain is flooded, conditions for pollution of such type of aquifer (F) occur. (after Hynie, 1961).



plains and in alluvial fans at the foot of slopes. Ancient populations of the arid regions in the Middle East developed groundwater resources in sloping alluvial foothills by constructing qanats also called kanat, foggara, or rhettara in Morocco or karez in Baluchistan. These are subsurface galleries or tunnels driven to below the water table and channelled downwards to the ground surface with a gradient somewhat less than that of both the groundwater table and the ground surface (Sine, 1974). Present-day development and vulnerability assessment of such groundwater supplies should take account of their infiltration area in relation to areas of flooding. Qanat-capturing systems are also vulnerable to human impacts, particularly to agricultural groundwater pollution. Highly productive aquifers in karst regions located beyond flood plains are also vulnerable to natural and human impacts and therefore, often not a safe source of drinking water in flood-related emergency situations.

The vulnerability of groundwater is related to its residence time. Generally, the longer the residence time (or age) of groundwater, the lower its vulnerability. The thickness and permeability of the unsaturated zone and groundwater level below ground are also important attributes in the assessment of groundwater vulnerability to floods.

Vulnerability of the population and ecosystems to floods

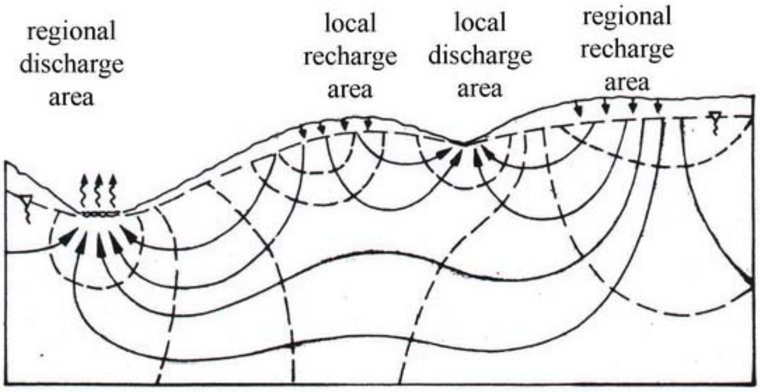
The suspension of water distribution and water supplies after a disastrous flood events affects the population's access to drinking water, especially in rural areas dependent on domestic wells. The rapid substitution of damaged water supplies is therefore, a very urgent task. However, emergency groundwater resources have often not been identified and drinking water has to be imported to the affected region in tankers, as bottled water, or through construction of provisional pipelines at great cost and inevitable delays. The knowledge of regional hydrogeological conditions and advance investigation, evaluation and development of potential emergency groundwater resources in areas repeatedly affected by flood events are therefore, key attributes in drinking water risk management in flood-prone areas. Such water policy significantly reduces a population's vulnerability and secures rapid access to safe drinking water sources in emergency situations. However, such governmental policy has not yet been developed in many countries. Account has to be taken of economic and demographic issues, legal framework, land owner aspects and cultural, religion and historical traditions of the society. In the absence of such institutional, legal and technical measures, emergency plans for drinking water import based on logistic facilities (access roads, suitable airports, ports, railways and available transport capacity with respect to emergency water demand in different localities) have to be developed.

Worldwide, local and regional **ecosystems** are harmed through flooding, large-scale erosion and flood related water and soil pollution. Changes in ecological systems of aquatic animals and plants along streams and riparian zones can be rapid and may result in large changes on a regional scale. An example is the estuary of the Huang He River (the Yellow River) in China that shifted from south of the Shangdong Peninsula in 1852 to north of Shangdong (Metelka et al., 1924). The entire stock of a pearl mussel farm was washed away during the catastrophic floods in the Czech Republic during August, 2002.

Resistance of groundwater resources to floods

When considering flood-resistant groundwater resources as a substitute for damaged or polluted water supply systems, the overriding consideration is the safety of the drinking water produced or possibly its treatment using simple techniques. Such safe groundwater resources, renewable and non-renewable, can be found in 1/ confined aquifers with a piezometric surface above ground level, the hydraulic pressure and overlying confining bed preventing the intrusion of surface water and pollutants 2/ aquifers overlain by rock formations of low hydraulic conductivity and permeability which inhibit river-bank infiltration of surface water, and 3/ groundwater flow systems with a

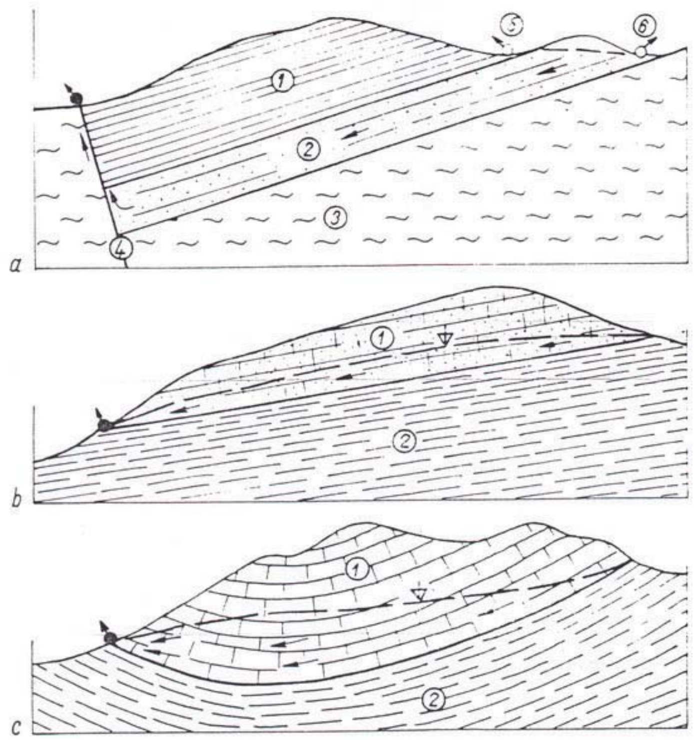
Figure 5.1.4. Groundwater flow net in a vertical section through an inclined rolling landscape. Full lines: groundwater flow lines; dashed lines: equipotential lines. It is evident that even in unconfined aquifers an upward flow of groundwater can occur.



hydraulic potential increasing with depth, i.e. with a natural upward flow. The hydraulic potential gradient in discharge areas impedes the intrusion of surface water and pollution (Fig. 5.1.4).

Springs occurring along foot hills may be used for emergency water supply for populations of flood plains. However, their hydraulic conditions and origin should be considered and carefully evaluated (Fig. 5.1.5). For emergency water supply, ascending springs are most suitable because groundwater is protected by impermeable layers from direct contact with the surface while descending springs are less suitable because of their usually short residence time and fluctuating yield. Contact and fissure springs are a suitable source for emergency water supplies too (Fig. 5.1.6). The considerable vulnerability and very variable yield are the main disadvantage of karst and talus springs.

Figure 5.1.5. Springs in different groundwater flow conditions

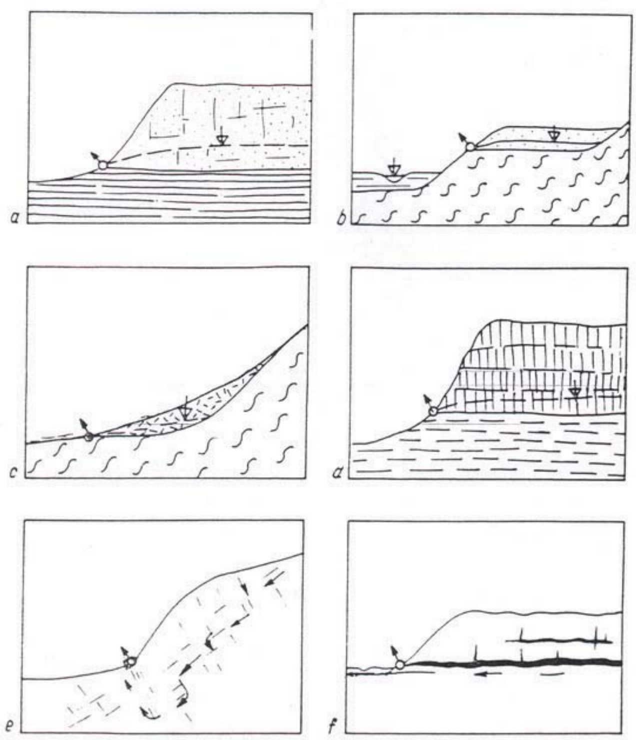


a) ascending spring:
   1 - impermeable marl,
   2 - permeable sandstone,
   3 - impermeable gneiss,
   4 - permeable fault,
   5, 6 - intermittent springs

b) descending spring:
   1 - permeable sandstone,
   2 - impermeable marl

c) overflowing spring:
   1 - permeable limestone,
   2 - impermeable shale.

Figure 5.1.6. Springs in different hydrogeological settings

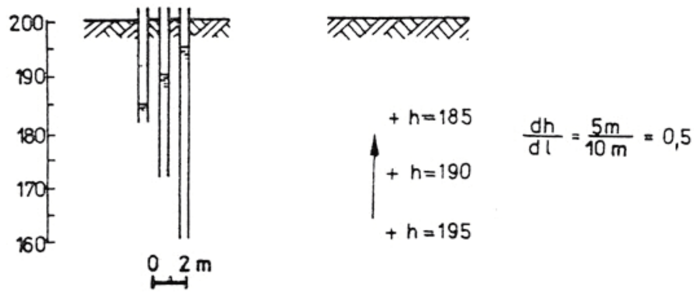


a) contact spring in permeable sandstone overlying impermeable bedrock,
b) contact spring in fluvial deposits of river terrace overlying impermeable bedrock,
c) talus spring in talus deposits overlying impermeable bedrock,
d) contact spring in a fissured lava flow overlying by an impermeable layer of volcanic tuff,
e) fissure spring along a fractured zone in igneous or metamorphic rocks,
f) karst springs in karstified limestone.

Identification and investigation of emergency groundwater resources

A first and essential step in identifying and investigating an emergency water resource is to become acquainted with accessible geological publications and file reports related to the study area, as well as topographic and geological maps, in addition to hydrogeological, vulnerability and groundwater chemistry maps if these are available. When drilling exploration wells the changes of water level in the boreholes can be used for determining the gradient of hydraulic potential and thus estimating the vertical component of the groundwater flow (Fig. 5.1.7). Drilling crews should be instructed to measure the groundwater level and its changes as drilling progresses. An upward directed flow of groundwater may be visible in a field investigation and mapped e.g. ascending springs, the presence of wet spots in otherwise dry ground, phreatophytic plants, or increased groundwater temperature.

Figure 5.1.7. Increase of hydraulic head with depth in a group of closely spaced boreholes indicates an upward component of groundwater flow. Vertical scale at the left: elevation in m a.s.l. (modified after Freeze and Cherry, 1979).



Groundwater data is usually collected by national institutes responsible for water-related monitoring networks and by water supply companies, and supports the study of the groundwater system and regime. A hydrocensus of existing water supply wells, monitoring boreholes and springs should be conducted and the acquired groundwater quantity and quality data collated, processed and stored. The Geographical Information System (GIS) is the most suitable framework for the assessment and management of geo-hydrological, climatological and other relevant data (see chapter 4.8). An assessment of the quantity and quality of the groundwater resource suitable for emergency supply is usually based on the hydrologic budget of the aquifer unit, hydraulic models of groundwater flow, calculation of aquifer storage capacity and analysis of groundwater chemistry. However, the outcome of groundwater resources assessment depends on the availability and quality of groundwater data and the degree to which aquifers and their recharge areas are spatially defined. Stream flow data, particularly the identification of gain and loss sections of the stream and calculation or qualified estimate of total groundwater discharge to streams and from springs is desirable as it affects the exploitable amount of emergency groundwater resources. Radon measurements can be applied in tracing groundwater inputs to stream flow. The identification of the origin and age of groundwater by isotope analysis supports the assessment of the vulnerability of groundwater resources to flood events. It also plays an important role in the formulation of flood risk assessment and management of emergency water resources. The methods of isotope hydrology are explained in more detail in chapter 4.4.

Compiling hydrogeological and groundwater vulnerability maps is another step in the investigation of emergency resources. Maps based on field investigations and groundwater data evaluation depict groundwater bodies, groundwater flow direction and other groundwater characteristics along with groundwater vulnerability attributes (see chapter 4.2). Such maps of flood-prone and surrounding areas are useful tools for policy makers, planners, water managers and local communities. Vulnerability maps depict and delineate inundation areas, the morphology of the flood plains, existing water supplies and water distribution networks. They show also existing and potential sources of pollution, classified with respect to their origin, chemical and physical type, mode of pollution discharge (hidden and surface leakages) and their extent (point, diffuse). The maps also pinpoint proposed new wells for drinking water supplies during and after flood emergency.

Flood-related risk assessment, mitigation and management of groundwater

Risk assessment is the necessary basis for the formulation of disaster mitigation measures. The disaster risk is expressed as the product of hazard and vulnerability, i.e. Risk=Hazard x Vulnerability. In populated regions economic and social aspects have to be considered and risk is determined from the product of the probability of occurrence and the degree of economic and social vulnerability in monetary terms (UN ISDR methodology): Risk (economic cost per year) = Probability (once in n years) x Vulnerability (economic cost/event). The frequency and magnitude of flood events and their potential damage to the population, environment, ecosystems and infrastructure (specifically water infrastructure) have to be identified and evaluated with respect to the various flood scenarios and population vulnerability. The potential risk of flood events on existing water supplies and sanitary facilities needs to be carefully assessed.

Risk mitigation encompasses structural and non-structural measures for limiting the adverse impacts of flood hazards or disasters. The risk mitigation framework includes 1) assessment of the risk presented by flood hazards to groundwater resources and the population, 2) evaluating the potential flood impact on drinking water sources based on investigation outcomes and vulnerability mapping, 3) education and training of rescue and other professional teams entrusted with the risk mitigation and management of disasters, and 4) the formulation and implementation of groundwater protective measures regarding the geographic layout of the area likely to be inundated; also, its integration in land-use planning and specifying technical measures to protect existing water supplies (e.g. securing water supply wells against inundation) and sanitation facilities. A participatory approach should be adopted to mitigate the risk of floods that will involve policy makers, planners, water managers and stakeholders, and local communities.

Risk management is based on the systematic application of policies, procedures and practices that seek to minimise flood disaster risks at all levels and locations in a given society and on a comprehensive strategy for increased awareness, assessment, analysis/evaluation, mitigation and management measures (Sine, 2004). Risk management of emergency groundwater resources is an inseparable part of flood risk management procedures and has to be integrated with land use planning, based on multi-sectoral governance water policy and public participation in the allocation, construction and protection of emergency drinking water supplies.

Risk assessment, mitigation and management procedures are supported by legal provisions and existing appropriate institutional structures at all levels as well as by capacity building systems for involvement, information and education of the population. The scope and responsibility of the above mentioned governance structures is to minimise flood impact and maximise flood preparedness and warning effectiveness, and to manage the operation of emergency drinking water supplies or rehabilitation of damaged water and sanitary facilities. Floods cannot be prevented but their damage can be effectively controlled. The following activities are highlighted with respect to risk assessment, mitigation and management of flood impact on water resources and water supply facilities.

Risk assessment and mitigation of flood impact on drinking water sources include: 1/ identification and assessment of the flood risk to and vulnerability of existing public and domestic water supplies, 2/ calculation of water demand of the population living in areas potentially affected by floods, including hospitals and other medical facilities and food requirements dependent on high quality water, 3/ designation of groundwater supply sources (quantity and quality) secure against flood impact, which can be used during and after the flood until the restoration of damaged or polluted water supplies, 4/ construction of vulnerability maps depicting inundation and other vulnerability areas as well as aquifers resistant to flood impact, 5/ drilling and testing of new emergency wells located away from potential inundation areas, and 6/ informing the population about the allocation of emergency water sources and formulation of the rules governing their use and distribution during flood events.

Monitoring and early warning programmes (both hydrological and climatic) are other important components of risk assessment and risk mitigation activities. Monitoring and early warning data gives advance warning of a flood events, helps to control and mitigate their impact and formulate measures for water supply protection. However, groundwater monitoring and early warning programmes geared to observing aquifers resistant to flood impact are rare at present. Particularly in less developed countries, there is not enough hydrogeological knowledge nor evidence about the occurrence of such aquifers or financial resources for their investigation and monitoring are scare.

Risk management of drinking water supplies during and after flood events, is focused on the assessment of the physical damage to public water supplies and domestic wells and their water quality, and on immediate internal and external help in distributing drinking water. Flooded domestic wells have to be temporally closed to prevent serious infectious diseases. The need for their rehabilitation immediately after flood events is stressed. Also to be considered are the human, equipment and financial resources available, and the time needed for the reconstruction of water facilities and water pollution remediation. In flood-prone regions where emergency water resources resistant to floods have already been identified, assessed and developed distribution of drinking water will be rapid and effective. However, in many regions the absence of hydrogeological knowledge severely delays drinking water availability. Water has to be imported, either bottled, or by mobile tankers from surrounding regions not affected by flood. These temporary measures are expensive and emphasise the population's helplessness and dependency on outside help.

Based on a previous evaluation of flood impacts on drinking water supplies institutions responsible for the management of emergency groundwater resources have to repeatedly re-evaluate flood risk mitigation plans, update risk and inundation maps and land use plans and more precisely formulate risk management and protection policy for emergency groundwater resources.

Role of governance policy in flood risk mitigation and management of emergency groundwater resources

The random characteristics and occurrence of catastrophic flood events, requires the preparation of the population particularly in regions where floods occur frequently. Preparedness is stressed in view of the increasing frequency of disastrous flood events linked to climate variability and change. Past events are usually recorded and evaluated by river basin authorities in cooperation with national hydrological services. Historical information and personal accounts of past events of contemporaries should also be recorded before memories fade. An assessment of the potential impact of catastrophic floods on water supply and sanitation facilities and the formulation of risk management strategy for emergency water resources is a matter of water governance emergency policy (chapter 7). This involves all actors (governmental institutions at all levels, rescue teams, water management authorities, water stakeholders, local communities) that have to take common responsibility for protection and management of emergency water resources in flood-prone areas.

If planned and prepared well in advance, activities related to mitigation of flood impact and management of emergency groundwater resources described in this chapter should be effective. Jegle (2005) pointed out that the most important aspects of effective disaster risk management are those activities that are undertaken and pursued precisely when there is no disaster. Moreover, it should be emphasised to the politicians of the day that the mitigation of the consequences of flood disasters is their responsibility and that they should approve and allocate the required financial support (Němec, 2006).

5.2 Drought: identification, investigation and risk management of emergency groundwater resources

Balt Verhagen

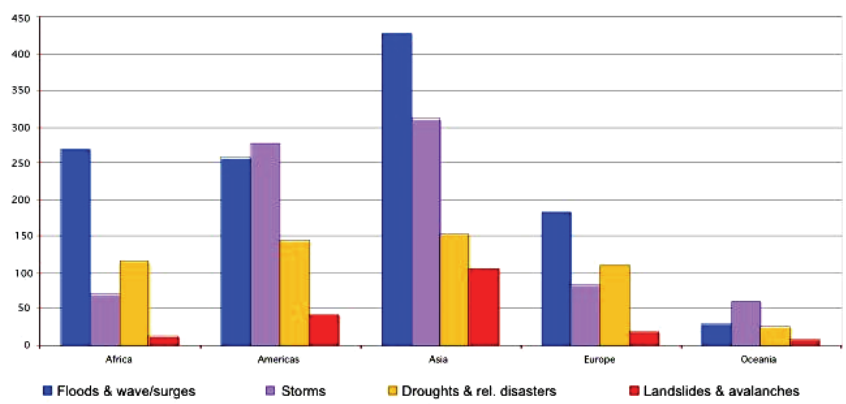
Introduction

A hazardous drought results in severe shortage of water supply causing crop failures, and in extreme cases famine, starvation, and the migration of people and livestock. Droughts, like floods, tend to recur in certain areas of the globe due to their geography and atmospheric circulation patterns. One of the better known global drought linkages is the El-Niño-Southern Oscillation (ENSO). Some of the more obvious regions frequented by droughts are countries in sub-Saharan Africa, in the Middle East and many South Asian countries where the monsoon periodically fails. Drought, and problems with its management, is responsible for degradation and desertification of nearly a third of the world's arable land.

A clear appreciation of aspects of drought mitigation and in particular the role of groundwater – the subject matter of the GWES project – could change when new information on further instances of drought and its effects comes to hand.

Drought ranks about equally amongst other natural phenomena that may constitute disasters in all environments and climates (Fig. 5.2.1).

Figure 5.2.1. Great natural disasters 1950–1999 (Vrba and Verhagen, 2006). Note: similar prominence and occurrence of drought in all continents



Unique aspects of drought, as opposed to other emergencies

Drought emergencies tend to differ from other emergencies (e.g. floods, earthquakes) in the rate of their onset, duration and knock-on effects. The two terms: drought and aridity (Fig. 5.2.2) should be separated explicitly:

- Drought is a recurrent natural climatic event, experienced in all geographical zones, but its characteristics vary significantly from one region to another,
- Aridity (low annual rainfall) is a perennial condition of a geographic region, which can experience periods of more extreme aridity, or drought.

Operational definitions of drought

- **Meteorological drought:** Every drought event effectively results from the lack of precipitation. Depending on its duration and intensity, meteorological drought may or may not develop into an agricultural or hydrological drought;
- **Agro-meteorological (agricultural) drought:** An agricultural perspective on water shortages. Natural vegetation may not yet show moisture deficit stress but root-zone soil moisture is insufficient to sustain crops between rainfall events in dryland agriculture;
- **Hydrological (flow and groundwater) drought**: Impacts on hydrological systems are referred to as 'flow drought'. 'Groundwater drought' – lagging behind the deficient precipitation - is a rather subjective and vague concept often due to the lack of long-term data on e.g. groundwater levels;
- The **response of groundwater to meteorological drought** is poorly understood, and may be out of phase with other impacts, due in part to the unique complexity of hydrogeological systems (SADC 2003a).

Impact of a meteorological drought

- **Severity and duration of the drought episode**. If groundwater responds slowly to rainfall deficit it generally also recovers more slowly after drought, resulting in complex and seemingly unrelated long-term linkages between rainfall and its impact on groundwater resources.

Figure 5.2.2. A scene characterising the severity of a recent drought in arid Western India: skeletal remains of perished livestock and mitigation measures through supply of drinking water (Vrba and Verhagen, 2006)

- **Design, depth and location of the groundwater well or borehole**. Hand-dug wells may be expected to be more sensitive to recharge variations than deeper boreholes. Drought will thus impact sources that are shallow, that rely entirely on seasonal storage replenishment – and thus often poorer populations - significantly more quickly than sources that tap deeper groundwater.
- **Hydraulic characteristics of the aquifer**. The connectivity of the aquifer to recharge sources and the storage properties of the aquifer itself. In basement aquifers connectivity may be good but aquifer storage can be highly variable and may depend to a large extent on the degree of near-surface weathering. In more productive, unconsolidated aquifers, the source may be able to meet even the high demands placed upon it throughout a drought.
- **Excessive demand and source failure**. Often, sources are sufficiently few in number for abstraction not to exceed *long term* aquifer recharge. Localised depletion due to increased abstraction during drought makes failure of the pump more likely, increasing demand on a neighbouring source, thus increasing stress and probability of failure – exacerbated by poor maintenance as relief drilling programmes and other measures take priority.
- **Long term increases in demand**. Long-term increase in demand can eventually push seasonal and drought-related fluctuations to such a level that demand will exceed supply. The cause may be population growth (natural, or as a result of migration), or economic change, such as the introduction of irrigation, urbanisation or other water-intensive activities.
- **Long term changes in climate** affect recharge processes and put both high and low yielding sources at risk. Recovery of groundwater depends upon adequate recharge during subsequent rainfall periods. Removal of vegetation and erosion of the soil cover as a result of climatic and demographic changes may increase runoff and reduce recharge (SADC 2003a).

Criteria for a drought emergency groundwater supply

The onset of a drought is usually gradual and it may take some time to tighten its grip, setting off a series of 'triggers', activating the emergency supply as normal, existing supplies begin to fail. It will then have to deliver for at least a year, under conditions of water use restrictions and involving other innovative water supply measures (Fig. 5.2.3) – often much longer, as normal supplies will take time to recover.

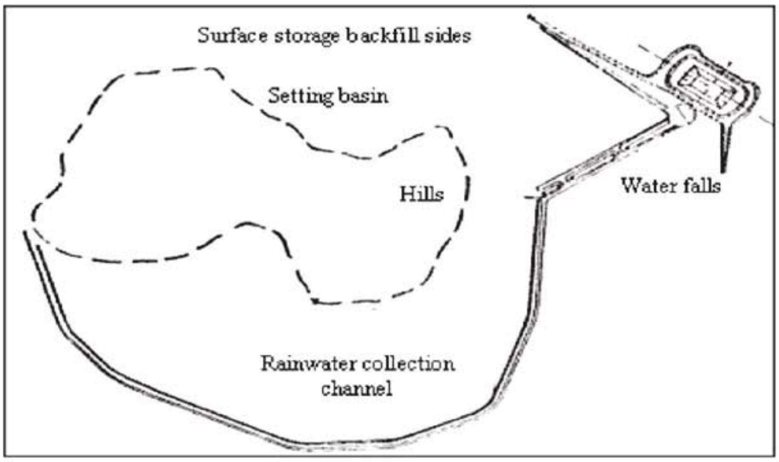
It should furthermore be kept in mind that emergency groundwater supplies will themselves experience the longer-term effects of the drought; the reduced or zero rain recharge having to be factored into the sustainability assessment. Where there is little or no anthropogenic threat of eg. pollution, protection will be a second-order concern as the emergency situation, in itself, does not threaten the infrastructure. Deep groundwater resources will therefore not necessarily be a primary target, except where, when available, their sustainability has been assessed, e.g. in terms of residence time, quality, and of storage.

All sources, shallow and deep, will have to be considered, depending on the hydrogeological and demographic situation. As such resources will have to be kept in reserve, strict management control will have to be exercised. Drought-prone communities tend to be vulnerable in other ways, and the longer-term temptation of utilising designated emergency supplies will be great. This might even be the case in urban environments, where there could also be pressure from commerce and industry (Fig. 5.2.4).

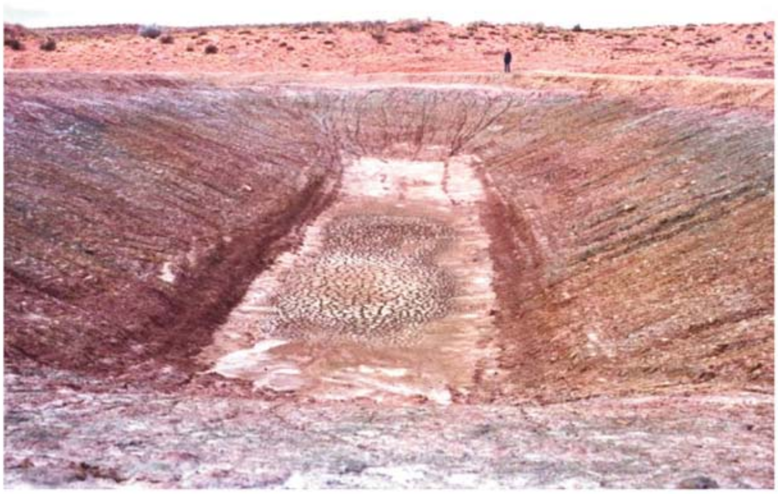
As sustained exploitation will be the norm during a drought emergency, it is important that exploitation will be sufficiently diffuse to prevent the 'pump failure domino effect' referred to above. Furthermore, pumps and boreholes will need to be tested regularly and maintained on an ongoing basis to ensure their full operation when required.

The long-term behaviour of the aquifer needs to be understood. Sustainability both in quantity and in quality needs to be assured. Even where exploitation is maintained to balance recharge, long-term hydraulic disturbance can cause the eventual drawing-in of lower quality or saline water, even in the same aquifer (chapter 6).

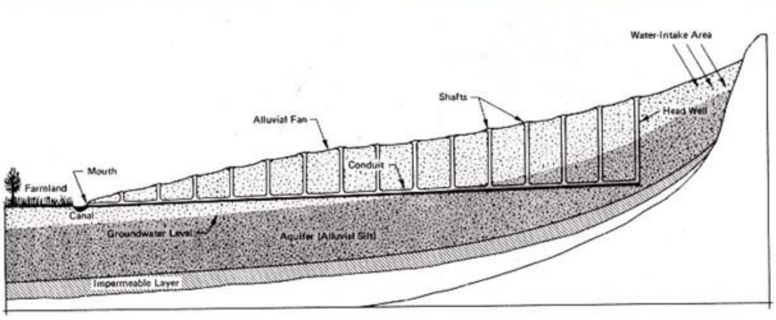
Figure 5.2.3. Some traditional surface/groundwater harvesting systems a) Hafir rain water runoff harvesting and storage systems of N. Africa and the Middle East b) Gatdamme – a South African innovation, in areas where ground water is saline, for rainfall harvesting from dry playa lake surfaces and storage in excavations (E. van Wyk, priv.comm) c) Qanats: traditional and sophisticated systems of gravitational groundwater harvesting of the Middle East (Prinz et al., 2000)



a) Hafir rain water runoff harvesting and storage systems of North Africa and the Middle East

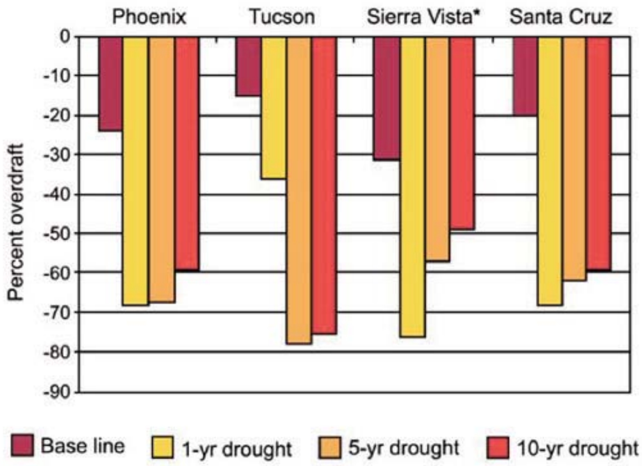


b) Gatdamme – a South African innovation, where ground water is saline, for rainfall harvesting from dry playa lake surfaces and storage in excavations (E. van Wyk, priv. comm.)



c) Qanats: traditional and sophisticated systems of gravitational groundwater harvesting of the Middle East (Prinz et al., 2000)

Figure 5.2.4. An urban groundwater drought impact study in Arizona, USA of how severe future drought impacts would be, based on records of severest one-year (1900), five-year (1914-1919), and ten-year (1946-1955) droughts. Stringent groundwater management is mandated under the 1980 Arizona Groundwater Management Act, achieving 'safe yield,' although supply and demand balance remains uncertain. Future severe droughts are shown to have the potential to cause significant economic and social impacts (FY, 2003)



Drought vulnerability maps

Drought vulnerability maps, as useful management tools, should include a variety of influencing factors. They are central to the optimum use of groundwater during drought and should indicate regions that are more vulnerable to groundwater drought. Key determinants are: aquifer type, depth of the weathered and unsaturated zone, well and borehole yields and rainfall (amount and variability) and related groundwater recharge (SADC 2003b).

Vulnerability maps incorporate different indices, or 'layers' (Fig. 5.2.5) and typically present the superposition of two sets of information: a *sociological* dataset that analyses the distribution of demand, and a *physical* dataset that identifies emergency resource availability and ease of access (Fig.5.2.5). These help in identifying vulnerable communities, target these communities to provide drought proofing in pre-drought periods, and ensure appropriate drilling methods and design of emergency wells and boreholes.

Such map information, important though it is for drought management, does not fully determine vulnerability to groundwater drought. Population density might outstrip low groundwater resource coverage with communities in certain areas heavily depending on traditional supply sources (Fig. 5.2.6).

Drought early warning systems

The concept of drought vulnerability mapping and its issues are separate from issues of early warning based on longer-term meteorological forecasting. Adequate early warning systems are often in place with regard to regional food security and meteorological drought. However, comparable systems with which to predict the onset of groundwater drought are often not in place, especially in developing countries.

Figure 5.2.5. The superposition of human (social) susceptibility and groundwater resource geographic factors produces a map of drought susceptibility/vulnerability (SADC 2003(b)).

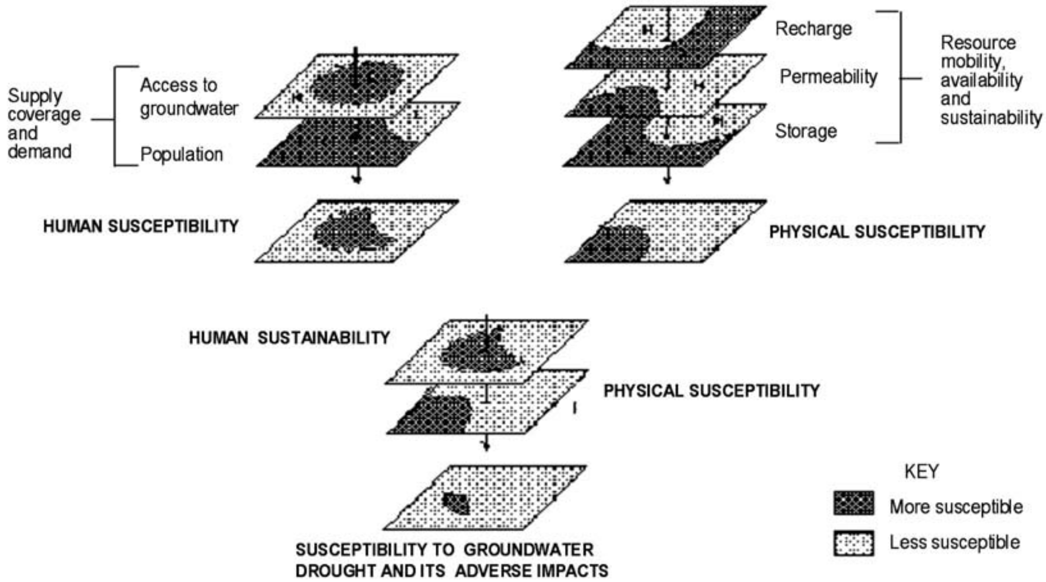
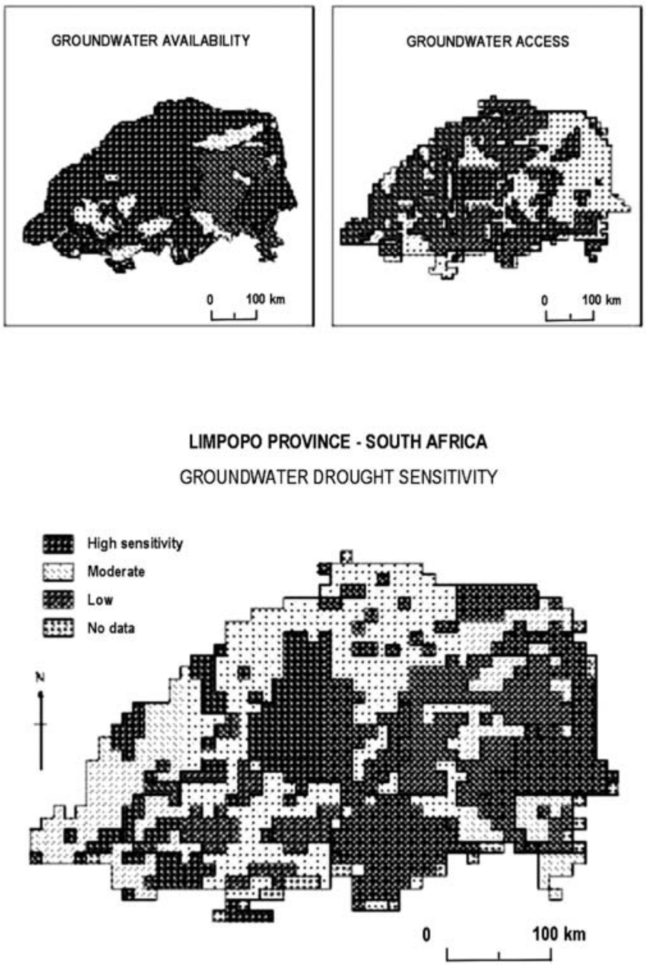


Figure 5.2.6. Example of drought susceptibility/vulnerability maps: Limpopo Province of South Africa (SADC, 2003b). Former 'homelands' are at risk due to a combination of skewed former ideology-based demographic coverage and difficult hydrogeological conditions.



Groundwater drought early warning can be carried out at two levels:

1. the global level (international meteorological community) – climate and climate variation, including possible long-term change ,
2. a regional scale (governments, donors and NGOs) – local signals flag progress of groundwater drought and likely consequences given certain courses of intervention.

Meaningful groundwater drought early warning is tied to reliable data and long-term meteorological and hydrological trends. Basic requirements are to:

1. compile and analyse data from observational networks,
2. determine user needs in terms of specific data requirements,
3. develop triggers and an early warning system, and
4. identify drought management areas.

Early warning systems require: a) monitoring data for antecedent meteorological and hydrological conditions and b) groundwater indicators e.g. water levels and yields. Such thresholds once exceeded should trigger actions defined in the drought plan. Indicators of water stress could also be incorporated e.g. information on the incidence of water-related diseases from clinics (Fig. 5.2.7).

Figure 5.2.7. Drawing water from a dry river bed in the Sahel – a potential health hazard.

Drought mitigation triggers

Drought triggers and responses should be staged with progressively stricter and more severe response measures reserved for truly emergency situations. A good drought contingency plan would consist of a series of staged water supply extension and water demand reduction measures which would be triggered by monitoring key sources of supply.

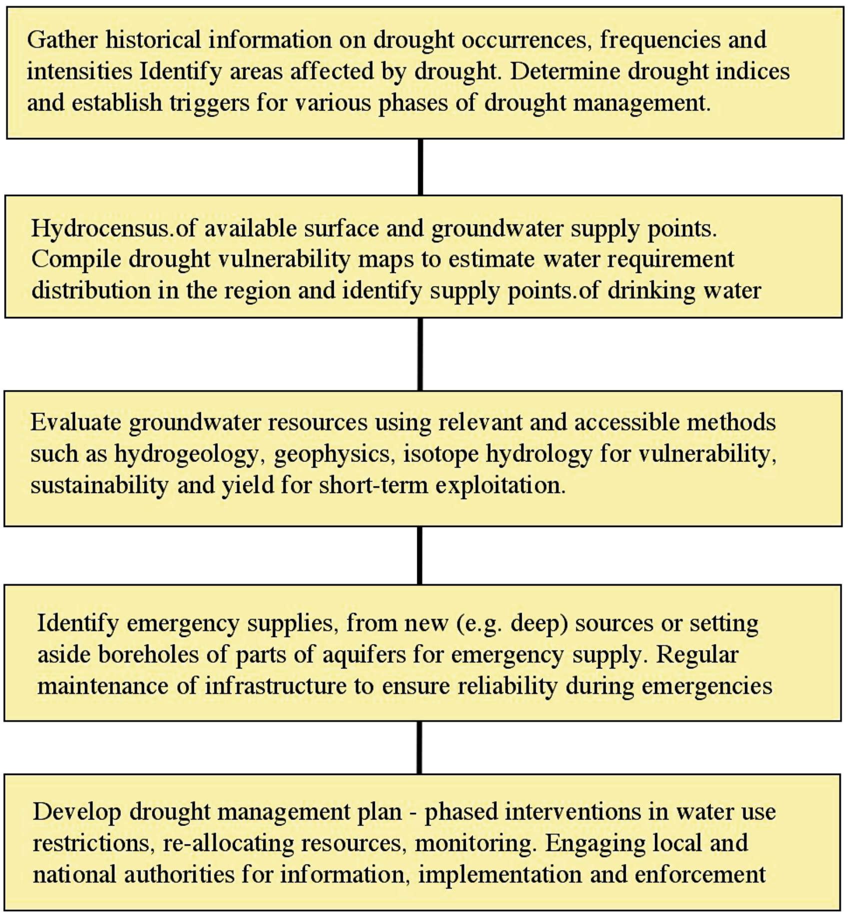
A number of drought indicator parameters are available for monitoring and triggering drought stages. These include reservoir storage levels, groundwater levels, and stream flows. Regional drought indicator criteria such as accumulated precipitation deficiencies and soil moisture indices may be used in combination with individual supply system indicators.

Central to our discussion in the GWES project is the utilization of an emergency source of supply. This could simply involve bringing on line a reserve well for temporary use and/or it could entail the temporary development of a variety of new sources of supply such as springs, reservoirs, lakes.

Drought risk management of groundwater

Risk management of groundwater is part of a framework of multi-disciplinary and integrated plans for drought management. A variety of groundwater activities at all levels (local, 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 risk associated with drought occurrence, integration of all sectors impacted by drought, people-centered 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. Figure 5.2.8 enumerates an example of the steps that could be taken towards risk management of groundwater in case of drought.

Figure 5.2.8. Example of steps to be taken towards drought risk management of groundwater



Some specific management measures in drought risk assessment, mitigation and management of emergency groundwater resources

- Consider actual and potential effects of climatic change in scenario building. This could involve ongoing research efforts.
- Instituting programmes of ground water monitoring and historical data collection to establish long-term information on existing ground water systems.
- Developing programmes of ongoing testing, maintenance and renewal of existing production wells and equipment.

- Through GIS, hydrogeological and geophysical techniques, identify aquifers potentially able to act as emergency supplies.
- Hydrogeological, hydrochemical and isotope hydrology techniques to evaluate resources for emergency supply, especially deep aquifers and their vulnerable areas.
- Develop a conceptual model on the basis of which numerical modelling of the groundwater system could be undertaken. The resulting information to be used in:
- Establishing emergency supplies from deep aquifers; deepening existing boreholes to extend their supplies through drought (SADC, 2003a); setting aside wells in sections of aquifers for emergencies; rain water harvesting.
- Developing integrated risk management strategies, including longer-term demographic analysis, vulnerability mapping, and adapting agricultural practice to address short to medium term sustainability of emergency supplies.

Regional groundwater drought management support

In large areas of the world groundwater is the only dependable source of water for basic needs and food production (Fig. 5.2.9). Careful management of these resources will be necessary if e.g. the Millennium Development Goals targets are to be reached.

Figure 5.2.9. Queue-ing at a village water supply - Sahel

Groundwater and environment managers from national agencies throughout a region should have access to an agreed mapping of transboundary and national aquifers as a basis for future joint management, improved knowledge on the value of groundwater, and a set of guidelines for local and transboundary groundwater drought management planning (Sheng and Devere, 2005).

In spite of the importance of groundwater resources for regional growth, fundamental tools for transboundary groundwater management, such as hydrogeological maps and maps of groundwater vulnerability and water scarcity, are often not available. The tools described in this methodological guide, together with the improved knowledge generated through research, meet some of the specific needs highlighted above.

A well-conceived drought contingency plan can greatly enhance the provision of adequate potable water for the health and safety of the population, even during severe drought events. The adoption of a drought contingency plan prior to drought events may eliminate the need for emergency meetings as well as the confusion and indecisiveness that often accompany last minute planning efforts (Calow et al., 1997).

Summary of groundwater resource drought management measures

In order to plan timeously for the mitigation of drought emergencies, the response of hydrological systems to be tapped for water supply needs to be understood. A range of relevant techniques and methodologies are to be found in this manual to ensure minimum water supply levels. The vulnerability of existing water supply systems has to be taken into account as well as the demographic situation, the two factors embodied in drought vulnerability maps as a basic management tool. Drought early warning systems, carefully designed on the basis of local conditions, can initiate the management process. A further tool is to develop drought mitigation triggers, indicators of the various control and supply initiation steps to be taken in the progression of a drought emergency. Technologies and infrastructure must be put into place for the reasonable maintenance, control and protection of emergency water supply systems.

Drought and resulting emergencies require a complex set of mitigation responses in planning, management and control. When these have been properly established, drought can be more successfully handled and mitigated than disasters caused by other natural phenomena.

5.3 Groundwater risk assessment and management in regions affected by earthquakes *Balbir Sukhija*

Introduction

Earthquakes are predominantly natural phenomena, wreaking destruction and devastating infrastructure, often resulting in high mortality rates. They usually occur unexpectedly, largely unforeseen by both geoscientists and affected populations, and of short duration (seconds to minutes) resulting from a major release of energy that accumulated as stress over a long period of time deep in the earth's crust. Notable phenomena associated with earthquakes are intense shaking, displacement of earth's surface laterally and/or vertically, deformation, tilting, liquefaction of sediments due to increased pore pressure, slope failures, landslides and tsunamis.

The effect of earthquakes on groundwater systems

Several examples from Japan suggest that a significant drop of water table can occur at topographically isolated hills or highlands where a local ground water system is developed and separated from aquifers of regional extent. In some cases the water table may continue to decline for more than a year after an earthquake, which poses a significant problem for those relying on this shallow groundwater system. Sometimes it is observed that ground water levels rise on one side of a fault, but drop on the other side, for example in the Chutesu earthquake (M 6.8), Japan 2004 (Yoshioka, 2007.)

The effect of earthquakes on groundwater has been known for decades and the impact is generally analysed as pre-seismic (before earthquake), co-seismic (during earthquake) and post-seismic (after earthquake) periods. Basically, changes are observed in the water level in wells related to seismically-induced expansion and contraction of the aquifer with concomitant change in fluid pressure resulting in the flow of water into or out of the well and resonant changes in the standing water column (Quilty et al., 1995; Reoloeffs et al., 1995). In the case of shallow wells located in alluvium, the phenomenon of liquefaction may be responsible for a step-wise increase of groundwater level (Reoloeffs, 1998a,b). A decline in groundwater level may be caused by the liberation of gases (degassing) from pore space in response to seismic waves and by the dilation of the strata. Thus the permeability of aquifers may be altered by unclogging, and widening or narrowing of fractures (Fleeger et al., 1999). Many studies have demonstrated the sudden change of groundwater level associated with earthquakes (Oki and Hirage, 1987; Muir-Wood and King, 1993; Tsukuda et al., 2000; Montgomery and Manga, 2003; Chadha et al., 2006). Recent observations of great earthquakes like those of the 1964 Alaska earthquake (M 8.5), have recorded water level fluctuations in more than 716 wells (Vorhis, 1966) in several countries. Very recently, the 2004 great Sumatra earthquake, which caused the giant SE Asia tsunami, was responsible for very significant ground water level changes in three monitoring wells in the Czech Republic more than 10,000 km away with a delay of 12 minutes (Fig.5.3.1, Pospíšil, 2005). In the case of the 2001 Bhuj earthquake, India (M 6.9) water levels in the Kutch area had changed by 2–3 meters several weeks prior to the quake (Fig. 5.3.2, Chadha et al., 2006). The most common response of groundwater to an earthquake is an instantaneous step change of water level (Fig 5.3.3; Sneed et al., 2006). Fluctuations of groundwater level (Figs. 5.3.1-3) result not only in changes of spring discharge but also:

- in changes of quality and chemistry of groundwater such as dissolved solids, Cl^-, HCO_3^-, SO_4^{2-} conductivity, pH, etc. (Fig. 5.3.4a, 5.3.4.b)
- that water in wells may become turbid;
- that there could be changes in the composition of dissolved gases such as Rn, CO_2, He (Fig. 5.3.5)
- that there could be changes in the isotopic composition of water such as in $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$ etc. (Cleasson et al., 2004).

Figure 5.3.1. The considerable and rapid reaction of the groundwater level in a monitoring well in the Czech Republic to the South-East Asia earthquake of 26 December 2004. The delay of 12 minutes for a distance of more than 10,000 km indicates the remarkable sensitivity of the groundwater regime to earth seismic activity (Pospíšil, 2006)

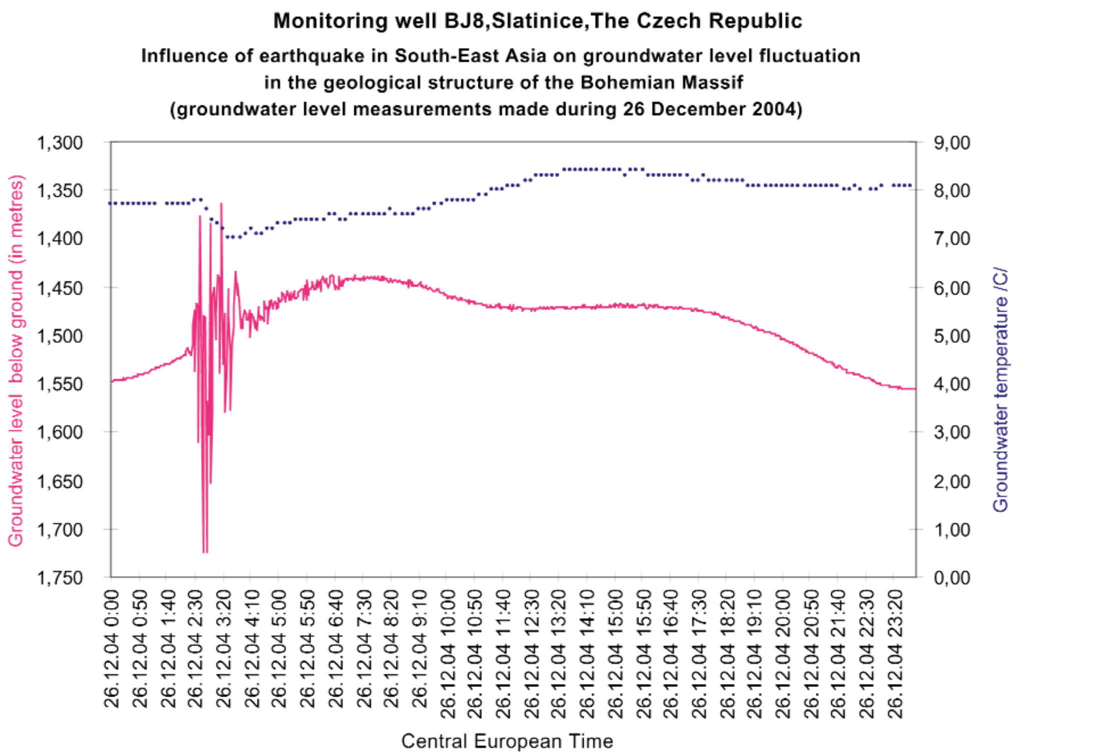


Figure 5.3.2. Declining groundwater levels before and abrupt recovery of groundwater level after the 2001 Bhuj earthquake (M 6.9), India (Chadha et al., 2006)

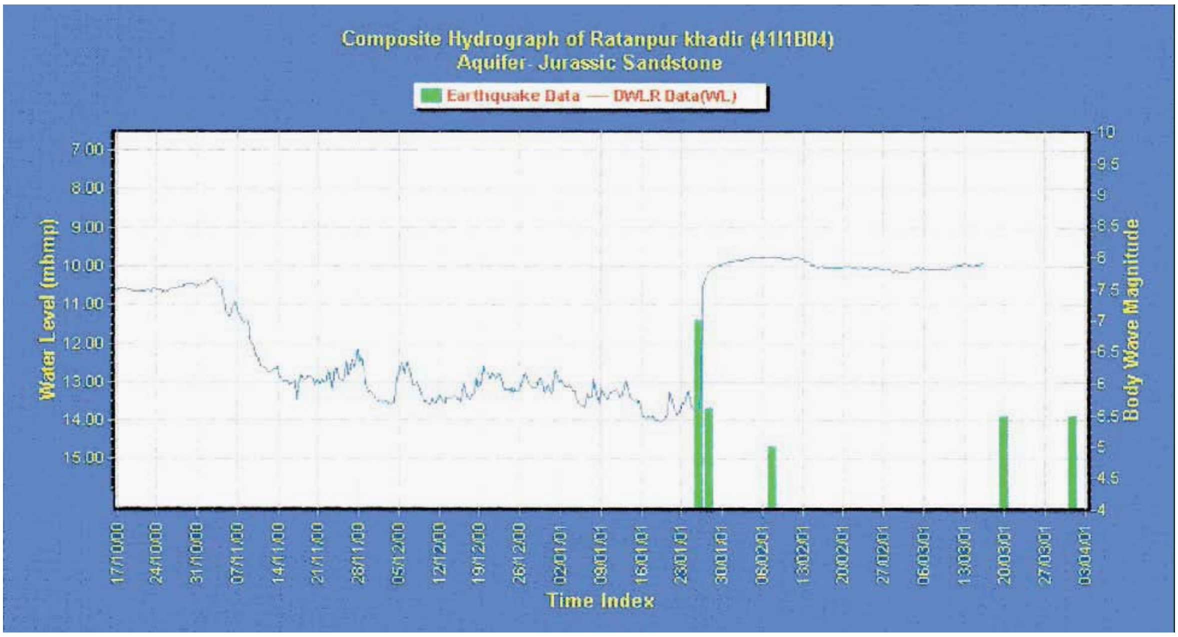


Figure.5.3.3. Changing groundwater levels before and after Landers, Northridge and Hector Mine earthquakes, USA (Sneed et al., 2006)

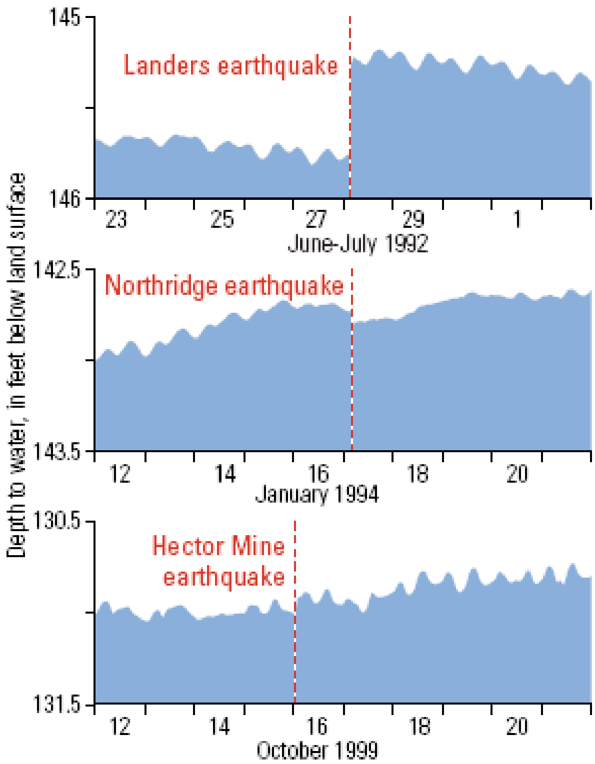


Figure 5.3.4a. Variation of the Cl^- concentration in groundwater before and after the Kobe earthquake. Also shown: the average Cl^- concentration for the pre-quake background period (June 1993-July 1994; dense solid line) with 1-variation range (light solid line)

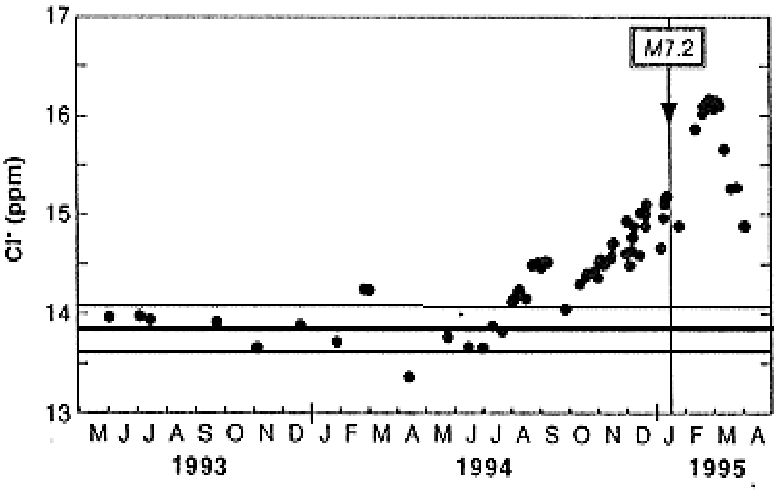


Figure 5.3.4b. Correlation between the Cl^- and SO_4^{2-} concentration of groundwater at the ROK site near the Kobe earthquake epicenter. The linear correlation coefficient of 0.94 suggests mixing of two water sources (Tsunogai and Wakita, 1995).

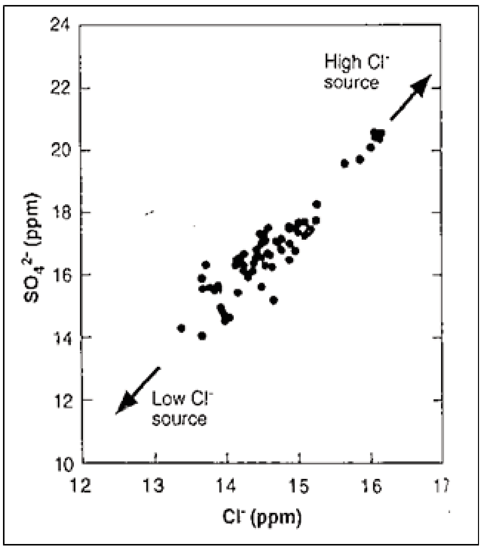
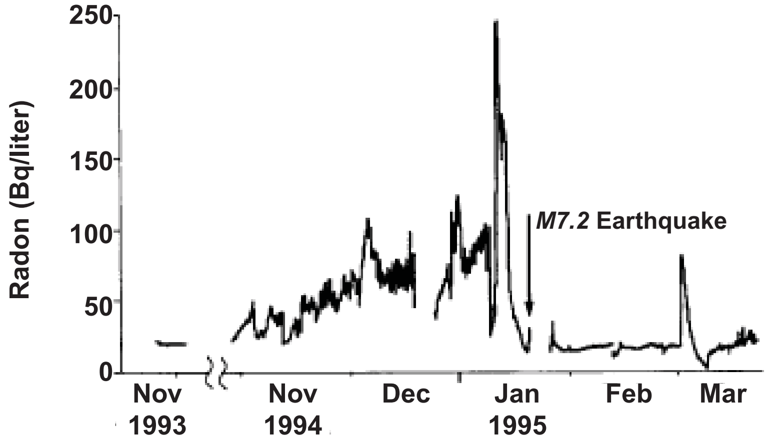


Figure 5.3.5. Increasing Radon concentration in groundwater before the 1995 Kobe earthquake (M 7.2), Japan (Igarashi et al., 1995)



Response of hydrological systems to earthquakes

Earthquakes can cause significant changes in the hydrological system comprising streams, lakes, springs etc. During earthquakes a number of instances has been observed in the U.S.A, Japan and other countries where new springs open where others disappear. During the 1903 earthquake in Tokyo for example, a new natural fresh spring (presently located in the botanical garden) became a welcome resource for earthquake refugees. Though occasionally newly emerged springs may be a windfall in an emergency, more often than not springs stop flowing, adding to the drinking water problems of the region affected by an earthquake. Increased stream flow has been noted for a few days after an earthquake, often declining to the pre-earthquake baseline. The increase may be due to groundwater-generated surface runoff or from direct groundwater/surface water interaction. Water levels in lakes, ponds, back bays generally decline before an earthquake and rebound immediately after, a phenomenon referred to as 'Seisches'.

Earthquake preparedness activities: early warning monitoring and indicators

Earthquakes are as yet not predictable in the sense of a reliable estimate of time of occurrence, their expected location, or magnitude. Thus far, except for the Haichang earthquake (1976) of China, no successful earthquake prediction has been made. On the other hand a false alarm (unreliable prediction) can lead to very large scale and negative social and economic impacts that undermine the public confidence in scientific advice. However, timely pre-emptive action, if feasible, can be very useful for preparedness. Precursors, signals which may precede an earthquake, often by weeks or days, are potentially useful in its prediction. Over the last three decades, a number of precursors, such as foreshocks (Tsumura et al., 1978), seismicity pattern (e.g. Ohtake et al., 1978) and crustal movements (e.g. Linde et al., 1988) have been investigated, but a prediction time scale remains elusive. However, precursory changes in the ratio of compression to shear wave velocities (Aggarwal et al., 1973) and ultra-low frequency magnetic emissions (Fraser-Smith et al., 1990) yield more useful information. Further hydrological and hydrogeochemical parameters including water level changes (Roeloffs, 1988, Chadha et al., 2006), radon (Igarashi et al., 1995; Virk and Singh 2000; Sukhija et al., 2007) and Cl^-, SO_4^{-2} concentration (Tsunogai and Wakita, 1995) in groundwater as well as changes of groundwater pH and temperature may act as early warning indicators on time scales of days to weeks. Recent work by Claesson et al. (2004) in Iceland, demonstrates that there could be significant anomalies in groundwater cation and anion concentrations about 2–9 days before an earthquake. Claesson further observed a change in stable isotope ($\delta^{18}O$) composition of groundwater which was interpreted as mobilising new fluid sources in response to fault sealing or un-sealing. The M 5.8 earthquake in Iceland on 16th September, 2002 caused such anomalies 1–10 weeks before the earthquake depending on the monitoring points. Such early warning monitoring can assist in earthquake preparedness and needs to be considered in terms of local conditions and capabilities. Although the examples cited above indicate research potential for earthquake prediction, it needs to be emphasised that as yet they are not established tools.

Groundwater risk management

One of the major concerns associated with earthquakes is damage to and destruction of infrastructure, including public water supply and sanitary systems, and domestic wells. In the Kobe earthquake that occurred in Japan in January 1995 (M 7.3), 80% of the city's households were left without water supply due to ruptured water pipes. The experience gained in the Kobe and other earthquakes allows for the calculation of minimum total water demand for fire fighting, medical care, daily drinking, washing and sanitation needs. Different water sources, particularly existing wells, need to be identified and characterised in the area potentially affected by an earthquake and classified according to groundwater quality for different usages, e.g. high water quality for medical and drinking purposes. A groundwater risk management plan is to be developed to mitigate the emergency for several weeks by securing water from these sources and put into action governmental mechanisms and volunteers. A groundwater level and quality monitoring system as well as registration and evaluation of existing public and domestic wells are further important managerial measures needed to secure groundwater in an earthquake emergency.

The registration of existing wells and the installation of new wells with hand pumps or diesel/petrol pumps should be prioritised. For example a list of 517 wells earmarked for emergency situations was established by the Kobe municipality one year after the great Kobe earthquake. Such systems of emergency supply sources were developed in several big cities in Japan. In Tokyo 2,767 domestic wells were registered in the municipal area and are regularly monitored for groundwater level and quality (Tanaka, 2007, Yoshioka, 2007). Answering a questionnaire following the Kobe earthquake 73% of hospitals stated that the main reason for closing down hospital operations was inaccessibility of water supply. Based on the Kobe experience some hospitals in Japan had deep wells drilled with diesel driven pumps and membrane filtration systems (see chapter 11.10).

Another example is that of the 26 January 2001, Bhuj Earthquake in India (M 6.9) which was responsible for major devastation of the entire walled city of Bhuj and most of its multistoried buildings as well as those of many adjoining towns. The maximum impact of the earthquake was experienced in the Banni area, where a series of surface fractures developed; at certain places large craters were found and subsurface water oozed for 20–25 days through small round and elliptical vents. Water supply lines were damaged and disrupted in certain places, besides the failure of electricity lines and damage to pump houses. In order to restore the water supply to the earthquake impacted area, new water supply wells were drilled in suitable deeper aquifer systems located by remote sensing, hydrogeological studies and geophysical surveys. To rapidly restore the water supply, a drilling rig was diverted on emergency basis to the Kutch district for construction of tube wells. A good aquifer down to the depth of 150–170 m was delineated, though at greater depth the aquifer was found saline. Thus for relief work, 55 tube wells were sunk, out of which 45 were equipped to supply 20,000 m^3/day. The entire water supply system was restored in about 4–6 weeks' time. The prompt and well planned action proved the importance of groundwater in emergency situations (Chadha et al., 2006). However, the delay could have been shortened significantly had the hydrogeological survey been done and some emergency boreholes established well before the disaster event.

The following specific measures are proposed to be taken towards risk management of groundwater resources in case of an earthquake emergency situation:

- Preparedness plans should include the study of precursors such as seismic, groundwater level, hydrochemical and isotopic changes. Though not yet fully established, these can be useful indicators in the time domain of weeks or days.
- For emergency management, it is vital to know the water demand (drinking, fire fighting, hospital and other emergency needs) in the potential earthquake-prone area as this allows for better preparation for drinking water supply after an earthquake.
- Experience from recent earthquakes has shown that an entire water supply system, power lines and sanitation network can be disrupted. Thus it is imperative to develop better quake-proof structures, especially related to water supply and sanitation.
- Different water resources not part of the reticulation system, particularly wells, need to be identified and characterised in potential earthquake areas, and classified according to chemical quality and water yield. Furthermore they should be equipped with hand, diesel, or petrol driven pumps not dependent on electric power to facilitate their use in an emergency.
- Ongoing monitoring of groundwater level, hydrochemistry (quality) and evaluation of all existing public and private wells and their registration and mapping should be undertaken.
- Small scale water supply systems employing membrane filtration and facilities for rainwater harvesting and conservation are additional important managerial measures with which to tackle drinking water supply failure following earthquakes.
- Groundwater risk mitigation and risk management plans are to be developed based on emergency drinking water resources to reduce the earthquake impact on water supply systems.
- The identification and maintenance of suitable access points to surface water sources for fire fighting, immediately after an earthquake is another high priority issue for water resources risk management.

5.4 Groundwater risk assessment and management in areas affected by volcanic activities

Balbir Sukhija

Introduction

Volcanic eruptions pose a formidable hazard to the people living in volcanic areas. The deadliest volcanic eruption of the 20th century, Mont Pelee (West Indies) in 1902, completely destroyed the city of Martinique and 28,000 people died. The 1980 eruption of Mt. St.Helen's (USA), did not cause such a devastating death toll but the eruption provided many lessons: many local inhabitants died when trapped by pyroclastic material but appropriate advice on protecting the skin against heat and preventing inhalation of fine ash could save many lives. In the 1984 eruption of Nevado del Ruiz in Colombia, South America, about 22,000 people were killed by lahar, or mud flow. Most of the lives could have been saved by a simple warning system as the population could have moved to higher ground outside of the range of the mud flow. Similar lessons learnt about the protection of water supply system call for a collaborative effort between scientists, policy and decision makers and those responsible for disaster management in areas affected by volcanic eruptions.

Volcanic activity, its origin and characteristics

Like earthquakes, volcanoes in particular are located along extensional geological plate boundaries (Fig.5.4.1) such as the Java Trench, the East African Rift Valley and convergent plate boundaries i.e. Pacific belts (Bell, 1999). Along such plate boundaries, oceanic plates are overridden by the continental plates, the descent of the oceanic plates along with their sediments, if any, to zones of higher temperature leading to melting and the formation of magmas.

A volcano (Fig.5.4.2) is a surface manifestation of a deep magma chamber, where magma accumulates with pipes or ducts forming that lead to surface vents through which magma and other volcanic products (gases, steam, ash, rock etc.) are emitted during eruptions. Volcanoes that have not erupted for some time (decades and centuries) are called dormant, and volcanoes that have not erupted in the recent geological past are called extinct. Alteration of tectonic plates triggers volcanic activity and results in landslides or earthquakes.

As manifested by their products (Fig. 5.4.2) there are different types of volcanic eruptions with their associated hazards:

- Phreatic: The volcanic explosion of steam, water, ash when rock magma comes into contact with groundwater and surface water
- Rhyolite flow: Flow of lava with silica content > 68%
- Basalt flow: Flow of lava with low silica, but high manganese and iron content
- Pyroclastic flow: Fast moving hot ash, gas and rock
- Lahar: Flow of mud and pyroclastic material down a (river) valley
- Gas: Carbon dioxide, sulphur dioxide, and other gas emissions.

Figure 5.4.1. The extent of various tectonic plates, location of active volcanoes and the Ring of Fire (Source: USGS)

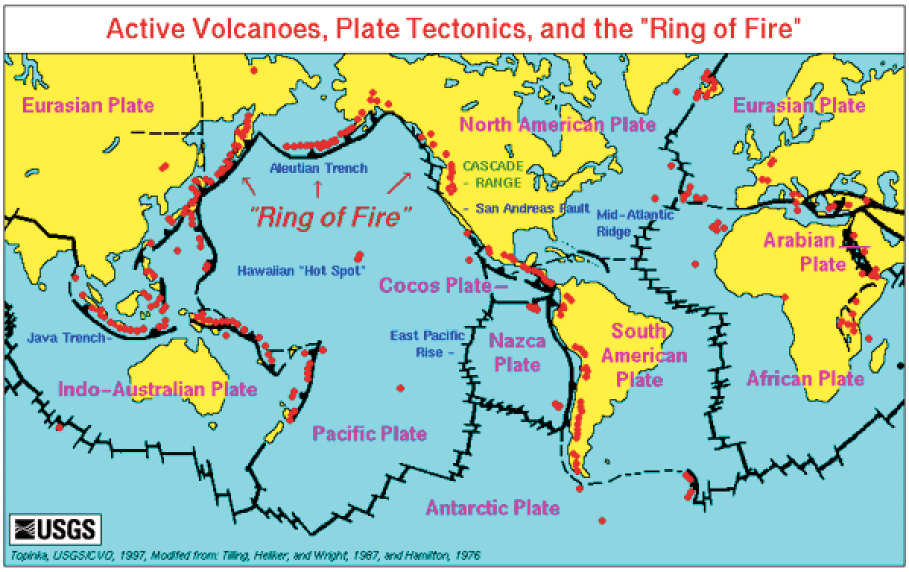
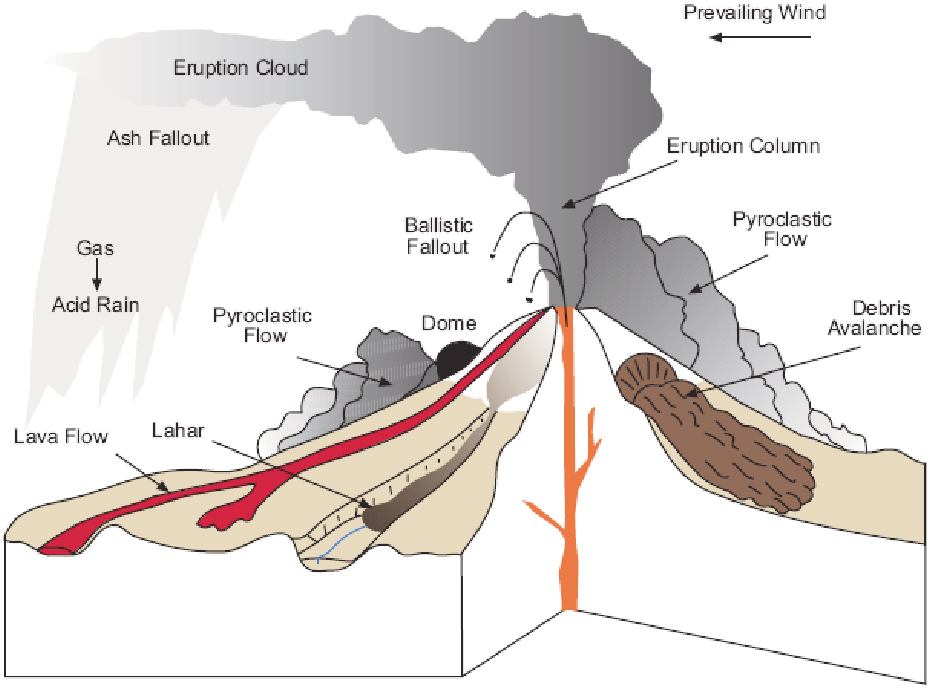


Figure 5.4.2. Schematic diagram of volcanic products emitted from and hazards presented by a composite cone volcano (after Myers et al., 1997)

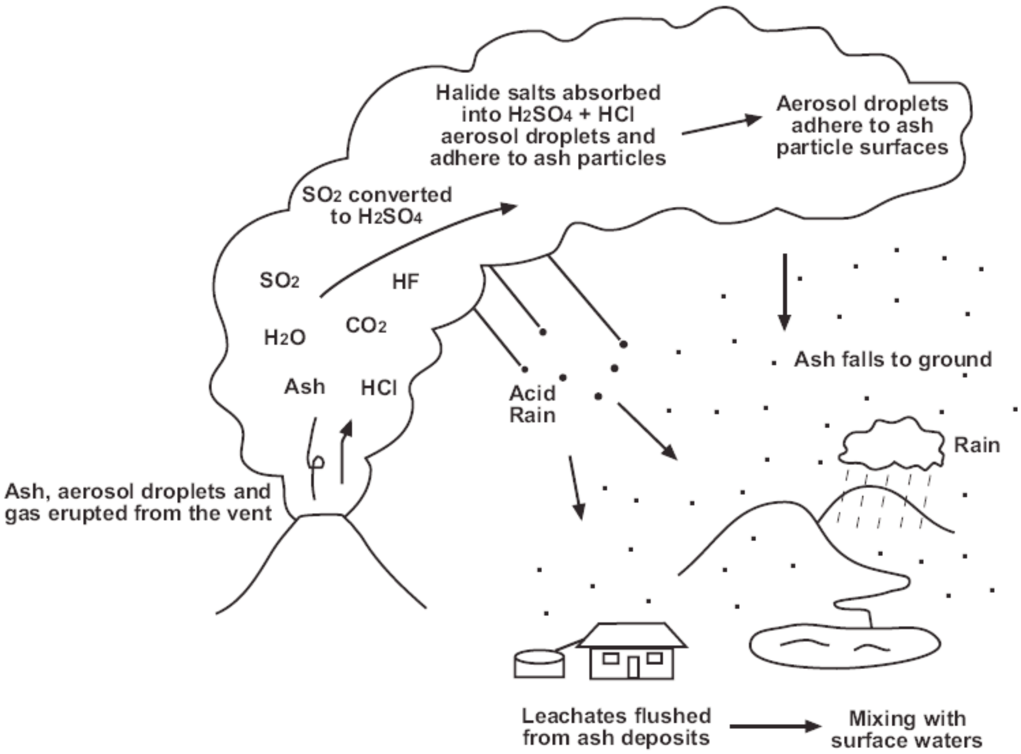


The resulting volcanic deposits exhibit various features: porous material, cavities and conduits that can constitute groundwater aquifers.

A volcanic eruption (Fig.5.4.3) is generally quite damaging to the environment. Besides emission of water vapour, it typically also involves emission of a number of toxic gases (carbon dioxide, sulphur-dioxide, hydrogen sulphide, carbon monoxide, hydrogen chloride, etc.) and volcanic metal along with pyroclastic material. Occasionally chemical reactions convert sulphur compounds into sulphuric acid that is precipitated as acid rain with additional effect on surface water and groundwater quality (Fig.5.4.3). The emission products of volcanoes pose not only an immediate hazard, including atmospheric (e.g. hazard to aviation) but may also produce long-term climatic and atmospheric perturbations.

The common sequence in a volcanic eruption is a highly explosive opening phase with a vigorous gas column carrying pumice to a great height and distance, followed by the formation of ash flow and lastly a comparatively quiet effusion of lava flow. Volcanic eruptions can last from few hours to months. Volcanic eruptions have precursors such as seismic tremors, radon gas and high CO_2 effusions, higher groundwater temperature, and changes in groundwater levels, chemical composition, and spring discharges.

Figure 5.4.3. The interaction between volcanic emission products and effects on water (after Johnston, 1997a).



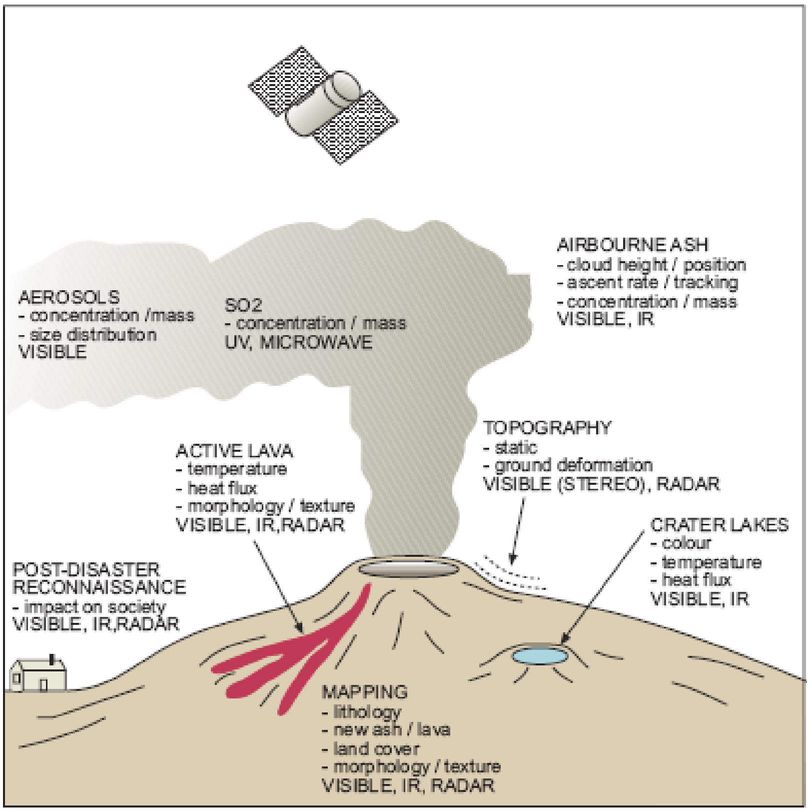
An early warning system of volcanic activity

Remote sensing (Fig.5.4.4) can monitor eruption clouds and distinguish them from meteorological clouds, sense gases such as sulphur dioxide, thermal signatures and escalated heating of the ground before an eruption, and document an eruption in progress including lava and pyroclastic flow. INSAR (Interferometric Synthetic Aperture Radar) can be particularly useful for detecting long term and even small geometric (spatial) changes in volcanic edifices, uplift and depression, mass movement and mass failure phenomena such as land-slides, rock falls, pyroclastic flows, mudflows etc.

As volcanoes about to erupt are almost always associated with seismicity, its measurement and monitoring is vital. Volcanic seismicity has three major characteristics: short period, long period and harmonic tremors. Short period tremors relate to the growth of a magma body near the surface, long period tremors indicate building up of gas pressure and harmonic tremors indicate magma pushing against overlying rock. This can also be felt/heard as humming or buzzing.

Hydrogeology can be valuable in monitoring the early signs of eruption. Rising groundwater levels are caused by gas pressure. Build-up and sudden drop of groundwater levels indicate a potential eruption. Occasionally, increased heat flow can even cause drying out of aquifers leading to loss of spring flow. Increased hydrothermal activity can be gauged from the temperature and flow rate of the springs and even from the sediments found along the river channels surrounding the volcano. Monitoring the width and depth of the river channel helps in assessing the likelihood of future volcanic eruption as volcanic deposits can easily be eroded. The United States Geological Survey aims at setting up a National Volcanic Early Warning System (NVEWS) by monitoring 169 young volcanoes on USA territory. However, the prediction of volcanic eruptions has not yet been perfected.

Figure 5.4.4. Remote sensing methods and their application to various expressions of volcanic activity (after Oppenheimer, 1997).



Preparedness and risk assessment

For the purpose of preparedness, it is vital to make an area specific assessment of risks associated with volcanic hazard. The first step includes an evaluation whether volcanoes in the area are active or extinct. The activity of volcanoes during the last few thousand years may be found from historical records. However, volcanoes that were dormant may now be due for eruption. Thus it is very important to assess the recurrence period of eruptions, the distribution of volcanic deposits and magnitude of past events from historical and geological records. In order to compile a preparedness plan, studies of geophysical (seismicity, temperature), geochemical (CO_2, SO_2, radon etc.), and geodetic (uplift, tilt, GPS, SRTM) precursors may be very useful. Of value too are satellite imageries in monitoring the movement of eruption plumes, changes in thermal radiation and the progression of a volcanic eruption.

Continued measurements of water chemistry of hot springs in a volcanic area may provide warning signals of an impending volcanic eruption (Kikawata et al., 2003). For example whilst investigating the hot springs (Manza-Yubatke) in the Kusatsu -Shirane volcano region since 1965, the concentration of dissolved ions K, Al, Fe, SO_4 was found to increase prior to and at the time of, the eruption. Anomalous changes can be linked to volcanism and its prediction (Shibata et al., 2003). Similarly, a recent study of volcanic springs in Mexico (Armienta et al., 2003) observed an SO_4 anomaly (increase from 218 mg/l to 1,225 mg/l), nearly three months before the largest volcanic event on May 8, 1986.

However, risk assessment should also include the number of lives at stake and the water requirements for an emergency situation, both vital parts of a risk mitigation policy. Because surface water is at far greater risk than groundwater, suitable aquifers need to be delineated and their resources for an emergency situation assessed both in quantity and quality.

Impact of volcanic eruption on water resources

Volcanic eruptions can have a dramatic hydrologic impact and hydraulic consequences, which may be direct and immediate or indirect, both affecting major components of the water balance in a volcanic area. Explosive eruptions which emit great quantities of ash and volcanic material can obliterate watershed divides, disrupt drainage patterns, modify the size, shape, pattern and structure of channels and thus affect runoff, erosion, and sediment transport (Major et al., 2000).

Damage to or destruction of vegetation may indirectly modify the water balance (mainly through evapotranspiration) of a watershed in a volcanic area. In regions above the snow line volcanism can accelerate the melting of snow and glaciers, increasing the rate and amount of surface runoff. It is observed that post-eruption runoff reaches river channels more rapidly as compared with pre-eruption conditions (Major, 2003). Major et al. (2001) observed that following the Mount St. Helen's eruption, river discharge had increased by as much as 30 to 70% for about five years. Sometimes the hydrological impact can be observed as long as 15 to 20 years after an eruption. Sediment deposits resulting from a volcanic eruption can change river channel hydraulics, drainage patterns, groundwater recharge conditions and even obliterate an existing valley structure.

Very few systematic studies have illustrated the impact of volcanic eruptions on groundwater. Continued increase of river run-off in the impacted area may result in a corresponding increase in the groundwater piezometric level in aquifers in fluvial deposits leading i.a. to changes in groundwater chemical composition.

One of the notable effects of the Mount St. Helens eruption on May 18, 1980 (Lee,1998) was the sudden rise of groundwater level in the study area as a consequence of the bed of the river Cowlitz being raised by mud-flow deposits by some 2 metres from mid June to September 1980. During the corresponding period in 1981, when the dredging of the river bed was undertaken, the groundwater regained its original level.

As far as the chemistry of water resources is concerned, the impact will depend on the magnitude of the eruption and also on the varying amounts of the eruption products such as pyroclastic material, volcanic ash, mud flow, volcanic gases. Depending upon the chemical constituents evolved during eruption, groundwater may be enriched in sulphate, chloride or bicarbonate formed by low temperature diffusion of volcanic gases CO_2, H_2S/SO_2 and HCl^- respectively. Hydrogeochemistry and isotope analysis of precipitation, groundwater and springs provide vital information on and understanding of their origin.

The impact of volcanic ash on water quality depends upon whether it is deposited as air fall or from pyroclastic surges, on wind velocity and its direction and is reflected in surface water turbidity. Such an impact on water quality was reported for the Mt. St. Helens eruption (Klein, 1984; Miller et al., 1981) which affected the landscape for hundreds of square kilometers surrounding the volcano. Ash from pyroclastic flow followed stream channels and travelled tens of kilometers, clogging the channel and producing inundation of the entire drainage basin. Such areas could not be used as a water supply source for many years. Soluble ash components degraded the chemical quality of surface and groundwater systems for months or even years.

Mud flow impacts the water chemistry by leaching of the sediments which reflects in an often rapid increase of turbidity as readily soluble components are mobilised into solution. A drop in pH may be transient, but turbidity may last as long as suspended material remains in the water system.

Organic debris may affect the chemical quality of surface water resources. Decomposition of such material by micro-organisms may produce a foul smell, lower the dissolved oxygen content and increase the dissolved organic carbon (DOC) and particulate organic carbon (POC). Further the dissolved material may carry gases produced by organic, chemical and thermal decomposition processes. Toxic and unpleasant gases such as carbon disulphide, hydrogen-sulphide and carbonyl-sulphide, which result from the breakdown of organic material, were identified in Spirit Lake as a consequence of the Mt. St. Helens eruption (Hopson, 1991). Surface water quality (e.g. lakes) becomes degraded by the growth of micro-organisms including algae, bacteria, increase in sulphur compounds, metals, increase in DOC accompanied by discolouring of water. It is expected that biological effects resulting from the physical and chemical impact of volcanic activity may last for a considerable time and may not recover fully (Dion and Embrey, 1981). Where the water body is situated close to the volcano, in addition to turbidity and acidity problems, the water may be contaminated by fluorine, e.g. the eruption of Hekla Volcano in Iceland on 14 May, 1970 caused high fluoride content in groundwater. Its excessive content is one of the most hazardous elements and consumption of water with fluoride more than 1,5 mg/l over long period causes dental mottling and osteofluorosis leading to deformities of human limbs. Continuous monitoring of groundwater quality is a prerequisite for the selection of safe aquifers to be used in emergencies. Table 5.4.1 shows the relative vulnerability of the various sources of water supply in a volcanic environment.

The identification, exploration and development of less vulnerable, deeper aquifers seem to be the most suitable mode of supplying drinking water in volcanic emergency situations as clearly indicated in Table 5.4.1. However, it must be mentioned that certain deep aquifers may also be vulnerable as quality may deteriorate due to water-rock interactions or opening of new fractures as a result of volcanism. Shallow groundwater developed by open dug domestic wells may be affected by volcanic ash. Thus the identification of suitable aquifers and the use of appropriate methods to extract groundwater may be a valuable contribution to mitigation plans for volcanic eruption emergencies.

Table 5.4.1. Relative vulnerability of the various water supply sources in a volcanic environment

Type	*River/ Stream vulnerability*	*Reservoir vulnerability*	*Groundwater vulnerability*	*Roof top/ water vulnerability*
Chemical composition	Low to medium	Low to medium	Low (deep) to medium (shallow)	High
pH	Low to medium - depending on ash thickness to water volume ratio	Low to high	Low	High
Turbidity	High	Medium to high	Low	High

Risk management of groundwater resources during and after volcanic eruption

Risk management of groundwater resources during and after volcanic eruption requires information on whether such resources can supply water in sufficient quantity and quality and are sufficiently protected for use during an volcanic emergency. Isotope, geochemical and geophysical methods support identification of groundwater resources safe from the impact of volcanic activities as well as produce useful data for their risk management.

Isotope and geochemical methods support management of emergency groundwater resources. It has been realised that it is exceedingly important to demarcate the recharge area of groundwater since it may be located quite a distance away from the area of influence of a volcano. Thus groundwater and springs recharged outside of the impacted areas will be included in risk management plans because these may be a valuable emergency resource in a volcanic disaster events. Delineation of recharge areas requires hydrogeological, hydrogeochemical and isotope studies. The stable environmental isotopes provide characteristic signatures of the recharge water depending upon the geographic location and altitude of the recharge area (chapter 4.4). For example, a study carried out in southwest Japan (Yasuhara et al., 2003) using ^{2}H, ^{18}O, and tritium revealed that an actively recharged shallow groundwater system has a mean residence time of 10–15 years and circulates to a depth of 300 m. Huge springs with daily discharge of 100,000– 1,500,000 m^3 (Shimabara city area, Japan), located close to a volcano, but with distant recharge areas, may provide a safe drinking water source throughout and after an eruption.

Similarly, Morikawa et al. (2003) showed that the hydrogen, oxygen, $^{4}He/^{20}Ne$ and $^{3}He/^{4}He$ isotope ratios could indicate that groundwater in the Kobe area of Japan is of meteoric origin but does contain thermal water (high temperature and chloride rich) in varying proportions from deeper aquifers. If the depth of exploitation of the aquifer is limited, the quality of groundwater could be maintained as a valuable drinking water emergency resource.

Geophysical methods help to identify safe aquifers and hence support their risk management. In active volcanoes groundwater may interact with magma intrusions to generate powerful and highly dangerous phreato-magmatic explosions. With the objective of delineating safe groundwater resource and understanding groundwater systems close to volcano vents, geophysical measurements could be a very useful tool. The basic idea is to delineate crater boundaries which act as preferential fluid flow pathways for the upward flow of hydrothermal fluids. The hydrothermal vapour can condense as it approaches ground surface. Part of this condensed water can form a shallow drainage network in which groundwater may flow down-slope toward a perched aquifer and can be used as an emergency source of water.

Risk management involving the **registration of wells safe from volcanic impact.** Registration of emergency wells at sites considered to be safe from volcanic impact should be part of risk management strategy. Such wells have to be 1/ properly registered and indicated on relevant vulnerability and risk maps and 2/ the casing of supply wells should be raised to sufficient height above the ground to ensure that the well head is not buried in ash or other volcanic emissions. In case of St. Helens volcano, a small town about 40 km northwest of the volcano was provided with water supply from groundwater from a shallow drilled well located in a river channel. The well was buried by a mudflow, and new wells had to be drilled.

Ash is the volcanic product which can have the most devastating effect on water supply. It may cause high and enduring water turbidity levels. Fine ash can remain in suspension for days or weeks. In the event of ash fall during a volcanic eruption the down pipes leading to the tank for roof runoff collection should be disconnected, open tanks need to be covered, water should be boiled before drinking, treatment filters should be cleaned, and a coagulation-flocculation agent may be used (Fig. 5.4.5). For example, the eruption of Ruapheo Volcano in 1995–1996 (New Zealand) resulted in ash fallout over wide areas in the north of the country (Gaurdu, 1997) that polluted water producing excessively low pH and turbidity. The ash contained water soluble salts, mainly sulphates and chlorides and the public was advised to disconnect the roof fed water tank supplies as a precaution and mitigation measure (Johnston et al., 2000)

Emergency sources of groundwater

Springs whose recharge area lies outside the probable sphere of influence of volcanic activity can prove to be a valuable resource of drinking water in an emergency. Such springs have to be monitored and evaluated with respect of their quantity and quality and their exploitation potential should be incorporated in drinking water resources risk management and emergency plans of the studied area.

Registering, evaluating and mapping water supply wells deemed to be resistant to volcanic impact is an important risk management strategy, as is raising the casing height of wells to safeguard their collars from burial under volcanic ash.

Figure 5.4.5. A private tank for roof rainfall collection water supply that should be disconnected in the event of ash fall during a volcanic eruption

5.5 Groundwater risk management in areas affected by landslides

Kunyi Guo and Jaroslav Vrba

Introduction

A landslide is a common geological calamity in hilly or mountainous terrain in which a large volume of soil, clay, weathered rock and other clastics accumulated through erosion on a slope becomes unstable and may slide down along a failure plane under the influence of gravity and often mobilised by water. A typical landslide is composed of a landslide wall, terrace, tongue depression, drumlin and plume fissures (Figure 5.5.1a,b). A study and evaluation of the elements of landslides and their stability is necessary to recognise their origin and evolution.

Conditions for landslide occurrence

The main factors inducing landslides are their geomorphological and geological setting, hydrological and other natural conditions, and also uncontrolled or poorly planned human interventions.

- **Geomorphology critically** determines landslide occurrence. Landslides could occur in particular in areas with an average slope gradient between 10º and 45º, especially with steeper sections at the lower and upper ends of the slope and a gentler slope between.

- **Geological conditions** are fundamental, such as rock and soil types, and geological structure. Generally, all types of rocks are susceptible to landslide occurrence near their surface, but mainly loess, loess loams, clay, shale, coal, tuff, and schist. Tectonic features (e.g. fissures, cracks, fault slopes) significantly facilitate rock erosion, and rain water penetration leading to landslides formation.
- **Groundwater** is a major hydrological factor giving rise to landslide occurrence. It softens rock/soil masses, reduces their consistency and produces dynamic/static water pressures in slopes.
- **Natural phenomena** such as heavy rainfalls, snow melt and earthquakes may trigger landslides mainly during the rainy season and snowmelt in spring. Even tsunamis may be such triggers.
- **Human activity,** often uncontrolled or poorly planned, such as excavations, explosions, and leaking water reservoirs can enhance the development of landslides.

Landslides, especially at large scale, may bury villages, destroy factories, railways, highways, damage farmlands and forests and more specifically disrupt water supply and sanitary facilities.

Relationship between groundwater and landslides

Groundwater influences the stability of the rock/soil mass in three ways: physical (porosity, static and dynamic hydraulic pressures), chemical (ion exchange, hydratation, hydrolysis, oxidation-reduction) and mechanical (sliding, weathering, sedimentation). The static pressure may decrease rock/soil mass stability by lowering its effective stress and the dynamic pressure may produce a tensile force which may lower the anti-shear cohesion of the rock/soil mass.

Another factor is the temporal and spatial fluctuation of groundwater level in a slope. This is controlled by the quantity and intensity of rainfall, floods in rivers and lakes, rock permeability and vegetation cover. The seepage capacity of the slope surface is exceeded during excessive rain, torrents form on the slope surface. Rain which infiltrates and recharges the groundwater body affects greatly the stability of the slope, particularly its foot which usually constitutes a groundwater discharge area. The groundwater system in slopes is affected also by physical conditions, particularly the permeability of the rock/soil mass. Well-fissured rocks and clays cracked after a long-term drought, potentially unstable, are saturated during the rainy season. The pore water pressure increases and initiates edge slope destruction which gives rise to landslide. Fissures in the edge slope rock mass are often irregularly distributed and show variable permeability. Groundwater pressure varies, even in different parts of the same fissure. Where the rock/soil mass at the edge slope shows good permeability, groundwater discharges in springs as the pore water pressure and seepage pressure are large. However, where the discharge at the leading end of the edge slope is restricted, the pore water pressure would be higher, but seepage pressure lower.

Influence of groundwater on landslide occurrence

The soil developed on a sliding surface, or a zone of weakness in this surface, often acts as a relatively water proof layer. The sliding, or landslide, surface (Fig. 5.5.1) therefore becomes the seepage base, with water flowing towards the leading edge of the potentially sliding mass to form groundwater dependent wetlands or springs. Penetration of excessive rainfall increases the dynamic pressure of groundwater as well as sliding forces, washing away soluble binding agents and fine granular material. The landslide mass becomes more soaked, therefore heavier, and its cohesive force is reduced. Inner friction will be lowered and the potentially sliding mass becomes more unstable. Fine sand is gradually displaced by groundwater which stimulates erosion of soil and rock and lowers their stability. Some

Figure 5.5.1a. ***Block diagram of a landslide 1. landslide wall; 2. landslide lake; 3. first landslide terrace; 4.second landslide terrace; 5. drunken forest; 6. landslide tongue depression; 7. landslide drumlin and its fissures; 8. plume fissures; 9. landslide surface; 10. landslide body; 11. landslide spring.***

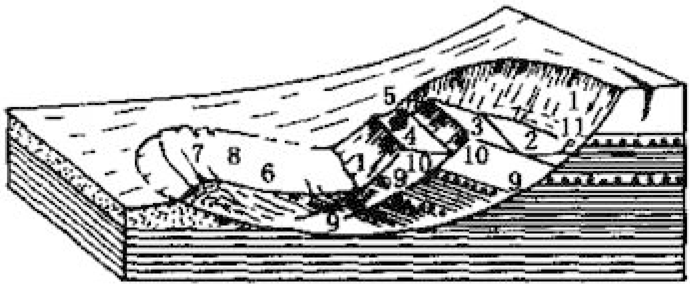
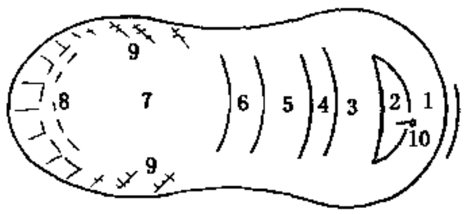


Figure 5.5.1b. ***Diagrammatic landslide plan 1. first landslide wall; 2. landslide lake; 3. first landslide terrace; 4. second landslide wall; 5. second landslide terrace; 6. third landslide wall; 7. landslide tongue depression; 8. landslide drumlin and its fissures; 9. plume fissures; 10. landslide spring.***



mountain slopes which host permeable fault zones with large amounts of stored groundwater also facilitate landslide development.

China, frequently affected by landslide disasters has provided some lessons regarding groundwater related landslide mechanisms. Landslides in the colder, northern areas occur mainly during seasons of freezing and thawing. With the insignificant precipitation in those parts, spring discharge observed at many slope feet maintains the groundwater level below the sliding surface. However, where springs are frozen in winter, groundwater discharge is impeded and the dynamic water pressure in the slope foot area increases. Large scale sliding beneath the frozen surface occurs mostly during freezing. Small-scale sliding is registered mainly during the spring thaw.

Chinese examples of geological disasters such as slope collapse, landslide and mud flow are to be found in the middle reaches of the Yangtze River and its tributaries and in the region of the present Three Gorges reservoirs. In the middle and upper reaches of the river, geotectonic uplift has produced steep rock slopes. Landslides are easily induced by torrential rains which infiltrate into the slope rock masses, rapidly increasing groundwater levels, enhancing the lubrication of the sliding surface and at the same time increasing both static and dynamic water pressures at the slope foot. The resulting instability caused by the large volume of water triggers the landslide.

With the construction of the Three Gorges reservoirs, surface water levels now influence the stability of the bank slopes. A rapid decline of reservoir level leads to groundwater discharge and simultaneously to rapid increase of the water pressures of the slope foot mass, leading to slope instability. Modelling results show mainly static water pressure at normal reservoir water levels. A sudden reduction in level produces large dynamic water pressures; for a reduction in reservoir level from 175 m to 145 m, the dynamic water pressure increases 13 fold. Conditions for landslides also occur when the water level in the reservoir increases rapidly; surface water infiltrates into the slope mass where rocks are permeable and, rapidly increases foot pressure too. The resulting decrease of the effective gravitational pressure, or increase in buoyancy, of the inundated rock mass plus the instability of the slope above both facilitate landslide development.

Groundwater investigations in landslide risk areas

Water, and particularly groundwater, is the principal factor in the onset of landslides. Therefore, a comprehensive investigation of ground water systems and their changes owing to natural processes and human activities in landslide-prone areas is a very urgent task. Groundwater studies have proven very useful in eliminating or reducing risks of water-induced edge slope destruction. Groundwater monitoring and remedial measures could be implemented, based on studies of geological structure, groundwater regime and dynamics, including run-off and discharge of groundwater, hydrochemistry, thermodynamics, isotope hydrology, and the evaluation of both natural and human environmental impacts. The resulting data is useful in establishing a conceptual model of the relevant groundwater system , in evaluating groundwater resources quantity and quality and in compiling landslide hazard zoning maps. The extent and scope of such activities will, of course, depend on the available financial and manpower resources.

Groundwater vulnerability in landslide-prone areas

Precipitation and its infiltration (groundwater recharge), the level of groundwater below ground, groundwater flow and its discharge are the main water related parameters which control the groundwater regime in landslides and landslide mass stability. These have to be carefully monitored and studied. Shallow, even perched, highly vulnerable water table aquifers are typical groundwater bodies formed in landslide~~s~~-prone areas. Typical too are the considerable seasonal variability in the level, discharge and storage of groundwater due to rapid reaction to precipitation infiltration implying aquifer vulnerability. Such aquifers usually discharge in springs and are often used for local drinking water supplies. However, they can not be regarded as a safe source of emergency groundwater supply. Their groundwater regime in landslide-prone areas is influenced by local environmental conditions, affected by human impacts (e.g. groundwater pumping, earth cuttings) or by natural disasters such as e.g. earthquakes or storms. In all cases, changes in groundwater dynamic and static pressures lead to the increase of potential of landslide formation. Thus, control over groundwater level and discharge is an important measure by which to regulate the groundwater regime and the weight of water mass in landslide-prone areas, thereby supporting landslide prevention and mitigation policy. The amount of groundwater discharge and dewatering of the rock mass can be controlled, as is common in landslides-prone areas by barrier walls, horizontal discharge boreholes, and different types of channels and relief tunnels. Where groundwater is developed for drinking water supply, amount of groundwater abstracted and related groundwater level decline have to be carefully managed and controlled with respect to seasonal climatic influences, in order to maintain stability in areas prone to slides.

Emergency groundwater resources in areas affected by landslides

Existing water supply facilities, both public and domestic, located in landslide-prone areas have to be comprehensively catalogued and monitored and the potential risk of landslide movement on individual water supply wells, springs, drinking water distribution networks and sanitary systems carefully evaluated. Generally, groundwater resources in landslide-prone areas are not safe sources of drinking water for emergency situations. In these areas there is a significant risk that groundwater capture facilities (e.g. wells, springs) or drinking water distribution network pipelines will be physically damaged during disastrous landslide events and remain out of operation for weeks or even months. Often they cannot be rehabilitated and new water supply facilities have to be constructed. Shallow water table aquifers in landslide terrains are also highly vulnerable to various pollution sources. However, groundwater resources from deeper aquifers in landslide-prone areas, provided they are well managed and protected, can be a suitable source of drinking water for the local population in in both regular and emergency situations.

The use of groundwater for both public and domestic supplies has to be based on sound knowledge of geological conditions and the groundwater system in order to maintain as far as possible natural conditions in landslide-prone areas. This requires the establishment of a groundwater monitoring and early warning system covering the whole landslide-prone area as well as precipitation and surface-flow monitoring networks and geotechnical monitoring to observe rock stability. Such basic monitoring activities facilitate the control of groundwater flow from recharge to discharge area; the assessment of exploitable groundwater resources; and the optimal location and mode (e.g. spring, shallow wells, horizontal drainage system) of groundwater development for drinking water supply purposes. Principles of regulated exploitation of groundwater resources in landslides-prone areas have to be clearly formulated and controlled. Such an approach optimises landslide prevention and risk mitigation policy as well as risk management of groundwater resources.

All human activities in landslide-prone areas have to be carefully evaluated in the planning phase and their potential impact on the groundwater regime and rock stability assessed. Local land use plans and vulnerability maps should list the type of structural development and other activities which cannot be allowed in landslide-prone areas. To secure emergency groundwater sources groundwater tap sites should be chosen well above the expected landslide wall (Fig. 5.5.1) at some distance from the estimated extent of the drumlin, out of the possible reach of the impact of sliding soil and rock material. To expedite rescue activities in the event of a landslide and make them more effective an assessment of groundwater resources surrounding the potential landslide areas should be implemented within the anticipatory and warning phases.

Principles of risk management of such emergency groundwater resources based on hydrogeological investigation, mapping and monitoring have to be formulated in advance to minimise the threat of landslides as well as to ensure emergency groundwater resources for drinking purposes following landslide disasters. The usual disaster responses of importing drinking water in tankers and/or bottled water are effective and help to overcome drinking water scarcity in the immediate aftermath of a landslide disaster; however these are expensive and temporary measures only.

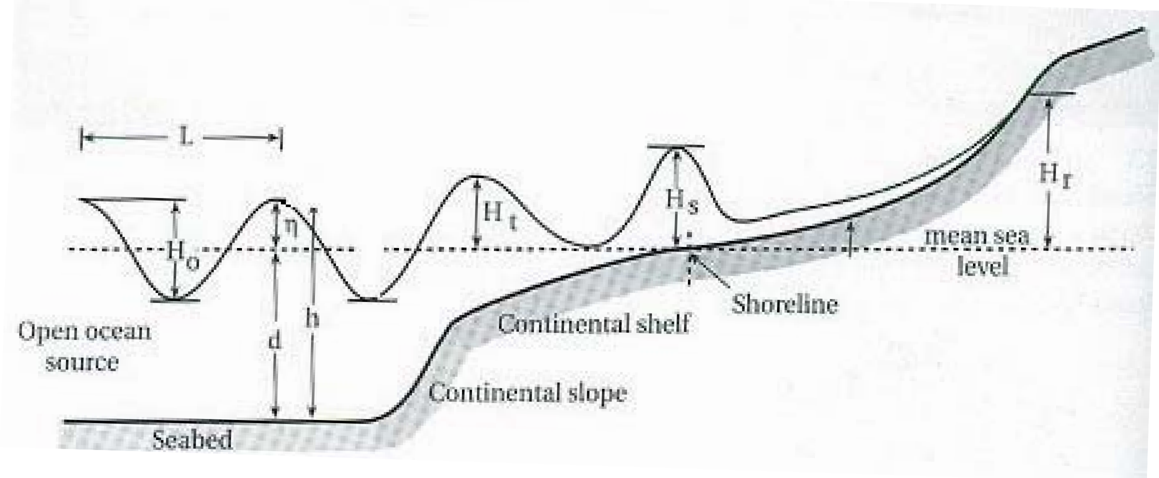
5.6 Tsunamis: risk assessment and management of groundwater resources

Balbir Sukhija

Introduction

Although tsunamis have been a common phenomenon in the Pacific region, with warning stations installed since the latter 1940's, the danger they pose to the Indian ocean regions and individual countries was appreciated fully and world-wide only after the devastating tsunami event of 26 December, 2004. In fact, the term tsunami is of Japanese origin and means harbour (tsun) wave (ami). Tsunamis are massive waves of sea water which move with large energy. They develop from submarine seismic activity (M > 6.5) produced by fault movement, explosive volcanism, a submarine landslide and even by major meteorite strikes in the ocean. A tsunami – resulting from the displacement of water – can be more destructive than the originating event itself and unleash extensive devastation in coastal areas. Tsunami waves are oscillatory (Fig. 5.6.1) with large wave length, or distance between two successive crests, of 10-15 km, and a period of 10–60 minutes the pressure disturbances affecting the entire ocean water column. These waves travel at a speed of some 600 km/hour in the deep ocean, 100-300 km/hour across the continental shelf and about 6 km/hour when approaching the shoreline.

Figure 5.6.1. Various terms are used to express the wave height of tsunami characteristics (Bryant, 2001).
H_0= wave height from crest to trough, H_t = wave height above mean sea level (msl), d = water depth below msl, L = Wave length, h= wave height from sea bed, H_s = wave height of tsunami at shore, H_r = run up height of tsunami



Origin and impact of tsunamis

The destructiveness of tsunamis depends upon the energy released by the causative events. Where it is seismic, it depends on the magnitude of the earthquake, depth, focus, and amount of vertical displacement of the fault. Most tsunamis originate from submarine earthquakes, which cause fault displacement of several meters, strike over of thousands of kilometers and impart tremendous potential energy to the overlying water. This energy, converted into kinetic energy often causes floating objects to travel so fast as to become water-borne missiles. Another important characteristic when making landfall is the transport of sediments and salt water as much as 9–12 km inland for a 40–50 m high tsunami (Hills and Mader, 1997).

Tsunamis can also be generated by volcanoes. It is recorded that the largest volcanic eruption of Krakatoa located in Indonesia during the 1880's, produced a tsunami with run up heights exceeding 40 m above mean sea level. The wave could be detected at the Cape of Good Hope in South Africa some 6,000 km away. Perhaps the most devastating tsunami followed the Santorini Island volcanic eruption around 1470 B.C., estimated to have generated waves up to 90 m height in the Eastern Mediterranean. In the Pacific Ocean region at least five events since 1600 A.D. have produced run up heights between 51–115 m (Brayant, 2001). One very important feature of a tsunami is the suddenness with which it engulfs the coastal areas. It is generally preceded by the sudden and extensive withdrawal of ocean water from the shore. Thus any hazard assessment or risk analysis must take into account the factors of suddenness and huge energy of the waves striking coastal structures such as water supply and distribution lines, waste water treatment plants as well as groundwater resources in shallow coastal aquifers. Another important aspect is the transport of sediments, debris and salt water – of great concern especially where drinking water is supplied from such shallow fresh groundwater overlying highly mineralised seawater.

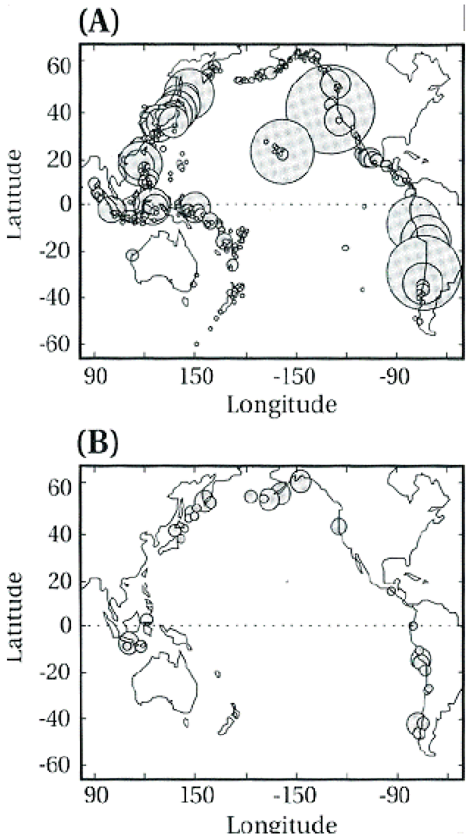
World-wide distribution of tsunamis

As they originate, along with earthquakes, along major submarine faults and volcanic belts, tsunamis are endemic to certain areas of the earth. The regional distribution of tsunamis is shown in Table. 5.6.1 and Fig. 5.6.2 (A and B). About 70% of the globe's tsunamis are found in the Pacific Ocean, the east Indian Ocean region and the Japanese and Russian sea-coasts (Table 5.6.1.). Experience gained and lessons learnt from tsunami events are described below.

Table 5.6.1. Regional distribution of Tsunamis in the World's Oceans and Seas (Source: Bryant, 1991)

Location	*Regional distribution of tsunamis in %*
Atlantic east coast	1.6
Mediterranean	10.1
Bay of Bengal	0.8
East Indian coast	20.3
Pacific Ocean	25.4
Japanese-Russian coast	18.6
Pacific east coast	8.9
Caribbean	13.8
Atlantic west coast	0.4

Figure 5.6.2. Location of tsunamis in the Pacific Ocean region: (A) Location of 1,274 tsunami epicentres since 47 B.C. Size of circle is proportional to the number of events per degree square of latitude and longitude. (B) Source of significant distant (teleseismic) tsunamis. Size of circle is proportional to the area affected and magnitude of the event (based on Lockridge 1985, 1988b; and Intergovernmental Oceanographic Commission, 1999).



Impact of the great Asia tsunami of 26 December 2004 on groundwater

The great Sumatra earthquake (Fig. 5.6.3A), rated as the world's second largest recorded, caused the great tsunami of 26 December 2004 that resulted in the death of 300,000 human lives (Geol. Society of India, 2005) and devastated buildings, roads, water and sanitary structures and electrical installations (Fig. 5.6.3 B) and degraded agricultural lands and soil. The tsunami arrived at the coast of Sumatra within half an hour of the earthquake and after 2 to 3 hours in Sri Lanka. The estimated wave height ranged from 10 to 15 m in Sumatra, several metres in Sri Lanka, India Thailand and even in Africa (Kenya) the waves were 2–3 m high. Satellite pictures of damage were available quickly but it took several days to weeks to re-establish communication networks. UNEP (2005) reports that fresh water flowed out of wells on the Maldives Islands prior to the arrival of the tsunami. Groundwater in shallow aquifers was very heavily impacted, with conductivity increases in the range of >1,000 to 36,000 µs/cm and salinity ranging 500 to > 2,400 parts per thousand. In situ measurements for biological contents showed a high degree of pollution (total coliforms and E-coli >100/100 ml). High nitrates exceeding the permissible limit for drinking water were measured in groundwater and wells were full of solid waste presenting a potential risk to public health.

According to Elango et al. (2006), Keshari et al. (2006), Neupane (2006) and Rajamanickam et al. (2006), the Tamil Nadu coast of India was heavily affected. A study focused on the southern coast of India at Cuddalore, Port Nova, and Nagapattinam and Karaikal found many damaged public and domestic

Figure 5.6.3. (A).The epicentre of the great earthquake of 26 December 2004 which generated the devastating tsunami. (B) A scene of devastation due to the tsunami event in Tamilnadu, India.

(A) (B)

wells. Shallow groundwater was heavily polluted, particularly by accumulated debris providing favourable conditions for the infiltration of pollutants. The chemical composition of shallow groundwater was completely changed following the tsunami. TDS, chloride and EC increased remarkably and the groundwater chemical type changed from HCO_3>Cl>SO_4 to Cl>SO_4>HCO_3. A similar situation was observed for shallow groundwater in Sri-Lanka by Illangasekhere et al. (2006). Several mitigation measures were recommended, e.g. identification of safe aquifers, development of guidelines for the installation of community wells and rain water harvesting structures, and modes of rehabilitation of water supply wells.

Summary of the water supply and groundwater lessons learnt from India, Sri-Lanka and Maldives impacted by the Great Tsunami

(Carpenter, 2005, UNEP, 2005, Elango et al., 2006, Keshari et al., 2006, Neupane, 2006, Rajamanikam et al., 2006, Rajendraprasad et al., 2006, Chidambaram et al., 2007, Ranjan and Ramanathan, 2007)

- Resistivity studies indicated that shallow aquifers had become contaminated by saline water brought by the tsunami, but that deep aquifers were not affected. Maximum impact of salination in aquifers was observed in the following post-monsoon month of August 2005 when surface salts deposits were leached and recharged to the shallow aquifers. Sediments deposited by the tsunami alter the infiltration characteristics.
- Problems were encountered with the emergency use of desalinization plants, as most of the islands such as the Maldives and Sri-Lanka lack the technical and financial resources to maintain the equipment. The use of such plants is unsustainable in such environments and can only be strictly short term.
- Widespread pumping of saltwater-polluted wells was an effective remediation measure but should be controlled to avoid disrupting the fresh water/saltwater interface. The knowledge of interface depth structure can prove valuable for groundwater risk management.
- Waste products and accumulated debris (uprooted trees, dead bodies, metal cans etc.) remobilised by secondary and tertiary waves posed a serious problem by releasing toxic substances to groundwater.

- Heavy metal (Cd, Cu, Cr, Pb and Ni) pollution was also observed in surface sediments and cores and was expected to migrate to groundwater during recharge.
- In the absence of any baseline data (for example the Cuddalore coast, India) on groundwater quality, the impact of the tsunami on groundwater could not be properly assessed. The use of new geophysical tools, space imagery, GIS and modeling provided valuable data for assessment of the impact of the tsunami. These tools also assist groundwater quality management as well as already existing capacities for groundwater quality survey.
- It is vital to identify safe aquifers, which can be used for drinking water and irrigation in emergency situations. Rehabilitation of wells requires great technical effort, enormous financial resources and is time consuming. Options such as rainwater harvesting and developing community wells located beyond the influence of tsunamis could be other important mitigation measures.

Risk assessment and preparedness

Tsunami warning system

The basic objective of setting up a tsunami early warning system is to provide timely publics information and warning especially to coastal inhabitants, by promptly detecting, locating and determining the magnitude of potentially tsunami-generating earthquakes. Generally, the alarm system is triggered by earthquakes of magnitude 6.5 or greater. Basically the system comprises seismic stations, tide gauges and a computer model for real time data gathering to allow at least a one to three hour advance warning to the general public, to the media well as to state and local emergency management officials.

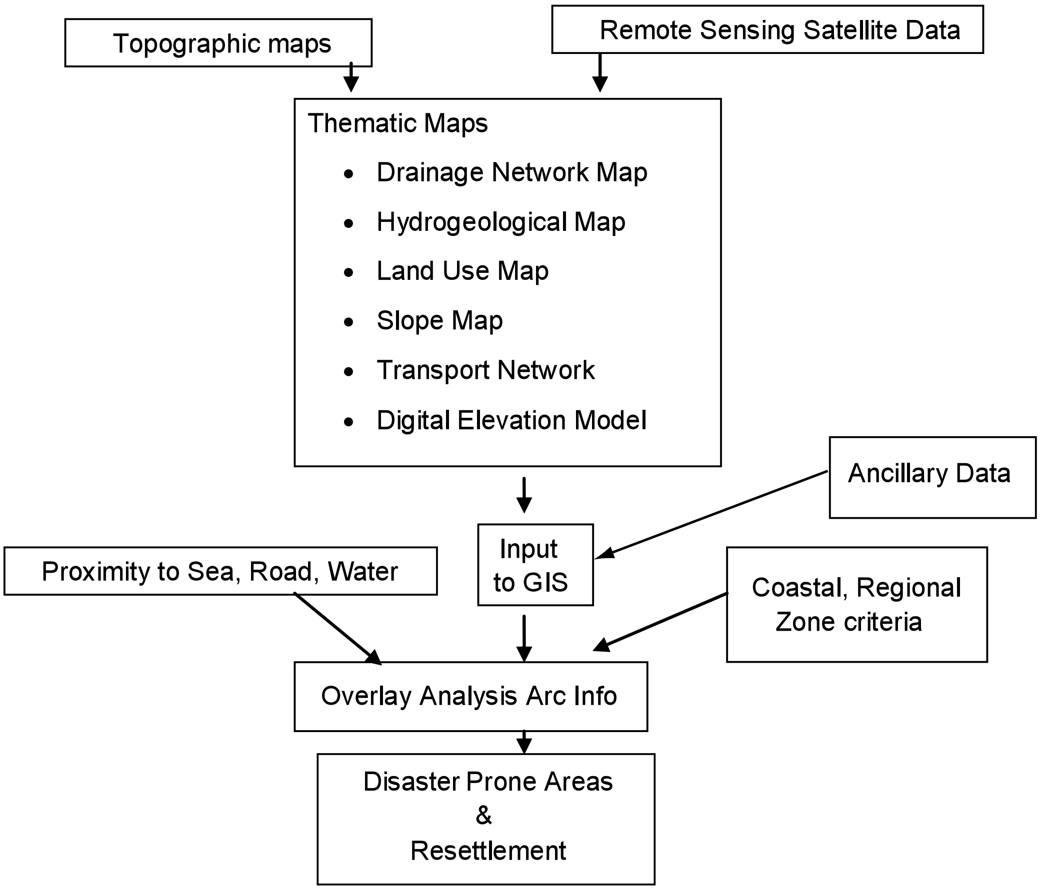
Warning systems such as the Pacific Tsunami Warning Centre and the Atlantic Warning System have been in operation for decades. An Indian Ocean Tsunami Warning System was recently established, (DOD, 2006). As early as in 1964, a warning was issued within 46 minutes of the Alaskan earthquake. About 25 countries located along the Pacific coast now co-operate in the Pacific Tsunami Warning system. However, warning systems have their limitations. There are locations along the Pacific coast where tsunami can strike within 30 minutes if the epicentre of the earthquake is close to the coast.

Vulnerability Maps

Risk assessment for tsunami is generally based on historical records. The recent south Asia tsunami of December 2004 has challenged the belief that historical records are sufficient for estimating the recurrence period of tsunamis. Estimates of recurrence periods are to be based on geological signatures of tsunamis and the use of palaeo-seismological techniques involving dating of transported organic material by radiocarbon and/or OSL (Optically Simulated Luminescence) of sediments (Brayant and Nott, 2001). In addition to the knowledge of recurrence periods, vulnerability maps need to be prepared. These take into account both social and environmental parameters such as population density, topography (especially coastal slope), geomorphology, hydrogeology, presence of natural and artificial barriers, expected tidal range and wave height.

The experience of the 2004 Asian tsunami has shown that vulnerability maps are an important component of hazard preparedness in order to know which aquifers, groundwater resources and water supply systems are more susceptible to the calamity. It has been observed that the impact of a tsunami is severe where the coastal region has a gentle slope, in deltas, in harbours where tsunami waves internally reflect– with damage particularly to public and domestic drinking water supplies. Fig. 5.6.4 shows the different steps in the preparation of vulnerability maps, which are useful for focusing and co-coordinating water supply projects.

Figure 5.6.4. Steps in the preparation of a tsunami vulnerability map (adapted from Arulraj et al., 2006)



Important questions to be answered in risk assessment are:

- To what extent is the drinking water supply in coastal areas dependent on shallow aquifers vulnerable to tsunami impact and are there deep aquifers which are unlikely to be affected by tsunamis that can be developed to serve as an emergency groundwater source.
- What are the mechanisms which may lead to the salinisation of the aquifers: a) through sea water infiltration from inundated land (Fig. 5.6.5), b) increased sea water intrusion, c) salinisation due to salt water infiltration from flooded lagoons and river mouths (Fig. 5.6.6).
- To what extent is the quality of groundwater in the coastal aquifers likely to be affected by tsunamis.
- What models can be applied and how much time will be required to rehabilitate the affected aquifers (IWMI, 2005).

Protective water supply measures

- Public and domestic wells should be protected by covers effectively sealing them against short-term penetration of salt and polluted water.
- Sanitation and waste water collection and treatment systems have to be improved and protected to better resist tsunami impact.
- To meet the drinking water demand during and after emergency, roof top water harvesting and other water conservation structures (chapter 5.2) have to be constructed to serve as emergency water supply as well as for augmentation of groundwater resources, such as through artificial recharge.

Figure 5.6.5. Influence of a tsunami on a costal aquifer, showing infiltration of saltwater from the land surface and water bodies (IWMI, 2005)

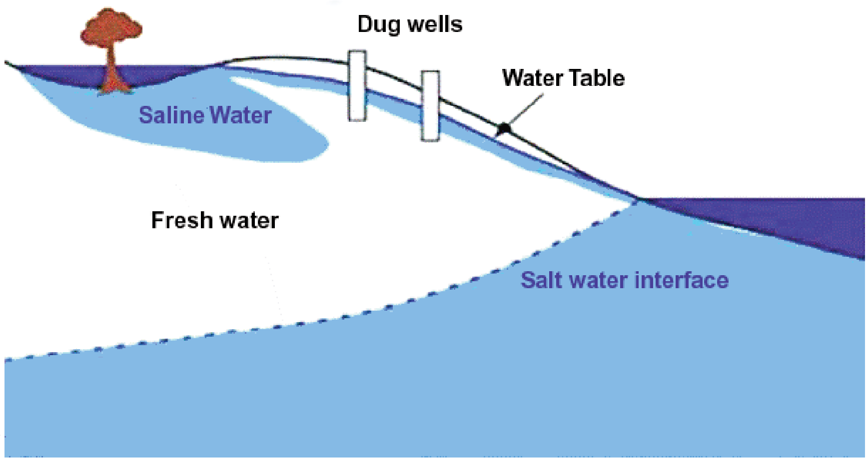
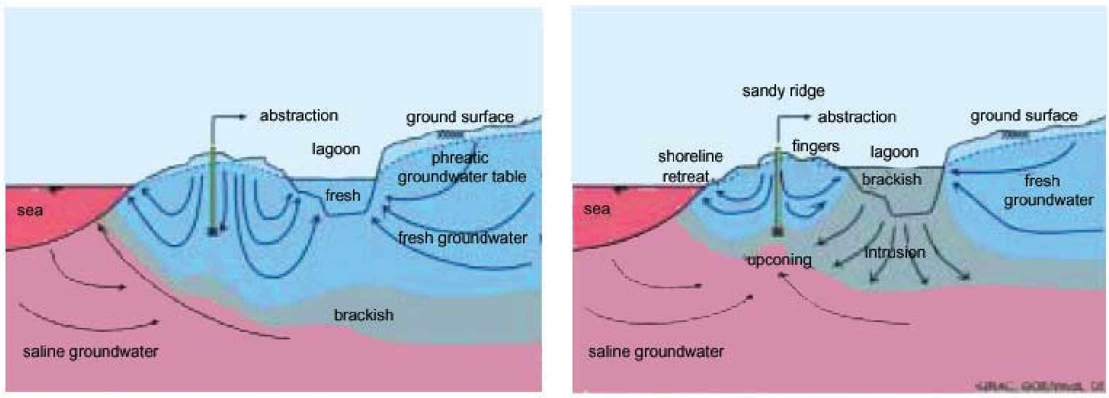


Figure 5.6.6. Influence of the tsunami on fresh water coastal lagoons and associated groundwater prior to and after tsunami (IWMI, 2005)



- The siting, drilling and testing of emergency tube wells with sealed collars
- Reticulation (network) water supply distribution systems should be adequately strengthened/ protected to resist tsunami waves.
- A national and local water resource risk management plan should be developed to ensure safe water in emergency situations in areas prone to tsunami damage. The involvement of local governments and communities, water managers, planners and non-governmental organizations is vital in creating awareness, reducing vulnerability of the population and participating in the implementation of aquifer risk management.

Relief and rehabilitation phases

Relief and mitigation of the impact of tsunami are required to rehabilitate the community especially with respect to their immediate water needs. Three aspects are very important: first and foremost is the evaluation of water requirements for the tsunami affected areas; second is the identification and evaluation of accessible good quality freshwater resources; third is the assessment of physical damage to and pollution of domestic and public water supplies including vulnerable aquifers as mentioned previously (Figs. 5.6.5 and 5.6.6). The immediate assessment of tsunami impact is carried out using space imageries, GPS and GIS and field investigations using mainly hydrogeological, geophysical and hydrochemical methods. The most direct and notable impact is the salinisation and pollution of shallow groundwater by sea water and various wastes and chemicals. Remediation measures may differ depending upon the salinisation/pollution process involved.

The rehabilitation of groundwater supplies affected by the tsunami in Sri Lanka is described in chapter 11.9. The important steps required for mitigating a drinking water crisis are discussed under immediate relief actions and long-term rehabilitation phase.

Relief phase

- Inspect water supply wells for both groundwater level and quality. Data is essential for the designation of methods and techniques suitable for well recovery and aquifer rehabilitation.
- Clean water supply wells by purging salt water, physical removal of debris, disinfect wells and purify water by in-situ chlorination.
- In purging wells care must be taken as excessive pumping may cause seawater intrusion by disrupting the saltwater-fresh water interface resulting in up-coning. Septic tanks should be inspected for possible damage and leakage of waste water and repaired if necessary to prevent groundwater pollution.

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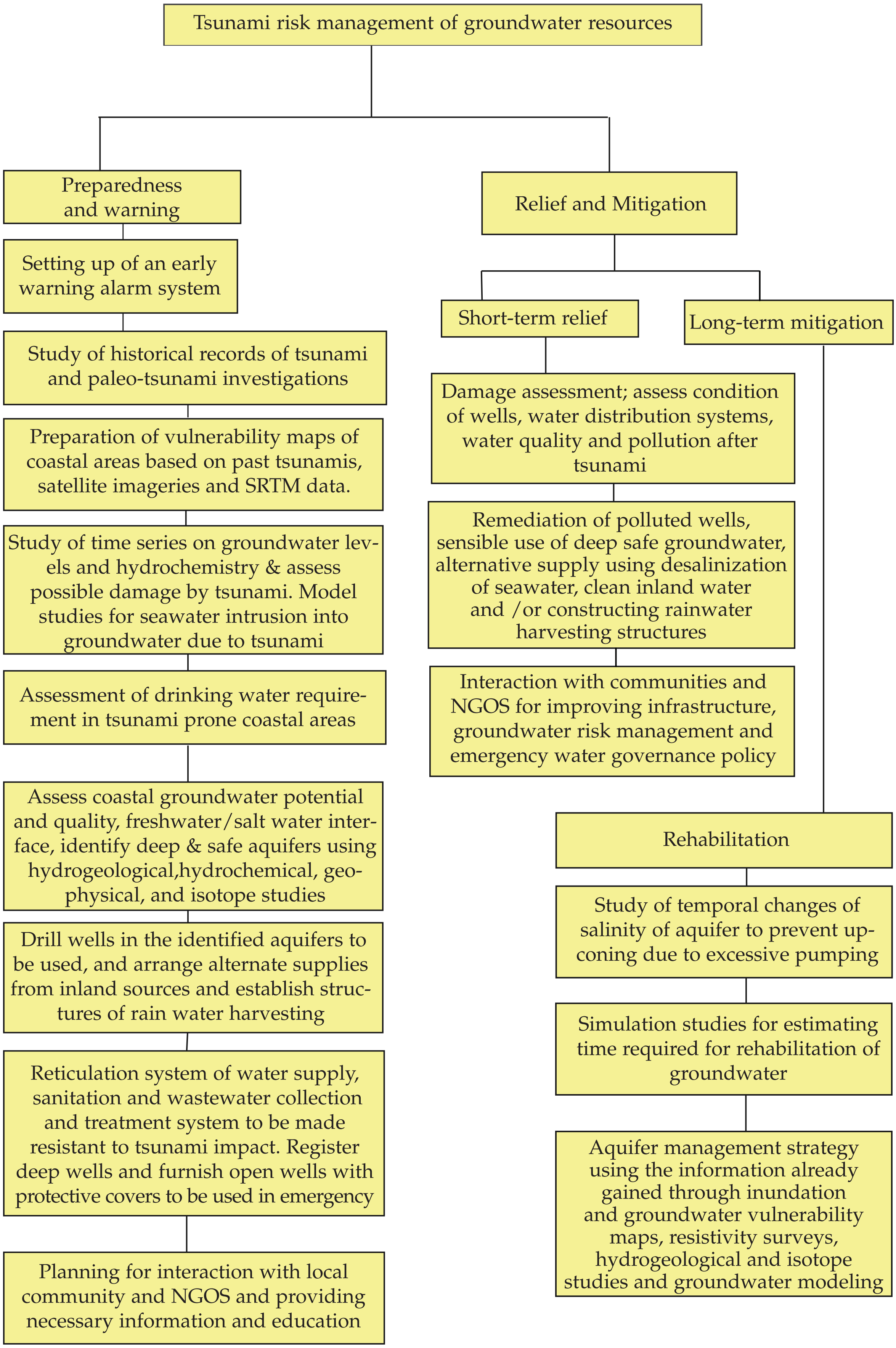
Rehabilitation phase

- The rehabilitation phase involves natural processes, through which groundwater quality is allowed to recover by infiltration of rainwater and surface water. This process may take months and up to a few years where groundwater is polluted by chemicals.
- Observing post-tsunami temporal changes in chemical quality of shallow aquifers helps to prevent up-coning of saltwater due to over pumping.
- Numerical models need to be developed for the tsunami impacted aquifers to estimate the time required for flushing of salinity in the inundated aquifers by simulating groundwater flow and transport of salts using aquifer hydraulic characteristics and boundary conditions. IGRAC (International Groundwater Assessment Centre) has produced simulation models (http://igrac.nitg.tno.nl/tsunami1.html) that estimated that the process of aquifer rehabilitation takes in the order of several years for groundwater to regain its pre-tsunami groundwater chemical composition. However, it should be pointed out that this simulation was carried out following the 2004 Asian tsunami under several assumptions and uncertainties, such as insufficient knowledge of hydrogeologic parameters, amount and pattern of pumping, rate of leaching of salts through zones of low permeability, disruption of the fresh water lens and contribution from polluted surface water bodies. Nevertheless, the outcomes from simulation models are valuable for future guidance.
- Post - tsunami information gained through maps of inundated areas, groundwater vulnerability and groundwater quality maps, resistivity and other relevant surveys are useful in designing aquifer risk management strategy in emergency situations.

The following flow chart summarises tsunami risk management of groundwater resources.


Tsunami risk management of groundwater resources
Preparedness and warning
Setting up of an early warning alarm system
Study of historical records of tsunami and paleo-tsunami investigations
Preparation of vulnerability maps of coastal areas based on past tsunamis, satellite imageries and SRTM data.
Study of time series on groundwater levels and hydrochemistry & assess possible damage by tsunami. Model studies for seawater intrusion into groundwater due to tsunami
Assessment of drinking water requirement in tsunami prone coastal areas
Assess coastal groundwater potential and quality, freshwater/salt water interface, identify deep & safe aquifers using hydrogeological,hydrochemical, geophysical, and isotope studies
Drill wells in the identified aquifers to be used, and arrange alternate supplies from inland sources and establish structures of rain water harvesting
Reticulation system of water supply, sanitation and wastewater collection and treatment system to be made resistant to tsunami impact. Register deep wells and furnish open wells with protective covers to be used in emergency
Planning for interaction with local community and NGOS and providing necessary information and education
Relief and Mitigation
Short-term relief
Long-term mitigation
Damage assessment; assess condition of wells, water distribution systems, water quality and pollution after tsunami
Remediation of polluted wells, sensible use of deep safe groundwater, alternative supply using desalinization of seawater, clean inland water and /or constructing rainwater harvesting structures
Interaction with communities and NGOS for improving infrastructure, groundwater risk management and emergency water governance policy
Rehabilitation
Study of temporal changes of salinity of aquifer to prevent upconing due to excessive pumping
Simulation studies for estimating time required for rehabilitation of groundwater
Aquifer management strategy using the information already gained through inundation and groundwater vulnerability maps, resistivity surveys, hydrogeological and isotope studies and groundwater modeling

5.7 Groundwater risk assessment and management in regions affected by storms

Balbir Sukhija

Introduction

Storms may be defined as high velocity wind systems generated by large scale atmospheric pressure patterns across the surface of the earth. The hazards associated with storms include ocean storm surges, high winds and torrential rain. Depending on geographical and meteorological characteristics and intensity in different regions, large and intense storms are called cyclones, typhoons, hurricanes or tornadoes. Tropical cyclones are defined as intense cyclonic storms that originate over warm tropical seas. In North America, they are called hurricanes and are characterised by strong winds which are likely to damage in particular taller structures and those with large exposed surfaces. In Japan and South East Asia, tropical cyclones are called typhoons. Fig. 5.7.1 shows the areas of occurrence and number of tropical cyclones per year for the period 1952–1977. Strong tidal surges (several metres high) , strong winds (exceeding 300 km/hr) and high rainfall, often exceeding 1000 mm per day) in coastal areas, are common and have enormous impact on populations with loss of lives, inundation of low lying areas damage to houses, buildings and infrastructure, crop destruction, and pollution of water resources.

Heavy rainfall may be responsible for floods, land slides, and mud flows that may render millions of people homeless.

A new study by U.S National Centre for Atmospheric Research shows the increasing trend in frequency of Atlantic storms, linking them to recent global warming (Fig. 5.7.2).

Figure 5.7.1. Global annual distribution of tropical cyclones indicated by their numbers in different regions during 1952–1977 (after Gray, 1975)

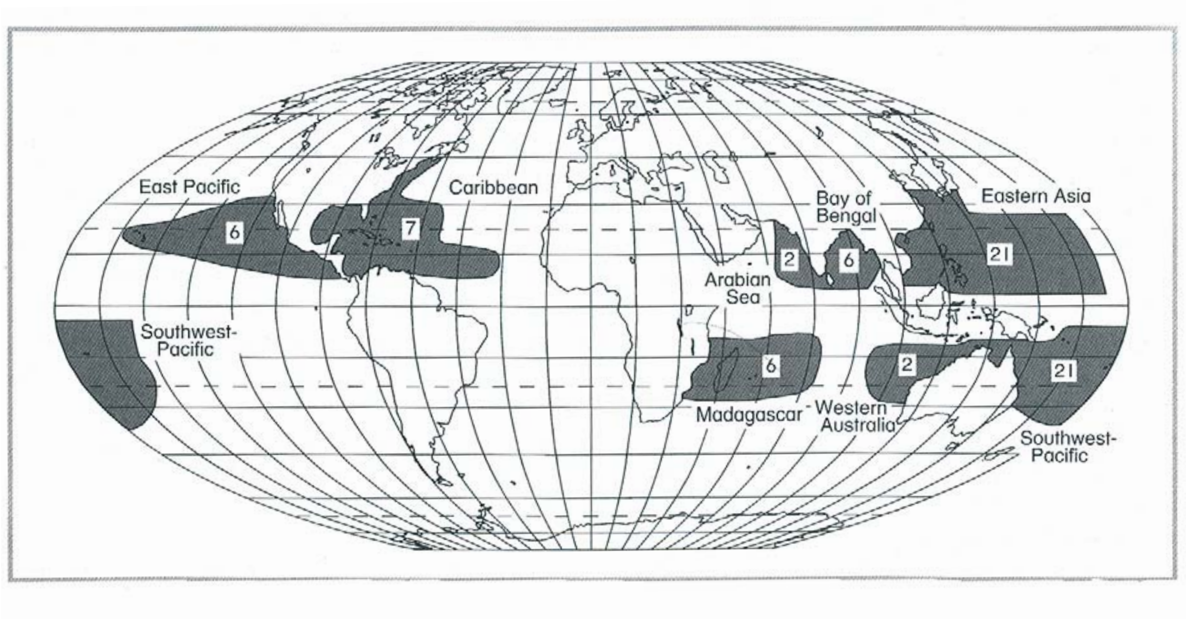
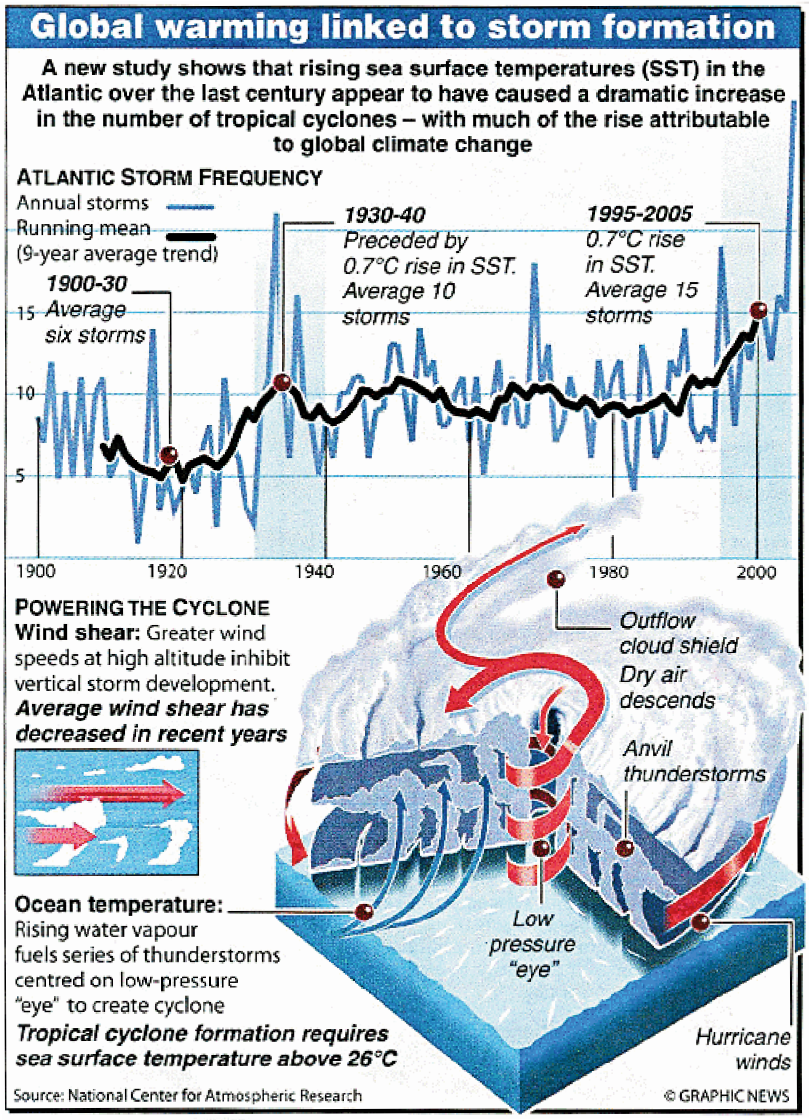


Figure 5.7.2. Global warming linked to increased frequency of storm formation in the Atlantic region (Source: US National Centre for Atmospheric Research, 2005)



Magnitude and intensity of storms

Taking into account the severity of the three characteristic components of a storm, intensity of storms is defined in the scale of 1-5 as given in Table 5.7.1.

There are at least four cyclones in recorded history that each as a single event killed over 300,000 people; three of them occurred in the Indian sub-continent. The most destructive cyclone in the twentieth century occurred in Bangladesh in November 1970 killing 500,000 people mostly by storm surge i.e. flooding by sea water rather than direct storm impact.

Table 5.7.1. Scale of storm intensity

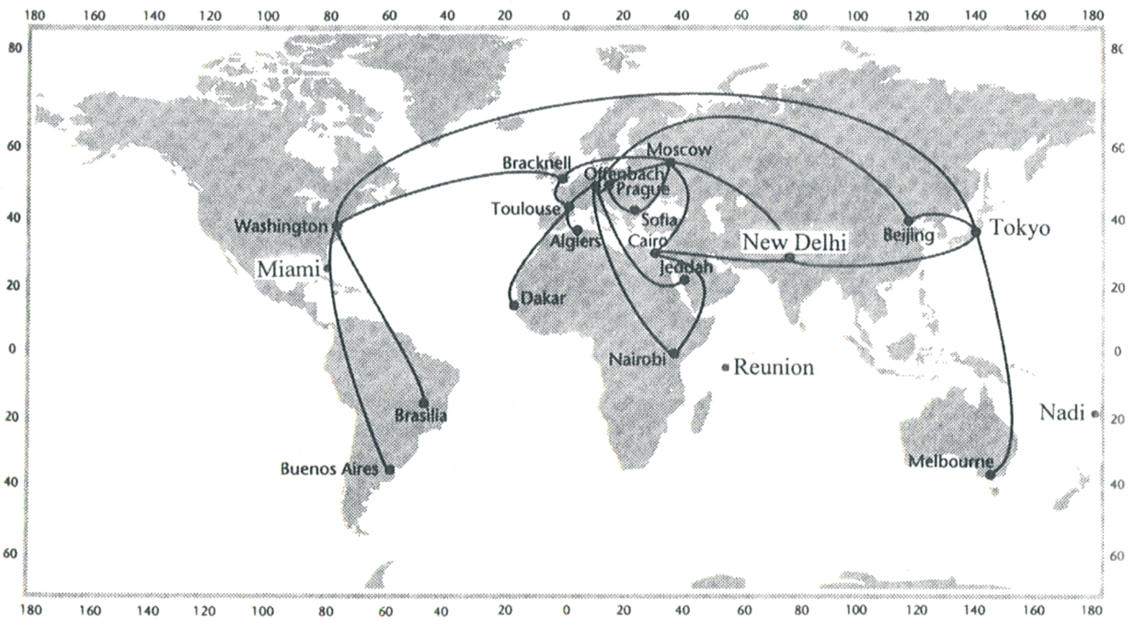
Saffir-Simpson Scale	*Wind speed (km/h)*	*Storm surge height (m)*	*Strongest gusts (km/h)*
1	119–153	1.2–1.5	125–170
2	154–177	1.8–2.4	170–225
3	178–209	2.7–3.6	
4	210–249	3.9–5.5	225–280
5	>249	>5.5	>280

Risk assessment and early warning systems

Preparedness and safety measures undertaken on the basis of a risk assessment of likely damage from storm surge, high wind velocity and torrential precipitation in a given region may reduce the impact of storms. The potential damage suffered by communities depends on the combined intensity of the three factors mentioned above but also on the specific local factors such as physiography, distance from sea, land use, infrastructure, presence of natural or artificial barriers, type of construction of buildings, and density of population. In this, the impact of such storms has much in common with tsunami. All the above factors have to be considered in risk assessment evaluation.

Recent development of space and communication technology and better understanding of the evolution of tropical cyclones and other severe storms has led to much better, earlier and efficient forecasts and early warning of such extreme climatic events. The approach essentially involves the prediction of the track and intensity of cyclones using conventional as well as satellite and radar based techniques. However, early warning systems must be designed in close co-ordination with rescue structures dealing with humanitarian concerns and especially with the involvement of the local population which has to receive and understand the content of the warning. Fig. 5.7.3 shows the main

Figure 5.7.3. The main network (solid lines) of a global telecommunication system of WMO World Weather Watch which links the network of world and regional/specialised meteorological centres



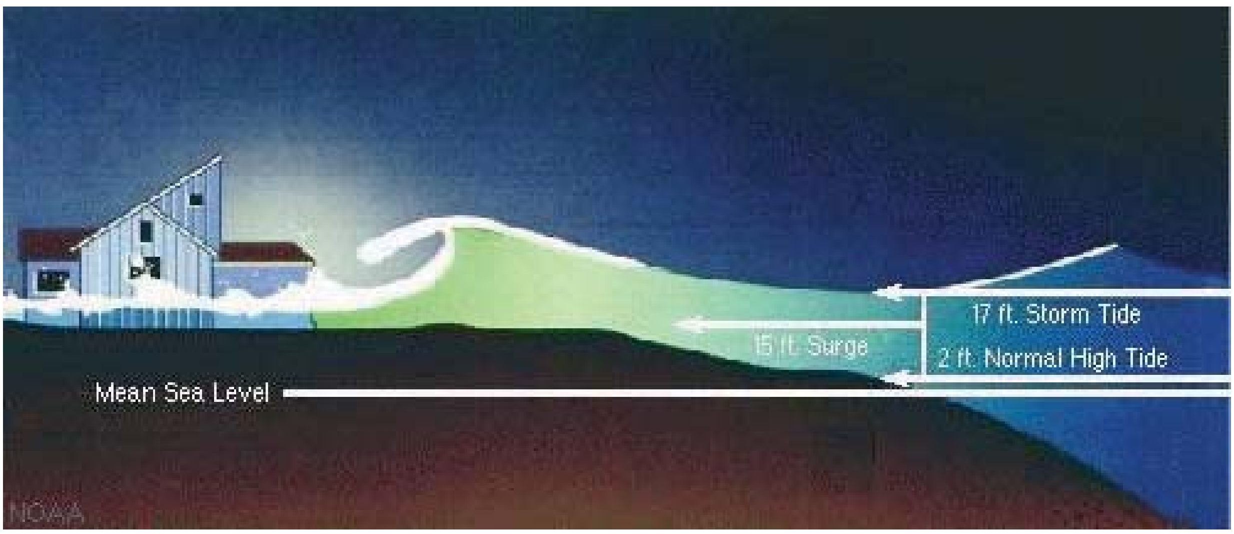
network of a global telecommunication system of WMO World Weather Watch. An effective warning system incorporates knowledge based on risk assessment and analysis of vulnerability to major storms which in turn can be improved through up to date mapping of flood plains, likely storm surges, changes in land use and protection of water facilities.

Impact of storms on water supply systems

Depending upon the intensity of storms, topography, and natural or artificial barriers, sea water inundation can occur up to several tens of kilometres inland from the coast. The devastation affects infrastructure, agriculture, natural vegetation, water supply systems and beaches. The experience from the recent two Indian cyclones (the 1977 cyclone of Andhra Pradesh and the 1999 Super cyclone of Orissa) indicates the profound effect on coastal surface water and shallow aquifers and dug wells. From spot chemical measurements carried out by the Central Ground Water Board (CGWB) of India, an increase in electrical conductivity, chloride and bacterial pollution was observed in more than 50% of dug wells of post-cyclone groundwater values in comparison to average values over the 10 years (1989–1999) preceding the 1999 Orissa Super cyclone (Narasimha Rao, 1999). Storms may affect water supply and distribution systems and groundwater in the following ways:

- Flooding of water structures such as water supply wells and their pollution with saline water and other pollutants due to tidal surge (Fig. 5.7.4).
- Diffuse pollution of groundwater in shallow coastal aquifers.
- Rupture and failure of water distribution pipelines due to subsidence of the underlying terrain produced by flooding in water-logged areas and damages to water supply facilities (e.g. treatment plants) by force of wind and heavy rains.
- Damage to water facilities by landslides caused by flash floods and reduced slope stability.

Figure 5.7.4. A schematic view of tidal surge of about 5 m after the normal high tide level as a consequence of a cyclone in a coastal area



Importance of data for the assessment of storm impact on groundwater

Base line data on groundwater level and quality as well as other fresh water resources in the coastal areas is a prerequisite for the assessment of storm impact on groundwater resources. It is important to draw up an inventory of all the possible water sources especially ground water supply sources, evaluate their chemical and biological parameters, and designate methods for their protection against storm events. It is important also to study the chemical parameters of groundwater immediately after the cyclone to obtain a realistic picture of the deterioration of groundwater quality. The changes in electrical conductivity, chloride and bacterial pollution are the principal parameters which can be readily measured and analysed. Prior hydrogeological and geophysical investigations should have been implemented to delineate the lateral and vertical extent of fresh water zones and the fresh/salt water interface in particular (Radhakrishna, 2001). Isotope and geochemical methods (Kulkarni et al., 1997) will provide support in understanding the groundwater system especially up to what depth and areal extent the aquifers are vulnerable to storm disaster and which aquifers can be utilised during emergency.

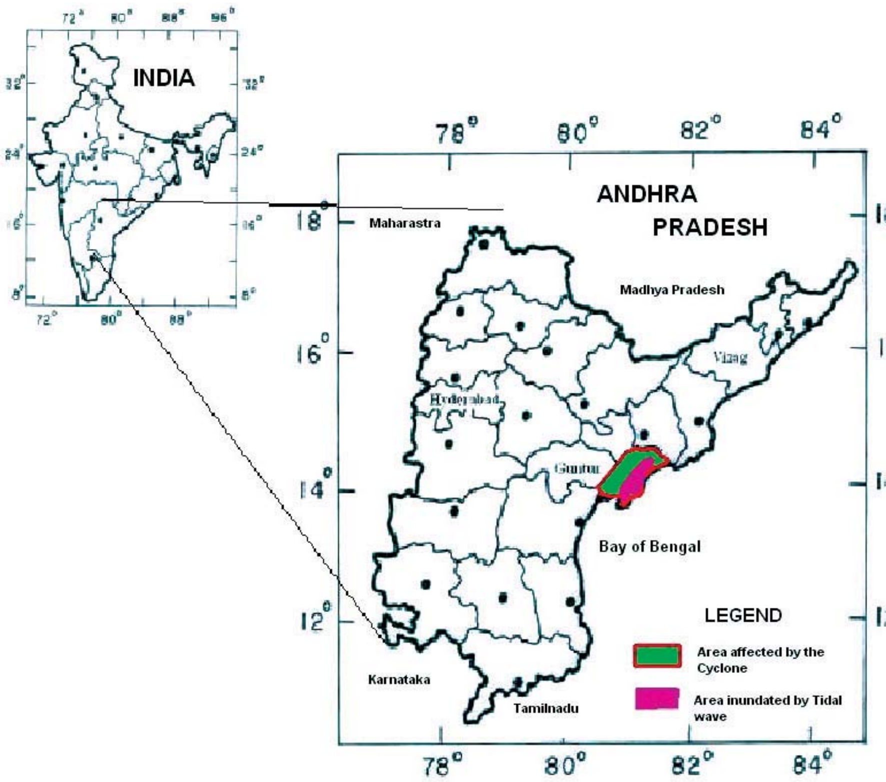
A lesson from Andhra Pradesh, India is presented here to illustrate the methodology. A detailed case study on the impact of a cyclone on groundwater resources is presented in the chapter 11.5.

The mitigation phase –experience gained from a storm in Andhra Pradesh, India

Experience from Andhra Pradesh, India is presented here as a lesson illustrating the methodology applied in the mitigation phase of storm disaster.

On November 19, 1977, the coastal area of Andhra Pradesh in south-eastern India, experienced a severe cyclonic storm followed by a storm surge. (Fig. 5.7.5). The combined effect of high winds, storm surge

Figure 5.7.5. Map of Andhra Pradesh, India, showing the area affected by the cyclone and tidal wave of November 1977, where technical assistance was rendered during relief operations by the Central Ground Water Board



and precipitation, resulted in a catastrophe and devastation hitherto unknown to the local people. The tidal wave of a great magnitude inundated a large area of Diviseema, a part of Bander and of the Krishna district leaving people without drinking water. The cyclone and the tidal wave paralysed life in an area of 900 km^2, up to about 30 km inland from the coast of the Bay of Bengal.

The surfacial deposits of the affected area consist of deltaic and coastal sediments of sub- recent to recent age comprising fine sand, clays and silts. Fresh ground water under water table conditions is located in shallow aquifers and developed by means of dug wells, shallow tube wells and filter points. From subsequent hydrogeological and geophysical surveys (Raghav Rao, 1978) it was learnt that ground water occurs in lenses and pockets at depths ranging from one metre to 14 m below ground. No extensive shallow aquifers with fresh water were identified. However, deep resistivity surveys carried out at 8 selected locations yielded 4 promising sites with significant aquifers down to 300 m depth under confined conditions. At about 300 m, however, groundwater became brackish with chloride 4,000–6,000 ppm. Post cyclone investigations led to the mitigation of the severe drinking water shortage and quality problems in two ways; firstly by delineating local shallow fresh water aquifers for sinking water filter points for emergency use which can be developed by hand pumps and secondly the high yielding deep aquifer (down to 300 m) was explored for longer-term use by more than 100 villages covering an area of 1,550 km^2.

Groundwater resources: Summary of storm impact mitigation measures

- Storms, in common with tsunamis, are responsible particularly for damaging the coastal environment. Most of the risk assessment steps and management approaches to both types of disaster are similar.
- The three most important components of storms: strong tidal surges, huge wind velocities and high rain fall can cause floods and even land slides and a huge influx of salinity to shallow coastal aquifers. These in turn directly impact coastal infrastructure, water supplies and water distribution facilities and the quality of groundwater .
- An early warning system based on space satellite and radar communication technology can lead to more efficient forecasting and better risk assessment and vulnerability analysis in terms of likely storm surges, extent of flooding, areas impacted, damage to water supply facilities and an evaluation of water requirements based on population numbers in the disaster-prone area.
- In order to provide a better assessment of the impact of storm on a groundwater system, it is important to have data from a prior study of coastal aquifers, especially on their vertical and lateral extent (aquifer geometry) along with baseline chemical characteristics of groundwater.
- Wells should be appropriately located and constructed with respect to potential storm impact, and the depth and areal extent of freshwater/saltwater interface be delineated by geophysical and hydrochemical measurements.
- Care must be taken to avoid saline water ingress to the well by relevant well construction, protection of the well head and maintaining an appropriate pumping rate.
- Monitoring of chemical and biological quality of both shallow and deep aquifers needs to be carried out by regular groundwater sampling following immediately after the storm to recognise the difference in groundwater chemical composition and storm impact on groundwater quality in water supply.

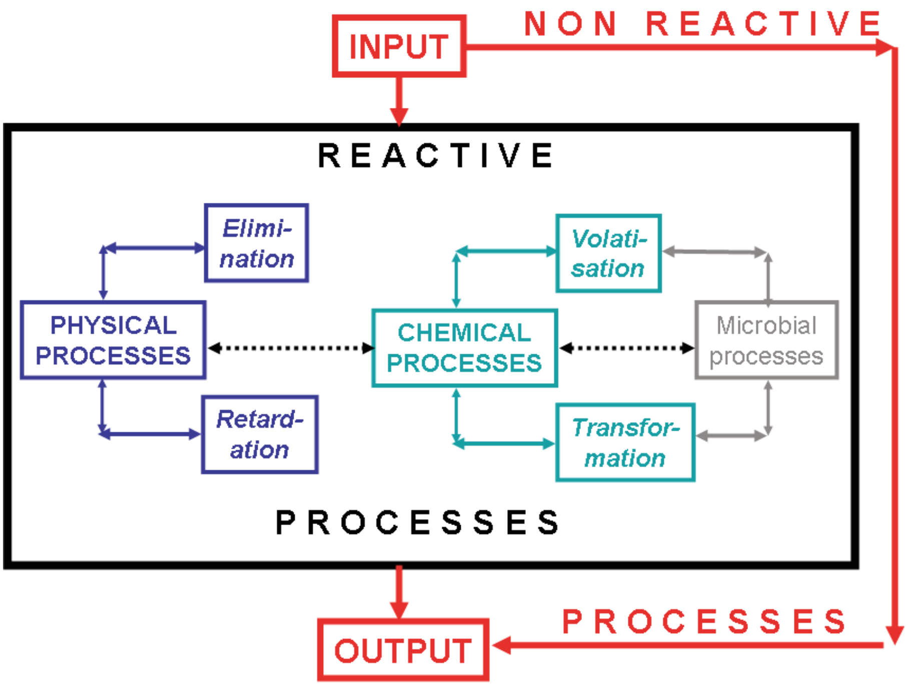
6. Protection of emergency groundwater resources

Klaus-Peter Seiler and Jaroslav Vrba

Groundwater is exposed to a variety of influences resulting from natural disasters and human activities. These often lead to a deterioration of the quality of groundwater and restrictions to its availability. These in turn may adversely affect human health and become life-threatening. The conservation of ground-water quality for the needs of populations and ecosystems should be a high priority, specifically in emergency situations.

All dissolved substances undergo a decrease in concentration through dilution and dispersion in the subsurface (eq. 6.1) and reactive chemicals additionally by retardation and elimination, sorption/desorption and mechanical filtering as well as by species transformation (Fig. 6.1). All these physical and chemical/biotic reactions have specific kinetics, depending on environmental boundary conditions

Figure 6.1. ***The fate of dissolved substances in the subsurface. Along their different pathways, both reactive and non-reactive chemicals undergo hydrodynamic dispersion whereas reactive substances also experience physical, chemical and microbial changes.***



such as ζ-potential (bulk electric surface charge of aquifer material), pH, Eh, temperature and the geometry of the pore space. Therefore, they are often difficult to estimate quantitatively. Further, the metabolite chain of about 85% of organic pollutants is not really known. A unified groundwater protection scheme is, therefore, difficult to devise. Rather, regulations for the storage, handling and application of specific chemicals have been developed in support of the aforementioned mechanisms and apply according to the nature and intensity of natural disasters.

These processes are summarised in the general dispersion equation:

$$\frac{dC}{dt} = D_L + \frac{d^2C}{dx^2} + D_{Ty}\frac{d^2C}{dy^2} + D_{Tz}\frac{d^2C}{dz^2} - v\frac{dC}{dx}$$

$$D = \alpha v + \beta D_{molecular} \tag{6.1}$$

where:

C= concentration [g m^{-3}], D=dispersion coefficient [m^2 day^{-1}], v = apparent groundwater flow velocity [m day^{-1}], t = time [day], subscripts L=longitudinal, $T_{y,z}$ = transverse in y- or z-direction, α = dispersivity [m], ß = tortuosity [-].

General and special groundwater protection

The concept of groundwater protection was first developed to keep pathogens out of drinking water supply; similar rules were later followed for chemicals in combination with matter-specific handling regulations and a special monitoring programmes. Many countries have a long tradition of groundwater protection responding to two challenges:

- **General protection** of groundwater optimised for the present and into the future. Its goal is to support natural attenuation taking resilience capacities into account, in particular for recharge and other vulnerable parts of the catchment area of aquifers, which often extend over several hundreds or even thousands of square kilometres. Human activities (agriculture, deforestation, urbanization) within these areas may be partially or fully controlled by relevant regulations.
- **Special protection** of a well or a group of production wells to guarantee high level water quality for drinking water supplies to secure human health and ecosystem conservation. Protection measures are applied in restricted protection or sanitary zones, securing any production well or well group from pollution sources. Protection areas usually consist of two zones, with different levels of protection against, and restriction of, human activities. Delineation of protection zones is based on the travel time/distance concept and their designation in a country's water legislation and relevant water supply protection regulations.

  The delineation of the **first degree wellhead protection zone** (also called capture zone) is usually arbitrary, however its extent is small (usually a radius of the order of at most 20−50 m) and covers the area around the water supply source. The zone is protected against unauthorised access by a fence. In the first zone all human activities which are not related to groundwater abstraction are not permitted. The zone serves particularly for protection of the source against physical damage and possible direct entry of pollutants.

  The **second degree protection zone** is often divided into an inner and an outer protection zone. The first, also called the zone of influence, is usually delineated according to the surface projection of the limit of the cone of depression. Its extent is related to the amount of water abstracted from the water well (authorised abstraction rate) and depends as well on hydrogeological conditions (type and geometry of the aquifer, groundwater recharge rate) and aquifer properties (transmissivity, hydraulic conductivity, effective porosity) which control both groundwater flow direction and velocity and therefore the horizontal flow time. In case of emergency wells temporal intensive, unsustainable groundwater abstraction has to be considered and its potential influence on groundwater and ecological systems has to be considered and calculated. Three dimensional groundwater flow modelling can be applied for delineating protection zones if relevant data (e.g. vertical aquifer permeability, hydraulic head variation) are available. However, some uncertainties should always be considered in groundwater protection zone delineation. Groundwater protection zones are defined for both confined and unconfined aquifers but a different hydrogeological approach is needed for their delineation (see following text of the chapter). The inner zone protects groundwater against pathogenic contamination. 50 days is considered a reasonable transit time, a value often applied to delineate the inner zone even if bacteria and viruses may survive in the subsurface environment for hundreds of days (see next subchapter).

The **outer protection zone** includes vulnerable areas of the aquifer from which groundwater resources are exploited and particularly aquifer recharge areas which often cover hundreds of square kilometres. Land use for agricultural and other purposes, particularly industrial or mining areas as well as inundation and other disaster risk areas have to be identified, delineated and their risk for groundwater pollution evaluated. However, recharge areas are not homogenous; they often need to be sub-divided. Different groundwater protection criteria can therefore be applied for their subdivision, based on natural conditions, type and intensity of agricultural, industrial and other human activities and potential risk and impact of natural disasters. Recharge areas, particularly those receiving high precipitation, with sandy soils, groundwater level close to the surface (less than 3 – 4 m) and an unsaturated zone composed of highly permeable sediments (e.g. fluvial deposits) are highly susceptible to diffuse nitrate pollution. In such areas agricultural activities have to be controlled or even prohibited, or require the conversion of arable land to grassland. Some highly vulnerable groundwater protection zones can be afforested. Generally, the outer protection zone should be as small as possible but but of adequate extent.

The approval of groundwater protection zones is an interdisciplinary process the implementation of which depends on legislative, hydrogeological, ecological, social-economic and political measures. In many countries, guidelines for the establishment of groundwater protection zones have been formulated and are part of the legal instruments for water protection policy and water governance emergency policy.

Establishing a conceptual model of a groundwater system is a base for both general and special groundwater resources protection and the delineation of protection zones. Crucial factors and data needed for model development are described in chapter 4.7.

Groundwater protection against microbiological and chemical contamination

Since the beginning of the 20th century general groundwater protection has played an important role in many safe (drinking) water supplies. During the first half of the century measures focused on biological protection, in the second half the emphasis shifted also to groundwater protection against chemical pollutants generated by agriculture, industry, mining, households, traffic and other human activities.

Various studies in the 1980s resulted in the rule-of-thumb (Pekdeger and Matthess, 1983) that a groundwater travel time of 50 days, the maximum lifetime of bacteria in humid moderate climates, efficiently protects the quality of groundwater supply against pathogenic micro-organisms in both normal and emergency water supply situations. Such protection measures have successfully been established and no significant microbiological problems have ever been reported from such protected wells, except in cases of mismanagement.

Protection of groundwater supply against chemical contamination, however, is not as simple to achieve. A conceptual model with boundary conditions and intrinsic data is usually established for shallow groundwater allowing for a good approximation of chemical groundwater protection with analytical flow models and numerical flow/transport models, based on traditional hydrogeological mapping and groundwater monitoring data. For emergency (deep and mostly confined) groundwater resources, this data base is often insufficient, leading to uncertainties in the prediction of natural and human impacts and the behaviour of contaminants, which cannot be improved by the usual groundwater monitoring, but must be assessed by site-specific and early warning monitoring systems.

Special hydraulic conditions in emergency groundwater exploitation

It has been stated in previous chapters that a deep and mostly confined aquifer is considered as a safe water supply source in emergency situations. High mean residence (or turnover) times of its groundwater imply that:

- its recharge rate is low, has lowest flow velocities and mostly low vulnerability. As such aquifers often represent major storage, the dilution potential is high: its reactions are hydraulically transient, if traditional groundwater management strategies apply, which orient on well yields and the over-all groundwater recharge;

- the hydraulic flow field is directed towards the exploitation well, thus differing significantly from that of wells in the active recharge zone and therefore differ respectively both in the size and regulatory measures of protection zones.

Once deep groundwater is exploited for water supply controlled by traditional management methods, its naturally low pressure gradients are stressed, thereby breaching natural, hydraulic barriers between shallow and deep groundwater. This enables the migration of pollutants from shallow towards deep aquifers. Shallow aquifers are highly vulnerable to floods, storms and tsunami which often introduce various types of chemical pollutants.

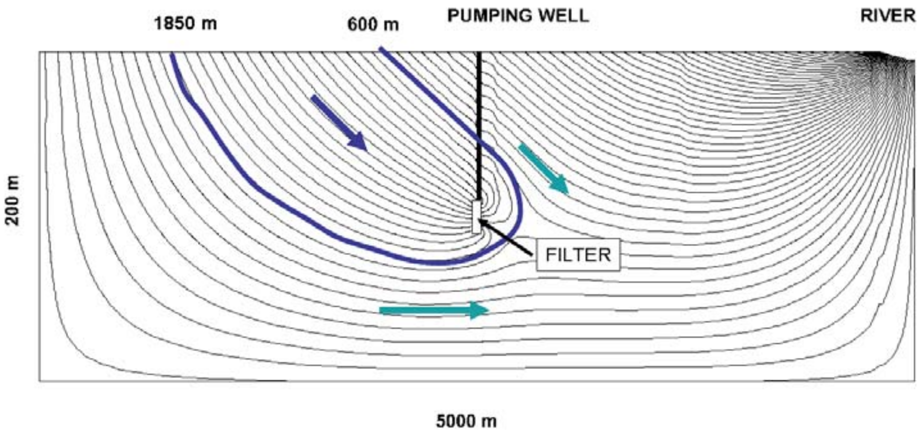
- This may remain unnoticed for a good number of years, decades or even centuries, due to the long-term transient hydraulic response of the aquifer system to hydraulic stress.
- Standard monitoring procedures show that, in that period, a long term impact on deep groundwater quality has already been established at the well site, which is difficult to remediate.
- Simultaneously, downstream of the pumping site, major and often irreversible degradation of water quality has developed on an areal scale.
- As can be seen from Fig. 6.2, the deep-sited filter of the pumping well draws in shallow groundwater from up-stream recharge - hence, pollution sources in the immediate vicinity of the well head hardly influence the pumping well.

Hydraulic short cuts are enhanced where earthquakes, landslides and volcanic activity disrupt sediment/rock fabrics.

The hydraulic inflow area during deep groundwater exploitation

Deep groundwater is always extracted through a deep well screen and pump connected to the well head by a riser pipe. This deep extraction creates a hydraulic inflow field (Fig. 6.2) similar to that of a Ranney well (Nemecek, 1961). For a homogeneous aquifer with a groundwater abstraction

Figure 6.2. Modeled streamlines representing the geometry and width of the inflow parabola to a well in a homogeneous aquifer with rectangular boundaries, extracting 25% of the all-over groundwater recharge from 100 m depth. Natural groundwater flow is from left to the right. At distances 1,850 m and 600 m from the well head the two boundary stream lines are at land surface, defining the area from which pollutants would reach the point of extraction.



amounting to 25% of the all-over groundwater recharge, apart from well head protection, requires a groundwater protection zone, ranging from 600 m to 1,850 m upstream of the production well head (Fig. 6.2). Pollutants entering either upstream or downstream from this zone will by-pass the deep-sited filter of the production well (Fig. 6.2). Considering an inhomogeneous aquifer system the boundary stream lines of the inflow parabola extend even further upstream than shown for the homogeneous aquifer. The area of inflow is in contact with shallow groundwater over extended areas of the upstream part of the catchment. This means in practice, that:

- a correctly constructed well with relevant deep screening does not require a protection zone close to the well head apart from physical protection of the well head installation;
- as deep exploitation alters the groundwater flow field within the inflow area and also downstream, production well protection should cover the catchment both upstream and downstream of the production well.

In the case of both homogeneous and inhomogeneous aquifers, the width of the inflow parabola (Fig.6.2) depends only on exploitation relative to the over-all groundwater recharge The axis of the inflow parabola moves further upstream with increasing filter depth.

This simple modelling example for steady-state conditions represents many model runs and underlines the difficulty of exactly defining special protection zones for deep/emergency groundwater exploitation. This difficulty is compounded by:

- transient hydraulic responses of deep groundwater to all changes in hydraulic boundary conditions;
- potential vertical short cut pathways between shallow and deep groundwater (see below).

Therefore every protection measure for a deep-sited emergency water supply or deep groundwater exploitation in general must be associated with an early warning system.

Indicators for and application of an early warning system

Many early warning systems are focused on the unsaturated zone and aimed at detecting the pollution plume before it reaches groundwater level and the saturated zone. In addition, so-called environmental or stakeholder tracers assist in defining, and indicate changes within, the groundwater flow and transport field. Such changes cannot be noticed in groundwater level observations, because they refer to rapid pressure equilibration and not to slow mass transport. Such largely non-reactive, environmental tracers/indicators, which significantly support emergency groundwater protection policy, are, i.e.:

- radioactive isotopes (^{3}H, ^{39}Ar, ^{14}C), as well as
- stable isotopes (^{2}H, ^{18}O) and noble gases and
- chloride.

These occur in both shallow and deep groundwater at concentrations depending on their radioactive half-life, input (eg. thermonuclear) or processes reflecting past climate conditions during groundwater recharge (chapter 4.4).

These tracers can be used in both simple qualitative, and sophisticated quantitative, ways:

- Radioactive environmental tritium and carbon-14 are considered an excellent pair of non-reactive subsurface indicators to recognise 'young' groundwater infiltration to deep groundwater wells in both hemispheres. Under real or quasi-undisturbed groundwater conditions all tritium bearing water falls in the area of young and all tritium-free waters in the area of old groundwater (Fig. 6.3). Measurable tritium together with low ^{14}C contents indicates mixing of young, recent recharge with old groundwater hence a hydraulic disturbance of the natural flow field, which may endanger water quality.
- In South Germany long term ^{14}C measurements from deep groundwater extraction are available

Figure 6.3. Schematic presentation of the occurrence of tritium (^{3}H) and radiocarbon (^{14}C) in a non-stressed groundwater body sampled at shallow depth (recent or 'young') and at depth ('fossil'), both with a groundwater table close to the land surface. Shallow groundwater contains ^{3}H (> 0 TU) and ^{14}C>60 pMC; deep groundwater is free of ^{3}H and has ^{14}C<60 pMC (<15 pMC for 'fossil' groundwater). Once the natural flow system originally with a quasi-stable ^{3}H and ^{14}C-distribution has been disturbed, groundwater with low ^{14}C contents and ^{3}H in the 'mixed water' zone. Note the different tritium scales for the southern and northern Hemispheres. (see Chapter 4.4)

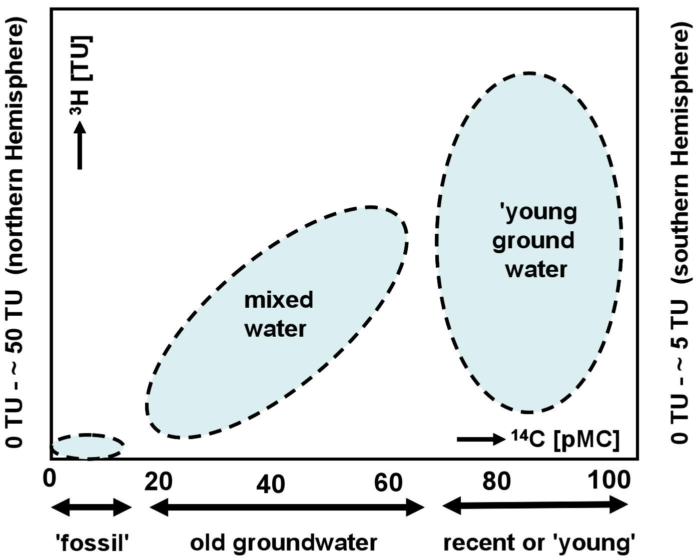


Figure 6.4. ***Results of a long-term monitoring of ^{14}C concentrations in groundwater from deep production wells in unconsolidated rocks of the Munich and Augsburg areas in south Germany. Similar results are obtained for consolidated rocks. Usually, only minor variations and trends are observed over time.***

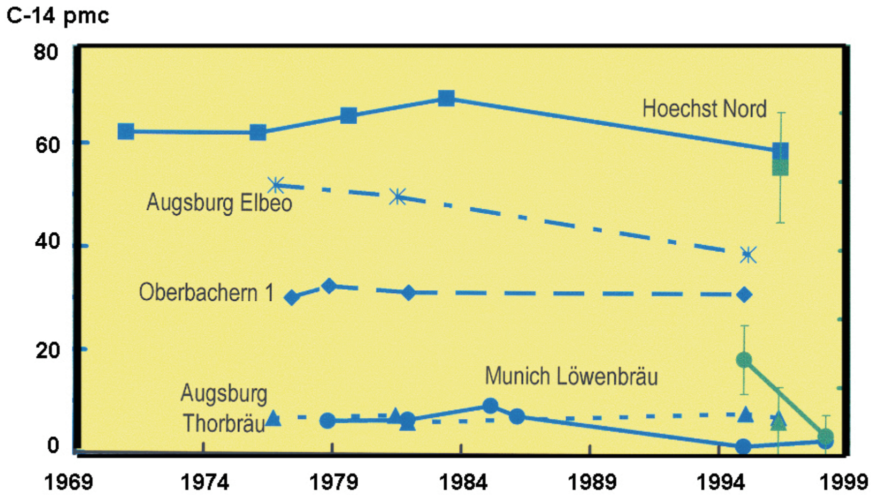
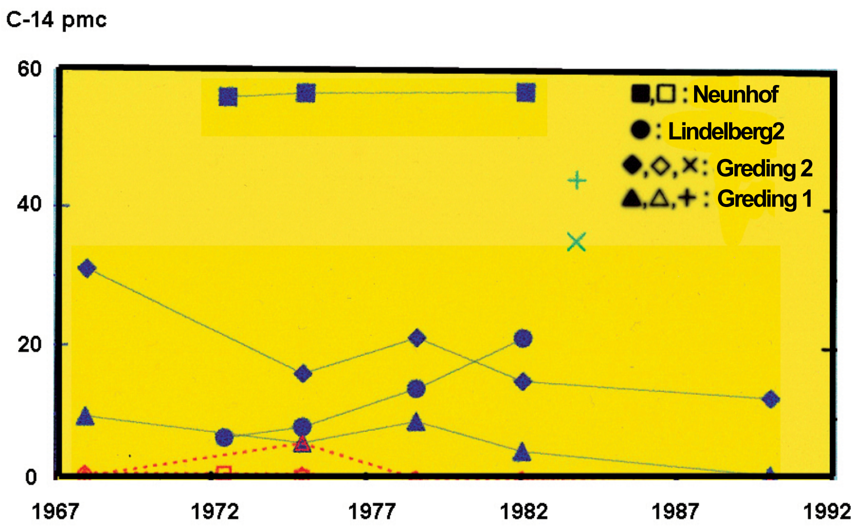


Figure 6.5. ***Results of a long-term monitoring of ^{14}C concentrations in deep groundwater production wells in consolidated rocks of the area of Nurmberg in South Germany***



for both unconsolidated (Fig. 6.4) and consolidated (Fig. 6.5) rocks. If pollutants reach the deep, primarily tritium-free exploitation level, the ^{14}C concentration would significantly increase with time under the given management practice; if ^{14}C remained unchanged or decreased, the production well was not endangered. Both figures also show that in case of deep aquifers a sampling cycle of 3 to 5 years was sufficient to timeously assess well pollution or to refine sophisticated mathematical models to better predict pollutant transport. Such a survey would have been even more sensitive had it been executed downstream from the exploitation well rather than at the production well site itself.

Pollutant and environmental tracer migration

Monitoring and analysing environmental tracers in deep/emergency groundwater resources under exploitation have been used by Seiler and Lindner (1995), Ghergut et al. (2001) and Verhagen et al. (2003) with successful applications (Weise et al. (2000), Hafen and Kölling (2000), Plümacher and Kinzelbach (2000), Mattle et al. (2001), Zoellmann et al. (2001) to recalibrate mathematical models on groundwater flow.

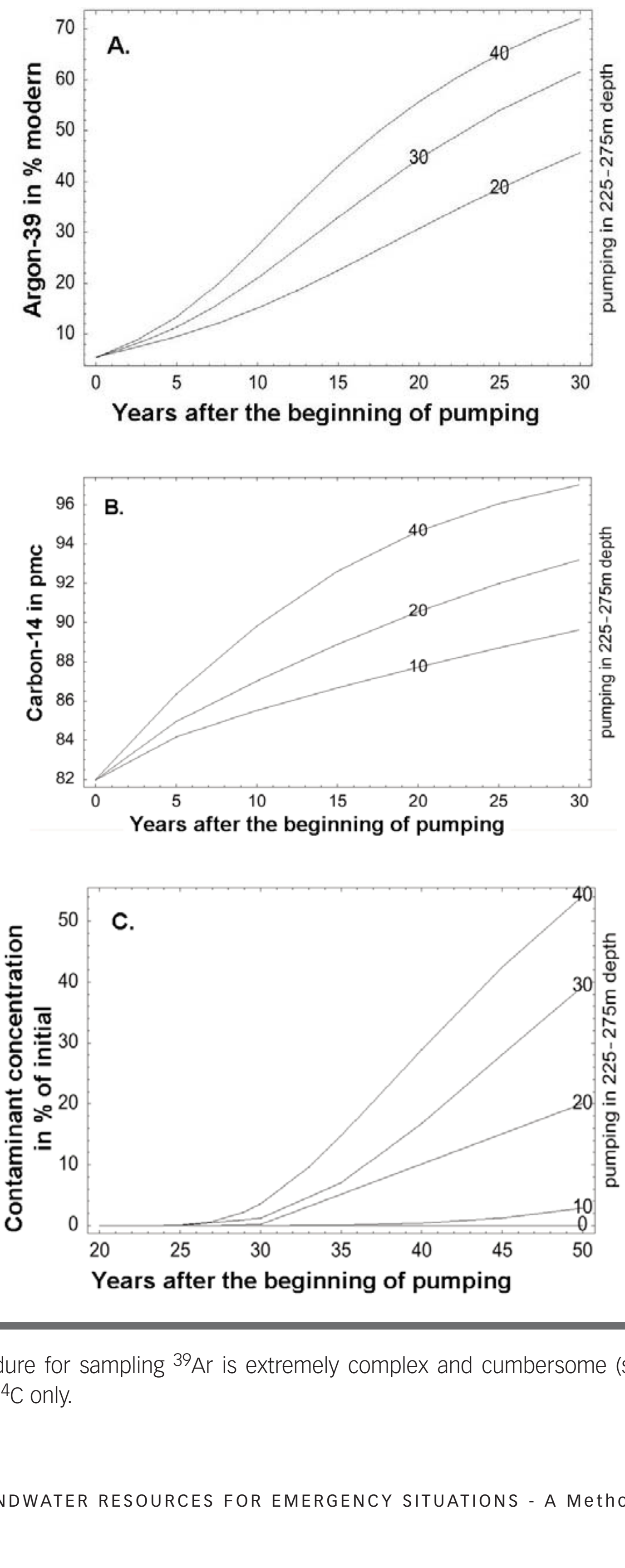
The allowable maximum abstraction from deep groundwater either in terms of tolerable hydraulic drawdown or of pumping rates (peak values or temporal averages) or of cumulative amounts pumped out, cannot be assessed from a simple (bulk) water balance and hydraulic considerations. It can only be derived from a comparative prediction of pollutant transport in the whole system for a range of pumping rates and regimes. The prediction has to rely on a groundwater transport model that has to be calibrated on the basis of transient aquifer response and transport data, as these are obtained under hydraulic stress conditions. Thus, the control of deep water abstraction will evolve with time during ongoing groundwater exploitation; i.e. it will be process-oriented.

The equilibration time of environmental radioisotope re-distribution under given hydraulic stress will lie in a range intermediate between the (depth-independent) hydraulic equilibration time and the (depth-dependent) groundwater age. The time horizon of radioisotope response to hydraulic stress will thus increase with depth, limited by radioactive decay which produces a decrease of the isotope concentration with depth. Analytical advances may lower the detection limit of the respective isotope thereby extending the time horizon to greater depths, depending on the integrity of sealing of the borehole above the point of abstraction.

For the migration of a generic pollutant some one hundred model runs were performed with typical intrinsic, initial and boundary conditions; in all cases a constant and uniform diffuse input through the surface recharge boundary is assumed for twenty years before the onset of deep pumping (Fig. 6.6). The response of environmental ^{39}Ar and ^{14}C in the pumped water (with ongoing input at the recharge boundary) to deep (225 m to 275 m depth) abstraction at rates amounting to 0%, 10%, 20%, 30%, 40% of the over-all aquifer recharge rate is shown for a production well and compared to the appearance of the pollutant.

Figure 6.6 shows that the pollutant appears 25 years after the beginning of exploitation in the production well, although the concentrations of ^{39}Ar and ^{14}C start changing immediately after the beginning of deep groundwater abstraction. At a monitoring depth of 150 m the more sensitive indicator of the ingress of shallow into deep groundwater is ^{39}Ar; at greater depth ^{14}C is more sensitive; this is related to the natural depth distribution of these isotopes according to their radioactive half-life.

Figure 6.6. ***^{39}Ar (A) and ^{14}C (B) responses with pumping time at the production well side at 150 m observation depth and pollutant break-through (C). The concentration of the environmental radioactive isotopes increases long before the pollutant has reached the pumping well. ^{39}Ar concentrations increase much more than ^{14}C concentrations, as the depth distribution of these radioactive isotopes differs according to their different half lives (^{39}Ar=269 years, ^{14}C = 5,730 years). In this case ^{39}Ar is more sensitive than ^{14}C as an early warning indicator[1]; the inverse is true at greater depth.***

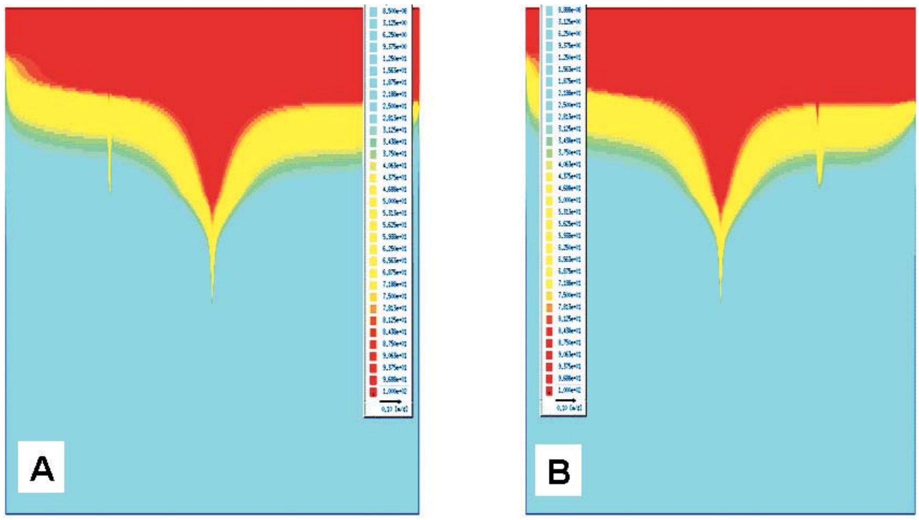


1. Note that the procedure for sampling ^{39}Ar is extremely complex and cumbersome (see Chapter 4.4). It usually suffices to measure ^{14}C only.

The effect of hydraulic short cuts on the exchange of shallow groundwater with deep groundwater under hydraulic stress

The effect of a local vertical heterogeneity of surface area of 100 m x 100 m with a 10,000 fold increase in hydraulic conductivity forming a short cut between shallow and deep groundwater upstream of (Fig. 6.7A) and downstream from (Fig. 6.7B) the production well. The figure shows how shallow groundwater (red) influences deep groundwater at a 20% abstraction of the over-all groundwater recharge at a depth of 225–275 m over an extraction time of 30 years. As expected from many other model runs (Chapter 3), the upstream hydraulic window influences deep groundwater extraction less than the short cut downstream. Such a hydraulic short cut contributes less than 3% to the extracted water, and hence has no real influence on water quality.

Figure 6.7. ***The influence of hydraulic short cuts (A) upstream of and (B) downstream from the production well with groundwater extraction at 225–275m depth. Shallow groundwater: red, deep groundwater: blue; transition: yellow/green. Abstraction rate: 20% of groundwater recharge over a period of 30 years.***



Despite the locally quite pronounced alteration of flow and age fields in the presence of a hydraulic short cut, the relative, pumping-induced change of vertical age profiles remained almost the same as in a ‘tight’ system. Although a hydraulic shortcut downstream affects the numerical calibration of an early-warning tool more strongly than a hydraulic shortcut upstream, the magnitude of the relative changes on which the process-oriented control relies will not be affected notably. Such potential hydraulic short cuts do not need special groundwater protection measures. This is important information for areas that are earthquake-prone and areas with subsidence due to mining (e.g. Ruhr area in Germany) or overexploitation of groundwater (e.g. Mexico City).

Groundwater monitoring support data for groundwater resources protection

Groundwater monitoring can be understood as a continuous, methodologically and technically standardised programme of observations, measurements and analysis of selected physical, chemical and biological variables of groundwater. Its objectives are: 1/ to collect, process and evaluate groundwater quantity and quality data as a baseline for assessing the current status and forecasting trends in groundwater in time and space due to natural processes and human impacts; 2/ to provide data and information for planning, policy and management of groundwater resource protection and conservation; to address groundwater quality and quantity problems in relation to economic development and social and ecological needs, as well as to timely identify and to give advance warning of a disaster impact on groundwater supplies.

The objectives of each monitoring programme govern the extent of monitoring activities, such as the design of monitoring networks, the construction of monitoring wells, methods and frequency of measurement and sampling and the number of variables to be analysed. Clearly defined objectives of groundwater monitoring are essential to achieve the expected results. A groundwater monitoring programme is an important component of groundwater protection policy.

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Monitoring of groundwater quantity and quality and collection and assessment of monitoring data help to clarify and analyse the potential risk and impact of disasters on groundwater systems and to formulate groundwater protection policy and management of emergency groundwater resources in areas affected by natural disasters. However, existing groundwater monitoring programmes are mostly concerned with the identification and control of the consequences of the impacts on groundwater and do not address preventive groundwater protection measures. The establishment and operation of site-specific and early warning groundwater monitoring programmes in disaster prone areas is therefore needed, to detect disaster impacts, particularly pollution, in the unsaturated zone before the aquifer is affected. Such monitoring strategy assists in the timely identification of natural or human impacts on a groundwater system while they are still controllable and manageable; also to better understand and predict processes leading to groundwater deterioration. Such a strategy also supports assessing risks to groundwater and designating effective groundwater preventive protection policy (Vrba and Adams, 2008).

The design of **site-specifi**c groundwater monitoring networks is predicated on the origin and risk of natural disasters, human impacts on groundwater, aquifer vulnerability and related time needed to take appropriate action with respect to the potential groundwater problem. They also control construction of monitoring wells – particularly the installation of well screens, selection and placement of monitoring devices, the frequency of groundwater measurements and sampling and the range of variables analysed.

Early warning monitoring allows one to identify and foresee the outcome of a process leading to groundwater deterioration both in quality and quantity, with enough leeway to put in place measures to mitigate the magnitude of the risk posed to groundwater by pollution still in the unsaturated zone. The design of an early warning monitoring programme and selection of variables observed, therefore, depend on the time needed to take appropriate action with respect to the specifics of the impact of a disaster on groundwater.

There are differences between early warning and site-specific monitoring of shallow water table aquifers and deep, mostly confined, aquifers.

In **shallow water table aquifers** monitoring of the unsaturated zone with respect to its ability to store, retain and attenuate the pollutants and delay their vertical downward influx to the saturated zone, is a crucial tool for protection and risk management of shallow aquifers in floodplains, coastal areas and river deltas. Such areas are often repeatedly affected by flood, tsunami and storm events producing groundwater salinity and other pollution problems. Protection of vulnerable shallow aquifers which contain groundwater with brief residence times and a rapid response to natural and human stresses require the operation of monitoring networks with specially designed monitoring wells that allow vertical profiling of both the unsaturated and saturated zone. Shallow aquifers rarely are a safe source of drinking water for emergency situations. On the other hand, they are technically and economically accessible by shallow wells and are developed for numerous domestic and public water supplies, particularly in developing countries. To protect water supply wells against structural damage and pollution in a disaster and the need to rehabilitate their function as soon as possible after the event requires the formulation of protective measures in the preparedness and warning phases of the potential disaster (see chapter 7). Monitoring programmes linked with other protection activities such as hydrogeological and vulnerability mapping, delineation of inundation and other risk zones, inventorising and mapping existing water supply wells, drilling of new emergency wells, the appointment of emergency governance policy and community involvement and active participation are the basic activities which effectively support protection policy and management of such shallow groundwater supplies.

In contrast, **deep, often confined aquifers** with a delayed hydraulic and quality response to natural and human impacts are usually a safe source of drinking water for emergency supplies. Groundwater exploitation of these aquifers should consider the transient hydraulic responses of deep groundwater systems to the changes in hydraulic boundary conditions as is described in greater detail above. To secure emergency groundwater resources protection site-specific monitoring programmes have to be combined with early warning monitoring such as proposed by Małoszewski et al. (1990), Ghergut et al. (2001), and Vrba and Adams (2002). Monitoring of deep confined aquifers is focused on the timely identification of potential vertical downward or upward migration of pollutants and their lateral movement in the aquifer. The target zones for site-specific and early warning monitoring of deep aquifers are their recharge areas, associated surface water bodies interacting with the groundwater system, and other vulnerable areas of the aquifer e.g. vertical downward or upward influx from the overlying or underlying aquifers owing to fracturing in tectonically active zone. In these areas the operation of monitoring networks based on regular groundwater level measurements and sampling, analysis of basic chemical components and analysis of non-reactive environmental tracers (radioactive and stable isotopes, chloride) help to define the origin and age of groundwater and the groundwater flow net. The assessment of such data supports the establishment of a conceptual model or recalibration of a mathematical model. This allows for enhancing the predictability of pollution impact on emergency water supplies and formulating or modifying groundwater management strategies for a more efficient groundwater protection policy. As explained above, many runs of numerical models with different initial intrinsic and boundary conditions and different intrinsic parameters, show that the transient hydraulic behaviour of deep, emergency groundwater may retard the ingress of pollutants by decades or even centuries.

Monitoring and early detection of incipient pollutant fluxes in groundwater recharge areas, in the unsaturated zone and groundwater table before they are diluted in the aquifer, gives ample time for implementing protective and management measures before massive groundwater pollution can occur. This stresses the importance of operation site-specific monitoring programmes.

For monitoring the vertical profile of the **unsaturated zone** sampling from lysimeters, extraction of interstitial water from core samples, suction caps, direct push sediment sampling are some of the available monitoring methods. These methods, in combination with soil gas monitoring and remote sensing (photographic imaging, geobotanical) methods facilitate early detection of groundwater quality problems and timely implementation of protective measures.

In the **saturated zone** of the aquifer, various monitoring and sampling techniques may be employed depending on the nature of the disaster and its potential impact on the groundwater system. Such methods may employ horizontal monitoring wells, groups of monitoring wells each with a single screened segment in different depths, a nest of small diameter piezometers extending to different depths inside a monitoring well, the installation of multi-layered samplers, applying packer or separation pumping techniques, sampling under anaerobic conditions using a suction or the direct push sampling techniques.

Satellite techniques provide spatially and temporally coherent data and rapid coverage of large areas and have become an effective tool in groundwater monitoring and groundwater protection policy. However, the spatial resolution and lower accuracy of satellite-based measurements, including the most promising gravimetric and radar altimetry methods, do not as yet provide sufficiently accurate data for evaluating groundwater level changes and storage. Space-based data therefore have to be calibrated and validated through data acquired from in-situ observations in monitoring wells or other groundwater monitoring points.

Various international satellite based programmes (e.g. WHYCOS – World Hydrological Cycle Observing Programme, IGWCO – Integrated Water Cycle Observation, IGOS – Integrating Global Observing System, GRACE – Gravity Recovery and Climate Experience, GOCE Gravity Field and Steady–State Ocean Circulation Explorer) provide spatially and temporally coherent data at the global and regional level and a view of major elements defining the water cycle independent of political boundaries. With respect to groundwater the most promising is the GRACE mission implemented particularly in studies focused on the assessment of variations in groundwater storage and their comparison with groundwater level changes measured in monitoring wells. Low spatial and temporal resolution results in an uncertainty in groundwater level measurements in the order of tens centimetres for aquifers with spatial extent lower than 200,000 km^2. Satellite images of topography, geology, vegetation cover, land use and soil type, however, provide useful data for protection of emergency groundwater resources, particularly for delineation of inundation and recharge areas, location of paleochannels, underground buried streams and hydrogeologically important tectonic structures.

In areas prone to **drought** groundwater monitoring is directed to measurements of groundwater level and quality and isotopic composition. In areas affected by **storms, floods and tsunamis** groundwater level measurements and groundwater salinity (Cl, conductivity) monitoring is usually applied in coastal aquifers. Vertical multi-layer hydrochemical profiling of coastal aquifers helps to control the fresh water-salt water interface and manage sustainable groundwater pumping. In shallow water table aquifers in flood-prone areas often used for drinking water supplies groundwater level measurements and groundwater chemical analysis on drinking water standard level is usually applied.

Groundwater monitoring and early warning in areas affected by volcanic activity, earthquakes and landslides requires specific approaches in selecting monitoring variables, in particular groundwater quality variables. In **volcanic areas** groundwater temperature, turbidity and chemistry (Cl, HCO_3, SO_4, conductivity, pH), isotopic composition, dissolved gasses (Rn, CO_2, He) as well as groundwater level measurements are the main variables observed. Groundwater monitoring in **earthquake prone** areas is directed at the measurement of groundwater level, spring discharge, groundwater environmental tracers, temperature, turbidity and chemistry mainly pH, SO_4, Cl. Groundwater level and pressure are the leading variables which have to be carefully monitored in **landslide** prone areas as they have a direct bearing on landslide stability.

Site-specific and early warning groundwater monitoring is technically demanding, time consuming, and costly. However, with growing reliance on groundwater and natural and man-made impacts, threats to this resource are increasing. Establishing and operating specific and early warning monitoring networks is therefore justified socially, economically and environmentally. Governmental institutions, water stakeholders and local communities in many countries may not yet be prepared to accept the need to implement groundwater monitoring programmes. However, the reality in the field and the restoration costs of affected aquifers suggest that site-specific and early warning monitoring may be an important cost-benefit approach for preserving and protecting groundwater as a strategic source of drinking water particularly in emergency situations. Evaluated credible, and consistent groundwater monitoring data should be available and readily accessible to decision and policy makers, planners, regulators, managers, rescue teams and local governments and communities. Such data enables the forecast of disaster potential impact and mitigation of disaster risk and enhances management and protection policy of emergency groundwater resources in areas repeatedly affected by natural disasters.

7. Groundwater governance policy in emergency situations

Jaroslav Vrba

Introduction

There is no internationally agreed definition of water governance. However, it is widely accepted that it can be effective when it involves society as a whole and is not the exclusive domain of governments (Pierre, 2000). Generally, governance is based on multilevel and trans-sectoral approaches and activities and includes governmental authorities at all levels, the private sector, various civil society groups and communities. Effective water governance relies on catchment-based integrated water resources management (IWRM).

Several attributes of water governance stated in Agenda 21 (1992) are based on dynamic, interactive, iterative and multi-sectoral approaches, integration of all water users, strengthening of institutional structures and on the reform of water laws.

The Second World Water Forum held in the Hague in 2000 identified water governance as one of the key challenges and expressed the need to govern water wisely and involve the public and other water stakeholders in the governance policy.

The following criteria for effective water governance have been specified in the World Water Development Report I (2003):

- participation of all citizens directly or through intermediate organizations representing their interests and throughout the processes of policy and decision-making,
- transparency in the free flow of information within a society,
- opportunities for all groups in society to improve their well-being,
- accountability of governments, the private sector and civil society organizations to the public or the interests they represent,
- coherent, consistent and easily understood water policy and associated actions,
- institutions and processes should serve all stakeholders and respond properly to changes in demand and preferences, or to other, changed circumstances,
- water governance should enhance and promote integrated and holistic approaches,
- ethical principles of societies and their traditional water rights have to be respected.

The following key messages on improvement of water governance policy are highlighted in the World Water Development Report II (2006):

- in some countries there is either a total absence of water institutions, or institutional structures are fragmented,
- there is no blueprint for good water governance,
- the rate of water reform is patchy and slow,
- there are significant and serious gaps in developing countries between land and water use policies and governance and between policy-making and its implementation,
- in the water sector, as worldwide, corruption is pervasive,
- increasing recognition is accorded to the right to water, in terms of a human right, to a supply of safe water; and to the role of water rights in helping to deal with local competition for water and in dealing with social, economic and environmental problems,
- the privatisation of water services by multinational water companies displays uneven results; the potential of local small-scale companies and civil society organizations to help improve water services has been overlooked by governments and donors,
- many governments recognise the need to localise water management but fail to delegate adequate powers, resources and information to make it work.

Role of groundwater governance in integrated management of water resources (IWRM)

It is widely accepted that groundwater governance policy and IGWRM are interdependent, based on holistic and environmentally sound approaches, reflect the social and economic value of groundwater and consider its close relationship with surface water and terrestrial and aquatic ecosystems. Both are linked to land use planning and practices, attentive to historical traditions of society and based on a participatory approach, involving decision and policy makers, managers, water stakeholders, NGOs and the general public. The main objective of the groundwater governance and management process is to ensure the safety and sustainability of groundwater resources as a vital necessity for human life (for drinking and sanitary purposes, and for emergency situations), economic development (e.g. agriculture, industry), and the healthy functioning of ecosystems. Intangible values related to ethical, religious and cultural traditions of society regarding groundwater also have to be respected. In many developing countries equitable governance and management of groundwater resources is the key for sustainable living and to poverty alleviation.

In many parts of the world it has been found that discrepancies between social and economic development and integrated water resources management reflect a deficiency in water governance policy. In this regard, the following water governance issues need to be improved:

- social – uneven water allocation within the social hierarchy of society, lack of public participation in the decision-making process,
- economic – poor efficiency in water distribution, use and management, lack of appropriate water pricing policy, inadequate investments in development of water infrastructures,
- legal – a legislative framework for water and property rights is often imperfect or absent,
- political – unequal rights of water stakeholders in the decision and policy making process, conflicting upstream and downstream interests in the use and protection of water resources, the need for building institutional water structures and legal mechanisms for catchment and aquifer-based international cooperation in the management of transboundary water resources and
- environmental – protection of water dependent ecosystems against uncontrolled depletion or pollution of water resources.

Water governance policy in emergency situations

There are several institutional, legal and technical issues specifically related to water governance policy and water resources risk management in emergency situations. Civil defence agencies, army, fire brigades and other special rescue and aid teams are important participants in governance policy oriented towards the mitigation of the risk and impact of disasters on water resources and the population. Water management and governance institutions should also control diverse (or even conflicting) interests of the various water stakeholders and coordinate the use of water resources in emergency situations. Both the economic potential to manage water resources in emergency situations and the contemporary status of emergency water governance policy differ significantly in developed and in developing countries. Communication gaps between all interested groups at governmental and community level, the absence or incompetence of local authorities in the decision-making process, gaps in the legal framework relevant to emergency situations as well as lack of qualified and trained human resources, early warning monitoring systems and emergency information structures – all are obstacles that impinge seriously on water governance policy and water resources risk management in emergency situations in several countries.

The Yokohama Strategy for a Safer World: Guidelines for Natural Disaster Prevention, Preparedness and Mitigation and its Plan of Action (Yokohama Strategy) adopted in 1994 have provided policy guidance and tools for mitigating the risk and impact of disasters. The following specific gaps and challenges have been identified:

- Governance: organizational, legal and policy frameworks.
- Risk identification, assessment, monitoring and early warning.
- Knowledge management and education.
- Reduction of underlying risk factors.
- Preparedness for effective response and recovery.

The World Conference on Disaster Reduction held in Kobe, Hyogo, Japan in January 2005 adopted the Framework for Action 2005–2015: 'Building the Resilience of Nations and Communities to Disasters'. The World Conference was convened through a decision of the General Assembly, with five specific objectives: 1/ To conclude and report on the review of the Yokohoma Strategy and its Plan of Action, 2/ To identify specific activities aimed at ensuring the implementation of relevant provisions of the Johannesburg Plan of Implementation on vulnerability, risk assessment and disaster management, 3/ To share good practices and lessons deemed to further disaster reduction, 4/ To increase awareness of the importance of disaster reduction policies, and 5/ To increase the reliability and availability of appropriate disaster-related information to the public and disaster management agencies in all regions.

The Conference adopted the following priorities of action:

- Ensure that disaster risk reduction is a national as well as a local priority with a strong institutional basis for implementation.
- Identify, assess and monitor disaster risks and enhance early warning.
- Use knowledge, innovation and education to build a culture of safety and resilience at all levels.
- Reduce the underlying risk factors.
- Strengthen disaster preparedness for effective responses at all levels.

Attributes of disaster risk reduction policy are identified among the priorities of the Millennium Development Goals. It is stated that disaster risk reduction attributes would be effectively supported by ensuring environmental sustainability, land use planning, enhancement of a global partnership for development, broader participation of institutions and individuals in decision making, participation by and empowerment of women, increasing public information and rights to access to information and education, and the reduction of human exposure and vulnerability to hazards in poverty-ridden areas.

Responsibility of water governance emergency policy actors

All actors in water governance emergency policy have to take responsibility for activities related to the protection of drinking water resources and populations in disaster-prone regions. Safety and emergency plans, institutional, technical and human capacities to cope with disasters and investments implemented to prevent and/or mitigate the impact of disasters on water supply sources and population involvement are reflected in decreasing both the vulnerability of water and the population and their exposure to disastrous events. The distribution of drinking water to the affected population is the most pressing priority during and after disasters. Regular water supply systems are almost always damaged by disasters and shallow domestic wells often polluted. Securing drinking water is therefore an emergency action which requires comprehensive national and international cooperation and solidarity of numerous governmental, professional and voluntary organizations and individuals. Particularly in regions regularly affected by natural disasters the establishment of drinking water risk management and mitigation plans significantly reduces or even eliminates drinking water failure following catastrophic events. In such plans the obligations of governmental authorities, local communities, rescue teams, private sector and individuals are formulated with the scope to mitigate disaster risk to water resources, to reduce human suffering due to lack of drinking water during and after the disaster period and to manage water resources in emergency situations in an equitable manner.

The principles of disaster prevention and mitigation and water governance emergency policy are discussed among others by Dooge (2004), Plate (2003), Affeltranger (2001), Vrba and Verhagen (2006), Young at al. (1994), and Blaikie at al. (1994) and in the documents of various UN Organizations (e.g. WWDR I, WWDR II, WWDR III, Hyogo Declaration).

7.1 Emergency drinking water supply governance policy and related activities in different phases of a disaster

The main aim of this chapter is to describe activities related to water governance policy in emergency situations with special regard to groundwater resources and drinking water supplies. These are described within the specific phases of a disaster formulated by Dooge (2004) – anticipatory, warning, impact, relief and rehabilitation.

The anticipatory (preparedness) phase

An evaluation of the risk of disastrous events and assessment of a population's vulnerability supports the formulation and implementation of an effective water governance policy in an emergency and the principles of water resources management in the anticipatory phase. In drinking water services the most important activities are:

- the delineation and mapping of areas most prone to potential disaster impact,
- the assessment in these areas of the potential risk to, and vulnerability or resistance of existing public and domestic water supply facilities to disasters and
- the identification, investigation as well as quantitative and qualitative evaluation and mapping of available emergency water resources resistant to natural disasters or human-induced hazards.

The available emergency water resources have to be compared to the drinking water requirements of the endangered population and the requirement of high quality water for hospitals and other health centres, and for food production. However, uncertainty in risk assessment always has to be considered because sudden catastrophic events of meteorological, hydrological and geological origin and their unexpected impact on water supply services are reported worldwide.

Integrated water and land use planning, specifically urban and rural development plans, emergency drinking water plans and maps depicting areas prone to inundation and the risk of other disasters – all are measures and documents essential in disaster preparedness and risk mitigation policy. The following insufficiencies in water and land use planning have to be particularly considered:

- People living in **unplanned urban or rural settlements,** e.g. below the flood line in areas likely to be inundated, on the foot-hills of volcanic cones, in landslide-prone areas and in coastal areas are repeatedly affected by sudden cataclysmic disasters. Their drinking water supply sources (mainly domestic wells) are often physically damaged and/or polluted. Serious effects of a catastrophic flood in August 2002 on a rural settlement, its infrastructure and local water supplies located in the area of inundation of the Labe (Elbe) river in the north of the Czech Republic are visible in the figure 7.1.1.
- **Unsustainable land use practices,** e.g. deforestation, have led to soil erosion and microclimate changes in many regions worldwide and thus increase their vulnerability to floods, droughts and landslides. The development of industry, growth in urbanization and intensification of agricultural production have all produced significant changes in land use patterns and impinged on water resources, both in quality and quantity, and the functioning of water dependent ecosystems.
- Unsustainable land use management is reflected in the **deterioration of conditions for ground-water recharge** and subsequently a decline in groundwater resource storage.

Figure 7.1.1. Effects of the catastrophic flood in August 2002 on a rural settlement, infrastructure and local water supplies located in the area of inundation of the Labe (Elbe) river in the north of the Czech Republic (Photograph by Raudenský and Dorazil, 2002)

Preparedness measures in emergency groundwater resources governance policy are mainly oriented towards:

- **Geological, hydrogeological and land use maps**, combined with disaster risk and groundwater vulnerability maps, satellite imagines and panoramic aerial photomaps need to be compiled. These are all important tools for outlining groundwater resources resistant to natural hazards. Where such maps at a suitable scale are not available and knowledge about groundwater resources is inadequate, complementary geological, hydrogeological, geophysical, isotope hydrological and other investigation and mapping (see chapter 4) are required.
- Inventorising and mapping **existing public and domestic wells** located in disaster-prone areas. Data on groundwater level, yield and quality of these wells has to be recorded. The wells resistant against flooding and other disaster impacts have to be registered, tested and evaluated with respect to their use and functionality during and after a disaster, recorded in emergency plans and depicted in disaster risks maps and associated emergency documentation.
- **New emergency wells** resistant to the impact of disasters can be located and drilled according to extant knowledge of hydrogeological conditions and/or the results of hydrogeological investigation. A timely groundwater investigation is an essential attribute in developing groundwater emergency policy and becomes imperative in risk management of groundwater resources resistant to natural disasters. Evaluation of the yield and groundwater quality of emergency wells is based on pumping tests and chemical and biological analysis. Wells have to be prepared for immediate use in an emergency situation, and should therefore be equipped with pumps and diesel driven generators maintained at well localities. They should be located in reasonable proximity to a disaster-prone area and, if possible, inside the area at some disaster-secure location and should be accessible to tankers or mobile cisterns for transporting and distributing drinking water during and after emergency. Emergency wells should be plotted on relevant maps, local governments and the population being informed about their specific location.
- **Availability of qualified and experienced human resources** trained to cope with the impact of disasters on the population and drinking water sources also significantly supports disaster preparedness governance policy. Teams composed of national and local governmental officers, experts on emergency issues, land use planners, water specialists, water managers and community representatives take the responsibility to coordinate, control and manage water related risk mitigation activities within the anticipatory phase of a disaster. However, it must be stated that diversified responsibility within the decision making sphere and lack of cooperation between risk managers, water stakeholders and local communities still exists in emergency governance water policy in many countries.
- **Community awareness and active public participation** are essential in developing and safeguarding water supply infrastructure that will function successfully in case of emergency. Devastating natural events often result in total dependence on outside assistance and, ultimately, groundwater resources for the sustenance of affected communities. Therefore, a very important aspect in drawing the attention of governments, organisations and individuals to the concept of preparedness for establishing alternative drinking water supplies, is empowerment. When properly empowered, people can take charge of their own situation, restore water supply from their own knowledge of groundwater resources, and thus release energies for general reconstruction.

The warning phase

The establishment and operation of water monitoring networks and early warning monitoring are the key activities in the warning phase. Both produce information that makes it possible to timely identify, recognise and to give advance warning of a disaster to governmental authorities and emergency and rescue teams. In particular they lead to a better understanding of the risk and impact of natural disasters on the local water supplies and population. Monitoring data and information also assist in conceptualising potential scenarios of disaster impacts on groundwater resources, evaluating emergency groundwater resources and their resistance against the potential impact of disasters, and in building effective alarm systems to timeously warn and protect the population against disasters.

However, in many countries lack of data is the key impediment in the formulation of disaster mitigation governance policy and a serious limitation in the risk management of water resources in emergency situations. Social impacts and economic losses resulting from **a scarcity of data on natural disasters** have been pointed out at the UN International Conference on Water and the Environment held in Dublin, Ireland in 1992. Lack of disaster preparedness owing to inadequate monitoring of water resources reflected in serious impacts of floods and droughts on the population and on the economy of many countries: ‘Development is being set back for years in some developing countries, because investments have not been made in basic data collection and disaster preparedness’ (The Dublin Statement, 1992).

Water data insufficiency and need of regular water monitoring have been pointed out in WWDR 1, 2003 (‘Various assessments of water resources that have been conducted invariably indicate that hydrological data are lacking in many parts of the world’) and in the WWDR 3, 2006 (‘Major investments are needed to reverse the decline of hydrologic information networks, including surface water and groundwater observations’).

Particularly in regions repeatedly affected by natural disasters, collection of **historical disaster related data** is needed. Analysis of historical data helps to assess the recurrence period of potential disasters, their intensity and their social, economic and environmental consequences. However, historical data is not always accessible and reliable and continuous data series are often missing or incomplete. Integrated **hydro-climatologic** early warning monitoring systems in regions vulnerable to floods, storms and drought are not yet in operation in several countries. That, along with growing influence of climate variability and change introduces uncertainty into the forecasting of water related disasters. **Geological** early warning monitoring systems have been developed and are in operation in many regions repeatedly affected by and vulnerable to earthquakes, volcanic activities and landslides. Early warning systems exist or are being developed in tsunami prone regions.

Drilling of new monitoring wells located and screened with respect to the potential impact of specific disasters on groundwater systems, the implementation of regular and standardised groundwater terrestrial measurements and sampling and laboratory procedures, standardised methodology for data assessment, management and reporting and availability of professional staff and financial resources – all are essential for the operation of groundwater monitoring and early warning programmes; both have been discussed in chapter 6. Hydro-climatic data from early warning and regular groundwater monitoring networks particularly in highly vulnerable floodplain and coastal areas, arid and semi-arid regions and small islands are essential for the assessment of the risk of climate variability and change on groundwater resources as well as public and domestic water supplies.

However, we are still facing difficulties arising from data inconsistency and poor compatibility in particular between **countries sharing watersheds and transboundary aquifers.** Transboundary coordination of water related monitoring activities by international units established by neighbouring countries and exchange and dissemination of monitoring data and information are often scarce for emergency groundwater resources. International organizations could more actively cooperate on the establishment and operation of regional and international water early warning systems and provide relevant economic, technical and human resources assistance to developing countries to ensure rapid and coordinated actions in emergency situations.

Reform of water governance structures is needed in many countries to effectively coordinate, financially support and strengthen the approach and willingness of responsible governmental authorities and institutions to the establishment and operation of groundwater monitoring and early warning programmes and systems. Early warning monitoring activities assist in forecasting and in minimising the risk to water resources and water supplies systems. They also reduce human social and economic vulnerability and give time for preparation of the effective evacuation plans and conditions under which an evacuation of the population from flood and other disaster-prone areas may be realised. All types of media and communication means (newspaper, television, broadcast, electronic facilities, posters) should be used to disseminate regular warning and emergency information.

The impact and relief phase

Water emergency policy within the impact and relief phase is mainly focused on identification and evaluation of the impact of disasters on water supply sources, immediate water supply rehabilitation efforts after disastrous events, on the reaction of affected local communities and on the organization of external assistance in supplying drinking water.

Distribution of drinking water is ranked among the most pressing priority because water supply and sanitary systems are usually extensively compromised by disaster events and unable to provide regular services. Surface water and shallow aquifers used for drinking water supplies are often polluted. The impact of disaster on groundwater resources and water supply facilities depends on their vulnerability and on the type, intensity and duration of the specific disaster.

In **floodplains and coastal areas affected by tsunamis and storms** immediate checks on the physical condition of domestic and public water supply wells registered in the preparedness phase (well construction, pump function, sealing around the well head) and tests of basic water chemical parameters and turbidity, give an initial indication of the disaster impact on the functioning of wells and groundwater quality. Dewatering, cleaning and disinfecting the wells, repeatedly if necessary, is often sufficient. Well yield should also be checked against pre-disaster values. Water for drinking, cooking and hospital services first requires comprehensive quality testing. Where severe pollution has been identified, remediation or reconstruction of the impaired water supply wells may prove time consuming and costly and a compensatory source of drinking water has to be secured.

The usually gradual onset of **drought** manifests itself particularly in groundwater level decline. This can set off triggers at pre-determined thresholds for engaging various emergency water supplies and interventions. Deepening wells to augment supply can be straightforward and an effective and immediate relief response. However, an assessment of groundwater resources in the region affected by drought is needed to know, whether additional supply can be developed or other sources of drinking water have to be found outside the affected area.

Earthquakes affect and modify groundwater systems and regimes significantly. A drastic decline of groundwater table is frequently observed, but increases as well and also changes in groundwater chemistry and significant changes in the discharge of springs. Damaged shallower wells can be rapidly reconstructed and used for supplying drinking water if the quality is suitable. Deep wells, pumping mechanisms and water distribution pipelines are mostly seriously damaged and their reconstruction usually requires several days, weeks or even months. Compensatory drinking water sources have to be secured. Hand pumps and diesel/petrol driven submersible pumps have to be available in the earthquake relief phase as electricity supply is often disrupted.

In areas affected by **landslides** similar, however less destructive, effects on water wells and water distribution networks have been reported. In the area of the actual slide, water supply wells are usually physically damaged and their reconstruction or relocation is implemented within the rehabilitation phase.

Where a **volcanic eruption** has occurred, water supply wells physically protected against ash and other volcanic ejecta and located away from the lava flow can serve as a emergency source of drinking water. Tanks for roof rainfall collection should be reconnected when volcanic activities cease. However, volcanic eruptions usually modify the shape and pattern of streams, affect runoff, water turbidity, sediment transport, erosion and landscape morphology and thus groundwater recharge conditions. Volcanic activity affects groundwater level and chemistry. Groundwater quality from deeper wells may be affected by volcanic gases and by upward flux of thermal water, rich in dissolved solids, which renders groundwater unsuited for drinking purposes. Relief activities in volcanic areas will be focused on both physical reconstruction of damaged water supply wells and designation of treatment techniques to restore groundwater to drinking quality.

Generally, there are three scenarios for the distribution of drinking water in the relief phase:

1/ Where safe emergency groundwater resources have already been identified and set aside, the distribution of drinking water during and after a disaster will be rapid and effective. However, up to the present such a conceptual approach has been implemented in only a few countries.
2/ Following the disaster new water wells can be rapidly drilled where aquifers resistant to natural disasters have already been investigated and evaluated, but not yet developed. This pre-supposes the availability of drilling facilities and the technical means to install emergency ground water supplies.
3/ In the absence of such hydrogeological knowledge relief responses can be severely retarded, exacerbating the impact on the social and health conditions of the population. Bottled water then has to be imported or water transported by tankers, often from distant unaffected drinking water sources. These are at best temporary measures, are expensive, and emphasise the population´s dependency on external help. For short term survival, 30 l water per day/person is needed: 10 l for drinking and 20 l for cooking purposes (WHO, 2005).

The effectiveness of water governance policy during impact and relief phases very much depends on **disaster preparedness plans** and on readiness of **governmental authorities, aid and rescue teams and involvement and active participation of local communities.** However, it must be noted that every natural disaster produces unique emergency situations in drinking water supply security and population vulnerability the solution of which requires specific approaches and skill levels. The role of hydrogeologists, water engineers and water treatment specialists is particularly important 1/ in establishing a priority group of water supply wells easiest to clean, rehabilitate and use, 2/ on supervision over cleaning of existing or drilling of new emergency water supply wells, and 3/ in recommending suitable techniques for remediating polluted water and reconstructing damaged water supply and sanitary systems. When based on local traditions and experience, the response of local communities to disaster impact can significantly support immediate implementation of relief measures to mitigate the impact of a disaster on local water supply sources and exposed population as well as implementation of effective local emergency drinking water supply policy.

The rehabilitation phase

Post-hoc assessment of activities implemented before and during the disaster, re-evaluation of disaster risk mitigation plans and drinking water risk management schemes and formulation of relevant proposals aimed at reducing risk of future disaster impacts are important water governance activities implemented within the rehabilitation phase. However, the physical rehabilitation of drinking water supplies, sanitary systems and drinking water distribution networks is of critical importance as well and is realised in two phases:

- short term actions implemented within days, already initiated within the relief phase and
- long term, and technically and financially demanding actions which depend on the type, extent and intensity of natural disasters and their impact on water supply and sanitation facilities. Where groundwater drinking water supplies are polluted by chemicals, remediation usually requires weeks to months; even years.

The following groundwater supply related rehabilitation activities are highlighted:

- reconstruction of damaged water supply and sanitary facilities, treatment plants, and water distribution pipelines; remediation of polluted groundwater,
- investigation and development of new emergency groundwater resources resistant to disaster impacts and their connection with existing drinking water distribution networks,
- updating of water governance and risk mitigation policy and drinking water risk management in emergency situations,
- re-evaluation of disaster mitigation plans and updating of inundation, risk and land use maps and groundwater vulnerability maps,
- re-evaluation of the activities of rescue and aid teams responsible for drinking water supply in emergency situations leading to relevant improvements in the composition of teams and in the scope and mode of implementation of their emergency activities,
- re-evaluation of the activities of local communities in emergency situations and proposed improvements considering their ethical, religious and cultural background and historical experience in management of local drinking water resources in regular and emergency situations,
- development of risk based groundwater indicators.

Comprehensive cooperation between water managers, water supply technical staff and rescue authorities is needed in the rehabilitation of damaged water supply system and in designated municipal and rural areas with priority exigency on good quality water, e.g. drinking water supplies, hospitals and other medical facilities, basic food production facilities and areas with high population density. Drinking and cooking water distribution by tankers must be also organised, taking account of limited tanker capacity for water distribution, and the turnaround time of a tanker that may run into hours. This intervention plus the import of large quantities of bottled water can only be temporary. The efficient and rapid solution is intensive pumping of existing deep emergency wells tapping water from deep aquifers resistant to disaster impact or to rapidly drill wells in deeper aquifers of low vulnerability in areas where their occurrence were already investigated and their productivity tested.

Efficient and equitable water governance policy in the disaster rehabilitation phase helps to reduce significantly water deprivation in the post-disaster period, secure resistant emergency drinking water resources and assess and mitigate risk of potential future disasters on population. Management of emergency groundwater resources and related rehabilitation works are described in detail in chapter 5. Figure 7.1.2 presents a *resumé* of activities and measures to be implemented within different phases of a disaster sequence.

Figure 7.1.2. Overview of groundwater governance policy and risk management activities in different phases of a disaster sequence. In blue: preventive phases, in red: impact, relief and rehabilitation phases

Anticipatory phase

- Assess the risk of and population vulnerability to natural disasters
- Devise integrated land use and water resources planning in disaster-prone areas
- Investigate and assess emergency groundwater resources; compile and / or update hydrogeological, vulnerability and disaster risk maps
- Inventorise existing wells and water supply facilities and assess their vulnerability and / or resistance to disasters
- Calculate emergency drinking water requirements of those living in disaster-prone areas as well as high quality water requirements for hospitals and health and first aid centres
- Drill new emergency water supply wells resistant to disaster impacts
- Availability of qualified and trained professional human resources
- Community information on and participation in disater preparedness plans

Warning phase

- Inventorise and evaluate historical and contemporaneous data records on climate, hydrology and disaster events
- Identify existing and potential pollution sources
- Establish and activate monitoring and early warning programmes
- Standardise monitoring, sampling and laboratory procedures and data assessment and management
- Conceptualise possible scenarios of disaster impacts on the population and on drinking water supply and sanitation facilities

Impact and relief phase

- Distribute drinking water from local emergency groundwater sources resistant to disasters, import of bottled water, transport of drinking water in tankers from surrounding unaffected regions, drilling of new water supply wells where aquifers resistant to disasters have already been investigated
- Effect emergency repairs of those compromised water supply and sanitary systems most readily rehabilitated
- Safeguard activities of rescue teams to mitigate impact of disasters on domestic water supply wells – dewatering, cleaning, desinfection
- Immediate response of local communities

Rehabilitation phase

- Reconstruct damaged water supply and sanitary facilities, treatment plants and water distribution networks; remediate polluted groundwater
- Investigate and develop new emergency groundwater resources resistant to disaster events
- Update water governance and risk mitigation policy and risk management of water resources in emergency situations
- Re-evaluate and update disaster risk mitigation plans and maps of groundwater vulnerability, risk and inundation maps
- Post-hoc evaluate emergency water supply related activities in all phases of a disaster sequence; re-assemble rescue teams, re-evaluate local community activities during emergency and propose improvements
- Improve land use planning with respect to the impact of disaster sequence on population and drinking water supply sources
- Develop risk based groundwater indicators

7.2 Institutional and technical capacity building for groundwater governance policy in emergencies

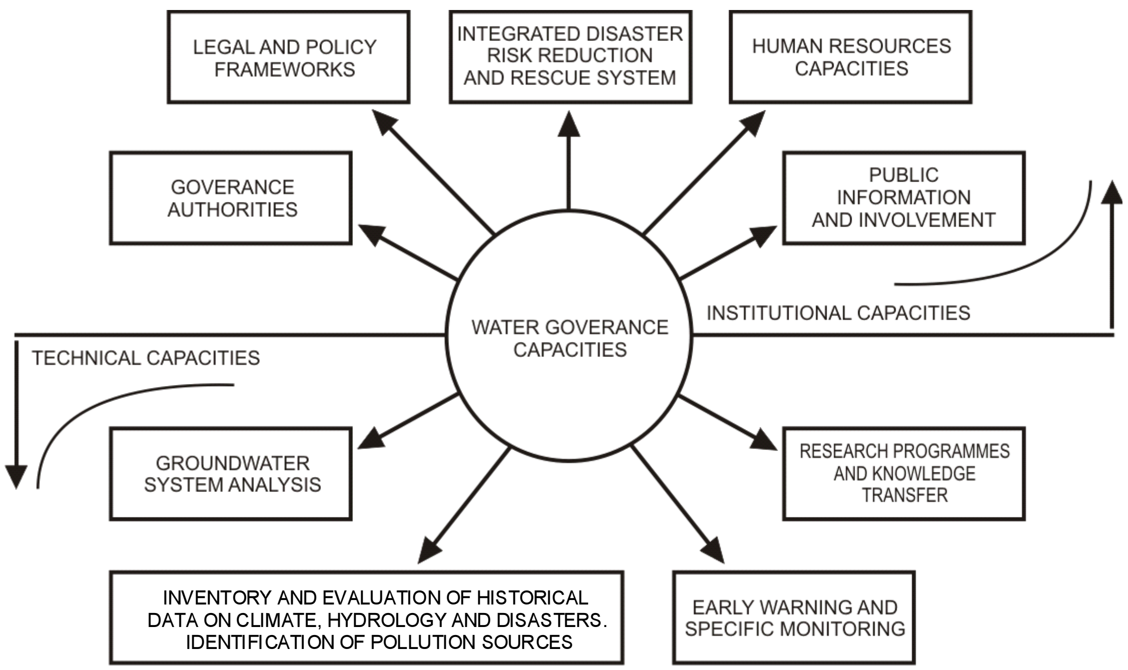
Implementation of groundwater governance policy and risk management in emergency situations strongly depends on all the dimensions of a country's institutional and technical capacity building, and whether such capacities are available and applied **in a coherent manner.**

Institutional capacity building

Institutional capacity building refers mainly to non-structural measures: governmental and water authorities, the legal and policy framework, emergency policy, the structure of rescue system and aid teams, the availability of professional human resources, information of and involvement by the public (Fig. 7.2.1). A governmental and legislative framework is the key in building water governance structures and capacities for disaster prevention and risk mitigation and in formulating efficient water resources risk management plans and policy in emergency situations.

Governmental water authorities must be able to coordinate emergency water policy, formulate and implement water disaster mitigation and risk management plans, support the operation of early warning monitoring systems as well as ensure information flow and communication between different sectors, organizations and groups of society. Many countries have established multi-sectoral disaster risk mitigation mechanisms and special rescue teams with representatives of governmental authorities, local communities, the army and civil protection forces and NGOs. These enhance governance for disaster risk preparedness and mitigation and effective management of post disaster rescue activities including the distribution of drinking water. Planning and financing these protective measures and

Figure 7.2.1. Framework for institutional and technical capacities for water governance policy in emergencies



investments in investigation and development of groundwater resources resistant to disasters are concrete outcomes of effective emergency water policy. However, in many countries risk management plans for drinking water resources in emergency situations and functioning water governance emergency policy are not yet developed and their formulation should be urgently addressed.

The establishment of a legal framework and regulatory status is essential for the implementation of effective water governance policy in emergency situations. In many countries the catchment based management and protection of water resources, including the delegation of responsibilities to secure drinking water services in emergency situations are applied in water law and in specific emergency rules. According to the WWDR II (2006) the establishment of well-defined and coherent water rights are reflected in various economic, social and health benefits for all water stakeholders and in the formulation of responsibilities for protection and sustainable exploitation of water resources. In many countries preventive protection measures of water resources are incorporated in the legal framework. Examples of these are: water supply protection zones, protection of recharge areas, operation of an early warning monitoring system as well as the right of the population to information related to disasters. Access to justice in environmental matters was discussed at the Fourth Ministerial Conference 'Environment in Europe' in Aarhus, Denmark in 1998. The so called Aarhus Convention focused on public participation in decision making, endorsed 'the right of the public to participate in integrating land use planning and environmental decision-making processes and to be informed and to have access to all information which could enable the public to take measures to prevent or mitigate harm arising from the threat caused by human activities or due to natural causes'(Aarhus Convention, Article 5, §1).

Risk reduction and rescue mechanisms focused on emergency water resources deal mainly with the protection of water resources against natural disasters, but also with human vulnerability to such disasters. Risk mitigation of natural disasters requires among others the maintenance of stream networks, river regulation works, planning and control of land use in recharge, inundation and other risk areas and delineation of water supply protection zones in areas prone to flooding, tsunami and other disasters. It requires also the identification, evaluation and protection of groundwater resources used or considered to be used as an emergency source of drinking water. As with man induced impacts on water resources, evidence of potential and existing pollution sources and relevant protective measures based on the 'polluter pays' principle and 'prevent pollution at source' approaches have to be implemented. Rescue and aid teams composed of professionals and volunteers are an integral part of water governance disaster risk reduction policy.

Human resources, properly qualified, experienced, trained and motivated, are a crucial non-structural component of water governance policy in all phases of coping with the impact of disasters on water resources. In the anticipatory and warning phase scientific and engineering services prevail e.g. hydrologists, hydrogeologists, water quality specialists as well as water managers, land use and water planners, legal experts and policy and decision makers. During the impact and relief 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,water engineers, economists, legal experts and policy makers are the key specialists in the restoration of damaged drinking water supplies, piped water and sanitary networks and in the remediation of polluted water and soil. Many less developed countries face the lack of skilled personnel to implement prevention and reconstruction programmes, and to secure measures that will reduce the impact of disastrous events on drinking water sources and the population. As proposed in the Hyogo Declaration, a very urgent task in the building the resilience to disasters of developing countries is to establish training and learning programmes in disaster risk reduction targeted on specific professions and organizations such as planners, water managers, community representatives and civil society organizations. Availability of professional human capacities for water resources (specifically drinking water), risk assessment and management in emergency situations, partnership and technical capacity building and knowledge transfer at national and local scale are particularly emphasised.

Active public information and involvement in the prevention and mitigation of natural and man induced impacts on water resources are further important non-structural measures in water governance policy. It is critical to decentralise decision-making and to raise awareness and empower local communities to play an active role in actions and plans for disaster preparedness measures and in rapid and effective disaster responses based on historical experience and knowledge. Democratic countries place public participation in environmental impact assessment procedures, disaster mitigation policy and integrated land use planning, on a legal basis. However, in several countries a communication gap persists between policy makers and the general public. Developing countries may face low literacy levels and have to introduce specific measures to inform, educate and involve the local population in all aspects of mitigation of disaster risk and impact on drinking water sources.

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 disaster mitigation and water resources governance policy (Dooge, 2004, Plate, 2003, Affeltranger, 2001, Young at al. (1994), Blaikie at al., 1994, WWDR I, 2003, WWDR II, 2006, WWDR III, 2009, Vrba and Verhagen, 2006, and others).

Technical and scientific capacity building

Technical and scientific capacity building refers to structural and non-structural measures mainly in groundwater system analysis, identification, inventory and assessment of natural disasters and pollution sources, groundwater monitoring systems, interdisciplinary research and international expertise and knowledge transfer (Fig. 7.2.1).

Groundwater system analysis refers to the origin and occurrence of groundwater related to both recent and earlier hydrological cycles. Setting up a conceptual model, based on identification of boundaries, recharge rate, flow nets and hydraulic characteristics of the studied groundwater system supports the assessment of emergency groundwater resources resistant to natural disasters and identification of the crucial factors influencing the quantity, quality and vulnerability of groundwater in disaster prone areas. The conceptual model should cover the uncertainties in defining the groundwater behaviour and provides the basis for determining further data requirements and developing a mathematical model for prediction the impact of a disaster on the groundwater system (see chapters 4 and 6).

Identifying, inventorising and assessing natural disasters and human impacts on groundwater resources are of particular importance. This involves the collection and evaluation of historical and contemporaneous records about the nature, extent, impact and return periods of natural disasters and identifying, inventorising and assessing existing and potential pollution sources – crucial activities to be defined in governance disaster prevention and mitigation policy.

Groundwater monitoring and early warning programmes produce data for 1/ assessing the current state of, and anticipating changes and forecasting trends in groundwater quantity and quality caused by human impacts and natural processes and 2/ risk management of groundwater resources in emergency situations. 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 programmes for early warning to prevent or reduce impacts on human life, and on ecological and water systems. The outcomes of the second UN International Conference on Early Warning held in Bonn, Germany (2003) stressed coordination and cooperation among all relevant sectors integrated into early warning monitoring programmes. Methods of early warning groundwater monitoring have been described also by Vrba and Adams (2008). The establishment of early warning systems with a view to ensuring that rapid and coordinated action is taken in alert/emergency is introduced among the priorities for action 2005–2015 of the World Conference on Disaster Reduction (2005). However, at the international and national scale, early warning and groundwater monitoring activities are still underdeveloped due to financial and logistic problems and international cooperation and coordination in the collection, exchange and dissemination of monitoring data are often lacking in particular in transboundary aquifers.

Interdisciplinary research and international expertise and knowledge transfer, important vehicles in improving water governance policy in emergency situations, have to be supported by international organizations and national governments. The outcomes and strategic goals of the World Conference on Disaster Reduction (2005) pointed out the importance of transferring knowledge, technology and expertise to enhance capacity building for disaster risk reduction and the sharing of research findings, lessons learned and best practices.

8. Concluding remarks

Jaroslav Vrba and Balt Verhagen

This Methodological Guide, one of the main outcomes of the GWES (Groundwater for Emergency Situations) UNESCO IHP project collects the contributions by different authors with various disciplines from several continents. They bring a wealth of experience and insight to the Guide, both in its methodological and technical chapters and in the numerous case studies that highlight the application of the techniques and institutional, legal, and political approaches discussed. Clearly, the Guide should not be seen as a comprehensive textbook for those charged with the supply of drinking water where disasters strike. What it does attempt is to raise the awareness of technical experts, as well as governmental authorities at various levels, and the public to the approaches and methods available to investigate and develop emergency groundwater resources to mitigate the recurrent crisis of potable water supply during and immediately after disasters and to formulate water risk and adaptive management plans, emergency measures and groundwater governance policy in emergency situations.

The GWES project is an integral part of the UNESCO International Hydrological Programme that significantly supports scientific activities and knowledge transfer oriented on hydrological extremes. Such extremes could be water-related and geological disasters, the impact of climate change on the hydrological cycle, groundwater system responses to global changes and human impacts. Several projects implemented within the sixth phase (2002–2007) of IHP were focused on developing 1/ approaches aimed at reducing ecological and socio-economic vulnerability to hydrological events and 2/ an understanding of extreme events by integrating various sources of data (historical, instrumental, remote sensing) over large scales in time and space.

The prediction of potential impacts of climate variability and change on groundwater resources and their management are an integral part of GWES project activities. Shallow, coastal and karstic aquifers in particular are highly vulnerable to climate changes, specifically factors such as temperature and precipitation, increasing desertification, sea level rise, and groundwater quality degradation by flooding; and also changes in groundwater recharge, evaporation, evapotranspiration and soil moisture, important components of the water balance. The GWES guide deals with the establishment and operation of groundwater monitoring and early warning systems and the collection and assessment of relevant data. These are essential in recognising the influence of climate change on groundwater, to decrease the uncertainties associated with the groundwater reaction to such changes and to identify the impact of climate change on groundwater while it is still controllable and manageable. In many areas of the world the impact of climate change may be exacerbated by man's modifications to the water cycle and impacts on groundwater resources resulting from changes in land use and land cover.

Adapting to the impacts of global changes on river basins and aquifer systems constitutes Theme 1 in the approved core programme of the 7th phase of the IHP (2008–2013). This theme in particular concentrates on global changes and feedback mechanisms of hydrological processes in stressed systems, impacts of climate change on the hydrological cycle and consequent impacts on water resources, hydro-hazards, hydrological extremes and water-related disasters and on managing the response of of groundwater systems to global and regional climate variability and change.

The second phase of the GWES project is implemented under the Focal Area 1.3 of IHP VII activities, entitled: Hydro-hazards, hydrological extremes and water related disasters. This focal area addresses both natural and man-made catastrophies that could adversely influence human health and life with the aim of mitigating, reducing and/or preventing certain disasters. The following activities related to the GWES project are listed in the Implementation plan of IHP VII:

- Supporting capacity building in member countries in order to gain and advocate better understanding and handling of hazards, vulnerabilities and benefits involved with floods and other water-related disasters.
- Proposing effective methodologies for identifying and establishing an inventory of surface and groundwater bodies less vulnerable to natural and man-made impacts in selected pilot regions and presenting relevant case studies.
- Publishing 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.
- Propose a methodology and legend for compiling a groundwater vulnerability map that will depict emergency groundwater resources resistant to natural disasters.
- Promoting the cooperation amongst countries sharing transboundary basins to facilitate integrated and coordinated basin management in combating hydro-hazards, hydrological extremes and disasters.
- Developing linkages with the UNESCO International Centre for Hazard and Risk Management (ICHARM) established in Japan.
- Implement a pilot study in a region that is prone to natural disasters. The coastal region of Orissa State, India has been selected recently as it is repeatedly affected by major storms.
- Organizing GWES seminars and /or workshops at the regional level.
- Forging an international network for addressing groundwater resources management in emergency situations.

Implementation of the GWES project supports the main theme of the 7th phase of the IHP: Systems under Stress and Societal Responses. There is a disquieting increase in the already large numbers amongst the world's population living under the stress of water scarcity. These in particular are the ones most affected by a range of disasters of hydrological and geological origin as well as those caused by man. The population experiences increasing rates of growth and migration as well as exposure to drought, floods and other natural disasters and pollution hazards. These factors, combined with social and economic development, are reflected in increasing demands for safe water resources, in particular those which can be used in emergency situations. In a single year, floods alone will affect some 520 million people around the world, up to 25,000 people may lose their lives, water supply facilities of the survivors damaged and drinking water resources polluted. Climate variability and change increase weather related disasters that affect water resources, in particular in arid and semi-arid regions with water scarcity.

Secure drinking water for endangered populations is one of the highest priorities during and immediately after disasters. This lies at the core of the GWES project. Its main scope is to identify, preferably in regions repeatedly affected by natural disasters, potential safe groundwater resources resistant to floods, droughts, storms and other natural impacts, that could replace, either temporarily or in the longer term, domestic and public water supplies damaged and/or polluted by disaster events. Effective methodologies and techniques are proposed for:

- identifying, investigating, assessing, managing and mapping groundwater resources of low vulnerability to be used in emergencies resulting from different extreme climatic and geological events,
- policy for the protection of emergency groundwater resources,
- effective water governance policy in emergency situations and
- building institutional and technical capacities for risk minimization and impact mitigation of disasters with respect to emergency drinking water sources.

The increasing frequency and magnitude of floods, droughts, storms and other natural disasters requires 1/ a better understanding, and thus prediction, of their possible impacts on groundwater resources (as well as changes in groundwater systems due to anthropogenic drivers) and 2/ the formulation of scientifically based groundwater risk mitigation and risk management plans and governance policy for or different physical, economical, social and environmental settings on both country and regional scales. The authors of this methodological guide express the hope that the publication of these guidelines may assist societies in significantly reducing their vulnerability to drinking water scarcity in emergency situations and in mitigating concomitant health, social, economic and environmental stresses.

9. References

Ackland, M.C. and Hunter, T.C. 2002. *Australia's Honeymoon Project- (Form Acquisition to Approval - 1997 to 2002)***.** 33th Technical Committtee Meeting on Uranium Resources, Production and Demand, IAEA, Beijing.

Affeltranger, B. 2001. *Public participation in the design of local strategies for flood mitigation and control.* Technical Documents in Hydrology, No. 48, UNESCO, Paris.

Aggarwal, Y., Sykes, L.R., Simpson, D.W and Richards, P.G. 1973. *Spatial, and temporal variations of* t_s/t_p *and in P wave residuals at Blue Mountain Lake, New York. Application to earthquake prediction.* Journal of Geophysical Research, Vol. 80, 718-732.

Aggarwal, P.K., Gat, J.R. and Froehlich, F.O. (eds.) 2005. *Isotopes in the Water Cycle*. Springer, Dordrecht, The Netherlands, 381 p.

Alexander, I. and Seiler, K.-P. 1983. *Lebensdauer und Transport von Bakterien in typischen Grundwasserleitern - Münchener Schotterebene.* DVGW-Schriftenr. Wasser 35 Eschborn, 113-125.

Alley, W.M., Reilly, T.E. and Franke, O.L. 1999. *Sustainability of ground-water resources*. U.S. Geological Survey Circular 1186, Denver, Colorado, 79 p.

Allison, G.B. and Hughes, M.W. 1978. *The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer.* Aust. J. Soil Res. 16, 181-195.

Allison, G.B. and Hughes, M.W. 1983. *The use of natural tracers as indicators of soil water movement in a temperate semi-arid region*. J. Hydrol. 60, 157-173.

Alvarado, J., Seiler, K.-P. and Trimborn, P. 1996. *Investigación hydro-geológica, isotópica e hidroquimíca de la cuenca del Lago de Valencia, Venezuela*. In: On Isotopes in Water Resources Management, Vol. 2,., IAEA, Vienna, 281-299.

Anand Rao.,V. and Kesri., M.P. 2008. *Electrical Resistivity Tomography (ERT) to delineate favourable groundwater zones in Ghatia Watershed, Ujjain District, Madhya Pradesh, India.* 45th Annual Convention and Meeting on Seismic Hazard and Crustal Earthquakes, Indian Scenario, 5- 7, November 2008, Banaras Hindu University, Varanasi, India,

Andres, G. and Egger, R. 1985. *A new tritium interface method for determining the recharge rate of deep groundwater in the Bavarian Molasse Basin*. Jour. Hydrol. 82, 27-38.

Angelito, V., Cervera, G. and Chapellier, D.1991. *La gravimétrie expéditive appliquée a la recherche d'aquifères en zone aride ; cas de la nappe alluviale du Teloua (Agade, Niger)*. Geoexploration, Vol. 27, 179-192.

Armienta, A., De La Cruz-Reynas, S., Carjavalam, A., Ramoss, S., Varley, N., Ceniceros, N., Cruz, O. and Aguayo, A. 2003. *Relations between hydrogeochemical anomalies and eruptive activities at Mexican volcanoes.* Effective and Inexpensive Detection Methods. IUGG 2003 Abstract, JSH02 – Posters, Groundwater and Volcanoes (IAHS/ICGW, IAVCEI).

Arulraj, M., Pandian, P. K. and Ramachandran, S. 2006. *Vulnerability, mapping and resettlement plan for Bortang Island Andaman, India.* Map India 2005, GIS Development, The Geospatial Resource Portal Disaster Management, 1-12.

Astier, J.L and Paterson, N.R. 1989. *Hydrogeological interest of aeromagnetic maps in crystalline and metamorphic areas.* In: G.D. Garland, Editor, Proceedings of Exploration '87. Ontario Geological Survey Special Volume 3, Toronto, 732–745.

Baldison, R., Seiler, K.-P. and Trimborn, P. 1995. *Investigaciones isotópicas ambientales,químicas e hidrogeológicas en la cuenca del Lago Atitlàn, Guatemala*. – In: Estudios de hidrologia isotópica en America Latina, IAEA-TECDOC-835, (IAEA) Vienna, 225-236.

Barker, R.D. 1978. *The offset system of electrical resistivity sounding and its use with a multicore cable.* Geophysical Prospecting, Vol. 29, 128-143.

Barker, R. D. 1992. *A simple algorithm for electrical imaging of the sub-surface First Break.* Vol. 10, 53-62.

Bates, R.L. and Jackson, J., A. (eds.) 1980. *Glossary of geol*ogy, American Geological Istitute. Falls Church, Virginia.

Beaudou, A., Cambrézy, L. and Zaiss, R. 2003. *Geographical Information System, environment and camp planning in refugee hosting areas.* Institut de Recherche pour le Développement, UNHCR.

Bell, F. G. 1999. *Geological hazards their assessment, avoidance and mitigation.* E&FN Spon, London, 16-58.

Berger, J.F. and Olafsdottir, S. 2005. *South Asia earthquake - Tragedy and destruction in Shmir.* Red Cross Red Crescent, Geneva, 1, issue 3, 4 – 9.

BGS. 2001. *Ethiopia map Project R7125, Uk DFID – BGS*. Keyworth, Nottingham.

Blaikie, P., Cannon, T., Davis, I. and Wisner, B. 1994. *At risk. Natural hazards, people vulnerability and disasters.* Routledge, London and New York, 284 p.

Blöschl, G. and Sivapalan, M. 1995. *Scale issues in hydrological modeling: A review*. – Hydrol. Processes 9, 251-290.

Brassington, R. 1988. *Field hydrogeology*. Open University Press, Milton Keyes and Halsted Press, John Willey and Sons, New York, Toronto, 175.

Bromley, J., Mannstrom, B., Nisca, D. and Jamtlid, A. 1994. *Airborne geophysics–application to a groundwater study in Botswana.* Ground Water, Vol. 32, 79-90.

Bryant, E. *1991 Natural Hazards*. Cambridge,. Cambridge University Press, 294 p.

Bryant, E. 2001. *Tsunami, the underrated hazard*. Cambridge University Press, 320 p.

Bryant, E. and Nott, J. 2001. *Geological indicators of large tsunami in Australia. Natural hazards.* Springer Netherlands, Vol.24, 231-249.

Bue, C. D. 1972. *Flood information for flood-plain planning.* In: Man and his physical environment (Eds.: McKenzie, G.D., Utgard, R.O.), Burgess Publishing Company, Minneapolis, Minnesota, 285-293.

Busenberg, E. and Plummer, L.N. 1992. *Use of chlorfluorocarbon (CCl_3F and CCl_2F_2) as hydrologic tracers and age dating tools: The alluvium and terrace system on Central Oklahoma.* Water Resources Res. 28, 2257-2283.

Butler, S. S. 1957. *Engineering hydrology*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 356 p.

Carmichael, R. S and Henry, G. 1977. *Gravity exploration for groundwater and bed rock topography in glaciated areas.* Geophysics, Vol. 42, 1084-1096.

Carpenter G. 2005. *Tsunami: Indian Ocean event and investigation into potential global risks*. Marsh& McLennan Companies.

Chadha, D.K., Sinha, A.K. and Jain, R.C. 2006. *Groundwater risk management during Bhuj earthquake*. In: J. Vrba and B. Verhagen, UNESCO, IHP VI Series on groundwater, Vol. 12, 75-80.

Chadha, R. K., A. P. Pandey. and Kumpe, H. J. (2003). *Search for earthquake precursor in well water levels in a localized seismically active area of reservoir triggered earthquakes in India.* Geophys. Res. Lett. 30, 1416, doi: 10.1029/2002GL016694.

Chebotarev, I. 1955. *Metamorphism of natural waters in the crust of weathering*. Geochim. Cosmochim. Acta 8, London, New York, 23–48, 13 –170, 198–212.

CGWB (Central Ground Water Board) India.1999. *Technical report of Central Groundwater Board on Orissa Coast Super Cyclone.* New Delhi, India.

Chidambram, S., Prasanna, M.V., Srinivasmoorthy, K., Anadhan, P. and John Peter A. 2007. *Characterization of groundwater in the tsunami affected coastal areas of Tamilnadu. A case study.*

International conference on 'Coastal zone environment and sustainable development - Vulnerability, adaptation and beyond'. New Delhi, India, 80 p.

Claesson, L., Skelton, A., Graham, L., Morth, M., Torssader, P. and Kockum, I. 2004. *Hydrogeochemical changes before and after a major earthquake*. Geology, Vol. 32, 641- 644.

Clark, I. D. and Fritz, P. 1997. *Environmental isotopes in hyrogeology*. Lewis Publishers, New York, 328 p.

Cook, P.G., Edmunds, W.M. and Gaye, C. 1992. *Estimating palaeorecharge and palaeoclimate from unsaturated zone profiles*. Water Resources. Res. 28, 2721-2731.

Davis S. N., and De Wiest R. M. 1966. *Hydrogeology*. J. Wiley, New York, London, Sydney, 463 p.

Directive 2000/60 EC of the European Parliament and of the Council. 2000. Framework for Community Action in the Field of Water Policy.

Dion, N. P. and Embrey, S. S. 1981. *Effect of Mount St. Helens eruption on lakes in Washington.* USGS. Circular, 850-G 25 p.

DOD (Department of Ocean Development). 2006. *Setting up of Early warning system for tsunami and storm surges in the Indian Ocean*. In Rajamanickam et al., 2006, published by Earth System Science, Department of Science & Technology, Government of India, New Delhi.175-176.

Domenico, P. A. 1972. *Concept and models in groundwater hydrology.* McGraw-Hill, New York, 405 p.

Dooge, J. 2004. *Ethnics of water related disasters*. Series on Water and Ethics, Essay 9, UNESCO, Paris, 28 p.

Drury, S. A. and Deller, A. 2002. *Remote sensing and locating new water sources*. http://www.oosa.unvienna.org/SAP/stdm/2002-Africa /presentations /session 09A/speaker01/.

Edmunds, W.M. and Walton, N.R.G. 1980. *A geochemical and isotopic approach to recharge evaluation in semi, arid zones – past and present*. In: Application of isotopic techniques in arid zone hydrology, IAEA, Vienna, 47-68.

Edmunds, W.M., Darling, W.G. and Kinniburgh, D.G. 1988. *Solute profile techniques for recharge estimation in semi-arid and arid terrain.* In: Simmers I. (Ed.). Estimation of natural groundwater recharge, (Reidel) Dordrecht, Boston 139-157.

Edmunds, W.M., Gaye, C.B. and Fontes, J.-C. 1992. *A record of climatic and environmental change contained in interstitial waters from the unsaturated zone of northern Senegal*. In: Isotope techniques in water resources development, (IAEA) Vienna, 533-549.

Einsele, G., Seiler, K.P., Bertleff, B., Lindner, W., Plum, H. & Weber, E.1987. *Erkundung tiefer Grundwasserzirkulationssysteme.* DVWK Schr. 81, (Parey) Hamburg, Berlin, 223 p.

Elango, L., Ashudash, D., Chidambaram, S., Kaliappan, S., Lawrence, J.F., Palanivel,K. and Ravichandran, R. 2006. *Water quality in the coastal areas of Tamilnadu after tsunami*. In Rajamanickam et al., 2006, published by Earth System Science, Department of Science & Technology, Government of India, New Delhi, 45-58.

Elfouly, A. 2000. *Faults and fracture intersections delineation as a tool for groundwater detection using remote sensing and ground penetrating radar techniques at Saint Catherine Area, Southern Sinai, Egypt.* IICEHM2000, Cairo University, Egypt, 293-310.

Engelhardt, W. 1960. *Der Porenraum der Sedimente.* Springer, Berlin, 207 p.

Eriksson, E. 1952: *Composition of atmospheric precipitation. II. Sulphur, chloride, iodine compounds.* Tellus 4, 280-303.

Fernandez Prieto, D. and Palazzo, F. 2006. *The role of Earth observation in improving water governance in Africa: ESA's TIGER initiative.* Hydrogeology Journal, Springer, Vol. 15, 101–104.

Fetter, C.W. 1988. *Applied hydrogeology*. Merrill Publishing Company, Columbus, Toronto, London, Melbourne, 592 p.

Fleeger, Gary M., Goode, D. J., Buckwalter, T.F. and Risser, D.W. 1999. *Hydrologic effects of the Pymatuning Earthquake of September 25, 1998, in Northwestern Pennsylvania.* U.S. Geological Survey Water-Resources Investigations Report. 99-4170, 8 p.

Foster, S.S.D., Bath, A.H., Farr, J.L. and Lewis, W.J. 1982. *The likelihood of active groundwater recharge in the Botswana Kalahari.* Jour. Hydrol. 55, 113-136.

Freeze, R.A. and Witherspoon, P.A. 1967. *Theoretical analysis of regional groundwater flow: 2. Effect of water table configuration and subsurface permeability variations.* Water Resources Res. 3, 623-634.

Freeze, R.A. and Cherry, J.A.1979. *Groundwater.* Prentice Hall, Englewood Cliffs,N.J., 604 p.

Fraser-Smith, A.C., Bernardi, A., McGill, P. R., Ladd, M. E., Helliwell, R.A and Velar, O.G. 1990.

Low-frequency magnetic field measurements near the epicenter of the M 7.1 Loma Prieta earthquake, Geophysics. Res. Lett, Vol. 17, 1465-1468.

Fried, J. 1975. *Groundwater pollution.* Develop. in Water Science 4, Elsevier, New York, 339 p.

FY. 2003. *Urban history*. US Global Change Research program: Our changing planet.

Gaudru, H.1997. *Des Volcanoes des Homemmes.* Published by Tricorne Edition–Geneva, 130 p.

Geol. Society of India, 2005. *Great Tsunami, 26th December, 2004, Sumatra Region.* Published by Geological Society of India, Bangalore, 143 p.

Ghergut, J. Maloszewski, P. and Seiler, K.-P. 2001. *Age, environmental isotope and contaminant transport uncoupling in heterogeneous aquifers following hydraulic stress.* In. Seiler, K.P. and Wohnlich, S. (Eds.). *New approaches characterizing groundwater flow.* Balkema, Lisse, Abingdon, Exton, Tokyo, 327- 334.

Gieske, A., Selaolo, E. and McMullan, S. 1990. *Groundwater recharge through the unsaturated* zone of south-eastern *Botswana: a study of chloride and environmental isotopes.* Regionalisation in Hydrology. IAHS Public., 33-43.

Giggenbach, W. F.1992. *Isotopic shifts from geothermal and volcanic systems along convergent plate boundaries and their origin.* Planetary Science letters, Vol. 113, 495-510.

Gray, W.M. 1975. *Tropical cyclones genesis atmospheric science.* Paper No.4, 1975. Colorado State University, Fort Collins, Colorado, 121 p.

Goldman, M., Gilad, D., Roney, A. and Melloul, A.1991. *Mapping of seawater intrusion into the coastal aquifer of Israel by the time domain electromagnetic method*. Geoexploration, Vol. 28, 153-174.

Griffiths, D. H., Turnbull, J. and Olayinka, A.I. 1990. *Two dimensional resistivity mapping with a computer controlled array*. First Break 8, 121-129.

Griffiths, D.H. and Turnbull, J. 1985. *A multi electrode array for resistivity surveying.* First Break 3, 16-20.

Griffiths, D.H. and Barker, R.D. 1993. *Two-dimensional resistivity imaging and modeling in areas of complex geology*. Journal of Applied Geophysics 29, 211-226.

Gupta, S.K. and Sharma, P. 1984. *Soil moisture transport through the unsaturated zone: Tritium tagging studies, in Sabarmati Basin, Western India*. Hydrol. Sci. J. 22, 177-189.

Hafen, U. and Kölling, Ch. 2000. *Grundwassermodell ingolstädter Becken mit einer Kalibrierung über Altersdatierungen.* In: S. Wohnlich & K. Zosseder, Isotopenanwendungen in der Hydrogeologie, Seminar, München, May 2000. München. University, Geological Institutes, 52-60.

Hall, D.H. and Hajnal, Z. 1962. *The gravimeter in studies of buried valleys.* Geophysics, Vol. 27, No. 6, 937-951.

Hartz, K.E ., Bhagat, S. K., Starlin, L.A., Mott, H.V. and Krivanek , K.R. 1984 . *Attenuation of leachate generated from co-disposal of volcanic ash and solid waste*. Water Research Center Report, Pullman, Washington, 97p.

Heath, R.C. 1983. *Groundwater regions of the United States.* Geological Water Supply Paper 2242, Washinton, D.C., 78 p.

Hendershot, W.H., Savoie, S. and Courchesne, F. 1992. *Simulation of stream water chemistry with soil solution and groundwater flow contribution.* J. Hydrol. 136, 237-252.

Hill, D.P., Reasexberg, P.A., Michael, A., Arabaz, W.J., Beroza, G., Brumbaugh, D. and Brune, J.N., et al. 1993. *Seismicity remotely triggered by the magnitude 7.3 Landers, California earthquake.* Science, Vol. 26, 1617–1623.

Hills, J. G and Mader, C.L. 1997.*Tsunami produced by the impact of small asteroids*. Annals of the New York Academy of Sciences, Vol. 822, 381-394.

Hindin, E.1983. *Occurrence of organic compounds in water and stream sediments due to St.Helens eruptions*. Pullman, Washington. Washington Water Research Centre Report 52, 91 p.

Hopson, F.R. 1991. *Potential impact on water resources from future volcanic eruptions at Long Valley Mono County California USA* .Environmental Geology, Vol. 15, 49-55.

Hladný, J., Kašpárek, L., Krátká, M., Kněžek, M. and Martínková, M. (eds.). 2005. *Catastrophic flood in the Czech Republic in August 2002.* Ministry of Environment, Prague, Czech Republic, 44 p.

Hynie, O. 1961. *Hydrogeologie SSR I, Prosté vody*. Nakladatelství SAV, Praha, 562 p.

IAEA. 2007. *Introduction to water sampling and analysis for isotope hydrology*. IAEA-IWSA, Vienna.

Igarashi, G., Saeki, S., Takahata, N., Sumikawa, K., Tasaka, S., Sasaki Y., Takahashi, M., and Sano, Y. 1995. *Groundwater radon anomaly before the Kobe earthquake in Japan.* Science, Vol. 269, 60–61.

Illangasekare, Tyler S. W., Clement, T.P., Villhoth, K.G., Perera, A.P.G.R.L., Obeysekera, J., Gunahlaka, A., Paraboklle, R., Hydman, D.W., Cunnighan, K.J., Kalurachchi, J.J., Yeh William, W.G., Yeh Van Geruchsen, M.T and Janson, K. 2006. *Impacts of the 2004 tsunami on ground water resourses in Srilanka.* Water Resources Research, 42.W05201, doi:10.1029/2006WR004876.

Intergovernmental Oceanographic Commission. 1999. *Historical tsunami data base for the Pacific, 47 B.C-1998 A.D.* Tsunami Laboratory, Institute of Computational Mathematics and Mathematical Geophysics. Siberial Division Russian Acadamy of Sciences, Novosibirsk, Russia http://tsun.sscc.ru/HTDB pac 1/

IWMI (International Water Management Institute). 2005. *Tsunami Impacts on shallow Groundwater and associated water supply on the East Coast of Srilanka.* Report of International Water Management Institute http://ww.imi.org, Nov, 2005, 67 p.

Jacobsen, K. 2005. *Analyses of SRTM Elevation Model.*, University of Hannover, Germany, www.ipi.uni-hannnover.de/html/aktivitaeten/EARSeL-Workshop2005_Paper/Jacobsen2.pdf

Jain, R.C. and Saleem, R. 2005. *Groundwater risk management in regions affected by tsunami.* A Technical Report of Central Groundwater Board, New Delhi, India.

Jeggle, T. 2005. *Introduction to Risk Assessment Process*. In: Disaster prevention and reduction. 9 p. Czech University of Agriculture, Prague, Czech Republic.

Jílek, P., Melková, J., Růžičková, E., Šilar, J. and Zeman,A. 1995. *Radiocarbon dating of Holocene sediments: Flood events and evolution of the Labe (Elbe) River in central Bohemia (Czech Republic).* Proceedings of the 15th International Conference on Radiocarbon Dating, Glasgow 1994, Radiocarbon, vol.37, No.2, Tucson, Arizona, p. 131-137.

Johnston, D.M. 1997. *Physical and social impacts of past and future volcanic eruptions in New Zealand.* Unpublished Ph.D. thesis, Department of Soil Science, Massey University.

Johnston, D.M. B.F., Houghton, V.E., Neall, K.R., Ronan and Paton, D. 2000. *Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand. An example of increasing societal vulnerability.* GSA Bulletin 112, Vol. 5, 720-726.

Karanth, K R. 2001. *Ground Water Assessment, Development and Management*. Tata McGraw- Hill Publishing Company Ltd, New Delhi, 437-509.

Keller, E. A. 1976. *Environmental geology.* Charles E.Merrill Publishing Company, Columbus, Ohio.

Kennedy, V.C. 1971. *Silica variation in stream water with time and discharge*. In. Hem, J.D. (Ed.): Nonequilibrium Systems in Natural Water Chemistry. Adv. in Chem. Sci. Washington, 106-130.

Keshri, A.K., Ramanathan, A.L. and Neupane, B. 2006. *Impact of the 26-12-2004 Tsunami on the Indian Coastal groundwater and emergency remediation strategy.* In. Vrba, J. and Verhagen, B.Th. eds. Ground water for Emergency situations, A Framework Document. UNESCO, IHP-VI, Series on groundwater, No 12, 94 p.

Kikawada,Y., Oi, Takao and Ossaka, J. 2003. *Change in water chemistry of hot water springs related with volcanic activities in Kusatsu-Shirane volcano region Gunma, Japan.* IUGG 2003 Abstract, JSH02 – Posters, Groundwater and Volcanoes (IAHS/ ICGW, IAVCEI).

Kinzelbach, W. 1986. *Groundwater modeling.* Elsevier, Amsterdam, Oxford, New York, Tokyo, 333 p.

Kirsh., R. (Ed.) 2006. *Groundwater geophysics - a tool for hydrogeology*. Springer, 493 p.

Klein, J.M. 1984. *Some chemical effects of the Mount St. Helens eruption on selected streams in the state of Washington*. U.S.Geological Survey, Circular 850 –E, 31 p.

Knorr, M. 1937. *Die Schutzzonenfrage in der Trinkwasserhygiene*. GWF 80, Munich, 330-334 and 350-355.

Kovalesky, V.S., Kruseman, G.P. and Rushton, K.R. 2004. *An international guide for hydrogeological investigations.* UNESCO, IHP VI, Series on Groundwater, No.3, 133-183.

Krishnamurthy, N.S., Chandra, S and Kumar D. 2007. *Geophysical characterization of hard rock aquifers. Groundwater dynamics in hard rock aquifers*. Capital Publishing Company, ISBN-81-85589-25-9, 64-86.

Kulkarni, K.M., Navada, S.V., Nair, A.R., Rao, S.M., Shivanna, K., Sinha, U.K. and Sharma, S. 1997. *Drinking water salinity problem in coastal Orissa , India – Identification of past transgressions of sea water by isotope investigations.* Isotope Techniques in the Study of Environmental Change. Proc. Intl. Symp. IAEA, Vienna, 293-306.

Lee, D.B. 1998. *Effects of the eruptions of Mount St. Helens on physical, chemical, and biological characteristics of surface water, ground water, and precipitation in the Western United States*, USGS report.

Linde, A, T., Suyvehiro, K., Miuras, Sacks, I. S. and Takgi, A. 1988. *Episodic aseismic earthquake precursors*. Nature, Vol. 334, 513-515.

Lisitzin, A.P. 1971. *Sedimentation in the world ocean: With emphasis on the nature, distribution and behaviour of marine suspensions*. Soc. Econ. Paleontol. Mineral 17, 218 p.

Lockridge, P.A. 1985. *Tsunamis in Peru-Chile. Word data centre A for Solid Earth Geophysics*. National Geophysical Data Center, Boulder and Rpt st. 39.

Lockridge, P.A.1988 b. *Historical tsunamis in the Pacific Base.* In. Sabh, M.I. and Murty T.S. eds. Natural and Man– made Hazard, Reidel, Dordrecht, 171-181.

Loke, M.H. and Barker, R.D. 1996. *Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method*. Geophysical Prospectings 44, 499-524.

Lloyd, J.W. 1980. *An examination of recharge mound decay and fossil gradients in arid regional sediment basins.* In. Arid-zone hydrology: Investigations with isotope techniques. IAEA Vienna, 69-75.

Magaritz, M., Kaufman, A., Paul, M., Boaretto, E. and Hollos, G. 1990. *A new method to determine regional evapotranspiration*. Water Resources Res. 26, 1759-1762.

Mahmood, A. 1996. *Lineaments as groundwater exploration guides in hard-rock terranes of arid regions*. Canadian Journal of Remote Sensing Vol. 22, No.1.

Maidment, D.R. 1997. *GIS Hydro 97 – Introduction*. Center for Research in Water Resources, University of Texas at Austin, USA.

Major, J. J. 2003. *Post eruption hydrology and sediment transport in volcanic rive systems*. Water Resources Impact, Vol.5, 10-15.

Major, J.J., Pierson, T.C., Dinehart, R.L. and Costa, J.E. 2000. *Sediment yield following severe volcanic disturbance- A two decade perspective from Mount St. Helens*. Geology 28, 819-822.

Major, J.J., Mark, L.E. and Spicer, K.R. 2001. *Response of peak flow discharges to the catastrophic1980 Mount St. Helens eruption*. EOS82 (47), F511.

Malozsewski, P. and Zuber, A. 1996. *Lumped parameter models for interpretation of environmental tracer data.* In. Manual on Mathematical Models in Isotope Hydrogeology. Tecdoc-910, IAEA, Vienna, 9-58.

Maloszewski, P., Moser, H., Stichler, W., Bertleff, B. and Hedin, K. 1990. *Modelling of groundwater pollution by river water bank filtration using oxygen-18 data.* Groundwater Monitoring and Management, IAHS Oubl. 173, 153-161.

Manning, J.C.1987. *Applied principles of Hydrology*. Merrill Publishing Company, A Bell & Howell Information Company, Columbus, Ohio, 278 p.

Matthess, G. 1982. *The properties of groundwater.* A Wiley – Interscience Publication, New York, Chichester, Brisbane, Toronto, Singapore, 406 p.

Mattle, N., Kinzelbach, W., Beyerle, U., Huggenberger, P. and Loosli, H.H. 2001. *Exploring an aquifer system by integrating hydraulic, hydrogeologic, and environmental tracer data in a 3-dimensional hydrodynamic transport model*. J. Hydrol. 242, 183-196.

Mayback, M. 1985. *The GEMS Water Programme 1978 – 1983*. Water Quality Bul. Vol. 10, No.4, Canada.

Mazor, E. 1991 (third edition 2004). *Chemical and isotopic groundwater hydrology.* Marcel Dekker, Inc., New York, Basel, Hong Kong, 451.

McMahon, A., Heathcote, J., Carey, M. and Erskine, A. 2001. *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface*. Report NC/99/38/2 National Groundwater & Contaminant Land Centre. ISBN 1 857 05610 8.

Meinzer, O. E. 1942. *Ground Water.* In: Meinzer, O. E. ed. Hydrology. Dover Publications, Inc., New York.

Merkel, B. and Planner-Friedrich, B. 2002. *Grundwasserchemie. Praxisorientierter Leitfaden zur numerischen modellierung von beschaffenheit, Kontamination und Sanierung aquatischer Systeme.* Springer, Berlin, Heidelberg, New York, Barcelona, London, Mailand, Paris, Tokyo, 219 p.

Michel, F.A. and Fritz, P. 1978. *Environmental isotopes in permafrost related waters along the Mackenzie Valley Corridor.* Proc. 3rd Int. Conf. Permafrost, Edmonton, 207-211.

Miller, C.D., Mullineaux, D.R. and Crandell, D.R. 1981. *Hazard assessments at Mount St. Helens. in*. Lipman, P.W and Mullineaux D.R. eds. The 1980 eruptions of Mount St. Helens, Washington. US Geological Survey. Prof. Paper 1250, 789–802.

Mook, W.G. 2000. *Environmental isotopes in the hydrologic water cycle. Theory, methods, review.* UNESCO/IAEA series, UNESCO, Paris, 280 p.

Montgomery, D.R., and Manga, M. 2003. *Stream flow and water well responses to Earthquakes*. Science, 300, 2047–2049.

Morikawa, N., Kazahaya, K., Nagao, K., Yasuhara, M., Inamura, A., Takahashi, M., Sumino, H. and Ohwada, M. 2003. *Helium isotopes in groundwaters from the Kobe Area: Application to thermal water circulation*. IUGG 2003 Abstract , JSH02 – Posters, Groundwater and Volcanoes (IAHS/ICGW, IAVCEI).

Mui, G. M., Goode, D. J., Buckwalter, T.F. and Risser, D.W. 1999. *Hydrologic effects of the Pymatuning earthquake of September 25, 1998, in Northwestern Pennsylvanya. U.S.* Geological Survey Water-Resources Investigations Report. 99, 4170 - 4178.

Muir-Wood, R. and King, G.C.P. 1993. *Hydrological signatures of earthquake strain*. J. of Geophysical Research. 98, No.B12: 22025-68.

Münnich, K.O. 1968. *Use of nuclear techniques for the determination of ground water recharge rates*. In: Guidebook on nuclear techniques in hydrology. IAEA, Vienna, 191-197.

Myers, B., Brantley, S.R., Stauffer, P. and Hendley, J.W. II. 1997. *What are volcano hazards.* U.S. Geological Survey Fact Sheet-002-97.

Narasimha Rao, B.S.R. 1999. *Report on cyclone affected areas of Orissa*, Central Ground Water Board, Ministry of Water Resources, Government of India, Bhubneshwar, India. 26 p.

Natermann, E. 1951: *Die Linie des langjährigen Grundwassers und derTrockenwetterabflusslinie (TWL).* Die Wasserwirtschaft 41, 12-14.

Naumann, U., Maloszewski, P., Ghergut, I., Seiler, K.-P. and Stichler W. 2005. *Estimating microbial denitrification parameters from in situ bioreactor operation under groundwater conditions.* IAH (in press).

Nemecek, E.P. 1961. *Horizontalfilterbrunnen zur Grundwassergewinnung*. Wasserwirt-schaft Wassertechnik 11, 99-107.

Neupane, B. 2006. *Effects of the Indian Ocean tsunami on coastal groundwater in south eastern coast of India*. World Water Forum (Mexico), Session: Groundwater and risk management.

Nir, A. and Lewis, S. 1975. *On tracer theory in geophysical systems in the steady and nonsteady state* I. Tellus 27, 372-383.

Ohtake, M., Matumoto, T., and Latham, G. 1981. *Evaluation of the forecast of the 1978 Oaxaca, southern Mexico earthquake based on a precursory seismic quiescence. I*n. Sampson, D.P., and Richards, P.G., Eds. Earthquake prediction. An international review, American Geophysical union, Maurice Ewing Series, Vol. 4, 53-62 p.

Oglivi, A.A. 1967. *Geophysical prospecting for groundwater in the Soviet Union.* Mining and Groundwater Geophysics. Economic Geol. Bull., Vol. 26.

Oki, Y. and Hiraga, S. 1988. *Groundwater – level monitoring for prediction of earthquakes*. Pure and applied Geophysics, Vol. 126, 211-240.

Oppenheimer, C. 1997. *Surveillance and mapping of volcanoes and their emissions by satellite remote sensing.* Geography, Vol. 82(4), 317-333.

Oster, H., Sonntag, C. and Münich, K.O. 1996. *Groundwater age dating with chlorofluorocarbons*. Water Resources Res. 32, 2989-3001.

Payne, B.R. and Halevy, E. 1968. *Introduction.* in: Guidebook on Nuclear Techniques in Hydrology, Technical Report Series No. 91, IAEA, Vienna, 1-20.

Pekdeger, A. and Matthes, G. 1983. *Factors of bacteria and virus transport in groundwater.* Environm. Geology, 5. 49-52.

Phillips, F.M., Mattick, J.G., Duval, T.A., Elmore, D. and Kubik, P.W. 1988. *Chlorine-36 and tritium from nuclear weapons testing as tracers for long-term liquid and vapor movement in desert soils.* - Water Resources Res. 24, 1877-1891.

Plate, E. J. 2003. *Human security and natural disasters.* Federal Ministry of Education and Research, Bonn, Germany, 24 p.

Plümacher, J. and Kinzelbach, W. 2000. *Calibration of a regional groundwater flow model using environmental isotope data*. In: A. Dassargues (ed.), Tracers and Modelling in Hydrogeology; Proc. intl. conf. Liege, “Tra’M 2000”. Oxfordshire. IAHS publ., 439-445.

Prinz, D. and Singh Anupam, K. 2000. *Water Resources in arid regions and their sustainable management.* Annals of Arid Lands, Special Issue on Research.

Priyadas, R.V.K., Weerasinghe, K.D.N., Liyange, Ja , A., Wijayawardhane, L.M.J.R., Kunara, D.S.E. and Lakmal, H.K.C.S. 2007. *Groundwater quality assessment of a tsunami affected coastal aquifer in Southern Srilanka*. Abstract volume International conference on "Coastal Zone Environment and sustainable Development-Vulnerability, Adaptation and Beyond". New Delhi, India. 83 p.

Puri, S. (ed.) 2001. *Internationally Shared (Transboundary) Aquifer Resource Management. Framework Document.* IHP-VI, Series on Groundwater No.1. UNESCO, Paris..

Quilty, E.G., Farrar, C.D., Galloway, D.L., Hamlin, S.N., Laczniak, R.J., Roeloffs, E.A., Sorey, M.L., and Woodcock, D.E. 1995. *Hydrologic effects associated with the January 17, 1994 Northridge, California, earthquake. U.S.* Geological Survey, Open-File Report, 95-813, 47.

Radhakrishna, I. 2001. *Saline fresh water interface structure in Mahanadi delta region, Orissa, India*. Environmental Geology, Vol. 40, 369-380.

Raghav Rao. 1978. *Report on the Technical assistance rendered in the cyclone tidal wave affected areas of Krishna and Guntur Districts (Field season 1977-1978)*. Central Ground Water Board , Southern Region, Hyderabad, India.

Rajamanickam, G.V., Subramaniyan, B.R., Baba, M., Ramesh, R., Elango,L. and Prithviraj, M.2006. *26th December 2004 tsunami causes-effects-remedial measures pre and post tsunami disaster management, a geo-scientific perspective*. Published by Earth System Science, Department of Science & Technology, Government of India, New Delhi, 1-232.

Rajendraprasad, P., Nageshwara Rao, K., Prasad, N .V . B. S.S., Raman, A,V., Bhanu Kumar, O,S,R,U., Swamy,Y,V., Das, S,N., Chaudhury, G,R., Kumar, A.R.S., Sudhakar, S.V., Rama Rao, P., Jagannadha Rao, S., Sampath Kumar, M., Deva Varma, D., Bhanumurthy, P., Ganesh, T., Somu Naidu, Y., Sanjeevaiah, G., Mary Padma, V. and Lokesh Kumar Reddy, N. (2006). *Effect of 26th December 2004 tsunami along the Andhra Coast- An integrated study*. In: Rajmanickam et al., 2006, Published by Earth System Science, Department of Science & Technology, Government of India, New Delhi, 116-138.

Ranjan, R.K and Ramanathan, A.L. 2007. *Assessment of heavy metals contamination in tsunamigenic sediments of Pichavaram and Mangroves, South east Coast of India*. Abstract volume, International conference on "Coastal zone environment and sustainable development-vulnerability, adaptation and beyond". New Delhi, India, 84 p.

Raudenský, M. and Dorazil, I. 2002. *Povodn 2002 – Letecké dokumenty*. VUT Brno, 127 p.

Reddy, D.V., Sukhija, B.S., Nagabhushanam, P., Reddy, G. K., Kumar D. and Lachassagne, P. 2006. *Soil gas radon emanometry: A tool for delineation of fractures for groundwater in granitic terrains*. J. Hydrol., Vol. 329, 186-195.

Richter, W. and Lillich, W. 1975. *Abriß der Hydrogeologie*. Schweizerbart, Stuttgart, 281 p.

Rodriguez, E., Morris, C.S., Belz, J.E., Chapin, E.C., Martin, J.M., Daffer, W. and Hensley, S. 2005. *An assessment of the SRTM topographic products.* Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 p.

Roeloffs, E. 1988. *Hydrologic precursors to earthquakes: A review*. Pure and Applied Geophysics, Vol. 126, 177–209.

Roeloffs, E., Danskin, W.R., Farrar, C.D., Galloway, D.L., Hamlin, S.N., Quilty, E.G., Quinn, H.M., Schaefer, D.H., Sorey, M.L., and Woodcock, D.E. 1995. *Hydrologic effects associated with the June 28, 1992 Landers, California, earthquake sequence.* U.S. Geological Survey Open-File Report, 95-42, 68 p.

Roeloffs, E.1998. *Persistent water level changes in a well near Park field, California, due to local and distant earthquakes.* J. Geophys. Res., 103 (B1), 869–889 p.

Rojas Molina, R. 2006. *Impacto de los eventos de "El Niño" en la infraestructura de abastecimiento de agua en el Peru*. Manuscript, Instituto Peruano de Energía Nuclear, Lima, Perú, 10 p.

SADC. 2003. *Groundwater & drought management in SADC*. GEF Project Brief Africa Regional Office, AFTU1, Lesotho.

SADC. 2003b. *Interim report to Southern African Development Community. Regional situation analysis.* RFP # WB 1861-571/02. Wellfield Consulting Services, Gaborone, Botswana and British Geological Survey, Crowmarsh Gifford, UK.

Saint-Jean, R. and Singhroy, V. 2000. *Hydrogeological mapping in the semi-arid environment of Eastern Jordan* *using airborne multipolarized radar images*. First Joint World Congress on Groundwater, Fortaleza - Ceara, Brasil.

Schirov, M., Legchenko, A. and Creer, G.1991. *New direct non invasive ground water detection technology for Australia.* Expl. Geophysics, Vol. 22, 333-338.

Seiler, K.P.and Rodriguez, C.O. 1980. *Geological and hydrologic boundary conditions for the interpretation of isotope data.* Interamerican Symposium on Isotope Hydrology, Bogotá, Colombia, 18-22 August, 1980, IAN, Bogotá, 43-59.

Seiler, K.-P. 1983. *Tiefe Grundwässer und Faktoren, die das Absenkungsgeschehen in tiefen Grundwässern beeinflüssen*. Z. dt. geol. Ges. 134, 845-855.

Seiler, K.-P. and Lindner, W. 1995. *Near surface and deep groundwater.* J. Hydrol. 165, 33-44.

Seiler, K.P. 2000. *Man's Impact on Groundwater Systems*. In. Series on Environmental Isotopes in the Hydrological Cycle, Vol. V, UNESCO, Paris, 105 p.

Seiler, K.P., Loewenstern von, S. and Schneider, S. 2002. *Matrix and bypass-flow in Quaternary and Tertiary sediments of agricultural areas in south Germany*. Geoderma 105, 299-306.

Seiler, K.P. and Gat, J.R. 2007. *Groundwater recharge from run-of, infiltration and percolation.* Springer, Dordrecht 224 p.

Seiler, K.-P., Gu, W.Z. and Stichler, W. 2007. *Transient response of groundwater systems to climate change*. In: Dragoni, W. & Sukhija, B.S.: Climate change and groundwater, The Geological Society, London, 111-119.

Sharma, M.L. 1989. *Groundwater recharge*. In: On groundwater recharge. Balkema, Rotterdam, Brookfield, 323 p.

Shibata, Matsumato, T. and Akita, N. F. 2003. *Change in groundwaterl level before the 2000 eruption of USU Volcano, Japan.* Abstract, JSH02 – Posters, Groundwater and Volcanoes (IAHS/ICGW, IAVCEI). USGS: Website of United States Geological Survey, Cascades Volcano Observatory Vancouver, Washington, USA.

Shikomalov, I. A. 1999. *World water resources*. *Modern assessment and outlook for the 21th century*, UNESCO, Paris, 50 p.

Schoeller, H. 1941. *L'influence du climat sur la composition chimique des eaux souterraines vadose.* B.S.G.F. 11, 267-289.

Schoeller, M. 1961. *Calculs du bilan des nappes d'eau des Sables des Landes en utilisant la teneur en chlore de l'eau des nappes et celles de l'eau de pluie*. C.R.Ac.Sc. 253, 1598-1599.

Schoeller, M. 1963. *Recherches sur l'aquisition de la compostion chimique des eaux souterraines.* Imprimerie Drouillard, Bordeaux, 231.

Šilar, J. 2002. *Groundwater resources for emergency cases in the lower reaches of the Labe (Elbe) River (Czech Republic)*. A contribution to the UNESCO IHP programme, IAEA-CN-104/P-140.

Sine. 1974. *International Glossary of Hydrology*. First edition, WMO/OMM/BMO – No.385, Geneva, 393 p.

Sine. 2004. *Living with risk*. A global review of disaster reduction initiatives. ISDR, C.D., UN.

Singh, S.B., Dhar, R., L, Radhakrishna, I. and Prasad Rao, N.T.V. 1990. *Deep resistivity studies for groundwater exploration in Barmer District, Rajasthan*. Technical Report No. NGRI-90-Environ. 82, 72 p.

Sklash, M.G., Farvolden, R.N. and Fritz, P. 1976. *A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer*. Can. J. Earth Sc. 13, 271-283.

Sneed, M., Gallway, D.L. and Cunnigham, W.L. 2006. *Earthquakes-rattling the earth's plumbing system. U.S*. Geological Survey Fact Sheet 096-03, http://pubs.usgs.gov/fs/fs- 096-03/.

Sugisaki, R., Ito, T., Nagamine, K. and Kawabe, I., 1996. *Gas geochemical changes at mineral springs associated with the 1995 southern Hyogo earthquake (M=7.2), Japan*. Earth and Planetary Science Letters, Vol. 139, 239–249.

Sukhija, B.S., Reddy D.V., Nagabhushnam, P., Syed Hussain, Giri, V.Y and Patil, D.J. 1996. *Environmental & injected tracer methodology to estimate direct precipitation recharge to a confined Aquifer*. J. Hydrol., Vol. 177, 77-97.

Sukhija, B.S. 2005. *Understanding Ground System for its Sustainability*. Jour. of Geological Society of India. Vol. 65, 655-657.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Mondal, N.C., Sujatha, D., Nagaiah, E. and Gupta H.K.

2007. *Radon precursor studies in Koyna – Warna seismic area*. Geochemical Precursors for Earthquakes (Prasanta Sen, Nisith K Das,Eds). Publ. by Macmillan India, 50-62.

Tanaka, T. 2007. *Groundwater use in earthquake emergency: A case study in Japan.* Paper presented at the UNESCO Working Group meeting on the project Groundwater for Emergency Situations (GWES), Tsukuba, Japan.

Tokunaga, T. 1999. *Modeling earthquake induced hydrological changes and possible permeability enhancement due to the 17 the January 1995, Kobe earthquake Japan*, J. Hydro, 223, 221-229.

Toth, J. 1963. *theoretical analysis of groundwater flow in small drainage basis.* Jour. Geophys. Res. 68, 4795-4812.

Toth, J. 1995. *Hydraulic continuity in large sedimentary basins*. J. Hydrol. 3, 4-16.

Tsukuda, E., Koizumi, N. and Yasuto, K. 2000. *Integrated groundwater monitoring studies in the intensified observation area and near major active faults.* Bulletin of the Geological Survey of Japan, Vol. 51, 435–445.

Tsumura, K., Karakama, I., Ogino, I. and Takahashi, M.1978. *Seismic activities before and after the IZU_Osima –Kinkai earthquake of 1978*. University of Tokyo, Earthquake Research Institute, Bulletin, Vol. 53, 309-315.

Tsunogai, U. and Wakita, H. 1995. *Precursory chemical changes in ground water: Kobe earthquake, Japan*. Science, Vol. 269, 61–63.

Tyler, S.W. and Walker, G.R. 1994. *Root zone effects on tracer migration in arid zones*. Soil Sci. Soc. Am. J. 58, 25-31.

UNEP (United Nations Environmental Protection Program). 2005. *Maldives, post tsunami environmental assessment.* Report of UNEP.

UNESCO. 1999. *World Map of Hydro-geological Conditions and Groundwater Flow*. HydroScience Press.

UNESCO. 2008. *The UNILC Draft articles on the low of transboundary aquifers.* In: Transboundary aquifers: Managing a vital resource. Arts Print-Pantin, 14–20.

UN WWDR. 2003. *Water for people – Water for life.* UNESCO, WWAP, Berghahn Books, 576 p.

UN WWDR. 2006. *Water a shared responsibility.* UNESCO, WWAP, Baseline Arts, 584 p.

UN WWDR. 2009. *Water in a changing world.* UNESCO, WWAP, Earthscan, 318 p.

Vachier, P., Dever, L. and Fontes, J.C. 1987. *Mouvements de l'eau dans la zone non saturée et alimentation de la nappe de la craie de Champagne (France).* In : Proc. Symp. Isotope techniques in water resources development. IAEA, Vienna, 367-379.

Van Overmeeren, R.A. 1994. *Geo radar for Hydrogeology*. First Break, Vol. 12, 401-408.

Varian, R.H. 1962. *Ground liquid prospecting method and apparatus*. US Patent 3019383.

Ven Te Chow.1964. *Statistical and probability analysis of hydrologic data*. In: Ven Te Chow, ed. Applied Hydrology, 8-1, McGraw-Hill Book Company, New York, San Francisco, Toronto, London, 8-97.

Verhagen, B.Th., Smith, P.E., McGeorge, I.L. and Dziembowski, Z. 1979. *Tritium profiles in Kalahari sands as a measure of rain-water recharge.* Isotope Hydrology, Vol. II, IAEA, Vienna, 733-751.

Verhagen, B.Th., Geyh, M.A., Froehlich, K. and Wirth, K. 1991. *Isotope hydrological methods for the quantitative evaluation of ground water resources in arid and semi-arid* areas. *Development of a methodology*. Research Reports of the Federal Ministry for Economic Cooperation of the Federal Republic of Germany. Bonn.

Verhagen, B. Th., Bredenkamp, D. B., Janse van Rensburg, H. and Farr, J. L. 1999. *Recharge quantification with radiocarbon: Independent corroboration in Three Karoo Aquifer studies in Botswana.* in: Isotope Techniques in Water Resources Development and Management. Proceedings Int. Symp. C&S Papers Series 2/C, IAEA, Vienna, 14 p.

Verhagen, B. Th., Butler, M. J., van Wyk, E. and Levin, M. 2003. *Environmental isotope studies as part of a rural ground water supply development: Taaibosch area, Limpopo Province, South Africa.* Tec. Doc., IAEA (in print).

Verhagen, B. Th. and Butler, M.J. 2004. *Isotopes and chemistry suggest natural processes for high nitrate in ground Water*. Proceedings, WISA Conference, Cape Town, May, 2004.

Virk, H.S, and Baljinder, S. 1994. *Radon recording of Uttarkashi earthquake*. Geophysical Research Letters, Vol. 21, 737-740.

Vorhis, R. C. 1967. *Hydrologic effects of the earthquake of March 27, 1964 outside Alaska*. U.S. Geological Survey Professional Paper 544-C, 54 p.

Vrba, J. and Adams, B. (eds). 2002. *Strategy for groundwater early warning monitoring system*. IHP V Series, UNESCO, Paris, 104 p.

Vrba, J.and Verhagen, B.Th.(eds). 2006. *Groundwater for emergency situations – A framework document*. IHP-VI, Series on Groundwater, No. 12, UNESCO, Paris, 94 p.

Vrba, J. and Salamat, A.,R.(eds). 2007. Groundwater for emergency situations. Proceedings of international the workshop, Tehran, 29 – 31 October 2006. IHP-VI, Series on Groundwater No. 15. UNESCO, Paris, 127 p.

Weise, S.M., Loosli, H.H. and Honal, M. 2000. *Qualitative Isotopenstudie an Tiefengrundwässern aus dem Bereich Augsburg-München*. In: Institut für Hydrologie Jahresbericht 1999. Neuherberg. GSF-Forschungszentrum, 32-36.

White, A.F., Benson, L.V and Perry, D.L .1981. *The influence of weathering of Mount St.Helens ash on chemistry of a small water shed*. Geological Society of America, Abstracts, Vol. 13, 579 p.

White, W.B. 1998. *Groundwater flow in karstic aquifers*. – In: Delleur., Ed.: The Handbook of Groundwater Engineering. 18/1-18/36, (CRC Press) Boca Raton.

WHO. 1996. *Guidelines for drinking water quality. Health criteria and other supporting information.* Vol. 2, World Health Organisation, Geneva, 973 p.

WHO. 2005. *Technical Notes for Emergency.* Regional Office for South – East Asia, WEDC, UK.

Wood, W.W. and Sanford, W.E. 1995. *Chemical and isotopic methods for quantifying groundwater recharge in a regional semi-arid environment*. Ground Water 33, 458-468.

Wundt, W. 1953. *Die Niedrigwasserführung in Baden-Württemberg als Maß für die verfügbaren Grundwassermengen*. Gas-Wasserfach 24, 719-722.

Wundt, W. 1958. *Die Kleinstwasserführung der Flüsse als Maß für die verfügbaren Grundwassermengen.* Forsch. dt. Landesk. 104, Remagen, 47-54.

Xue Songgui 2005. *The flood and sediment regulation experiments in the Yellow River. Keeping Healthy Life of Rivers*. Yellow River Water Press. Zhengzou, China, 7 p.

Yasuhara, M., Kazahaya, K., Inamura, A., Kono,T., Oshawa, S., Yusa, Y. and Kitoka, K., 2003.*Geochemical Interpretation of Groundwater Hydrology on Unzen Volcano, Southwest Japan. IUGG 2003* Abstract , JSH02 – Posters , Groundwater and Volcanoes (IAHS/ICGW, IAVCEI).

Yoshioka R., 2007. *The earthquakes recently occurred in inland regions of Japan and life lines focusing on groundwater – comparison between The Hydro Narbu earthquake (1995) and Nilgata Chuetsu earthquake (2004).* Paper presented at the UNESCO Working Group meeting on the project Groundwater for Emergency Situations (GWES), Tsukuba, Japan.

Young, G.J., Dooge, J.C.I. and Roods, J.C. 1994.*Global water resources issues.* Cambridge University Press.

Zoellmann, K., Kinzelbach, W. and Fulda, C. 2001. *Environmental tracer transport (^3H and SF_6) in the saturated and unsaturated zones and its use in nitrate pollution management*. J. Hydrol. 240, 187-205.

Zuber, A. 1993. *Mathematical models for the interpretation of environmental radioisotopes in groundwater systems*. in: Fritz, P. and Fontes, J. Ch., eds. Handbook of environmental isotope geochemistry, Vol. 2, Part B., Elsevier, Amsterdam, 1-55.

10. Glossary

The following technical terms were compiled mainly from UNESCO – WHO International Glossary of hydrology (1992) and UN ISDR terminology

Abstraction: Removal of water from any source, either permanently or temporarily.
Annual runoff: Total volume of water that flows during a year, usually referring to the outflow of a drainage area or river basin.
Aquiclude: Saturated bed, formation, or group of formations of low hydraulic conductivity which yield 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 a rather impervious and semi-confining nature which transmits water at a very slow rate compared with an aquifer.
Area of influence (syn. Zone of influence)**:** Area around a pumping or a recharging well in which the water table (in unconfined aquifer) or the piezometric surface (in 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.
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: The portion of rainfall entering streams, lakes, aquatic ecosystems and recharging groundwater.
Boundary conditions: Set of conditions for 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 1000 – 10 000 mg/l.
Brine: Very concentrated salt solution (conventionally above 100 000 mg/l.
Catchment: An area that collects and drains rainwater.
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 between two reference periods.
Cone of depression: Depression, in the shape of a cone with convex upward limits, of the piezometric groundwater surface which defines the area of influence of a pumping well..
Confined aquifer (see also artesian aquifer)**:** Aquifer overlain and underlain by an impervious or almost impervious formation.

Conjunctive use: Combined use of surface water and groundwater.
Conservative pollutants: Non-biodegradable pollutants.
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 renders the water unfit for its intended use.
Darcy's law: Law expressing the proportionality of the specific discharge of a liquid flowing through a porous medium to the hydraulic gradient 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 of 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.
Depletion: Reduction of groundwater storage in an aquifer caused by discharge exceeding natural replenishment.
Disaster: A serious disruption of the normal functioning of a community or a society, which causes widespread human, material, economic or environmental losses that exceed 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 human-induced).
Discharge (syn. Rate of flow)**:** Volume of water flowing through a river (or aquifer) cross-section in unit time.
Disposal well: Well used for the disposal of polluted or drainage water, brines, etc.
Drainage: Removal of surface water or groundwater from a given area by gravity or by pumping.
Drainage basin (syn. Catchment area, River basin, Watershed)**:** Area having a common outlet for its surface runoff.
Drought: Absence of marked deficiency of precipitation.
Drawdown: Lowering of the water table or piezometric surface caused by the extraction of groundwater by pumping.
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: Basin without surface or subsurface outflow.
Evaporation: The process by which water passes from the liquid to the vapour state.
Evaporation rate: Quantity of water which is evaporated from a given water surface per unit time.
Evapotranspiration: Quantity of water transferred from the soil to the atmosphere by evaporation and plant transpiration.
Exorheic basin: Basin with surface and/or subsurface outflow.
Flood: Rise, usually rapid, in the water level in a stream to a peak from which the water level recedes at a slower rate.
Foil water (syn. Non renewable)**:** Water infiltrated into an aquifer during an ancient geological period under climatic and morphological conditions different from the present and stored since that time.
Fracture porosity: Porosity resulting from the presence of openings produced by the breaking or shattering of the rocks.
Fresh/salt water interface: Imaginary surface separating a body of fresh water and one of brackish or salt water, positioned somewhere within the transition zone between the two fluids.
Fresh water: Naturally occurring water having a low concentration of salts, or generally accepted as suitable for abstraction and treatment to produce potable water (ISO/6107).
Gaining stream (syn. Effluent stream)**:** Stream or stretch of stream which receives water from the saturated zone, and whose flow is being increased by inflow of groundwater.

Grey water: Wastewater generated from human activities mainly domestic but also industrial, mining, and agricultural.

Groundwater: Subsurface water occupying the saturated zone.

Groundwater basin: Physiografic 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 divide: Imaginary line on a water table or piezometric surface on either side from which the groundwater flow diverges.

Groundwater flow: Movement of water in an aquifer.

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

Groundwater mining: (Strict) – Groundwater is persistently withdrawn at a rate clearly exceeding annual recharge, (Extended) – Groundwater storage is continuously depleted.

Groundwater overexploitation: Withdrawal from a groundwater reservoir in excess of the average rate of replenishment.

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 percolation 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.

Hazard: A potentially damaging physical event or phenomenon that can harm people and their welfare. Hazard can be a latent condition that may represent future trends, and could be natural or induced by human processes.

Hydraulic conductivity: Property of a saturated porous medium which determines the relationship, called Darcy's law, between the specific discharge and the hydraulic gradient causing it.

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

Hydrodynamic dispersion: Spreading of a solute in flow through porous media, resulting from molecular diffusion and from inhomogeneities in the microscopic velocities.

Hydrogeological boundary: Lateral 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 in its different forms passes from the ocean through the atmosphere to the land 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 observation: Direct measurements or evaluation of one or more hydrological elements, such as stage, discharge, water level, water temperature, etc.

Hydrological observing station: Place where hydrological observations for hydrological purposes are made.

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 through the soil surface into a porous medium.

Inflow: Flow of water into a stream, lake, basin, aquifer.

Influent seepage: Movement under gravity of 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: 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

Inundation: The state of flooding of land resulting from the impact of surface streams, storm surges, tsunamis or other fluid hazards.

Ion exchange: A process in which an ion in a mineral lattice is replaced by another ion that was present in a aqueous solution.

Isotopes: Atoms of the same element or atomic number that differ from each other in their atomic (nuclear) mass.

Juvenile water: Water derived from the interior of the Earth that has not previously existed as atmospheric or surface water.

Kanat (syn. Foggara, Karez, Qanat, Rhettara)**:** Subsurface gallery for water supply starting from below the water table and sloping downwards to the ground surface with a gradient flatter than both the water table and the ground surface.

Karst: Limestone and dolomite areas that possess a topography peculiar to and dependent upon underground solution and the diversion of surface waters to underground routes.

Karst hydrology: That branch of hydrology which deals with the hydrology of geological formations having large underground solution passages or fractures which enable underground movement of large quantities of water.

Laminar flow: Flow of a fluid in which the viscous forces are predominant.

Leakage: (in groundwater), The flow of water from or into an aquifer through the underlying or overlying semi-pervious layer.

Lithology: The systematic description of rocks, in terms of mineral composition and texture.

Losing stream: Stream that is losing water to the ground, and contributes water to the saturated zone.

Lysimeter: Vessel containing local soil and vegetation allowing drainage placed with its top flush with the ground surface for the study of water balance.

Mineral water: Water which contains significant quantities of mineral salts.

Model: A conceptual, mathematical, or physical system obeying certain specified conditions, whose behaviour is used to understand the physical system to which it is analogous in some way.

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

Observation well: Well used for measuring the static head of groundwater, and specially to observe the frequency and magnitude of changes in head or another physical or chemical parameter.

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.

Perched groundwater: Groundwater body, generally of moderate dimensions, supported by a relatively impermeable stratum and which is located between a water table and the ground surface.

Permeability: The ability of a rock or soil to transmit water.

pH: The negative logarithm of the hydrogen-ion activity.

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

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

Piezometric surface: (Imaginary) surface that joins points which are at an elevation equal to the piezometric head in an aquifer system.

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

Pollution (see also contamination)**:** Addition of pollutant to water.

Porosity: Ratio of the volume of the interstices in a given sample of a porous medium, e.g. soil, to the gross volume of the porous medium, inclusive of voids.

Pumping test : Pumping of water from a well at one or more selected discharge rates, during which piezometric levels are measured regularly at the pumping well and at nearby observation wells. The data are used to determine the aquifer parameters in the vicinity of the pumping well.

Radioactivity: The property of isotopes of certain elements to undergo spontaneously a transition of their nuclei during which sub-atomic particles (alfa or beta) or rays (gamma) are emitted at a rate specific to the particular isotope.

Radioisotope: An unstable isotope of an element that decays or desintegrades spontaneously, emitting radiation. Also called radionuclide.

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

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

Residence time: Period during which water or a substance remains in a component part of the hydrological cycle.

Resistivity: The electrical resistance offered to the passage of a current, expressed in ohm-meters; the reciprocal of conductivity.

Return flow: Any flow which returns to a stream channel or to the groundwater after use.

Runoff: That part of precipitation that appears as stream flow.

Risk: The probability of harmful consequences or the expected loss (of lives, people injured, property or environmental damage, and livelihoods or economic activity disrupted) resulting from interactions between natural or human hazards and vulnerable conditions. Conventionally, risk is expressed by the equation: Risk = Hazard x Vulnerability.

Risk assessment: Investigation 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.).

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

Sea-water intrusion: Penetration of sea water into a coastal aquifer.

Soil texture: Relative proportion of the various soil separates in a soil as described by the classes of soil texture.

Soil water: Water suspended in the uppermost belt of soil, or in the zone of aeration near the ground surface, that can be discharged into a the atmosphere by evapotranspiration.

Specific conductance: The ability of a cubic centimeter of water to conduct electricity; measured in micromhos per centimeter; varies with the amount of ionised minerals in the water.

Seismic method: Any of the various geophysical methods for characterizing subsurface rock properties based on the analysis of elastic waves artificially generated at the surface.

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

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

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.

Storm surge: Elevation of a eustary level caused by the passage of a low pressure centre.

Subsidence: Lowering in elevation of a considerable area of land surface, due to the removal of liquid or solid underlying material or removal of soluble material by means of water.

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

Texture: The interrelationship between the size, shape, and arrangement of minerals or particles in a rock.

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.

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

Tsunami: Massive waves of sea water which move towards the coastal areas with large energy. They develop from submarine seismic activity ($M \geq 6.5$) produced by fault movement, explosive volcanism, a submarine landslide and even by major meteorite strikes in the ocean.

Unconfined aquifer: Aquifer containing unconfined groundwater, that has a water table and an unsaturated zone.

Unsaturated zone: The zone between the land surface and the water table that contains both water and air. It includes the soil water zone, intermediate zone, and a capillary zone.

Vulnerability: 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: An arid-zone channel or water course 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 body: Mass of water distinct from other masses of water.

Water balance: Balance of input and output of water within a given defined hydrological area such as aquifer system, basin, lake, etc., taking into account net changes in storage.

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

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

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

Water need (also water demand)**:** Quantity of water required, over a given period, to satisfy fully a known or estimated requirement.

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 resources assessment: Determination of the sources, extent, dependability and quality of water resources for their utilization and control.

Watershed management: Controlled use of drainage basins in accordance with predetermined objectives.

Water stress: The condition of insufficient water of satisfactory quality and quantity to meet human and environmental needs.

Water supply system: All storage reservoirs, pumps, and works required for providing water of a desired quantity and quality to the different sectors of consumption.

Water table (syn. Groundwater table)**:** Surface within the zone of saturation of an unconfined aquifer over which the pressure is atmospheric.

Water table contour (syn. water table isohypse)**:** Line connecting all points on a water table which have the same elevation above a given datum.

Well: Shaft or hole sunk, dug, or drilled into the earth to extract water.

Well capacity: Maximum rate at which a well will yield water under a stipulated set of conditions, such as a given draw down.

Withdrawal (see also abstraction)**:** Extraction of water from surface and subsurface reservoirs.

Yield: The quantity of water per unit of time that may be pumped from a well under specific conditions.

Yield, permissive sustained: The maximum rate at which water can economically and legally be withdrawn perennially from a particular source for beneficial purposes without bringing about some undesired results.

Zone of saturation: A hydrologic zone in which all the interstices between particles of geologic material or all of the joints, fractures, or solution channels in a consolidated rock unit are filled with water under pressure greater than atmospheric.

11. Case studies

Authors of the *Case Studies* (Chapters 11.1 to 11.10)

Authors of case studies are listed in alphabetic order.

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11.1 Identifying a potential emergency groundwater supply in a fractured rock quartzitic aquifer with environmental isotopes

*Balt Verhagen**

Abstract

The fractured, quartzitic rock aquifers of the Cape Folded Belt in South Africa are being studied as a regional resource for this water-scarce region. The nature of the aquifers and physiography of the region pose specific problems in studying their geohydrology. In a localised investigation isotopic data was gathered from a small well field in a high altitude valley. Using the water balance approach, it could be shown that the storage of the aquifer being tapped by the well field could be as much as an order of magnitude greater than the volume of saturated rock drained by a spring. A considerable resource of very good quality groundwater is therefore available that could be (over-)pumped efficiently in case of emergency.

Introduction

The highly metamorphosed rocks of the Cape Supergroup slung along the south coast of South Africa over a linear outcrop distance of some 900 km (Fig. 11.1.1) have only recently been identified as a potential major, regional ground water resource. The quartzitic sandstones of the lower zone, the Table Mountain Group (TMG) have lost their primary porosity, and achieve thickness up to 3,000 m. The Cape orogeny has highly deformed this quartzitic formation, producing a hierarchy of brittle fractures on a wide range of scales, from the local micro-scale on the order of metres (Fig. 11.1.2) - the bulk of the fracture porosity - to regional faults and fracture zones up to 100's of kilometres in length (Fig.11.1.1). Many smaller to larger cold and thermal springs issue from the TMG.

The region has very limited surface water and is in great need of additional water resources for development. In the early nineties attention was drawn to the potential of the TMG fractured rock aquifers, and their large scale deep faulting and fracturing, as major sources of fresh water (Issar, 1994).

A series of national research programmes has been mobilised by the water authorities with the aim of clarifying the hydrology of this complex fracture aquifer system. Environmental isotope hydrology is seen as an important component of this research. This paper details one of these studies in the Vermaaks River valley in the Kammanassie Mountains (Figure 11.1.1).

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Figure 11.1.1. Map of Table Mountain Group quartzitic rock outcrops and regional structural features (after de Beer, 2002). Position of Kammanassie Mountains is indicated.

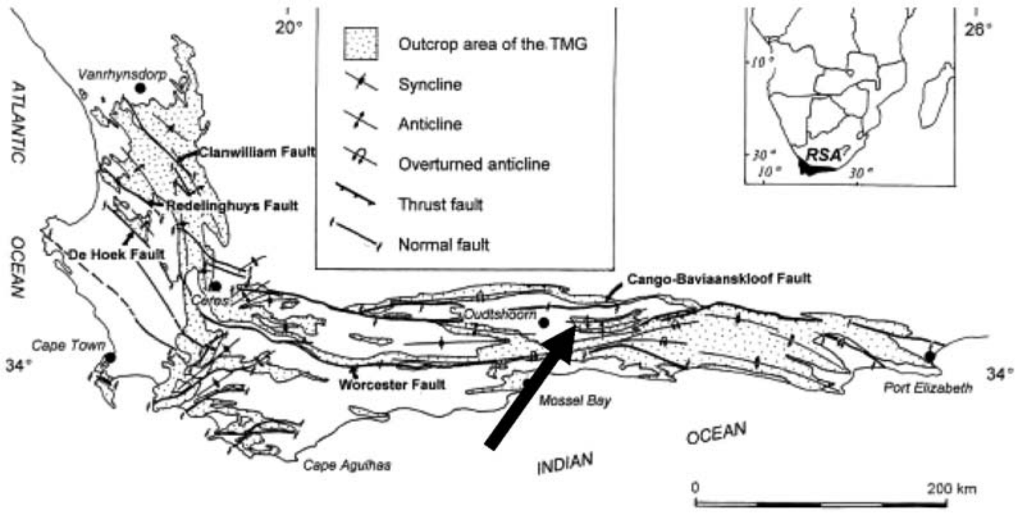
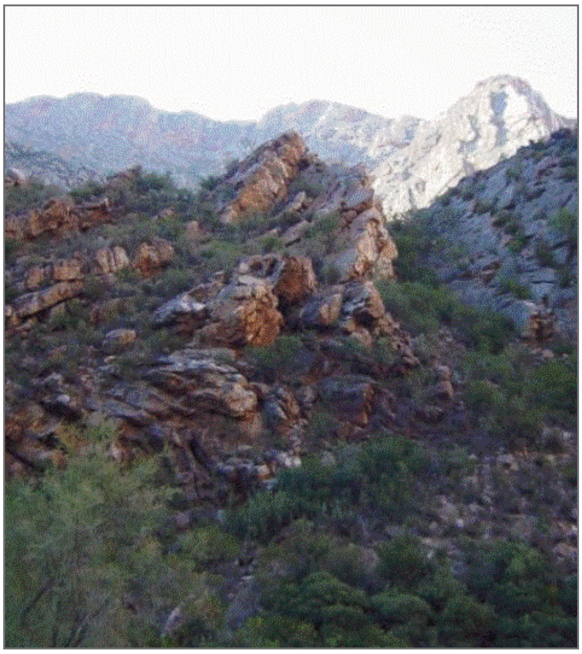


Figure 11.1.2. Typical fractured rock formations of the Cape Folded Belt



Features of the Table Mountain Group

In this hydrogeological setting a number of features influence groundwater environmental isotope characteristics and their interpretation:

- The almost pure quartzitic nature of TMG aquifers renders them effectively chemically inert. Ground water is usually acidic (pH < 5) with low alkalinity, the TDIC (total dissolved inorganic carbon) almost exclusively as dissolved CO_2 and $\delta^{13}C$ < -15‰ PDB. As for tritium, radiocarbon is therefore an almost conservative tracer along with, arguably, CFC's (dissolved chlorofluoro-carbons).

- Due to the low values of TDIC it is necessary to extract the inorganic carbon from up to 500 L of sample water for ^{14}C analysis. This was achieved by performing the extraction in the field using large plastic bags.
- Rain falls mainly in the winter months (Mediterranean-type climate) ranging from < 150 mm a^{-1} up to 2,000 mm a^{-1} in some high mountain sites.
- A marked stable isotope altitude effect is observed in rainfall in the often extremely rugged mountain terrain, which is reflected in water of lower-lying thermal springs associated with regional fracture systems.
- The assessment of mean residence time (MRT) suffers from the difficulty in estimating a meaningful representative value of the fracture porosity and extrapolating recharge estimates, even within a small basin (Verhagen et al., 2009).
- The extremely complex secondary porosity of the fractured aquifers often complicates the choice of a suitable mixing model to interpret environmental tracer data and recharge assessment.

Water balance approach - Vermaaks River valley

Problems with recharge assessment can partially be overcome by the water balance approach. Uncertainties regarding how representative the data from occasional pumping of observation boreholes may be avoided by studying operational supply boreholes. Abstraction in the Vermaaks River valley occurs through a small high altitude well field (Fig. 11.1.3) plus spring flow were taken to balance recharge.

Tensional stresses on the Kammanassie mountain anticline produced keystone faulting resulting in extensive fracturing and fracture porosity. Two facies of the TMG are separated by a shale band, which acts as an aquiclude, generating a spring at the contact (Fig. 11.1.4).

Figure 11.1.3. Vermaaks River valley catchment showing estimated recharge values, spring and production borehole positions

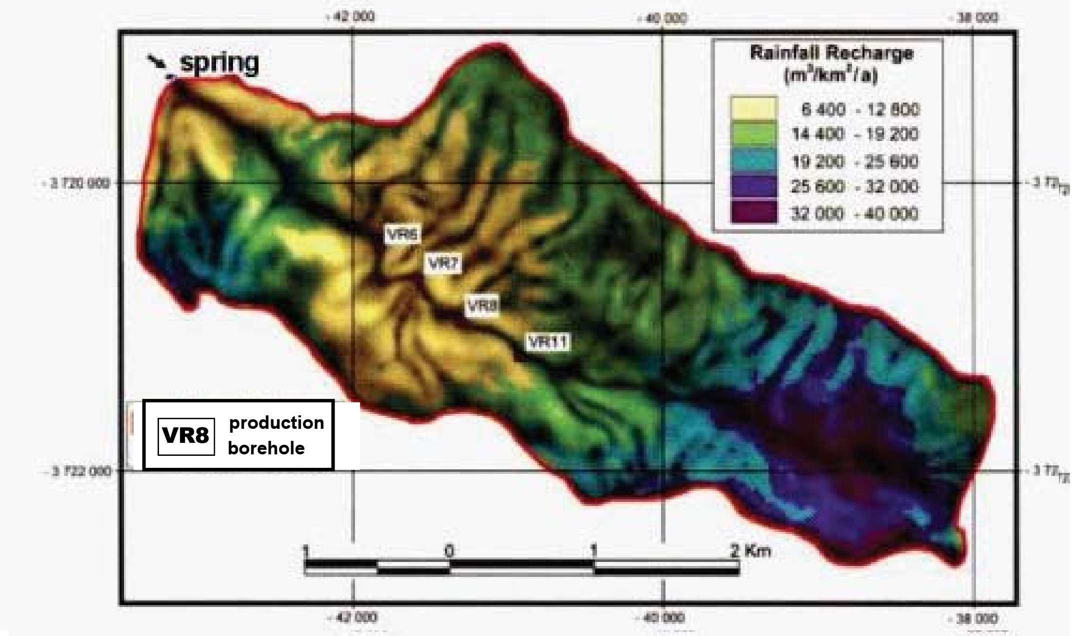
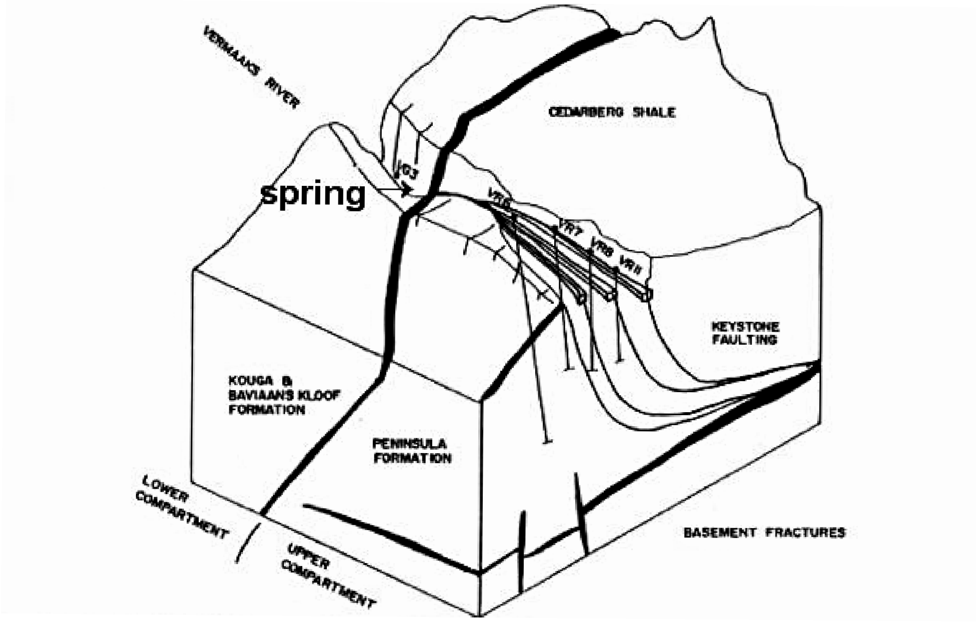


Figure 11.1.4. Schematic structural model of deep keystone faulting forming the Vermaaks River valley. A shale band separates two facies of the Table Mountain quartzites (Hälbich and Greef, 1997)



Vermaaks wellfield production boreholes were sampled for chemical, radiocarbon, tritium, stable isotope and dissolved CFC analysis. Samples were taken also from thermal springs in surrounding valleys as well as local, shallow groundwater derived from local rainfall in the valleys (Fig. 11.1.5).

The stable isotope signature of intermontane valley thermal springs matches values observed in high mountain ground water (Fig. 11.1.6), as observed elsewhere in the Cape folded belt (Mazor and Verhagen 1983, Diamond and Harris, 2000).

Figure 11.1.5. Schematic axial section of Vermaaks River valley with ^{14}C values for production wells. The effectiveness of the aquitard/aquiclude is shown by the spring and considerably lower ^{14}C value for the well downstream. (Verhagen, 1997)

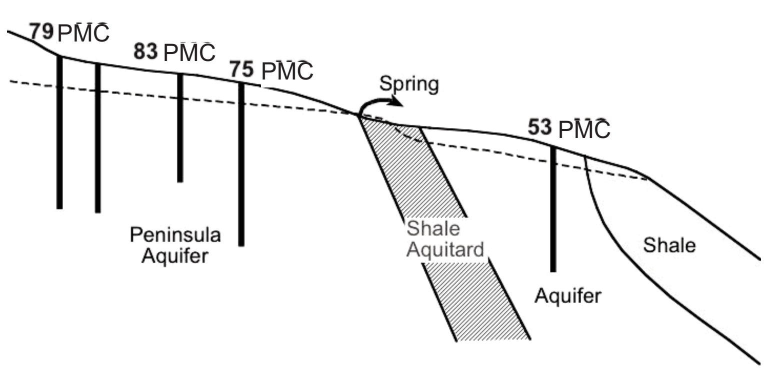
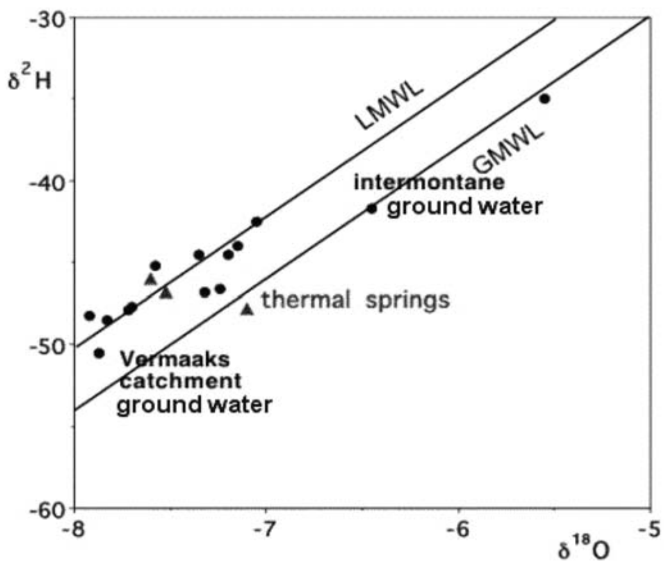


Figure 11.1.6. ***δ^2H-$\delta^{18}O$ (in ‰ SMOW) diagram of the Vermaaks catchment, thermal springs and intermontane local ground water. LMWL/GMWL – local/global meteoric water lines***



Water balance and its implications

The average water level in the operating well field was effectively constant for 4 years with reduced spring flow. It is assumed that during this period spring flow plus abstraction balanced the effective recharge to the aquifer. Tritium and CFC's are near the limit of detection (Table 11.1.1). This indicates that the recharge is essentially pre-bomb and that a reasonable mean residence time can be calculated directly from the ^{14}C content.

Table 11.1.1. ***Isotope data and estimated mean residence times for the Vermaaks River well field boreholes. Data from Verhagen (1997), Talma et al. (2000). Initial (recharge) ^{14}C for the MRT calculation is taken to be 95% of atmospheric ($\delta^{13}C$< -18‰). CFC concentrations calculated as percent modern freon (pmf).***

Borehole No	*^{14}C PMC*	*Initial ^{14}C PMC*	*Tritium TU (1σ)*	*CFC - 11 pmf*	*CFC -12 pmf*	*CFC - 113 pmf*	*MRT years*
VR 6	79.4	95	0.4±0.2	1	3	0	1,600
VR 7	83.0	95	0.0±0.2	1	3	0	1,200
VR 11	74.6	95	0.3±0.2	4	1	0	2,300
						mean	**1,700**

Assessing catchment storage

Structural analysis (Hälbich and Greef, 1997) has shown that the volume of rock drained by the

Vermaaks spring, i.e. above the spring datum line (Fig. 11.1.7) is 1.2 x 10^{10} m^3 . With a fracture porosity of ~ 1%, the

storage drainable by the spring V_S =1.2 x 10^8 m^3

The isotope data cannot be used to assess recharge directly, as no reasonable aquifer model can be devised. Several recharge estimates have been made, based on i.a saturated volume fluctuations, cumulative rainfall departures and chloride balance. In these complex topographic and aquifer situations, none of these figures can individually be assessed critically. The mean of the values estimated by Kotze (2002) and Parsons (2002) (14% of mean annual precipitation (MAP)) is therefore employed as a ballpark value for the Peninsula aquifer.

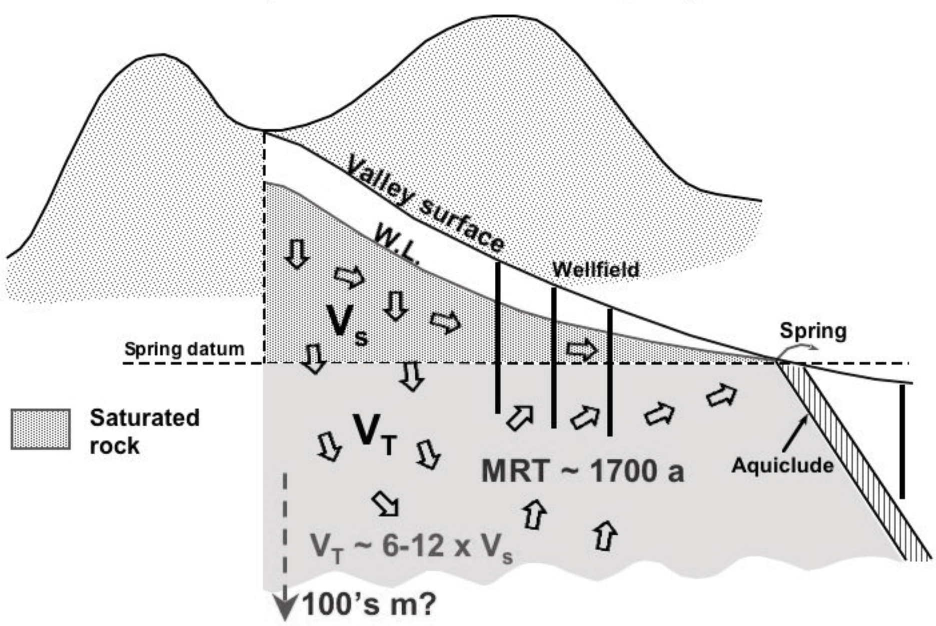
The total recharge input R to the catchment groundwater, with MAP = 550 mma^{-1}; catchment area A = ~10 km^2 is therefore R ~ 7.7 x 10^5 m^3a^{-1}. This value is quite compatible with the figure for the measurable total outflow: abstraction from the well field at balance (~5 x 10^5 m^3a^{-1}) plus spring flow (~2 x 10^5 m^3a^{-1}). The calculated recharge rate therefore appears to be realistic.

The storage of the aquifer is calculated on the basis of the well-mixed model (Maloszewski and Zuber, 1996; Verhagen et al., 1991) for a mean residence time (MRT) = 1,700 yr:

$$V_T = R \times MRT = 1{,}700 \times 7.7 \times 10^5 \sim 1.3 \times 10^9\ m^3$$

Therefore V_T/V_S ~ 11 i.e. the total calculated storage could be an order of magnitude higher than the storage drainable by the spring as inferred from structural estimates. The depth of both storage and circulation in this relatively small mountain catchment basin may be much larger than anticipated (Figure 11.1.7). This can be explained only partially by the higher fracture porosity (up to 5%; Kotze, 2002) for the upper sections of the keystone block. The overall average porosity for the valley catchment is likely not greatly to exceed 1% (Hälbich and Greef, 1997).

Figure 11.1.7. Conceptual flow model for the Vermaak's River valley catchment. V_S = volume above spring datum line; V_T = total fracture storage. Active flow could occur down to 100s of metres.



Implications for an emergency supply

i) The bulk of the ground water storage in the catchment should occur in fractures well below the spring datum line.
ii) Depth of circulation into the fracture zone could be several hundreds of metres. This could imply potential ground water losses into deep regional fractures. The apparent balance between recharge and outputs suggests that such losses should be modest in comparison.
iii) The thermal springs in the adjacent valleys, taken as evidence of losses by deep circulation, are low-yielding, thereby confirming the conclusions under ii).
iv) The aquifer is effectively phreatic. In spite of deep circulation the groundwater flowing from the spring or pumped from the well field is at ambient temperature.
v) Fracturing, which formed this small catchment, even at considerable depth, has remained open and interconnected since the orogeny. This can be understood in terms of the competency of the quartzitic rocks and the aggressive chemistry of the groundwater.
vi) The aquifer below the Vermaak's River valley constitutes a potentially ideal sub-regional emergency water supply.
vii) With deeper production wells there would be ample scope for temporarily achieving greater drawdowns. Abstraction would, however, have to be spread over more boreholes, to limit individual pumping drawdowns and the resulting oxygenation which could cause clogging due to the high iron content of the water.

Conclusions

This is an example of a small, mountain groundwater basin, routinely used as a local potable water supply, that has been shown to be capable of acting also as a standby emergency potable water resource. Supply sustainability was predicated on balancing long-term abstraction against average recharge, groundwater levels reacting promptly to rainfall events. When investigated further, tritium measurements, supported by CFC values, indicated residence times in excess of 100 years. Radiocarbon measurements, very reliable in this hydrochemical environment, indicated mean residence times of the order of 1700 years, in apparent contradiction to its hydrological behaviour. The volume of saturated rock above the spring datum line was assessed through structural geological analysis, and with an estimated fracture porosity the storage above that datum line. With a value for the rain recharge, averaged from estimates by various different methods, and the MRT for the basin, a total storage could be assessed that is an order of magnitude greater than the volume drainable by the spring. Very deep storage is therefore indicated, allowing in principle for emergency overdrafts through deep boreholes. Various disciplines were combined in this fairly simple study demonstrating the power of environmental tracers when coupled to other sources of information. Highlighted too is the need for basic research in the task of identifying groundwater resources for emergency situations.

References

De Beer, C.H. 2002. *The stratigraphy, geology and structure of the Table Mountain Group*. In: K.Pietersen and R.Parsons (eds), A Synthesis of the Hydrogeology of the Table Mountain group, Report TT158/01, Water Research Commission, Pretoria, 8 p.

Diamond, R.E. and Harris, C. 2000. *Oxygen and hydrogen isotope geochemistry of hot springs of the Western Cape, South Africa: Recharge at high altitude?* Journal of African Earth Sciences 31: 467-481 p.

Hälbich, I.W. and Greef, G.J. 1995. *Final report on a structural analysis of the west plunging nose of the*

Kammanassie Anticline. Geology Department, University of Stellenbosch, Consulting report to DWAF, Directorate of Geohydrology.

Issar, A.S. 1994. *Proposals for the study of regional groundwater flow in South Africa, with reference to the Transvaal and Northern Cape dolomite, the Table Mountain sandstones and the Karoo basin and a proposal to study the impact of climate change on the hydrological balance in South Africa.* Department of Water Affairs and Forestry, Technical Report No. GH3833.

Kotze, J.C. 2002. *Towards a management tool for groundwater exploitation in the Table Mountain Sandstone fractured aquifer.* S.A. Water Research Commission. Final report no. 729/1/02.

Kotze, J.C., Verhagen, B.Th. and Butler, M.J. 2000. *An aquifer model based on chemistry isotopes and lineament mapping: Little Karoo, South Africa.* In: O. Silolo, (ed.) Groundwater, Past Achievements and Future challenges, Balkema, Rotterdam, 539-544.

Maloszewski, P. and Zuber, A. 1996. *Lumped parameter models for interpretation of environmental tracer data.* Manual on mathematical models in isotope hydrogeology. Tecdoc-910. IAEA, Vienna.

Mazor, E. and Verhagen, B.Th. 1983. *Dissolved ions, radioactive isotopes and noble gases in thermal waters of South Africa.* Journal of Hydrology, 63, 315-329 p.

Meyer, P.S. 2002. *Springs in the Table Mountain Group, with special reference to fault-controlled springs.* In: K.Pietersen and R.Parsons (eds), A Synthesis of the Hydrogeology of the Table Mountain group, Report TT158/01, Water Research Commission, Pretoria. 224 p.

Parsons, R. 2002. *Recharge of Table Mountain Group aquifer systems.* In: K.Pietersen and R.Parsons (eds), A Synthesis of the Hydrogeology of the Table Mountain group, Report TT158/01, Water Research Commission, Pretoria, 258 p.

Talma A.S., Weaver J.M.C., Plummer L.N. and Busenberg E. 2000. *CFC tracing of groundwater in fractured rock aided with ^{14}C and ^{3}H to identify water mixing.* In: O Silolo, (ed.) Groundwater, Past Achievements and Future challenges, Balkema, Rotterdam, 635-639 p.

Verhagen, B.Th., Geyh, M.A., Froehlich, K. and Wirth, K. 1991. *Isotope hydrological methods for the quantitative evaluation of ground water resources in arid and semi-arid areas. - Development of a methodology.* Research Reports of the Federal Ministry for Economic Cooperation of the Federal Republic of Germany. Bonn.

Verhagen, B.Th. 1997. *Use of environmental isotopes in the characterisation of the Table Mountain Sandstone aquifer, South Africa.* Progress report to the International Atomic Energy Agency, Research Contract 8983/RO/Regular Budget Fund.

Verhagen, B.Th., Talma, A.S. and Butler, M.J. 2009. *Aspects of groundwater flow in a regional fractured aquifer evaluated using environmental isotopes and geochemistry.* Submitted: J. Hydr.

Isotope hydrology assists in revealing a regional emergency groundwater resource in South Africa

11.2

*Balt Verhagen**

Abstract

An environmental isotope and hydro-chemical study was undertaken to assess a conceptual model developed earlier on which a major, regional rural groundwater supply from a basalt aquifer was to be based. Isotope-based mean residence time and porosity figures indicated that recharge, and therefore sustainable extraction, could be as low as 10% of the model estimates. Spatially variable chemical and isotope data also questioned model predictions of balancing drainage along a major fault line. These results, suggesting upwelling groundwater, prompted a major re-investigation of the area, involving further exploratory drilling and geophysics. A deeper sandstone aquifer, previously thought to be unproductive, was found however to produce high yields of excellent quality groundwater and constituting a potentially major regional and emergency resource. Further work is aimed at its development and management through conjunctive exploitation.

Introduction

An investigation was conducted in the 1980s into the feasibility of a ground water supply to 26 villages in Limpopo Province, South Africa. This resulted in a hydrological model (Fayazi and Orpen, 1989) proposing that groundwater, recharged to a plain of some 600 km^2 in extent drains northwards, away from the mountain watershed in the south, mainly through a superficial basalt aquifer (Fig. 11.2.1). The Tshipise fault zone in the north would act as a sink as well as a drain of ground water westwards towards an ephemeral surface drainage.

The underlying Karoo sandstone (cf. Fig. 11.2.3), historically encountered mainly in test drilling of up-thrown blocks along the fault zone, was found usually to be poorly yielding and not regarded as a worth-while target for further exploration. The regional supply was designed to be drawn mainly from the fault zone, the abstraction potential estimated at some 1 x 10^6 m^3 per km fault strike per annum.

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Figure 11.2.1. The original groundwater flow model, showing iso-piezometric contours (after: Fayazi and Orpen, 1989), interpreted N-W flow in the basalt and balancing drainage along fault zone (see Figure 11.2.3)

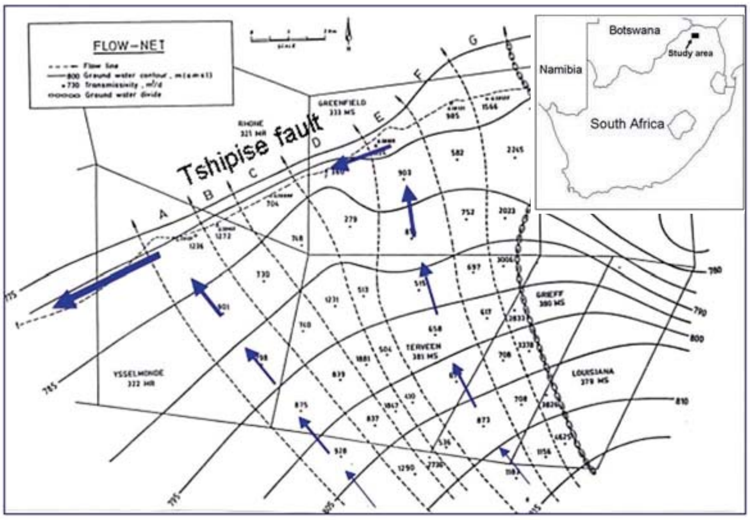
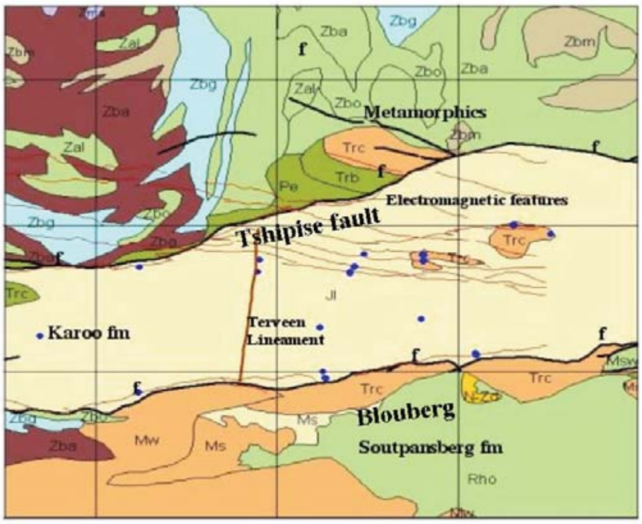


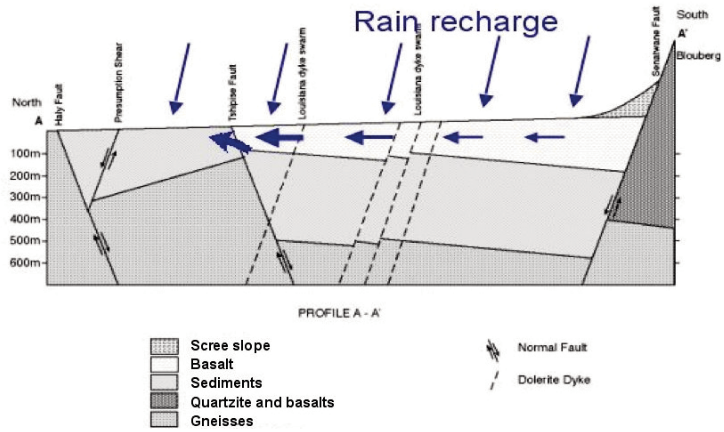
Figure 11.2.2. Geological map (Brandl, 2002) of the area showing the Karoo graben between older sediments in the south and metamorphics in the north. Electromagnetic features observed during this study were identified as dykes compartmentalising the Karoo



Hydrogeology

The area is characterised by a plain underlain by tertiary to cretaceous Karoo sediments, down-faulted against older Soutpansberg sediments of the Blouberg mountains in the south and in the north against basement metamorphic rocks by the regional Tshipise fault (Fig. 11.2.2). The Karoo sequence consists of sandstone capped by superficial basalt up to more than 200 m in thickness (Fig. 11.2.3). Groundwater exploitation, mainly for local village supply and some irrigation farming, was traditionally restricted to the basalt.

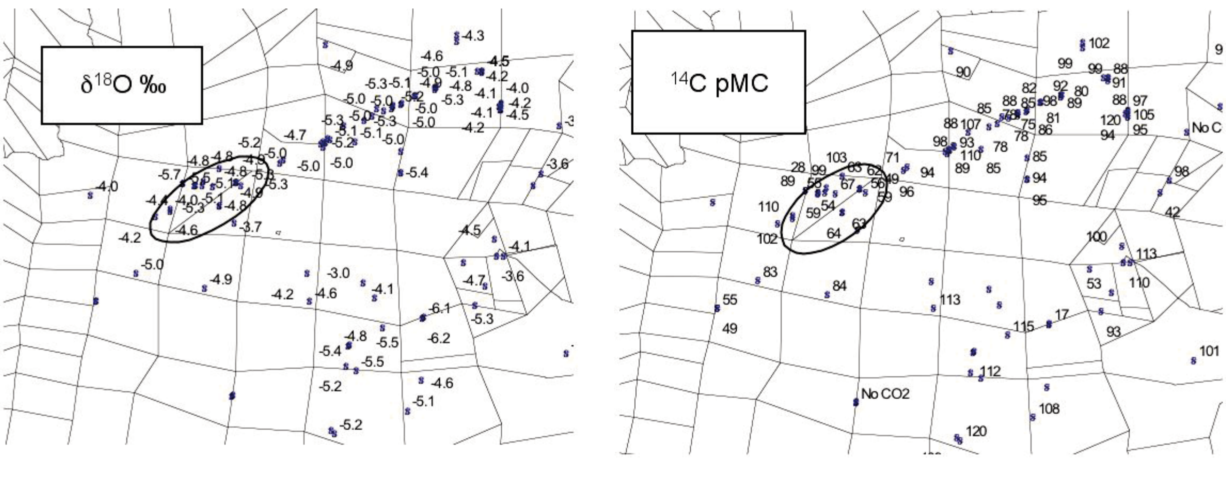
Figure 11.2.3. Schematic geological section (after Brandl 2002) showing downthrown Karoo block and original conceptual groundwater model of flow through the shallow basalt aquifer (see Fig. 11.2.1)



Isotope and hydrochemical study

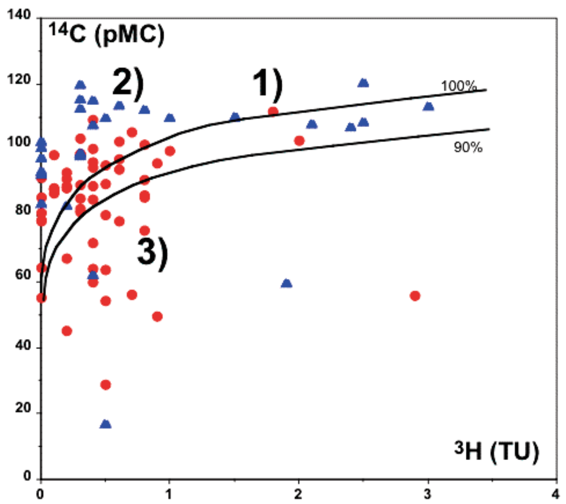
The isotope and hydrochemical investigation focused initially on the Tshipise fault zone. Equipped boreholes of small production well fields were first sampled; later a mobile pump was used to sample unequipped exploration boreholes. Stimulated partly by the isotope investigation, contract drilling both on the western and eastern extensions of the fault began to reveal greater complexity of the fault structure than initially believed (Fig. 11.2. 4).

Figure 11.2.4. Geographic spread of $\delta^{18}O$ and ^{14}C values. The linear cluster of sampling points follows the Tshipise fault line. The area containing exceptionally low values of both parameters in the SW of the fault zone is ringed



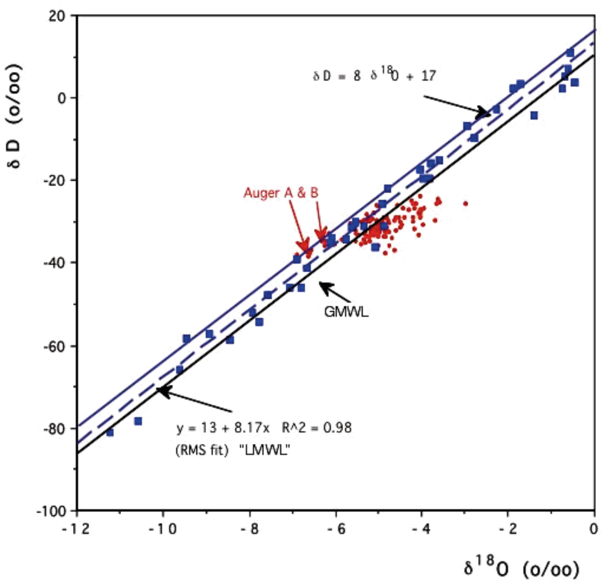
Numerous samples taken from along the fault zone itself and elsewhere presented a pattern of high radiocarbon values, generally in the range of 80-100 PMC, with accompanying tritium mostly in the range 0-1 TU. These are displayed in a scattergram (Fig. 11.2.5). Exponential model plots (Maloszewski and Zuber, 1996; Verhagen et al., 1991) of atmospheric ^{14}C (Gonfiantini et al., 1998) and rainfall ^{3}H (Verhagen unpub.) data revealed three categories: 1) a substantial number generally conforming to the model, in spite of the heterogeneity of the basalt aquifer; 2) a category, at low ^3H values that lies above the model curves, ascribed to phreatophyte root activity and 3) ^{14}C values < 80 PMC accompanied by ^3H values > 0.5 TU, ascribed to mixtures with older water.

Figure11.2.5. Scattergram of radiocarbon against tritium values for two sampling episodes (red circles and blue triangles) with exponential model plots for different initial ^{14}C values in % atmospheric (PMC).



Monthly composite and single major event rain water samples collected from the three collection stations over three years show a spread of $\delta^{18}O$ from –12‰ to –2‰ with a regression of $\delta^2H = 8.1\ \delta^{18}O + 14$ (Fig. 11.2.6). Groundwater stable isotope values cluster in a fairly narrow range of $\delta^{18}O \sim -4$ to -6 ‰, with a regression slope of ~ 5.5 ‰. These facts are taken to indicate that recharge conditions to the basalt are fairly uniform, with a degree of surface ponding, often observed after heavy rains on the plain, producing an evaporation imprint on the data.

Figure 11.2.6. δ^2H-$\delta^{18}O$ diagram. Notice the close clustering of groundwater values (red dots) with evaporative trend as against the much wider spread of rainfall values (blue squares) over a period of three years.



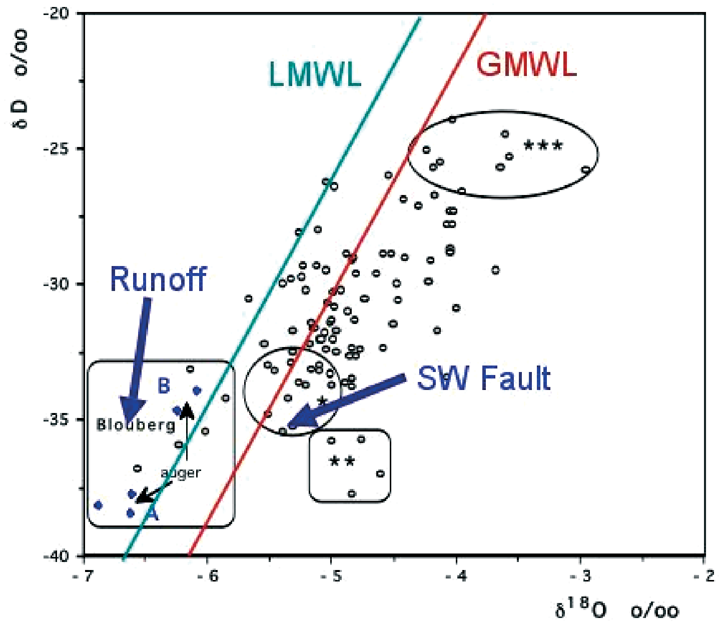
Although groundwater values in the region do not show a major spread, smaller variations along the fault, e.g. in ^{14}C and $\delta^{18}O$ (Fig. 11.2.4), accompanied by variable hydrochemistry, suggest that the concept of consistent, regional drainage along the fault, such as postulated in the initial model, could not be sustained.

In assessing recharge, it was realised that scant hydrological information was available on the highly anisotropic basalt aquifer. The important parameter of porosity had to be based on inspired guesses. However, it became obvious that even optimistic recharge figures based on isotope-derived MRT values (Fig. 11.2.5) amounted to at most 10% of those arrived at during the original investigation. Furthermore, the variability of isotopic and hydro-chemical parameters in numerous samples taken along the strike of the fault began to 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.

Upwelling along the fault strike

Along the SW section of the fault line, borehole samples gave lower radiocarbon values than seen in the rest of the area, associated with more negative stable isotope values (ringed values, Fig. 11.2. 4), resembling those seen closer to the mountains in the south. Even more negative were the stable isotope values observed in shallow peat samples augered from a wetland at the foot of the Blouberg mountains (Fig. 11.2. 7), taken to represent mountain slope runoff. This suggested local upwelling of deeper, older groundwater along the fault, with characteristics of groundwater possibly recharged along the scree slopes and fault zone along the mountain to the south. Flow observations on the standing water column in a borehole along the Tshipise fault showed conclusively that there is indeed upwards movement of ground water into the basalt. This may explain some of the apparently anomalous values ascribed to mixing seen on the ^{14}C – ^{3}H diagram in Figure 11.2.5.

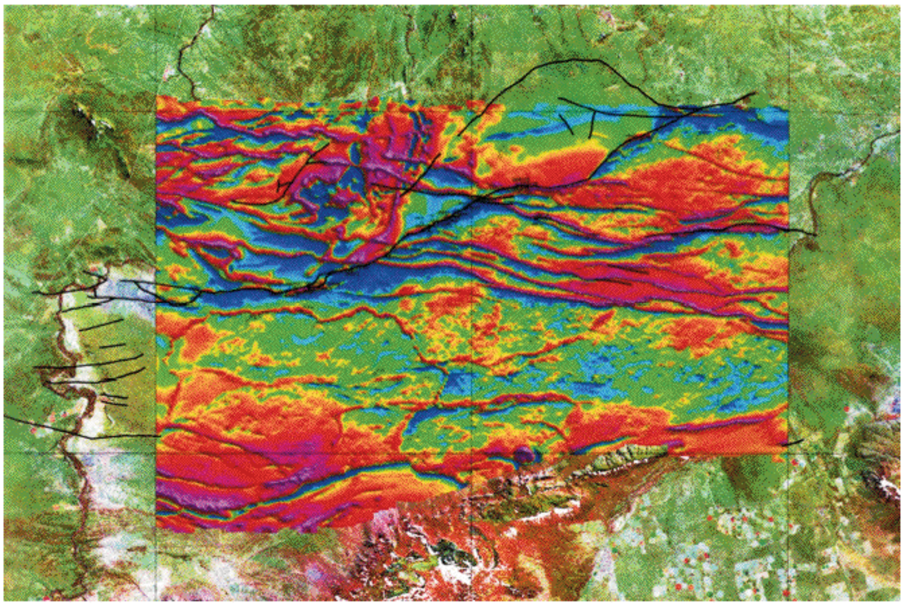
***Figure 11.2.7.** δ^2H-$\delta^{18}O$ diagram (detail of Figure 11.2.6) showing groundwater values with various geographical categories ringed. Note values including the SW fault zone (cf. Figure 11.2.4) and from samples obtained by hand auger from a wetland at the foot of the Blouberg ('Runoff' box), taken to represent mountain runoff.*



Further investigations prompted by the isotope study

An airborne geophysical survey (Fig.11.2.8) and its structural interpretation revealed much greater complexity, such as the W-E dyke swarm and N-S structures that may have far-reaching hydro-geological implications [2]. In the N-E the Karoo aquifers are compartmentalised. The Tshipise fault was shown to be bisected at various points, as already suggested by the isotopic and hydro-chemical data.

Figure 11.2.8. Results of aeromagnetic survey, superimposed on Landsat image of the Taaibosch area, showing Tshipise fault in the north, graben bounding fault in the south and E-W dyke swarm cutting across the Tshipise fault and compartmentalizing aquifers in the N-E (van Wyk 2001)



Modification of the conceptual model

This wealth of information from various observations led to the modification of the original conceptual model. The revised model (Fig. 11.2.9) postulates major N-W flow through the underlying sandstone, regulating the regional piezometry observed mainly in the basalt aquifer, with local upwelling along faults and fractures into the overlying basalt (Verhagen et al., 2007).

The Tshipise sandstone

Wherever the sandstone is exposed at surface its porosity and hydraulic conductivity proved to be significantly reduced by induration of its matrix. This fact discouraged any systematic development of this formation and the basalt was traditionally targeted for ground water supply. Prompted by this study, deeper drilling, down to 340 m, showed that where the sandstone is covered by basalt, its primary porosity and permeability is preserved, and possibly increased through leaching by circulating groundwater. Water was always struck just below the basalt/sandstone contact, and yields increased with depth. The contrasting hydrogeological conditions in the two aquifers are highlighted in down-the-hole sonic surveys of newly drilled observation boreholes (Fig. 11.2.10).

Figure 11.2.9. Updated conceptual groundwater flow model, based on isotopic, chemical and geophysical data. Major recharge to sandstone is from mountain run-off infiltrating along scree slopes and the graben southern bounding fault zone

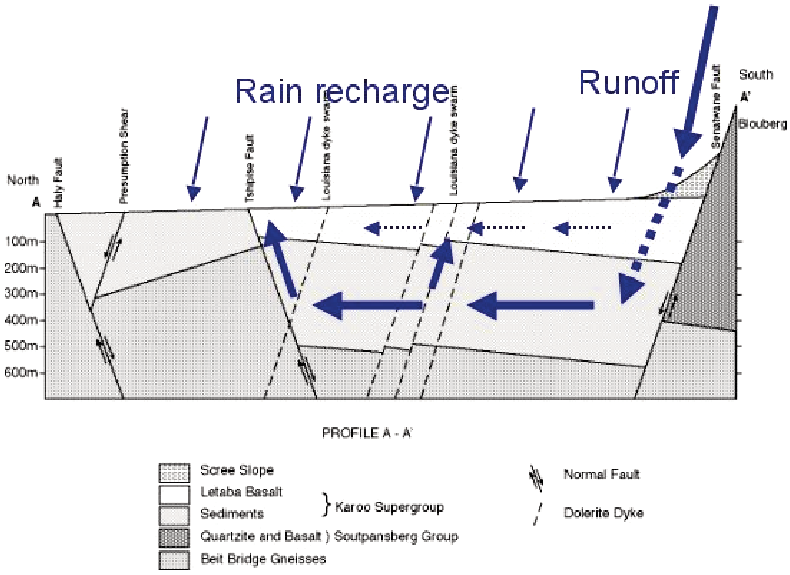
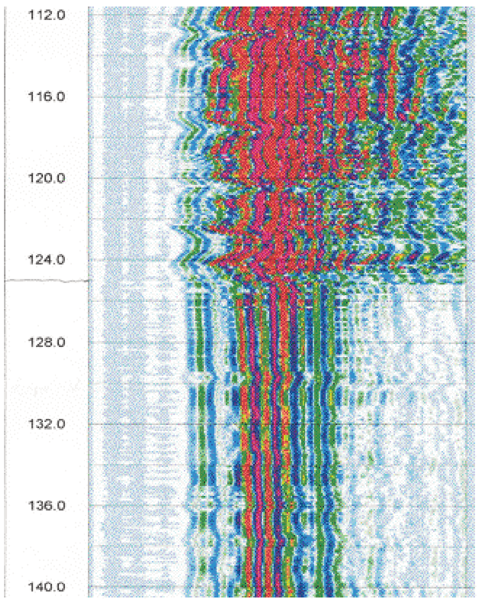


Figure 11.2.10. Down-the-hole sonic scan of the basalt/sandstone contact. Note the more uniform conditions in the sandstone, especially the rapid absorption of sonic energy due to the much higher water content (van Wyk, 2004)



Ground water in the sandstone is usually found to be less mineralised than in the basalt, particularly in very low nitrate contents, compared to often problematic high values in the basalt.

^{14}C values range from 55 pMC to 24 pMC with vanishing tritium. Especially the lower radiocarbon, higher residence time samples have lower stable isotope values, with $\delta^{18}O < -5.5‰$ without the evaporative imprint characteristic for the basalt. These values trend towards those ascribed to infiltration of mountain run-off and confirm, along with the chemistry, the effective separation of the two main aquifers.

Although groundwater residence times in the sandstone are higher than for the basalt, when coupled to the high storage significant turnover rates are indicated. The chemistry further suggests that the sandstone is recharged mainly through preferential pathways, along faults and fracture zones at the foot of the mountain, rather than diffuse recharge which could only occur through the basalt. Of note too are the very high yields (up to 40 L s^{-1}) showing that the sandstone, in addition to its general reliability as an aquifer, can locally support high extraction rates.

Development and management of a regional emergency groundwater supply

The features enumerated above identify the Tshipise sandstone as most suitable as an emergency regional water supply. A further study phase has been initiated specifically targeting the Tshipise sandstone. It is aimed at developing an aquifer management model of a regional groundwater supply based on the sandstone aquifer and various deep exploration boreholes have been drilled. Already, two high-yielding wells have been earmarked as emergency water supply to a nearby town.

The management model will, i.a. have to deal with maintaining the exceptional quality of the sandstone groundwater, that could be compromised by uncontrolled exploitation. An effective recharge rate will have to be arrived at to assess long-term sustainable exploitation rates. In some areas, the basalt and sandstone will have to be developed in parallel to allow conjunctive exploitation and blending of water to reasonable potable standards. In all these developments, environmental isotope data will undoubtedly play a crucial role.

Conclusions

This study again demonstrates the value to be extracted from systematic multi-disciplinary investigations of groundwater systems. A thorough understanding of the geology is essential. Geophysics reveals large-scale structural features and local borehole lithology. Geohydrology provides information on the basic behaviour of the aquifers and efficiency of wells. Hydrochemistry and in particular isotope hydrology are fundamental in understanding the origin, recharge, flow and mixing of groundwater. In this particular case study in Limpopo Province, South Africa, a major, deeper groundwater resource was overlooked as the basic information on its potential was not available. A re-examination of a previous evaluation of groundwater supply in the area lead to the recognition of this resource; the techniques employed can support its development, long-term management and possible partial reservation for emergency supply. This is a highly cost-effective approach when balanced against the very large potential benefit represented by this regional potable water resource in a semi-arid environment.

References

Brandl, G. 2002. *Summary of the preliminary report on the project: Construction of a geological-structural model for the Tshipise Fault Zone in the Alldays area, District Bochum, Northern Province*. Department of Water Affairs and Forestry, Pretoria.

Fayazi, M. and Orpen, W.R.G. 1989. *Development of a water supply for Alldays from groundwater resources associated with the Taaibos fault.* Techn. Rep. GH 3664, Department of Water Affairs and Forestry, Pretoria.

Gonfiantini, R., Froehlich, K., Araguás-Araguás, L. and Rozanski, K. 1998. *Isotopes in Groundwater Hydrology in: Isotope tracers in catchment hydrology* (Kendall and McDonnell, Eds) 203-246 p.

Maloszewski, P. and Zuber, A. 1996. *Lumped parameter models for interpretation of environmental tracer data. Manual on mathematical models in isotope hydrogeology.* Tecdoc-910. IAEA, Vienna.

Van Wyk, E. 2001. Department of Water Affairs and Forestry, South Africa. Pvte. Communication.

Van Wyk, E., 2004. Department of Water Affairs and Forestry, South Africa. Pvte. communication.

Verhagen,B.Th., Butler, M.J. and van Wyk, E. 2007. *A deep, highly productive aquifer is identified using isotope, hydrochemical and geophysical techniques*. IAEA-CN – 151,109. IAEA, Vienna.

Verhagen, B.Th., Geyh, M.A., Froehlich, K. and Wirth, K. 1991. *Isotope hydrological methods for the quantitative evaluation of ground water resources in arid and semi-arid areas*. - Development of a methodology. Research Reports of the Federal Ministry for Economic Cooperation of the Federal Republic of Germany, Bonn.

The Molasse Basin of South Germany: a classic example of emergency groundwater resources

11.3

*Klaus-Peter Seiler**

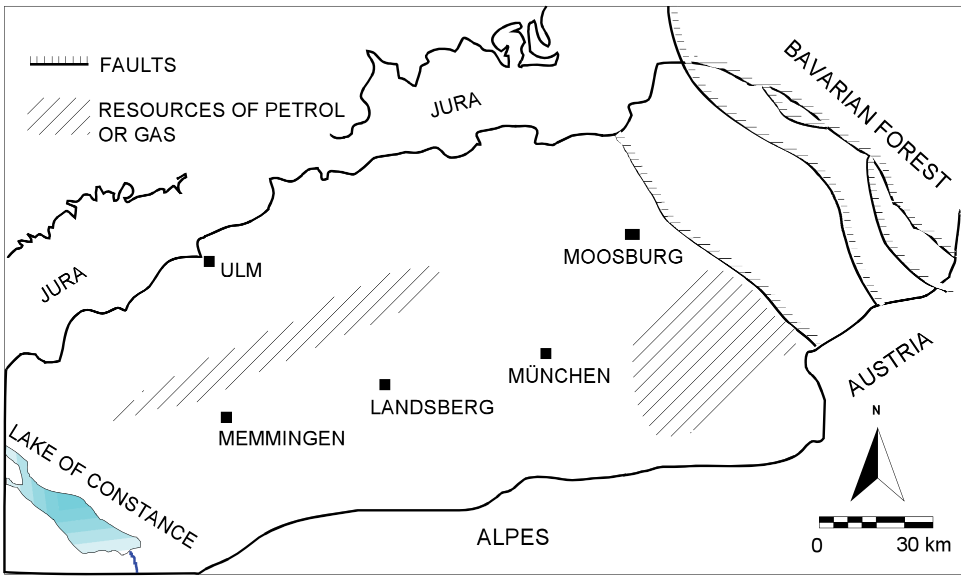
Introduction

Te Molasse Basin crops out along the north/northwest border of the Alps from Lake Geneva to Vienna. The German section of the Molasse basin is shown in Fig. 11.3.1; it is bordered in the south by the Alps, in the north by the Jura and the Bavarian Forest.

- The Molasse trough developed as a response to the uplift of the Alps at the beginning of the Tertiary period;
- The resulting trough was filled with gravel, sand, silt and clay sediments during two fresh water and to two marine sedimentation cycles of the Tertiary and with Quaternary gravels during several glacial periods;
- Half of the Molasse trough was over-thrust by the Alps in the late Tertiary period.

The northern section of the trough, forming the foreland of the Alps, was extensively explored by petroleum drilling; only scant knowledge is available for the southern half underlying the Alps.

Figure 11.3.1. The Molasse Basin in south Germany



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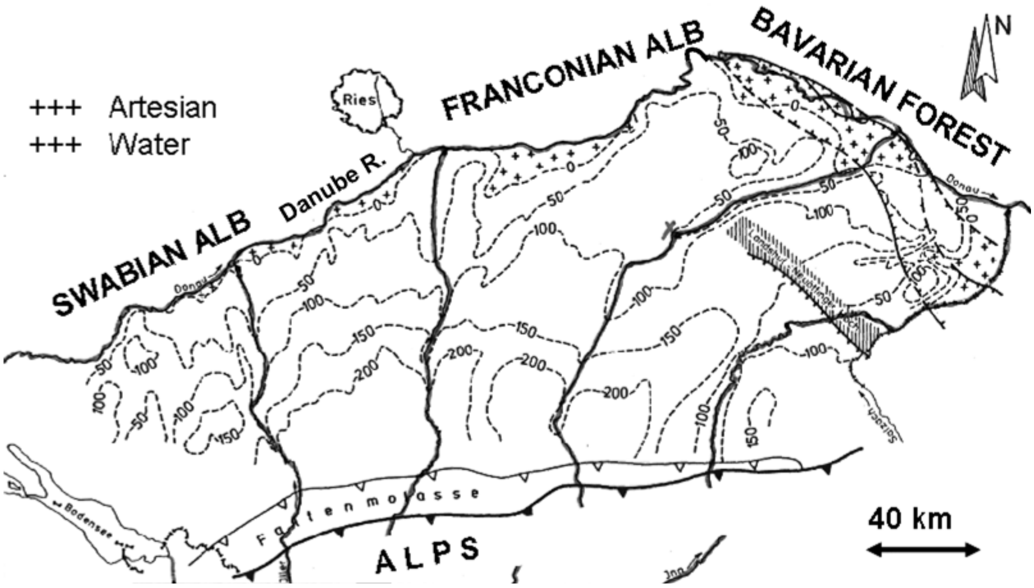
Upper Jurassic carbonates underlie the Tertiary Molasse sediments that were karstified during the Jurassic to Cretaceous transition. During the Lower Cretaceous, these units became very permeable and now act as a deep groundwater drainage in the Molasse basin. The hydraulic heads in these carbonates are thus always much lower than the respective hydraulic heads of groundwater in the Molasse/ Quaternary aquifers (Fig. 11.3.2).

Figure 11.3.2. Depth to water table in the Upper Jurassic carbonates in metres below ground surface. Groundwater levels in Tertiary and Quaternary sediments in the north of the Molasse basin are at either land surface or at a maximum depth of 30 m.



The Jurassic carbonates underlying the Molasse Basin crop out along the course of the Danube river and continue along the Swabian and Franconian Alps (Fig. 11.3.2) north of the Danube River. Hence, the Danube River forms a drain not only of the groundwater recharged along the two Alpine ranges in the north, but also groundwater of the Molasse basin in the south. Petroleum and hydrogeological exploration in the Molasse basin have shown that

- the groundwater in the Molasse basin constitutes a hydraulic continuum,
- the fluid content of the Tertiary trough fill has not been completely turned over since the Danube river started draining the Molasse basin 2 million years ago, and
- the groundwater beneath the Tertiary sediments contains abundant S, CH_4, I and F, which is not typical for the Upper Jurassic, but is related to Tertiary sediments with their petroleum and earth gas resources (Lemcke, 1976). All these elements began to drain downwards when the drainage of the basin opened through the upper Jurassic about 2 million years ago and thus decreased the pressure in the hydrocarbon traps, along with strata containing connate water.

In the years 1970 to 1985 the upper horizons of the groundwater resources in the Molasse basin were systematically investigated, to develop management strategies for, and to asses the vulnerability of, an emergency water resource for dealing with catastrophic events in general and more specifically as a security water supply (Einsele et al., 1987, Seiler and Lindner 1995, Ghergut et al., 2001). These investigations focused on a depth range up to 300 m b.g.l. Today, depths of up to some 3,000 m are investigated in the Molasse basin for geothermal and balneological (recreational) purposes.

The balneological use of groundwater requires modest aquifer yields and does not stress the groundwater hydraulically; the geothermal use of the groundwater resources in the Molasse basin refers mostly to the very highly permeable Upper Jurassic carbonates. It does not significantly affect the water balance, as cooled water is re-injected into the aquifer. Only the emergency water supply would stress groundwater resources in the Molasse basin and special attention needs to be paid to various forms of overexploitation.

Emergency water supply in the Molasse basin

A general perception worldwide is that deep drilling and screening of wells guarantees a seemingly continuous supply of good quality water in as far as no evaporites, connate waters or special trace elements occur in the aquifer sequence.

It is, however, also known (e.g.from the Molasse basin) that

- emergency groundwater may contain traces of S, As, F, I, CH_4 - amongst others - in concentrations exceeding drinking water health standards. Leaching in deep aquifers develops very slowly, as low rates of recharge lead to low groundwater flow velocities and
- pollutants in shallow groundwater may appear in deep groundwater only after long delays where depth-related available groundwater recharge is not taken into account in resource management.

For a better understanding of these observations a systematic hydrogeological and numerical study (Egger, 1978, Einsele et al 1987, Seiler and Lindner, 1995, Ghergut et al., 2001) and an evaluation of extant published material was undertaken (Seiler and Lindner, 1995). The results of these activities have been generalised, which lead to defining shallow and deep groundwater in terms of an active and passive groundwater turnover space in the subsurface, reacting to imposed groundwater stresses without, or with, a transient response, respectively. These new definitions represent an extension and precision of the description of the general groundwater flow field in great basins proposed by Toth (1963) and for the first time lead to proposals for sustainable groundwater management practices. Since controlled management of a highly transient hydraulic system also requires an early warning system, such control systems have also been developed for the Molasse basin (Ghergut et al. 2001) and find applications elsewhere.

Tools for defining areas for emergency groundwater exploration and exploitation

Shallow and deep groundwater differ basically in the rate of groundwater recharge and thus in water ages (chapter 3). Therefore, groundwater in the unconsolidated Molasse sediments in the area Munich-Landsberg-Ulm-Moosburg (Fig. 11.3.1) has been systematically sampled at different well (screen) depths and analysed for the isotopes ^{2}H, ^{18}O, ^{3}H, ^{13}C, ^{14}C, ^{3}He and ^{39}Ar, as well as for 11 anions and cations and trace elements such as As, F, I. Plotting these parameters against depth results in e.g. tritium vs. depth sections (Fig. 11.3.3) and isotope, chemical vs. depths relationships (Fig. 11.3.4). In areas with moderate groundwater extraction from both the shallow and deep groundwater levels (area between Munich and Augsburg, Fig.11.3.3), the TNL (Tritium Naught Line, below which tritium cannot be detected) is encountered at 40-50 m depth b.r.l. In areas with significant deep groundwater extraction, such as under the cities of Munich and Augsburg (Fig. 11.3.3) the TNL

Figure 11.3.3. Tritium concentration zones - the TNL (Tritium-Naught Line) - in a profile from Munich and Augsburg in the Molasse Basin of south Germany

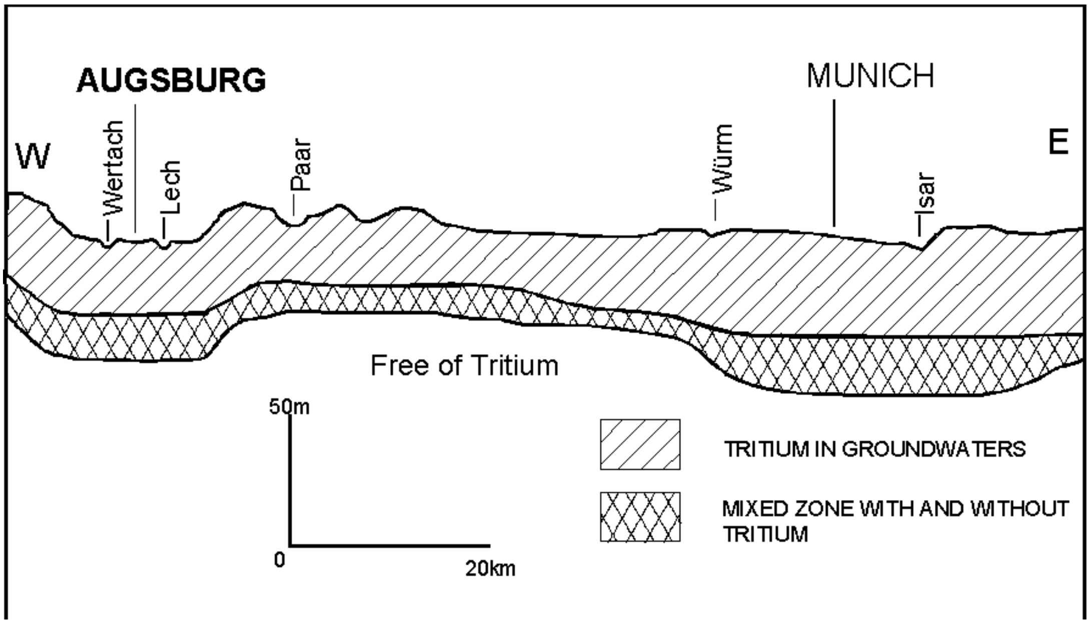
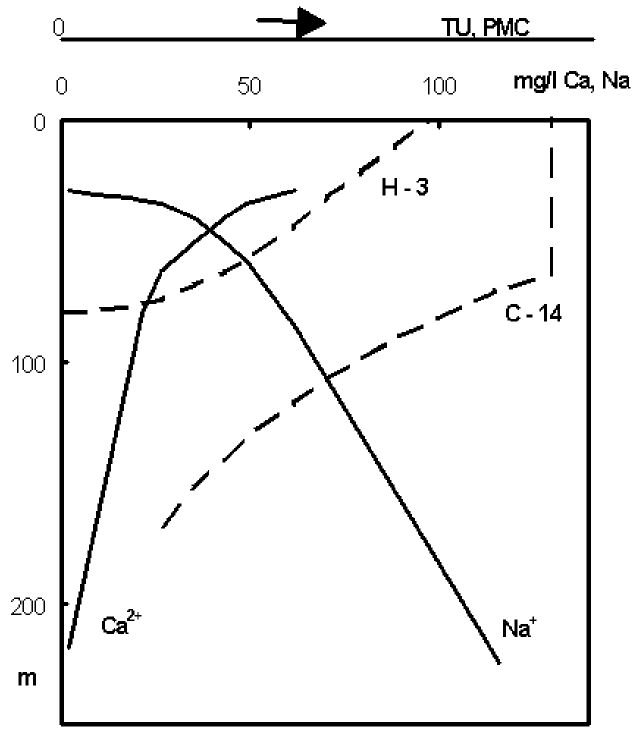


Figure 11.3.4. Plot of ^{3}H and ^{14}C values; Na and Ca concentrations in groundwater against depth for the area Munich-Augsburg-Danube



lies deeper, although groundwater levels beneath both cities has not declined measurably. Deep lying TNLs indicate a hydraulic short cut from shallow to deep groundwater, groundwater extraction exceeding the depth related availability of groundwater recharge. These short cuts have been quantified by Andres and Egger (1985) in terms of additional recharge input to deep groundwater through ‘overexploitation’.

In the cities of Munich and Augsburg, contamination of deep groundwater is encountered, albeit randomly. This has been interpreted in terms of

- inappropriate well construction (Rauert et al., 1993) and
- hydraulic short cuts between shallow and deep groundwater around well casings, due to over-extraction (Seiler and Lindner, 1995).

Such contamination of deep groundwater as found in the above-mentioned cities is not observed where ever deep abstraction does not involve overstressing of groundwater resources.

The hydrochemical development from $Ca(HCO_3)_2$ to Na_2CO_3 (Fig. 11.3.4) by ion exchange along clay surfaces is mostly, albeit not always, a time dependent process which can produce, with simple analytic methods, a good approximation of the depth of the TNL (Fig. 11.3.4). Further methods to determine the thickness of the active groundwater recharge zone are described in chapter 3.

Changes in the values of the stable isotopes or non-reactive chloride in groundwater serve as a climate finger print related to changes in evaporation and condensation processes in the water cycle, rather than as a means of timing a particular process. Under natural conditions such changes occur over time spans of hundreds to thousands of years rather than of decades. The stable isotopes of the water molecule as well as environmental chloride therefore do not materially contribute to assessing shallow and deep groundwater, but rather represent useful tools in establishing early warning systems (chapter 6).

Profiling of ^3H such as performed in the Molasse Basin, applied in different climate zones (humid tropical, humid temperate and semi arid), has shown that

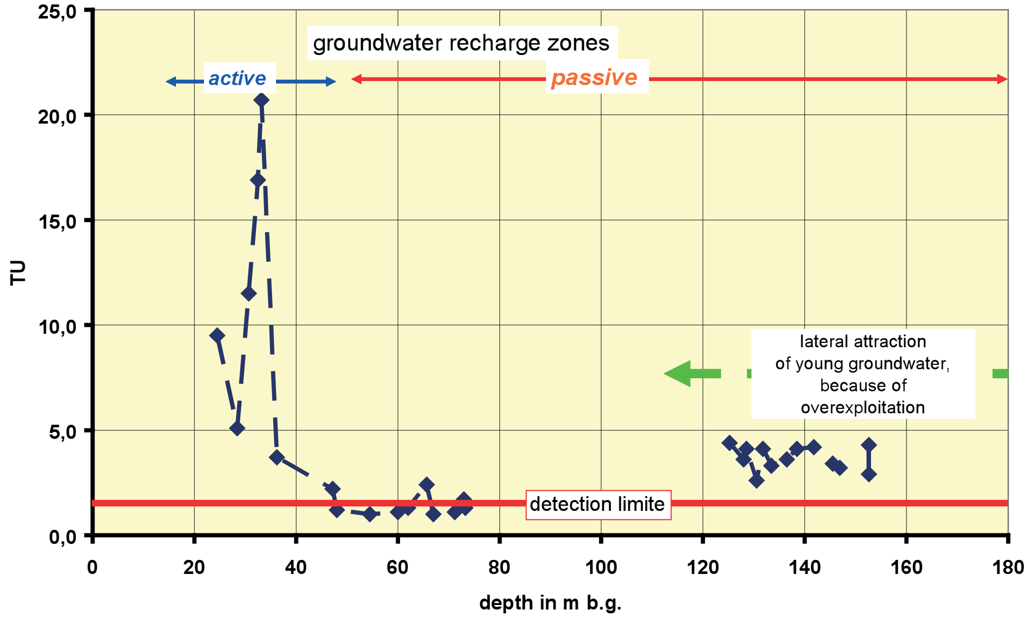
- it allows for differentiation between shallow and deep groundwater generally and
- the depth of the TNL depends basically on the amount of groundwater recharge and the storage properties of the aquifer (Alvarado et al., 1996, Seiler, 1983).

Aquifer profiling (pers. comm.: H. Raanan, PhD student the author) in the unconsolidated coastal aquifers of Israel, indicate that shallow groundwater in this area extends to depths of 40 m (Fig. 11.3.5), whilst overexploitation of the coastal aquifer system results in young groundwater being drawn laterally into deep groundwater to depths exceeding 80m (Fig.11.3.5). With this lateral admixture of shallow water with measurable tritium to deep groundwater with tritium levels below detection, contaminants may also reach the deep groundwater, which was naturally well protected against them.

Groundwater underlying the emergency water supply area

The Molasse Basin sediments originate from two marine and two fresh water cycles, beginning with marine sediments and ending with fresh water sediments of the second cycle. Since the water content of the Molasse basin has not been turned over once during the last 2 million years by the

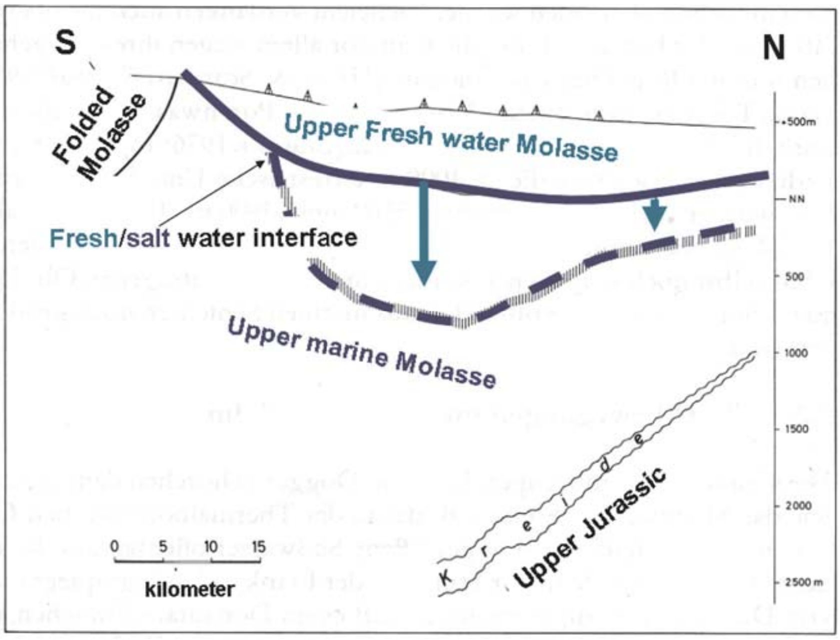
Figure 11.3.5. A vertical tritium profile through the coastal aquifer of Israel. Note increase in tritium due to lateral inflow of young groundwater.



drainage of the underlying karstificated Upper Jurassic carbonates, connate water still exists in this basin. As shown by a comparison of electric bore hole logs with the geologic profile, the interface fresh/salt water is now beneath the stratigraphic interface fresh water/marine sediments (Fig. 11.3.6); these bore hole logs indicate that there exists a vertical drainage; however the horizontal drainage of groundwater is much more efficient.

The fact, that the interface salty/fresh water does not decline in the southerly direction, although the water table in the Upper Jurassic beneath the Tertiary sediments declines to several 100's of metres b.g

Figure 11.3.6. A comparison between the fresh/saline groundwater interface and the stratigraphic interface between freshwater and marine sediments in the upper part of the Molasse basin (Lemcke, 1976)



(Fig. 11.3.2), is explained as following: Approaching the Alps, the lateral tectonic stress increased in the geologic past and still acts today; sediments therefore compacted more along the tectonic border of the Alps than in the remote foreland. Evidence of this high lateral stress is still seen at present in wells with artesian water levels and in generally higher seismic velocities along the tectonic border of the Alps.

References

Alvarado Rivas, J., Seiler, K.-P. and Trimborn, P. 1996. *Investigación hydrogeológica, isotópica e hydroquimíca de la cuenca del Lago de Valencia, Venezuela*. IAEA Vienna, On Isotopes in Water Resources Management, Vol. 2: 281-299.

Egger, R. 1978. *Das Grundwasser in der Oberen Süsswassermolasse im Raum München und Augsburg.* PhD Thesis, Univ. Munich, 110 p.

Einsele, G., Seiler, K.-P., Bertleff, B., Lindner, W., Plum, H., Weber, E. 1987. *Erkundung tiefer Grundwasser-zirkulationssysteme.* (Parey) Hamburg, Berlin, DVWK Schr. 81, 223 p.

Ghergut J., Maloszewski P. and Seiler K.-P. 2001. *Age, environmental isotope and contaminants transport uncoupling in heterogeneous aquifers following hydraulic stress.* In: Seiler, K-P and Wohnlich, S. (Eds.): New approaches characterizing groundwater flow, (Balkema) Lisse, Abingdon, Exton (PA), Tokyo: 327-334

Lemcke, K. 1976. *Übertiefe Grundwässer im süddeutschen Alpenvorland*. Bull. Ver. Schweitz. Petroleum-Geol. u. Ing., Riehen/Basel 42: 9-18.

Rauert, W., Wolf, M., Weise, S.M., Andres, G. and Egger, R. (1993): *Isotope hydrological case study on the penetration of pollution into the deep Tertiary aquifer in the area of Munich, Germany*. J. Cont. Hydrol. 14: 15-38.

Seiler, K.-P. 1983. *Tiefe Grundwässer und Faktoren, die das Absenkungsgeschehen in Tiefen Grundwässern beeinflussen*. Z. dt. geol. Ges., 134, Hannover: 845-855.

Seiler, K.-P. and Alvarado Rivas, J. 1998. *Ground water exploration and exploitation of the Caracas aquifer, Venezuela.* In: Int. Symp. on Isotope Techniques in the Study of Past and Current Changes in the Hydrosphere and the Atmosphere, (IAEA) Vienna: 856-863.

Seiler, K.-P. and Lindner, W. 1995. *Near surface and deep groundwater.* J. Hydrol. 165: 33-44.

Toth, J. 1963. A theoretical analysis of groundwater flow in small drainage basis. - J. Geophys. Res. 68: 4795-4812.

Groundwater for emergency situations: Labe (Elbe) River flood in the Czech Republic, August 2002

11.4

***Jan Šilar* † ***

The final version of this paper was prepared by Jaroslav Vrba following the death of the author

Abstract

Floods in the East of the Czech Republic in the summer of 1997 and 1998 caused serious problems in the drinking water supply. In a similar situation in August 2002, a catastrophic flood of a 500 year recurrence interval inundated the valleys of the Vltava and Labe Rivers and affected and polluted shallow vulnerable groundwater resources used for drinking water supply in many settlements. However, in the densely populated industrial region of northern Bohemia, there are significant confined aquifers in the Cretaceous basin which have been developed since the end of the 19th century for drinking water supplies and industry. The total abstraction of groundwater from such aquifers is more than 200 l/s at the present time. In the urban areas of Ústí nad Labem and Děčín towns in northern Bohemia, the confined water is at positive pressure (above ground level) and can be used in emergency situations. In the Děčín area the thermal water is used for heat production to supply residential quarters and industry. Isotope hydrology data on groundwater resources in the aquifers developed in the Cretaceous basin are available for the whole area along the Elbe River. According to the mean residence time (more than 10,000 years) based on radiocarbon dating, the major part of groundwater samples in the confined aquifers is of Pleistocene origin. Groundwater from such aquifers is resistant to natural and human impacts and can be recommended for emergency water supply.

Introduction

Groundwater resources of low vulnerability with a long residence time resistant to natural and human impacts are present particularly in deep hydrogeological structures of Cretaceous basin. They tend to occur in sedimentary basins, in extensive effusive lava-flow structures as well as in deep-seated fissured systems in crystalline and other hard rocks. The groundwater residence time, an indicator of the groundwater vulnerability to human and natural impacts, has been studied in numerous regions using isotope hydrology methods (Fig. 10.4.1).

The necessity to find substituting groundwater resources for emergency situations is obvious. The paper presented here aims to propose isotope hydrology as a method of investigation when prospecting for groundwater resources resistant to natural disasters; also, to analyse the case of a catastrophic flood on the Labe (Elbe) River in 2002.

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The August 2002 flood of the Labe (Elbe) River

The section of the Labe River valley in the northern part of the Czech Republic was selected as a pilot area to test isotope hydrology methods in a groundwater resources investigation. As many towns in northern Bohemia use groundwater resources from the fluvial sediments and from the underlying aquifers in the Cretaceous basin, an adequate amount of hydrogeological and isotope hydrology-related data was available to test the method. There are also numerous groundwater resources exposed to the risk of being flooded. This proved to be true during the extremely high flood in the summer of 2002.

The Labe River is the largest in the Czech Republic with a drainage area of 51,000 km^2, which is almost identical with historical Bohemia. The mean and minimum flows of the Labe close to the border with Germany are 293 $m^3 \cdot s^{-1}$ and 58 $m^3 \cdot s^{-1}$, respectively (Hladný et al., 2005). However, during the flood in August 2002, the flow of the Labe River reached 4,700 $m^3 \cdot s^{-1}$.

The main cause of the extraordinarily high flood was intensive persistent precipitation. Hladný et al., 2005 reported that movement of two successive significant pressure lows from south to central Europe rapidly produced extreme floods in central Europe, including the Czech Republic. During the first event on August 6 and 7, 2002, the total volume of the precipitation received by Czech Republic was 2.4 km^3 (Fig. 11.4.1), whilst during the second event from August 11 to 13, 2002, it was 6.7 km^3 (Fig. 11.4.1.). Fig. 11.4.1 shows the spatial distribution of total precipitation (almost 9.7 km^3) on the Czech Republic territory in the period from August 6 to 15, 2002. The highest 10-day precipitation totals exceeding 400 mm occurred in the Novohradské Mts. in southern Bohemia along the border with Austria and in the eastern peaks of the Krušné hory Mts. along the border with Germany. In August 2002, the mean precipitation on the territory of the Czech Republic was at the level of 225% of the long-term mean. However, in the district of South Bohemia it reached 381% of the mean (Hladný et al., eds., 2005). In the Novohradske and Krušné Mts. the precipitation reached 1.6 times the 100 year recurrence value. The flood wave moved from South Bohemia, caused serious damage in Central Bohemia, particularly in Prague (14 August) and within two days (16 August) reached Ústí nad Labem in northern Bohemia.(Fig. 11.4.2).

Figure 11.4.1. Meteorological situation on the territory of the Czech Republic in August 2002: First map of precipitation in the period from August 6 to 7, 2002; Second map of precipitation in the period from August 11 to 13, 2002; Third map of precipitation in the period from August 6 to 15, 2002 (Hladný et al., 2005).

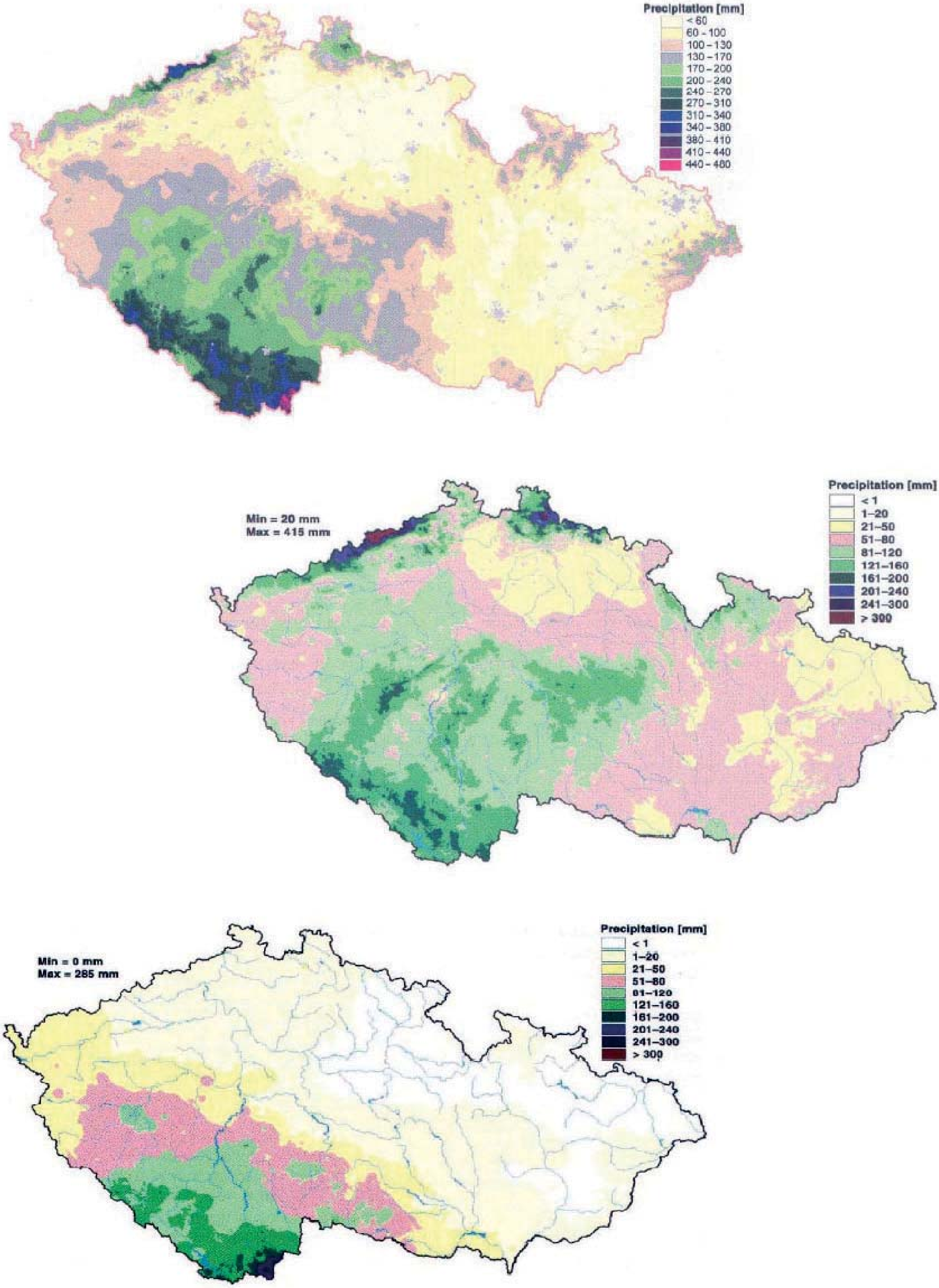
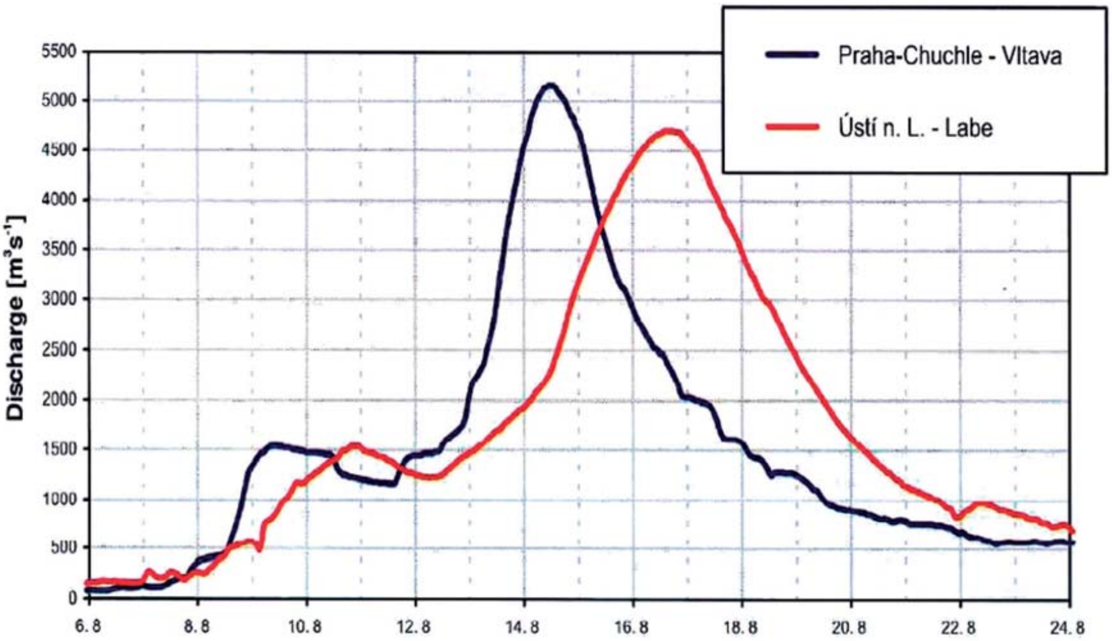


Figure 11.4.2. Graph of the culmination of the flood of the Vltava River in Prague and of Labe (Elbe) River (after confluence with Vltava River) in Ústí nad Labem (Hladný et al., 2005).



The aim of the investigation

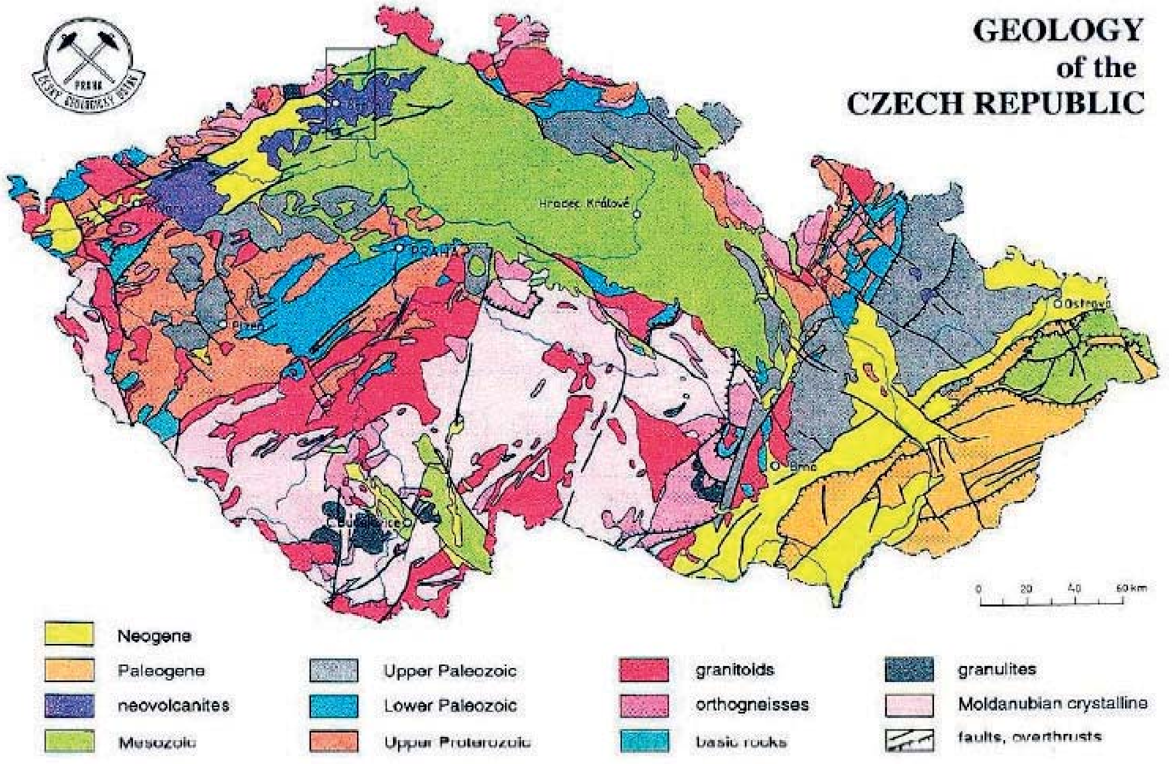
The aim of the investigation was to test the application of isotope hydrology methods in the geological setting of the Czech Republic in cases of catastrophic events. The outcome of these isotope hydrogeological test studies has been published (Šilar, 1976). Recently, isotope groundwater dating has been applied in the region in northern Bohemia which had been affected by the extreme flood of 2002. The studied region consists of Cretaceous strata containing deep aquifers at the base of the Cretaceous basin and covered with neo-volcanic rocks, mainly basalts (Fig. 11.4.3).

Methods used

Isotope-hydrology techniques were used to assess the residence time and vulnerability of ground water. In general, a long residence time of groundwater may indicate a low degree of groundwater vulnerability. In the consolidated Bohemian Massif, the longest residence times may be expected in the basin structures of its sedimentary platform cover, apart of some deep fractured structures along faults. Thus, radioactive dating and analyses of the stable isotope analyses of light elements were found adequate, together with conventional hydrogeological working methods, for investigating groundwater systems in confined aquifers in the Cretaceous basin of northern Bohemia.

To compare groundwater residence time in various geological structures in the Bohemian Massif, the groundwater radiocarbon ages were calculated uniformly considering its initial activity 85 p.m.c. (percent of modern carbon) as determined empirically (Vogel 1967, 1970; Münnich and Vogel, 1959; Geyh, 1972; Verhagen et al., 1991). Groundwater containing carbon dioxide of magmatic origin was excluded from the evaluation.

Figure 11.4.3. Geological map of the Czech Republic (Czech Geological Survey, Prague, 1993). The studied area is indicated by the rectangle at upper left.



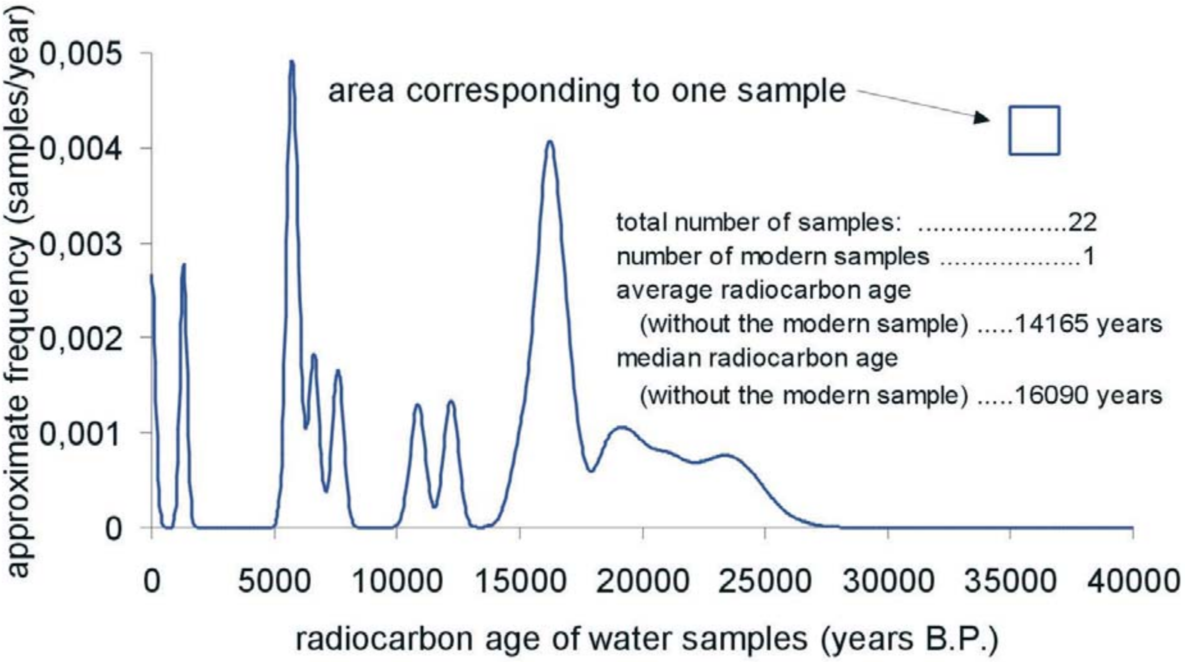
The results of ^{14}C groundwater dating were illustrated by means of various histograms which make it possible to compare data from a larger area and suppress local influences in individual hydrogeological structures. In the histogram, each radiocarbon age including its standard statistic deviation 1σ is illustrated by a Gaussian curve which limits a unit area, which is the same for each represented radiocarbon age and which equals the area of the rectangle at upper right (Fig. 11.4.4). More accurate results with a low statistic deviation are represented with high and narrow Gaussian curves and less accurate ones with lower and wide ones. The histogram is constructed by graphic summation of the areas of the Gaussian curves along the horizontal co-ordinate axis.

Results and benefits

The histograms of the residence time of groundwater in the whole Bohemian Massif show that most of the groundwater in deep hydrogeological structures originated during the past 14,000 years (Šilar, 1989). The samples from the deep aquifers in the Cretaceous basin along the lower reaches of the Labe River are characterised by high radiocarbon ages (Fig.11.4.4). Seventy-five percent of the groundwater samples from deep wells show a Pleistocene age and the remaining 25% are Holocene. groundwater of modern age, and was not found in any of the deep wells.

It can be concluded, that several types of groundwater resources are available in the studied area along the Labe River; however, only some of them can be recommended as a substituting supply in case of floods or other emergency situations.

Figure 11.4.4. Histogram of radiocarbon ages of ground water in the studied area (lower reaches of the Labe (Elbe) Rive) in the territory of the Czech Republic (Šilar, 2003)



In the Litoměřice city area, neither the shallow water table aquifers in fluvial deposits nor unconfined aquifers of the Cretaceous strata provide safe groundwater resources because the impermeable protecting strata is not developed. In spite of being used for public water supply they cannot be recommended for emergency water supply.

During the flood in 2002, the damaged groundwater supply from contaminated domestic wells (Fig. 11.4.5) had to be substituted by transporting drinking water by tanker trucks and in bottles. In the alluvial plain of the Labe River upstream from the confluence with the river Vltava, the chemical plant at Neratovice was flooded (Fig. 11.4.6), resulting in the pollution of soil, groundwater and agriculture products.

In Ústí nad Labem city area, the main artesian deep aquifer at the base of the Cretaceous basin is from 30 m to 50 m thick and is covered and protected from surface-derived potential pollution by a 350 m thick impermeable layer of marlstone. Moreover, the water is protected also by its own artesian pressure level which at the time was about 20 m above surface. The total discharge of the artesian wells is about 50 l/s. The groundwater quality is poor because of high dissolved solids (1,200 ppm to 1,800 ppm) and a high concentration of fluorine; the temperature reaches 36°C. The groundwater of the artesian aquifer is used in the local industry, swimming pools and zoo. The public water supply system exploits surface water from reservoirs on streams in the Krušné hory Mts.

During the flood in 2002, the downtown area of the city was flooded but neither the public water supply system of Ústí nad Labem nor the groundwater resources in the deep artesian aquifers were affected. Hence, the deep artesian groundwater can be recommended for emergency water supply in cases of public surface water supply failure. However, the unconfined groundwater of the shallow aquifers present in the uppermost Cretaceous strata and Quaternary deposits in the surroundings of Ústí nad Labem cannot be considered as a suitable source of drinking water in emergency situations.

Figure 11.4.5. Rural settlements in the flood plain of the Labe (Elbe) River during the flood on August 16, 2002. Groundwater supply from damaged and contaminated domestic wells had to be substituted by transporting drinking water by tanker trucks and in bottles (Photograph by Raudenský and Dorazil, 2002).

Figure 11.4.6 The chemical factory Spolana in Neratovice on the Labe (Elbe) River was flooded by the backwater from the Vltava River. Several organic compounds penetrated into and polluted the shallow groundwater and the soil nearby (Photograph by Raudenský and Dorazil, 2002).

In Děčín city area (close to the border with Germany), the main aquifer in the Cretaceous basin is 250 to 300 m thick and at depths varying by several hundred metres because of faulting. It is developed by wells as deep as 545 m. The piezometric pressure height is about 50 m above the ground. The total limiting discharge is about 150 l/s from which 110 l/s are used for supplying the population, industry, swimming pools and heat production. The quality of water is good, with about 400 ppm of dissolved solids and only a slightly elevated concentration of iron (about 0.5 ppm). The groundwater is a suitable source of drinking water. During the flood in 2002, the Děčín original municipal water supply system was not affected, as it is fed from distant groundwater resources in the hilly surroundings.

Benefit of groundwater resources during hazardous events. The investigation has shown that in the valley of the Labe (Elbe) River in the area between the towns Ústí nad Labem and Děčín, there are confined safe groundwater resources available at the base of Cretaceous basin, which can be used as a safe emergency source of drinking water. They can be used not only in case of floods but even when the surface water supply to the city of Ústí nad Labem from streams and reservoirs in the mountains is impaired by local man made pollution or climatic factors.

Conclusions

It has been found that within the Bohemian Massif, aquifers with the longest groundwater residence time and groundwater resources resistant to disasters are developed in the inner and deeper parts of the Cretaceous basins in the platform cover. This refers also to the region along the lower reaches of the Labe (Elbe) River, which was seriously affected by the flood in 2002.

In the whole densely populated industrial region of northern Bohemia, there are significant aquifers in the Cretaceous basin which have been developed since the end of the 19th century for water supply of the population and industry and for recreational purposes. Recently, they have been used also as a source of heat. The total groundwater abstraction at the present time is more than 200 l/s. In the areas of Ústí nad Labem and Děčín cities, the confined groundwater is at positive pressure above ground level with temperatures up to 36°C. Besides this, some towns are supplied with surface water from reservoirs on local streams which are prone to be affected in case of air pollution, drought, floods and other hazards. The resistant groundwater resources in deep artesian aquifers can be used for drinking water supplies in case of emergency when conventional public water supply systems are damaged by natural hazards or human impacts.

References

Clark, I. and Fritz, P. 1997. *Environmental Isotopes in Hydrogeology.* Lewis Publishers, Boca Raton, New York, 328 p.

Geological Map of The Czech Republic, Geological Survey, Prague, 1993.

Geyh, M.A. 1972. *Basic studies in hydrology and ^{14}C and ^{3}H measurements*. Proc. Int.Geol.Congr., 24th Sess., Sect.11, Hydrogeology, Montreal: 227-234.

Hladný, J., Kašpárek, L., Krátká, M., Kněžek, M. and Martínková, M. (eds.) 2005. *Catastrophic flood in the Czech Republic in August 2002.* Ministry of Environment, Prague, Czech Republic, 44 p.

Libby, W.F. 1955. *Radiocarbon dating.* Second Edition, Fifth Impression 1965, The University of Chicago Press, Chicago, 175 p.

Münnich, K.O. 1957. *Messungen des C^{14}-Gehaltes von hartem Grundwasser*. Naturwissenschaften 44, H.2: 32-33.

Münnich, K.O. and Vogel, J.C. 1959. *C^{14}-Altersbestimmung von Süßwasser-Kalkablagerungen*. Naturwissenschaften, 46, (5): 168 –169.

Raudenský, M. and Dorazil, I. 2002. *Povodn 2002 – Letecké dokumenty*. VUT Brno, 127 p.

Šilar, J. 1976. *Radiocarbon ground-water dating in Czechoslovakia - first results*. Věstník Ústředního ústavu geologického, 51, Praha: 209-220.

Šilar, J. 1989. *Radiocarbon dating of ground water in Czechoslovakia and paleoclimatic problems of its origin in central Europe.* Zeszyty Naukowe Politechniki Slaskiej, Ser. Mat.-Fiz. 61, Geochronometria 6: 133-141.

Šilar, J. 2003. *Ground-water resources for emergency cases in the lower reaches of the Labe (Elbe) River (Czech Republic).* A contribution to the UNESCO IHP Programme. Poster, IAEA-CN-104/P-140, Vienna.

Verhagen, B.T., Geyh, M.A., Fröhlich, K. and Wirth, K. 1991. *Isotope hydrological methods for the quantitative evaluation of ground water resources in arid and semi-arid areas - Development of a methodology.* Research Reports of the Federal Ministry for Economic Cooperation of the Federal Republic of Germany, Bonn, 164 p.

Vogel, J.C. 1967. *Investigation of groundwater flow with radiocarbon*. In: Isotopes in Hydrology, IAEA, Vienna: 355-369.

Impact of the October 1999 super cyclone on the groundwater system and identification of groundwater resources for providing safe drinking water in coastal Orissa, India

11.5

Balbir Sukhija[1] *and B.S.R. Narsimha Rao*[2]

Abstract

The super cyclone which hit the coast of Orissa state, India on 29–30 October 1999, devastated the state in an unprecedented manner causing many casualties and misery for 13 million people in 8,000 villages of 12 districts. This case study reports the relief measures taken by the concerned authorities to provide safe drinking water using groundwater as a resource. The super cyclone was associated with 7 m storm sea water surges reaching 15 km inland resulting in saline inundation, accompanied by intense rain (426 mm) in a single day causing flooding, with high energy winds battering the infrastructure including that of the drinking water supply.

Using the satellite imagery obtained a few days before and after the cyclone, the impact of the super cyclone on land, water and vegetation was evaluated and priority areas requiring relief were demarcated. Immediately after the cyclone a hydro-chemical survey was undertaken in the worst impacted area. It was noticed that except for a few bore wells, there was no change in the deep groundwater chemistry, while the surface water and shallow groundwater (being utilised through dug well) showed a large increase (a factor of 2-5) in the chemical constituents.

Prior information obtained from hydrogeological, hydrochemical, geophysical investigations, a freshwater/salt water interface structure map and isotope studies was utilised to divide the area into four broad hydro-geological zones. Isotope methods provided significant information regarding recharge conditions of the aquifers. Some modern recharge (indicated by the presence of tritium) along with palaeo-recharge (indicated by interpreted radiocarbon ages of 12,000 to 16,000 yr B.P) during favourable climatic condition was observed in some deep aquifers. Judicious selection of freshwater aquifers and effective elimination of saline horizons was done using electrical and gamma logging and sealing-off effectively the undesired aquifers. Thus based on hydrogeological, geophysical, geochemical and isotopic data, 12 new bore wells at medium (80–150 m) and deep (150–300 m) depth were constructed and 34 piezometers were converted to provide an important resource (100 litre per capita per day) for mitigating drinking water problems in the cyclone-affected areas.

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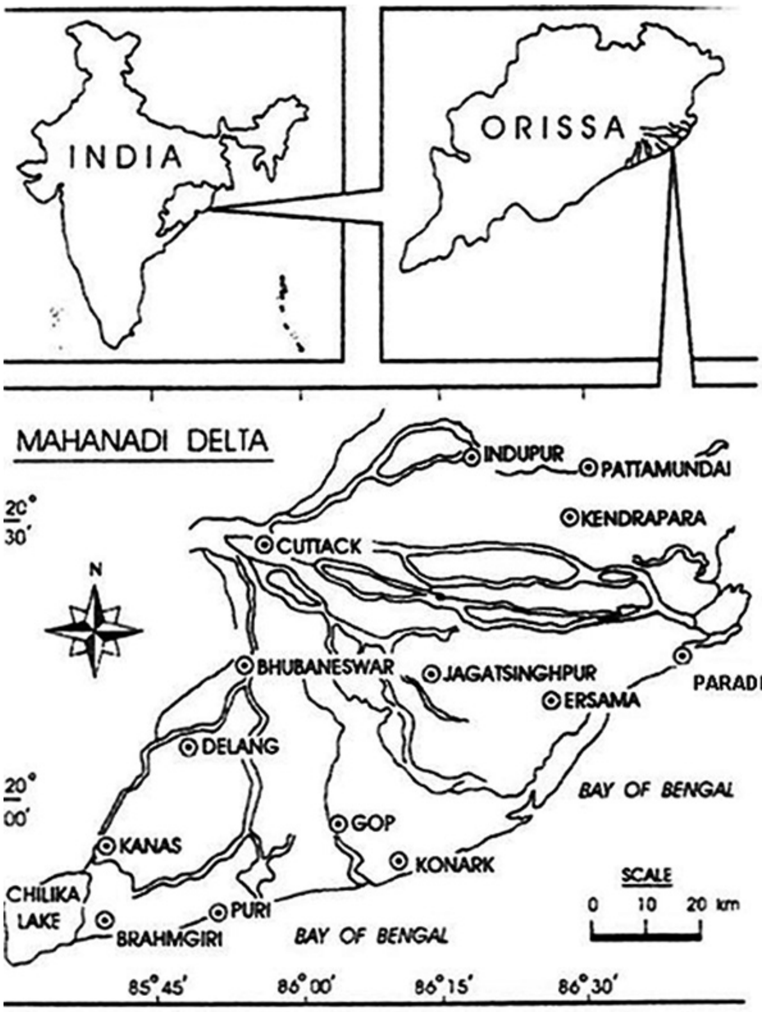
2. *Central Ground Water Board, Bhubneshwar, India*

Introduction

This case study reports relief measures undertaken by the Central Ground Water Board, Bhubaneshwar, India (Narasimha Rao, 1999) for providing safe drinking water using groundwater as a resource during the super cyclone which hit the coast of Orissa, India – the 20th century's worst in that province, on 29–30 October, 1999. The devastation wrought by the super cyclone to Orissa state is unprecedented, and caused misery to 13 million people. About 8,000 villages and 12 districts (Fig. 11.5.1 and 11.5.2) were severely affected.

There was a loss of about 10,000 human lives and about 2,500 persons injured, about four hundred thousand head of cattle perished and about 2 million hectare loss of crops due to the super cyclone. The cyclone was of catastrophic intensity (grade 5 on the scale of 1 to 5) with high wind speeds of 150 to 300 kmph. The super cyclone also resulted in 7 m storm sea waves, penetrating almost 15 km inland and very intense rainfall of 426 mm on a single day, where Orissa has an average annual rainfall of 1,200 mm. The combined impact of sea wave surge, intense rain and high energy wind resulted in major devastation of infrastructure, saline water inundation of land and drinking water sources, and flooding. Fig.11.5.2 shows in detail the area impacted, categorising 1. cyclone plus saline water inundation, 2. flood alone, 3. cyclone alone and 4. cyclone plus flood. The cyclone further caused severe

Figure 11.5.1. Super cyclone impacted Orissa, India during 29–30 October, 1999



devastation of the natural vegetation, a qualitative change in the areal extent of water and vegetation cover being evaluated using remote sensing methods, comparing satellite imageries between 11 October 1999 and 14 November 1999 (Table 11.5.1, Fig.11.5.3). Fig.11.5.3 shown in FCC (false colour composite), light red to deep red representing vegetation and bluish white to deep blue as absence of vegetation.

Figure 11.5.2. Categorisation of the area impacted by the super cyclone of the 29–30 October 1999, Orissa. The Mahanadi Delta area (see Fig. 11.5.1) is outlined in A.

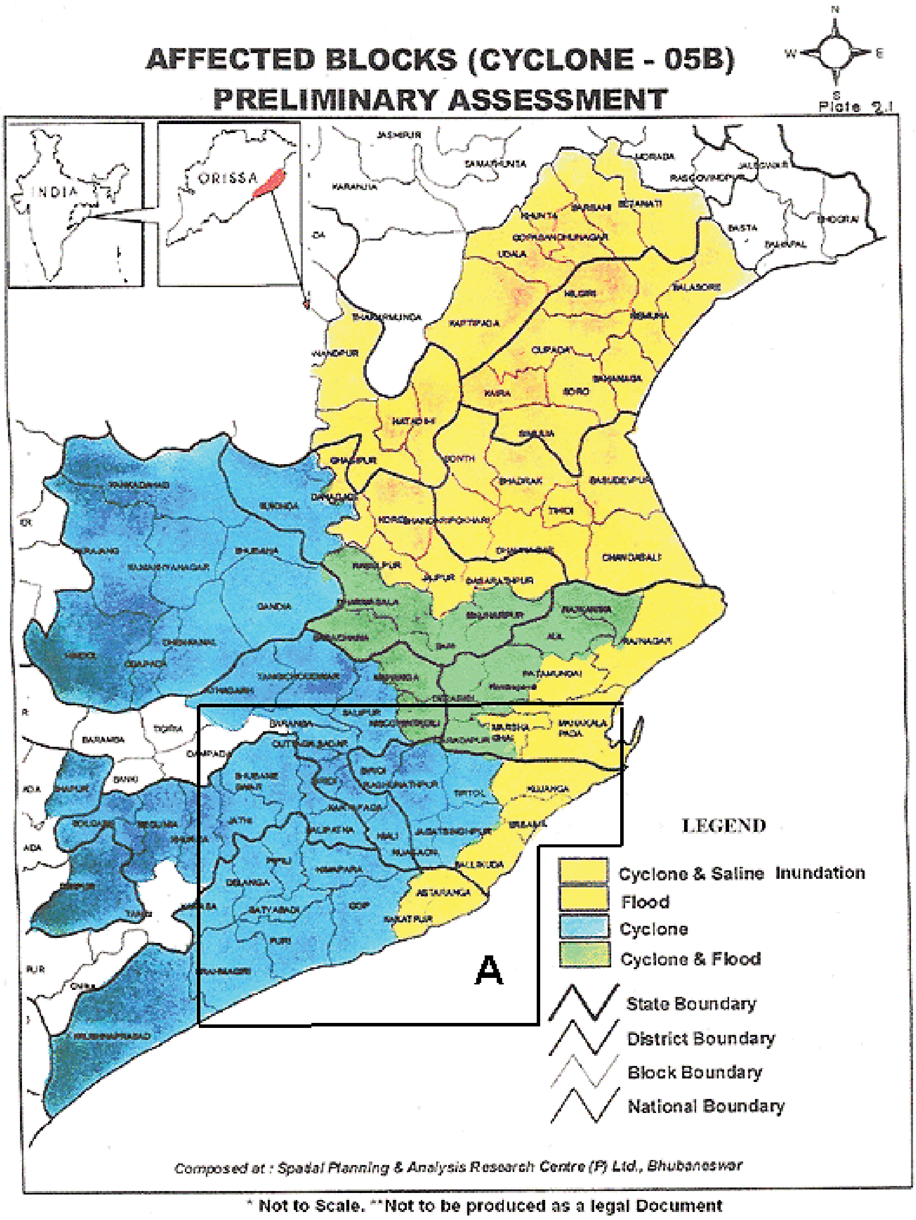
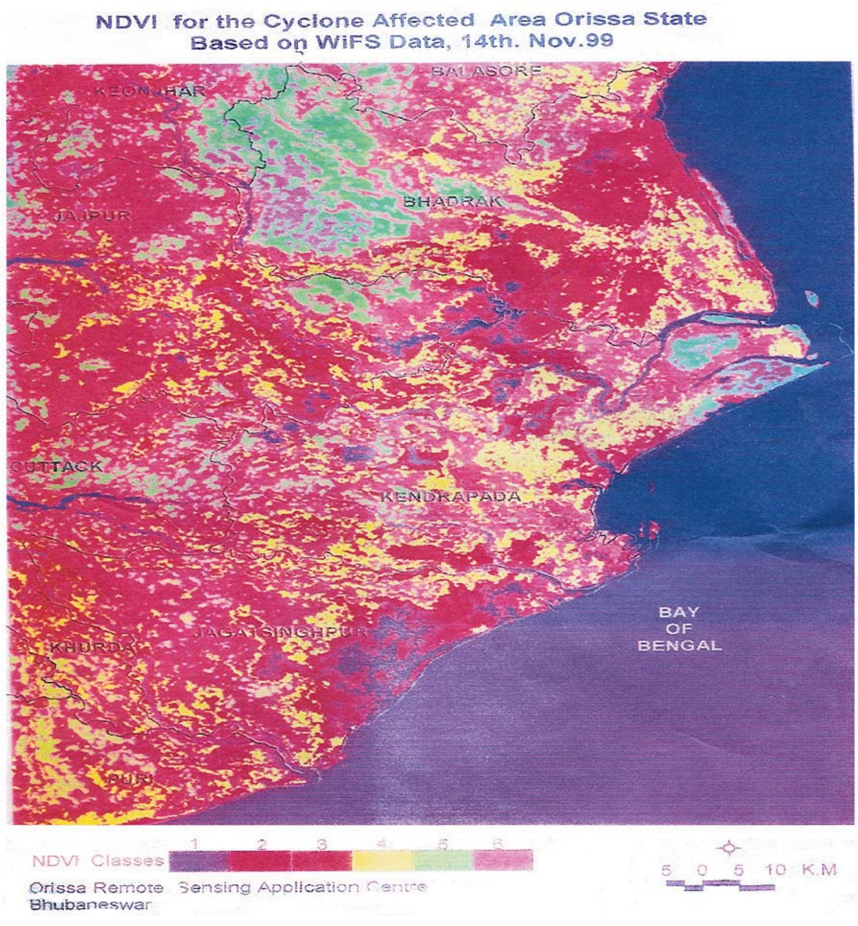


Table 11.5.1. Comparison of land, water and vegetation covers before and after the super cyclone of 29–30 October 1999 based on satellite imageries before (11 October 1999) and after the cyclone (14 November 1999)

Sl No.	*Cover*	*Gray range in Satellite Imageries*	*Pre-cyclone area in km^2 (11-10-99)*	*Post-cyclone area in km^2 (14-11-99)*	*Pre-/post-cyclone area difference in km^2*
1	Water body	0–103	3,991.04	5,226.48	1,235.44
2	Fallow land	104–135	1,735.13	2,250.10	514.97
3	Fallow land	136–151	2,611.81	4,699.24	2,087.43
4	Vegetation	152–189	2,301.05	1,864.24	(–) 436.81
5	Vegetation	190–215	4,124.81	1,166.93	(–) 2,957.88
6	Dense Vegetation	216–255	614.79	171.64	(–) 443.15

Figure 11.5.3. Satellite imagery of Orissa on 14 November 1999 after the devastation of the October 1999 super cyclone. Table 11.5.1 and Fig 11.5.3 indicate that there was a substantial increase in water covered and fallow land areas and a substantial reduction of vegetation due the super cyclone.



Groundwater system: hydrogeological and geophysical investigations

The state of Orissa along the east coast of India presents a flat, gently undulating terrain and a network of rivers and tributaries, the Mahanadi delta with an areal extent of 9,000 km^2. Recent sediments of alluvial deposits and upper Tertiary formations form the principal aquifers. Groundwater occurs under phreatic conditions (3–10 m above m.s.l.) in the shallow aquifer and under semi-confined to confined conditions in deeper aquifers. Some of the deep wells are artesian, particularly those close to Chilika Lake. Water balance calculations carried out by CGWB (Narasimha Rao, 1999) based on the inventory of wells and bore wells, and yield and recharge estimates, indicate a large balance of utilizable groundwater available in the state. A schematic geological section (Fig. 11.5.4) shows that the thickness of alluvium increases from north to south from 20 m at Jagdalpur to 60 m at Puri.

Extensive hydrogeological investigations (Narasimha Rao, 1999, Radhakrishna, 2001) and mainly deep resistivity geophysical surveys by the National Geophysical Research Institute (Dhar et al., 1992), DANIDA (Singh, 1991) and the Central Ground Water Board (Chandra et al. 2002) indicated a complex phreatic, semi-confined and confined aquifer system with fresh, brackish and saline groundwater at different depths (Fig. 11.5.4 and Fig.11.5.5). Based on geophysical logging, exploratory drilling and chemical analyses of formation water, a fence diagram of the Orissa Coast, from Chilika Lake (South) to Jaleswar (North) was prepared incorporating the hydrochemical profiles and data of 151 wells (Fig.11.5.5). The salinity pattern is classified into five categories namely: 1/ fresh water overlying saline

Figure 11.5.4. Multi-aquifer system delineated by detailed hydrogeological and deep resistivity surveys in Delang-Puri sector (Source: CGWB, NGRI and DANIDA)

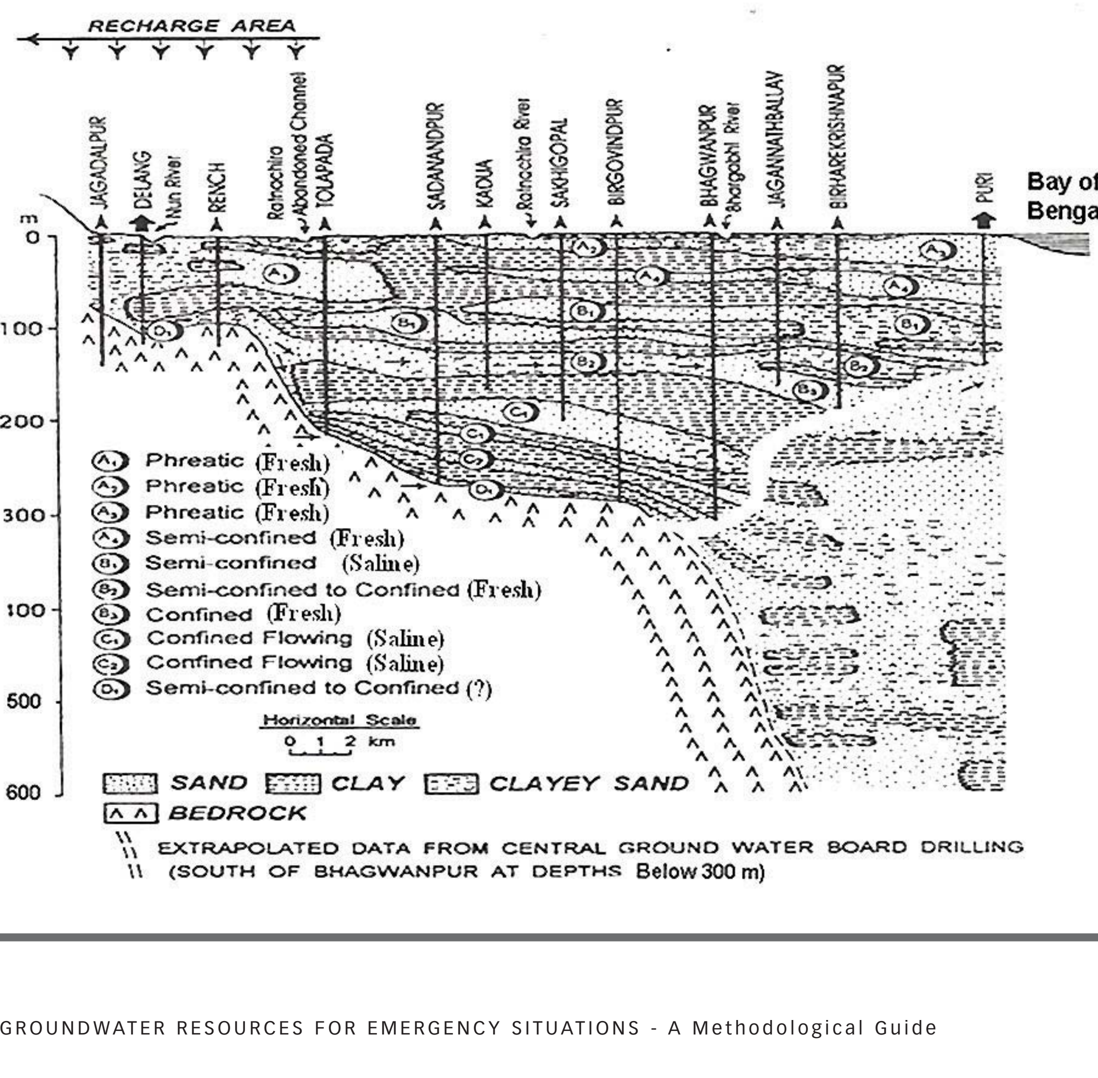
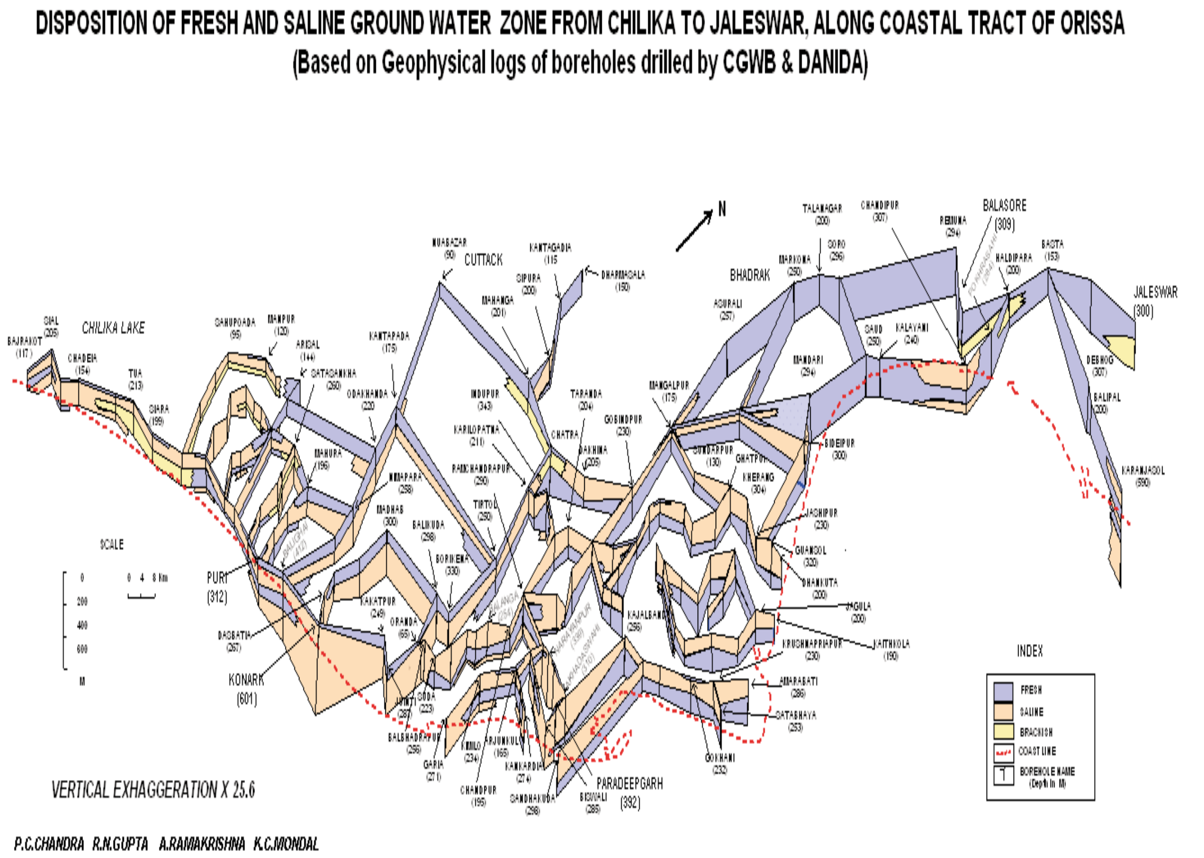


Figure 11.5.5. A fence diagram delineating fresh and saline ground water zones based on the geophysical well logging, exploratory drilling data and hydrochemistry



water (Fig. 11.5.4, A1, A2, A3, A4), 2/ saline water overlying fresh water (Fig. 11.5.4, B1), 3/ entirely fresh water (Fig. 11.5.4, B2, B3), 4/entirely saline water (Fig.11.5.4, C1, C2) and 5/ alternate fresh and saline water zones(Fig 11.5.5). In the south-eastern part around Chilika Lake, a shallow fresh water zone between 12 and 20 m depth along dune areas and a brackish to freshwater zone between 120 to 210 m was identified. Around Brahmagiri block, all the aquifers down to the explored depth of 230 m are saline, including the upper dune zone.

An extremely complex system of fresh and saline horizons was encountered over the entire region as is summarised in the fence diagram of Fig. 11.5.5. Several areas have shallow fresh water zones. Dense population concentrations in many areas are dependent on shallow brackish groundwater with fresh horizons found at depth. There are areas in which no fresh water can be found at any depth.

Impact of Orissa Super Cyclone on groundwater system

The Central Groundwater Board of India (Narasihma Rao, 1999) undertook the task of assessing the change in chemical quality of groundwater as a consequence of the disaster. Immediately after the cyclone, a hydrochemical survey of the groundwater samples was undertaken using a mobile chemical laboratory. A fairly good number of water samples (30) was collected from selected sites in the two worst affected districts of Jagatsinghpur and Puri and on the spot chemical measurements were undertaken. In the Jagatsinghpur district out of 30 samples collected, 12 samples were from deep borewells, 13 from dug wells and the remaining 5 were surface water (river, pond and sea).

As can be seen from the chemical data presented in Table 11.5.2, the chemical quality (EC,Cl, Na, K)

Table 11.5.2. Chemical analyses (mg /L) of water samples from cyclone affected area in the coastal Orissa (Narasimha Rao, 1999)

Sl. No.	*Location*	*Sample Type*	*pH*	*E.C.*	*CO_3*	*HCO_3*	*Cl*	*NO_3*	*F*	*TH*	*Ca*	*Mg*	*Na*	*K*
1	NUAGAON	T.W.	7.81	722	0	275	71	6.4	0.46	245	60	23	68	2
2	BARAGOBAPUR	T.W.	7.29	1,344	0	348	195	3.2	0.39	405	100	38	102	1
3	NUAGAON	T.W.	7.29	1,100	0	354	121	0.8	0.42	275	70	24	132	1
4	BALITUTH	T.W.	7.57	1,074	0	372	142	3.8	0.34	295	70	29	95	2
5	CHATUA	T.W.	7.25	1,021	0	372	74	2	0.44	305	76	28	89	1
6	ERASAMA	T.W.	5.75	405	0	28	64	48	0.75	80	24	4.9	30	1.5
7	BODHEI	T.W.	7.24	1,045	0	323	124	7.5	0.81	60	16	4.9	176	0.6
8	RAJPUR (GODA)	T.W.	6.81	341	0	79	53	4.9	0.51	60	20	2.4	35	1.5
9	ERASAMA	T.W.	7.04	1,537	0	244	319	0	0.26	395	100	35	118	2
10	BIRKISHORPUR	T.W.	7.91	3,608	0	439	922	4.3	2.25	140	24	19.5	720	4.3
11	PADAMPUR	T.W.	6.86	851	0	146	163	32	0.26	185	44	18	88	3
12	PADAMPUR	T.W.	7.08	754	0	256	106	17	0.31	310	64	36	28	0.5
13	NUAGAON	D.W.	6.89	1,469	0	329	174	111	5.1	315	90	22	104	27
14	BALITUTH NHS	D.W.	6.74	2,942	0	390	532	83	4.6	440	84	56	288	48
15	CHATUA	D.W.	7.29	13,200	0	702	3,580	103	2	2,500	360	389	1,990	80
16	MANIJANGA NHS	D.W.	6.8	470	0	244	14	2	0.37	190	60	9.7	22	0.4
17	KUJANG NHS	D.W.	6.81	773	0	323	43	17	0.49	275	90	12	38	1.3
18	BHUTMUNDAI	D.W.	7.15	8,880	0	354	2,588	8	0.73	1,080	232	122	1,340	2
19	PARADEEPGAR HNHS	D.W.	6.06	246	0	70	25	11	0.14	80	28	2.4	18	0.7
20	SUNAKHALA	D.W.	6.84	650	0	146	78	37	0.86	160	56	4.9	57	3
21	PARADEEP NHS	D.W.	7.44	1,320	0	119	288	3	0.88	210	60	15	136	2
22	JAGANNATH-PUR NHS	D.W.	6.81	641	0	220	64	5	6	130	38	8.5	58	11
23	ERASAMA NHS	D.W.	7.12	655	0	226	82	6	0.72	175	58	7.3	65	2
24	BIRKISHORPUR	D.W.	6.78	3,006	0	189	744	13	1.9	500	72	78	370	12
25	PADAMPUR	D.W.	6.21	833	0	61	206	4	0.48	180	36	21	85	6
26	SEA WATER alpuri	Sea	8.09	33,570	0	128	11,344	2.3	1.25	3,800	320	730	5,680	48
27	SANKH RIVER	River	7.58	15,623	0	110	5,899	4.3	1	2,060	136	418	2,980	20
28	Surface water near river	Surface W	7.99	11,581	0	98	3,985	3.3	0.9	1,420	120	272	2,000	18
29	BARAGOBAPUR	Pond	7.81	15,648	0	116	5,247	3.1	1.6	1,800	120	365	2,720	20
30	Bara River (Patna vill)	River	7.57	259	0	110	18	3.7	0.34	80	26	3.6	19	1.3

was degraded in ponds, rivers and shallow groundwater. A notable change in the chemical characteristics was observed in dug wells. Most deep wells (T.W.) showed fairly good quality. In the Puri district, the impact of the cyclone was rather low: one surface pond showed an EC of 1,211 µS cm^{-1} where another gave low EC, Na and Cl values. A similar impact on shallow groundwater was noticed at Nuagarh (EC 1,112 µS cm^{-1}). Nearly 50% of dug wells showed an increase in electrical conductivity and chloride concentration (Table 11.5.2). Table 11.5.3 shows the hydrochemical changes in the dug wells of Jagatsinghpur, the worst affected district. Table 11.5.4 and Fig. 11.5.6 show the post-cyclone changes in

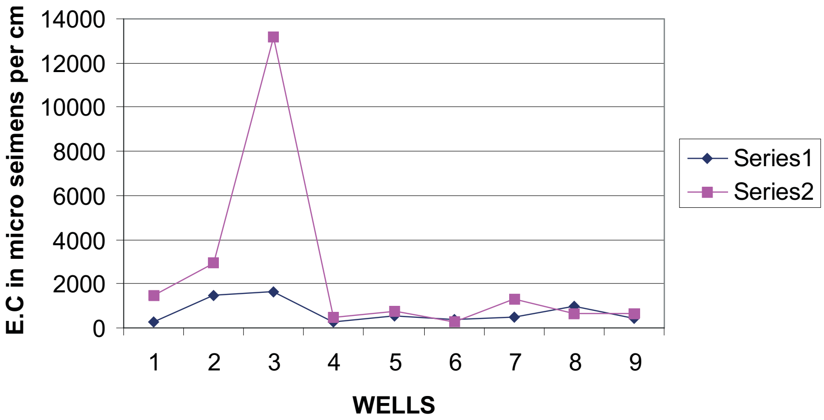
Table 11.5.3. Chemical quality (concentration in mg/L) changes in dug wells of Jagatsinghpur, before and after the super cyclone

Location		*pH*	*EC (µS/cm@ 25°C)*	*CO_3*	*HCO_3*	*Cl*	*NO_3*	*F*	*Total hardness*	*Ca*	*Mg*	*Na*	*K*
Chatua	Precyclone	8.45	2,769	7.8	231	629	9.4	0.53	634	85	3	276	90
Chatua	Postcycline	7.29	13,200	0	702	3,580	103	2	2,500	360	389	1,990	80
Paradeep	Precyclone	7.73	532	0	156	44	48	1.3	179	50	13	28	17
Paradeep	Postcyclone	7.44	1,320	0	119	288	3	0.88	210	60	15	136	2
Baliluth	Precyclone	8.64	1,687	7.8	303	239	63	3.7	27	44	37	184	106
Baliluth	Postcyclone	6.74	2,942	0	390	532	83	4.6	440	84	56	288	48
Ersama	Precyclone	8.15	451	0	147	41	17	0.31	102	36	2.9	44	12
Ersama	Postcyclone	7.12	655	0	226	82	5.8	0.72	175	58	7.3	65	2

Table 11.5.4. Electrical conductivity (µS cm^{-1}) of water samplers from different dug wells of district Jagatsinghpur after the super cyclone and its deviation from average value

Sl No.	*Location*	*Well No.*	*1989*	*1990*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*Average 1989–1998*	*Post-cyclone values*
1	NAUGAON	72L-4A6	300	327	380	372	260	N.A	120	255	288	1,469
2	BALILUTH	73L-4C1	N.A	N.A	N.A	1,640	1,522	1,344	1,130	1,687	1,465	2,942
3	CHATUA	73L-3B12	N.A	N.A	N.A	472	524	489	4,040	2,769	1,659	13,200
4	MANIJANGA	73L-3B1	320	330	310	N.A	190	232	140	215	248	470
5	KUJANG	73L-3C1	694	684	550	605	665	358	420	465	555	773
6	PARADEEP-GARH	73L-3C3	N.A	N.A	N.A	N.A	565	480	340	187	393	246
7	PARADEEP	73L-3C2	460	684	495	646	202	236	N.A	532	465	1,320
8	JAGANNATH	73L-4B5	N.A	N.A	N.A	N.A	970	1,044	790	1,040	961	641
9	ERASAMA	73L-4BA	N.A	456	330	360	420	680	280	451	425	655

Figure 11.5.6. Deviation from mean values of chloride of wells of Jagatsinghpur after the super cyclone. Series 1 shows average value and the series 2 after the cyclone.

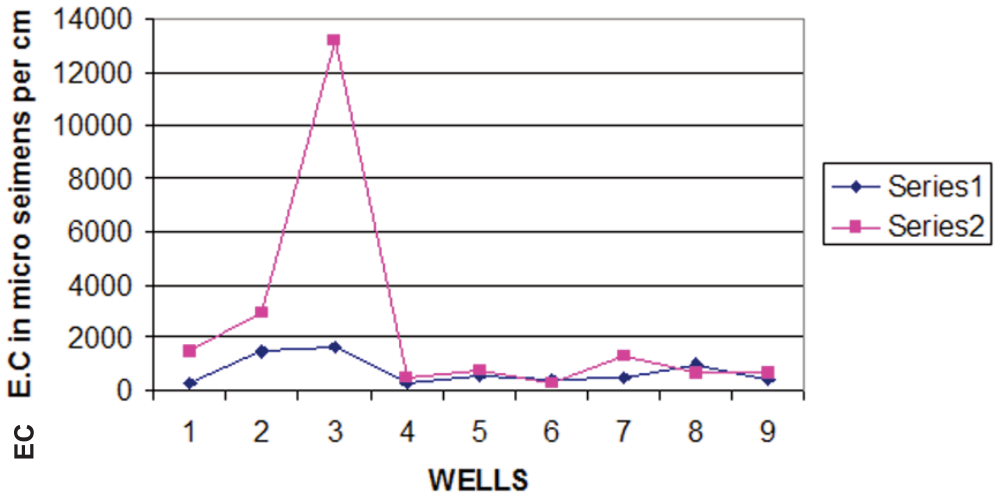


the electrical conductivity to be very high in comparison to the average value of the previous 10 years (1989–99) for the same district, with very drastic changes in the chloride concentration (Table 11.5.5 and Fig. 11.5.7) in the dug wells.

Table 11.5.5. Chloride values (mg/L) of water samples from different wells of District Jagatsingpur after the super cylone and its deviation from average value

Sl No.	*Location*	*Well No.*	*1989*	*1990*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*Average 1989–1998*	*Post-cyclone values*
1	NAUGAON	72L-4A6		28	28	18	18	18	N.A	14	16	20
2	BALILUTH	73L-4C1	N.A	N.A	N.A	252	227	177	206	239	220	532
3	CHATUA	73L-3B12	N.A	N.A	N.A	92	78	78	1134	620	400	3,580
4	MANIJANGA	73L-3B1	18	25	12	N.A	14	14	14	11	15	14
5	KUJANG	73L-3C1	110	106	43	39	39	35	60	51	60	43
6	PARADEEP-GARH	73L-3C3	N.A	N.A	N.A	N.A	78	28	50	14	43	25
7	PARADEEP	73L-3C2	50	71	60	67	25	32	N.A	44	50	288
8	JAGANNATH	73L-4B5	N.A	N.A	N.A	N.A	184	209	156	163	178	64
9	ERASAMA	73L-4BA	N.A	67	32	39	46	131	57	41	59	82

Figure 11.5.7. Deviation from ten year mean values of electrical conductivity of wells of Jagatsinghpur after the super cyclone. Series 1 shows average values and Series 2 after the cyclone.



Isotope investigations

The Bhaba Atomic Research Centre (BARC; Kulkarni et al., 1998, Shivanna et al., 1998, Rao, 2006) carried out extensive isotope investigations in coastal Orissa Province in order to understand the source and origin of groundwater and salinity in different aquifers by measuring tritium, ^{14}C and stable isotopes ^{2}H, ^{18}O and ^{13}C of fresh, saline shallow and deep groundwater. Fig. 11.5.8 shows the locations of the samples collected for the isotope measurements in a transect from Jagdalpur to Puri. From Table 11.5.6 and Fig.11.5.4, it can be seen that the top freshwater zone (A1, A2 and A3) and deep fresh water zone (B2 and B3) both represent 'young' water with measurable tritium indicating modern recharge to the aquifers. Fig. 11.5.9 shows the depth variation of ^{14}C concentration in groundwater as measured in groundwater samples from different wells. The plot indicates an active recharge zone down to 50 m. Further, significantly, the freshwater aquifer at depths between 100–160 m has ^{14}C ages between 12,000 –16,000 yr B.P. along with significant levels of tritium. This is interpreted as the aquifer having received recharge from the favourable past climatic episodes, inter alia from the thermonuclear bomb peak in the 1960s, and it does have a modern component. However, the intermediate depth aquifer (60–100 m) and deeper aquifers (C1 and C2) are not suitable for groundwater exploitation due to higher salinity. It may be noted from Fig. 11.5.10 that recharge to shallow groundwater (A1, A2, A3) and medium deep freshwater aquifers (B2 and B3) had experienced evaporative enrichment of stable isotopes. Considering this information along with the hydrogeological section (Fig. 11.5.4), it appears that recharge takes place through laterites and outcrops of basement rocks exposed on the hills northwest of Delang. It indicates also that the recharged water has flushed out marine water where still present in the formations (Rao, 2006), as the aquifer has normal salinity. However the samples from the depth range of 50–100 m (B1), with high salinity do not show evaporation and are tritium free indicating absence of modern recharge. On the other hand, the radiocarbon ages as illustrated by the samples of Partapramchandrapuram and Puri (Table 11.5.6) are 9,850 yr BP and 12,550 yr BP, thus indicating palaeomarine transgression in the Holocene. Further groundwater at depth around 180–250 m in aquifer C1 and C2 is saline. Plots of $\delta^{2}H$-$\delta^{18}O$ for samples from these aquifers lie on evaporation regressions with slopes ranging from ~5 for surface water and fresh, deep groundwater to ~7.9 for intermediate groundwater (Fig. 11.5.10) and have radiocarbon ages 16,500-30,000 yr B.P. with much higher conductivity range (2,430–29,700 µS/cm). This water would have originated as a mixture of fresh and sea water being trapped during the late Pleistocene transgression (Shivanna et al., 1993; Kulkarni et al., 1998).

Figure11.5.8. Location map of the samples collected for isotope studies in coastal Orissa along the Jagdalpur –Puri transect

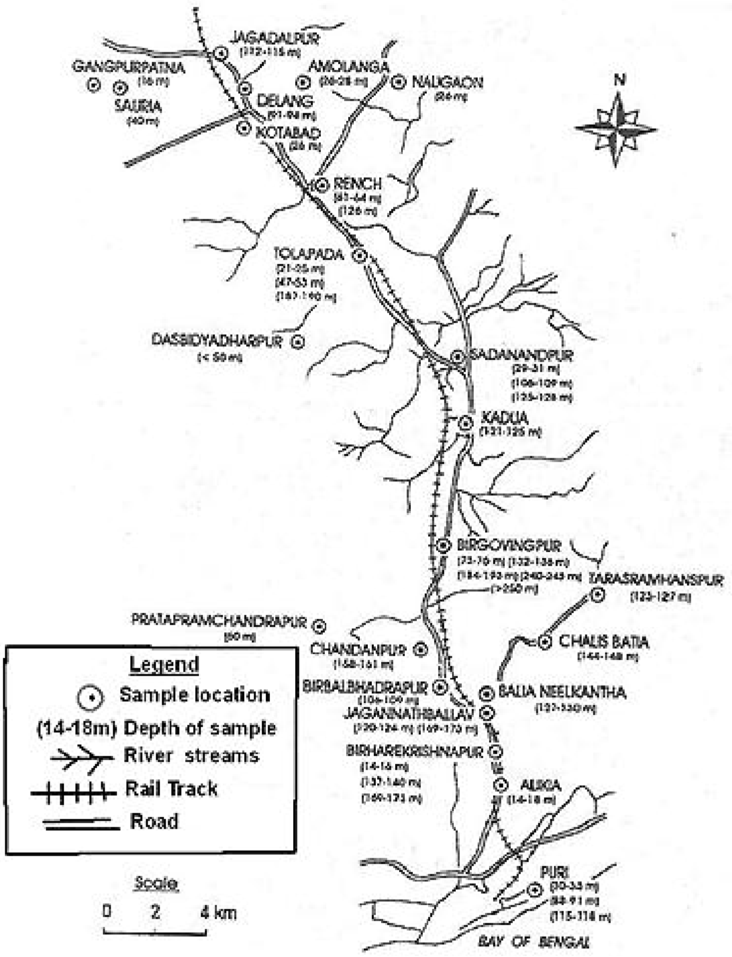


Figure 11.5.9. Radiocarbon depth profile of groundwater in coastal Orissa

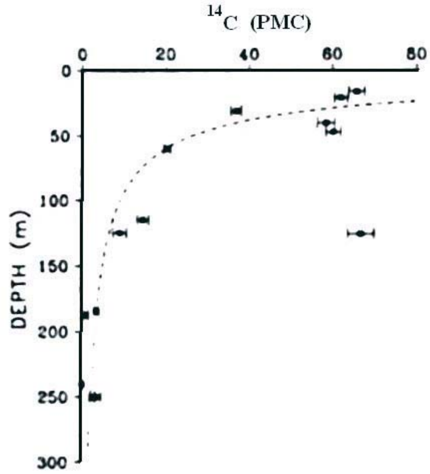


Figure11.5.10. $\delta^2H(\delta D)$-$\delta^{18}O$ relationship of surface water, shallow, intermediate, fresh medium deep and deep saline groundwater

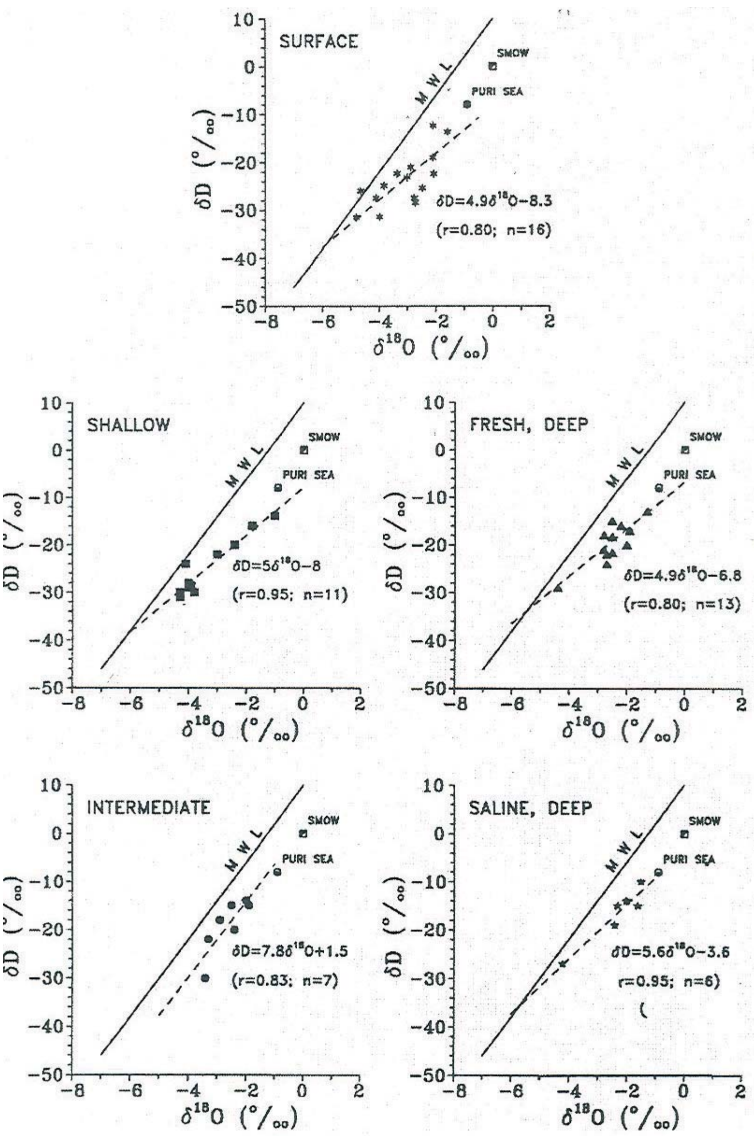


Table 11.5.6. Tritium and interpreted radiocarbon ages of groundwater samples in coastal Orissa

Tritium data for the different waters are as given below.

Aquifers	Depth Range (m)	Tritium (TU)
A_1, A_2, A_3 (Fresh)	Shallow (up to 50)	1 - 4
B_1 (Saline)	Intermediate (60-100)	n.d
B_2, B_3 (Fresh)	Deep (100 – 160)	3 - 8
C_1, C_2 Saline	Deep (180-250)	n.d

n.d = not detectable

Carbon-14 data of groundwater samples are as follows.

S.No	Place	Depth (m)	EC (µS/cm)	^{14}C (pmc)	$\delta^{13}C$ (‰)	^{14}C age (a BP)
1	Gangapurpatna	16	780	65.8	-14.1	Modern
2	Sauria	40	540	58.5	-13.6	Modern
3	Rench	31	2230	36.8		4950
4	Rench	126	660	67.1		Modern*
5	Tolapada	21-25	530	62.0		650
6	Tolapada	47-53	560	60.3		880
7	Tolapada	187-190	3580	1.2		33,300
8	Prat'ram'pur	60	16200	20.4	-12.4	9850/7350#
9	Sadanandpur	125-128	2430	9.2		16450
10	Sadanandpur	Flowing	14000	2.7	-12.6	26550/24850#
11	Birgovindpur	184-193	5570	3.7	-9.4	24450/19650#
12	Birgovindpur	240-293	21100	0.24	-17.0	46600/46350#
13	Birgovindpur	>250	29700	4.1		23100
14	Puri	115-118	12200	14.7		12550

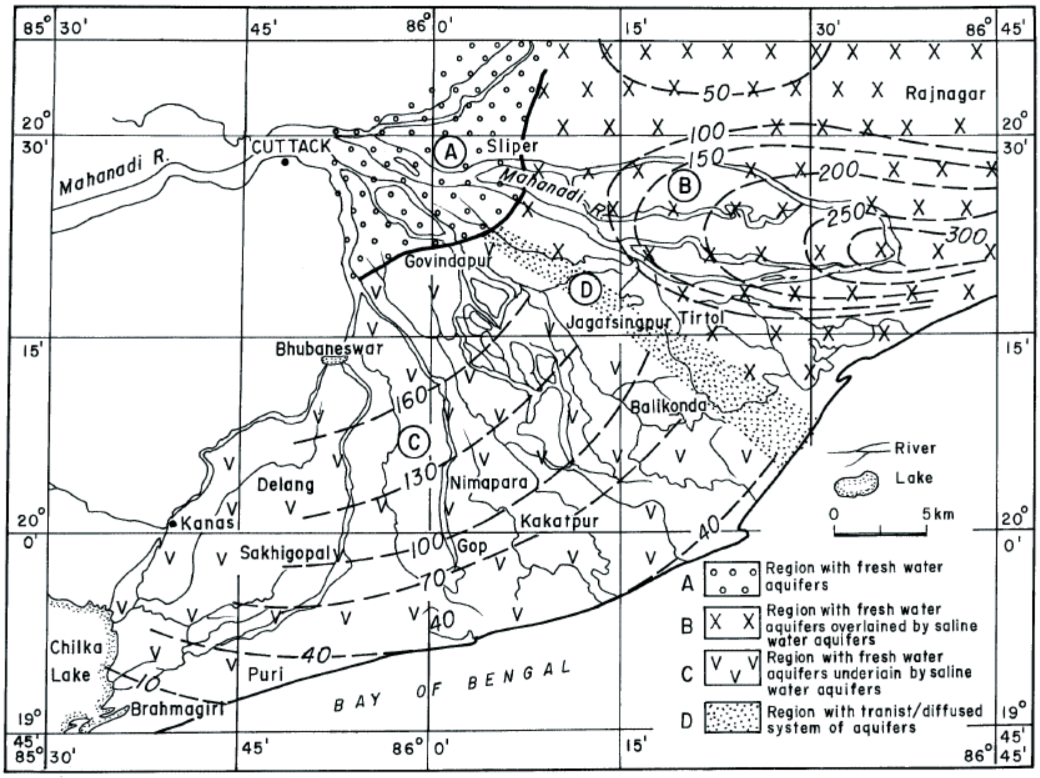
* 67.1 PMC of this deep fresh groundwater sample that has present day tritium level is taken Modern and ^{14}C ages are calculated accordingly

\# These values were calculated using a model based on available ^{13}C data.

Groundwater management strategies for the super cyclone impacted areas: identification of suitable groundwater resource

Groundwater management strategies need to identify suitable groundwater resource for providing safe drinking water in the coastal area of Orissa, which has an inherent salinity problem, demands judicious selection of fresh water aquifers and effective sealing against saline horizons using electrical and gamma logging in the well design. Well construction has to cater for situations such as whether the fresh water overlies or underlies a saline zone or is sandwiched between two saline zones. The interface depth profiles and interface depth structure map for the Mahanadi delta provides a complicated pattern of interrelationships between fresh-saline water aquifer systems. Based on an interface structure map (Fig.11.5.11), the delta region could be broadly divided into the four hydrogeological zones mentioned earlier (Radhakrishna, 2001), namely zone A with fresh water; zone B with fresh water overlain by saline water; zone C with fresh water underlain by saline water or sometimes alternating with a fresh-brackish water aquifer systems, and zone D with mixing patterns of salinities between aquifers of zones B and C. This type of interface structure map that summarises the detail shown in the fence diagram (Fig.11.5.5) should provide the essential basic parameters for coastal zone groundwater management, well-field development programs and for understanding saline water intrusion mechanisms. The interface structure map and the aquifer configuration indicate that zone A acts primarily as a recharge zone to several freshwater-bearing aquifers in zone B.

Figure 11.5.11. Interface depth structure map for the Mahanadi delta (Radhakrishna, 2001). Generalised interface contours are shown with depths in meters.



In the case of cyclone impacted areas, the strategy necessitates the demarcation of aquifers which have been degraded and examine the better options available based on the hydrogeological, hydrochemical and geophysical surveys. Isotope methods further provide valuable input regarding the recharge of the aquifer, its source area and the residence time of groundwater. Based on these criteria and using the hydrogeological section (Fig. 11.5.4), hydrochemical and isotope data (Table 11.5.6) different aquifers in the area can be considered. It is clear from the table and tritium data that although shallow (50 m) groundwater aquifers (A1, A2, A3) have favourable recharge conditions, they nevertheless develop salinity as shown by high EC and chloride measurements of several shallow groundwaters (Table 11.5.5), due to impact of the cyclone. Maximum impact of the cyclone by way of inundation by sea water surges on groundwater samples was observed in the dug wells tapping the shallow aquifer. Further from Table 11.5.6 it is observed that aquifer B1 (60–100 m) is unsuitable being saline. On the other hand, the medium deep aquifer of 100–160 m depth (B2 and B3) is fresh with good chemical quality and is not impacted by the cyclone. As noted by Radhakrishna (2001) and CGWB, the fresh water aquifer occasionally can extend to a depth of 300 m. At the same time this aquifer has measurable tritium, indicating some modern recharge but with radiocarbon ages of 12,000 to 16,000 yr B.P. indicating paleo-recharge during favorable climatic periods. Further deep aquifers are saline and thus are not suitable.

Considering the various possibilities, depending upon the available aquifers and chemical quality the CGWB therefore recommended shallow (40–60 m) tube wells in certain areas of Cuttack, Balasore and Puri districts. The yield of these wells varies from 36 m^3hr^{-1} to 234 m^3hr^{-1} with a drawdown of 5–9 m. Wells of intermediate depth (80–150 m) are feasible in the entire Balasore coastal zone and give yields of 75–246 m^3hr^{-1} with drawdowns of 7 to 15.6 m. Deep wells (150–300 m) are recommended depending upon the fresh-water/saltwater interface depth with effective cement sealing between filters. Thus medium deep bore wells are highly useful for mitigating the drinking water problem of the cyclone impacted areas. A typical bore well could meet the needs of 15,000 persons, providing about 100 liters of water per person per day with sustained quality.

Conclusions

The coastal state of Orissa, India was hit by an unprecedented super cyclone on 29–30 October, 1999, causing many casualties, misery for 13 million people and severe devastation to vegetation and drinking water structures. Shallow groundwater was found to be highly impacted by salinisation. Though some organizations brought in reverse osmosis equipment to provide safe drinking water from existing saline/brackish water, the effort was of short duration. The Central Ground Water Board (CGWB) immediately swung in to action to demarcate the areas and aquifers chemically most impacted. Based on the detailed information already made available by different organisations on the groundwater system based on hydrogeological, geophysical well logging, salt water-freshwater interface and isotope investigations, a number of wells were drilled by the CGWB tapping depths of 100 to 160 m in the medium deep freshwater aquifer. The drinking water supply was fully restored within four months giving relief to approximately one million people by supplying 100 litres of water per capita per day. The success of the measures described in this case study encourages the authors to go ahead with more detailed and better planning and preparedness to combat the impact of cyclones and similar disasters and to provide safe drinking water to the people of coastal Orissa.

References

Chandra, P.C., Gupta, R.N., Ramakrishna A. and Mondal, K.C. 2002. *Surface and Bore Hole Geophysical Investigations for Fresh Water Aquifers of Coastal Orissa*. Central Ground Water Board, India (unpublished report).

Dhar, R.L., Singh S.B. and Prakash, B.A. 1992. *Exploration of Deep fresh Aquifers in the Saline Environs of Mhanadi Delta, Orissa.*Technical report NGRI-92-ENVIRON -12. National Geophysical Research Institute, Hyderabad (Council of Scientific and Industrial Research).

Kulkarni, K.M., Navada S.V., Nair A.R., Rao S.M., Shivanna, K., Sinha, U.K. and Sharma, S. 1998. *Drinking Water Salinity Problem in Coastal Orissa , India – Identification of Past Transgressions of Sea Water by Isotope investigations, Isotope Techniques in the Study of Environmental Change.* Proc. Intl. Symp. IAEA, Vienna, 293–306.

Narasimha Rao, B.S.R. 1999. *Report on Cyclone Affected Areas of Orissa*. Central Ground Water Board South Eastern Region, Ministry Of Water Resources, Government of India.

Radhakrishna, I. 2001 Saline Fresh Water Interface Structure in Mahanadi Delta Region, Orissa, India. *Environmental Geology,* Vol. 40. No. 3, 369–380.

Rao, S.M. 2006. *Practical Isotope Hydrology*. New India Publishing Agency, 1–195.

Shivanna K, S.V. Navada, K.M., Kulkarni, U.K., Sinha and S. Sharma. 1998. *Application of Isotope Techniques to Investigate Groundwater Pollution in* India. IAEA-TECDOC-1046.

Singh, H. 1991. *Report on Shallow VES investigation.* Special hydrogeological investigations, Danish International Development Agency Assisted. Orissa Drinking Water Supply Project, Bhubneswar.

11.6 The implementation of best management practices for emergency groundwater in China – a case study of Shenzhen Xikeng reservoir area

Wenbin Zhou[1], Ru Zhang[1] and Shaw L. Yu[2]

Abstract

The paper describes several governance measures based on best management practice principles to increase and protect groundwater resources for emergency situations, which have been undertaken at Xikeng Reservoir area in Shenzhen, China. Sustainable groundwater resources development is an especially difficult task in populous cities such as Shenzhen. This city, as China's special economic zone established in 1980, has urbanised very quickly. It is worth nothing that a long-term initiative and commitment are needed to battle the challenges posed by rapid urbanization and protection of its potential drinking water resource. In particular, groundwater and storm water management still have a long way to go. Innovative concepts such as Best Management Practices should be incorporated into long-term strategic planning of city growth. This project is sponsored by the EPA, Shenzhen Water Authority, the University of Virginia, and Nanchang University. It is a pilot project that will provide the model for water resources management in urban areas generally.

Introduction

Ground water use in China has become very significant during the recent population boom. Many large urban authorities obtain municipal water supplies, such as drinking water from groundwater sources. As the use of ground water resources increases, it will become critical to implement effective ground water protection programmes. Clearly, there is a need to integrate the management of ground water and surface water. Furthermore, ground water management should focus not only on quantity but also on quality.

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China faces four severe and long-term challenges in the water resource area: 1/ Flooding impacts, 2/ the gap between water resource supply and water demand, 3/ heavy soil erosion, and 4/ water pollution.

This severe situation has captured the urgent attention of the Chinese government, that has strengthened protection of the water environment and ensured water security in the following aspects: A prior claim to water quality in drinking water source areas; improve water pollution control in particular in key drainage areas; implement management of ecological systems and rejuvenate the 'river of life'; step up enforcement of environmental protection laws and resolutely punish various illegal pollutant discharges; implement the public's right to know regarding the environment and its protection.

For the most part in China, drinking water is treated by the combination of chemical and physical processes which, whether simple or sophisticated, are required to make that water safe to consume. While little has be done to prevent pollution of source water by natural, ecological factors, more attention should in the next decade be given to protect source water areas (watersheds and aquifers) from man-made threats of pollution, such as urbanization. Urban activities that contribute to ground water pollution include the use of surface impoundments, septic systems, underground storage tanks, the application of fertilisers and pesticides to lawns, parks and golf courses, accidental chemical and other hazardous waste spills, commercial and industrial waste disposal and sewer systems. The rapid increases in population and building density that occur as formerly predominantly rural catchment areas become progressively urbanised, can have a far-reaching effect on groundwater.

However, efforts to more effectively manage these non point sources of ground water pollution are at an early stage and rely heavily on the use of best management practices. Non-point source pollution is generally associated with storm water runoff which carries sediment, nutrients, toxins and organic material into receiving areas. In addition, groundwater, which eventually discharges in to surface water, can become polluted by water percolating through the soil. The most important hydraulic factors affecting urban groundwater infiltration are the quantity of rain and the extent of impervious surfaces directly connected to a stream or drainage system. Directly connected impervious areas include paved streets, driveways, and parking areas draining to curb and gutter drainage systems, and roofs draining directly to a combined storm/sewer pipe.

Brief Description of Best Management Practices (BMPs)

Best management practices (BMPs) commonly include structural and nonstructural elements. Structural BMPs are engineered facilities that detain, filter or retain pollutant-carrying storm water runoff, increase infiltration rate, such as bio retention cells, detention ponds, constructed wetlands, lawns and grassed strips or buffers, and underground treatment tanks. Nonstructural BMPs are management practices aimed at reducing the generation of pollutants at their sources, such as street cleaning, land use control and nutrient management. Under the premises that biological integrity can be attained when the physical and chemical properties of water bodies are adequately maintained, the implementation of watershed BMPs is, therefore, an important step in reaching the goals of a sustainable groundwater management.

Examples of implementation plan for groundwater at Shenzhen Xikeng Reservoir in emergency (storms) situations

Urbanization in China proceeds most rapidly in the City of Shenzhen. With a population over 10 million, the City is facing a severe water-environment challenge. The main water supply sources are storage reservoirs, both on- and off-channel. The Xikeng Reservoir is one of the major water supply reservoirs in Shanzen drawing water from the local Guanlan River however, mainly depends on water transported by a channel from a big regional Dong River. The Guanlan River watershed has a total area of 202 km^2 and is heavily urbanised. The land use pattern shows about 42% forests; 38% urbanised, i.e., industrial, commercial and residential; 10% agricultural and 10% open land.

One of the main objectives of this study is to protect both groundwater quality and quantity, test the infiltration rate, pollutant removal efficiency of selected BMPs or a BMP treatment train implemented in the Xikeng reservoir watershed. BMPs to be considered should include conventional ones such as detention ponds and swales, and also innovative types such as bio-retention cells and new soil erosion control techniques.

The administration building area near the Xikeng Reservoir has incorporated several features that manage stormwater in a responsible manner to increase the infiltration quantity of storm waters and reduce the amount of pollutants in the storm water runoff. Among the features that are currently employed are: 1) the use of porous paving bordering the parking area, 2) the use of grassy areas that serve as buffers to the southeast of the parking area, and 3) the use of a storm water wetland below the pond. However, additional measures have been taken to further improve the management of storm water and groundwater from the administration building area, and include: 1) capture, infiltration and treatment of roof runoff, 2) additional management of parking area runoff, and 3) improvement in the design of the storm water wetland. These three areas are shown in Fig. 11.6.1. The following sections discuss how the storm water management in these areas can be improved.

Sorm water runoff from the roof of the administration building (Fig. 11.6.2) currently is discharged from roof gutter down-pipes on the east and west sides of the building into concrete open channels. These channels transport the runoff to inlets, and there to underground ducts. The runoff from both sides of the building eventually is discharged into the storm water wetland that is situated downstream from the pond.

The two downpipes (white) are clearly seen. The concrete channel is not visible, but runs along the building to the front wall, then turns 90º west and runs between the two rows of hedges. A small grating can be seen where the channel again turns southward. The concrete channel efficiently collects and transports the roof runoff, but does not allow infiltration and does not improve the quality of the runoff water being discharged. This system has been improved by replacing the concrete channel with an infiltration planter box (Fig. 11.6. 3).

The infiltration planter box increases the infiltration of runoff and improves its quality. Water enters the box through the existing roof downspouts and spreads out into a boxed area. The boxed area contains plants – the existing hedges of the administration building can easily be incorporated into an infiltration planter box constructed along the east and west walls.

The soils next to the building wall within the infiltration planter box are the typical soils of the area and provide the growing media needed for the plants. Underlying the soils on the outer portions of the infiltration planter box is a gravel-filled trench. This trench is sized to store and infiltrate the ‘low-impact' infiltration volume. Runoff in excess of the required infiltration volume is drained by an overflow pipe.

Figure 11.6.1. Area plan, showing storm water and groundwater management areas

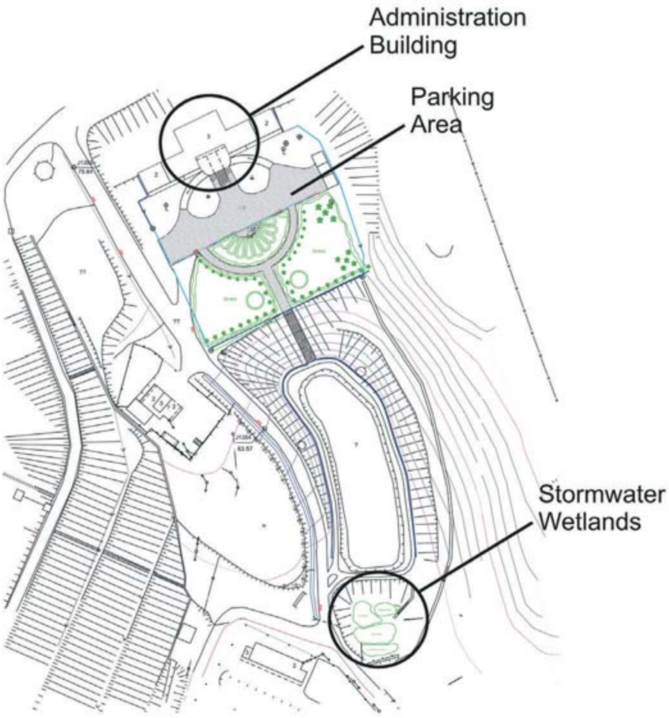
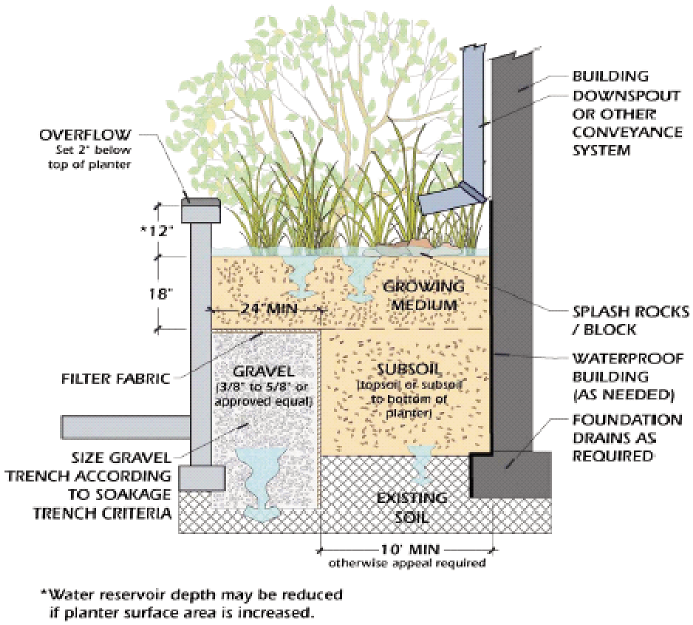


Figure 11.6.2. The western side of the administration building

Figure 11.6.3. Infiltration planter box



The parking area is bordered to the northeast and northwest by two permeable paved areas. Figure 11.6.4 shows the permeable paving in the northeast section of the administration building parking area: square concrete slabs with soil and grass between allowing storm water to infiltrate, thus improving both infiltration and water quality. However, the southern sections of the parking area are paved with brick, which may allow part of the storm water to infiltrate, although most of the storm water becomes runoff.

Figure 11.6.4. Permeable paving - northeast parking area

Storm water wetland. Storm water runoff from the paved portion of the parking area flows southward, collects at the curb, and enters four grated drop inlets. The drop inlets connect with an underground conveyance duct which carries the storm water runoff to the west. The runoff eventually discharges into the storm water wetland below the pond (Fig.11.6.5).

If high flows fill the planting chamber the water ponds on top of the mulch. If this occurs, a notch in the separating wall allows water to flow into the overflow chamber. This prevents flooding of the parking area during times of high flow. The overflow chamber drains to an 18" diameter conduit that connects to a duct, decanting in the storm water wetland.

Figure11.6.5. Storm water wetland

Discussion

Water quality index is greater than 100 indicating the poor water quality of the Shenzhen Xikeng Reservoir before implementing the BMPs. Now, storm water is allowed to infiltrate before it enters the drainage system, through infiltration trenches, grass swales, porous pavements or percolation ponds in upland areas. This will substantially reduce the effect on groundwater of inappropriate, contaminated discharges into the drainage system.

Conclusions

Groundwater is an important natural resource in China, which is used as a primary source of community drinking water and is generally regarded as being fresh. Measures are developed to protect and restore this water reserve by minimising pollutant loading and negative impacts resulting from urbanization, reducing soil erosion and sedimentation problems, maintaining pre-development hydrologic conditions, protecting groundwater resources, and managing aquatic and riparian resources. As a priority for the future, the Shenzhen Water Bureau realises the need to work closely with municipalities to carry out source inventory surveys and assist with best management practices for groundwater based drinking water supplies.

References

Yousef, Y.A., et al. 1985. *Consequential Species of Heavy Metals.* State of Florida. Dep. Trans. Environ. Res. Rep. No. FWHA/FL/BMR-85-286, Bureau Mater.

11.7 'El Niño' impact on water supply and sewage drainage infrastructure in Peru

Ruben Rojas Molina

Abstract

El Niño events in Peru and adjacent countries are characterised by heavy rainfalls in some regions and dry periods and very low temperature in others, causing loss of human life, fishing, agriculture production and damage to transport, energy and water supply infrastructure. During the El Niño event of 1997–1998, the second most destructive event after 1982, the water supply and sanitary systems of cities in the northern provinces of Peru collapsed almost completely, with severe water supply and health impacts. Fortunately, groundwater forms an important part of water resources in this area, which allowed for relatively quick restoration of water supplies and so limited the effects of the El Niño event. In the paper the preventive, mitigation and remediation activities related to El Niño event are described.

Introduction

The 1972–1973 El Niño event contributed to the collapse of the Peruvian anchoveta fishery industry, the world largest at that time. Victor Eguiguren, a climate investigator, reviewed the history of heavy rains registered along the usually dry Peruvian coast. He found the following possible El Niño events during the IXX Century: 1791, 1804, 1814, 1817, 1819, 1821, 1828, 1837, 1845, 1864, 1877, 1878, 1884, 1891. The 'Servicio Nacional de Meteorología e Hidrología' (SENAMHI) registered the following events at the XX Century: 1918, 1925–1926, 1929, 1932, 1939, 1940–41, 1943, 1951, 1953, 1957, 1965, 1969, 1972–73, 1976, 1982–83, 1987, 1991–92 and 1997–98. Looking backward in our history, seems possible that El Niño events could explain the collapse of some pre Inca cultures.

Geographical position and climate in Peru

Peru is located on the west coast of South America, has a surface area of 1.2 millions of km^2 and has 27 million inhabitants (Fig. 11.7.1). The coastal zone covers 10% of the land surface and carries

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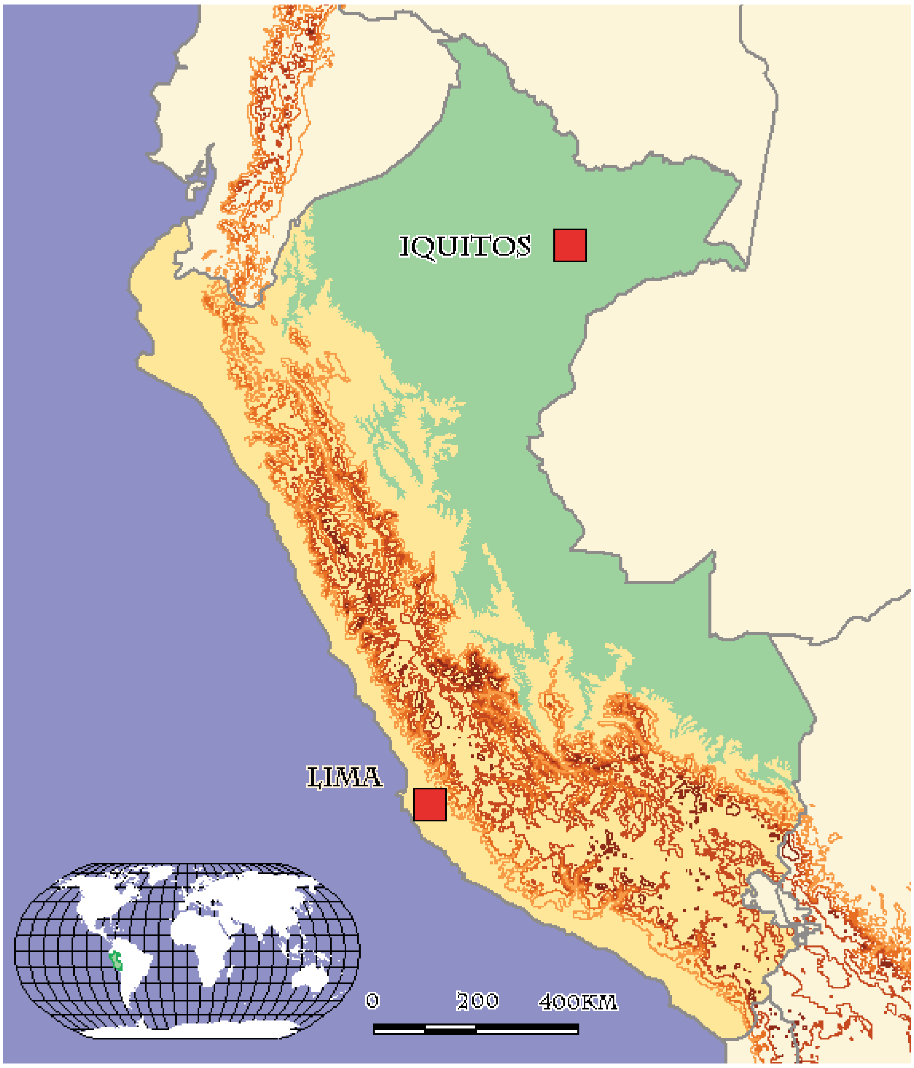
Figure 11.7.1. Geographical map of Peru. Light brown areas: very dry climate, green: tropical forest



about 50% of the country's population, 30% of these in the Lima-Callao metropolitan area. Wedged between the 'Humboldt' cold sea current from the Antarctic flowing up the coast, and the Andes mountains, the narrow coastal strip has a very dry climate (average annual precipitation 30 mm/year), although lying within a tropical zone. The water supply for human consumption and agriculture is normally derived from small rivers that arise in the mountains (*sierras*) and flow to the sea. In El Niño event years the rainfall may reach 2,000 mm in the course of 3–4 months.

The **coastal belt** covers 10% of the country's surface. About 50% of the country's population lives in the coastal area and 30% of these in the Lima-Callao metropolitan area. The narrow coastal strip has a very dry climate (average annual precipitation 30 mm); however, in El Niño event years the rainfall may reach 2,000 mm in 3–4 months. The water supply for human consumption and agriculture is derived from small sierra-born rivers that flow to the sea.

The **Sierra** covers 30% of country's surface reaching 1,000 to 5,000 m. above sea level and carries 40% of the country's population. The climate is semi-arid, annual rainfall varying from 250 to 800 mm.

The **Amazon forests** cover 60% of the country's surface and only 8% of country population. The climate is very hot with an annual rainfall from 1,000 to 2,000 mm.

The **Altiplano** is located at the southern Sierra between 4,000 to 5 000 m above sea level. Its surface covers 20% of the Sierra zone. The rivers flow toward the Titicaca lake located at 3,800 m above sea level. About 5% of the population lives in this area.

The population distribution in Peru is therefore very unbalanced with respect to available water resources. Agriculture is well developed in the coastal area, with the role of groundwater in water supplies is increasing.

Impact of the 1997–1998 El Niño event on the Peruvian environment

Although the El Niño event in 1997–1998 was destructive, there were some positive effects on the environment. The main effects are shown in Table 11.7.1.

Table 11.7.1. Negative and positive effects of the 1997–1998 El Niño event

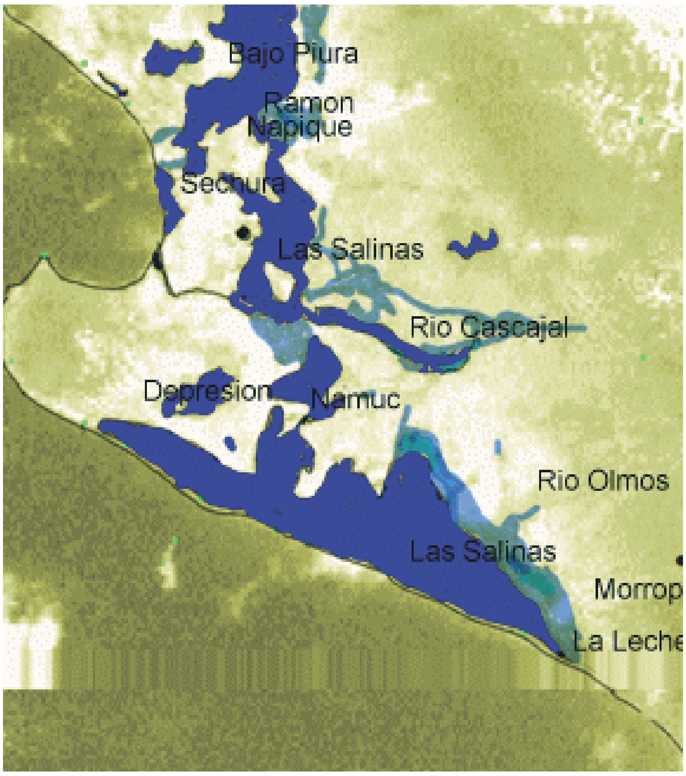
Sector	Positive effects	Negative effects
Drinking water supply and sewage systems	Formation of a large lake in a former desert area. Increase of reservoir storage. Recharge of aquifers.	Damage to water intake structures and equipment. Collapse of potable water supply and sewage infrastructure. Water contamination. Damage of water supply wells. Impact on the environment. Silting up of water reservoirs.
Power	Increase of power generation at some stations	Damage to power generation stations, water intake structures, channels, towers. Decrease in power generation.
Transport		Damage to roads, railroads, bridges, oil and gas lines.
Agriculture	Reforestation of arid zones. Increase of agricultural production in some areas. Increase of biodiversity. Rise in water table. Leaching of saline soils.	Flooding of agricultural lands. Damage to irrigation infrastructure. Decrease of agricultural production. Decrease of storage capacity of reservoirs Decrease of employment in rural areas.
Fishing	Temporary appearance of new species.	Decrease in traditional fishing. Decrease in industrial fish production.
Industry and Trade		Recession in industrial production. Recession in business.
Health		Climate-induced increase in human and cattle diseases Increase in mosquitos and other plagues. Damage to some health facilities.
Housing		Damage to houses and equipment. Migration of people.

The direct and indirect costs of the damage suffered in the 1997–1998 and 1982–1983 El Niño events (adjusted for inflation during the period) was estimated by the ONU-instituted 'Comisión Económica para América Latina' (CEPAL) and 'Corporación Andina de Fomento' (CAF). For the years 1983 and 1998 these amounted to 3,500 and 3,283 Million US$, or 7% and 5% of the GDP of Peru respectively.

Impact on water supply and sewage drainage systems

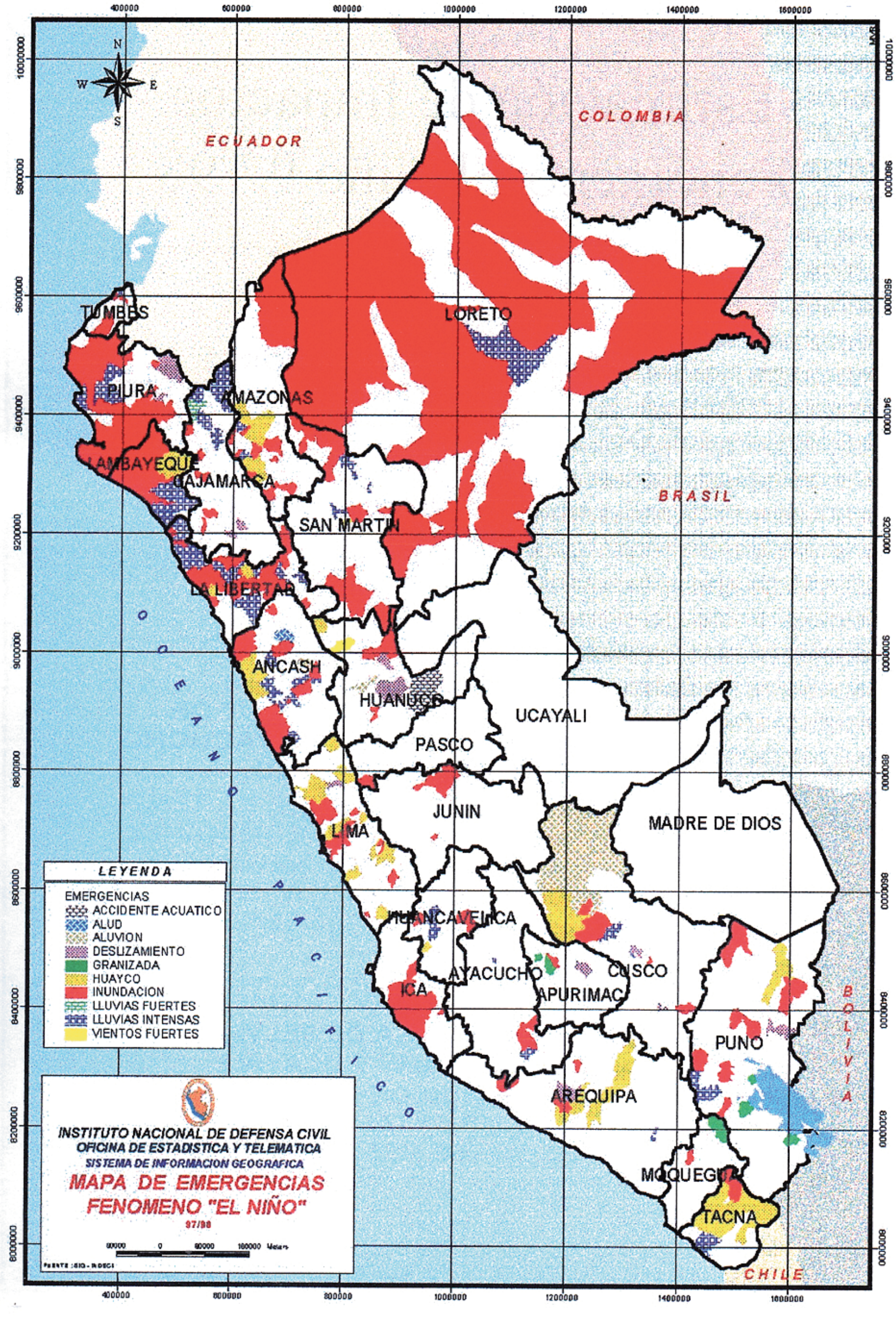
The main damage to water supply and sewage drainage ducting systems occurred in the cities Tumbes, Piura, Chiclayo and Trujillo and 3.8 million inhabitants of the northern provinces Tumbes, Piura, Lambayeque and La Libertad were affected (Fig.11.7.2). Minor damage occurred in the northern provinces Loreto, Amazonas and Cajamarca, mainly because they are less populated (Fig.11.7.3).

Figure 11.7.2. Ephemeral lake (in blue) in the Sehura desert, province of Piura during and after the 1997–1998 El Niño event. The lake has since disappeared, the area returning to desert conditions.



The source of drinking water supply for these northern coastal cities are the rivers of Tumbes, Chira-Piura, Reque, Moche and groundwater from the fluvial water table aquifers located close to the cities. Groundwater is tapped by a number of wells connected to a system of reservoirs and recharged by bank infiltration from the rivers. The sewage drainage system consists of network of concrete ducts.

Figure 11.7.3. Map of the locations damaged by 1997–1998 El Niño event. Source: **Proceso y atención del fenómeno del El Niño 1997–1998,** *Instituto Nacional de Defensa Civil – INDECI, Lima, Perú. October 2003.*



The main cause of the collapse of the water supply systems was the damage to the river water intake structures and the impact of sedimentation on the treatment plants owing to the high discharge rates and high rate of sediment transport in the rivers during the El Niño event. Similarly, the clogging of ducts with sediment was the main cause of the collapse of the sewage drainage system, that was not designed for the drainage of the great mass of water produced by the heavy rainfall during the event. Fracture of the concrete ducting was registered in many places.

Prevention, mitigation and reconstruction work

The government institutions responsible to deal with the prevention, mitigation and reconstruction of damage caused by emergency situations are the "Instituto Nacional de Defensa Civil" (National Institute for Civil Defense). INDECI is one of five national institutions that form a multi-sectoral board named 'Estudio Nacional del Fenómeno del Niño'. ENFEN, in turn, is a member of the 'Comisión Permanente del Pacifico Sur', a multinational board of institutions dealing with the El Niño events.

Five months before the El Niño event of 1997–1998, the scientific community and the Peruvian institutions dealing with El Niño initiated a works development in anticipation of possible damage. The activities in the northern provinces embraced among others: clearing river courses, reinforcing river banks, cleaning road and rail road drainage systems, reinforcing bridges as well as storing of food, medicines, basic domestic requirements and water. Despite these precautions, the magnitude of the 1997–1998 El Niño event caused more costly damage than the unforeseen El Niño in the years 1982–1983. However, without implementation of the preventative measures, the damage could have been much more extensive.

Fortunately, the El Niño events did not significantly affect the water supply reticulation system including water wells, pumps and water tanks. The levels of shallow water table aquifers increased due to the increase of river bank infiltration. However, because several water intake structures were damaged and electric power supply in several places interrupted, distribution of drinking water was curtailed. Repair of affected sewage networks required much more time than the restoration of water supply systems.

Based on the experience of El Niňo impact, the Peruvian government created the above-mentioned national institutions for dealing with El Niño events and established cooperation with private institutions linked to the management of the water resources and with relevant international agencies and scientific institutions. Within the framework of the El Niňo monitoring programme, there is an ongoing investigation of groundwater resources resistant to El Niňo impacts, particularly in coastal areas.

Conclusions

One of the main impacts of El Niño events has been shortage of water supply in urban areas (flood damage to water supply and water treatment facilities) and droughts (decrease in surface water flow and shallow groundwater tables). The best way to overcome the water problem produced by El Niño is to identify and investigate hydrogeological localities suitable for storing water in the ground. Therefore, the protection of recharge areas of such localities became an important part of the Peruvian emergency water policy.

The abundance of water generated during El Niño also present significant benefits. Developing engineering projects to divert flood discharge to areas where the water can be stored on surface, in reservoirs or for enhancing groundwater recharge, will significantly support the agricultural sector. Therefore, future approaches to El Niňo events in Peru have to be focused on the regulation of, and control over, the transient abundance of water to secure economic and environmental advantages from the El Niño phenomenon.

11.8 The effect of the 2004 tsunami on groundwater in the Maldives islands

*Wim van der Linden**

Introduction

The Asian Tsunamis of 26 December 2004 had a devastating impact across the Indian Ocean, causing unprecedented economic, human and environmental damage to those countries in its path. The Maldives, an archipelago of some 200 inhabited atoll islands, with an average elevation of 1.5 m and a maximum land height of just 3 m, whilst suffering relatively small human losses, has per capita received the largest amount of economic damage of any country, with more than 70 islands directly affected with consequential destruction of basic infrastructure services (UNEP, 2005).

Groundwater conditions

Geographical Setting

The Maldive archipelago consists of 1,192 islands on 26 natural atolls. The country's total land area is estimated to total roughly 300 km^2, with islands varying in size from 0.5 km^2 to 5.0 km^2. Only 200 islands are inhabited with 88 islands adapted as exclusive tourist resorts (UNEP, 2005).

Geological Setting

The islands occupy the central portion of the 3,000km-long Lacadive-Chagos submarine ridge, which is a major feature of the Indian Ocean seafloor. They form a double chain of north-south oriented parallel atolls separated by an inner sea. The atolls rest on a submarine plateau that is 275–700 m deep, 700 km long and up to 130 km wide. Several east-west trending deep channels (~1,000 m) separate the atoll groups.

The islands are low-lying and began forming between 3,000 and 5,500 years ago. They represent the most recent deposition along a submarine plateau that is underlain by approximately 2,100 metres of mostly shallow-water carbonates resting on a slowly-subsiding volcanic foundation.

The reef foundations have been in existence for millions of years. The islands, however, are some of the youngest land surfaces on earth. Because of their unconsolidated nature, the islands should be considered ephemeral from the perspective of geologic timescales. Island shorelines consist of sand, gravel,

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A large part of the text of this case study is based on reports from UNEP (2005), Carpenter (2005) and Oude Essink (2005).

and a variety of engineering structures. The country's beach systems are highly dynamic and subject to seasonal conditions, especially from monsoons. Although Maldives is located away from the main pathways of tropical cyclones, the presence of gravel beach ridges and cemented conglomerates attest to the fact that storm waves are an important element in the development of the islands.

Erosion and accretion are, in fact, ongoing processes to which local communities have adapted in the past. Increases in population and the development of permanent infrastructure in close proximity to shorelines, however, have made erosion a prominent hazard to the country's social and economic well-being.

It is estimated that 80% of the islands are one metre or less above sea level. Their low elevation makes them particularly vulnerable to storms and changes in sea level. The prospect of global sea level rise and its potentially catastrophic impact on low-lying islands makes erosion management all the more urgent (Fig. 11.8.1, UNEP, 2005).

Figure 11.8.1. Maldives: Features of the South Asian tsunami (UNEP, 2005)

Hydrogeological Setting

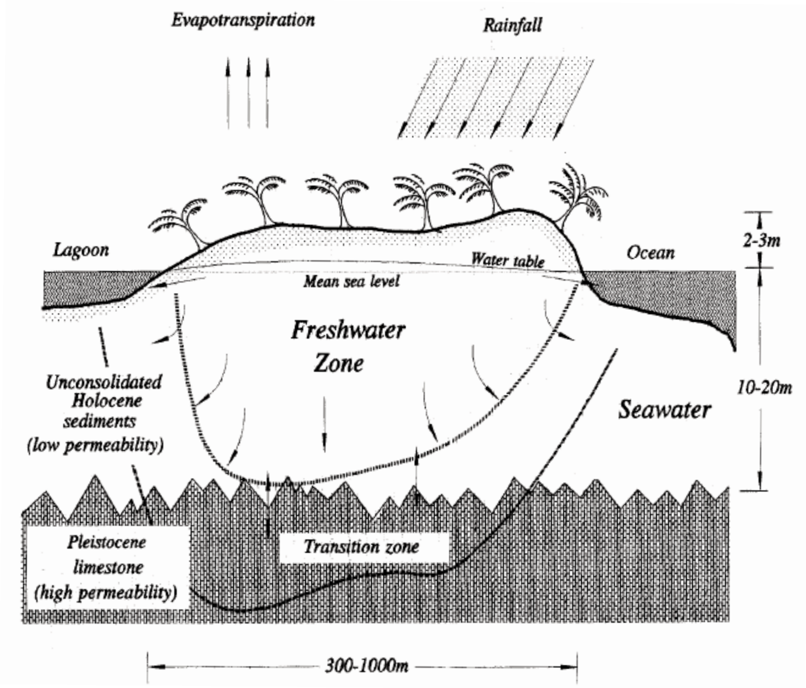
The Maldive islands are composed of limestone rocks covered with a thin sandy soil. A hard pan layer 0.05 to 0.3 m thick exists within the tidal limits of groundwater levels over much of the island. Although this layer is relatively impervious it is penetrated by some hundreds of wells. Below the hardpan there is coarse to medium coral sand with some larger fragments of corals and shells. The thickness of these uncemented layers is 4–5 m or less near the shore, but reaches 12 m or more near the centre. Below this there is generally coral reef structure (Grimmelmann, 1985).

The soils must have a very high permeability for water. Much of the rainfall occurs as intense storms but no signs of erosion were observed, confirming the presumed high infiltration capacity. The hydraulic conductivity (K–value) of medium sized sand should be at least several metres per day. Also the underlying coral bedrock has a high permeability (K–values of at least 5–10 m/day, estimated on the basis of a rough well test) (UNEP, 2005).

Development of the freshwater lens

A proportion of the freshwater falling as rainfall on an island infiltrates and accumulates as fresh groundwater. This freshwater, being less dense than saline seawater, floats on the saline groundwater that infiltrates the island laterally at depth from the sea (Fig. 11.8 2). Because of density differences, a freshwater lens develops, which in general terms is thickest in the centre of the island, where groundwater levels are highest (compared to mean sea level). The typical ratio between the height of freshwater above mean sea level compared to the depth of freshwater below mean sea level is of the order of 1:20. Groundwater levels on small islands may be 0.10 to 0.50 m above sea level, resulting in a freshwater lens depth of 2–10 m thick.

Figure 11.8.2. Schematic conceptual illustration of a freshwater lens (after Falkland, 2004)



The size of the fresh groundwater lenses below the islands depends on the rainfall, the width of the island and the permeability of the aquifer. On small islands the depth is only a few meters, on larger islands the depth is probably to about 10 meters. A too high abstraction of groundwater causes upcoming of saline water, rendering well water unsuitable for drinking (Carpenter, 2005).

Groundwater quality

Groundwater levels in the Maldives islands are shallow and normally lie between 1 and 1.5 metres below the soil surface. The proximity of the groundwater to the island surfaces makes them vulnerable to pollution and contamination from human activities. In addition, population and development pressures have led to increased groundwater extraction, resulting in depletion of the country's freshwater lenses during the past several years by saltwater intrusion. For all of these reasons, the availability of groundwater as a freshwater resource has been limited. According to the *2004 State of the Environment Report*, only 39 inhabited islands had groundwater that was suitable for drinking before the tsunami 2004.

During its 2005 field mission, UNEP confirmed that a number of pre-tsunami conditions, including salinity, washout from sanitary facilities and point source contamination had apparently harmed groundwater supplies over time. Elevated levels of abstraction, for example, had caused seawater to intrude into the freshwater aquifer, increasing salinity levels. Sanitary facilities consist solely of soakpits from which sewage can freely migrate through the highly porous island soil and contaminate groundwater sources. Oil products, fertilisers and pesticides are also contaminating groundwater (UNEP, 2005).

Water use

Water remains one of Maldives most scarce and precious resources, and access to safe drinking water is a challenge. Historically, groundwater was regularly used for drinking, especially during the dry season. A number of major water-borne disease outbreaks linked to polluted groundwater in the 1970s and 1980s, however, led to the introduction of rainwater tanks as the primary source of drinking water. Today, most Maldivians – an estimated 75% of the population – collect water from communal rainwater storage tanks or individual household tanks. If Malé, where drinking water is desalinated, is not considered, the proportion of the remaining population deriving drinking water from rainwater tanks increases to 87% (GoM-UNICEF, 2000). Except during two or three dry season months when rainwater supplies have become too depleted, groundwater is used mainly for non-potable purposes. In most cases, the combined use of rainwater and groundwater has been sufficient to meet normal water demands.

Water is also supplied to some islands by reverse osmosis desalination plants and bottled water. To date, four islands comprising 28 percent of the population (including Malé) have desalinated water available. Desalinization ensures consistently high water quality. It is, however, an expensive option and has much higher operation and maintenance requirements than rainwater harvesting and groundwater extraction. In addition, the overuse of reverse osmosis as a solution to meeting water supply demands can have the long-term effect of encouraging continued mismanagement of groundwater resources.

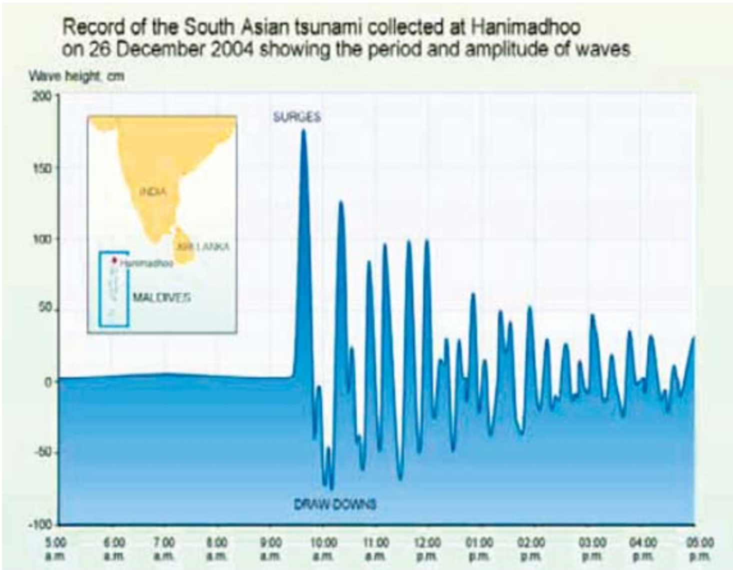
In general, groundwater supplies have been under significant pressure for a number of years. The tsunami 2004, however, clearly increased stress on Maldives water resources. According to reports by the Maldives Water and Sanitation Authority (MWSA), a high percentage of rainwater storage tanks and/or catchment areas were damaged on the worst impacted islands (UNEP, 2005).

Tsunami 2004

Three hours and 18 minutes after the Sumatran earthquake, the tsunami reached the shores of the Maldives islands. Government officials received several reports that, immediately prior to the tsunami's impact, freshwater flowed out of wells and up from the ground.

Sea-level station records reported by the University of Hawaii Sea Level Centre (http://ikai.soest.hawaii.edu) show a southward decrease in the amplitude of the tsunami tidal-record signal from ~1.8m above mean sea level (msl) at Hanimaadhoo in the north, ~1.5 m for Hulhule, Malé in the central region, and ~0.8m for Gan in the south. The sea-level station data are filtered and do not show absolute heights of tsunami (Fig. 11.8.3).

Figure 11.8.3. Record of the South Asian Tsunami showing the period and amplitude of waves (UNEP, 2005)



The Research Group on the December 26, 2004 Earthquake Tsunami Disaster of Indian Ocean (http://www.drs.dpri.kyoto-u.ac.jp/sumatra/maldives/Maldives.htm) reported corrected tsunami heights for 59 locations throughout the Maldives. According to the Group, tsunami inundation heights ranged from 0.65 m in South Malé to 3.22 m in L. Fanadhoo. A maximum run-up height of 4.43 m above msl was measured at L. Fanadhoo. Uncorrected tsunami water levels measured by UNEP showed a range from barely measurable to 3.25 m, with most measurements in the 2.0–2.6 m range.

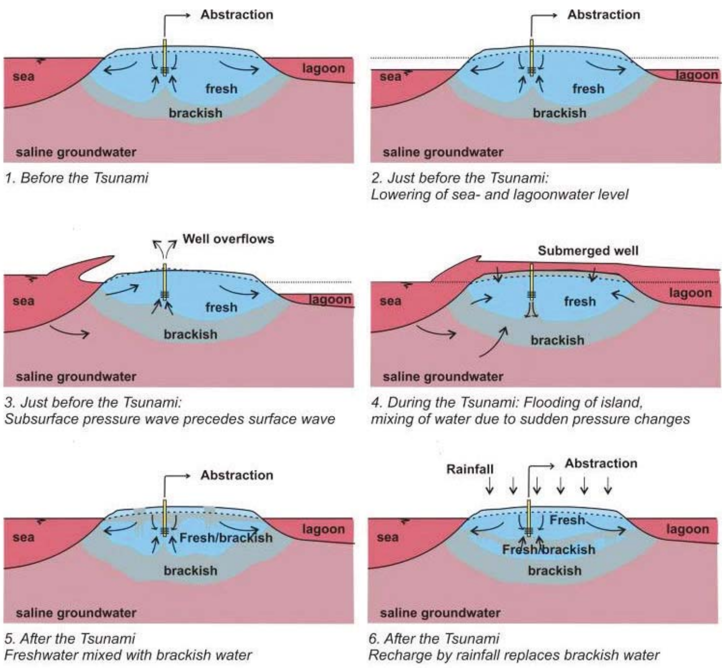
The tsunami's height typically decreased from east to west as it travelled across islands. Many islands reported the tsunami approaching from the west, quite probably because it refracted around the ends of the islands. Eyewitness accounts often referred to several (usually three) waves approaching in rapid succession (30 seconds to minutes) with minimal draining of water between waves. Wave effects were most pronounced on eastern shores, but flooding and damage to coastal infrastructure was widespread among the islands. The tsunami arrived in Maldives during daylight hours near low tide. These two factors probably contributed to a relatively low death toll (UNEP, 2005).

Tsunamis effect on groundwater conditions

Impact on fresh groundwater by flooding

In response to the need of information on the effect by the flooding caused by the tsunamis on groundwater conditions in coastal areas, IGRAC (International Groundwater Resources Assessment Centre, www.igrac.nl) prepared and collected relevant overviews and documents on its web-site. One initiative was to prepare conceptual models of the intrusion of saline water from the surface for different conditions. The modelling of the impact on fresh groundwater of a coral island refers to the situation on the Maldives islands. The sequence of events, which can take place when a tsunami hits a coral island, is demonstrated in six steps (Fig. 11.8.4).

Figure 11.8.4. Impact on fresh groundwater of a coral island during a tsunami

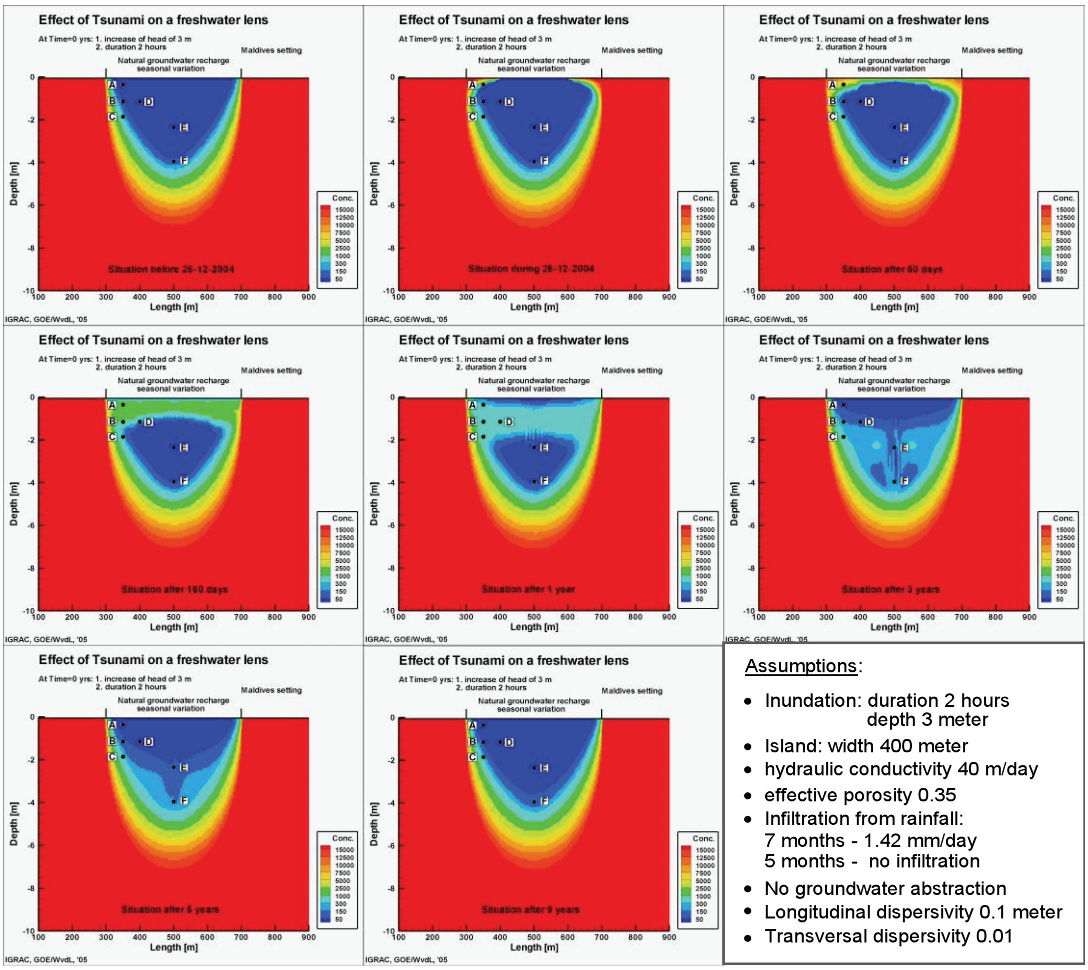


- Before the tsunami: a freshwater lens is recharged by infiltration of rainfall (and also by infiltration of waste water) and is pumped from shallow wells. The abstraction causes an upconing of brackish and saline water, which in case of overpumping results in high salinity levels in the pumped water.
- Just before the tsunami: the water level in the sea and in the lagoon is lowered. This is of a short duration and has negligible impact on the fresh groundwater.
- Arrival of the tsunami: a subsurface pressure wave precedes the surface wave (because the surface wave quickly loses speed when reaching the island) and causes an upward movement of the freshwater lens. Water levels in wells rise. Previously fresh parts of the aquifer turn brackish. Hydrogeological properties (permeability, storage) may change, especially in locations where outflow of groundwater is easy (e.g. at wells or rock fractures).
- During the tsunami: the island is completely flooded and saline water infiltrates through the unsaturated zone especially in areas with permeable soils. Salt water fills wells and enters the aquifer. Other pollutants present on the surface are spread with the water and will also contaminate the groundwater.

- Shortly after the tsunami: the floodwater recedes and saline water remains in pools and puddles, increasing the duration of the infiltration. The saline water mixes with the fresh groundwater and intrudes the freshwater lens in brackish fingers. Pumping of wells will remove the saline water in the infiltrated well, but care should be taken not to attract brackish water by over pumping.
- After the tsunami: rainfall will recharge the freshwater and slowly brackish groundwater will move down to the freshwater/saltwater mixing zone. Gradually the situation before the tsunami is restored. However conditions may have changed (local increase of permeability affects the upconing and the position of the mixing zone) and wells with previously fresh water may now be brackish.

The concept of intrusion of saline water in a freshwater lens was simulated using a 2-D numerical model. The intrusion shows as a brackish front moving through the freshwater lens. The lens itself remains intact, but a front of brackish groundwater passes through the lens. An important feature of this (worst case) concept is that after the tsunami passes the islands, a certain amount of sea water remains on the land. That salty water intrudes into the ground, and will pass through the aquifer the moment rainwater infiltrates into the subsoil. In this concept, we assume that during the dry season of 2005 the amount of rainfall is 10% of an average wet season and that dilution of sea water with rainwater results in a concentration of infiltrated water of 12,000 mg Cl^-/l. Hydrodynamic dispersion causes the mixing of fresh, brackish and saline groundwater. Figure 11.8.5 shows the results of one out of several simulations.

Figure 11.8.5. Example of brackish groundwater moving through a freshwater lens (Oude Essink, 2005)



The positions A-F, indicated in figure 11.8.5, represent wells at various locations and different depths. The salinity of the groundwater in a well close to the surface (e.g. well A at −0.35 meter below mean sea level) increases in the first weeks after the intrusion and returns to the original value within a few years. With depth, the increase in salinity is retarded, as well as the return to the original value. How fast exactly depends on factors as the magnitude of the hydraulic conductivity as well as the rate of recharge of freshwater during the monsoon. After the tsunami the shollower the well, the larger the increase in concentration.

Several numerical simulations with different sets of parameters were prepared. The parameters varied were: hydraulic conductivity 10 and 40 m/day, tsunami duration 2 and 4 hours and flood depth 3 and 5 meter, island width 400 m, 1,000 m and 2,000 m. Also the concept with no sea water remaining on the land has been considered. A lower hydraulic conductivity reduces the intrusion of sea water into the aquifer.

Conclusions

Based on the simulations, it can be deduced that the duration of the inundation was probably long enough to contaminate the freshwater lens with sea water in some way. This may result in contaminated sections of the freshwater resources persisting for at least several years (depending on the hydrogeological conditions and not taking other negative factors into account). A front of brackish groundwater passes through the freshwater lens and chloride concentrations go up significantly, especially at the upper part of the freshwater lens. The increase in chloride concentration will probably reach values higher than WHO-standards for drinking water (Oude Essink, 2005).

Field observations

The unavailability of historical baseline monitoring data for most islands visited by UNEP in 2005 made it difficult to distinguish definitively tsunami-related impacts on groundwater quality from historical pollution. It is clear, however, that freshwater lenses were significantly affected by the tsunami throughout the impacted islands. The tsunami's high waves and flooding caused sea water to intrude and infiltrate groundwater resources horizontally, due to increased sea level, and vertically into the ground in flooded areas. Fresh water was forced up and out of some wells, whilst others were inundated by floodwater.

Groundwater supplies experienced high levels of salinity and faecal coliform contamination. Sewerage systems are generally located close (within 5–10 metres) to private wells that supply water for bathing, and for washing food and dishes. UNEP found minimal evidence of damage to sanitary facilities, suggesting that microbial contamination of groundwater supplies, though undoubtedly worsened by the tsunami 2004, was a serious pre-existing and chronic problem. Nevertheless, it is clear that the tsunami flushed out waste and sanitary installations, very probably worsening groundwater quality significantly (Fig. 11.8.6).

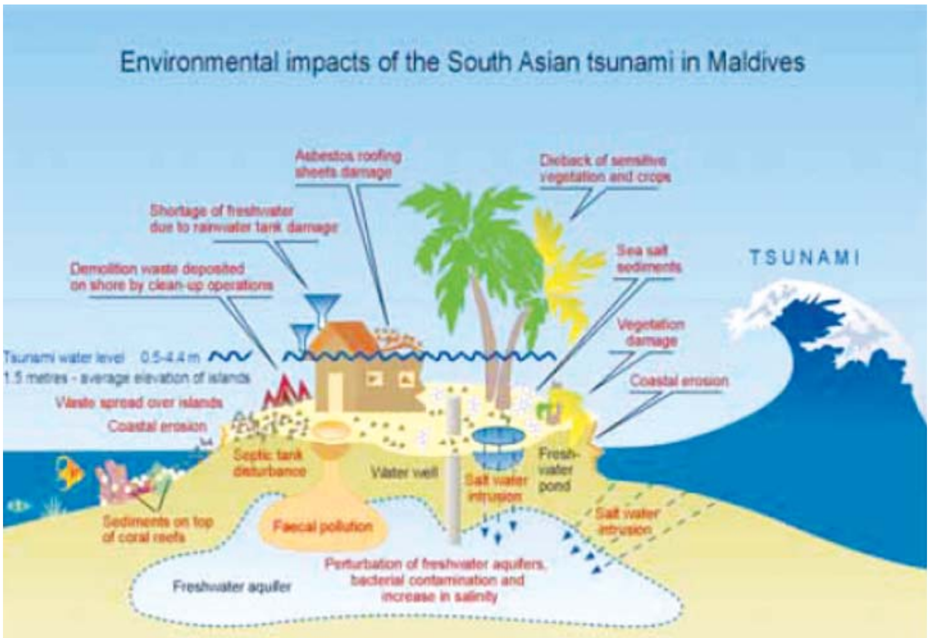
Most of the groundwater wells UNEP inspected had not been destroyed. Some wells in the southern part of the country (L. Fonadhoo, L. Gan), however, had been constructed using concrete made with coral sand and were destroyed. In highly affected areas, especially areas with damaged and abandoned buildings, demolition waste and household waste was found in the wells. The waste left in wells poses a potential risk to public health and could very well further spread contaminants (e.g., nitrates, ammonium, biological contaminants) to the aquifer. The contaminated wells may also provide breeding grounds for disease vectors such as mosquitoes.

The government has reported that pressure from the tsunami buckled house floors upward, a phenomenon observed by UNEP. This would seem to confirm the high permeability of the subsurface and a direct connection between groundwater and the surrounding seawater.

On some of the islands UNEP visited (e.g. HA. Filadhoo), the tsunami waves washed off topsoil. On others (e.g., M. Kohulfushi), flooding partly covered the topsoil with sediments and sand. Overall, however, the tsunami had only a slight impact on topsoil.

By far the worst effect on soils was the extent to which the tsunami deposited salt from seawater. The change in soil composition impacted local vegetation and agricultural productivity and home food gardening. FAO has reported, however, that by March 2005 there had already been enough rain to leach most of the imported soils from root zones. The remaining salts can be expected to leach out after additional rains during the monsoon season (UNEP, 2005).

Figure 11.8.6. Environmental impacts of the tsunami in the Maldives (UNEP, 2005)



Actions taken

Immediate relief

Following the tsunami relief efforts concentrated on the supply of drinking water. Bottled water was sent to the islands with no available fresh water supply. Desalinisation plants were installed also to provide fresh water.

Assessment of groundwater conditions

The assessment of the groundwater conditions after the tsunami was initially conducted as part of general assessment studies. UN-supported surveys started within days after the tsunami and continued during 2005. An overview is provided in UNEP (2005). A specific water resources survey was commissioned by WHO at the request of the Maldives Water and Sanitation Authority (MWSA) in July 2005 (Carpenter, 2005). The objective was to study the tsunamis impact on water resources and to study sustainable water sector recovery strategies. Three islands were selected for detailed surveys: Kulhuduffushi, Dhidhdhoo and Filladhoo.

Carpenter (2005) noted the following, based on visits to these three islands:

- The priority water supply for reasons of quality and sustainability has to be rainwater harvesting. This is widely practiced but can be improved to increase the roof area being utilised, storage tank volume and re-routing of excess rainwater into household wells. Fresh groundwater is widely available in Kulhuduffushi (70%) and Dhidhdhoo (80%), although is presently non-existent on Filladhoo. The potability of the groundwater on the Kulhuduffushi and Dhidhdhoo is affected more by inadequate sanitation than the tsunami. Improvements in sanitation would enable groundwater to be used for potable uses island wide. At present when the rainwater tanks empty, most households take potable water from the communal mosque wells. Boiling of groundwater or other treatment (e.g. chlorine dosing using bleach) would enable most (60%) of the groundwater to be used for potable activities on Kulhuduffushi and Dhidhdhoo.

- It is recommended infiltration galleries be used during the dry season for improved groundwater abstraction connected to reticulated or communal standpipe systems. The galleries need to be surrounded by groundwater protection zones (50–100 m wide) to ensure sewage contamination does not reach them. Sports/playing fields should be investigated on a site specific basis as future infiltration gallery locations.

- 37 desalination plants have been brought into the country as part of the emergency response to the tsunami, and for some islands (e.g. Filladhoo) these provided the only source of freshwater until the wet season allowed rainwater harvesting to recommence. The use of desalination outside of Malé and tourist resorts is however considered to be problematic in the medium to long term, with almost all islands lacking the technical and financial resources to operate and maintain the equipment. Spare parts, fuel, and communal management systems for this type of infrastructure are all absent on the islands. The use of desalination as anything other than an emergency response option is considered unsustainable

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Lessons learned

The hydrogeological conditions at the Maldive Islands yield shallow and vulnerable groundwater resources. Alternative groundwater resources are not available and water supply is already augmented by water from rainwater harvesting and desalinisation. The groundwater is already under much stress from abstraction and pollution and the available resources on most islands are insufficient to meet the increasing water demand.

In times of urgency, such as immediately following the tsunamis water supply for drinking purposes is organised from bottled water or from (mobile) desalinisation plants. Such measures are a solution in coastal areas where alternative safe and good quality groundwater resources are unavailable. This method of supply is expensive but the hydrogeological conditions leave no choice. With time previously existing water supply systems may be restored and replace such costly emergency measures.

The events after the tsunami in the Maldives indicated two important aspects, which are essential in preparation for future tsunamis:

1. Availability of historical groundwater data.
   An accurate assessment of the impact of the seawater flooding on groundwater resources is possible only when data is available:
   - From regular monitoring of groundwater levels and water quality.
   - Regarding the hydrogeological conditions and properties of the sub-surface of the islands.
2. Organisational infrastructure for groundwater management.
   Actions to undertake surveys on tsunamis impact and to determine measures to improve groundwater supply conditions can be organised swiftly and with little outside support in case of an existing management structure with clear responsibilities for groundwater resources management and up-to-date groundwater expertise.

References

Carpenter, 2005. *Water Resources Tsunami Impact Assessment and Sustainable Water Sector Recovery Strategies.* WHO mission August 2005.
http://w3.whosea.org/EN/Section23/Section1000/Section2091.htm

Falkland, 2004. *Groundwater Investigations for K. Kaashido and A.A. Feridhoo and Design of a Pilot Infiltration Gallery.* WHO and MSWA.

Grimmelmann, W.F. 1985. *Initial assessment of groundwater resources on small islands.* In: Water resources of small islands: technical proceedings (Part 2) of the Regional Workshop on Water Resources of Small Islands, 27 June - 9 July 1984, Suva, Fiji. CSC, London: 290-304.

Oude Essink, G.H.U., van der Linden, W. Feb 2005. *Impact of the 26-12-04 Tsunami on groundwater systems and groundwater based water supplies.* TNO report 2006-U-R-172/A

UNEP, May 2005. MALDIVES: *Post-Tsunami Environmental Assessment*
http://www.unep.org/tsunami/maldives_rpt.asp.

Tsunami impacts and rehabilitation of groundwater supply: Lessons learned from Eastern Sri Lanka

11.9

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Abstract

This case study reviews the outcomes and experiences gained from comprehensive research and support work in Sri Lanka related to the impacts on groundwater and the destruction and rehabilitation of the local water supply systems after the December 26, 2004 Indian Ocean tsunami. An overriding problem was the flooding of 75% of the highly populated coastal areas of Sri Lanka, and the saltwater entry into soils, groundwater, and open wells, the latter traditionally the backbone of local water supply. The salinity imprints of the tsunami on groundwater and water supply were detectable up to 1.5 years after the tsunami. The primary remediating agent of groundwater salinity was found to be the natural rainfall and ambient groundwater flow and not the intensive pumping campaigns conducted in the aftermath of the event. Immediate relief and interim alternative solutions were provided from a host of actors who should be commended for an immense and effective effort that ensured an uninterrupted supply of freshwater to the great number of affected coastal communities. Apparent shortcomings in the water supply rehabilitation were related to a focus on salinity rather than pathogenic contamination, and towards well water cleaning rather than on primary information and consultation/involvement of affected populations. Recommendations for addressing similar flooding events from a water security point of view are given including reference to a set of guidelines developed as part of this work for the cleaning and rehabilitation of drinking water wells and groundwater protection after saltwater flooding events.

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Introduction

Huge devastation and human tragedy followed the December 26, 2004 tsunami in the Indian Ocean. After Indonesia, Sri Lanka was the second-hardest hit, with an estimated death toll of approximately 35,000 people. Of immediate concern after the catastrophic event was the destruction of the traditional water supply system in the rural and semi-urban areas of the coastal belt. This was, for 80% of the population, based on private shallow open wells (Leclerc et al., 2008). Practically all wells within reach of the flooding waves (up to a couple of km's inland) were inundated and filled with saltwater and contaminated with solid matter (sediment, waste), pathogens and other unknown chemicals, leaving the water unfit for drinking (Fig. 11.9.1a). The density of wells in these areas is high, up to 600 per km^2 and the total number of affected wells in Sri Lanka was estimated at half a million while the total number of people affected by disruption of their water supply from wells was in the range of 2.5 million (Villholth et al., 2008). The local villagers reported that the water level rose to near the tops of the coconut palm trees (approx. 5 m). Approximately 75 % of the coastline of Sri Lanka was impacted by the tsunami. It was obvious that salinity imposed a pressing constraint on drinking water, simply based on the criterion of taste. On top of this, pathogenic contamination was inevitable because of the concomitant flooding of pit latrines, which often are located in close proximity to the wells (Fig. 11.9.1b), and because of a general mixing of water during the inundation (ACF, 2006).

When extracting lessons learned from the case presented by the tsunami in Sri Lanka in the context of the GWES project, it is important to realise that no resistant, well-protected groundwater resources existed in the coastal areas, or even further inland (Villholth and Rajasooriyar, 2009), which could form the basis for alternative relief water supply. The challenge was therefore to assess the impact on the shallow and unconfined sandy aquifers, provide provisional water from other freshwater surface water sources inland or from coastal groundwater left unaffected by the tsunami, to protect the groundwater from further deterioration resulting from the tsunami and devise methods to enhance the recovery of the aquifers.

Intense efforts of well cleaning were initiated by local authorities, NGO's (non-governmental organisations), international aid organisations, incoming volunteers and individual well owners immediately

Figure 11.9.1a,b. Tsunami 2004 impact on an open well and the general devastation of the coastal area in east Sri Lanka (a: Courtesy Karen Villholth; b: Courtesy Scott Tylor and Jayantha Obeysekera)

after the event in an attempt to quickly restore pre-tsunami water quality conditions. However, due to the emergency character of the situation and the lack of technical knowledge, the methods applied were quite ad-hoc and haphazard, and poorly documented and monitored. Limited data suggested that the cleaning and repeated emptying of wells did not have the expected positive impact on salinity (Leclerc et al., 2008; Lytton, 2008; Villholth et al., 2008; Lipscombe, 2007; Fesselet and Mulders, 2006; Clasen and Smith, 2005). It was realised that to optimise efforts and resources devoted to the relief and rehabilitation process, proper understanding of the problem and best and most efficient practices had to be developed (Lytton, 2008).

The objective of this paper is to present the experiences and outcomes of a comprehensive and integrated approach to supporting the restoration of the groundwater-based water supply and the drinking water quality after the tsunami in Sri Lanka.

Methodology

The approach involved short-term support to the water supply relief efforts, initiated immediately after the tsunami 2004 as well as a more long-term research to increase the understanding of the processes related to saltwater flooding and the implications for best practices for groundwater quality restoration and well water supply rehabilitation.

The following activities were initiated:

1. On-the-ground guidance on well cleaning and awareness raising on water salinity issues;
2. Monitoring of salinity and other water quality parameters in wells in affected areas;
3. Household survey of perceptions of water quality aspects and remediation of water supply;
4. Detailed studies of the physical processes related to saltwater flooding in coastal-near regions and the impacts of groundwater pumping and natural flushing on water quality restoration;
5. Development of a set of internationally endorsed guidelines on well cleaning and groundwater protection after saltwater flooding.

On-the-ground guidance of well cleaning and awareness raising on water salinity issues

It was clear that well cleaning was a major challenge. Procedures were carried out in an uncoordinated and haphazard manner with limited understanding of the physics of groundwater and wells and the possible risks associated with the cleaning procedures, such as physical instability of the well, ingress of contaminated water from other areas, e.g. from toilet pits, burial grounds or from accumulated salty surface water, and saltwater up-coning from below. Furthermore, the repeated pumping of wells diverted important human resources from other emergency relief tasks. The most common well cleaning practice entailed a simple procedure of emptying the wells by using electric pumps and discharging the saltwater next to the wells. Wells were cleaned and chlorinated repeatedly (Keba, 2006), up to five times during the 16 months following the tsunami (Villholth et al., 2008). However, excessive pumping and the recycling of the discharged saltwater may have retarded the rehabilitation of the freshwater conditions (Vithanage et al., 2009). Although limited observations showed slow or no beneficial effects and concerns about over-pumping and seawater intrusion were raised, pumping continued unabated for a long time.

Part of the confusion related to well cleaning arose from the lack of easily available well cleaning guidelines (Illangasekare et al., 2006; Clasen and Smith, 2005, Villholth et al., 2005). No formalised guidelines existed that were relevant and appropriate for the situation encountered after a tsunami disaster. The existing emergency guidelines for cleaning of open shallow wells either addressed the problem of wells being contaminated after flooding with dirty freshwater, and related more to the problems of microbiological contamination (e.g. WHO, 2005; CDC, 2008), or improperly addressed the problem of saltwater flooding (NGWA, OXFAM). These guidelines recommended the purging, or emptying, of the wells to remove contaminated water prior to and after a chlorination step and/or advised to continue pumping until the well water becomes clear and free of saltwater. Such methods may work in some cases (Vrba and Verhagen, 2006), but best remediation strategies have to hinge on specific assessment of each case and associated monitoring and possibly backed up by numerical modeling.

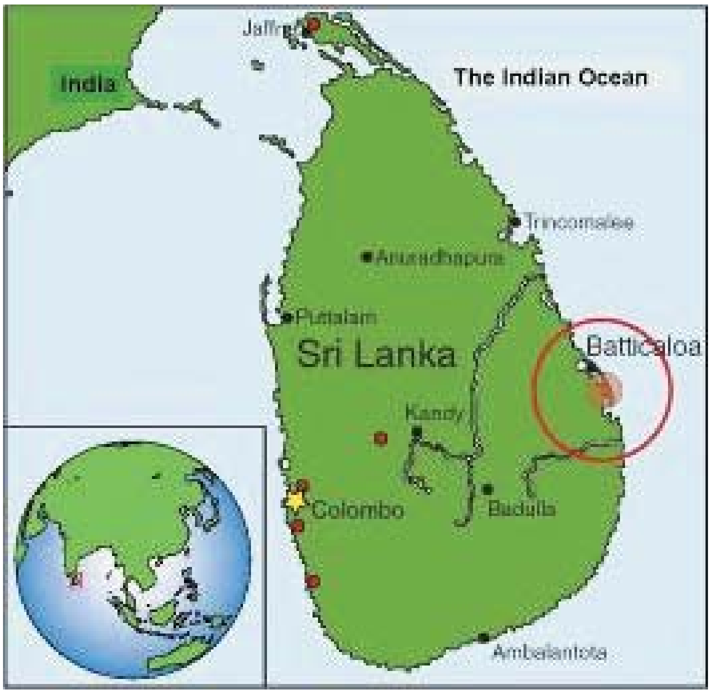
The International Water Management Institute (IWMI), with headquarters in Colombo, Sri Lanka, facilitated the well and water supply rehabilitation efforts:

1. Participation in and contribution to various meetings related to water and sanitation (WATSAN) rehabilitation, at local and national level, targeting various partners and stakeholders: the national WATSAN coordination unit of international donors and relief organisations, national and local authorities, and local and international NGO's. Contributions included inputs to discussions, delivery of information on the potential impacts of the tsunamis from saltwater flooding, the physical processes involved in saltwater-freshwater interactions in coastal-near areas, best practices for well cleaning in terms of salinity remediation, and potential risks and adverse impacts of faulty procedures.
2. Information sharing and coordination of on-going activities related to the saltwater contamination and rehabilitation of water supply, to incoming and existing partners.
3. Development of workshops for local health workers involved in the provision of safe drinking water and the development of joint guidelines for water pollution remediation, well cleaning and groundwater protection after the tsunami (IUCN, 2005; UNICEF, 2005). Dissemination of adapted guidelines for staged well cleaning and groundwater protection during the aftermath of the tsunami (Villholth, 2007; Villholth et al., 2005).

Monitoring of salinity in drinking water wells in affected areas

A monitoring program was initiated in three representative villages on the east coast of Sri Lanka (Fig. 11.9.2), with a rudimentary first sampling taken one month after the tsunami, followed by a systematic and more comprehensive monitoring program covering a total of approximately 150 wells, mostly shallow (average depth 3.4 m) open drinking water wells (Villholth et al., 2005). The shallow unconfined aquifer system in these areas is developed in the coastal sediments dominated by Quaternary unconsolidated sand deposits intermixed with more fine materials, on the top of Precambrian metamorphic rocks (Panabokke and Perera, 2004; Cooray, 1985). The bedrock, consisting of granitic rock of the Precambrian metamorphic basement (the Vijayan complex), is found at around 15–25 m depth (Wickramaratne, 2004). The underground freshwater is delimited by a saltwater wedge entering from the seaboard, limiting the overall availability of freshwater in these systems, which in many cases is also limited by more or less brackish lagoons on the inland side (Fig. 11.9. 2). Hence, these coastal groundwater systems are naturally vulnerable to salinity problems, even in the absence of tsunamis. Average annual rainfall experienced in the area varies between 1,000–1,700 mm. Eighty percent of the annual rainfall falls in the north-east monsoon period from November to April (Panabokke et al., 2002).

Figure 11.9.2. Study area in east Sri Lanka



Household survey

A household survey was conducted in the same areas as the salinity monitoring program in order to gain insight into the conditions prevailing in the villages with respect to the relief water supply, the water quality, the implication for daily routines related to water use, and the perception of the affected population regarding these matters. The survey was conducted in two rounds (in Apr./May of 2006 and Jan./Feb. 2007, corresponding to 16 months and 2 years after the event, respectively) in the same 120 households – 60 in each of the two most heavily impacted villages. The first survey took place during the phase of rehabilitation where tankered water constituted the major source of drinking water supply and alternative to shallow wells, and the second survey was conducted after the discontinuation of the emergency supply and after the population partially returned to use their wells (Villholth et al., 2008).

Detailed studies of the physical processes related to saltwater flooding

Field, laboratory and numerical modeling experiments

Laboratory and numerical experiments were conducted using uniform homogeneous media and hydraulic conditions representing sandy aquifer settings in a flat terrain similar to the east coast of Sri Lanka, with hydraulic conductivity in the range of 1e-4 to 6e-3 m/s and a hydraulic gradient of 1% (Goswami and Clement, 2007; Goswami et al., 2007; Hogan et al., 2006). A detailed model description and calibration was not attempted due to the lack of data and information about necessary boundary and initial conditions such as the initial conditions at the time of the tsunami (e.g. groundwater level, soil moisture content), the stress function related to the tsunamis waves (e.g. height and number of the waves, duration and extent of inundation(s), and exact mechanisms of saltwater entry). Laboratory experiments were conducted to visualise the general post-tsunamis sub-surface flow, transport and mixing patterns and processes under representative conditions and to investigate some of the factors influencing the processes. In addition, numerical modeling was conducted using the variable density groundwater model SEAWAT (Langevin and Guo, 2006). The model was validated by successfully simulating a concentration breakthrough curve from a saltwater tracer injection experiment in a three dimensional tank (Goswami et al., 2007).

Field investigations of the comparative process of recovery of the groundwater quality in undisturbed and disturbed areas

This part of the study investigated the chemical characteristics of the shallow post-tsunami groundwater in two areas: an uninhabited area undisturbed by pumping and cleaning and a nearby village where cleaning of wells and domestic use after the tsunami occurred. The two areas were located within 500 m distance in the same overall study area encompassing the monitoring program (Fig. 11.9.2). The water quality was monitored in the disturbed site in twelve existing affected open wells (out of which four were abandoned, i.e. not in use after the tsunami), and in the undisturbed site the quality was measured on samples from twelve shallow purposely drilled piezometers in the affected zone. The wells were located on two separate transects transversing the 2 km land strip from the sea to the inland lagoon (Vithanage et al., 2009). The monitoring of water quality was performed at least three times for electrical conductivity (EC) and other chemical parameters, over a year, from October, 2005 to October, 2006.

Results

Monitoring of salinity in drinking water wells in affected areas

The results of the monitoring program showed that (Villholth, 2007; Villholth et al., 2005):

1. The inundating waves had reached up to 1.5 km inland and 39 percent of the wells from the coast line were flooded by the tsunami waves,
2. The impact varied between sites, probably depending on the specific initial force of the tsunami waves, and differences in topographic and coastline characteristics,
3. The groundwater was affected only in those areas flooded by the tsunami waves with some local spreading trends,
4. The areas remained impacted by elevated salinity for up to 1.5 years after the tsunami 2004, by which time the impacted wells had on average reached the same levels as the unaffected wells (Fig. 11.9.3),
5. Reductions in average salinity levels are visually correlated with rainfall, indicating that rainfall was a primary agent for restoration of the aquifers and the well water salinity (Fig. 11.9.3).

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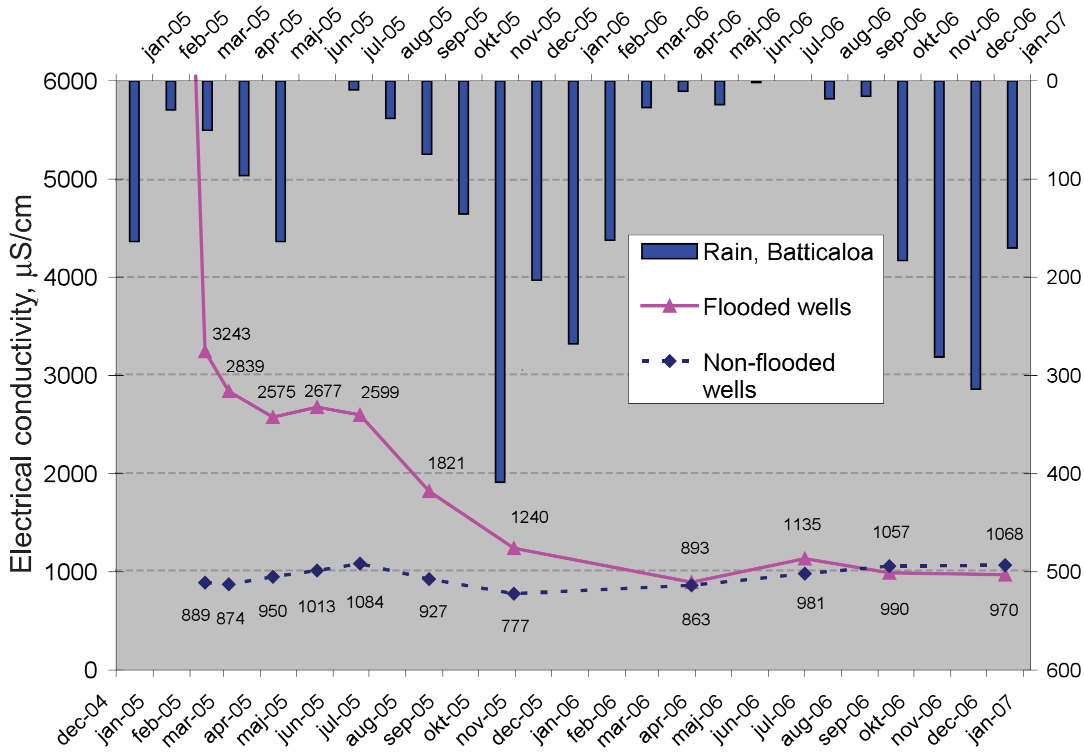
These findings are in line with those of Lytton (2008), Leclerc et al. (2008), and Fesselet and Mulders (2006). The prolonged elevated salinity levels in the wells indicated that the pumping and cleaning of wells did not have the overall intended impact of rapidly restoring the wells to pre-tsunami drinking water quality. Furthermore and very importantly, the data suggest that despite prolonged effects and possible non-optimal cleaning and pumping procedures, the aquifers have not suffered permanent and irreversible salinity damage.

Figure 11.9.3. Average well water salinity and monthly rainfall after the tsunami in the Batticaloa area in eastern Sri Lanka. Non-flooded wells are assumed to represent the background salinity level (from Villholth, 2007)



Household survey

The salient findings of the household survey showed that:

1. Basically, all the households used their wells prior to the tsunami 2004 as their main/sole water supply and were quite satisfied with its reliability and water quality. Practically all wells of the households investigated (94.2%) were flooded and salinised by the tsunami
2. Salinity was perceived as an over-riding immediate problem and constraint for the use of wells for drinking water provision. However, superstition and indefinite fear was also associated with the reluctance to using the wells just after the tsunami. Well cleaning, in addition to a perceived physical cleaning, had a psychological impact, supposedly cleansing the water of the evil imprint of the tsunami
3. No unsafe (unprotected) water sources were used just after the tsunami. This, in combination with a major focus on hygiene just after the tsunami meant that infectious deceases did not prevail in the immediate aftermath
4. Many people (approximately one quarter of respondents) expressed health problems after the tsunami related to the water supply, reporting skin rashes and diarrhea as the main problems, in the 1st and 2nd survey, respectively. Skin rashes were interpreted as being caused by excessive and injudicious well chlorination just after the tsunami and later incidences of diarrhea to be due to diminished attention to hygiene later after the relief phase
5. People coped with the lack of access to traditional well water by various means: saving water, sharing 'good' wells, improving hygienic practices to avoid water-related diseases, using various water sources for different purposes, e.g. water for drinking and cooking from tankers and well water for washing and cleaning.
6. Alternative water sources, especially the tankered water, did not provide a consistent and reliable

source and acceptable quality of water (also found by Keba (2006)). Sometimes the chlorine taste was objectionable to the users and the supply falling short of demand

7. Two years after the tsunami, approximately half of the households (46%) still did not use their well for drinking but resorted to using neighbours' wells or public stand posts happening to give freshwater, while they had reverted fully to using their own well for purposes of bathing and washing and partly for cooking. When asked for their reason for not using their well for drinking at this time they still reported salinity as their main cause of concern. This result shows that after the major relief and rehabilitation efforts had terminated a large fraction of the population continued to face problems or concerns regarding their drinking water supply
8. The focus on salinity as part of the rehabilitation efforts may have been exaggerated, purveying the erroneous impression to the users that salinity was a critical health problem. This may in turn have retarded the acceptance of the people returning to the use of their wells for drinking when in fact salinity levels were not higher than levels accepted pre-tsunami. This focus may also have diverted continued efforts of securing hygienic practices. In addition, people may have become accustomed to better quality water and hence were reluctant to use water of a quality which before the tsunami was acceptable to them
9. People were unclear about the process of rehabilitation of their water supply, e.g. the timing of the discontinuation of the tankering and the safety of returning to their wells (finding supported by Keba (2006)).

There was a general need for more and balanced information to the affected people, in terms of the impacts on their wells, water quality and health considerations, the implications of cleaning, disinfection, the use of wells along with the provision of alternative sources, and the timing and process of the return to well use. These information activities could have been more interactive and participatory through parallel and integrated surveys extracting and applying the immediate perceptions of the people and using local champions as disseminators, multiplying messages. This would yield more confidence in the rehabilitation support and a smoother transition from relief to rehabilitation, to gradual recovery of livelihoods and 'normal life'. In addition, the results indicated that there was a general lack of competence in the more technical aspects and coordination of e.g. well cleaning, and chlorination of wells and tankered water. Had efforts been prioritised, rationalised, and targeted some resources devoted to repeated well cleaning could have been better spent in such activities.

Detailed studies of the physical processes related to saltwater flooding

Field, laboratory and numerical modeling experiments

Results obtained from the combined numerical and laboratory experiments included:

1. The numerical model successfully reproduced the patterns of saltwater movement from the simultaneous entry from the ground surface and through wells, as observed in the laboratory (Goswami and Clement, 2007)
2. The saltwater from the various sources of saltwater entry migrated as separate plumes, in the lateral and vertical direction towards the coast (Hogan et al., 2006)
3. Stability of the saltwater plumes and mixing with contiguous freshwater depended on the ambient groundwater flow rate. Stability was found to increase with flow rate, resulting in less mixing of freshwater and saltwater (Hogan et al., 2006)
4. Saltwater from the plumes migrated towards the coastal saltwater wedge and moved over the freshwater-saltwater interface without any noticeable mixing (Hogan et al., 2006)
5. A major fraction of the saltwater that was injected into the wells rapidly and naturally descended as a large slug or plume from the bottom of the wells leaving only some residual saltwater in the well (Hogan et al., 2006).
6. Early pumping of a contaminated well (within a week) and removal of discharged water signi-

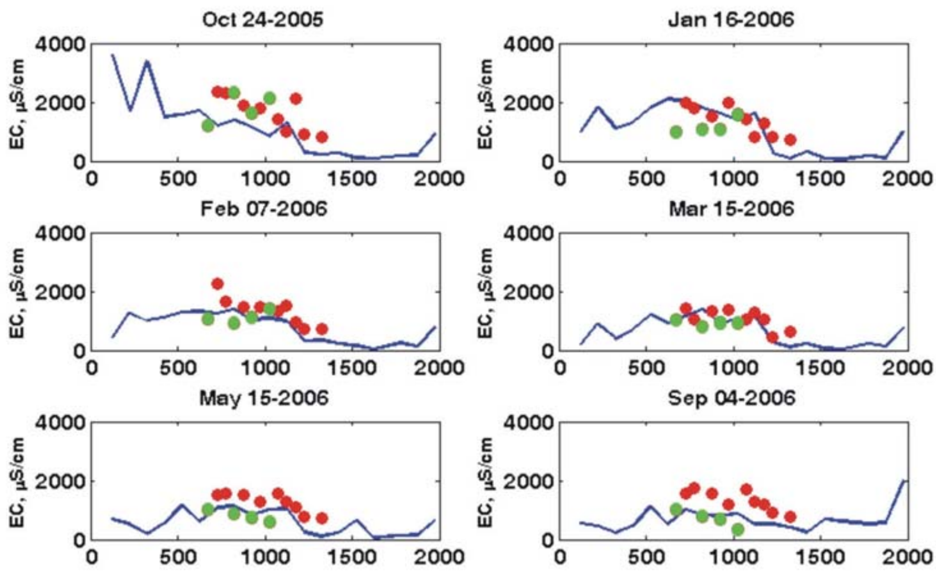
ficantly reduced well salinity. However, even without pumping the salinity declined, partially due to the sinking and dispersion of the saltwater from the well. Pumping conducted at a later time would at best result in a temporary and minor reduction of salinity because the re-entry of saltwater from upstream sources or from the ground surface caused a longer-term but less concentrated contamination of the well (Goswami and Clement, 2007).

The experiments simulate saltwater-flooding processes and the overall effects of pumping on well contamination and remediation. They also present the influence of natural cleaning on well salinity due to density-gradients and ambient groundwater flow. Rainfall enhances this process though it was not directly included in the modeling effort. Whereas deliberate cleaning of wells by pumping seemed to have a limited effect on salinity reduction, except when done very early, re-contamination of wells is very likely from other upstream sources and from the saltwater front moving down from the soil surface. These findings support the observations in the monitoring program that wells were not rehabilitated to pre-tsunami salinity conditions by the large-scale, intensive cleaning efforts in the months after the tsunami. The results presented above illustrate the processes pertinent to sandy, permeable unconfined aquifer systems which are representative of large parts of the Sri Lankan coast line (Panabokke and Perera, 2004) and typical coastal settings around the world. However, conditions different from those simulated here, e.g. hard rock or fractured systems, may need special consideration and assessment.

Field investigations of the comparative process of recovery of the groundwater quality in undisturbed and disturbed areas

The results of the comparative study of the recovery of disturbed and non-disturbed areas showed a discernible difference in the water quality and the recession of the contamination between the sites, focusing on parameters such as EC, concentration of Ca, Na, Cl, sulphate, and alkalinity (Vithanage et al., 2009). In general, the differences were in agreement with a larger degree of tsunami residual imprint on the wells in the disturbed area, e.g. showing higher levels and more small scale variability of EC and slower recovery in this area as compared to the undisturbed area (Fig. 11.9.4). This

Figure 11.9.4. EC levels observed both in undisturbed (solid line) and disturbed sites (red circles: wells in use; green circles: abandoned wells) between October 2005 and September 2006 plotted against the distance from the sea (m)



suggests, assuming that the sites were similar in other respects (e.g. rainfall conditions, geological setting, pre-tsunami conditions), that the pumping and cleaning of wells in the disturbed site had the effect of disturbing the natural sinking and dissipation mechanisms of saltwater that entered the aquifer and prolonging the tsunami imprint by the continuous mixing of water caused by pumping, cleaning and recycling of waste water and local discharge of water pumped from wells. The finding was corroborated by the fact that abandoned wells in the disturbed area similarly to wells in the undisturbed area showed less of a tsunami imprint substantiating that cleaning and pumping of wells retards the natural cleaning process (Figure 11.9. 4).

Development of internationally endorsed guidelines on well cleaning and groundwater protection after seawater flooding

Recognising the need for practical guidelines dedicated to the emergency situation of cleaning wells after a seawater flooding event, the project developed, in consultation with experts from WEDC and WHO, a set of guidelines which was integrated into their series of technical fact sheets (WHO, 2008). The guidelines supplement existing emergency well cleaning and disinfection guidelines (WHO, 2005) and focus on saltwater flooding. Their objective is to facilitate and accelerate provision of safe and contaminant-free water for drinking and other domestic purposes, protecting the coastal aquifer and minimising the potential for saltwater intrusion.

The guidelines emphasise that well cleaning should be performed only once initially and as early as possible after the event by removing debris, sludge and pumping contaminated water standing in the well. Subsequent intensive pumping for cleaning, salinity removal, and disinfection should be avoided in order to limit the disturbance of the natural ambient flushing and remediation processes. This advice is generally applicable for saltwater flooding in coastal areas where aquifers are unconsolidated, dominated by sandy materials and wells are open and shallow, a typical case in coastal villages in developing countries.

Conclusions and Recommendations

In the case study presented here, shallow and vulnerable groundwater resources were the only available freshwater source for the local population before the disaster. In a disaster situation, like after a tsunami where a major part of this resource is contaminated by saltwater, the challenge of sustainable rehabilitation centres on restoring this resource to freshwater conditions. Hence, the efforts of well cleaning and groundwater protection were paramount to the success of the disaster relief efforts. It was concluded that not only was it important to apply informed well cleaning techniques based on monitoring data, scientific knowledge and possibly numerical modeling techniques – it was also of great importance to get this knowledge to the actors on the ground in a comprehendible and timely manner. Though the attempts to accomplish this may not have been totally successful (it was hard to spread the message and gain general acceptance of the do-little or do-nothing approach in terms of pumping the wells), the tools and guidelines developed in this study may serve to direct efforts in future similar events. It is advisable that the modeling approach be applied in individual cases using specific and context-relevant data and conditions to guide best cleaning and protection measures.

It is concluded also that involving the afflicted populations in information collection and dissemination deserves much more attention. For example, the fact that cleaning the wells had a positive psychological effect, may advocate repeated pumping of wells. This could still be done without overpumping and re-contaminating the aquifer if proper guidelines were given initially. Care should also be taken not to distort the proportions of the problems. Salinisation was not a health issue as saltwater generally does not cause health problems in the concentrations accepted for drinking by humans. It was rather an issue of restoring the freshwater resource in the aquifers and wells as rapidly as possible and rapidly discontinue the disaster relief support.

The work attempted to build a bridge between research and rehabilitation work, and in a sense supports a relief-rehabilitation-development nexus in a visionary approach. The tsunami 2004 presented a unique opportunity to gain fundamental insight into physical natural large-scale seawater flooding phenomena, a rare phenomenon normally studied only in small-scale artificially constructed systems. However, the issue of saltwater ingress and saltwater flooding is likely to become increasingly important due to climate change and increased variability and extremes. Hence, further research and support in terms of developing easily accessible information, guidelines and tools are needed, with a view to preempt catastrophic events and preempt severe consequences, should they occur.

Acknowledgements

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References

ACF, Batticaloa, Sri Lanka 2006. *Well hand over process - Water trucking phasing out, Manmunai North (Seelamunai / Dutchbar / New Dutchbar / Thiruchenthur)*. Internal paper.

CDC, Centers for Disease Control and Prevention. http://www.bt.cdc.gov/disasters/wellsdisinfect.asp (accessed on June 20, 2008).

Clasen, T. and Smith, L. 2005. *The Drinking Water Response to the Indian Ocean Tsunami Including the Role of Household Water Treatment*. Water, Sanitation and Health. Protection of the Human Environment, WHO.

Cooray, P.G. 1985. *Geology of Sri Lanka*. National Museum of Sri Lanka.

Fesselet, J.-F. and Mulders, R. 2006. *Saline wells in Aceh*. Waterlines 24(3), Jan. 2006.

Goswami, R.R. and Clement, T.P. 2007. *Technical details of the SEAWAT model simulation results used to develop well cleaning guidelines*. Technical Summary Report. Department of Civil Engineering, Auburn University.

Goswami, R.R., Villholth, K.G., Vithanage, M., Clement, T.P., Sakaki, T., Illangasekare, T.H. and Jensen, K.H. 2007. *Variable Density Transport during Well Rehabilitation after a Tsunami-induced Saltwater Contamination Event*. Paper presented at ModelCARE, Copenhagen, Denmark, September 10-13, 2007.

Hogan, M.B., Goswami, R.R., Villholth, K.G., Illangasekare, T.H. and Clement, T.P. 2006. *Understanding the Flow and Mixing Dynamics of Saline Water Discharged into Coastal Freshwater Aquifers*. Selected peer-reviewed paper presented at the SWIM-SWICA meeting. Cagliari, Chia Laguna, Sardinia, Italy. September 24-29, 2006.

Illangasekare, T.H., Tyler, S.W., Clement, T.P., Villholth, K.G., Perera, A.P.G.R.L. Obeysekera, J. Gunatilaka, A., Panabokke, C.R., Hyndman, D.W., Cunningham, K.J., Kaluarachchi, J.J., Yeh, W. W-G., Van Genuchten, M-R. and Jensen, K.H. 2006. *Impacts of the 2004 Tsunami on Groundwater Resources in Sri Lanka*. Water Resources Research, 42(5). W05201, doi:10.1029/2006WR004876.

IUCN 2005. Series on Best Practice Guidelines (Sri Lanka). *After the Tsunami: Water Pollution*. Information Paper No. 11.

Keba, A.J. 2006. *The role of beneficiary participation in the phase-out of post-emergency water tankering*, Ampara, Sri Lanka. Cranfield Univerity at Silsoe.

Langevin, C.D. and Guo, W. 2006. *MODFLOW/MT3DMS-based simulation of variable density ground water flow and transport.* Ground Water, 44(3): 339-351.

Leclerc, J.-P., Berger, C., Foulon, A., Sarraute, R. and Gabet, L. 2008. *Tsunami impact on shallow groundwater in the Ampara district in eastern Sri Lanka: Conductivity measurements and qualitative interpretations*. Desalination, 219: 126-136.

Lipscombe, S. 2007. *Groundwater salinity and handdug wells in Ampara, Sri Lanka*. Waterlines. July, 2007, 26(1): 12-13.

Lytton, L. 2008. *Deep impact: why post-tsunami wells need a measured approach*. Civil Engineering. 1612: 42-48.

NGWA, National Groundwater Association (accessed on march 10, 2005).

OXFAM. *Technical Brief – Repairing, cleaning and disinfecting hand dug wells*. http://www.oxfam.org.uk/resources/downloads/emerg_manuals/draft_oxfam_tech_brief_well cleaning.pdf (accessed on June 20, 2008).

Panabokke C.R. and Perera, A.P.G.R.L. 2004. *Groundwater resources of Sri Lanka*. World water Assessment Program, Oct., Sri Lanka.

Panabokke, C.R., Pathirana, S.R.K. and Wijekoon, D. 2002. *Water quality of agro-wells in the coastal sand aquifer in Trincomalee District*. Proceedings of the symposium Use of Groundwater for Agriculture in Sri Lanka, Sep. 30, 2002, University of Peradeniya, Sri Lanka, pp. 85-98.

UNICEF 2005. *Consequences of the tsunami on the coastal aquifer in Eastern Sri Lanka – Guidelines on wells rehabilitation*. Trincomalee, May, 2005.

Villholth, K.G. 2007. *Tsunami impacts on groundwater and water supply in eastern Sri Lanka*. Waterlines. July, 2007, 26(1): 8-11.

Villholth, K.G. and Rajasooriyar, L.D., 2009. *Groundwater resources and management challenges in Sri Lanka – An overview*. Int. J. Water Res. Dev. (Accepted).

Villholth, K.G., Jeyakumar, P., Manamperi, A.S.P., Jegan, G., Thilipan, M. and Navalan, V. 2008. *Perceptions of water quality and water supply impacts and coping of the local population with the 2004 Sumatra-Andaman tsunami on the east coast of Sri Lanka*. (Submitted to Natural Hazards).

Villholth, K.G., Amerasinghe, P. and Jeyakumar, P. 2008. *Tsunami impacts on shallow groundwater and associated water supplies on the east coast of Sri Lanka*. In: P. Bhattacharya, AL. Ramanathan, A.B. Mukherjee and J. Bundschuh (eds.), *Groundwater for Sustainable Development: Problems, Perspectives and Challenges*. AA Balkema (Taylor and Francis Group), London/Leiden/New York/Philadelphia/Singapore, pp. 211-222.

Villholth, K.G., Amerasinghe, P.H., Jeyakumar, P., Panabokke, C.R., Woolley, O., Weerasinghe, M.D., Amalraj, N., Prathepaan, S., Bürgi, N., Lionelrathne, D.M.D.S., Indrajith, N.G. and Pathirana, S.R.K. 2005. *Tsunami Impacts on Shallow Groundwater and Associated Water Supply on the East Coast of Sri Lanka*. Colombo, Sri Lanka. International Water Management Institute (IWMI). ISBN 92-9090-622-7. 68 pp.

Vithanage, M., Villholth, K.G., Mahatantila, K., Engesgaard, P. and Jensen, K.H. 2009. *Effect of well cleaning and pumping on groundwater quality of a tsunami-affected coastal aquifer in eastern Sri Lanka*. Water Resour. Res., 45, W07501, Doi:10.1029/2008WR007509.

Vrba, J., and Verhagen, B.Th. 2006. *Groundwater for Emergency Situations* – A Framework Document. IHP-VI, Series on Groundwater No. 12. UNESCO-IHP, 94 p.

WHO 2005. *WHO - Technical Notes for Emergencies. Technical Note No.1. Cleaning and disinfecting wells in emergencies*. http://www.who.int/water_sanitation_health/hygiene/envsan/technotes/en/ (accessed on June 20, 2008).

WHO 2008. *WHO - Technical Notes for Emergencies. Technical Note No.3. Cleaning wells after seawater flooding - Emergency guidelines*. http://www.who.int/water_sanitation_health/hygiene/envsan/tech-notes/en/ (accessed on June 20, 2008).

Wickramaratne, H.U. 2004. *Use of groundwater for coastal water supply schemes, minimizing the salinity problem*; A case study at Kattankudy in Batticaloa District, Sri Lanka. M.Sc. Thesis. Post Graduate Institute of Science, University of Peradeniya, Peradeniya, Sri Lanka.

Groundwater use in an emergency: impact of, and experience gained in the huge Hanshin-Awaji, Japan earthquake

11.10

*Tadashi Tanaka**

Abstract

The purpose of this case study is to describe the importance of groundwater for secure emergency water resource after the huge Hanshin-Awaji (Kobe) earthquake which occurred in 1995. Around 1,270,000 households were cut off from municipal water supply after the earthquake and medical activities in many hospitals were seriously affected by water scarcity. However, it was possible to pump groundwater from several wells immediately after the earthquake. Resistance of wells against the impact of earthquakes has been noted and registration system of citizen's wells has been established in 1996 in Kobe. Within next two years 517 suitable emergency wells were registered and their location entered on maps. Based on the Kobe experience similar emergency water well systems have been established by many municipal and local governments in Japan to be used as a safe source of water in emergency. In some hospitals deep wells have been drilled, equipped with pumps and diesel driven generators and are prepared for immediate use in an emergency situation.

Introduction

The purpose of the case study is to describe the importance of groundwater as a secure emergency water resource after the huge Hanshin-Awaji (Kobe) earthquake (M 7.3). This was the worst disaster to hit Japan after World War II and occurred on January 17, 1995. Around 6,400 lives were lost, 40,000 people were injured and 200,000 households disrupted. This huge earthquake occurred on the Niigata-Kobe belt of strain concentration as shown in Fig. 11.10.1. Many other big earthquakes rocked Japan Island recently along this strain belt.

In the Hanshin-Awaji earthquake, around 1,270,000 households were cut of from the municipal water supply in the immediate aftermath of the earthquake and 490,000 households remained cut off even after one week. Medical activities in many hospitals were seriously affected by water scarcity. The

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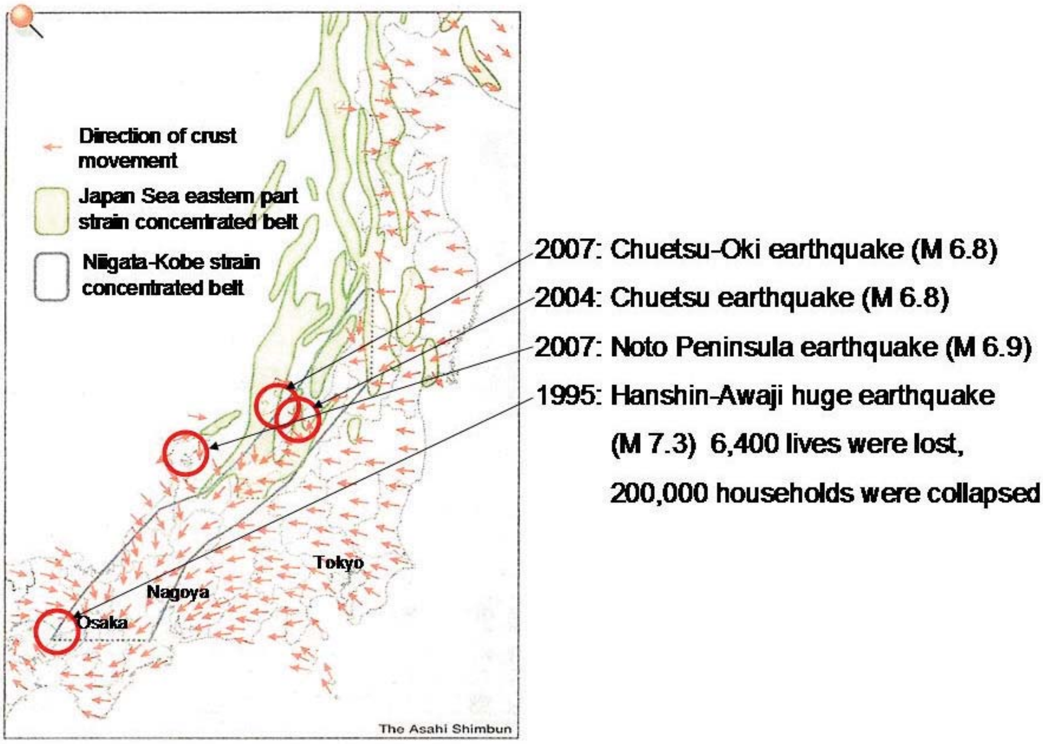
Figure 11.10.1. Recent earthquakes in Japan (Asahi NP, 2007)



maximum length of cut of from the municipal water supply was 3 months following the earthquake in some severely affected districts. However, it was possible to pump groundwater from several wells immediately after the earthquake. Resistance of wells against the impact of earthquakes has been noted and registration system of citizen's wells has been established in 1996 in Kobe. Within the next two years 517 suitable emergency wells were registered and their location entered on maps. Based on the Kobe experience similar emergency water wells systems have been established by many municipal and local governments in Japan to be used as safe sources of water in emergency. In some hospitals deep wells have been drilled, equipped with pumps and diesel driven generators and are prepared for immediate use in emergency situations.

Groundwater supply and use after Hanshin-Awaji earthquake

Earthquakes usually cause extensive damage to lifelines such as water, gas and electricity supply systems. Among those, security of water is the most serious problem in disaster areas, especially in major urban centres such as Kobe because of the time required for restoring the municipal water supply system after the earthquake.

The main problems with water use reported in the Hanshin-Awaji earthquake (Research Committee on Securing of Water in Huge Earthquakes, 1999; Project Committee of MLIT, Japan, 2007) are the following:

- Fire fighting: Inability to use hydrants presented a major obstruction to fire fighting, principal reasons being damage to feeder lines and rupture of water mains;

- Drinking/Cooking: Citizens had to secure bottled water for drinking and cooking;
- Toilet flushing: Huge amounts of water are required, presenting problems in transportation;
- Medical attention: Hospitals required transportation of special, high quality water;
- Medical activities are often seriously impaired. In the Hanshin-Awaji earthquake, responses to a questionnaire showed that in 73.6 % of the cases the main impediment to the functioning of hospitals was being cut off from the municipal water supply (Yoshioka, 2007).

Figure 11.10.2 shows the sources of drinking water of Kobe citizens accessed in the Hanshin-Awaji earthquake. It is clear that most of the people obtained drinking water from tankers and from stores for bottled water. Well water and shallow groundwater were low on the list. This implies that clean water, a basic requirement for drinking and cooking, could be secured provided that the quality of groundwater is managed on an ongoing basis, especially in urban areas like Kobe. Figure 11.10.3 shows the sources of domestic water such as for washing, bathing and flushing toilets, as in Fig. 11.10.2. In this case, water quality is less of a basic issue. The use of well water is slightly higher than for drinking and sources are more varied such as leaks from the water supply lines, public street water point, and river or sea water (Fig. 11.10.3). More generally, water demand in an earthquake disaster and the required water amounts and quality are described in Chapter 3.

A special case was Awaji island. The recovery of water supply after the Hanshin-Awaji earthquake was prompt because most of residents had wells on their properties allowing ready access to the shallow groundwater using pumps, either hand driven or by electricity, which had been restored within the same day of the earthquake (Yoshioka, 2006).

Groundwater use in the Kobe city was also reported as follows (Kamiya et al., 1998):

- 17 January (day one): well water used by 500 citizens for fire fighting by bucket relay;
- 18 January (day two): 100 m pipeline installed for supplying well water;
- 20 January (day three): 200 citizens used groundwater by pumping from a 7 m deep well
- 24 January (day seven): "Kikumasamune", the famous Sake (Japanese rice wine) brewing company, opened its "Miya-mizu", or brewing groundwater supply, for use from 9 am to 3 pm daily;
- 28 January. (day eleven): water used from a 55-year old well constructed before World War II.

Figure 11.10.2. Sources used by citizens of Kobe to access water (Research Committee on Security of Water in Huge Earthquake Disaster, 1999)

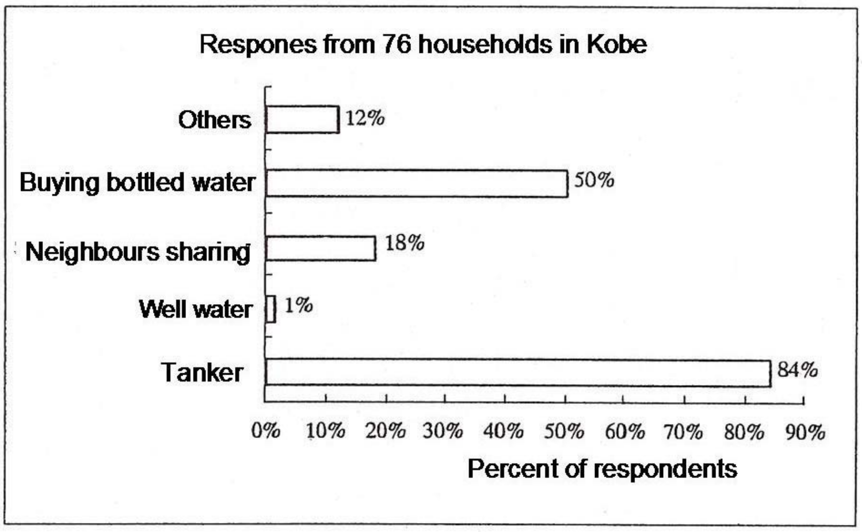
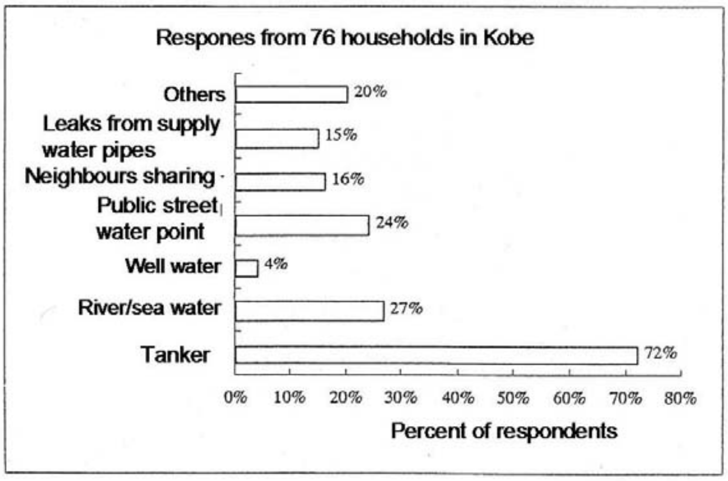


Figure 11.10.3. Sources of domestic water of Kobe citizens (Research Committee on Security of Water in Huge Earthquake Disaster, 1999)



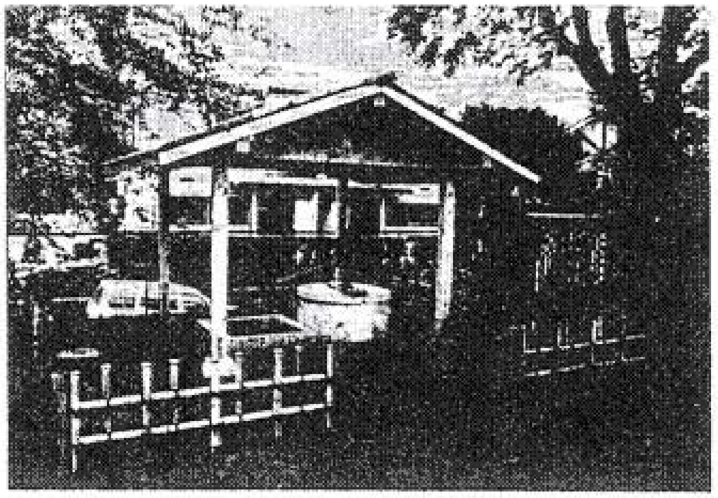
Measures to secure groundwater in earthquake emergencies

After the Hanshin-Awaji earthquake, measures to secure groundwater for disaster emergencies have been considered by many local governments in Japan. One of such measures is the registration system of citizen's wells for use in disasters. Figure 11.10.4 shows a sign indicating a citizen's cooperation well for disasters in Kobe city. This registration system of citizen's open wells was initiated in 1996 in Kobe city, just one year after the earthquake, and the number of registered wells reached 517 by October 1998. The list of registered wells with a location map was prepared by the Administration

Figure 11.10.4. A sign indicating a citizen's cooperation well for disasters in Kobe city (Research Committee on Security of Water in Huge Earthquake Disaster, 1999)

Office of the city and a survey of well water quality has been carried out periodically. Similar registration systems have been launched by many other local governments, especially in mega-cities such as Tokyo and Yokohama. For example, the Tokyo Metropolitan Government had identified 2,769 wells in 23 wards for use in disasters by 1995. In Yokohama city, the number of registered wells reached 3,517 by 1995 and water quality checks conducted monthly to the same analytical standard as for municipal supply water. Kokubunji City in the Tokyo Metropolis has constructed old style well facilities consisting of a hand pump, a street kiosk and infiltration measure system as shown in Fig. 11.10.5.

Figure 11.10.5. Old style facility in Kokubunji city, Tokyo. Well with hand pump (Research Committee on Security of water in Huge Earthquake Disasters, 1999)



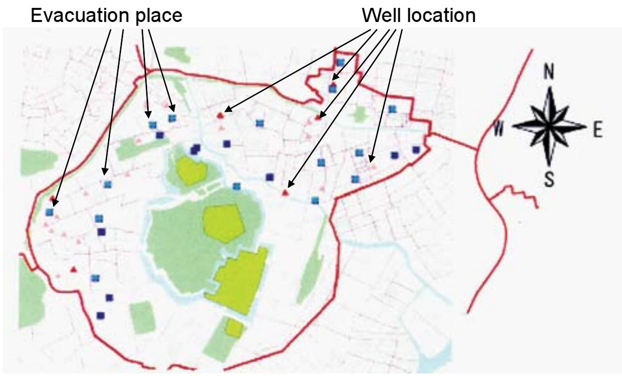
Eight sets in total had been constructed in and around the city by 1990 and the maintenance of the facility has been entrusted to the City Administration and Citizen's Prevention Committee.

Figure 11.10.6 shows of map springs, based on citizen input, for Ginza, the most famous shopping area in Tokyo. This like map could be very useful in a disaster emergency where high-rise urbanization has

Figure 11.10.6. Spring map in Ginza, Tokyo compiled by citizens (Kamiya et al., 1998)

obscured natural features. Figure 11.10.7 shows the map of evacuation assembly points and well locations in Chiyoda Ward, in the metropolitan centre of Tokyo, for use in earthquake emergencies. Evacuation assembly points tend to be located near wells.

Figure 11.10.7. Map of evacuation places and well locations in Chiyoda Ward, Tokyo



Utilization of rainwater on the roof of households, which is led to the street furniture (water tank) with a hand pump is also spread in recently in Ward districts of Tokyo Metropolis for the purpose of using stored rainwater in the emergency as shown in Fig. 11.10.8. This type of street furniture, which collects rainwater for life water using, had been used in Japan already in the Edo era, more than 150 years before, as shown in Fig. 11.10.9. This picture shows the rainwater pail (bucket) existing in front of the house. It also can be seen that the Kanji (Japanese) of 'Mizu (water)' is described on the surface of the pail. This self-help rainwater harvesting system was re-introduced recently as an important source of public drinking water as well as for emergency supply in disasters.

Figure 11.10.8. Street facility with a hand pump to access rainwater from roof runoff n Sumida Ward, Tokyo

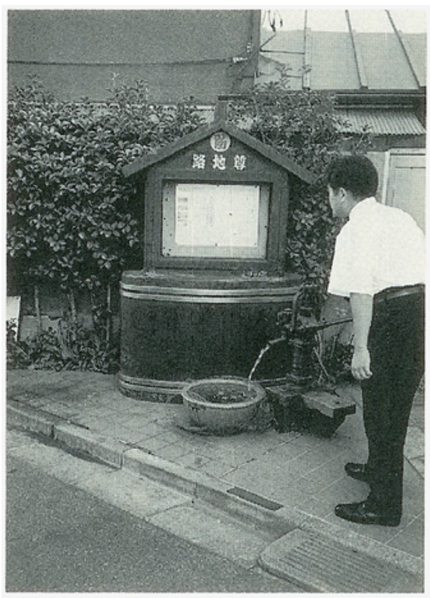
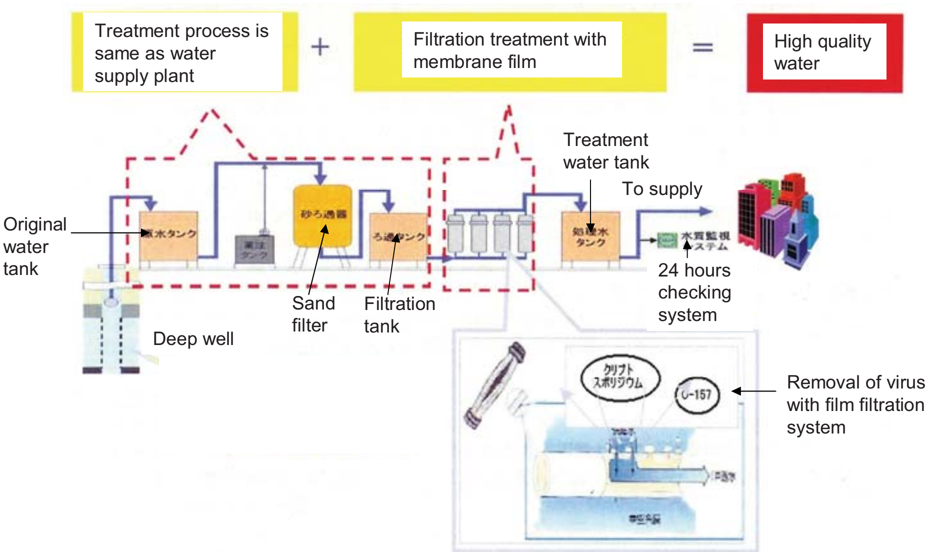


Figure 11.10.9. Rainwater pail (vat) collecting roof runoff in the Edo era (Kamiya et al., 1998)

As described in Chapter 4.3, water of high quality and in considerable quantities is required for medical activities, from the immediate aftermath of an earthquake with the supply sustained thereafter. This could pose a major water transportation bottleneck with the disruption during an earthquake emergency. To overcome this problem, some hospitals in Japan have introduced a deep well facility such as shown in Fig. 11.10.10, which can supply 80 % of normal drinking water supply, with a membrane filtration system and an in-house power plant. A total of 353 of such facilities had been introduced in Japan by April 2004 including 116 for hospitals (Sugimoto, 2004).

Figure 11.10.10. Schematic diagram of a deep well facility with a membrane filtration system and a private power plant system introduced by hospitals in Japan against disasters emergency (Kawahara, 2004)



Concluding remarks

As described in this paper, a groundwater source available close to where there is a supply need, is considered as a significant water source in an earthquake emergency. A groundwater source may have advantages also at the domestic level for initial fire fighting and toilet flushing, listed as crucial water use problems in earthquake emergencies, especially in a Mega City such as Tokyo. Using groundwater for drinking and cooking water requires ongoing quality checks. Hand pumps or diesel/petrol-driven pumps have to be kept operational as the required electricity supply may be disrupted in an earthquake. The establishment of a continuous monitoring system of groundwater level as well as regular water quality checks, and the establishment of a registration system of citizen's wells – as is conducted by many Japanese local governments after the Hanshin-Awaji earthquake – are the most important relief and rehabilitation measures for securing groundwater supply in an earthquake emergency.

References

Asahi, N.P. 2007. *Morning News Paper* on 26 July, 2007.

Kamiya, H. et al. 1998. *Well and Water Roo.* Hokuto Shuppan, in Japanese, 202 p.

Kawahara, K. 2004. *Practice of four dimensional water cycle*. http://www. higashinihon.ne.jp/news/pdf/, in Japanese, 11 p.

Project Committee of the Ministry of Land, Infrastructure and Transport (MLIT), Japan. 2007. *Future-Oriented Groundwater Resource Management*, in Japanese, 81 p.

Research Committee on Secure of Water in Huge Earthquake Disaster. 1999. *On Secure of Water in Huge Earthquake Disaster in a Mega City,* in Japanese, 106 p.

Sugimoto, J. 2004. *Increasing the Groundwater Use in Hospitals.* New Medical Treatment, in Japanese.

Yoshioka, R. 2006. *The Earthquakes Recently Occurred in Inland Regions of Japan and Lifelines Focusing on Groundwater.* Presented Paper at the WG Meeting on GWES, UNESCO IHP-VI, Paris, 8 p.

Yoshioka, R. 2007. *Impact of Hyogo Nanbu Earthquake on Groundwater Use in Emergency.* Presented Paper at the WG Meeting on GWES, UNESCO IHP-VI, Tsukuba, Japan, 3 p.

This Methodological Guide provides background information on groundwater protection with particular reference to its use in emergency situations as result of natural hazards and hydrological extremes. It also outlines the governance policy framework in which groundwater as an emergency resource may be integrated into overall emergency management and service provision. To illustrate the principles and techniques presented in the Guide, a varied number of real world case studies from widely differing regions is presented.

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