International Association of Hydrogeologists

Netherlands Hydrogeological Research in International Cooperation

Netherlands Committee for the IAH

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Netherlands National Committee for the International Association of Hydrogeologists

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- Directorate General for International Cooperation, Ministry of Foreign Affairs (The Netherlands)
- IWACO BV, Consultants for Water and Environment
- Netherlands Hydrological Society
- Netherlands Section of the International Association of Engineering Geology
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- TNO Institute of Applied Geoscience

Editors:
J.C. Hooghart
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PREFACE

The Netherlands National Committee for the International Association of Hydrogeologists (IAH) has great pleasure in presenting the proceedings of a meeting held in March 1994 at the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE) in Delft, The Netherlands. At this meeting, hydrogeological research done by Dutch specialists and their colleagues in developing nations as part of Dutch international cooperation was presented. The emphasis was on the application of hydrogeology to solve problems of groundwater management.

The proceedings start with an overview of techniques and new developments in hydrogeological research. This is followed by case studies, illustrating the various techniques. Finally, education and training in relation to Dutch international cooperation are discussed.

The agencies contributing to this meeting are listed at the end of this volume. They are ready to advance further information.

The International Association of Hydrogeologists is a non-governmental, non-profit making, scientific organization established to advance hydrogeology, especially the study of groundwater and aquifers. The IAH, which is affiliated to the International Union of Geological Sciences, seeks to promote international cooperation among groundwater scientists and engineers and to encourage the worldwide application of hydrogeological skills to the benefit of mankind. There are currently about 3000 individual members in over 80 countries throughout the world. To increase membership in developing nations the IAH has set up a sponsored membership scheme for colleagues in low-income countries.

The Netherlands National Committee for IAH wishes to express special thanks to the TNO Institute of Applied Geoscience in Delft which greatly supported the organisation of this meeting and the publication of the proceedings.

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Netherlands Hydrogeological Research in International Cooperation (Proceedings of the meeting in Delft, The Netherlands, 31 March 1994)

DEVELOPMENTS AND NEW METHODOLOGIES IN HYDROGEOLOGICAL RESEARCH

J.L.J. de Sonneville

ABSTRACT

Groundwater is not only a basic necessity but also an important catalyst for economic and social progress in the developing countries. Vast areas in the world depend on groundwater. However, there is a growing concern about the availability of groundwater which is being limited by sustainability factors and environmental constraints. Hydrogeological research in development cooperation deserves a place commensurate with the social relevance its results have for the economic development of the countries concerned. The challenge to hydrogeological research is to provide the knowledge to solve the increasingly complex problems with regard to the sustainable use of groundwater resources. Triggers to the development in hydrogeological research are the 'technology push' in the geosciences and the 'problem-oriented questions' resulting from the broader function of groundwater in society. Developments in research are examined under two main themes. The first theme reviews angles of subsurface hydrogeological research: (i) subsurface imaging (knowing the structure of the subsurface), (ii) subsurface characterization (knowing the hydrogeological properties) and (iii) subsurface processes (analyzing the flow processes). The second theme examines hydrogeological decision-supporting research: (i) groundwater development (the optimization of water production) and (ii) groundwater resources management (the integration of hydrogeological research in a multi-disciplinary framework under the constraints posed by the environment and economic and social development objectives). New developments are discussed in some detail. The integration of disciplines and the surge in data needs urges the development of hydrogeological information management systems. The present knowledge and information 'crisis' in the developing countries calls for the further development and strengthening of research institutes in these countries entrusted to develop knowledge and skills to understand and describe an increasingly more complicated groundwater environment and to support decision makers in groundwater resources management.

1 INTRODUCTION

The developments and new methodologies coming available as a result of hydrogeological research and their social relevance for society are of major interest to the hydrogeologist, both in developing and industrialized countries. Not so long ago the main challenge for the hydrogeologist was the exploration for groundwater. Most of the work of the hydrogeologist was related to finding and selecting favourable aquifer zones and designing schemes for groundwater development. Over the last decades however serious concern has been raised about the sustainability of groundwater development. Although in global terms the annual surface and groundwater runoff into rivers far exceed the total water demand, factors such as the variation of water availability in space and in time, environmental aspects and water quality problems make that water scarcity and unsustainable development occur in many regions of the world.

A fundamental cause of the threats to sustainable development is the rapid growth of the population. While in Europe the population over the last 100 years has doubled, those in Africa and Latin America have increased 8-fold. The role which groundwater plays as a source of water and key to development for the population in developing countries is considerable. The majority of the rural population and also a substantial part of the urban population depend on groundwater, partly because it can be made available at lower cost than surface water or simply because surface water is not nearby. Vast tracts in Africa, the Middle East, Central and South America and Asia are characterized by arid climates and conditions where there is an almost complete dependency on groundwater.

The dependency on groundwater is increased by the observed trend of out-migration, due to overpopulation in the high potential lands, to arid and semi-arid lands where the environment is fragile and crop production risky. Where arable agriculture has substituted livestock, the end result has often been low level production and shifting of livestock to more arid zones. With less land available the resulting overstocking has led to serious degradation of rangelands and to soil erosion.

In view of the threats to the sustainable use of groundwater, the development and implementation of guidelines and policies directed towards safeguarding quantity and quality, become of increasing importance to the developing countries concerned.

It will be a challenge to the hydrogeological profession to respond adequately to the new problems posed. What will be required of the hydrogeologist is on the one hand a deepening of his knowledge to provide better answers to the questions related not only to occurrence of groundwater and its flow, but also to its interactions with the geological environment and to the aspects of its replenishment; on the other hand a broadening of his profession towards groundwater resources management and environmental management planning.

The social relevance of applied hydrogeological research, on the basis of which products and services become available to support water management decisions, is considerable. However, the number of research institutes in developing countries, entrusted to develop knowledge and skills to understand and describe an increasingly more complicated groundwater environment and capable of supporting decision makers in groundwater resources management is very limited. In this respect, hydrogeological research in development cooperation deserves a place commensurate with the social relevance its results have for the economic development of the countries concerned.

2 TRIGGERS TO DEVELOPMENT IN HYDROGEOLOGICAL RESEARCH

Looking back over the last ten years it is possible to observe significant development in the hydrogeological profession. The direction of hydrogeological research has been influenced by two steering mechanisms: (i) the technology push from the development in geosciences and (ii) the problem-oriented questions resulting from the broader function of (ground)water in society. The first mechanism concerns the investigations and research in the physical domain, the subsurface. The second mechanism concerns the integration of hydrogeological know-how with other disciplines in a broader management framework, to support sustainable economic development and to improve the welfare of society, which occupies its surface.

It is important to note that the financial resources which are needed to carry out the research activities in the physical domain originate from society. Therefore the applied hydrogeological research carried out should be relevant to solving the problem-oriented questions of society, if funding is to be secured. The last ten years saw the following developments:

2.1 Technology push

'Autonomous' Development in Groundwater Related Disciplines
Developments in the field of groundwater have had several 'breakthroughs'. One, dating back more than ten years is the development of the numerical approach to problem solving, next to the traditional analytical methods. The second concerns the development of the flow systems approach. This approach is first described by K. Hubbert, 40 years back, but had no immediate consequences in application. Tóth, in 1967, presented a fundamental, more quantifying treatment of the subject. Especially the last ten years this approach has developed significantly due to the increased emphasis on the pollution of groundwater and the consequences for the environment.

Computer Technology
The last ten years have seen an enormous advance in computer technology both in main frames and personal computers. Especially the rapid development of the PC's and work stations has revolutionized the possibilities in the field of hydrogeological calculations and data storage. Examples are:

- Flow simulation made possible in 2D and 3D domain.
- Design of complex information management systems, including geographical information systems.
- Stochastic modelling using vast amounts of data (Monte Carlo methods).
- Inverse modelling processes.

Software Development
The last ten years have seen a proliferation of software development for hydrogeological investigations. This development professionalised the discipline of the practising hydrogeologist, increasing considerably his 'toolkit'. Software development has increased world-wide, which actuated the decision to set up the International Groundwater Modelling

Centre (IGWMC), with the aim to collect all information on groundwater modelling codes, provide information and act as a clearing house for software.

Satellite Imaging Technology

The last decade has seen an enormous improvement in the resolution of satellite images. Also processing capability, both raster and vector data, graphical visualization and interactive processing has made the information much more accessible.

Micro-Electronics Technology

Advancements in solid state technology has revolutionised the acquisition of data and the continuous monitoring of data sets. Examples are:

- The development of geophysical instruments. Solid state circuitry has made it possible to design more advanced electrode measuring systems, using the digital processing capabilities in the field. Examples are found in the development of resistivity equipment and georadar.
- The 'EPROM' and the digital storage of water quality data, water level data and climatological data made it possible to install dedicated monitoring systems at remote places.

Parallel Developments in Geo-Energy Related Disciplines

Developments in the oil and gas industry are of much interest to the groundwater industry. The relatively high price for oil, compared to that of water and the economic interest at a national level has resulted in continuous large investments in research to improve the success rate of locating reservoirs and to improve recovery rates. Research in the oil industry has similarly benefitted from the advances in information technology and computing power. The advances in the processing of geophysical acquisition data, geologic modelling and simulators are of much interest to some of the groundwater disciplines.

The advances in technology generally has resulted in an increase in data output and data quality, increased accuracy in results, a more complex and integrated analysis of processes, leading to an increased understanding and insight in the hydrogeological problems.

2.2 Problem-oriented questions from society

Population in developing countries has increased generally more rapid than the growth in economic development. Although the per capita water use, particularly in Africa, has remained constant in the last 100 years, it may be expected that, in spite of possible effects of demand management activities, the total and per capita water demands will continue to expand, most markedly in areas where per capita use is currently comparatively low. The issue of sustainable development and the concern for the environment will tend to reduce the availability of water resources. Thus it can be expected that water scarcity problems will aggravate in areas where they are already present and that they will tend to emerge elsewhere. The main problems in groundwater development are:

- Depletion of groundwater resources, as a result of overexploitation.
- Deterioration of the groundwater quality by salination or pollution.
- Negative environmental impact of groundwater abstraction.
- Insufficient technical, financial or organizational capacity for adequate operation and maintenance of groundwater abstraction works.

These problems threaten the socio-economic development of society in general. What is required is (a) the integration of the various policy fields (water development, environmental protection, economic growth, etc.) and (b) a state-directed intervention towards (integral) water resources management and planning.

The problem-oriented questions of society, in which the state has an important role as financier, imply the need for multi-disciplinary investigations and research. It implies a part-shift from discipline-oriented research to problem-oriented research and investigations. It implies that applied hydrogeological research, on the basis of which products and services become available to support water management decisions, must be continued, intensified or initiated.

2.3 Present status on basic data availability

Although the technology 'push' has triggered research and development of methodologies which offer a better understanding of hydrogeological problems, the quality of the results depend heavily on the availability and accuracy of basic data. The 'problem-oriented questions' require more data and integration of more disciplines: hydrogeology, hydrochemistry, eco-hydrology, environmental hydrology, etc. The general consensus is that in the industrialized countries there is at present insufficient basic information to act decisively on issues regarding groundwater and groundwater management, this in the light of its complexity increased by sustainability and environmental considerations. The situation is rather worse in the developing world where basic data on hydrogeology is very scarce or not easily accessible. The information and hydrogeological parameter 'crisis' may be ameliorated by:

- Reversing the trend of decreasing field investigations.
- Executing systematic national investigations, in particular groundwater flow systems analysis and geochemical investigations.
- Opening up of the available groundwater information though the development of 'state of the art' groundwater information management systems and making this accessible to all users.
- Developing methods to optimize the extraction of a maximum amount of relevant hydrogeological information from limited data resources.

3 DIRECTION OF HYDROGEOLOGICAL RESEARCH

Applied hydrogeological research should be directed towards making available reliable information and 'state-of-the-art' tools to underpin a sustainable use of groundwater of sufficient quality and quantity, with due regard for the environment. In this respect can be mentioned international meetings concerning sustainable growth and the environment as the New Delhi Conference (Global consultation on safe water and sanitation for the 1990s, 1990), the Delft Agenda (A strategy for Water Resources Capacity Building, 1991), the Dublin Conference (Water and the Environment, 1992), Groningen (Development-related research and the role of The Netherlands, a second look, 1992) and the Conference in Rio de Janeiro (UN conference on Environment and Development, 1992). The conferences emphasize the need for sustainable development and protection of the environment, the need for strengthening the institutional capacity to support, among others, integrated water resources planning and management, and the reinforcement of research capacity in developing countries. In the coming years a further integration and interaction will be necessary of the various scientific and social disciplines, such as hydrogeological, hydrochemical, geochemical, hydrogeophysical, environmental, socio-cultural, socio-economic and economic disciplines. The hydrogeological research and development of methodologies are outlined under (a) subsurface hydrogeological research and (b) hydrogeological decision-supporting research (see Figure 1).

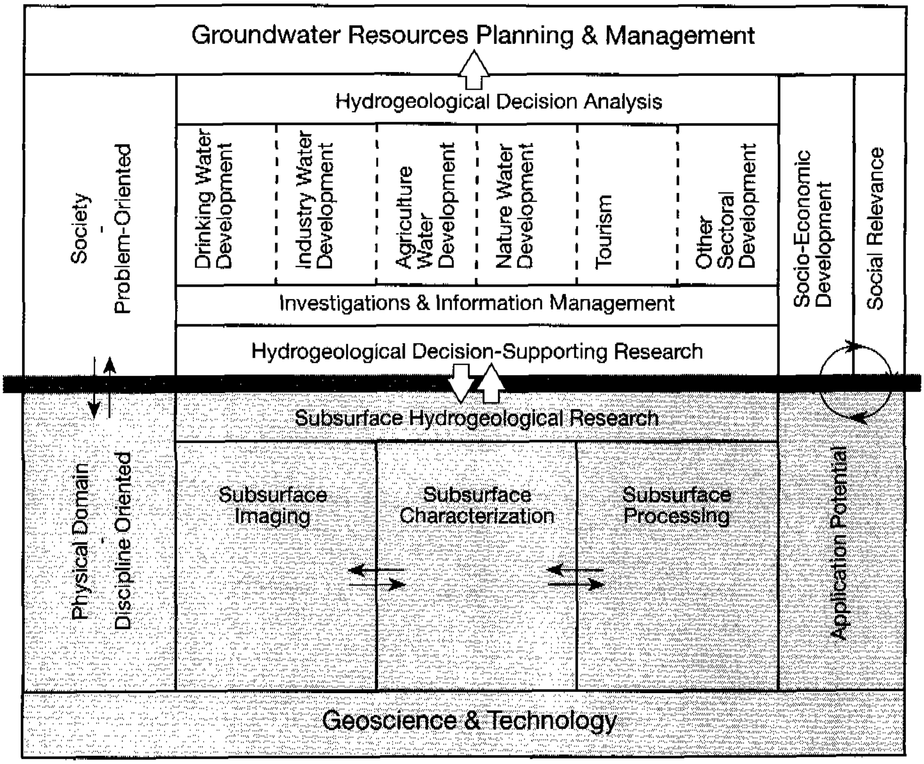


Figure 1 Subsurface Hydrogeological Research and Hydrogeological Decision-Supporting; Research Towards Sustainable Use of Groundwater

3.1 Subsurface hydrogeological research

Subsurface research may be formulated along different scientific angles, presented as subsurface imaging, subsurface characterization and subsurface processes.

Subsurface Imaging

Subsurface imaging aims at determining the structural properties of subsurface elements. The structural properties primarily comprise the geometry - depth, thickness, lateral extent - of the subsurface elements. The methods to determine the structural properties include drilling, surface geological surveys, surface geophysics (seismic, electromagnetic, resistivity), geophysical measurements between boreholes and the surface, and around and between boreholes. Various processing, geostatistical and interpretational methods can be applied to analyze the images. Some of the methods used to determine the structural properties are also used to determine material properties of subsurface elements.

Subsurface Characterization
Subsurface characterization aims at determining the various properties of the subsurface elements determined. These properties include the hydrogeological and geotechnical parameters of the subsurface elements, as well as physical, chemical and biological properties of the water contained in the subsurface matrix. The methods to determine the material properties include, next to the previously mentioned geophysical measurements, borehole cuttings analysis, water sampling, outcrop analyses, subsurface in-situ measurements and laboratory measurements of samples. Geological modelling, geostatistical techniques and systems analysis can be applied to analyze the data. A number of methods used in the determination of material properties are also used to analyze subsurface processes.

Subsurface Processes
The study of subsurface processes aims at analyzing processes acting within and between the subsurface elements and at the interaction between the subsurface and the processes at the surface. The processes mainly include the natural and man-induced flow of groundwater and the interaction between the groundwater, the water in the unsaturated zone and the surface water. Water is also the transport medium of chemicals and other substances which interact with the fractured media. The methods to analyze the natural and man-induced processes include monitoring and flow systems analysis.

3.2 Hydrogeological decision-supporting research

In groundwater management and, in a stricter sense, groundwater development, strategies must be evaluated and design decisions made for projects in which the hydrogeological environment plays an important role. In development decisions and/or management planning which require the knowledge of the hydrogeological environment, uncertainty as to the system properties and expected conditions is far greater than in most other 'engineering' designs. A distinction is made between (ground)water development and (ground)water resources management.

Groundwater Development
Groundwater development aims at the design of optimum production strategies for groundwater. It may mean the design of a well field to supply water to a community; the design of an agricultural drainage scheme; the design of the hydrogeological isolation of a waste dump. The methods to be used include the application of simulators, data acquisition and simulation with decision analysis.

Groundwater Resources Planning and Management
The groundwater production strategies developed above form an inextricable part of a wider, strategic plan for water resources planning and management: groundwater is not only produced but it must also be properly conserved and adequately protected against quality degradation. In general, groundwater management includes interventions by government agencies in the behaviour of individuals, for the sake of the general interest and that of future

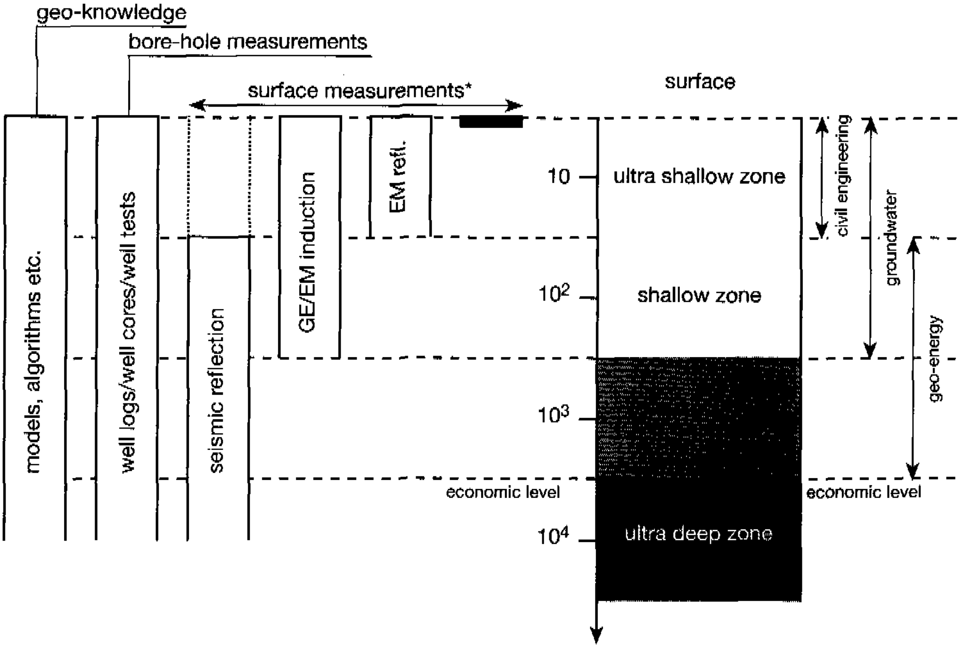
generations. Groundwater resources planning and management integrates the know-how of hydrogeological research in a much wider multi-disciplinary framework which operates under the constraints posed by the environment and the economic and social development objectives. The methods in groundwater management include the application of various optimization and simulation models, uncertainty analysis, decision analysis and multi-criteria techniques.

4 STATUS OF HYDROGEOLOGICAL RESEARCH, DEVELOPMENTS AND NEW METHODOLOGIES

4.1 Subsurface hydrogeological research

4.1.1 Subsurface imaging

The subsurface imaging techniques (see Figure 2) have the objective to gain hydrogeological structural information of the subsurface. Imaging involves mapping or delineating subsurface elements, i.e. drawing their boundaries. In hydrogeological studies, groundwater flow models require insight in the hydraulic properties over the total width and depth range of the flow region. The lack of information extends thus over the total range, with a growing demand for more detailed information in the shallow zone.



* including airborne

Figure 2 Geoscience Applications Related to the Different Levels in the Subsurface, and the Sources of Geoscience Information (Source: Berkhout, Speelman, 1992)

In mapping the boundaries of the groundwater flow system(s) geophysical imaging techniques and geologic modelling play an increasing role and are further outlined below:

- Geo-electrical methods have been used extensively to map boundaries between fresh and saline water and the occurrence of sandy and clayey layers.
- Electro-magnetic measurements have been in use for mapping pollution zones around waste dumps, mapping buried channels and mapping fractures.
- High resolution seismic reflection measurements have been developed for groundwater applications during the last decade, but this method is up to now rarely applied to hydrogeological problems because of the costs and because it is relatively unknown to hydrogeologists; the upper 20 meters are not imaged.
- Georadar (ground penetrating radar or GPR) is a technique in development in the last decade. It is extremely useful for mapping the unsaturated zone and groundwater levels.
- Geophysical well measurements yield detailed information on subsurface formations and water quality, used in the interpretation of geophysical surface data. The results are also used for the interpretation of the geophysical surface data. They do not yield information about properties changing laterally.
- Geological modelling can be applied for imaging and for characterizing the subsurface. Next to the common technique of deterministic modelling, new techniques, such as process based modelling and stochastic modelling, are frequently used in modelling hydrocarbon reservoirs, but not yet systematically applied in groundwater studies.

Table 1 shows that all depth intervals are covered with at least one technique and that no geophysical technique is capable of imaging all depth ranges optimally.

Table 1 Imaging Capability of various Techniques (Source: Meekes, 1992)

Technique type	Potential	Diffusive	Propagating	Propagating	Geophysical Well *Logging*	Geological Modelling
Technique	geo-electric	electro-magnetic	geo-radar	seismic reflection		
Physical Property	ρ_{cl}	ρ_{cl}	ϵ	V,ρ_{dens}		
Depth range:						
Shallow	+ -	+ -	+	no signal +	+	+
Deep			no penetration		+	+

New Developments:

Shallow Zone

The occurrence and detection of an increasing number of pollution problems puts a premium on the development of techniques which provide the necessary information which enables the hydrogeologist to construct detailed models for flow and flow control.

- Electromagnetic techniques have a large potential for shallow groundwater studies. They are being applied, but there is scope in the development of different measurement configurations, and processing algorithms (inversion tools).
- Radar techniques are gaining in popularity world-wide; its data acquisition, processing and interpretation can further be improved.
- Resistivity surveys may be useful for determining the amount of organic waste in the shallow subsurface by assessing a frequency-dependent resistivity; this cannot be done using the electromagnetic technique.

Faster and more data acquisition is more likely to be achieved by radar and electromagnetic techniques as no electrodes need to be planted. The application of micro-electronics in geo-electrical instruments, such as the GEA-58 developed by TNO Institute of Applied Geoscience, improves the quality of data. The same needs to be done for electromagnetic instrumentation, e.g. the development of a multi-receiver frequency domain electromagnetic instrument.

More intelligent inversion schemes for resistivity mapping are required, incorporating principles of geological modelling. Three-dimensional geo-electrical and electromagnetic measurements applying many sensors (comparable to the seismic reflection method) may be an efficient way of acquiring data for 3D imaging.

Example of Georadar

Georadar is a new geophysical technique which, under favourable conditions, provides detailed continuous images of the shallow subsurface to a depth of 40 m. Research is being carried out aiming at attuning data acquisition, processing and interpretation of ground penetrating radar to hydrogeological and related environmental and ecological applications. Georadar test surveys, with objectives defined by the 8 Dutch water supply companies collaborating with TNO Institute of Applied Geoscience in the project, have been conducted at 20 sites in the Netherlands. Figure 3 represents a discontinuity in the water table imaged by georadar and confirmed by test drilling. Georadar proved to be successful for four types of target:

- Mapping water tables in sandy deposits found in push moraines, river terraces and sand dunes (not strictly imaging).
- Mapping perched water tables and distinguishing them from true water tables (not strictly imaging).
- Mapping tectonic structures.
- Mapping sedimentary structures, such as the determination of the lateral extent and continuity of clay and peat layers.

Further research is needed concerning the improvement of the processing and interpretation of radar images, using seismic data processing techniques.

Deep Zone

The deep zone (> 40 m) is vulnerable to pollution in the more distant future. Next to exploration drilling, seismic reflection is the only method to provide detailed structural information in the deep zone. A combination of geo-electrical and electromagnetic techniques is useful when mapping the quality of water in this depth range. The relation between the physical and hydraulic parameters of high resolution seismics and combined electromagnetic/geo-electrical techniques need to be further clarified. For this depth zone, much efforts are required as the lay-out of the instrumentation must be appropriate to the depth studied. A data acquisition system of relative small size is feasible only for time-domain electromagnetic applications. No such system is on the market yet.

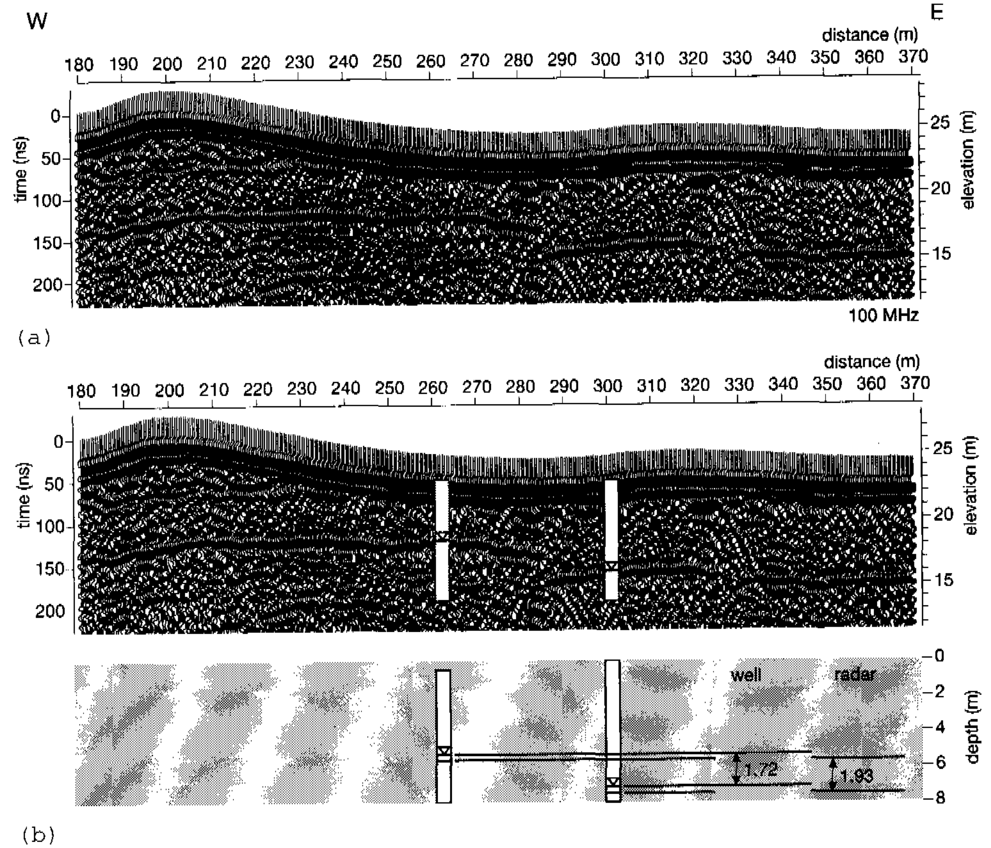


Figure 3 (a) Georadar Section with Offset in Groundwater Reflector; (b) Groundwater Step Confirmed by Test Drilling (Overmeeren, 1993)

4.1.2 Subsurface characterization

Subsurface characterization aims at assigning hydrogeological parameter values to the subsurface elements identified through subsurface imaging. The previously mentioned geophysical techniques are also applied in subsurface characterization. The potential capability is depicted in Table 2 (Meekes, 1993). The estimation of hydrogeological parameters using geophysical techniques however is indirect and often gives ambiguous results.

More direct methods include the analysis of outcrops, aquifer tests, subsurface in-situ measurements and laboratory measurements of samples. These methods however give point measurements and give no information on the lateral variation of the parameter values of the subsurface elements. As regards geophysical borehole measurements, the development of cross-hole measurements (geo-electric, electromagnetic and seismic), which is already an operational capability in geo-energy applications, may be important in defining the distribution of the physical and related hydraulic properties more accurately.

Table 2 Parameter Determination Achieved by Various Imaging Techniques

Technique	Geo-Electric	Electro-Magnetic	Geo-Radar	Seismic Reflection	Geophys. Well Logging	Geological Modelling
Parameter						
Lithology						
Permeability	+	+	+	+	+	+
Porosity	+	+	0	+	+	+
Specific Storage Coefficient	-	-	-	related n.y. applied t.b. studied	?	?
Heterogeneity	+, if applied in combination		+	+	+	+
Water quality	+	-	+	-	+	-

New Developments:

Geologic Modelling

During the past 10 years scientific activity has gradually turned towards understanding the basic physics of porous materials. Recent technological development, resulting in very advanced, high performance computer systems has made it possible to model details beyond the quantitative knowledge. This has led, first in the oil industry, to a renewed interest in the further development of modelling tools and detailed geological models. Parallel development in hydrogeology, also led to an increased use of stochastic modelling techniques for the characterization of the subsurface. Approaches in stochastic modelling techniques, presently researched in the oil industry, are also of interest to the field of hydrogeology.

Three modelling techniques may be distinguished in geological modelling (Elewaut, 1993): (i) empirical or deterministic modelling generating distributions of geological heterogeneities based on geological knowledge, the traditional technique (ii) stochastic modelling, generating stochastic distributions of geological heterogeneities based on statistical descriptions of so called analogues, and (iii) process-based modelling involving the modelling of the physical process that generate geological heterogeneities.

Deterministic or empirical modelling has been going on in the minds of geologists ever the since the concept of actualism had been developed. It uses the empirical experience geologists have gathered over time to build geological architectures. The technique uses the observations or measurements within the 'to be modelled' environment, interprets them in terms of origin and evolution and applies deterministic geological 'laws' to it to build a geological model that according to his best knowledge would be the truth.

Stochastic modelling generates a statistical representation of possible geological situations based on statistical descriptions of so called analogues. The modelling technique is typically used in situations where a geological model has to be inferred from a limited amount of data (e.g. a limited amount of wells in a heterogeneous aquifer). The problem with these techniques is that in geology, there is no such thing as an analogue. Large differences between geological units or structures may occur as a result of differences in the sedimentary setting, the burial history or geochemical evolution and models will always have to be build taking into consideration the margins of uncertainty. There are two approaches:

- Object based modelling is a technique that creates random distributions of well defined bodies or events in an otherwise uniform matrix. The technique is suited for the modelling of river channels (sandstone) in broad river plains (clayey matrix), for the modelling of interdune lake sediments (clays), in desert environments (sandstones), for the modelling of patchy post depositional cementations or for modelling subseismic faults and fractures (geometrical scales between metre and tens of metres). One technique consists of locating centre points for the objects and define for those centre points a thickness for the objects to be modelled. Based on reservoir analogue data, the thickness would automatically be connected to a width, length and orientation of the object to be modelled. This technique depends heavily on outcrop data.
- Sequence based modelling is a technique that creates continuously varying (hydrogeological) conditions in a presumed overall homogeneous matrix. This technique intends to model continuously varying (petrophysical) parameter values in a certain hydrogeologic environment. The technique would typically be used to model more or less small scale variations within single sedimentological units. Typical examples are the modelling of variations in porosity and permeability in carbonate rocks, the modelling of grainsize distributions (permeability) in channel sands or the modelling of diagenetic events along larger scale fault systems (geometrical scales between centimetre and meters). This technique uses information from semi-variograms that are the result of outcrop measurements or from data from densely drilled fields.

Process-based modelling physically models the genetic processes that would generate heterogeneous structures. Modelling the physical processes is a difficult task, requiring an understanding of very complex processes. There are many different parameters that are often unknown and therefore need be inferred or estimated by the scientists. Modelling these complex physical processes requires computer facilities that are often beyond the present possibilities of the technology and simplifications are necessary. Using these techniques helps to understand the physics of the processes, unravels the complexities of the processes and highlights the knowledge gaps. Different process based techniques that are currently being developed or used are:

- Large scale basin modelling, based on rates of subsidence and sediment deposition; these techniques generate models with geometrical scales of the order of tens of kilometres to even hundreds of kilometres, they deliver the basic framework for large scale stratifications

and large scale faulting.
- Intermediate scale basin modelling, based on sedimentological or structural processes on the scales between tens of meters and a few kilometres; typical examples are the development of outbuilding deltas, river fills by meandering river systems resulting in distributions of channels fills, bar sands and overbank sediments, geomechanical modelling resulting in faults, folds and flexures as a result of stresses;
- Small scale modelling, based on sedimentological or structural processes with geometrical scales in the order of a few centimetres to tens of metres; typical examples are the generation of fractures as a result of compaction, permeability heterogeneities as a result of ripple formation in dunes or fluvial channels.

There are constraints: none of the modelling techniques would result in one unique solution for the characterization of the flow system. The spread in solutions would strongly depend on the uncertainty of the data and the algorithm used. In order to fulfil the requirements for stochastic modelling, a number of data sets should be available for each sedimentary facies (fluviatile, deltaic, turbiditic, near shore, aeolian, etc.) to provide a critical mass for statistical data manipulation.

In the short term, the lack of sufficient data may prevent the wide-spread application of these techniques in the field of hydrogeology. In the longer term, as more data become available, the development of these techniques present an interesting prospect.

4.1.3 Subsurface processes

Subsurface processes aim at analyzing processes acting within and between the subsurface elements, such as the natural and man-induced flow of groundwater and the interaction between groundwater and surface water. Until the 1960's and even beyond,hydrogeologists concentrated on the exploration and study of the occurrence of fresh, saline and brackish groundwater, but most of their work was related to groundwater flow. E.g. in the framework of the selection of favourable aquifer zones and sites for well fields, or to predict possible declines of the phreatic levels.

The nature of the problems and the concentration, primarily on promising aquifers to be found more easily in the unconsolidated sediments, where sandy aquifer beds alternate vertically with clayey aquitards, stimulated the hydrogeologists in the so-called 'aquifer approach' (see Figure 4). Within aquifer beds, attention was paid to lateral variations, while vertical variations were assumed to be negligible; for computations and simulations, 2D- or quasi 3D models were considered satisfactory. Aspects of water quality, except those of the fresh-saline interface, were not considered.

Under the steadily improving detection limits of water quality analysis in the laboratories and under the strongly increasing pollution loads by modern agriculture, the views on groundwater quality quickly changed during the last decades. Explaining the pollution patterns, and especially predicting how the bodies of polluted groundwater will move through the aquifer system, met with considerable problems. Thinking in lithologically defined units in the 'aquifer approach' was a barrier to the proper understanding of the migration of solutes (Van der Gun et al., 1992).

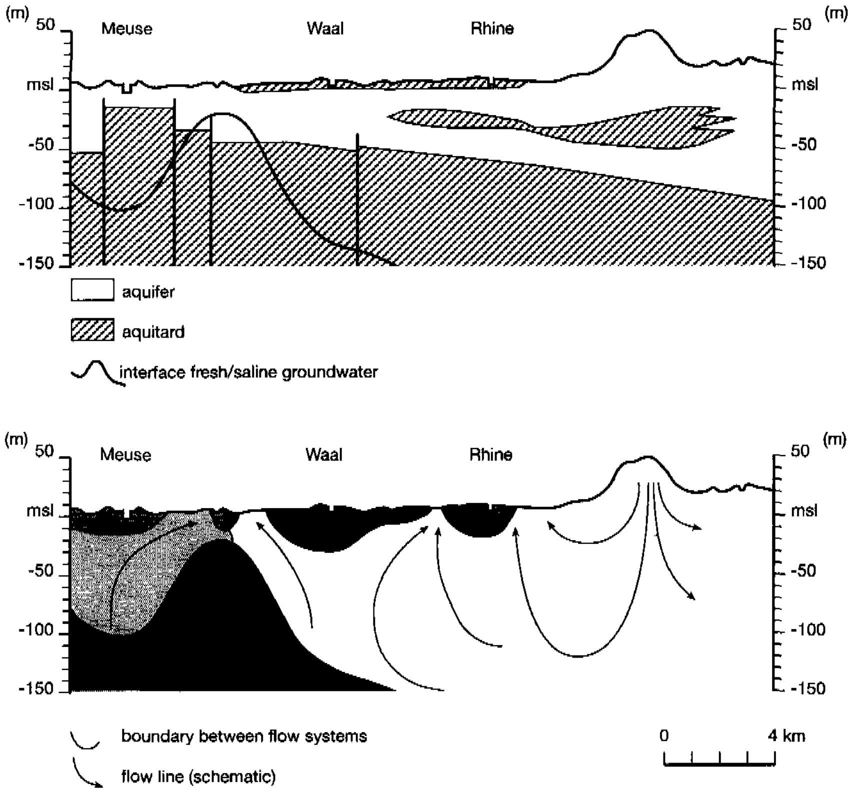


Figure 4 'Aquifer Approach' (top) and 'Groundwater Flow Systems Approach' (bottom) (source: Van der Gun et al.,1992)

Adopting the 'groundwater flow systems approach' (see Figures 4 and 5) - originally developed by Tóth (1963) and complementary to traditional approaches - has caused a breakthrough and provides a useful key to understanding and evaluating groundwater pollution processes. It allows a better understanding of how and to what extent control of aquifer contamination is feasible. Here the orientation is towards the qualitative definition of groundwater bodies. Aspects of flow caused by recent groundwater development are more difficult to assess. Although in many developing countries groundwater pollution is not yet considered as a first-order problem, it may become so in the near future and the flow systems approach may prove equally valuable.

New Developments:

Transport and exchange of dissolved substances

The ability to characterize the subsurface fluid regimes is already quite developed. However, further advances can be made, both conceptionally and technologically if the functional role of groundwater is emphasised as topics for further research. Töth (1990) promotes the perception of groundwater as a subsurface geologic agent.

Moving groundwater dissolves and precipitates mineral matter through chemical processes, mobilizes, transports and deposits mass mechanically and is the subsurface component of the hydrologic cycle. The reason for this geologic agency of groundwater is the systematic, pattern forming, distribution of regional flow (Figure 5).

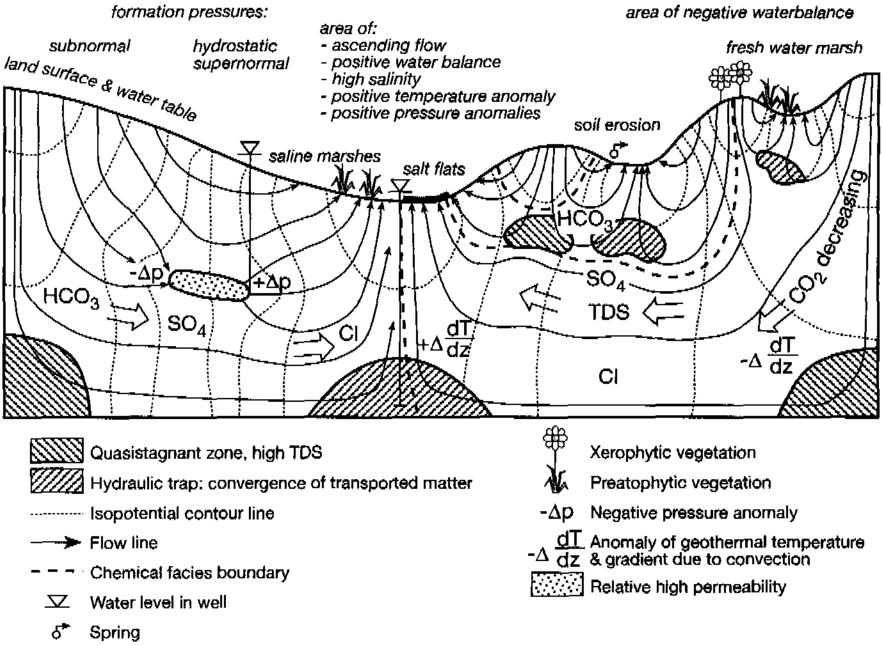


Figure 5 Regionally Unconfined Groundwater Flow and Transport and Exchange of Dissolved Substances (Töth, December 1992)

The function of groundwater as a geological agent is manifest in the development of geochemical transport models. Geochemical transport models combine the functionality of a geochemical model - which describes the development of water qualities within a batch of water - with a transport model, to calculate the evaluation of water quality along a flow tube. An example of this approach is the modelling of the fresh-/sea water displacements in aquifers with a geochemical transport model incorporating ion-chromatography in the geochemical exchange model. The ion chromatography of cation exchange allows a historical interpretation of water flow in both space and time (Appelo et al., Free University, Amsterdam, 1989).

Further research in the characterization of flow regimes should be aimed at improving the ability to characterize the natural controls on, and the parameters that describe, the basin-scale movement of groundwater and its dependence on time. Improvements are needed on (i) flow pattern geometry, (ii) flow rates and (iii) long-term transient conditions of flow (Tòth, 1992).

Flow-Pattern Geometry

In groundwater flow-patterns the different geologic locations and conditions in the inflow and outflow regions of the various flow systems cause significantly different dynamic, chemical and thermal conditions in the different systems. Research should concentrate on the identification of subsurface chemical, mineralogical, isotopic or other indicators of flow; the study of vertical gradients of pore-fluid pressures and the systematization and cataloguing of field indicators (plants, soil types, salinities, rock conditions. The production of thematic hydrogeological maps prepares the way for the use of remote sensing models in groundwater mapping.

Flow Rates

Research should be conducted to develop theories, methods and techniques for the description and measurement of hydraulic parameters representing the rock framework at scales appropriate to the spatial and temporal scales of specific problems at hand, including quantifiable criteria for distinguishing between rock masses of fracture- and equivalent porous-medium permeability.

Long-term Transient Conditions: the rates, timing and controlling factors

The recognition and characterization of groundwater flow-conditions that are transient on time scales not in reach of human observation is indispensable to the solution of groundwater-related problems in the applied geosciences such as the determination of the source of natural hydraulic gradients for purposes of water-resource evaluation (e.g. the Nubian and Kalahari aquifers), the prediction of flow paths through radioactive waste repositories consequent upon possible future changes in boundary conditions, and so on. Research should include the identification of possible driving forces that contributed to the generation of now extinct or transient flow-systems; estimating the timing of the origin, and the degree of adjustment to current boundary conditions, of presently transient groundwater flow-systems, and the reconstruction of paleo-patterns of already extinct, or currently transient, i.e. modified, flow systems.

4.2 Hydrogeological decision-supporting research

4.2.1 Groundwater development

Groundwater development in the hydrogeological context may be defined as the design of optimum groundwater production strategies, whereby the management of the dynamic processes in the subsurface are based on technical and economical criteria. The process of standard engineering design is often described as a sequence of decisions between alternatives under conditions of uncertainty. The type of engineering projects that arise in the groundwater industry particularly fulfils that definition: uncertainty as to the system properties and expected conditions is far greater than in most traditional engineering practice.

New Developments:

The approaches to optimization in groundwater engineering projects nowadays combine several types of simulation models such as the combination of data acquisition and simulation with decision analysis or uncertainty analysis with simulation. A further step of integration, - incorporating data acquisition, uncertainty analysis, simulation and decision analysis into one single analysis framework -, is described in a recent series of papers by Freeze, Massmann et al. in the journal 'Groundwater' (1990, 1991 and 1992). The focus of these papers is on groundwater-related 'engineering design' and coined 'hydrogeological decision analysis'.

4.2.2 Groundwater resources management

Sustainable development of groundwater resources, - in the sense that groundwater is not only developed but that it is also properly conserved and adequately protected against quality degradation - , is world-wide still in its infancy. In general, groundwater management implies interventions by a government agency in the behaviour of individuals, for the sake of the general interest and that of future generations. Among the many aspects of groundwater resources management, strategic planning is of paramount importance; it determines what should be done to maximize benefits and minimize problems. In the process of strategic planning (sometimes called 'policy analysis'), alternative strategies for groundwater resources management are developed and compared, in order to select the most appropriate one.

Until recently, hydrogeologic studies in support of groundwater resources management used to focus on data acquisition or - since the late 1960's - on groundwater hydraulic simulation modelling, or on both. Gradually the flaws in these approaches became evident: (a) simulation results in hydraulic or chemical terms are often not particularly suitable for decision-making; (b) decision-making should be guided by some kind of decision-model; (c) full attention should be paid to the uncertainties regarding the groundwater systems, because they affect the reliability of predictions made.

Development of methodologies for strategic planning of water resources management is of relatively recent date. Methodologies available nowadays recognize the importance of explicitly stating water resources management objectives and related criteria; they usually contain a framework of interconnected optimization and/or simulation models. Sometimes they include more or less sophisticated techniques that provide guidance for decision-makers if several objectives are considered simultaneously (multi-criteria techniques). Most of the current approaches in strategic planning are deterministic still, in spite of the many uncertainties involved. This leaves in practical applications often questions as regards how reliable the selection of 'preferable strategies' really is.

New Developments:

The concept of hydrogeologic decision analysis by Freeze at al, referred to above seems suitable to be extended to the field of groundwater resources management. The framework of analysis envisaged (TNO Institute of Applied Geoscience, internal report, 1992) defines the overall procedures in water resources management studies and specifies the linking of the different modules in this framework. A provisional picture of its structure is shown in Figure 6 (modified after Freeze, Massmann et al. 1990). It conveys ideas on how to structure the analysis for water resources management and which components of analysis are included. Conceptually, the approach outlined by Freeze, Massmann et al. (1990) is closely followed.

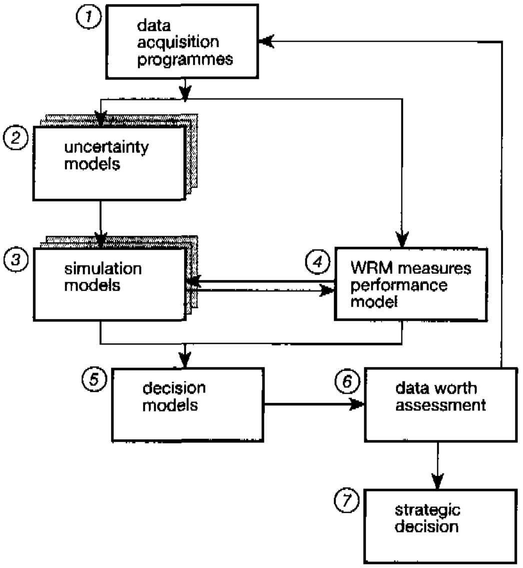


Figure 6 Proposed Framework of Analysis for Water Resources Management Studies (modified after Freeze, et al, 1990)

Data acquisition programmes (box 1) are a conventional element in any water resources management study. The novel feature in Freeze's framework is the direct feed-back (via data worth assessment) from the decision model to the data acquisition model. This is possible if the uncertainties related to the groundwater system are made visible in the outcomes of the decision model as a risk term. The trade-offs between risk and additional data acquisition provides a guideline for efficient data acquisition planning.

Uncertainty models in the framework (box 2) may be based on stochastic and on search techniques. The uncertainty of parameters and variables can be represented by estimated probability density functions and auto-correlation functions. Kriging may be used to adjust interpolated values and uncertainty parameters after new data are added. Freeze, Massmann et al. (1990) suggest that search techniques may be used to efficiently reduce geological uncertainty. Kalman filtering techniques have been widely used by TNO Institute of Applied Geoscience to take into account uncertainties in interpolated groundwater levels. Propagation of the uncertainty through the simulation models can be done by various methods, among others by Monte Carlo simulation.

Simulation models (box 3) will in the first place include groundwater piezometric models. A wide range of 2D, 2.5D and 3D model codes is readily available; if two fluids have to be taken into account (sharp interface models) or continuously variable groundwater densities (solute transport models), the choice is more restricted. In many cases it will not be sufficient to model the hydraulics of the groundwater system only: connected systems, such as surface water flow and allocation models, agrohydrological models, agricultural production models, economic models, etc. will have to be developed as well and linked properly to the groundwater model in a 'modelling framework'. Examples of how to apply these to water resources management are the TNO-assisted water resources management studies for the Surdud Area and the Marib Area, Yemen (Van der Gun et al., 1991; Saif et al., 1993).

A water resources management measures performance model (box 4) links measures to strategies and decision variables. The need for such a model is particularly clear in the case of administrative measures such as economic incentives or enforcements. The model will estimate the behaviour of individuals under influence of such measures; this will provide input to the simulation models regarding the values the decision variables will assume under the management strategy considered.

A decision model (box 5) relates strategies to water resources objectives, making use of objective functions that have to be optimized. A relatively simple approach is to use a single cost-benefit-risk objective function (see Freeze, Massmann et al., 1990). In a multi-objective setting more complex multi-criteria decision models have to be used; impressive progress was made in recent years in this field, resulting in a wide range of methods now available.

Data worth assessment (box 6) may yield information on the worth of proposed field work prior to actually carrying it out *(pre-posterior analysis)*. The worth of additional data collection depends on the ratio between risk reduction and cost of field work.

5 CONCLUSIONS

The research and further development of products and services to underpin a sustainable and environmentally sound management of the groundwater resources should aim for the following results.

5.1 Subsurface hydrogeological research

Subsurface Imaging
To produce a detailed and accurate image of the subsurface; it is important to be aware of the large amount of knowledge on data acquisition, processing and interpretation developed in the petroleum industry and interpret this knowledge to electromagnetic imaging methods for the shallow subsurface and to airborne geophysical/remote sensing methods for the surface.

Subsurface Characterization
To produce precise values for the hydrogeological parameters of the subsurface; geological modelling should be advanced into a quantitative discipline where models are also validated;

Subsurface Processing
To produce an accurate description of both natural and man-induced fluid flow and geomechanical processes in the subsurface and to produce an accurate insight in the environmental effects-both abiotic and biotic - of subsurface processes, especially those that

are man-induced. It is increasingly realised that the integration of technical sciences with geoscience is essential with respect to sustainable development. Environmental hydrogeology should be developed rapidly, e.g. for the remediation of polluted sediments, the preservation of natural groundwater systems and related biotic values, and for the remediation of land subsidence.

5.2 Hydrogeological decision-supporting research

Groundwater Development
To apply decision analysis to engineering design for water development projects. The approach includes the coupling of decision models based on a risk-cost-benefit objective function, a simulation model for groundwater flow and transport, and an uncertainty model for both geological and parameter uncertainty.

Groundwater Management
To produce an accurate modelling framework for strategic, problem-oriented planning in groundwater management under conditions of uncertainty, applying hydrogeological decision analysis and integrating technical, economical and ecological criteria.

5.3 Derived products and services

Continued research and integration of the various hydrogeological disciplines has caused a surge in data generation. Efficient, dedicated monitoring networks to optimize data collection and hydrogeological information management systems to process, manipulate and analyze data and support hydrogeological research and groundwater management practices are going to become more and more important.

This wealth of information needs to be efficiently disseminated to the right public, at the right level and by the right institution(s) in a well-developed research and management infrastructure. As hydrogeological research and water management infrastructure is often less developed, research activities in international cooperation should include the strengthening of local research and management capacity through transfer of knowledge.

Additional activities which are an inherent part of the hydrogeological research effort should strive for the following results.

Hydrogeological Monitoring Networks
To produce guidelines, methodology and standardization in the design and implementation of dedicated hydrogeological monitoring networks to optimize the acquisition of long term continuous data sets.

Hydrogeological Information Management Systems
To support hydrogeology related activities by information management systems; further progress should be made towards the development of a common data science model, which includes geophysical imaging, hydrogeological characterization, flow simulation and groundwater development. Large economical and ecological risks can be avoided if measurements and simulations are regularly repeated (monitoring) and predictions are carried out dynamically to allow adaptive control. This will be the major challenge for the nineties

and beyond.

Transfer of Hydrogeological Know-How
To ensure an efficient dissemination of hydrogeology-related knowledge, important to students, policy makers and the general public, and to promote the development and strengthening of institutes in the developing countries in charge of groundwater resources management.

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APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS

A.M.J. Meijerink

ABSTRACT

The groundwater issues related to development and management depend on interaction of the storage characteristics, the recharge and the demand. Therefore the way remotely sensed imagery GIS is used depends on the main issues, which shows the versatility of both tools. The practical application by hydrogeologists from developing countries of remote sensing and GIS is illustrated by way of five examples. The first one is related to ecological management to safeguard future good quality water supplies in a part of West Java, the second one to a prognosis with regard to a famous groundwater wet land in southern Kenya. The third example illustrates briefly the combined use of RS and GIS for assessing the recharge. The analytical capacity of a GIS for groundwater assessment in the Dry Zone of Sri Lanka is mentioned in the fourth case, while the fifth illustrates the groundwater planning function of a GIS.

1 INTRODUCTION

In hydrogeological studies Remote Sensing (RS) and Geographic Information Systems (GIS) are tools. RS offers a comprehensive unbiased and detailed view of the terrain and this information should be handled not by a remote sensing specialist but by an experienced hydrogeologist. GIS has been designed to combine spatial data of different nature. It has a strong analytical function and well as data integration capability. Too often groundwater projects have been restricted to the current geohydrological aspects. In our view, the outlook at the medium term and longer term should be considered, including effects of environmental changes and changes in demand. Although both RS and GIS are high-technology products, these tools can be used in a practical manner, as will be explained below, requiring cheap computing equipment and peripherals. The developments in the quantification approaches, i.e. groundwater modelling, has given impetus to the application of remote sensing, because many spatial variables can be derived by remote sensing, although sometimes in an indirect manner. This impetus has been fortified by the use of GIS for preparing the various spatial input data for the modelling, as well as the use of spatial patterns in the calibration process.

There has been an evolution in the application of aerospace imagery (i.e. aerial photography and satellite RS), and GIS to groundwater studies, following the technological developments. The evolution is reflected by the following succession of questions:
- Where is groundwater water? (from the 1950's onwards).
- How much is there and for how long and of what quality? (since the 1970's).
- What is the best management, considering environmental and socio-economic constraints and trends (1990's).

Answers to the last question use Geographic Information System (GIS) because of their capability to:
- Store and retrieve hydrogeological data and ancillary data (rainfall, infrastructure, census data, land cover classifications form Remote Sensing, etc.), which are required for planning of groundwater development.
- Combine spatial information of a different nature for the planning process.
- Analyze and quantify groundwater resources, if coupled to groundwater models and by using data integration techniques, e.g. geophysics, remotely sensed land use or hydrogeologic features, digital elevation models, and so on.

2 HYDROGEOLOGICAL SETTING AND DEMAND

The way how remote sensing and GIS is used depends on the nature of the groundwater management problem vis-a-vis the sustainable groundwater resources. A short overview of the situation with regard to groundwater, with emphasis on rural areas in developing countries, will be attempted first. From a groundwater point of view, three factors have to be considered, the aquifer storage, the recharge as a function of climate and the demand for water, in the form of drinking water, irrigation water, water for industrial use and ecology (base flow, groundwater fed wetland, etc.). These three factors form the axes of the block diagram of Figure 1a. The recharge-storage plane is characterized by the climatic and hydrogeologic conditions. These conditions control the sustainable use of the water and in an ideal case should control the groundwater water demand. The latter is often not the case.

On the demand-recharge plane, Figure 1b, aggravation of problems will take place, in the direction shown, i.e. demands surpassing recharge. The storage-demand plane contains the buffering capacity for dry periods, as well as the rate of depletion. Vectors projected on the axis through the origin represent the level development or output of the groundwater system, which could be expressed as capital investment and the orthogonal axis the magnitude of the loss of capital.

Each compartment of the 'groundwater situation cube' requires different approaches for groundwater development and management. This is reflected on the role of GIS and RS as sketched in Figure 1c. There is a need for good spatial determination of the surface processes and thus the spatial input variables as derived by RS in the quantification of the groundwater resources, perhaps more so when the resources are scarce and geographically variable.

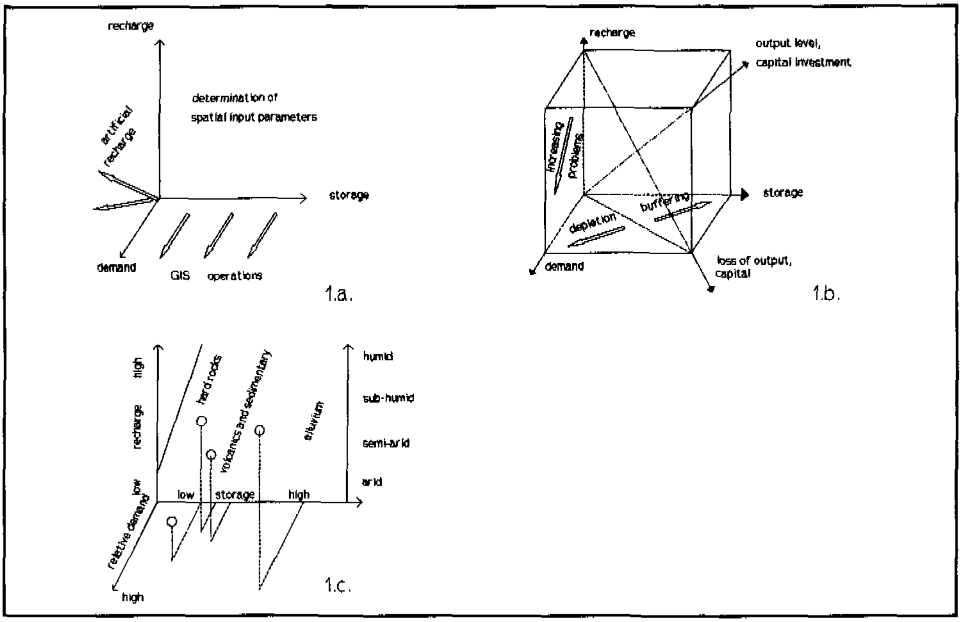


Figure 1 The groundwater situation cube, settings of storage, recharge and demand

An area of low storage, low recharge and a high relative demand is shown in Figure 2. (Indian Remote sensing Satellite, IRS-2). By simple image processing the areas irrigated by wide, open wells are shown in white. From the irrigated acreage, the potential evaporation rate, the cropping cycle and irrigation efficiencies it can be calculated that the total draft equals or exceeds the average effective rainfall. Hence in this particular catchment there is no scope for further groundwater development. Below-average rainfall will cause serious problems to the farming community, and thus the catchment should be earmarked as a priority area for artificial recharge.

If the storage is low, with moderate recharge and low demands, the attention may be directed to establishing water budgets (see the Orissa and Sri Lanka examples below) and formulating policies to avoid a situation as sketched above. The low storage make the areas vulnerable to dry periods. Even in a high-storage, high-recharge environment, timely steps may be required to protect the recharge areas to safeguard the future water supply, as is discussed by way of the Gede-Pangrango example.

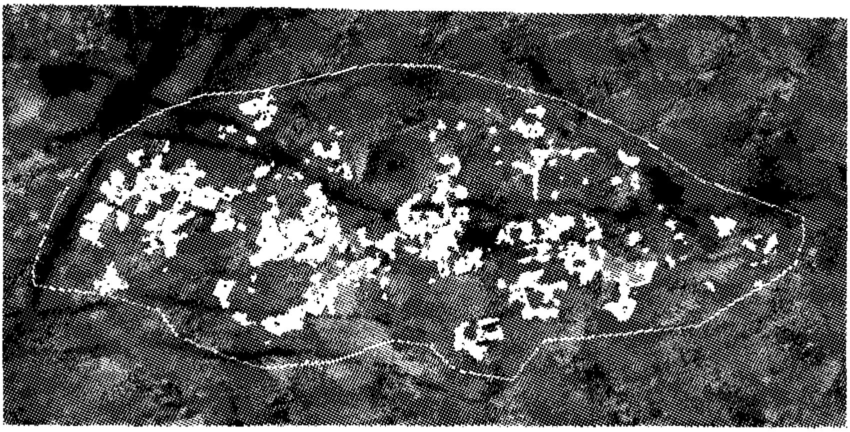


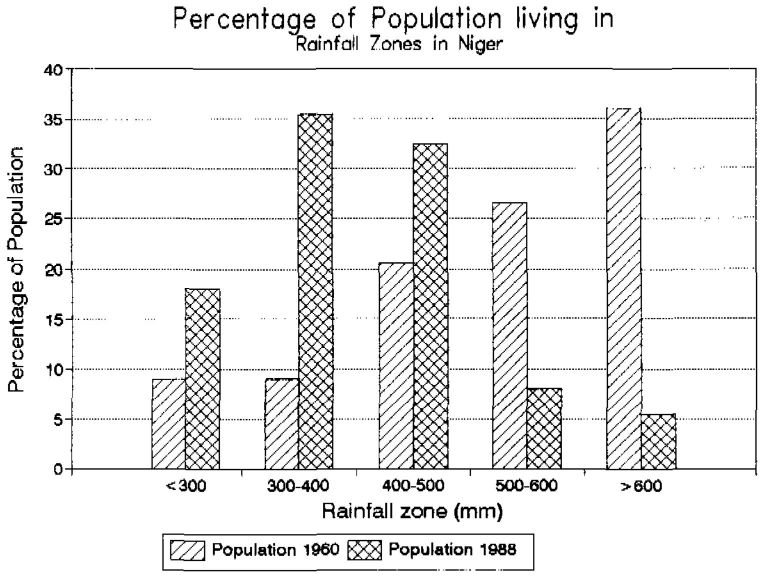
Figure 2 Satellite image (IRS-2) of semi-arid hard rock area, central India. Irrigated areas in sample catchment shown in white, after image classification, for determining water budget

3 OTHER CONSIDERATIONS DIRECTING THE USE OF RS AND GIS

Aerospace imagery, coupled to fieldwork and standard groundwater surveys, should be the backbone of hydro-geological inventories. The synoptic overview of geology, physiography, vegetation covers and settlements make it possible not only to do analytical hydro-geological interpretations, but also to consider other factors of importance in the groundwater development.

3.1 Social and economic considerations

Poor communities have no access to capital and there is the danger of a non-equitable groundwater use. Thus, the low-cost development of shallow groundwater resources may be stressed, through hand dug wells, well blasting cheap tubewells, in some areas bamboo tubewells, which proved to be successful in Bihar (India) (Appu, 1974). In the Anantapur district in India detailed hydrogeological maps of the hard rock terrain have been prepared on request of the district administration for deciding whether a farmer would be eligible for agricultural credit. Only if the - open, wide diameter - well was successful, the loan could be repaid provided the irrigable holding exceeded 3.5 hectares. Anyone knowing the variability of groundwater in hard rock terrain and the small financial basis of most of the farmers in this region realizes the burden on the hydrogeologist. Without the intensive use of stereo aerial photographic interpretation and local experience, such a map cannot be made in an adequate manner. On a more regional scale, a simple but effective illustration of how a GIS operation may be used in analyzing demands is shown in Figure 3. The census data of 1960 and 1980 is overlaid (or crossed) with the isohyetal zones. A remarkable shift of the proportion of the population in Niger to the semi-arid zone may be noted. The effects on the water demand are obvious, considering also the increase of the population.



Source: MHE and UNDP/DTCD, Niger

Figure 3 Shift of proportion of population from sub-humid zone to semi-arid zone in Niger. Chart prepared from overlaying census data with isohyets in GIS

3.2 Infrastructure

The data base of a GIS should contain information on various aspects of the infrastructure. It obviously makes no sense to recommend deep tubewells requiring submersible electric pumps if there is no rural electrification network. This argument could exclude, at least for some time, the development of deeper groundwater. Census data contained in the data base could be queried for the priorities of providing water, e.g. hospitals, schools, and so on, as well as the status of the existing infrastructure for village drinking water supplies. Specific information related to groundwater management should be included in the GIS data base, such as the localization and various types of service centres. Maintenance of pump installations from a technical and organizational/social point of view is a well known bottle neck.

3.3 Agriculture, ecology

Aerospace imagery often forms the only reliable source of information with regard to the irrigated areas, see the example of Figure 2. The natural and semi-natural vegetation can be studied and this may affect the groundwater development. Wrong localization of tubewells in nomadic pasture territory can lead to tensions and to land degradation around the wells because of concentration of cattle. Phreatophytic vegetation and groundwater fed wetland are affected by groundwater development. Hence overlaying in a GIS of such vegetation types, as derived by RS, with the results of simulated lowering of the groundwater level under various assumptions of exploitation will show the effects on the ecology. Soil- and water-conservation works may increase, but reforestation may decrease, the recharge, although it is difficult to make generalizations on these subjects. The results of simulation modelling of the groundwater-soil-plant-atmosphere continuum in a full spatial context still leave much to be desired. Therefore, it is wise to study the trends of the groundwater situation as caused by environmental change. Old aerial photography or even the first satellite imagery of the early 1970's, coupled to rainfall and groundwater level data and records of the base flow in rivers, are very important documents to study the effects of such changes. In our opinion, the empirical determination of the trends carries more weight than the results of deterministic modelling. Monitoring of the vegetation responses by weather satellites has become practice in the drier parts of Africa and the 10-day accumulated vegetation index imagery is produced, also by local organisations such countries as Burkina Fasso, Zambia (Mulenga et al. 1993). The level of information from these images surpasses all other conventional information sources for establishing seasonal groundwater budgets and their temporal variation, because raingauge densities are low in view of the spatial variation of the rainfall, and the status of the vegetation and consequently their evapotranspiration losses remain unknown. Combination of this and hydrogeologic information can be done effectively in a GIS.

4 CASE STUDIES

In order to illustrate the use of RS and GIS, a few examples are discussed, which all have been worked out by individual staff members from groundwater organizations from the developing world in their home countries, within the context of M.Sc. research. Three of the four examples are related to data scarce areas and that is precisely where the RS is the most effective and sophisticated modelling is not applicable because of the lack of data. The first two pertain to groundwater and ecology, the third demonstrates some of the analytical function of a GIS and the fourth includes the planning function.

4.1 The Cibodas Forest reserve and the groundwater supply

The vegetation succession of southern slopes of the Gedeh-Pangrango volcanic complex in Western Java consists of forest on the upper slopes, tea gardens and intensive vegetable cultivation on the upper-middle volcanic slopes and rice cultivation on the middle and lower volcanic slopes, where the town of Sukabumi and many villages are located. The groundwater resources are used for the urban water demand and, in the form of base flow, for irrigation. Since the 1930's the role of forests on the hydrology of the volcanoes has been debated, but there is still little comprehensive data. Emmawan (1991) studied the hydrogeology of the mentioned area and started with aerial photo-interpretation. The attention was drawn to the large number of springs on the middle volcanic slopes, which can be identified easily because spring sapping takes place, creating semi-circular valley heads. The question was raised whether there exists a regional flow system with an intake area at the forested upper volcano, transient flow in the middle volcanic slopes and a discharge area in the middle-lower slopes, feeding the spring discharges. If this was true, there should be large amounts of groundwater available, and of good quality as long as the intake area is forested. In superposition to the regional flow system, local flow systems are likely to occur because of the strong dissection of the upper and middle volcanic slopes, and the groundwater in the latter one could be contaminated because of the liberal use of agro-chemicals, particularly for the vegetable cultivation.

Two-dimensional groundwater modelling was attempted using existing geohydrologic data from the area and data from similar areas. This approach was used with success in a previous study (v.d. Sommen, et al., 1990). Various assumptions with regard to possible configurations of the impermeable base of the sedimentaries below the volcanics, to the geology of the volcanics and corresponding transmissivities, led to various model results. The field work was devoted to measurement of base flow and spring discharges at selected diagnostic locations and hydrogeologic observations, in order to arrive at the most likely one of the modelled situations. The field evidences led to selecting the situation which may be summarized as follows:

- Some 95% of the infiltrated water in the upper forested volcano flows out within that zone itself and forms a reliable supply of clean water. This is a strong argument to stop the trend of upwards shifts of the forest boundary and encroachments within the forest.
- Most of the remaining water (5%) reaches the upper part of the middle slopes. This water can be exploited by deep tubewells at considerable costs, the shallow groundwater is liable to contamination.
- The discharges of the many powerful springs on the middle-lower slopes can be explained by local recharge, in the areas just upstream of the springs.

4.2 Amboseli groundwater wetlands

The tourist industry is a main source of income for Kenya and the Amboseli park is one of the attractions because two large groundwater fed marshes support a variety of large herbivores. The springs are located on the contact of the lower volcanic footslope of the Kilimanjaro and a dry and saline lacustrine plain. However, in 1989, one of the spring-fed swamp area extended suddenly in downstream direction, creating a lake and causing damage to the touristic infrastructure. Furthermore, a rise of about 7 m to 1.5 m below ground level of the groundwater level has been observed in the saline lacustrine plain. There was appreciable concern for the future. Irungu (1992) made an inventory of the hydrological data and attempted to model the groundwater flow system on the northern flank of the Kilimanjaro volcano, which is the recharge area of the large springs. The pressure distribution in all modelling situations is such that water recharged mainly in the Tanzanian part, because of orographic rainfall, should be discharged much upstream of the springs. This is definitely not the case, as was established by inspecting RS imagery and field surveys. It seems that the shallow part of the flow system is tunnelled off, by lava tunnels and fracture flow, to the springs, giving good quality water, whereas the lower part of the flow system with water of higher salt content extends to the lacustrine plain. Discharge measurements in the swamps at various places learned that the size of the swamp, as observed on the RS imagery, equalled the swamp area multiplied by the potential evaporation rate. Therefore interpretations of the swamp areas on old aerial photography (Westen, unpubl.) and on satellite imagery have been used to obtain an idea of the past fluctuations of the swamp area, see Figure 4.

From this it is concluded that since the 1960's or so, no obvious trend seems to occur. The rise of the lacustrine groundwater cannot be explained from the long term rainfall records. It is possibly caused by more frequent runoff inflow into the saline Amboseli lake from the ephemeral Namanga catchment, due to overgrazing in parts of the catchment, although perhaps there could be a tectonic reason (Meijerink et al.). It is not expected that the higher saline groundwater will affect the swamp vegetation, but it will affect parts of the present tree and shrub vegetation. The increase of the cattle population of the Masai is not in favour of decreased flash flows of the Namanga river.

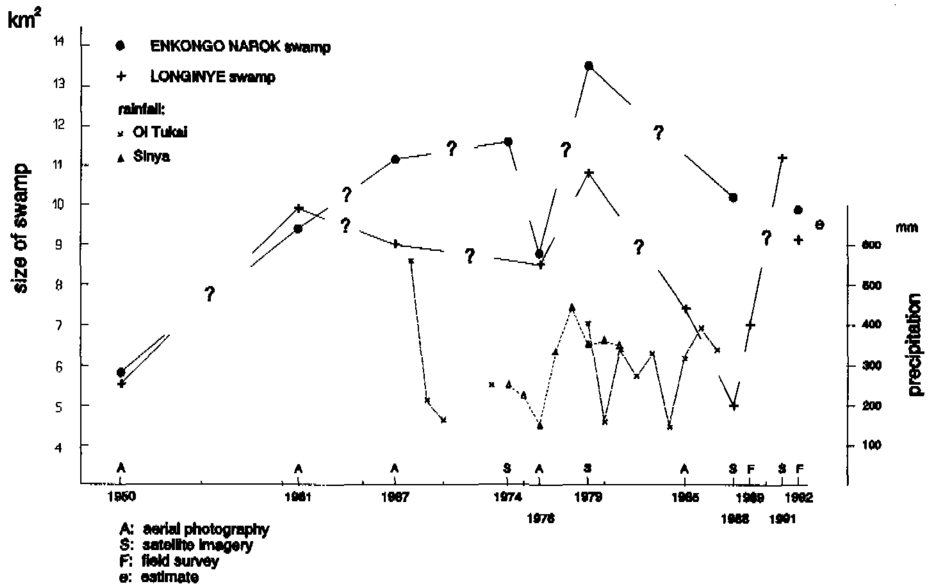


Figure 4 Reconstruction of extensions of the two fresh water swamps in Amboseli National Park, Kenya, used for determining the trend of the discharges of the springs

4.3 Recharge

The annual recharge of a hard rock catchment in Orissa, eastern India, was determined by Joseph (1992) from the base flow to be 7.5% of the annual rainfall (1367 mm). He compared this figure with the one obtained by interpolating in a GIS the groundwater level fluctuations in a large number of wells and the specific yield data for a smaller number of wells, extrapolated by using on morpho-lithological terrain units. The estimate is 9.5% of the annual rainfall. A soil-water budgeting method was developed using cover types derived by RS and water holding capacity per terrain unit as well as the presence of terraced rice lands. The parameters of the fairly simple but fully distributed (spatial) model have been calibrated for use in nearby areas without geohydrologic data. This information is essential for setting the limits for further groundwater development. In addition, an exploratory data set with close wells was available of a small area traversed by one of the many large quartz reefs. Joseph (1992) used a groundwater model (MODFLOW) to establish that a quartz reef transmits much groundwater, probably along the contacts.

4.4 Probabilistic modelling in GIS, Sri Lanka

The analytical capability of the GIS is illustrated by the application of a method which has been developed for ore exploration (Bonham-Carter, 1989). The method was used for the localization of areas with a high probability for high-yielding wells. The weights of evidence modelling is purely based on the frequency of observed occurrences. By selecting and testing the hydrogeologic parameters, Kodituwakku (1991); Hansmann et al. (1992) brought in a deterministic component. The method in itself is not very complex mathematically, but the operations are so laborious that a versatile GIS is needed (e.g. ILWIS). A data base containing data for 1150 shallow tubewells was used for a part of the Dry Zone in north-west Sri Lanka, which consists of basement rocks. A number of geographic parameters have been determined from aerospace imagery and added to the data base. The parameters are related to valley characteristics, distances from drainage divides and from valleys, distances from lineaments in various directions, and so on. Simple tests have been performed to select 'promising' parameters. The GIS was programmed to find the highest weights of evidence for the parameters in the probabilistic model. These weights are used in the overlaying procedure. The result is shown in Figure 5.

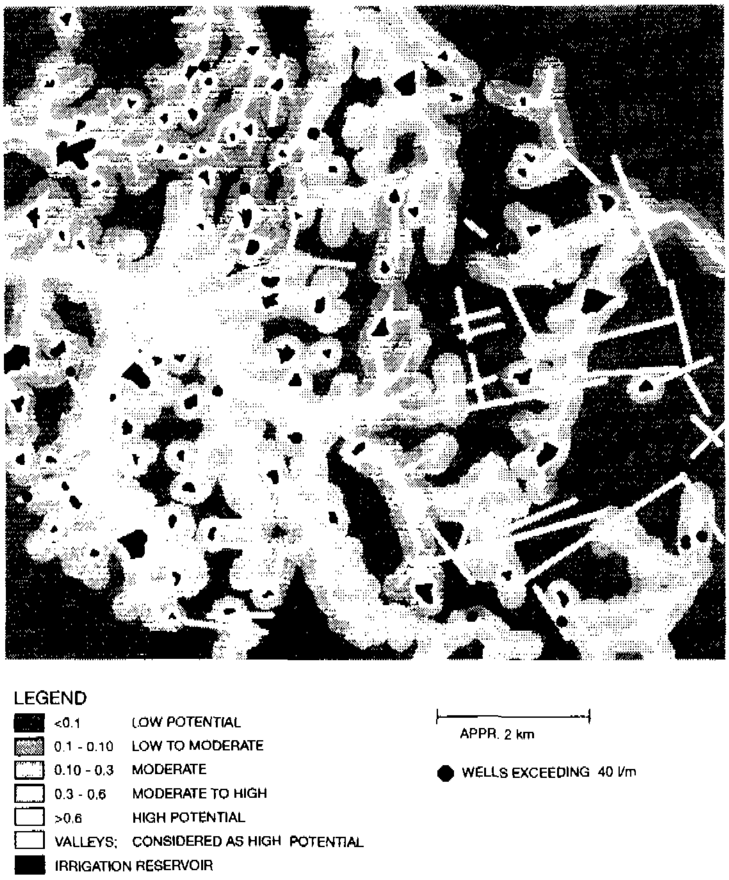


Figure 5 Result of the weights of evidence modelling using GIS for zoning areas for high yielding wells. The highest a-posteriori probability exceeds 60%

According to method followed, there are areas where the probability of drilling high yielding wells is some 60%. As gradually more hydrogeologic information is captured in data bases, the application of the method may be applied to other regions. It is interesting to note that the important parameters in the Sri Lanka case are quite different ones from those used in an expert system for groundwater location in western Africa by Detay et al.(1990). This suggests the highly variable nature of groundwater hydrotopes of the tropical hard rock regions.

4.5 Use of RS and GIS for groundwater resource planning, semi-arid Samburu District Kenya

This example is a simple one, as it was developed to demonstrate the use of GIS for water resources to planners (UNESCO/ITC GIS demo), who have difficulties enough to leave their domain of tables, statistics and trends and are not used to think in terms of spatial locations and dimensions of problems. A map of the present and future water demand was made, using census data, but improving the geographic density distribution by excluding un-inhabited areas, which have been interpreted from remotely sensed imagery by Karanga (1989), who has worked in the district. This water demand map was compared with the groundwater availability map. The latter was difficult to prepare because of the lack of recorded hydrological data and well data. It was decided to work with three data planes in the GIS:

- A meteorologic plane, showing the evaporation versus the rainfall.
- A plane with geomorphological units interpreted from the aerospace imagery, followed up by a field survey. The units have been classified according to their estimated infiltration and water holding characteristics.
- A plane showing the aquifers, in part based on the published 1:50,000 geological map and a fracture and lineament density map from the satellite imagery, classified in four classes.

The spatial rainfall pattern is very poorly known because of the few rain gauges (one per 7,000 km^2 in the northern part of the district). The conventional approaches are shown in the upper two inset maps of Figure 6.

It was decided to use a generalized digital elevation model and a rainfall-altitude regression, resulting in a transformed DEM, see the two lower left inset maps. The remote sensing imagery was used to prepare a rainfall map using the method of Van der Laan (1986), shown in the lower right hand inset map. The high rainfall areas coincide with the forested areas, which, according to the Agro-ecological map (Kenya Soil Survey, 1980) need 1000-1200mm/y. Rainfall shadows with less than 400 mm/y have also been derived from the interpreted vegetation responses.

Hence, there are three rainfall maps in the GIS and none of them correct. A combination of all three was made, placing most weight on the vegetation responses, but honouring the station data. By using a two dimensional table, the first and second data plane contents have been combined, and this produces an estimated map showing classes of potential recharge. This product was combined with the aquifer-aquiclude map to yield the estimated groundwater availability map. A major problem is that, by absence of data and verified transfer functions, these procedures lean heavily on experience and there may be an important component of bias. However, the comparison of the groundwater demand map and the water availability map shows that for most of the area, present demand and availability are in balance. The areas where demand surpasses availability, should be investigated in more detail and with priority. Alternative sources of water storage in the form of small reservoirs should be looked into, and preferably the water filtered through channel deposits below the reservoir dams could be used for drinking water supplies to safeguard health aspects. The areas with estimated surplus could be a factor of importance in regional development planning.

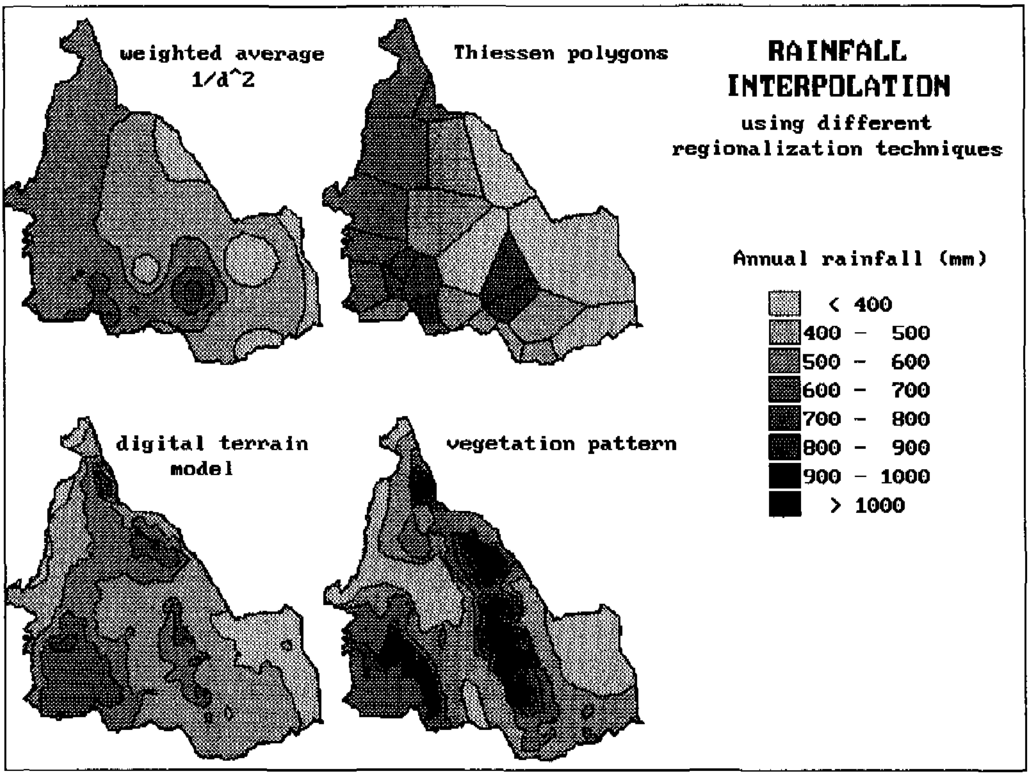


Figure 6 Four isohyetal maps of the large semi-arid Samburu district, Kenya. Conventional methods are shown by Thiessen polygons and interpolation. To obtain improved isohyets, vegetation responses to rainfall interpreted from satellite imagery have been used and regression of altitude (DEM) against rainfall

5 CONCLUSIONS

The use of RS and GIS can be very effective in water development projects, particularly if they are placed in a wider context than that of purely hydrogeologic inventories and groundwater modelling studies. Use of the comprehensive views offered by RS of the terrain can be made, incorporating environmental factors, but also social and economic aspects in the water development projects. The examples given illustrate that experienced hydrogeologists and not remote sensing specialists, should handle the remotely sensed imagery and transformation methods. The same is true for GIS. Both the analytical function and the planning function have been illustrated. All the cases mentioned here have been worked out by hydrogeologists from developing countries. Although the instruments are based on high technology, the application often makes use of simple modelling and reasoning. There is no steep learning curve for the efficient operation of the new tools for solving rapidly practical hydrological problems.

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HYDROGEOLOGICAL ASPECTS OF GROUNDWATER RESOURCES EVALUATION
A Case Study from Semi-arid Botswana

J.J. de Vries

ABSTRACT

Sustainable groundwater resources development should be based on an evaluation of groundwater occurrence, aquifer characteristics and groundwater recharge. The present study reviews the different phases of such an evaluation for a groundwater exploration and evaluation project in the Precambrian shield area of semi-arid Botswana. A regional inventory of borehole yields, combined with a structural geological analysis has revealed that groundwater occurrence in this area coincides with regional geological synformal structures. The distribution of permeable structures within these regional groundwater basins is controlled by local fracturing and lithologies. Aquifer characteristics were obtained by an evaluation of seasonal groundwater level fluctuations and pumping test data. The process and rate of recharge are controlled by seasonal rainfall characteristics and the geomorphology. Groundwater flow modelling and environmental tracers were applied to determine recharge, its timing and areal distribution. Finally, the recharge recurrence interval was evaluated from the statistics of recharge producing rainfall events, and a simple model for monitoring recharge from climatic data and groundwater level observations was established.

1 INTRODUCTION

The aims of this study are to (i) illustrate how geological and climatological conditions at various time and areal scales control the occurrence and behaviour of groundwater, and (ii) present an account of the various methods that can be applied to evaluate groundwater resources in a semi-arid Precambrian shield area. The present review is based on results from the Groundwater Recharge and Evaluation Studies (GRES) project in Botswana; an ongoing cooperation between the Free University Amsterdam, Department of Geological Survey Botswana and the University of Botswana. The program is funded by both the Botswana and Netherlands Governments. The aims of the GRES project are to:

- Identify the relationships between geological/geomorphological structures and groundwater occurrence.
- Study the processes of groundwater recharge in a geomorphological context.

- Evaluate replenishment amounts in relation to rainfall events and to reconstruct past recharge events in the context of climatic change.
- Develop appropriate methods to monitor recharge and to determine future fluctuations in groundwater resources.
- Strengthen hydrogeological research and training capacity in Botswana.

The present paper describes phase-1 of the GRES Botswana project, which began in 1987, and hydrogeological investigations by the present author that preceded the GRES project. GRES-1 focused on the Precambrian shield area of Southeast Botswana. The second phase, which started in 1993, deals with the vast sand area of the Kalahari semi-desert; the framework of this study will also be outlined. A full account on the GRES-1 study is given in the final GRES reports, of which the main report is also available as the Ph.D. thesis of Gieske (1992).

2 BOTSWANA: GENERAL HYDROLOGICAL CONDITIONS

The Republic of Botswana is a landlocked country, situated on the South African Plateau at an elevation of about 1000 m. It covers an area of 560,000 km^2 and has a population of slightly over one million; 80% of the countries lies in the Kalahari semi-desert, the largest continuous sand body in the world. The remaining, eastern part of Botswana is dominated by outcrops of the Precambrian African Shield (Figure 1).

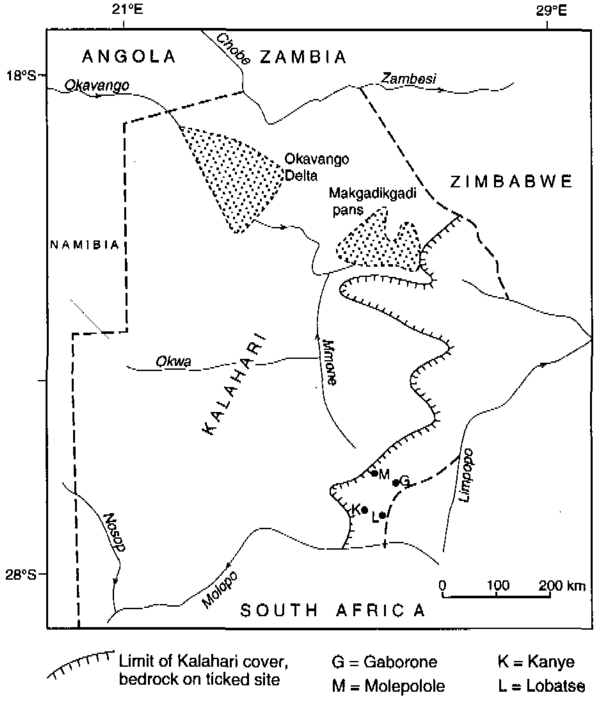


Figure 1 Botswana; features and locations referred to in text

Botswana is a semi-arid country with very limited water resources. The erratic rainfall is restricted to the hot season and varies from 250 mm per year in the extreme southwest to 650 mm in the northwest. Perennial water is restricted to the far north of the country where the Okavango and Chobe Rivers bring water from catchments in Angola and Zambia (Fig. 1). Surface water is ephemeral in the rest of Botswana and reservoirs are subject to high evaporation losses (circa 2000 mm/year).

Groundwater is therefore of paramount importance and extensive exploration programs have been carried out in recent decades to meet the fast growing demands. Aquifers are generally poor and replenishment is meagre in most of the country. The generally flat topography with sandy soils causes most of the precipitation to infiltrate, but the moisture retention capacity and the high transpiration of the dense savannah vegetation impede deep percolation and most, if not all of the precipitation surplus eventually evaporates. This condition especially prevails in the Kalahari.

Conditions for groundwater accumulation are more favourable in the eastern part of Botswana which is underlain by older rocks of Precambrian age. Here, rapid percolation through fractures and weathered material prevent infiltrating rainwater from evaporating given the more suitable geomorphological and geological structures. Aquifers are formed along synforms and fracture zones and constitute groundwater basins of limited size, in the order of 10 km^2. These basins often form topographic basins, because of the structural control over geomorphology.

3 GEOLOGICAL STRUCTURE AND GROUNDWATER OCCURRENCE

The thorough induration and metamorphism of Precambrian shields pose special problems for groundwater exploration, since permeability and storage capacity depend almost exclusively on fractures. However, fractures are notorious for their ability to form groundwater conductors in one environment and barriers in another. It is usually difficult, therefore, to regionalise the local hydraulic properties of these features into coherent patterns of groundwater occurrence.

Eastern Botswana is part of the southern African Precambrian shield and is characterized by an Archaen granitoid/metamorphic complex, partly covered by a Proterozoic volcano-sedimentary succession of strongly lithified platform deposits. A compilation of groundwater data has revealed that the occurrence of groundwater is not primarily controlled by large-scale fracture systems and lithologies, but by folds in the Precambrian basement. Two sets of superimposed synforms and antiforms (F_1 and F_2) have created a 'chess-board' pattern of dome and basin structures (Figures 2 and 4). Successful boreholes and well fields appear to be preferentially situated in areas where synforms intersect, suggesting that these tectonic basins coincide with groundwater basins. Small-scale fractures and favourable lithologies doubtless improve the permeability within a groundwater basin, but would seem to be subordinate in determining the distribution of large-scale aquifer characteristics (Dietvorst et al., 1991).

The mechanism responsible for producing permeability in the tectonic basins is not yet clear, but the following processes and circumstances have been recognized to contribute to the evolution of the groundwater basins.

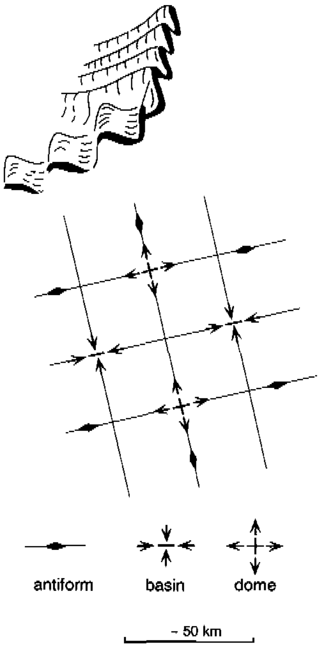


Figure 2 The intersecting Precambrian system of syn- and antiforms

- All Precambrian rocks in the area are more than 1200 million years old. Over this time interval all rock units have been to a greater or lesser extent metamorphosed, obscuring original variations in primary porosity and mechanical behaviour. This explains the poor relationship between rock type and aquifer characteristics.

- Groundwater has continuously circulated along an extensive system of bedding and joint planes in the long period that has elapsed since formation of the folds, thereby enhancing secondary permeability through chemical weathering. This circulating groundwater was concentrated by gravity, into the synformal depressions. Decomposition of arenitic rocks under tropical conditions, thus causing pseudo-karst phenomena along fracture systems, is well known; Shaw & De Vries (1988) have described the formation of pseudo-karst cavities in sandstone, dolerite and shale along fractures in Karoo and Precambrian strata beneath the Kalahari cover. An additional factor is the formation of collapse structures and subsurface erosion, causing depressions at the surface. The accumulation of runoff water in such structures stimulates infiltration under (semi-)arid conditions, enhancing groundwater circulation.

- Another possible contribution to mechanical disruption of fractures is the effect of earth tides. Gieske & De Vries (1985) studied such earth tide oscillations, with a maximum fluctuation of 25 cm, using boreholes in fractured shale and dolomite near Ramotswa on the limb of a large F_2 antiform (Figures 3 and 4). Similar oscillations were also observed on the limbs of anticlines in quartzite and dolomite in other areas of eastern Botswana. The continuous contraction and expansion of fractures over millions of years could conceivably have played a part in selective permeability enhancement. It is noteworthy in this respect that the borehole with the highest tidal fluctuation also gives the highest yield (> 50 l/sec) and is situated in normally rather impervious shale.

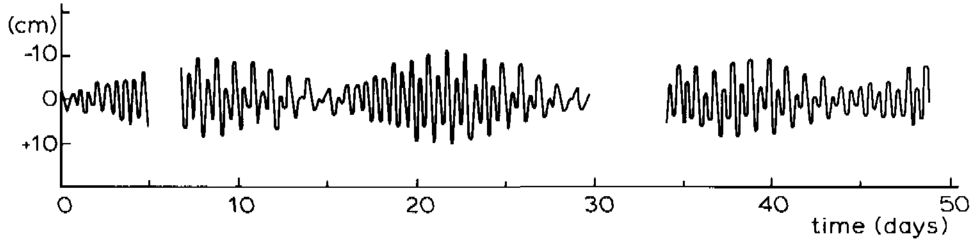


Figure 3 Earth tides in a borehole near Ramotswa in Precambrian shale (Gieske & De Vries, 1985)

4 EVALUATION OF GROUNDWATER RESOURCES IN A SMALL PRECAMBRIAN BASIN

The GRES-1 project included three Precambrian basins with different geological/ geomorphological conditions (Figure 4): the Lobase basins, Molepolole East well field and Kanye South well field. The present account focuses on two small interconnected basins north of the small town of Lobatse: the Pitsanyane and Nnywane Basins, with a total area of about 17 km^2. These basins are formed along a NNE-trending fracture zone in dolomites, shales and quartzites, and are morphologically reflected by a small, elongated system of surface catchments (Figure 5). The axis of these basins is formed by a poorly defined valley with steep slopes on the western side and slightly sloping planation surfaces at the eastern margins. The valley fill consists of alluvial and colluvial soil and coarse rubble from the slopes, locally to a depth of 30 m. The fractured aquifer system has a breadth of circa 700 m, a depth of about 80 m and occupies an area of approximately 6 km^2. The hydrogeological situation was studied by drilling and monitoring about 40 exploration, observation and extraction wells, and a geophysical survey.

Field observations revealed that recharge is concentrated in fan-like colluvial deposits at the foot of the western slope, where small episodic gullies discharge runoff from the surrounding areas. Diffuse percolation takes place in the alluvial valley bottom and sandy soils on the eastern pediments. Nnywane Basin occasionally receives infiltration from the ephemeral Nnywane River when the Nnywane Dam is spilling (Figure 5). Subsurface discharge is to the north where Nnywane Basin merges with the much wider Moroekwe Basin. No clearly defined aquifers could be identified in this area.

Groundwater table depth increases from about 15 m in the Nnywane Basin to 30 m in Pitsanyane basin. Long-term annual rainfall and potential evaporation are in the order of 550 mm and 2000 mm respectively; the area supports a dense bush and tree savannah vegetation.

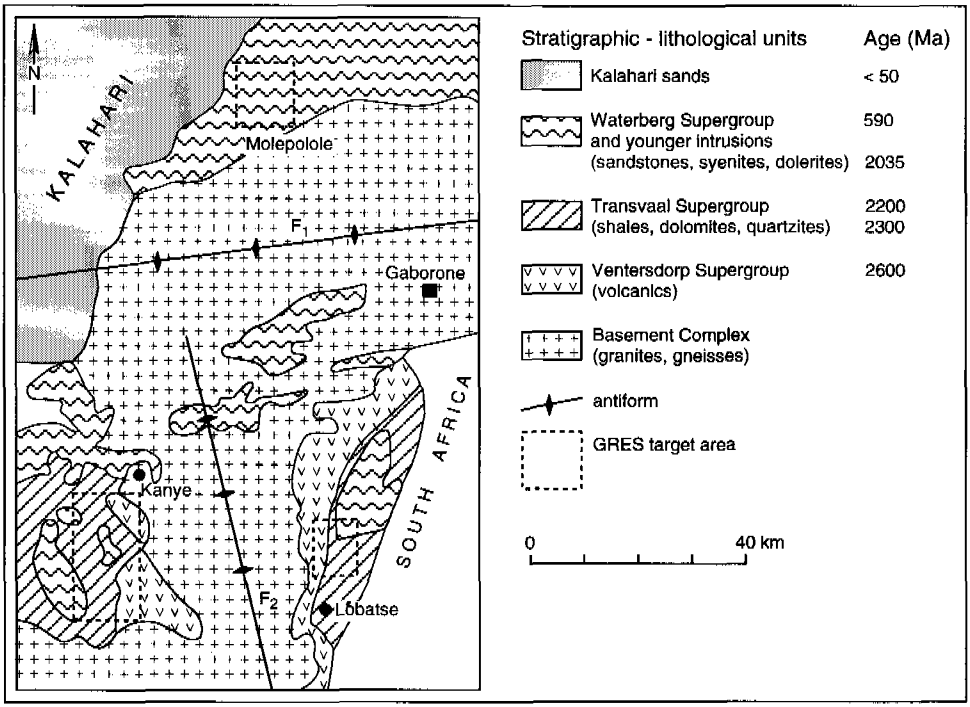


Figure 4 Schematic geological map of SE-Botswana, showing the GRES-1 target areas Lobatse, Kanye and Molepolole

4.1 Aquifer characteristics

Test-pumping was carried out in P1 for a period of 10 days. The slopes of time-drawdown curves for observation wells increase from 1:2 to 1:4 on a log-log plot, suggesting early to medium time conditions in a fracture aquifer (Boehmer & Boonstra, 1986). The aquifer behaves as unconfined with pumping, but also shows a high barometric efficiency, indicating confined characteristics. De Vries & Gieske (1988) explain this contradictory behaviour as an expression of partly-saturated confined conditions.

The drawdowns during long-term abstraction from P1, P4 and P5 are indicated in Figure 6; pseudo-radial flow seems to prevail during the first 300 days. Analysis of the data using the Theis-Jacob straight line procedure resulted in an average transmissivity (T) of 30 m^2/day and an average storativity/specific yield (S) of 5%. An evaluation of the recovery following a 19-day interruption of extraction from P1 gave a T-value of 29 m^2/day. Analysis of the early drawdown suggests that transmissivity of the fracture system itself is more than 100 m^2/day. A linear relation between drawdown and time was observed for the period after 300 days, indicating a quasi-steady depletion of the groundwater basin; obviously the cones of depression had reached the aquifer boundaries by this time (De Vries, 1985).

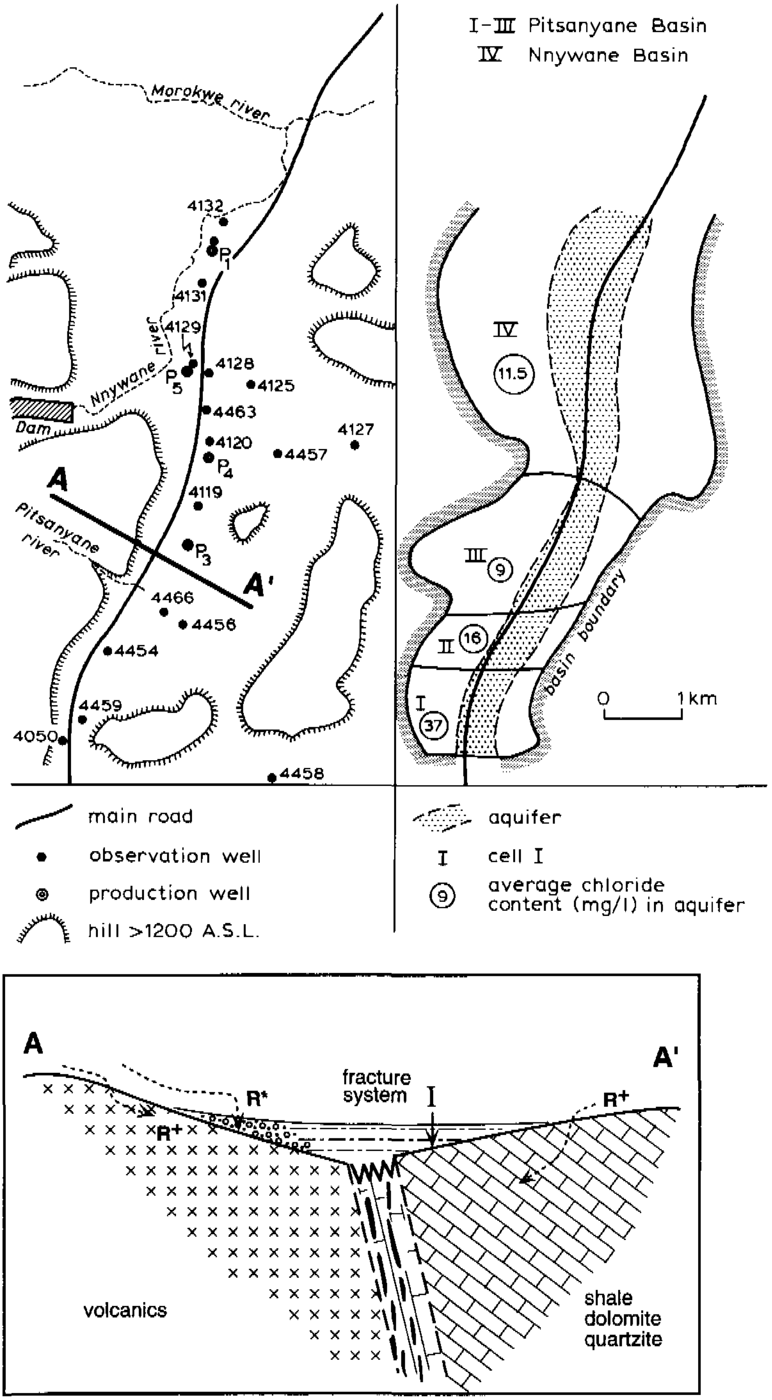
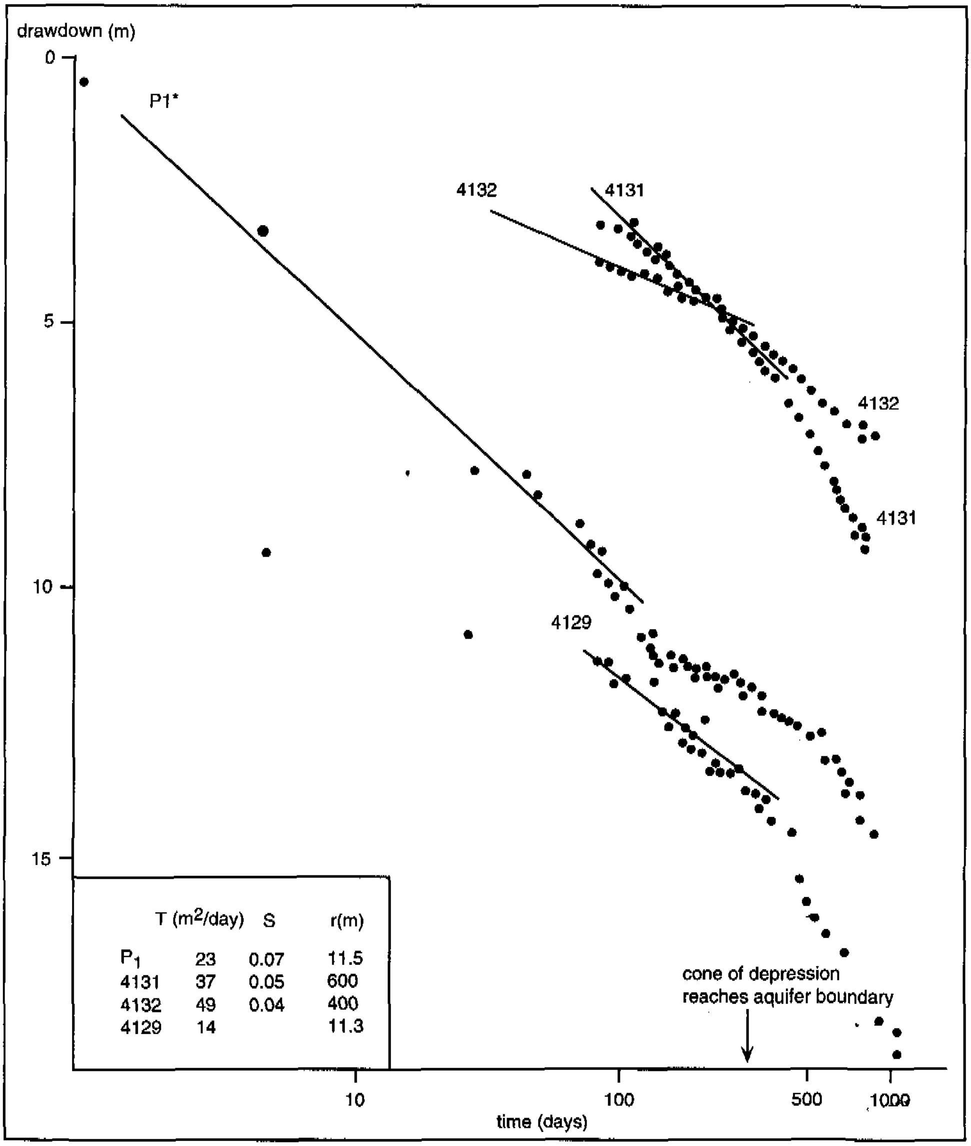


Figure 5 Pitsanyane and Nnywane Basins, north of Lobatse. R* = concentrated recharge from runoff; R^+ = direct infiltration in fractured rock outcrops; I = diffuse recharge



	T (m^2/day)	S	r(m)
P_1	23	0.07	11.5
4131	37	0.05	600
4132	49	0.04	400
4129	14		11.3

Figure 6 Long-term time-drawdown curves due to extraction from Pl (550 m^3/day) and P5 (450 m^3/day). Transmissivity (T) and Storativity (S) according to the Theis/Jacob method for the first 300 days (De Vries, 1985)

The total abstraction from Nnywane Basin between 300 and 900 days was 628,000 m^3, causing a lowering of the groundwater table by 5 m over an area of about 4 km^2. This indicates an overall specific yield of 3% during this phase of depletion. The radius of influence (R_e) for the cone of depression after time t can be derived from the Theis formula for transient radial flow:

$$R_e = 1.5(Tt/S)^{0.5}$$

Substitution of results from the pumping test give a radius of influence of 822 m, which agrees reasonably with an estimated width for the permeable part of the basin of about 1.5 km.

4.2 Tracer studies

Chloride balance

Chloride is an excellent tracer because of its conservative nature. The only source of chloride in the study area, with its predominantly arenitic sediments, consists of dry and wet deposition from the atmosphere. Variations in soil moisture and groundwater chloride concentrations in a downstream direction can thus be attributed to changes in water flux (De Vries & Gieske, 1990). The atmospheric chloride deposition and the chloride concentration in the saturated zone have been monitored since 1983. Chloride in soil moisture has been investigated since 1986 in a large number of vertical profiles in which isotope analyses were also carried out (Gieske, 1992).

Average chloride deposition was determined to be 500 mg/m^2/year. With an average rainfall (P) of 550 mm/year, this indicates an average chloride content for infiltrating rainwater (C_0) of 0.9 mg/l. The chloride content in soil moisture (C_i) is fairly constant over the area, averaging 35 mg/l in Pitsanyane Basin (Figure 7) and 55 mg/l in Nnywane Basin. The distribution of chloride in the saturated zone is indicated in Fig. 5, giving a weighted mean (C_s) of 14 mg/l. A considerable contribution of direct infiltration (R) from interflow on the slopes and concentrated surface runoff must therefore occur to account for the relatively low concentration in the saturated zone.

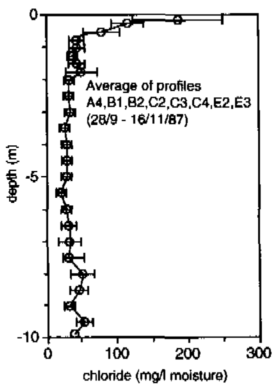


Figure 7 Average chloride concentration in soil moisture with depth in sandy loam for Pitsanyane Basin at the end of the 1987 dry season (Gieske, 1992)

The chloride and water mass balances give an overall recharge of $(C_0/C_s)P$ = 36 mm/year. If we assume a steady state vertical flux in a non-sorbing chloride solute system in the unsaturated zone, then the recharge by diffuse infiltration (I) is given by I = $(C_0/C_i)P$. This leads to I(Pitsanyane) = 14 mm/year, I(Nnywane) = 9 mm/year, and a weighted average of 11 mm/year over the alluvial valley bottom. However, alluvial soils occupy about half of the total basin area of 17 km^2 , the remaining area of shallow soils and exposed rocks producing direct infiltration (R). Thus 0.5I + 0.5R = 36 mm/year, so that R = 61 mm/year over the western valley slope and eastern pediment, hence accounting for an average of 31 mm over the whole basin.

A more advanced distributed approach was also applied by Gieske & De Vries (1990), by routing additional chemical and isotope components through various hydrologically homogeneous cells and making use of linear regression statistics (mixing cell method).

Unsaturated zone transport following a high rainfall event

Figure 7 shows the average chloride profile for Pitsanyane Basin at the end of the dry period that started in the late 1970's. The high concentration near the surface reflects the end of the dry season; below 1 m the concentration becomes fairly constant at 35 mg/l. From the total chloride content of 35 g per 10 m soil and with a surface chloride deposition of 500 mg/m^2 , solute velocities of 0.14 m/year are derived.

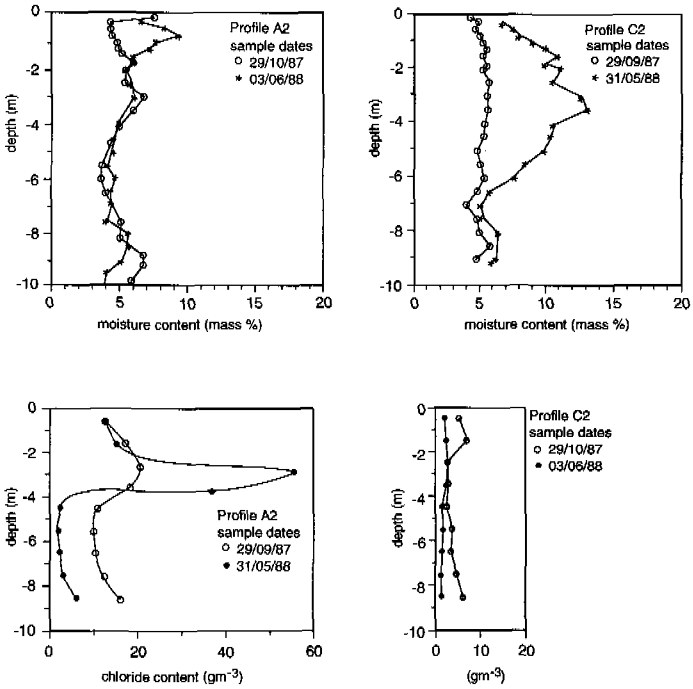


Figure 8a Soil moisture and chloride distribution in two representative profiles, A2 and C2, before and after the 1987-1988 rainy season (Gieske et al., 1990)

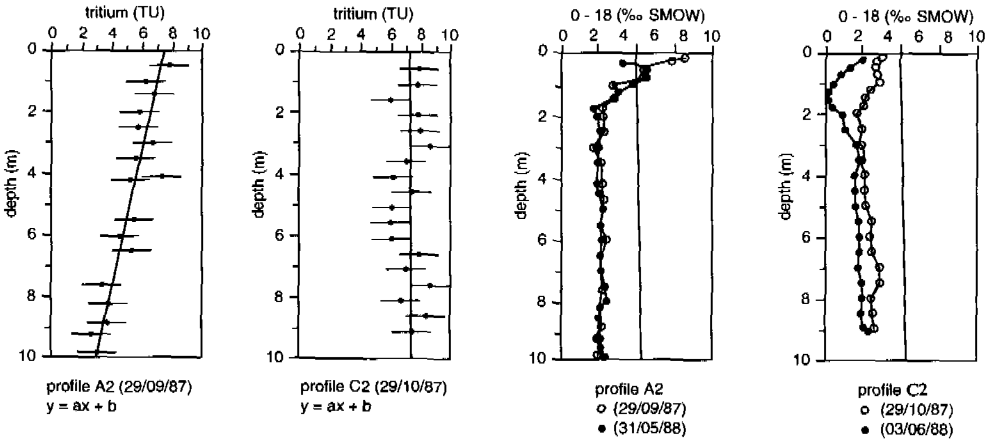


Figure 8b Tritium and ^{18}O distribution in profiles A2 and C2 before and after the 1987-1988 rainy season (Gieske et al., 1990)

These calculations imply a simple steady-state model with piston flow displacement. However, moisture and chloride analyses of soil samples collected after the 1987-1988 rainy season (with an above average rainfall of 850 mm) show a dramatic increase in moisture and a decrease in chloride content for profiles B1, B2, C2 and E2 (Figure 8a). Chloride distributions have clearly been affected to a depth of at least 10 m; the concept of steady-state chloride transport with an average speed of 0.14 m/year therefore becomes very unlikely.

Profile A2 shows hardly any infiltration of moisture and a high increase in chloride at a depth of 3 m, followed by a decrease downward. The explanation is given in Figure 9 which displays a vertical section through the area. These figures suggest a horizontal solute transport component in the direction of A2. Due to the low surface infiltration rates, soil suction will be much higher along line A2-A3 than in the surrounding areas, with a permanent moisture sink at 3-4 m caused by the roots of shrubs and trees. Profiles B, C and E are situated on micro-surface drainage lines, producing an accumulation of runoff water. (Gieske et al., 1990).

The ^{18}O distribution also testifies to a low infiltration at A and a strong vertical mixing of moisture in the other sections (Figure 8b). Similarly, the radioactive isotope Tritium only shows a depletion with depth in A2, thus indicating time stratification because of a low infiltration rate.

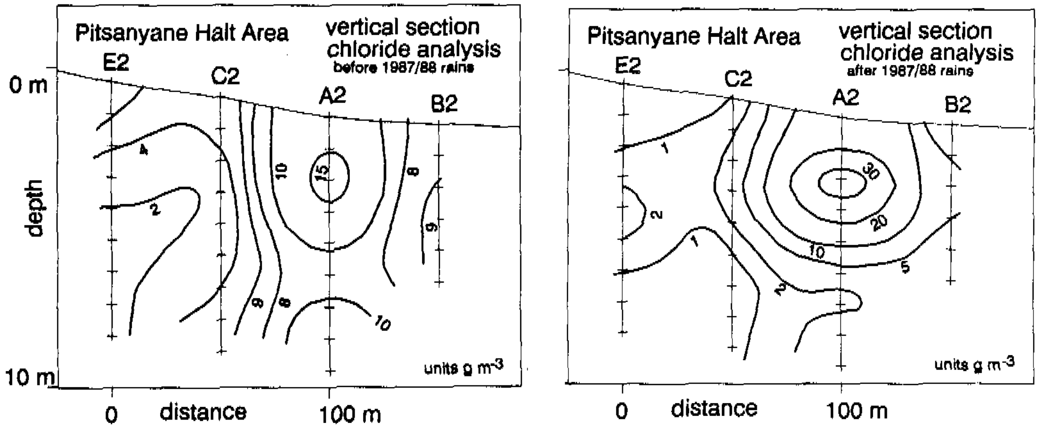


Figure 9 Distribution of chloride in a vertical section before and after the 1987-1988 high rainfall event, showing vertical as well as horizontal chloride transport (Gieske et al., 1990; Gieske, 1992)

4.3 Computer simulation of groundwater flow

The infiltration patterns obtained from the mixing cell chloride mass balance calculations were further used as input to a transient groundwater model for the area based on the code 'MODFLOW'. Hydraulic characteristics were obtained from pumping tests, long-term abstraction hydrographs and from recession curves of the water table after a recharge event. The model was calibrated using hydraulic gradients, and the resultant areal distribution of transmissivity and storativity values accounted well with the parameter set given in section 4.1.

A lumped parameter model was also developed to simulate infiltration and transport of rainfall excess through the unsaturated zone (Gehrels & Van der Lee, 1990). This model ('EARTH') makes use of a simplified Richards' equation for unsaturated transport and a linear reservoir approach to account for moisture redistribution and transport delays. Actual evaporation is calculated as a function of potential evaporation and soil moisture content. Groundwater level fluctuations could be simulated from the modelled recharge when combined with a linear reservoir model for discharge through the saturated aquifer. Notably good results were obtained if the model was calibrated with field soil moisture observations. 'EARTH' thus proved very suitable for simulating recharge events from climatic records and groundwater level observations, especially when combined with measured soil moisture data.

A direct calculation of infiltration from soil physical data and the Richards' equation could not be applied on a regional scale because of the subsoil inhomogeneity, the strong evidence for preferential flow paths and insufficient data over the whole area. However, moisture balances were established from neutron probe readings using the zero-flux plane method; recharge estimates from these procedures were remarkable similar to those from the tracer experiments.

Recharge statistics

After calibrating the site parameters for 'EARTH' with observed groundwater level fluctuations, the series was modelled backwards in time using historical rainfall data and a simple empirical seasonal evaporation function. The reconstruction indicated 26 years with recharge events during the past 68 years, with an average replenishment of 55 mm for each recharge year and an overall average of 22 mm/year for the total period. Linear regression between rainfall and recharge produced a threshold value of annual effective rainfall at about 400 mm, below which no recharge takes place (Gieske, 1992).

Results from the present study, when combined with those from similar studies in other SE Botswana basins (Molepolole East well field and Kanye South well field) within the GRES-1 project, have led to the conclusion that annual recharge in the Precambrian basins ranges from 10 mm for alluvial soils to 30 mm for shallow soils and fractured rock outcrops. Recharge from concentrated runoff can be much higher. The Pitsanyane River flow measuring weir spilled 44 mm from a catchment of 1.5 km^2 during the 1987-1988 season with a precipitation of 838 mm. This was only part of the runoff production, however, as additional water flowed under the weir through the coarse channel fill.

5 WATER RESOURCES DEVELOPMENT

The GRES results were applied in the National Water Master Plan for Botswana; this includes a sustainable water resources development plan, which is based on the strategy of depleting groundwater reserves when surface reservoirs are depleted and shifting to surface water supply in wet years, allowing the aquifers to become replenished.

6 GROUNDWATER CIRCULATION AND REPLENISHMENT IN THE KALAHARI

The Kalahari Beds comprise unconsolidated Late-Cretaceous to Recent eolian, fluvial and lacustrine sandy deposits, with an average thickness of about 150 m, deposited in a tectonic basin. Interspersed are concretion layers of calcrete and silcrete derived from the chemical activity of percolating water. The Botswana Kalahari is rather densely vegetated and is classified as a bush and tree savannah with alternating grassland, though often thought of as a desert because of the virtual absence of surface water and springs. Groundwater is encountered in a large number of boreholes in the arenitic Karoo (Palaeozoic-Mesozoic) and Precambrian bedrock underlying the Kalahari sands. The S_2 faulting phase (see sect. 3) persisted during Karoo sedimentation, causing horst and graben structures. The downthrown sides of the fractures often coincide with better aquifer characteristics, due to the deposition of coarser sediments along these synsedimentary structures.

The Kalahari Beds themselves do not form extensive aquifers at the present time. Locally perched water bodies are found related to depressions (pans) and duricrust horizons, thus possible groundwater recharge by infiltration through the Kalahari Beds under present climatic conditions is a matter of continued debate.
Isotope analyses of water samples from a large number of boreholes and wells have indeed indicated recent rain recharge. Sampling, however, was rather selective since use was made of existing wells which are normally found in the above mentioned favourable infiltration sites with relatively shallow groundwater. Tritium studies from a few soil moisture profiles near

Letlhakeng revealed the occurrence of recent rain water to a depth of at least 5 m, suggesting infiltration beyond the reach of evapotranspiration. Also, the accumulation of chloride in this profile to a depth of 10 m compared with present chloride deposition from the atmosphere suggests deep percolation of several millimetres of water per year (preliminary results from GRES-2 project).

A study of the regional hydraulic gradient and the amount of groundwater flow through the Kalahari leads to a different view on possible replenishment. The present hydraulic head ranges from 1100 m a.s.l. at the water divide in the southwest to 900 m at the internal discharge base of the Makgadikgadi salt pan depression 500 km to the northeast. The land surface also slopes in the same direction from 1250 m to 925 m (Figure 10). Assuming a transmissivity of 500 m^2/day for the Karoo aquifer, this gradient gives a groundwater discharge of about 0.3 mm/year. Steady state conditions thus imply that the average overall recharge also amounts to 0.3 mm/year. The present hydraulic gradient, however, can also be considered as a residual from a head decay since the last pluvial when the groundwater table was near the surface. A specific yield for the Kalahari sand and Karoo sandstone of 10% and 3% respectively, can therefore explain the present groundwater table as a result of groundwater depletion over a period of 12 000 years without replenishment (De Vries, 1984); this 12 000 year period is the time elapsed since the end of the Pleistocene period with important wet phases (Thomas & Shaw, 1991).

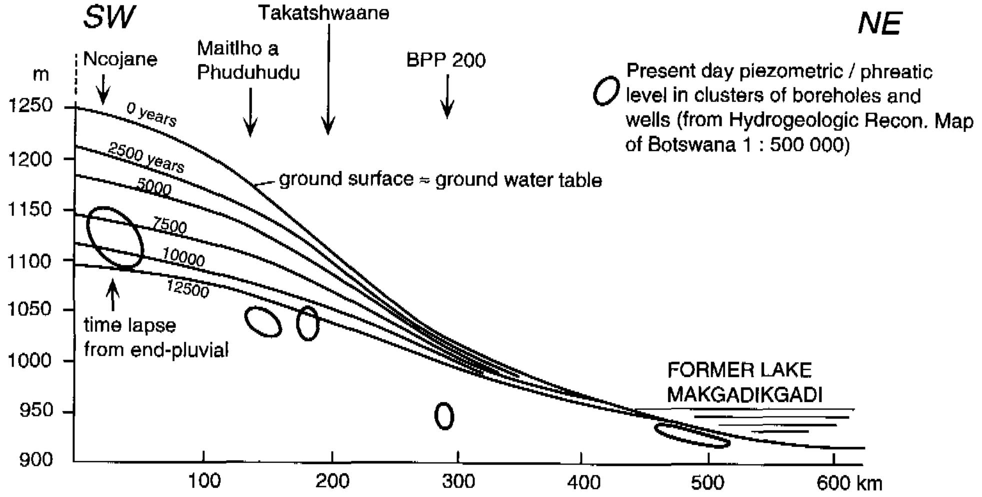


Figure 10 SW-NE topographic-hydrological section through the Central Kalahari Basin and groundwater head decay during the past 12 000 years (De Vries, 1984)

The second phase of the GRES project will concentrate on the Kalahari, and will hopefully resolve this conflicting isotope and hydraulic evidence. An important aspect of the further research will be to trace water and solutes in the unsaturated as well as the saturated zone using isotope and geochemical methods such as ion-chromatography. A reconstruction of palaeohydrological conditions in response to climatic and environmental evolution is one of the prerequisites for proper evaluation of the present day water resource and its sustainable use.

Geomorphological investigations of palaeohydrological phenomena have revealed that the depressions of Okavango Delta and Makgadikgadi Pans, which form the southern limit of the East African Rift Zone, were once part of a system of lakes and rivers connected with the Zambezi River system. Tectonic tilting and change in climate have caused the desiccation of some of these depressions (Thomas & Shaw, 1991). Old shorelines indicate high lake levels during the Late-Pleistocene. These lakes were once the drainage base for the internal Okwa-Mmone river system, which now forms dry valleys. A remarkable phenomenon is the gorgetype valley heads which, near the Molepolole water divide, reach a depth of 30 m and a width of 1000 m. Deep weathering and groundwater erosion along Pre-Kalahari lineaments were encountered when drilling beneath this valley. These subsurface structures, in combination with the valley head morphology and extensive duricrust development, led Shaw & De Vries (1988) to attribute the valley forming, in at least the head water reach, to spring sapping and groundwater movement rather than to past fluvial episodes.

7 CONCLUSIONS AND RECOMMENDATIONS

1 There is no unambiguous relation between groundwater occurrence, geological structure and lithology. The forming of secondary permeability and subsequent aquifer development depend in fact on the geological history, including palaeoclimatic and palaeohydrological evolution, and is more or less unique for any region.

2 A proper evaluation of aquifer characteristics from pumping tests and groundwater flow modelling requires a sound knowledge of the geological structure.

3 The processes as well as the rate of groundwater recharge in a given climatic situation depend on the seasonal rainfall and geomorphological conditions (surface infiltration characteristics). To allow planning of sustainable groundwater production, recharge amounts and their recurrence interval should be evaluated within the framework of recharge producing rainfall statistics.

In summary, proper and sustainable groundwater resources development must be based on an evaluation of groundwater occurrence, aquifer characteristics and recharge production within a framework of the geological, geomorphological and long-term climatic conditions.

ACKNOWLEDGEMENT

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WATER RESOURCES ASSESSMENT TOOLS: GEOPHYSICS AND MAPPING

F.J.H. Dirks

ABSTRACT

Safe water supply and sanitation are considered to be main conditions for improvement of the well being of the poor in developing countries. Therefore, water supply and sanitation projects are important elements in the policy and implementation of the Netherlands development cooperation. Water resources studies are invariably an important element in water supply development. Also in water resources planning activities, hydrological studies are a basic element. The application of two tools for water resources assessment: geophysics and the production of hydrogeological maps are discussed here in the framework of development cooperation projects, as carried out by IWACO. The application of geophysics in each study is critically analyzed for its merits/cost ratio. An extensive evaluation of rural water supply projects in hard rock in the semi-arid country of Burkina Faso indicates the positive impact of the systematic application of geophysics on the results of the drilling works. General and special hydrogeological maps reflect ideally the latest knowledge on groundwater resources and as such are a useful tool in Water Resources Management (WRM). In developing countries such maps are usually not available. In the context of water supply or WRM projects, financed by Netherlands development cooperation funds, IWACO has been involved in water resources development in a number of countries. An overview is given of several aspects of the map-making process and the techniques involved. Special attention is given to the use of a standard legend.

1 INTRODUCTION

Improvement of the well-being of the poor in developing countries is the main objective of the Netherlands development cooperation. The availability of basic infrastructure such as safe water supply and sanitation is considered conditional to the achievement of this objective. Therefore, water supply and sanitation projects are important elements in the policy and implementation of the Netherlands development cooperation.

Since 1974, IWACO has been involved in rural and urban water supply and water resources projects in developing countries around the world. The experience, gained in the Netherlands,

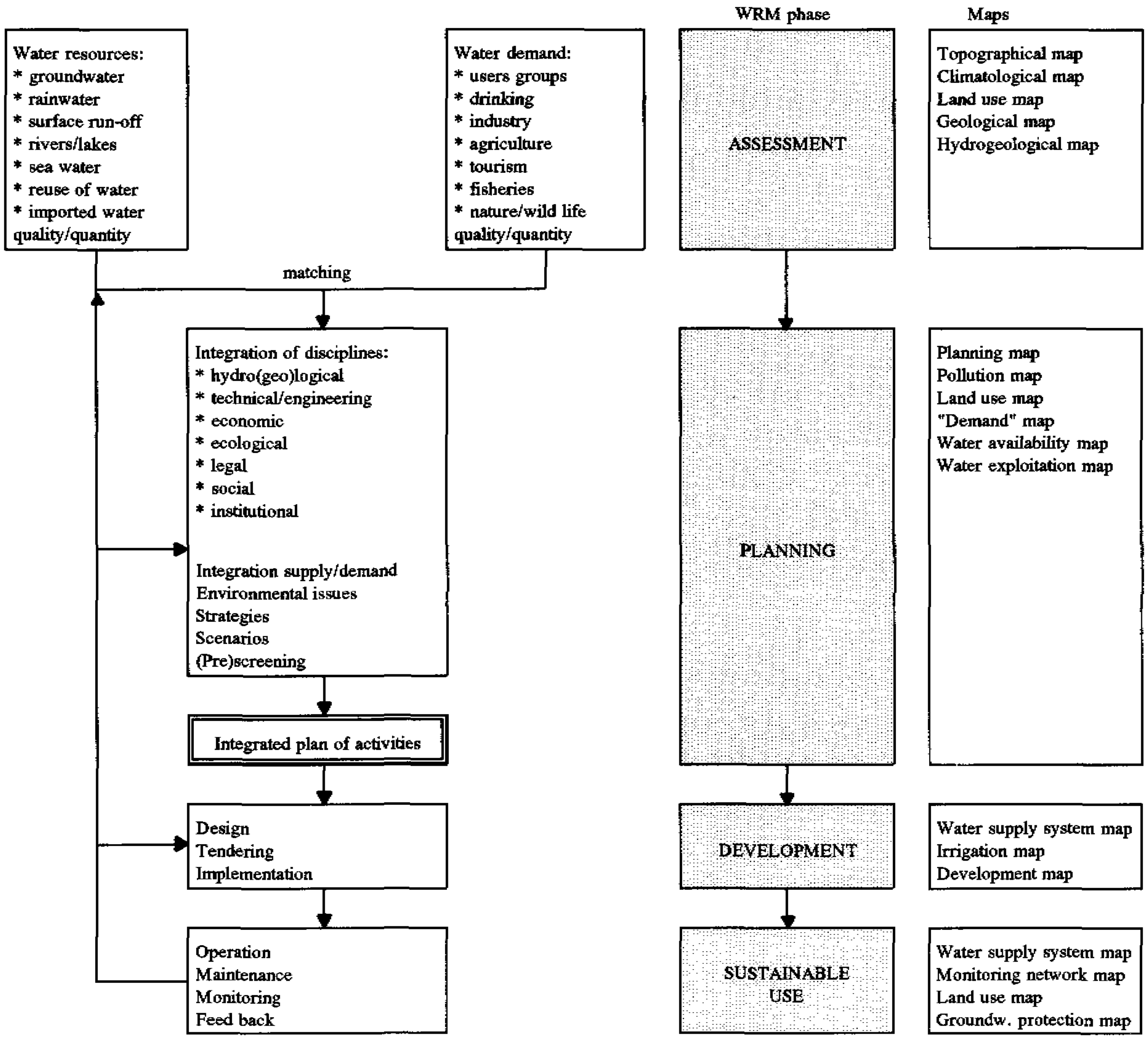


Figure 1 Steps in Integrated Water Resources Management

has been applied and further developed in many countries under widely varying circumstances.

While in the early years technical assistance in water supply projects emphasized amongst others on the assessment of water resources, recent activities are oriented more towards the entire spectrum of (Integrated) Water Resources Management, from assessment to planning and sustainable use. (See Figure 1). During the years, the input, required from IWACO has shifted also from the supply of technical expertise (doing the job) to institutional development expertise (facilitating, making sure that the counterpart organization can carry out the job).

The discussion here focuses on some aspects of the experience that IWACO has gained through the years with two tools in water resources assessment and planning: the application of geophysical methods and the production of hydrogeological maps in projects around the world, carried out in the framework of development cooperation.

In chapter 2, the effectiveness of the application of systematic geophysical surveys in rural water supply projects in hard rock areas is discussed. The experience gained with hydrogeological map-making in several countries is discussed in chapter 3. Finally, the lessons learned are summarised in chapter 4.

2 GEOPHYSICAL METHODS

Geophysical methods are extensively used in groundwater studies for urban and rural water supply projects around the world. Geophysics can be applied for a wide range of problems, ranging from general hydrogeological mapping to the study of specific hydrogeological problems.

The hydrogeologist should have a working knowledge of the available geophysical methods in order to be able to decide whether application is useful and if so, which method to be used. The geophysical methods but more specifically the equipment and interpretation techniques are in continuous development. The questions which the hydrogeologist likes to answer for himself before deciding on the application of geophysics are:

- Quality: how good and reliable is the obtained information.
- Price: is the application of geophysics more economical than another method to get comparable information.
- Time: how time consuming is the application.

The quality of the information resulting from the geophysical measurements and interpretation is of course of extreme importance. The information, which is asked for by the hydrogeologist, is never measured directly. Interpretation of the data should "translate" the measured data into parameters such as thickness of overburden, presence of faults, groundwater quality, etc.

The cost of application of geophysics can vary widely and depends on method, location, etc. As alternative for the "traditional" geo-electrical method, other techniques, which are less expensive to operate, have received much attention. Non-contact electro-magnetic methods (e.g. the horizontal loop multi-frequency method and VLF) have been marketed as very cost effective in their application.

Geophysical ground methods commonly used in hydrogeological studies.

Geo-electric sounding: A vertical profile of apparent resistivities of the sub-soil is measured by a set of four electrodes, two current and two potential electrodes, using a direct current source. This method requires ground contact and is labour intensive. Quantitative interpretation techniques are well developed.

Geo-electric profiling: Lateral apparant resistivity variations of the subsoil are measured by using the same four electrodes as used for geo-electric soundings, in a fixed configuration and by moving the entire configuration along a line. This methods requires also ground contact and is labour intensive. Quantitative interpretation techniques are developed to make apparent resistivity pseudo-sections.

HL Electromagnetic profiling: An electromagnetic field is generated in a portable coil and introduced in the subsoil. A second coil at a fixed distance measures the electro-magnetic field, which is the result of the combination of the original field in the field which in reaction is generated in the subsoil. This method does not require ground contact and is less labour intensive. Equipment is available in different forms and quantitative interpretation techniques are well developed.

HL Electromagnetic sounding: Applying the same principle as used for electromagnetic profiling, the distance between the coils and/or the frequency is not kept constant but varies to get a vertical profile of the subsoil. Quantitative interpretation techniques are in development.

VLF: Local distortions of the eletro-magnetic fields as produced by strong military radio emitters are caused by underground conductors and can be measured. The basic qualitative interpretation technique of the measured field, to derive the shape and location of the conductor is available but needs further development. The equipment has improved considerably during the last five years and can be operated by one man.

Seismics: Pressure waves, generated on or near the surface are penetrated in the subsoil and travel back to the surface where they are received by recorders. Recorded traveltime can be related to rock types and depth. Expensive equipment and interpretation techniques are available for the petroleum exploration. High resolution seismic equipment is developed during the last decade and can be applied in hydrogeological studies. PC-based interpretation techniques are available.

Other techniques: Other techniques are available such as magnetics and gravimetrics. These methods are applied in specific cases. Borehole logging is a common technique to measure parameters in the subsoil by lowering measuring equipment in a borehole. For water, a simplified version of the highly complex and expensive equipment, as developed for the petroleum industry, is available.

Time can be a very important parameter in specific applications of geophysics. Apart from the development of non-contact methods which are very fast, most new equipment include computers for data quality control and storage and rapid on-site interpretation. Often, new developments reduce the measuring time considerably as is the case with the newest VLF equipment which automatically selects the best radio station.

In the example which is presented hereafter, the application of geophysical methods in well-siting in (large) rural water supply programs in Burkina Faso is discussed.

Application of geophysics in Burkina Faso

Groundwater in hard rock areas occurs in i) fractures and fissures in the basement (secondary porosity) and/or ii) in the weathered zone (see Figure 2). For deep wells usually the fractures and fissures are looked for because of the relatively high transmissivity in these discontinuities. In this concept the weathered layer acts as a reservoir, feeding the underlying fractures and fissures.

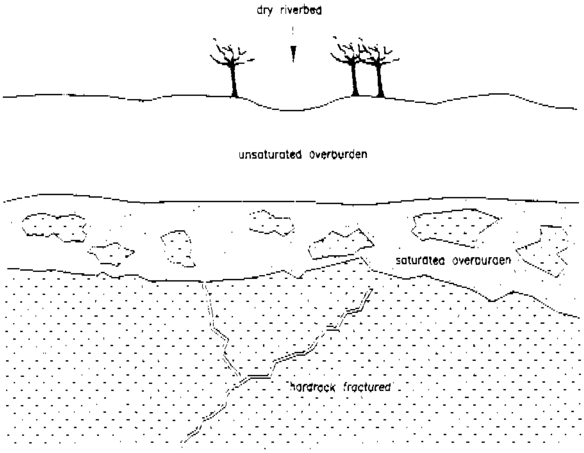


Figure 2 Schematic Hydrogeological cross-section in hard rock areas

The general approach for site selection for deepwell construction is presented in Figure 3. Whether all steps are included in a site study depends on i) availability of data, ii) relevance of the study and/or step for that specific well and iii) availability of equipment/services.

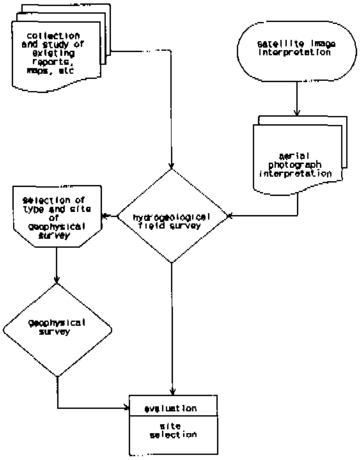


Figure 3 General approach for site selection for deep wells in hard rock areas

In the late 1970's and early 1980's, the application of geophysics became very popular and was mostly justified by an significant increase in the success rate: the percentage of wells yielding at least the minimally required quantity of water. With different geophysical methods favourable sites are identified in the field, where the weathered layer is sufficiently important and fractures are present. Geophysical methods which are used include:

- Reflection seismics.
- Geo-electric profiles and soundings.
- Electro-magnetic methods (HLEM, VLF).

With the execution of larger drilling programs and an increase in drilling efficiency, the price of drilling has decreased considerably during the 1980's. This development led to a decrease in the systematic application of geophysics in siting studies for deep wells. In the late 80's, however, new requirements caused an increase in the use of geophysical methods in site studies for deep wells. The new requirements are:

- As a result of the International Water Decade, amongst others the objective was adopted to raise the per capita consumption in rural areas to 30 l/d per capita. This resulted in the need to have the water point at close distance to the users as the walking distance, necessary to fetch the water, directly influences the quantity of water consumed. See also Figure 4.
- An additional requirement is generated by the increased living standard and the increasing number of the users of the water points. In many cases, deep wells are equipped with electrical pumps rather than a low yielding hand pump. The yield of the deep wells, therefore, needs to be higher than the low yield of 600 l/h minimally required for a handpump or the 5 m^3 /h minimally required for semi-rural and small urban water supply.

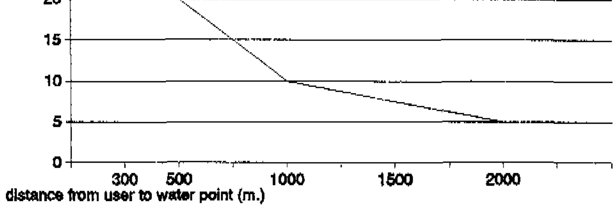


Figure 4 Relation between daily water consumption and distance between user and water point (Rural Water Supply, Burkina Faso). Source: IWACO-CIEH, 1987

In order to evaluate the effectiveness of the systematic application of geophysics, 15 large rural drinking water supply programs in Burkina Faso, involving the construction of some 6300 deep wells, have been evaluated. The evaluation resulted in the following conclusions related to the systematic application of geophysics (see also Figure 5).

- The systematic application of geophysics for well siting in hard rock in semi-arid regions is recommended, except in deeply weathered granitic areas.
- The success rate varies in function of the thickness of the overburden and the lithology of the bedrock but increases considerably with the systematic application of geophysics. In average the increase is 10.3%.
- In deeply weathered granitic areas, the application of geophysics does not significantly contribute to an increase of the success-ratio or yield of deep wells.
- The merits/cost ratio of application of geophysics is highest in areas with intermediate depth of weathering (20-40 m).
- Considerable reduction of the distance between the water point and the habitat of the users is achieved.

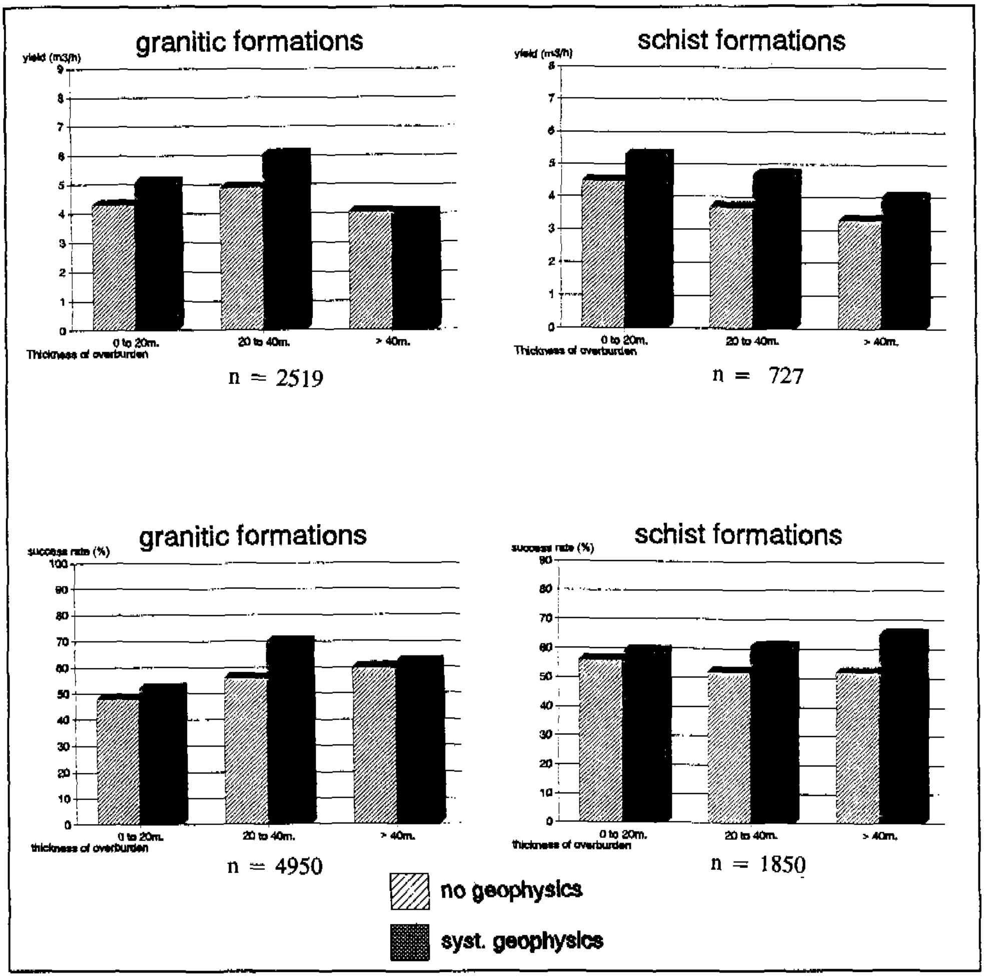


Figure 5 Evaluation of the impact of systematic application of geophysics on success rate and yield of deep wells in hard rock areas (Burkina Faso). Source: Bloemen, P., et.al, 1991

- Except for deeply weathered granites, the well yield shows a substantial increase, in function of thickness of the overburden and the lithology of the bedrock. The average increase amounts to 23%.

3 HYDROGEOLOGICAL MAPPING

General

Most projects in the field of water supply or water resources necessarily start with the assessment of the available water resources as a first step in the direction of integrated water resources management. See also Figure 1.

Characteristic for developing countries is not so much the lack of data but more the lack of reliable and useful data and the lack of reported evaluation of data. Furthermore, data usually are available at many different institutions and offices. Although in theory the recipient governments are expected to supply all available data to a project as their counterpart contribution, in reality this is seldom the case and the consultant, which is assigned to the project has to collect the data himself.

A hydrogeological map, combining all groundwater data, relevant for groundwater development, is usually not available. The need for hydrogeological maps is often felt during a groundwater development project such as rural drinking water supply. Therefore, projects to improve the drinking water facilities are often accompanied by water assessment studies. When financed by the Dutch government, invariably, the project is aiming at map-making but also at transfer of knowledge in order to increase the sustainability of the activity.

During the last five years, IWACO has been involved in the production of general hydrogeological maps in four countries abroad, three of which being developing countries under widely varying climatological conditions: Indonesia (humid tropical), Burkina Faso (semi-arid, sahelian), United Arab Emirates and Egypt (arid to hyper-arid). See also table 1. Additionally, in many developing countries specialised hydrogeological maps have been produced by IWACO, showing specific parameters such as piezometric levels, seasonal fluctuations of the water table, thickness of the aquifer, salinity of the groundwater etc.

Table 1 Overview of General Hydrogeological Maps prepared by IWACO

Country	Location	Scale	Number of maps/sheets	Year
United Arab Emir.	United Arab Emir.	1:250,000	1	1986
Egypt	Egypt	1:2,000,000	1	1988
Egypt	Eastern Delta	1:1,000,000	1	1988
Egypt	Nile Delta	1:500,000	1	1992
Egypt	Nile Delta	1:100,000	12	1988-date
Indonesia	West Java	1:100,000	16	1989-1991
Indonesia	D.I. Aceh	1:100,000	6 (black/white)	1993
Burkina Fasso	Burkina Fasso	1:500,000	6	1991-1993

Methodology

The map-making process consists of a number of consecutive steps, to be taken to arrive at an useful result. Usually, the topographic data and geological data are available on a map (hard-copy format). The result of the map-making may be a general hydrogeological map or specific hydrogeological maps presenting specific parameters in their geographical distribution, depending on the requirements of the project. The following main steps can be identified:

- Collection and evaluation of existing data, reports, maps, etc.
- Hydrogeological field surveys (if needed).
- Data handling and evaluation.
- Presentation of data on the map.

With the availability of desktop computers, modern tools have become within reach of the projects, even at remote locations. Data handling and storage is usually carried out by means of a database. Special hydrogeological databases as developed by IWACO include DAWACO (based on DATAFLEX) and DABACO (based on DBase). Correlation and presentation of data in their geographical context is nowadays done with the use of a Geographical Information System. (See Figure 6).

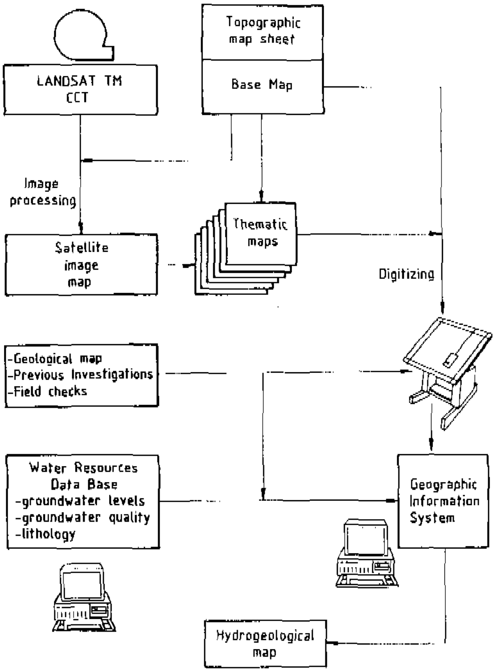
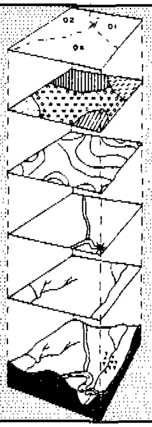


Figure 6 Application of RS and GIS for hydrogeological mapping

Geographical Information Systems (GIS) represent a rapidly developing field lying at the intersection of many disciplines: among them cartography, computing, geography, photogrammetry, remote sensing, statistics, surveying, and other disciplines concerning with handling and analyzing spatially referenced data. The GIS store, retrieve, manipulate and display these data efficiently according to user-defined specifications. They store various thematic maps in geo-referenced layers and these can be manipulated using a built-in relational Data Base Management System. New thematic maps can be generated in a GIS by selecting specific features from previously entered information layers.



These tools are used to make overlays and in the end to produce the hydrogeological map. Most steps in the map-making process can be carried out in the developing country, making use of the usually abundant labour. Prior training is required as qualified expertise is not frequently found. Only the transition of the digital data from the GIS into transparent colour separation sheets, which are used for the actual printing of the coloured maps requires specific equipment, which normally can not be found in all developing countries.

Small scale inset-maps are used to present specific information which can not be presented on the main map. Information which is usually presented on the inset-maps can include: location map, climatological data, land-use map, vegetation density, data type and location, cross-sections, etc.

The Legend of Hydrogeological Maps

The International Legend for Hydrogeological Maps, published by UNESCO (1983, revised edition) in most cases is used as the basis for the legend of the maps. The UNESCO legend is based on earlier versions of an International Hydrogeological Legend, developed by the IAH, the IAHS and UNESCO. As much as possible, this legend is applied as the standard legend for both the general and the specific hydrogeological maps.

However, in practise it appears that the legend can not always be applied as such without loosing information, relevant for the general hydrogeological map. Therefore the legend needs adaptations for a specific situation. The most striking example of this inadequacy of the legend is in the environment of hard rock areas:

- The thickness of the overburden (weathered bedrock) as well the saturation of the overburden are important characteristics, for which the standard legend has no provisions. An example of the colour legend, as used in Burkina Faso is shown in Figure 7a.

Another problem encountered in applying the standard legend is that only one type of aquifer can be shown. In case of different types of aquifer laying on top of each other, it is recommended to choose the most important aquifer. In the case of the hard rock area in Burkina Faso, it is decided to represent the overburden and limit the information on the bedrock to lithological information in the background (black).

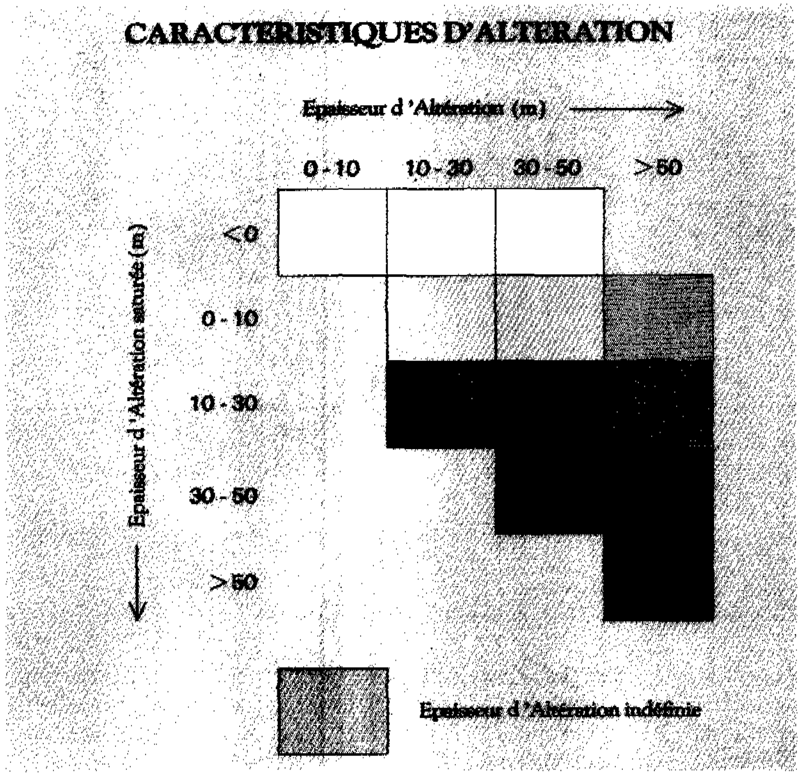


Figure 7a Colour legend of hydrogeological map of Ouagadougou, Burkina Faso

In specific cases it may be necessary to identify different aquifers, even when the lithology is similar. The standard legend does not cater for such a situation and adaptations need to be made. An example is found in the hydrogeological map of Egypt, scale 1:2.000.000 R/ Gw (IWACO, 1988), where the Miocene fluviatile sediments (a former Nile delta, now transformed into a desert area) are separated by colour from the younger fluviatile sediments in the present-day Nile delta (See also Figures 7b and 8). After lengthy discussions it was decided that the colours in the group "Granular Rocks" indicate the rate of recharge of the aquifers. In larger scale maps the recharge component has been omitted.

The application of the standard legend in Indonesia posed little problems, confirming that the legend is most suitable for humid climates. The large quantity of various data necessitated the extensive use of insert-maps to present specific parameters. Data presented in insert maps for parts of the main map are a.o. transmissivity values, draw-down data, elevation and density and type of available data. Selected water quality data have been presented around the well symbols on the main map.

Given the rapid development of infrastructure in Indonesia, the use of recent remote sensing images proved valuable to update the available topographic maps. During the project in Indonesia, it became clear that the counterpart wanted to use the mapping activity as a

INTERGRANULAR AQUIFERS

▓ Extensive and highly productive aquifer

▨ Extensive or local, generally moderately productive aquifer

FISSURED AQUIFERS, INCLUDING KARSTIFIED ROCKS

▨ Extensive or local, generally moderately productive aquifer

REGIONAL MIXED INTERGRANULAR AND/OR FISSURED AQUIFERS (NUBIAN COMPLEX)

▒ Extensive and highly productive aquifer

□ Extensive, moderately to low productive aquifer

ROCKS WITH LIMITED GROUNDWATER RESOURCES

▓ Extensive or local, low productive aquifer

▓ Hard rocks (igneous or metamorphic rocks); local groundwater occurrence in fissured and weathered zones

NON AQUIFERS

■ Aquiclude (non-aquiferous rock)

Figure 7b Colour legend of hydrogeological map of Egypt

planning tool for water resources. Therefore, apart from the hydrogeological map a so-called "water system map" was produced where the results of preliminary planning of water exploitation for public water supply and principal other users (agriculture, industry) are presented for policy- and decision-makers (see Figure 8).

One aspect which can easily be underestimated is the cost aspect of hydrogeological map-making. Experience learns that often activities such as data compilation, field surveys and data evaluation can easily be financed as routine activity of an institute responsible for groundwater management. However, the expenses related to the actual production of a colour map (production of colour separation sheets, printing) can easily surpass US$ 6,000 per sheet and allocation of these funds is problematic in developing countries.

4 CONCLUSIONS AND RECOMMENDATIONS

- Geophysical methods, equipment and interpretation techniques are continuously further developed. The "traditional" geo-electric method is more and more replaced by fast, less labour intensive methods. Computers are often incorporated in the equipment for on-site data quality control, data storage and fast interpretation.

- Systematic application of geophysics in the study for the siting of deep wells in hard rock in semi-arid regions is recommended. The application has a positif impact on the success rate (average + 10.3 %) and the average yield (average + 23%) of the wells.

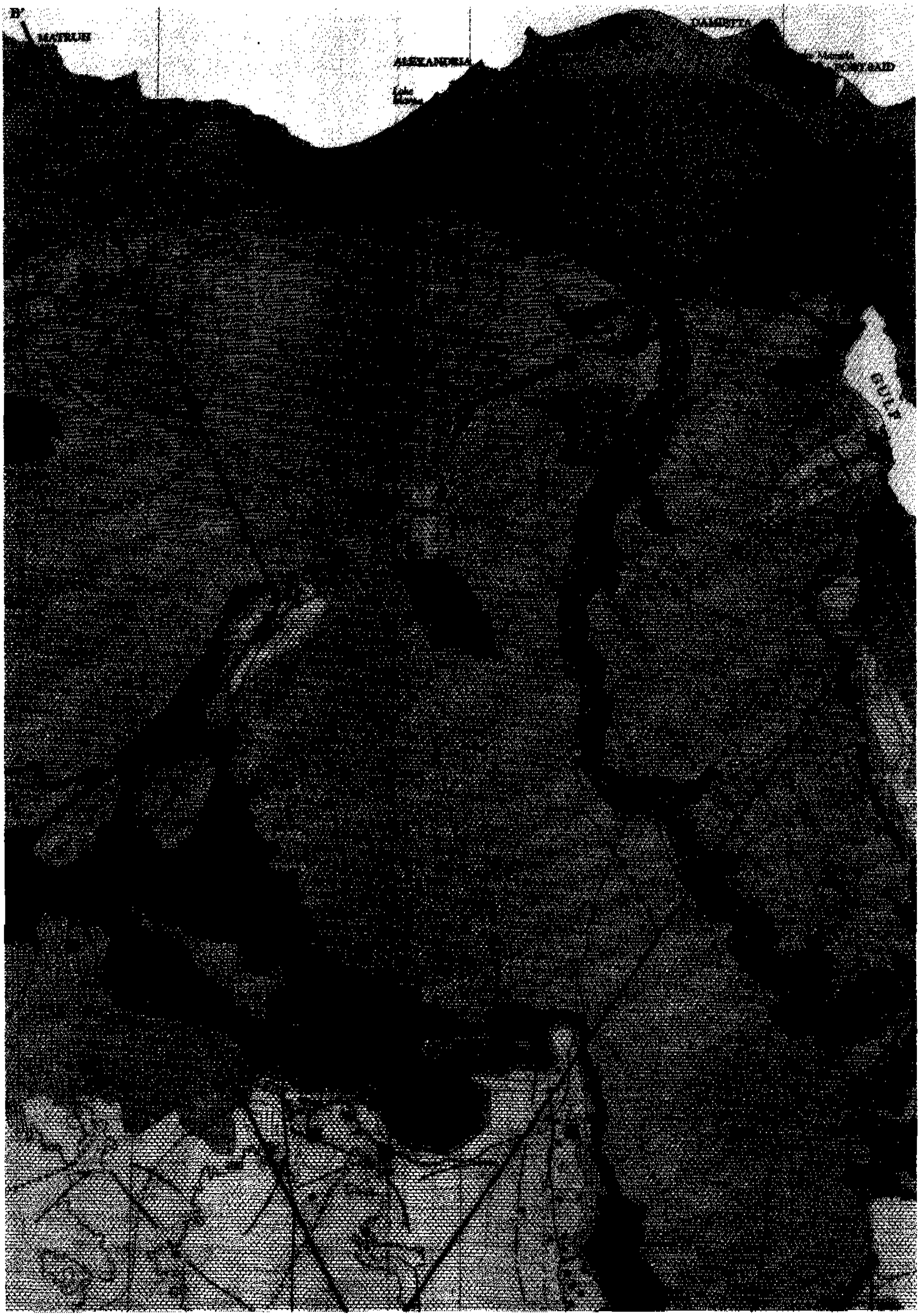


Figure 8 Hydrogeological map of Egypt

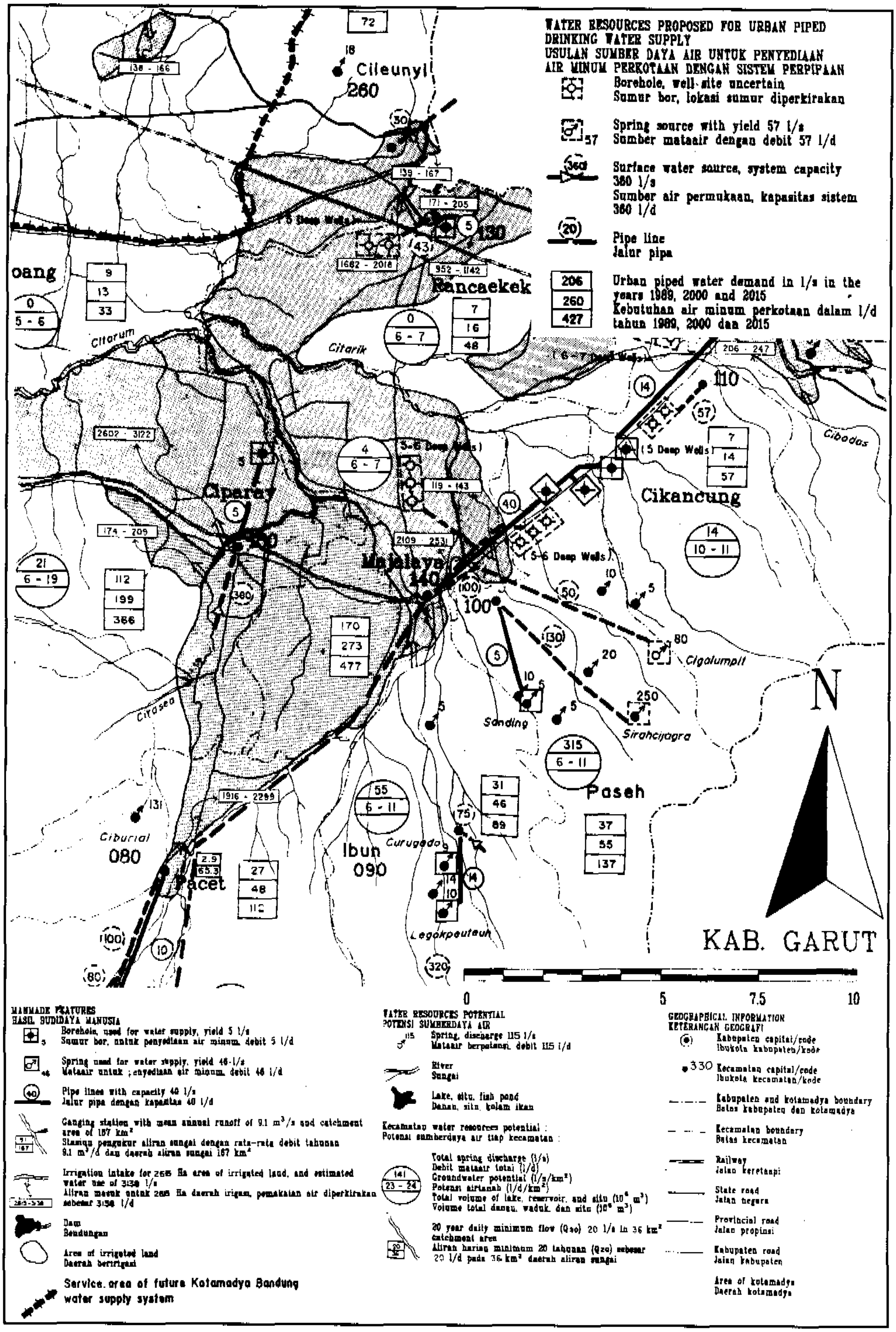


Figure 9 Example of a water system map near Bandung, West Java, Indonesia

- Application of geophysics for well siting in semi-arid regions in deeply weathered granitic areas is not recommended as it does not contribute significantly to the success ratio or yield of deep wells in this environment.

- The application of geophysics is often considered as a black box, which allows laymen to solve hydrogeological problems. The qualified input of an experienced hydrogeologist remains a valuable and indispensable condition for the successful completion of hydrogeological studies.

- In most developing countries good quality hydrogeological data are not readily available. Interpretation of data usually needs further improvement. Mostly, general hydrogeological maps are not available nor are specific hydrogeological maps.

- Often, the production of hydrogeological maps and the training of counterpart agencies as well as local consultants are incorporated in WRM and drinking water supply projects, financed under the Netherlands development cooperation. Usually, in WRM terms, the map-making process takes place in the assessment phase where general hydrogeological maps are concerned and in the planning phase where more specific hydrogeological maps are applied.

- It is highly recommended to use the hydrogeological legend as presented by UNESCO (1983) as standard for general hydrogeological maps. For the application of the legend in specific conditions (e.g. (semi-) arid hard rock areas) additions are necessary but should be kept at a minimum.

- For specific hydrogeological maps it is also recommended to use where possible the symbols and ornaments as used in the "UNESCO" legend.

- Experience in a number of developing countries shows that hydrogeological field surveys are necessary to correct, cq complete the available hydrogeological data, used for the making of the hydrogeological map.

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DETERMINATION OF HYDRAULIC CHARACTERISTICS OF FRACTURED ROCK AQUIFERS

W.K. Boehmer

ABSTRACT

Pumping test analysis in fractured rock aquifers are complicated due to the secondary nature of the permeability and porosity of the rock. Analysis of these tests with conventional methods for porous aquifers is often not possible. This paper gives a brief description of some methods developed for the analysis of pumping tests on fractured rock aquifers during the last 20 years. The methods are applied on pumping test data of a weathered zone aquifer, a composite dike aquifer and an anisotropic fractured shale aquifer. They proof to be very useful in determining the aquifer characteristics of these aquifers required for a more accurate evaluation of the groundwater potential and the yield of a borehole. The results of a test on a karstic dolomite aquifer shows that not all the problems of testing secondary aquifers have been solved yet.

1 INTRODUCTION

Hard rocks in general have a very low permeability and, apart from sedimentary rocks, also a low porosity. However, at a larger scale rocks may store large quantities of water in a more or less inter-connected system of fractures and bedding-planes which are of great importance for groundwater exploitation by wells. Fracture permeability and, in many cases, secondary porosity are often more important for groundwater exploitation from hard rock aquifers than the original permeability and porosity of the rock. In order to make reliable estimates of the water level behaviour around pumped wells, and for groundwater model studies, aquifer characteristics should be determined and flow equations should be developed.

Groundwater flow in fractured rock differs considerably from groundwater flow in porous homogeneous media for which numerous flow equations are available such as of Theis (1935), Cooper and Jacob (1946), Hantush (1964), a.o. Groundwater flow in hard rock takes mainly place in the fractures of the rock and depends highly on the fracture pattern which is seldom known precisely. Several models using a schematic pattern of fractures assumed to describe groundwater flow in natural fractured rock aquifers have been developed. These models allow conventional type curve matching techniques to be applied and assume the same conditions as for pumping test methods on porous media.

Muskat (1937) was one of the first who analyzed the flow in fractured media, Gringarten (1982) reviewed the extensive literature and found that three main types of approach to the problem are used:

- The deterministic approach, which is based on an accurate and detailed description of individual fracture systems, and is mainly used for small-scale problems in geotechnical engineering.
- The double-porosity medium approach, which assumes a uniform distribution of matrix blocks and fissures throughout the reservoir.
- The equivalent homogeneous reservoir approach, which considers only main trends of the pressure behaviour of the fissured reservoir, and tries to relate them to a known model of lower complexity.

This paper describes the analysis of a number of pumping tests using methods developed for flow in fractured media and porous media. This in order to investigate the possibilities of these methods for the analysis of pumping tests in fractured rock aquifers and their usefulness in groundwater resource evaluation.

2 METHODS FOR THE DOUBLE POROSITY APPROACH

The concept of the double porosity model was first developed by Barenblatt et al. (1960). They assumed two flow domains:

- The matrix block of large storage capacity but of low permeability.
- The open fracture with low storage capacity and high permeability.

The water level in fractures react much quicker to changes in water pressure than the porous matrix blocks. The flow is time-dependant; the pressure in the fractures and blocks adjusts to changes in pressure the duration of which depends on the elastic characteristics of both the fractures and the blocks, their permeability and size. Variants have been developed by Warren and Root (1963), Kazemi (1969) and Bourdet Gringarten (1980).

Gringarten (1982) remarked that the type curves for double porosity flow are identical to the time-drawdown curves for an unconsolidated unconfined aquifer with delayed yield as presented a.o. by Neuman (1972).

Figure 1 shows an example of a pumping test on a weathered rock aquifer composed of Precambrian gneiss at Kenhardt in the Cape province, South-Africa. The analysis of this test is carried out by the Bourdet-Gringarten method for a fractured rock aquifer of the double-porosity type. Water is struck in fractures in the deeper part of the weathered zone. These fractures form a network draining water from a low permeable matrix of weathered rock of higher effective porosity. Analysis following procedure 17.1 in Kruseman and De Ridder (1990) yields:

- The early time - drawdown of the observation well at a distance of 11.2 m from the pumped well, matched with the Theis type curve and yields a fracture transmissivity T_f = 88.5 m^2/d. The storativity of the fractures amounts 3.9 x 10^{-4}.
- The stabilized drawdown of the intermediate part of the time-drawdown curve yields the

inter-porosity flow coefficient λ = 0.0215. The value of λ determines, with T_f and the pumping rate Q, the drawdown at which the transition occurs from fracture flow to flow from fractures and matrix blocks.

- Matching the late-time drawdown data plot on the type curve yields T_f = 88.5 m^2/d and $S_f + b.S_m = 1.08 \times 10^{-2}$. Substitution of b= 1/3 for a three-dimensional orthogonal fracture system assumed for the weathered rock aquifer yields the matrix storativity S_m = 0.0312.

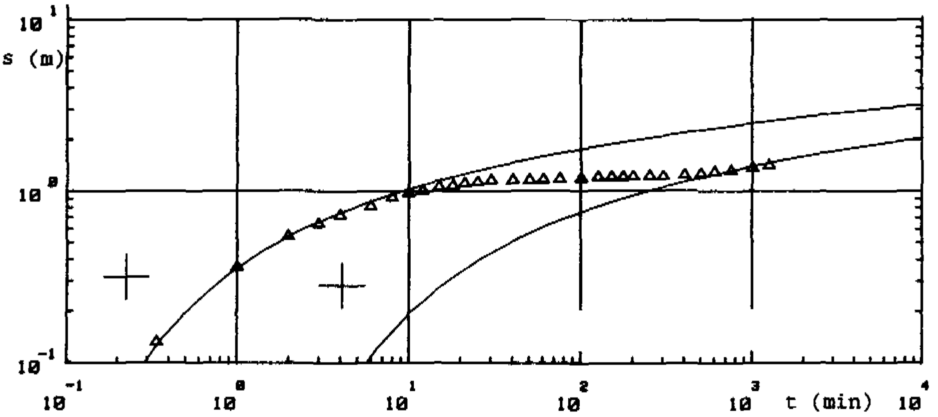

Figure 1 Time-drawdown graphs of an observation well of a pumping test in a weathered gneiss and schist aquifer at Kenhardt, Cape province, showing double porosity behaviour

With all the aquifer characteristics determined, the drawdown in and around the pumped well as well as the area influenced by pumping can be determined at any time.

3 METHODS FOR THE EQUIVALENT HOMOGENEOUS APPROACH

The equivalent homogeneous approach contains models describing (i) the pressure behaviour of a well that intersects a single vertical fracture of finite length and conductivity in otherwise low permeable rock described by Cinco et al. (1978) and (ii) the drawdown behaviour in and around a well tapping a highly permeable intrusive dike or fault of infinite length in otherwise low permeable rock described by Boehmer and Boonstra (1986,1986,1987,1989). The latter method may be applied, with only minor adjustments, to flow to wells in dike contact zones. In this method the well produces at a constant rate from a highly permeable conduit in an otherwise low permeable homogeneous porous medium.

Permeable faults and intrusive dikes play a major role in the groundwater regime of the Rada basin in the centre of the Republic of Yemen. In the Rada basin prominent NW-SE step-faults intruded with magma run parallel over Rada town and cross the plain with the Rada wellfield NE of the town. Figure 2 shows the groundwater flow pattern around the major faults. These faults are major conduits for groundwater flow from below a lava plateau of Jabl Isbil, a huge volcanic centre in the generally low permeable Cretaceous Tawilah sandstone and the impermeable Precambrian basement. These faults are the major suppliers of water for the Rada water supply tapped by boreholes of the Rada wellfield. The low permeable Tawilah sandstone and weathered Precambrian rock form the low permeable groundwater reservoir mainly recharged and drained by water flowing along these faults.

Groundwater flow in and near these faults has been simulated by a groundwater model of the Rada basin described by Boehmer (1988). Figure 2 shows that in the upper part of the faults, below and near the lava plateau, 2.6 x 10^6 and 0.62 x 10^6 m^3/year enter the Rada basin along the two main faults. Below and near the lava plateau where the water levels in the faults are deeper than that in the country rock, the flow in the faults increases gradually by drainage of the sandstone to maxima of 3.2 x 10^6 and 0.93 x 10^6 m^3/year. In the lower part the presence of bulges on the water level contours at the faults, shows that the water level in the faults is higher than in the adjacent sandstone and water discharges from the fault.

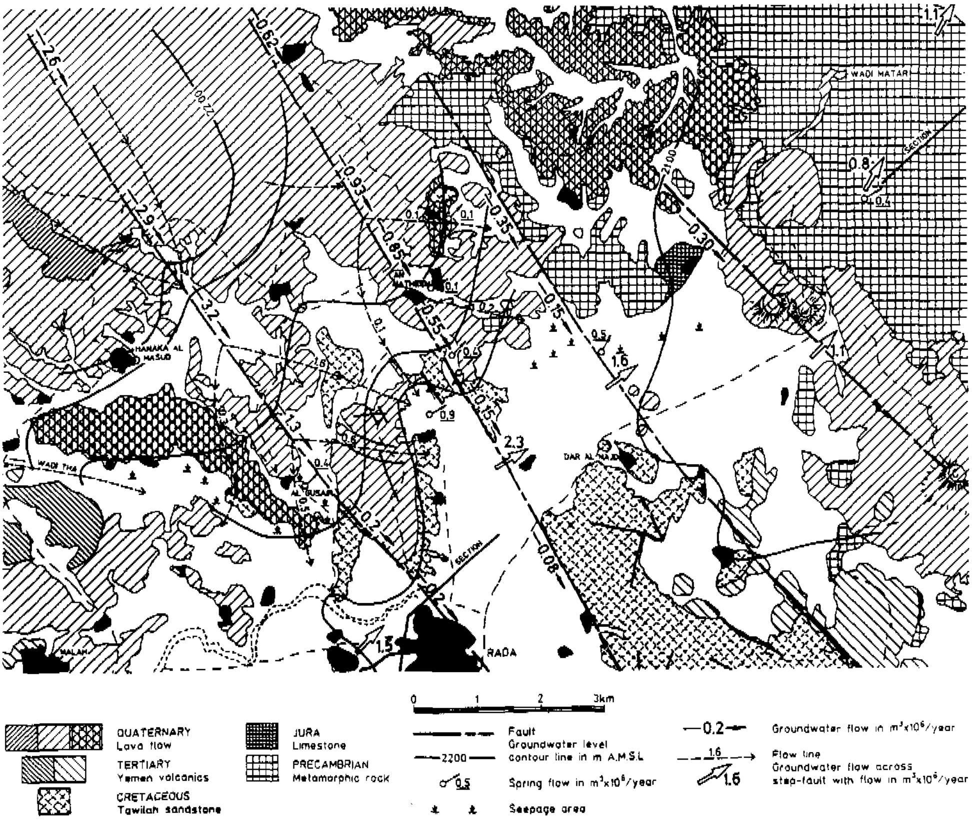

Figure 2 Natural groundwater flow regime around major faults yielding water for the drinking water supply of Rada town in central Yemen

The major fault over Rada recharges the country rock in total by 3 x 10^6 m^3/year of which 1.4 x 10^6 m^3/year is discharged by springs and natural evaporation. Only 0.2 x 10^6 m^3/year reaches the groundwater in the plain along the fault. The second major fault recharges the country rock by 0.78 x 10^6 m^3/year, 0.6 x 10^6 m^3/year of which flows out of springs and only 0.15 x 10^6 m^3/year of flow reaches the plain along the fault. These faults have been selected as sites for production wells. The boreholes drilled in them have very high yields of more than 50 too 100 l/s against yields of less than 5 l/s for wells tapping minor fractures in the sandstone.

Figure 3 shows the time - drawdown of a pumped well and an observation well in the 25 m wide fault zone in the centre of Figure 2, 1 km south of An Natheen. The Tawilah sandstone cut by the fault serves as low permeable groundwater reservoir. The analysis of this test follows the procedures for this method described in chapter 19 of Kruseman and De Ridder (1990).

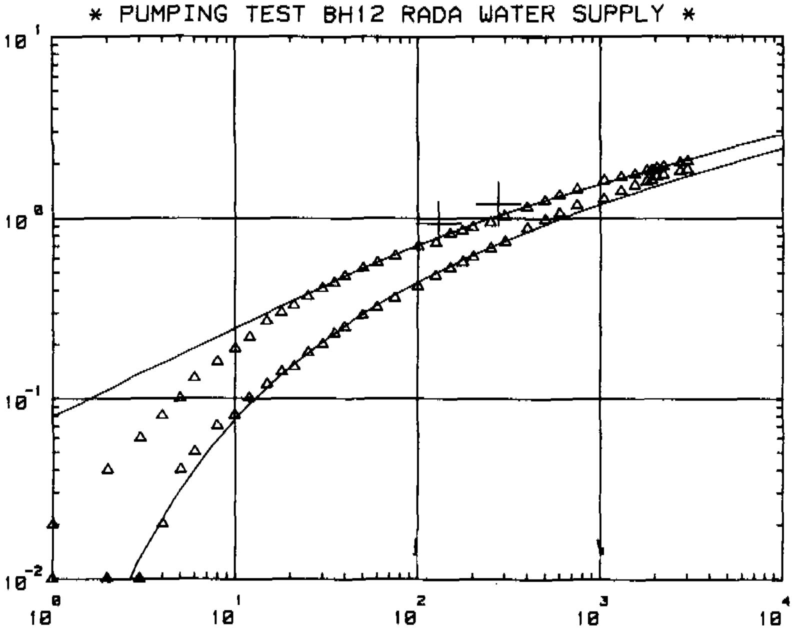

Figure 3 Time-drawdown graphs of the pumped well and an observation well in the fault matched with type curves of the dike aquifer function $F(\chi,\tau)$ versus τ (matchpoint $\tau, F(\chi.\tau)$ = 1,1)

Matching the time-drawdown plots of the pumped well and the observation well in the fault with curves of the family of type curves of the dike aquifer function $F(\chi,\tau)$ versus τ yields:
- For the pumped well using procedure 19.3:

time coordinate = 224 minutes
drawdown coordinate = 1.1 m
$(W_dT_d)(W_dS_d) = 144\ 000\ \mathrm{m^4/d}$

$(W_dT_d)(ST)^{1/2} = 194\ 000\ \mathrm{m^4/d^{3/2}}$

$(ST)/(W_dS_d)^2 = 2\ \mathrm{d^{-1}}$

- For the drawdown and recovery of the observation well in the fault matched with type curve $F(\chi,\tau)$ versus τ with $\chi = 0.3$ using procedure 19.1 the following values of W_dT_d, W_dS_d and ST shown in table 1.

In Figure 4, following procedure 19.2 in Kruseman and De Ridder 1990, the time-drawdown ratio plot of the observation well in the Tawilah sandstone is matched with the function $F(u_a)$ versus $1/u_a$ of the aquifer and yields with a time coordinate of 282 minutes a value of $T/S = 139\ 000\ \mathrm{m^2/d}$. The well lies 330 m NE of the fault on a line across the pumped well and perpendicular to the fault. The irregular plot of early time data is due to the absence or very small drawdown during the first 100 to 200 minutes of pumping.

Table 1 W_dT_d, W_dS_d and ST values of the fault aquifer test on well No. 12 near Rada calculated from time-drawdown data and time-recovery data of the observation well in the fault for matchpoint coordinates τ, $F(\chi,\tau) = 1,1$

Period		Matchpoint coordinates			Hydraulic characteristics		
	x m	χ	time minutes	drawdown m	W_dT_d $\mathrm{m^3/d}$	W_dS_d m x 10^{-3}	ST $\mathrm{m^2/d}$
drawdown	175	0.3	154	1.0	626 000	0.29	0.097
recovery	175	0.3	120	1.0	640 000	0.15	0.077
Final solution					550 000	0.19	0.097

An optimum solution is found by substitution and adjusting above aquifer characteristics into the fault aquifer equations until a best fit is found of calculated and observed drawdown and recovery in the pumped well and the two observation wells in the fault and sandstone aquifer. This optimum solution is:

for the fault aquifer:

$W_dT_d = 550\ 000\ \mathrm{m^3/d}$
$W_dS_d = 0.19$

for the sandstone aquifer:

$ST = 0.097\ \mathrm{m^2/d}$
$T/S = 139\ 000\ \mathrm{m^2/d}$
$T = 116\ \mathrm{m^2/d}$
$S = 8.4 \times 10^{-4}$
$T_dS/TS_d = 21$

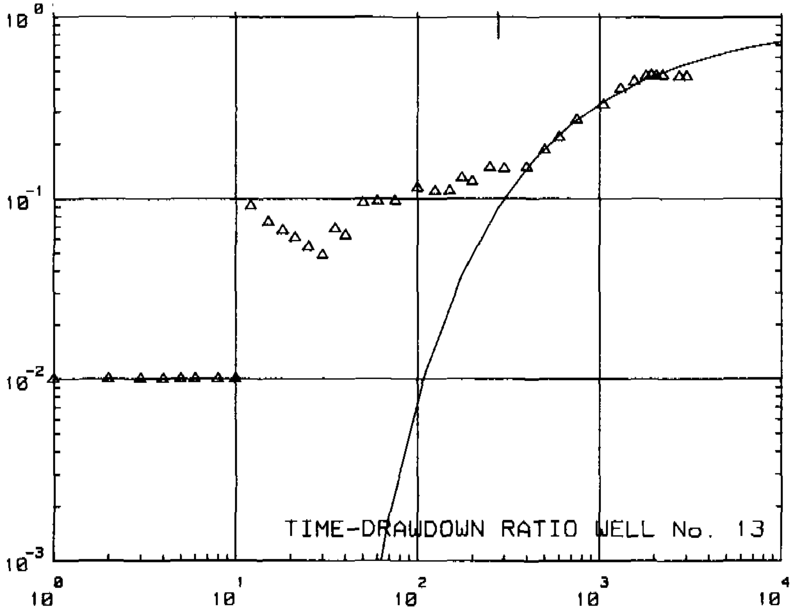

Figure 4 Time-drawdown ratio data of the observation well in the low permeable Tawilah sandstone aquifer matched with the type curve $F(u_u)$

Figure 5 shows that the time-drawdown in the pumped well and the two observation wells matches quite well the drawdown calculated with the dike equations after substituting above aquifer characteristics.

The flow capacity of the faults is a product of their transmissivity T_d and width W_d, which is in the order of 250 000 to 550 000 m^3/d, and the transmissivity of the Tawilah sandstone is only 5 - 150 m^2/d as derived from the pumping tests on the wells in the faults. Using these values and the slope of the regional groundwater level near the boreholes deduced from the water level map of Figure 2 yields a flow along the faults which is similar to the regional flow calculated by the groundwater model of the Rada basin. This indicates that nearly all the groundwater flow takes place along faults and only to a minor degree through the sandstone.

4 METHODS FOR POROUS MEDIA

Despite the difference between flow in porous media and fractured hard rock aquifers, pumping test methods developed for porous media have been applied many times successfully for the evaluation of hydraulic characteristics of hard rock aquifers.

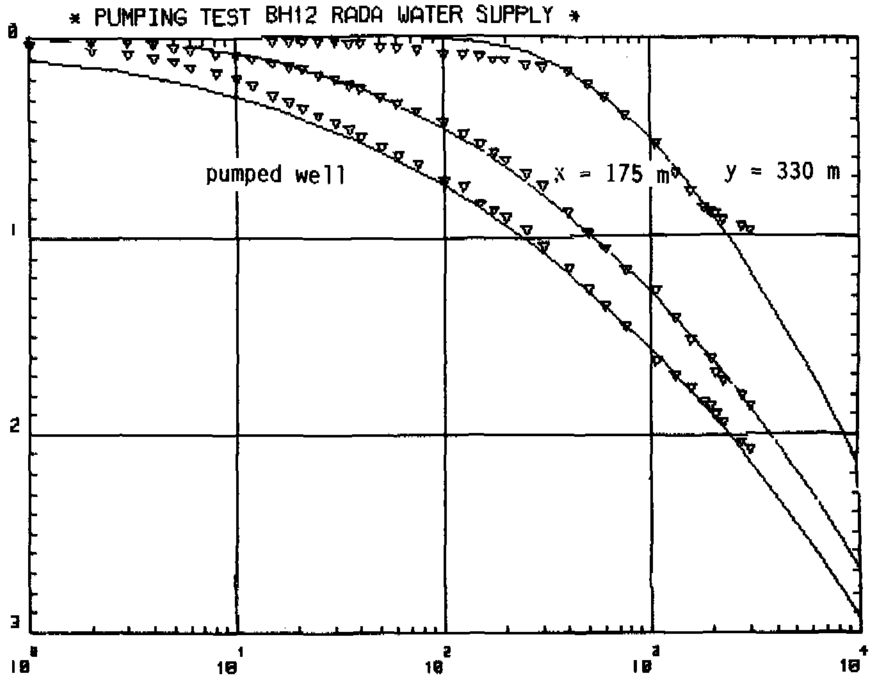

Figure 5 Observed and calculated drawdown in the pumped well and the two observation wells in the fault at x = 175 m and in the sandstone aquifer at y = 330 m

The application of the method for leaky aquifers of Hantush and Jacob (1955) developed for homogeneous aquifers, on the volcanic rock formations of the Snake River Basalt in Illinois, USA, in Walton (1970), is only one of the numerous examples of successful applications of these methods on hard rock formations with secondary permeability.

This example deals with a pumping test on a well in the Daspoort shale aquifer of the Pretoria series of Precambrian age at Pretoria. The thickness of the shale aquifer amounts approximately 180 m and is bounded at its base by the impermeable Ongeluks lava, and at the top by a 90 m thick impermeable diabase sheet. The formation dips 27° North. The Pretoria shales has a good developed secondary permeability along the planes of schistosity and forms at the well site an anisotropic strip aquifer with a marked higher permeability in the strike direction than perpendicular to the plane of schistosity. Despite the complex groundwater situation with boundary effects and secondary fracture permeability, pumping tests carried out on several boreholes tapping this aquifer could be analyzed by the Hantush method, 1966 for anisotropic aquifers. Figure 6 shows a plan of the pumped well the observation wells, the direction of maximum and minimum permeability and the impermeable boundaries. Observation well 1 lies at 75 m south of the pumped well. The line drawn through the pumped well makes an angle of 15° with the direction of the lowest permeability. Observation well 2 lies 250 m east of the pumped well. The line drawn through the pumped

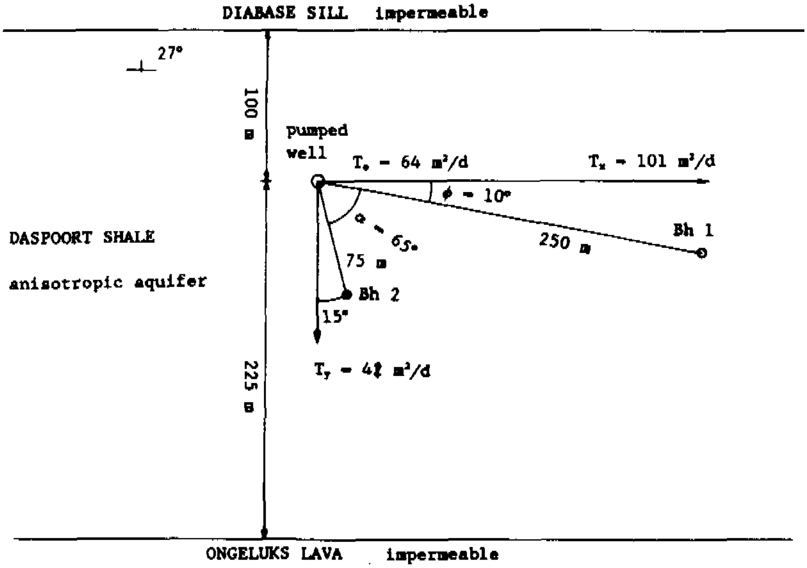

Figure 6 Plan of the anisotropic Pretoria shale aquifer bounded by a Diabase sill and the Ongeluks Lava showing the position of the pumped and the two observation wells in relation to the main directions of permeability

well makes an angle $\phi = 10°$ with the direction of the highest permeability, the strike direction of the schistosity of the formation. The angle between observation wells 1 and 2 measured from the pumped well $\alpha = 65°$. The impermeable boundary of the aquifer formed by the diabase sheet lies 100 m north of the pumped well and by the impermeable boundary of the Ongeluks lava lies 225 m south of the pumped well. Figure 7 shows the time-drawdown of the pumped well and of the two observation wells plotted versus time on semi-logarithmic paper. All three time-drawdown graphs show extra drawdown caused by the boundaries. The analysis of this pumping test is carried out by Hantush method for anisotropic aquifers assuming that the principle directions of anisotropy are known. The solution follows procedure 8.1 for this method in Kruseman and De Ridder (1990).

First the values of the effective transmissivity T_e, the value of the ratio S/T_1 and S/T_2 are determined following the Jacob method. This yields:

- Using the time-drawdown of the pumped well; $T_e = 63.9$ m^2/d.
- Using the time-drawdown of the observation well at 250 m in the direction of the highest permeability; $S/T_1 = 7.22 \times 10^{-7}$.

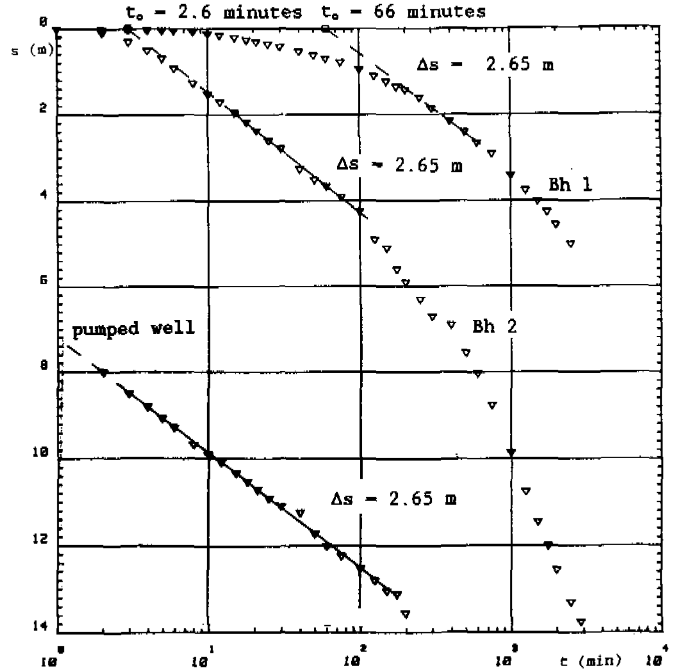

Figure 7 Time-drawdown of the pumped well and two observation wells in an anisotropic aquifer analyzed by Jacob's method

c) Using the time-drawdown of the observation well at 75 m in the direction of the lowest permeability; $S/T_2 = 1.65 \times 10^{-6}$.
d) The ratio $a = T_1/T_2 = 2.286$.
e) Substitution of $a = 2.286$, $\alpha = 75^\circ$, $\phi = 10^\circ$ and $T_e = 63.9$ into:

$$m = \frac{a \cos^2 \phi - \cos^2(\phi + \alpha)}{\sin^2(\phi + \alpha) - a \sin^2 \phi} = 2.49$$

f) Knowing the anisotropy factor $m = 2.49$ and the effective transmissivity T_e yields the transmissivity in the x-direction: $T_x = 100.8$ m^2/d and in the y-direction $T_y = 40.5$ m2/d.
g) Using the values T_x, m and the angles α and ϕ the transmissivities at both the observation wells are calculated, yielding; $T_1 = 96.5$ m^2/d and $T_2 = 42.2$ m^2/d.
h) Substation of $T_1 = 96.5$ m^2/d into the ratio S/T_1, and $T_2 = 42.2$ m^2/d into the ratio S/T_2 yields the storativity $S = 7 \times 10^{-5}$.

Small deviations of the drawdown in both the observation wells from the Theis type curve for confined aquifers, indicates semi-confined conditions for this aquifer. Analysis of the time-drawdown graphs using the Walton's type curve method for semi-confined aquifers, Walton 1962, yields the vertical hydraulic resistance of the overlying aquitard. The aquitard on top of the aquifer is formed by the highly weathered shales or clay-zone forming the confining layer on top of the underlying anisotropic aquifer. The time-drawdown graph of well 1 yields C = 4100 days and for well 2, C = 3300 days.

With (i) all the aquifer characteristics determined, (ii) the water level configuration measured in a large number of wells in the area used for regional groundwater flow calculations to determine natural recharge and natural discharge, (iii) one year of water level observations and (iv) an analysis of the long rainfall record, safe abstraction rates and the total drawdown for all the tested wells could be determined.

5 LIMITATIONS TO THE DEVELOPMENT OF PUMPING TEST METHODS FOR FRACTURED ROCK AQUIFERS

Fracture flow

Electrical resistivity logs, borehole descriptions and testing reveal that water is generally struck in a few major fractures or fracture zones in the rock. For this reason we may assume that wider fractures occur at a larger spacing than the smaller ones but are mainly responsible for the high permeability of the rock. To demonstrate this phenomenon the following calculations have been made. The flow in a 10 m wide intrusive dike is regarded to take place only in the fractures. These vertical, equidistant fractures run parallel with the sides of the dike and have equal width. The calculations have been made for the same equivalent porous medium permeability (Freeze and Cherry, 1979; Snow, 1968). Table 2 shows the results of these calculations carried out with the following equation:

$$K = \frac{g\, w_f^3}{(12\ v\ d)}$$

with:

K = equivalent permeability
w_f = width of the fracture
d = distance between fractures
g = acceleration of gravity
v = dynamic viscosity

Table 2 Number, width, and distance of fractures for the same equivalent porous medium permeability in a 10 m wide intrusive dike

N[1]	w_f μm	d cm	K m/d
3	1000	333	21.04
6	800	167	21.55
10	650	100	19.26
30	450	33	19.17
200	250	5	21.92
3000	100	0.33	21.04

[1] N = number of fractures in a 10 m wide intrusive dike

Table 2 shows that, for example, 3 one-thousand micrometres wide fractures have the same flow capacity as 3000 one-hundred micrometres wide fractures. So, a few wide fractures are already sufficient to make a dike or fault highly permeable.

Fracture width and thickness, distance between the fractures and the width of the fault zone or a dike influences the flow in it and thereby the yield of the wells. The great influence of single wide and open fractures on the total permeability of the rock and the rapid change of the width of these fractures over short distances causes heterogeneity in most hard rock aquifers which is hard to analyze and describe by any aquifer test method. In all the methods flow is assumed to be laminar.

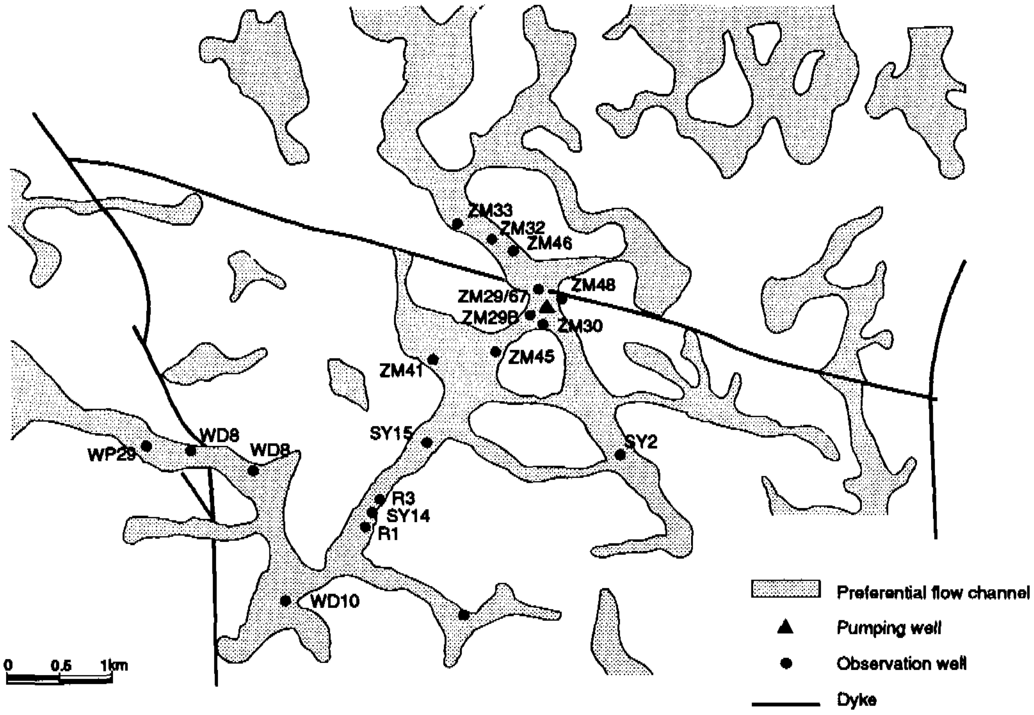

Figure 8 Plan of solution channels and observation wells around a test well in the Gemsbok compartment of the Precambrian dolomite at the Witwatersrand after Bredenkamp et al. (1991)

Pumping tests on wells tapping widely spaced fracture networks or solution channels in karstic rocks show similar but very characteristic drawdown relations which cannot yet be fully analyzed with the existing methods. We shall now discuss the analysis of a pumping test on a well tapping widely spaced permeable solution channels in otherwise nearly impermeable dolomite rock. Figure 8 shows a test site of a pumping test carried out in the heterogeneous dolomite rock aquifer of the Gemsbok east compartment at the Witwatersrand, Bredenkamp et al. (1991).

In Karstic limestones successful boreholes strike water in often one highly productive solution channel that may be part of a very irregular network of solution channels and caves as shown in Figure 8. The drawdown with time in such boreholes may follow a regular decline rate like in case of radial flow to a well in a homogeneous porous aquifer. Table 3 presents the results of an analysis by the Theis and Jacob methods of the time-drawdown measured in the observation wells during a long duration test at 76.5 l/s.

Table 3 Aquifer characteristics of the dolomite aquifer determined from the time-drawdown graphs of the first 11 days of the Gemsbokfontein pumping test at a rate of 76,5 l/s. Analysis by the Theis and Jacob methods

Bh.	No.		Theis method		Jacob method	
		r (m)	T (m^2/d)	S	T (m^2/d)	S
ZM48	1	88	3319	0.824	3319	.825
ZM47	2	125	4275	0.23	4364	.198
ZM29B	3	250	4375	0.104	4372	.11
ZM45	4	875	3900	0.0141	3871	.013
ZM41	5	1250	3319	0.0078	3300	.0085
SY2	11	1763	4275	0.0033	4275	.0033
SY15	12	1925	4083	0.0037	4083	.0037
SY14	13	3063	4687	0.0014	4500	.0015
WT.M4	14	3338	3319	0.00147	3800	.0014

Table 3 shows that the calculated regional transmissivity of 3300 m^2/d to 4500 m^2/d for dolomite does not show a too large spreading for a test site of these dimensions. Figure 9 shows that the observed water level (curve A) is nearly horizontal in the central part of the cone of depression. This form deviates completely from the distance - drawdown relation, or the form of the cone of depression in a porous aquifer with a transmissivity = 4000 m^2/d and a storativity of S = 0.0015 of curve B, which becomes steeper nearby the pumped well. Analysis of the time-drawdown data by the Theis and Jacob methods of this pumping test yields unrealistic high storativity values of S = 0.85 for observation wells near the pumped well continuously decreasing to S = 0.0014 for time-drawdown graphs of observation wells at larger distance from the pumped well.

Similar findings are characteristic for all pumping tests on wells tapping widely spaced networks of solution channels in karstic limestones as well as widely spaced fracture networks in other low permeable hard rock formations.

For the following reasons is it very difficult to develop models and methods describing the flow in these types of widely spaced fracture network aquifers and karstic aquifers:

- The heterogeneous nature of the network of faults and solution channels.
- The unknown and rapid changing width and permeability of the solution channels.
- The sometimes turbulent flow type in these channels.

Calibration of a numerical model using historical water levels and water balance data is at the moment the only method to find a storage coefficient of such a karstic aquifer. The storativity derived from a groundwater model study of this Karstic aquifer yields a specific yield of 1 to 3 percent.

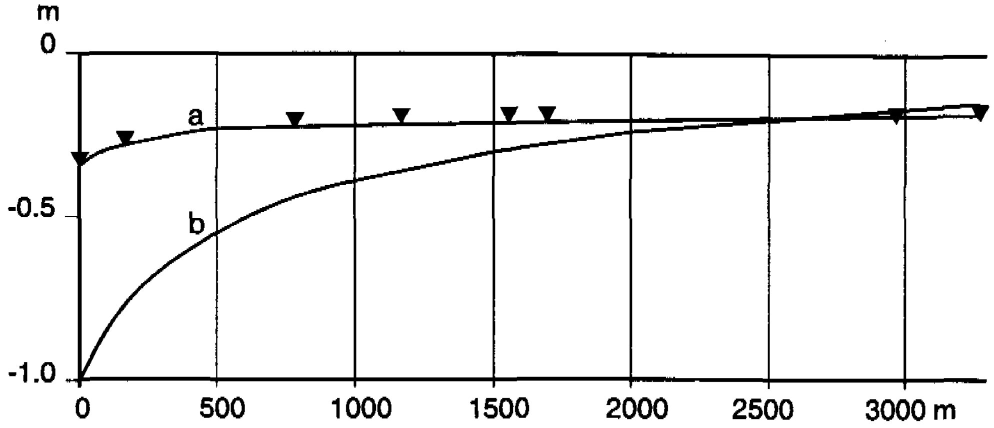

Figure 9 Cross sections of the observed cone of depression in the dolomite aquifer (curve A) and a cone of depression calculated with the Theis aquifer function (curve B) for a homogeneous aquifer with a transmissivity of 4000 m/d and a storativity of 0.0015 after 7200 minutes of pumping

6 CONCLUSIONS

Application of existing analysis methods for the evaluation of pumping tests on fractured rock aquifers showed:

1. Methods for the evaluation of double porosity media, composite dike or composite fault aquifers and for porous media have been applied successfully for the evaluation of pumping tests and aquifer characteristics of fractured rock aquifers.
2. The results may be used in determining the yield of boreholes, the influence of pumping on the aquifer in time and space, and for the evaluation of the groundwater potential of many times complicated fractured rock aquifer systems.
3. Evaluation of pumping tests on a network of widely spaced permeable major fractures in low permeable hard rock and networks of solution channels in karstic limestones and dolomites is not well possible with the existing methods although a conceptual model can be defined that may be developed into a working method.

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THE RATIONALE BEHIND EGIS: A HYDROGEOLOGICAL INFORMATION MANAGEMENT SYSTEM FOR APPLICATION WORLDWIDE

T.T. Kuipers

ABSTRACT

The TNO Institute of Applied Geoscience has much experience in administering groundwater data in the Netherlands and in implementing water resources management projects in developing countries. It has long been aware of the need to collect, manage and process various data (typically, geological, pedological, climatological, hydrological, agricultural, socio-economic and water-use data), as well as to safeguard their availability. This led to the Institute helping to set up central hydrogeological information centres in various project countries, where maps, reports and field data are stored and can be accessed for further research. In the project countries the Institute's experts, assisted by local counterparts, originally stored field data in software systems based on Personal Computers, which are relatively cheap and easy to maintain and programme. Software programs were written on site, taking account of local conditions and aiming to meet the local requirements and exploit local potential. Central availability and data quality were given priority in this short term pragmatic approach, and organization analysis, database design, software maintenance and customer support were relegated to second place. Meanwhile, the Institute continued to expand and deepen its expertise in managing information systems via its work to develop and exploit the national information system for the Dutch groundwater monitoring network. This experience, coupled with an appreciation of the needs and constraints in developing countries, resulted in the Institute embarking on the development of a uniform integrated hydrogeological management system that could be applied effectively and efficiently worldwide. This Evaluation of Groundwater resources Information System (EGIS) is intended to be used in national, regional or local projects, after being modified to meet local requirements. It will also be available commercially.

1 TNO INSTITUTE OF APPLIED GEOSCIENCE AND THE MANAGEMENT OF HYDROGEOLOGICAL DATA

1.1 Experience in the Netherlands

The TNO Institute of Applied Geoscience has been responsible for the maintenance of the National Groundwater Monitoring Network in The Netherlands since 1948. In this network, data from over 13,000 monitoring stations (wells and shallow piezometers) are available on-line to TNO staff and to clients throughout The Netherlands. It currently contains time series of over 12 million water levels and chemical analyses of more than 30,000 groundwater samples. The static data of the monitoring stations (lithology, stratigraphy, topography, etc.) and the administrative data on legal aspects of the sites (who is the owner of the property, who is the observer - there are over 2,000 volunteer observers) are stored in a huge relational database with a capacity exceeding 600 Mb. More than 360 software modules assist the 12 staff members who are employed full time to maintain the data and to supply data to hydrogeologists and clients engaged in hydrogeological research. Since 1992, topological data (e.g. on water courses, waste disposal sites, groundwater protection zones) and other spatial data have been stored in a Geographical Information System (GIS).

1.2 Experience abroad

In the last decade the Institute has been involved in many projects worldwide, for instance in Colombia, Kenya, Yemen, Sudan, Pakistan, India, Oman, Greece and China. In many of these projects, one of the main targets has been to transfer, and subsequently bring into service, the Institute's expertise in geoscientific technology and organization structures to local institutes and organizations, to promote the efficient use and management of subsurface natural resources. Occasionally, the emphasis has been on ascertaining the producible volume of water, or the structure required for an efficient management of the water resources. In all cases, the availability and accessibility of data has been crucial. Users of water data in these countries were confronted with high costs, because the data required were unavailable or inaccessible, or laborious editing was required to obtain data of the correct format and quality.

The demand for available and accessible data, and for data to be processed faster led to the need to store data automatically and centrally. The availability of relatively cheap personal computers which, unlike mini computers, make few demands in terms of cool, dust free work environments and are easily programmable, resulted in hydrogeological databases being developed for a number of projects.

At an early stage, it was perceived that the introduction of computer technology would improve the motivation of local staff, who found traditional ways of manual storage and processing of data time-consuming and tedious. However, it was also realized that imprudent application of this technology could lead to undesired situations, because it is impossible to maintain hardware and software without outside support. Therefore, important elements in the strategy to introduce computer technology were a stepwise approach and effective training.

When this strategy was followed, the data became easily accessible and the exchange between the various departments was simplified; furthermore, the retrieval of data became less time consuming, and quality control, selection and data processing became easier.

Examples of the application of this strategy in three countries are presented below, followed by an assessment of the experience the Institute acquired from projects of this type.

1.2.1 The national information centre in Sudan

The Water Resources Assessment Program (WAPS), a joint venture between the Dutch Ministry of Foreign Affairs and the Government of Sudan, started in 1979. The objective was to assist the institute in Sudan, the National Water Corporation (NWC), in water research and water management. This was to be achieved via training, exchange of knowledge and improving the accessibility of data.

In the absence of a national water resources database in the Sudan, it proved extremely difficult to obtain a complete picture of the available data collected during previous assessment or reconnaissance studies. A database for water resources data was therefore urgently needed in order to make data accessible, to avoid unnecessary duplication, to prevent the loss of invaluable data and to promote and facilitate the analysis and proper use of existing data. It was therefore decided to set up a national information centre, to prevent loss of valuable data and to allow the available data to be evaluated reliably. The nucleus of the information system was two Apple-II microcomputers. Data acquisition was standardized and programmes were developed to process and present the data collected.

The NWC stores a wide variety of information of varying quality, including hydrogeological, geological, hydrochemical, geophysical and surface water data. The data administration is decentralized; the original data are filed in the Regional Offices of NWC, copies up to 1977 are stored at 'Kilo 10' at Khartoum. At Kilo 10 there is a catalogue ("red books") of hydrogeological data, organized per province and year of recording. Approximately 5,000 wells are recorded in the catalogue (data up to 1977). Since 1976 a further 3,000 wells have been drilled in Sudan. At Kilo 10 lithological logs are organized according to province. The quality of the logs varies greatly. There are about 5,000 lithological logs. Other data (hydrogeological, hydrochemical and geophysical) are stored in approximately 500 files in Khartoum. Roughly, the total amount of data (characters) available at NCW is:

- General data	800,000
- Lithological data	3,000,000
- Hydrogeological data	200,000
- Hydrochemical data	500,000
- Geophysical data	1,000,000
- Surface data	5,000,000

At the NCW data are collected, entered and stored and software is written. After the data have been collected, they are entered on data entry forms composed according to the file structure of the data model. The data model used by the NWC has been adapted to accommodate the type of data common in hydrogeological studies and the hydrogeological characteristics of the Sudan. It comprises the following files:

- Catalogue files.

- Lithological file.
- Hydrogeological files.
- Geophysical files.
- Hydrochemical file.
- Surface water files.

The data model can be modified and extended in the future, as the need arises. Data from the data entry forms are entered in the computer and sorted according to the file structure, on a magnetic medium. In order to ensure the necessary consistency in the data, software has been developed to control the quality of the data. Quality control not only involves appraising the individual data values (upper and lower limits for the specific items in the files have to be defined), it also involves checking that the same information is consistent in the different files. The latter procedure requires adequate listings and plots; of course these are also useful for clients using the database. Data retrieval and processing requires advanced programming and a detailed analysis of which programmes are relevant for the database. A database management system that is specially tailored for a hydrogeological database has been introduced so that the stored data can be used optimally.

1.2.2 The Water Resources Information Centre in Yemen

In 1982 the government of Yemen and The Netherlands signed an agreement to embark on the 'Water Resources Assessment Yemen' (WRAY) programme, forming institutional development through technical assistance. A Water Resources Information Centre was established during this programme. Its objectives are: a) to create and operate a centralized national repository for hydrological and hydrological data in the Yemen Arab Republic, b) to establish and maintain routine inflow of data, so that the WRIC database remains up to date and covers the entire country, c) to provide extensive retrieval services and to disseminate important hydrological and hydrogeological information to other agencies and to the general public.

Not all the data are stored in a digital format. Reports, maps, aerial photographs and other information important for hydrogeologists are collected and stored after quality control. The data are gathered from sources throughout the Yemen Arab Republic. As a result of all this, WRIC has developed advanced water resources information and consultancy services in water resources management, and can supply information on climatology (rainfall, sun, wind etc.), hydrology (wadi discharge, surface water levels), hydrogeology (groundwater levels), geophysics and wells.

Two separate software systems called Water Resources Information System (WRIS) and STO have been developed. WRIS can be used for the storage of administrative information on wells (location, depth, nearest village, etc.), whereas STO is used for the storage and presentation of time series of parameters measured daily and monthly. It has always been intended to present data graphically where possible, and therefore a GIS is used to store and present geographical data. All this information is available for government agencies, projects, companies and individuals. Data were published in annual reports from 1985-1991.

1.2.3 The Documentation Centre in Kenya

In Kenya the reasons for setting up a central information centre within the Water Resources Assessment Planning Project (WRAP) can be summarized as follows:

- To provide assistance to the Water Resources Documentation Section (WRDS) with regard to:
  - . Database: determination of database structure, copying data from files of the Ministry of Water Development (MoWD) or other institutions and projects, systematic updating, quality control and standardization;
  - . Collection of hydrological and hydrogeological data, maps, books, reports and journals.
- To cooperate with the Computer Services Section of MoWD.

The activities of the Documentation Section set up during WRAP can be summarized as follows:

- Developing data-processing computer programmes.
- Providing assistance in processing field data.
- Storing field data, reports, books, maps, aerial photographs, satellite images, etc.
- Testing, interfacing, installing and maintaining computer hardware and electronic devices.
- Training staff in application programmes and developing their programming skills.

The usual processing procedures are carried out, the raw data are transferred onto floppy disks from the MoWD minicomputer database to the PCs of the Documentation Section. Software is used to analyse the raw data and cross-check them with the observer readings. This enables typing and interpretation errors to be corrected for most time-series. Rating equations can also be checked and updated. A variety of software packages have been introduced to store, interpret, manage and present the data.

1.3 An assessment of the pragmatic approach

The above examples demonstrate the Institute's policy regarding central information centres in which all relevant water-related data will be available for everyone for reasonable costs. In the early days, because of the lack of suitable PC software and the need for on-the-job training, it was decided that TNO staff with a hydrological or hydrogeological background should develop the software. The budgets for such staff and for the persons to be trained were limited. Local conditions (heat and dust) had to be taken into account. It would have been impossible to provide the conditions required by larger computer systems. This, plus considerations relating to price and support in the partner-countries was why it was decided to deploy micro-computers. TNO had to develop many applications, as suitable commercial software packages were not available in the 1980s. The programming language used was BASIC; later, spreadsheet and database packages such as LOTUS and dBASE were used. Real information analysis, as is commonly used nowadays, was not done, because the project staff lacked the required background. Pragmatic solutions were needed, to reconcile the existing demand in the projects and the limited means available. So, many software programmes were created. This pragmatic approach meant that certain problems common to all projects were solved in different ways, often after laborious work by the computer programmers. For instance, the problem of null values (= non-existent values), missing values (= values with an undetermined result), and values outside the detection limits were solved differently in each of the projects. Local staff also came up with calculations to convert geographical coordinates e.g. to UTM coordinates, although more flexible conversion programs were available commercially.

Within the projects it soon became apparent that a support infrastructure must be in place during software development. Local venders could be prevailed upon to give basic hardware support, but software support remained problematic, even from the Netherlands. The distance between the Netherlands and the project country, the use of different computers and software, and the unfamiliarity with local problems resulted in much confusion.

2 GEOHYDROLOGICAL INFORMATION MANAGEMENT SYSTEMS (GHIS)

2.1 The need for GHIS

At present, much interest is being shown in the integration of different data types, to enable the hydrogeologist to obtain a clear picture of the hydrogeological preconditions that constrain the potential to manipulate a given hydrogeological situation. The information required includes hydrogeological data indicating the permeability and porosity of the ground and the position of the waterbearing and impermeable layers. The local geochemical properties of the subsurface and of the groundwater must be known, so that the chemical changes over time and space can be analysed. It should be possible to investigate the influence of surface water on groundwater, and vice versa, and to have direct access to data on meteorological factors that influence the water balance. Data on the flora and fauna can give additional useful information on a project area and information on the presence of waste dumps or discharges, can aid the hydrogeologist to understand the problem being investigated. He should have access to all relevant data and he should have the tools to be able to manipulate them in such a way that he can analyse the situation optimally from the work location, and draw up the optimal management plan.

Given the above considerations, it is clear that a hydrogeological information system is essential for providing the necessary support for the work done during a hydrogeological project. In general, such projects have two main objectives; to assess the groundwater resources in the area of interest, and then to manage them appropriately. During the assessment phase, quantitative and qualitative information about the groundwater resources in the project area, about the external factors influencing these resources and about the groundwater reservoir are acquired, processed, interpreted and finally transformed into a comprehensive hydrogeological model of the area. This model, which should account for the spatial (3D) and temporal (4D) aspects of the groundwater system being investigated, will be used during the management phase, to evaluate certain groundwater management scenarios. It will continue to be refined as a result of the implementation of these scenarios and the acquisition of additional data.

In order to be able to support the projects outlined above, a hydrogeological information system should provide:

- Facilities to store and maintain all hydrogeological data collected in the area.
- Functionality to derive and maintain a hydrogeological model of the area being investigated.

- Functionality to use this model in the management phase e.g. to support simulation of the effect of management scenarios e.g. support questions of the 'what if' type?

Nowadays, there is abundant software for hydrogeological purposes. In recent years, Geographical Information Systems (GIS) have also been introduced into this field. In many organizations, the stepwise introduction of automation has resulted in a patchwork of unrelated software packages for database management, for the interpretation of different types of data, for the graphical presentation of interpreted results and for modelling. As a result, the software currently available in hydrogeology is still restricted to an agglomerate of independent programs showing incompatible data and user interfaces in a fragmented environment.

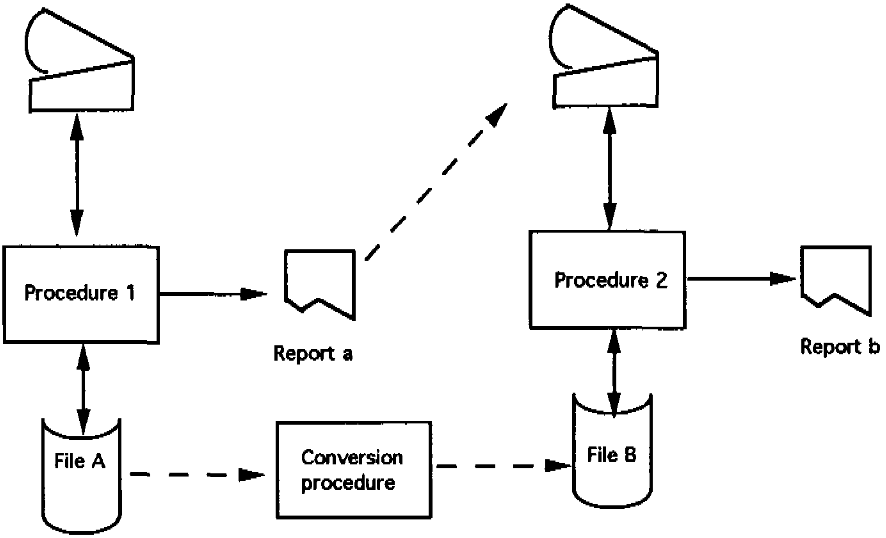

Figure 1 Not integrated procedures, often encountered. Results of programme 1 have to be re-entered to allow the use in programme 2. Sometimes conversion procedures are developed to link different programmes. The data are not stored in one database and each procedure has a different user interface

A hydrogeological information system can therefore considerably improve the hydrogeologist's working environment only if it overcomes the inconveniences of this fragmented environment. A GHIS should therefore not only incorporate the required data and functionality, it should also be designed with four major features in mind: integration, scalability, adaptability, and support for multiple users. Integration can be defined at three levels: integration of data, integration of functionality, and integration of user interface. Scalability and adaptability influence flexibility. A GHIS is scalable when it is able to cope not only with local scale projects but also with regional and nationwide studies. Moreover, it should be possible to tune the system in such a manner that only topics of real interest to a certain problem can be covered and irrelevant topics are omitted. Adaptability requires a system that can be customized to the specific needs of a particular project. Finally, because hydrogeological projects are often conducted by a team of hydrogeologists, the system should be configured as a fully-fledged multi-user system.

2.2 The characteristics a GHIS should have

The following characteristics, specific to hydrogeological information, must be taken into account when selecting or designing a GHIS:
- The data consist of a mix of 'engineering' types of data - a large number of repeating groups related to a feature or a geographical location - and 'administrative' types of data.
- In general, vast amounts of data are involved in hydrogeological engineering. A typical seismic section may contain up to 4 Mbyte of data; some groundwater archives store more than 10 million groundwater level readings.
- During subsequent stages in the life-cycle of a hydrogeological database, the contents of the database will grow continuously, as the data will undergo several stages of processing and interpretation. Along the way, the multitude of interim results and final interpretations derived from one basic set of data will have to be stored.

A powerful and easy-to-use system that is intended not only to store and maintain information, but also to process and interpret it, will have to deal with the following specific aspects of data processing encountered in specifically hydrogeological engineering:
- Data processing and interpretation are often carried out in sub-projects that focus on a geographical or thematic subset of the main project.
- During the interpretation stages of a hydrogeological project, all relevant data must be available at any time. A valuable interpretation can be produced only if the interpreter can access all available information about the area being investigated.
- After completing a sub-project, all or part of the data will have to be archived; it should never be discarded. Hydrogeological information nearly always requires re-examination, even after a considerable time, especially in regions where data acquisition is still costly and time-consuming.
- If required, it should be possible to keep the archived data on-line so that they can be accessed by third parties.

2.3 The characteristics of hydrogeological projects

The Institute of Applied Geoscience is keenly aware that hydrogeological projects differ in scale and goals, and hence in what they require of a GHIS. A distinction has already been made between assessment studies and management studies, but one can also think of projects to establish regional or even national hydrogeological information desks, for which a GHIS could be extremely useful. As mentioned earlier, a GHIS should not only be able to maintain a hydrogeological database, but should also offer the user facilities for data manipulation. Therefore, it is useful to examine the stages of elaboration that hydrogeological data may go through, and the features that a GHIS has to offer if it is to support the activities carried out during these stages:

- The information relevant to the user's domain of interest will be collected during an acquisition stage. It will either consist of field data, collected during acquisition surveys, or historical data, stored on paper or on magnetic media. User-friendly data load modules have to be linked to modern data acquisition tools to onload or offload these survey data into the database. Moreover, data input options have to be available for manual input, and there must be a data conversion facility for loading and converting existing databases. Digitizing programs and a scanner module have to be used to digitize paper maps and convert paper documents or images into their digital equivalent.
- During data loading, and directly afterwards, the quality of the data must be controlled. This quality control has to be automated to a great extent, by validating the input data. Moreover, the option of running procedural quality checks on the stored data, either in the form of statistical control procedures or by means of graphical presentation and visual control of the data will have to be provided.
- One of the basic needs when dealing with the vast amounts of hydrogeological data will be the graphical presentation of these data. Graphical presentation encompasses the drawing and presentation of maps, graphs and, if required, animation-like sequences of pictures.
- Once the data have been stored and checked for their quality, they can be processed and interpreted. A complete package of basic and advanced interpretation and processing tools, fully integrated with the database management system and the user interface, and covering a wide range of common techniques and algorithms has to be offered for every data type that is supported. It must be possible to link existing applications to the system using data import and export facilities, or they must be adjustable in order to conform to an interface.
- The last step in the data manipulation path, or the start of a new interpretation or reinterpretation cycle, will be data integration. In this step, the answers and hypotheses that have been worked out in different application domains have to be integrated into one or more feasible hydrogeological models of the region being investigated. Advanced tools for deterministic and stochastic modelling will have to complete the system and turn it into the full functionality tool for the hydrogeological engineer. Graphical editors and word processors interfaced to the database will support the generation of draft and final reports.
- If a project is abandoned, the data have to be archived. It should be possible to transfer the project data back to the system database or to store them on archive media. Networking facilities will have to allow the access to the system database from remote locations, in order to support distributed data access.

3 EGIS: THE PRODUCT OF EXPERIENCE PLUS KNOWLEDGE

3.1 The philosophy underlying EGIS

Drawing on its extensive experience in hydrogeological projects in the Netherlands and abroad, TNO Institute of Applied Geoscience is currently developing a new interactive hydrogeological information system called EGIS, to support hydrogeological investigations and groundwater management in the Netherlands and throughout the world. EGIS supports hydrogeological projects at three levels. First of all it allows all the hydrogeologically relevant data collected in the area to be stored and maintained, secondly it provides the functionality required to derive and maintain a hydrogeological model of the area being investigated and finally it supports the use of this model in the management phase e.g. by simulating the effect of different management scenarios. EGIS is being developed to meet the four requirements of a GHIS outlined in section 2.1: integration, scalability, adaptability and multi-user operation. Integration is apparent on the data, functionality and user-interface levels. Thanks to its scalability, EGIS can be used locally, regionally and nationwide e.g. from waste-dump control to national drought-hazard programmes. A high degree of adaptability ensures that the system can be customized, i.e. adjusted to the specific needs of a particular project or problem. The multi-user capabilities of EGIS allow larger numbers of hydrogeologists to work together as a team.

3.2 The EGIS Data Model

The data model incorporated in EGIS covers those types of information that are relevant to the domain of hydrogeology. This includes information characterizing:
- The groundwater reservoirs in the project area.
- The quantity and quality of the groundwater in these reservoirs.
- The dynamics of the groundwater.
- The external factors influencing the groundwater.
- The infrastructure set up for groundwater production and monitoring in the area of interest.
- The production and use of groundwater.

A more detailed list of types of data that are being supported is given in Table 1.

3.3 Functionality of EGIS

The basic functionality included in EGIS covers:
- Data capture, either by manual data entry using forms, or by batch loading from external sources.
- Capture of maps, drawings and pictures by scanning or digitizing.
- Data maintenance and quality control.
- Data presentation by means of forms, reports, maps and graphs.
- Data selection allowing specification of both spatial and non-spatial predicates;
- Statistical analysis.
- Map analysis.
- Text manipulation.

In addition, advanced hydrogeological applications cover:
- Processing and interpretation of geophysical data.
- Elaboration of a 2D-3D hydrogeological reservoir model.
- Processing and interpretation of data on groundwater level, groundwater quality and groundwater production.
- Interpretation of pumping tests.
- Support for well inventories.

- Interfacing to numerical groundwater models.
- Time series analysis.

Reservoir characterization	**Groundwater**	**Infrastructure**
. geophysical measurements . electrical resistivity . electromagnetometric . gravimetry . magnetometry . seismics . well logs . geology . borehole logs . hydrogeological parameters . well tests . core analyses	. groundwater levels . groundwater quality . chemical composition . isotopes . organic . inorganic . bacteriol. composition . physico-chemical prop. . density . EC	. well and piezometer completion logs . springs . galleries

Groundwater production	**Groundwater dynamics**	**External factors**
. abstraction rates . water usage	. groundwater system classification . flow paths . water balances	. meteorology data . surface water data . land use data

3.4 The information technology used in EGIS

EGIS is based on the state-of-the-art relational DBMS Oracle and the technically innovative geographical information system, Smallworld GIS. As a consequence, EGIS will be continuously adapted to the state of the art, both in the area of data management and in the field of spatial data analysis. These basic resources have been extended with hydrogeological software. EGIS contains two subsets, the data storage kernel (EGIS*DSK) and the application environment (EGIS*AE). The DSK enables the data required to be captured, stored, maintained and retrieved. In addition, general-purpose functionality for visualization and ad-hoc processing is available from within the DSK. The application environment contains a set of applications specifically designed for hydrogeological processing, interpretation and decision-making.

Large parts of the system have been built using the Object Oriented development environment provided by Smallworld. The object library developed for the GIS application has been extended with numerous 'hydrogeological' objects. The development environment allows interfacing to alien programs written in conventional languages such as Fortran or C. This mechanism is used to accommodate software requiring substantial numerical processing.

The advantages of object-oriented development, resulting in a reduced throughput time during the development of the system, are also available to people customizing the system.

The graphical user-interface of EGIS is based on X-Window and uses the OpenLook or OSF/Motif GUI toolkits. The look and feel of the different components of EGIS are kept consistent over the entire system, thereby providing a high degree of interface integration, which reduces the time necessary to become familiar with different parts of the system. An extensive help system is available. The interface can be customized to different languages.

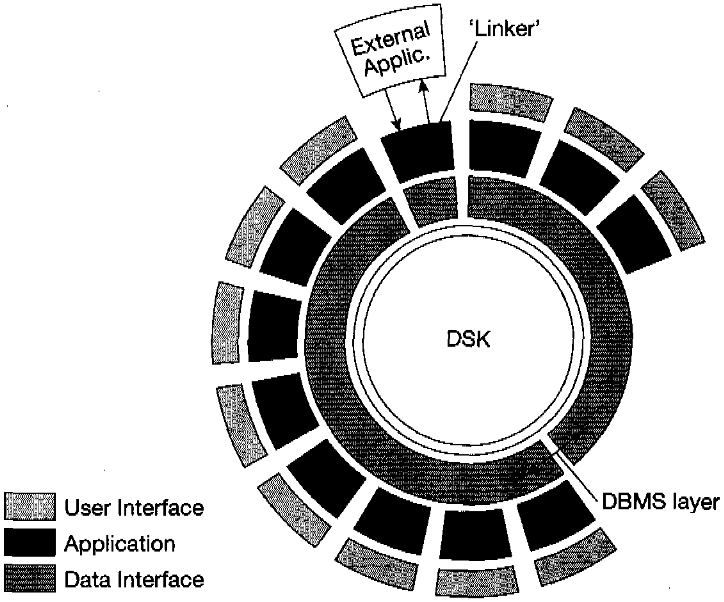

Figure 2 In EGIS all data are stored in one data storage kernel (DSK). A DataBase Management System (DBMS) takes care of the data handling. All applications use this DBMS to communicate with the DSK to select the data needed by this procedure. A user interface (UI) allows the user to operate the applications in a uniform way. External applications can communicate with the DSK by a special module the 'linker'.

The object-oriented development environment and the object library of hydrogeological objects are available to the person customizing the system and make EGIS an open and flexible system. Customization of EGIS can be addressed on six levels:

- User customization of styles, colour settings etc.
- Minor adaptations to the user interface (a number of tools are available for this).
- Extension of functionality using the customization hooks available in the different modules.
- Extension of the functionality using the object-oriented language and core classes.
- Interfacing with software entities written in a 3GL.
- Extension or modification of the data model.

4 CONCLUSIONS

Various conclusions can be drawn from the Institute's work on managing hydrogeological data.

- Developing a GHIS requires close cooperation between hydrogeologists and software engineers.
- A GHIS should integrate all relevant data needed for the proper management of the subsurface (i.e. groundwater quantity and quality, surface water quality and quantity, geophysical data, geological data, administrative data, etc.).
- With respect to software development there is not that much difference between the developing countries and the Netherlands. Financial and scientific constraints may allow only a subset of the available system. On the other hand, if the objectives are different, it may be justifiable to adapt the system.
- The use of proper geographical information systems can assist the hydrogeologist to obtain a better three-dimensional understanding of the area being investigated.
- Modern technologies can motivate people in developing countries if sufficient attention is given to training and support.

5 RECOMMENDATIONS RELATING TO GHIS

- Existing (commercially available) software should be used whenever appropriate. There should also be a policy of restricting the number of such 'off-the-shelf' components to a strict minimum. Increasing their number results in increased costs and additional incompatibilities in user and data interfaces, both of which hamper integration.
- More attention must be paid to the reliability and quality of the data and how the data were acquired.
- More attention must be paid to the relationship between hydrogeological processes that have traditionally been studied separately.

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GROUNDWATER RESOURCES MANAGEMENT CONCEPTS, EXPERIENCES AND THE ROLE OF INTERNATIONAL COOPERATION

A. Tuinhof

ABSTRACT

Water resources management (WRM) is concerned with the balanced distribution of the earth's water resources. WRM has long been focused on the assessment of the water resources with the objective to satisfy the demands without taking into account the scarcity of the resource. There is however a growing awareness that water is a limited resource. This accounts particularly for groundwater in arid and semi-arid regions. The distribution of a limited resource requires a broader approach to WRM in which the social, economic, legal and institutional issues must be integrated. Integrated WRM (IWRM) is a continuous process in which the subsequent steps of assessment, planning, development and sustainable use need the involvement of different administrative levels and of other sectors of the society including the water users.

Water resources assessment is an important element in IWRM, especially where groundwater is concerned as groundwater is the invisible part of the hydrological cycle. Hydrogeological research is needed to provide the reliable information on the occurrence and dynamics of the groundwater regime. There is a growing need to pay more attention to water quality and environmental concerns in the assessment phase. Hydrogeological tools and methods can also contribute to other key elements of IWRM such as the integrated planning of water resources, development of water resources in accordance with the integrated plan, monitoring and feed back of field data to update the plan.

The example of Egypt illustrates the growing awareness for IWRM in developing countries and shows the role of international cooperation programmes in promotion of these issues.

1 INTRODUCTION

Water resources development has long been directed to satisfying the demands without taking into account the scarcity of the resources. Water resources investigations including hydrogeological research and investigations, were focused on providing the demand without taking into account all short and long term effects. In recent years the awareness has risen that the ever growing water demands exceed the available quantities of fresh (ground)water, especially in arid and semi arid regions. Water scarcity is increasingly becoming a limiting factor for social and economic development in many parts of the world, creating tension between user groups and causing a degradation of the resource. This counts in particular for arid and semi-arid regions, where the effects of over-exploitation become more and more severe and have even resulted in political tension between states. Also in more humid regions good quality water becomes a scarce commodity especially in urbanized and industrialized areas.

The scope of water resources management (WRM) is changing accordingly. WRM should take into account the scarcity of the resource and the often conflicting interests of the different beneficiaries. This means that new approaches and new concepts are being evaluated (World Bank 1993). Sustainable WRM requires a comprehensive framework for analyzing policies and options to guide decisions about water resources management.

These changes in WRM have also had an impact on the role of hydrogeological research. Hydrogeological studies and research should become more oriented in helping the decision makers in planning and development of the resource.

Also in the international cooperation projects there is a shift from water resources assessment oriented projects towards technical assistance in integrated water resources planning and development. This is illustrated by the Netherlands technical assistance to the water sector in Egypt.

2 WATER RESOURCES MANAGEMENT CONFLICTS

Side effects of water resources development

Water resource constraints and conflicts are encountered in many places and in different degrees. They usually appear as side effects of water development projects to users of other sectors of the economy and to a degradation of the resource itself in time. In table 1 an overview is given of typical examples of groundwater management problems. Some of these problems are already long existing.

Conflicts

Ineffective WRM leads to water conflicts between users be it individuals, companies, water supply agencies or others. It may vary from local conflicts about individual water projects to national and even international disputes.

The complex problem of sharing the limited water resources in an arid region like the Middle East has already led to political differences and conflicts between the upstream and down stream countries. This concerns all three major internationally shared river basins in the Middle East: the Euphrates-Tigris Basin which involves Turkey, Syria and Iraq; the Jordan which flows through Lebanon, Syria, Israel and Jordan and the Nile which affects nine African countries including Ethiopia, Sudan and Egypt. In addition, there are many underground aquifers in this region that are shared by two or more countries (IWRA, 1992).

Table 1 Examples of water resources constraints

Type of development	Main beneficiaries	Negative impact	Affected user or sectors	Examples
Groundwater development in urban areas	Drinking, Industry	Falling groundwater levels and land subsidence	Urban poor and urban infrastructure	Bangkok, Jakarta
Groundwater development in desert areas	Irrigated agriculture	Falling water tables	Rural poor and farmers with shallow(er) wells	Egypt, Middle East countries
Water resources development for irrigated agriculture	Agriculture	Waterlogging and soil salinization in areas without land drainage	Rural poor and farmers in the water logged areas	Egypt, Pakistan, United States
Groundwater development in coastal (deltaic) areas	Drinking, Industry	Salinization due to salt water intrusion and/or upconing of brackish water	All groundwater users, in particular the drinking water sector	Indonesia, Mediterranean coast
Groundwater development in densely populated areas	Industry, Agriculture	Groundwater pollution	Drinking water (public health)	Netherlands

Water resources conflicts in humid regions are generally related to quality deterioration of internationally shared river basins. The Netherlands, for example, is a small country occupying the deltaic region of the international river Rhine. It is dependant upon the water from this river but is also an importer of pollution originating from the other four countries that are sharing the river Rhine in Western Europe. The Netherlands therefore had a great interest in water quality control and water management of the Rhine in an international context. The five countries have been negotiating a joint Rhine Action Programma for many years before this treaty was signed in Strasbourg in 1987.

International awareness

Since the United Nations Water Conference in Mar del Plata in 1977 there is a growing awareness that proper water management is one of the key issues in improving the living conditions of low income groups and in promoting social and economic development. The meeting initiated the Drinking Water Supply and Sanitation Decade (IDWSSD) in the eighties. The IDWSSD did not fully meet the expectations for both developing and developed countries. Since then the issue has been on the agenda of many international meetings and conventions, and international organizations have renewed and adapted their commitments. Meanwhile much effort has been made to analyze and evaluate the problems and constraints that are encountered in water resource management.

A review of the present status has been published in a recent World Bank paper (World Bank 1993). It summarizes that the main constraints for effective water management are:
- Inadequate institutional arrangements and malfunctioning of institutions.
- Negligence of the need for economic pricing, financial accountability and user participation.

- Insufficient attention to water quality, health and environmental concerns.

3 CONCEPT OF INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

It is generally accepted by many agencies that "integrated management" is the right approach to improve the inefficiency in the present water resources management practises. Integrated WRM (IWRM) is based on the perception of water as an integral part of the ecosystem, a natural resource and social and economic good. IWRM is a continuous and complex process that addresses a wide range of issues (box).

Elements of integrated water resources management

WRM is a process with many dimensions and with the involvement of not only the different administrative levels but also of other sectors of the society including the private water users. It is strongly interdisciplinary and multi-sectoral and should include many conflicting issues. WRM has many dimensions and pays attention to a large number of often related issues:

- Interaction between quantity, quality and biological aspects of both groundwater and surface water.
- Sectoral co-ordination: water demands and residual generation by different sectors of the economy are considered in relation to the sectoral development and management plans, objectives, and policies. Allocation of water resources should be in correspondence with the social and economic benefits of water utilization in these sectors.
- Environmental sustainability: full account is made of the relevant on-site and off-site environmental issues, in particular the long-term carrying capacity of natural systems.
- Institutional arrangements: proper attention is paid to the tasks and responsibilities of all public and private agencies involved and to their linking mechanisms.
- Public participation: social and cultural issues are considered, including the role of women and the traditional use of water.
- Implementation aspects, including financing, monitoring and control, play a decisive role in planning for water resources management.
- Capacity building: institutional and human resources development for the execution of management tasks is an important component.
- International water rights: effects of water management interventions in international water courses and aquifers may exceed national boundaries and require consultation between the sharing countries resulting in a water use right established by treaty.

There is a need to simplify the complex WRM process in a number of steps in which the different issues are addressed. A structure is also useful in giving a definition of the different names that are often used in relation to the WRM process: assessment, planning, development, sustainable use and management (figure 1).

Assessment

The first step in the IWRM process deals with the assessment of the resources (supply) and the demands. Assessment refers to the quantitative and qualitative information that is needed as input into the planning and decision making process. Water resources assessment is based on the recognition of the continuity of the hydrological cycle water and its many physical relationships and interactions such as between groundwater and surface water.

An important aspect of water demand assessment is the forecast of future water use based on projection of demographic developments and changes in the per capita consumption and agricultural water use.

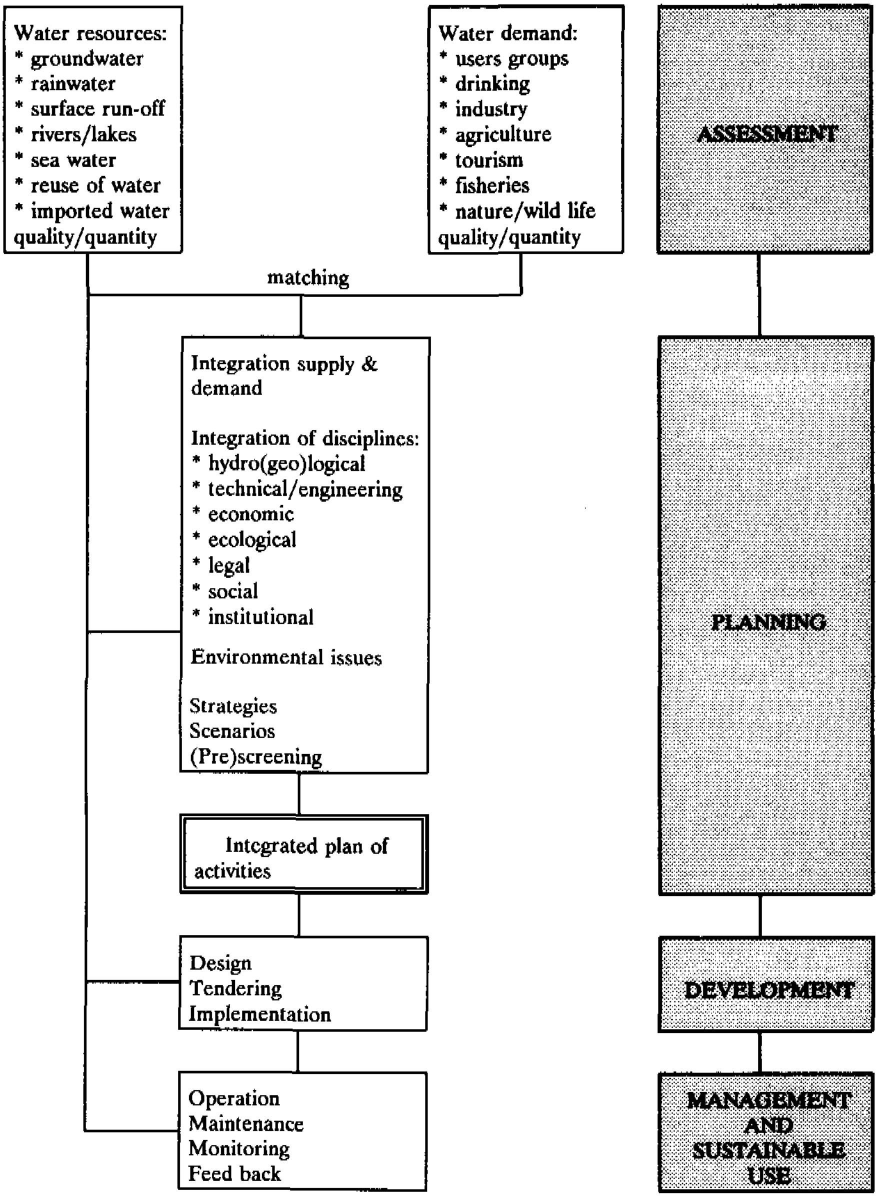

Figure 1 IWRM process

Assessment

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Planning

The planning process in IWRM deals with matching supply and demand through the evaluation and screening of strategies and scenarios for water resources development based on a set of criteria and objectives and taking into account the different constraints.

Keyword in the planning process is integration. Integration refers to many related disciplines (see figure 1) and the interrelation with other planning areas such as agricultural development, industrial development and urbanization. IWRM as the approach to formulate management strategies for scarce water is based on principles such as water conservation and demand management. Demand management refers to the concept that demand oriented measures are an integrated element of water resource planning (see box).

Demand management

Generally water is not dealt with as an economic resource, but is still often considered a free good, which should be provided at low cost in the amounts and qualities desired. Water conservation techniques and water demand management are still rarely applied. However, it is expected that those concepts will become very important in the coming decades.

Demand management refers to the formulation and application of implementation incentives, which can be grouped in two categories:

- Economic instruments, such as charges for the utilization of water resources often directly related to the production costs, and subsidies, for example tax exemptions if certain measures are taken.
- legal instruments, such as licenses for water abstraction, and effluent charges which appear to be highly effective to reduce industrial water use.

There is a growing understanding that the application of demand oriented measures will play a crucial role in future groundwater resources planning. However, there is a general reluctance to implement the incentives because of the administrative effort that is required.

Planning and subsequent decision making result in an integrated plan of activities. Planning may be related to long term effects with a time horizon that varies from five to twenty years (strategic planning) or to operational plan for short term water resources development.

Development

Water resources development refers to the design and implementation of water resources projects on the basis of the integrated plan of activities. Water resources development projects may range from small interventions by individuals (like the drilling of wells) to large infrastructure like dams well large well fields.

Management
Management of water resources is concerned with the operation and maintenance of water supply systems. A key element for sustainable management of water resources is monitoring of changes in time and feed back of this information to the planners and decision makers. Feed back of monitoring data is a prerequisite for the integration of changing conditions and circumstances in the continuous process of planning and decision making.

4 ELEMENTS OF GROUNDWATER RESOURCES MANAGEMENT

Groundwater is the invisible part of the hydrologic cycle and available and reliable data on groundwater are often scarce (WMO/UNESCO, 1991). This is particularly the case in developing countries. However reliable information is a prerequisite for groundwater planning. Therefore groundwater resources assessment is the very basis for development and management of the resource.

IWRM is based on the awareness that groundwater is becoming a scarce resource and that its development and management is a integrated, multi-disciplinary and continuous process. The scope of groundwater assessment has accordingly become broader. Hydrogeological studies for IWRM are not only focused on the quantitative description on the hydrogeological system but play also attention to the:
- Dynamics of the groundwater system as a basis for evaluation of different development scenarios and of the effects of future changes in conditions and circumstances.
- Interaction between groundwater and surface water (or other available sources such as treated waste water or imported water).
- Quality of the groundwater and to environmental effects.
- Dissemination of hydrogeological information to planners, decision makers and water users.

The tools and methods presented in the foregoing papers show that much work has already been done in this field and that many recent developments have greatly contributed to a better understanding of the groundwater systems in many countries. Some examples of most relevant tools and methods are briefly discussed in the following:

Groundwater models
Groundwater models (groundwater flow models and groundwater quality models) are one of the powerful tools in the prediction of the effects of groundwater development scenarios. Some groundwater flow models are also capable to simulate the interaction with surface water. The reliability of models is highly dependant on the availability of the necessary input. Sophisticated models for regional groundwater evaluation require large amounts of data in order to benefit from its potential capabilities. These data are not generally available especially when a groundwater evaluation for a region is carried out for the first time. A good approach is to design a groundwater model in accordance with the available input rather than filling in the missing input with (gu)estimates. The model can later be extended and refined when more data become available.

A regular update of the groundwater development plan is needed to incorporate the new hydrogeological information. Because groundwater development plan is just one link in the dynamic process of water resources management it will be subject to continuous requests for changes and adaptions. In practical terms this will imply that all inputs to the plan are to be reviewed and incorporated from time to time.

Environmental Impact Analysis (EIA)

Hydrogeological research and investigations will be more focused in the future on the aspects of groundwater quality and groundwater pollution. The latter will often be part of an environmental impact analysis (EIA). EIA's become increasingly a standard procedure during the assessment phase as a tool to anticipate potential future impacts of alternative groundwater development activities. EIA's are also applied during the planning and development phase to select the "optimal" alternative which maximizes beneficial effects and mitigate adverse impacts on the environment.

Hydrogeological information and GIS

Hydrogeological information is not easily understood by the water planners and decision makers as they often speak a different language. Also the water users may not easily understand their role in maintaining and monitoring the water resources. Planners and water users will benefit if information is presented to them in an understandable and systematic way. This contributes to a better communication and hence facilitate efforts of integration.

Figures, maps and graphs transfer information easier than written text and tables. One of the most effective means is the use of hydrogeological maps and of thematic maps which show the spatial distribution of a single parameter. Such maps can easily be produced with the help of a Geographic Information System (GIS). Time dependent data such as water level fluctuations and water quality variations may be presented in hydrographs, as shown in the example in figure 2.

Groundwater monitoring

Monitoring is an essential component of effective groundwater management as it provides the data to verify the predicted changes in groundwater heads and groundwater quality. This information is needed to refine the groundwater model and to update the groundwater resources development plan.

Processes that have to be monitored include hydrogeological, financial, economic and environmental issues such as:

- Decline of the water table in phreatic aquifers and groundwater head in deeper confined aquifers
- Rising water tables
- Upcoming of deeper salt or brackish groundwater
- Lateral movement of salt water (sea water intrusion)
- Migration of manmade pollution and other environmental issues
- Financial and economic parameters

Monitoring is not yet a regular routine in many developing countries. Hydrogeological research and experiences in developing countries can be used to promote this important component. This includes the design of networks, set up and organization of the monitoring schedule, computerized data analysis and interpretation.

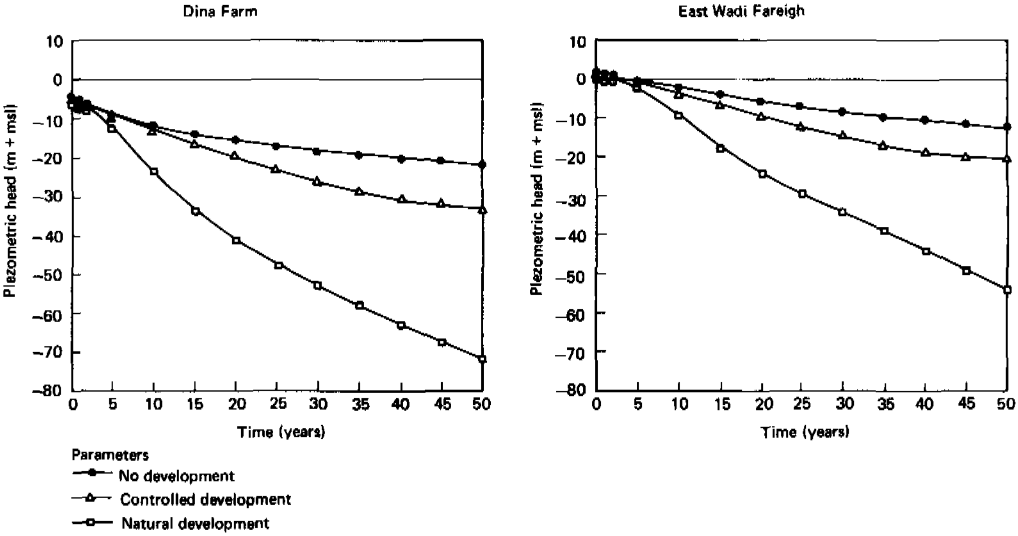

Figure 2 Simulated hydrographs for groundwater development in the Western Nile Delta Region (Egypt)

5 EXAMPLE: GROUNDWATER RESOURCES MANAGEMENT IN EGYPT

Water resources

Egypt is an arid country where both surface water (river Nile) and groundwater play an important role in daily life. The river Nile is completely controlled by the many barrages and dams of which the High Aswan Dam is the biggest and most well known. Since the completion of the HAD in 1968, Egypt has a share of 55 milliard m^3 water per year as laid down in the Nile Water Agreement with the Sudan.

Groundwater in Egypt can be divided in two categories. The first comprises the groundwater underneath the Nile Valley and Delta. This groundwater is in hydraulic contact with surface water and hence not a resource in itself. It does however represent a large reservoir (200 milliard m^3) which can be used as a regulator in water resources management. The second groundwater resource exists under the desert areas. It concerns mainly fossil water and is hence not a renewable resources. Estimates indicate a total storage of 40 000 milliard m^3 with a salinity between 200 and 6700 ppm. Use of this water depends on the cost of pumping, depletion of storage and the potential economic return over a fixed period of time.

Other water resources in Egypt are vast amounts of brackish groundwater, limited rainfall (maximum 200 mm along the Mediterranean coast) and sea water.

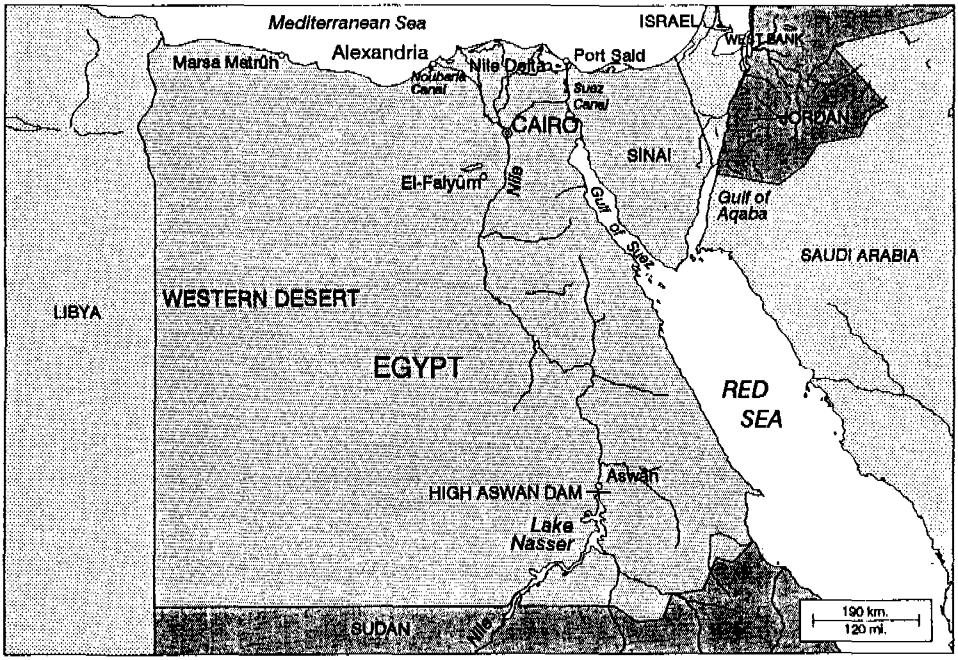

Figure 3 Egypt and the river Nile

Water policy

Egypt's water policy is focused on maximizing the agricultural production in order to reduce the costly import of food. This is achieved by different measures such as:

- Increasing the Nile water share by participation in the Jonglei canal project (Sudan).
- Increased reuse of drainage water.
- Reduction of Nile water releases to the sea for navigation (during the closure period).
- Improvement of irrigation water distribution efficiency and of on farm water management.
- Increasing the rate of groundwater extraction in the desert areas.

All these measures are directed to provide water for new reclaimed desert areas such as the North Sinai Development project and the reclamation areas in the Western Nile Delta.

Groundwater management constraints

The implementation of the national water policy in Egypt has led to the following main constraints with respect to the groundwater resources:

- The quality of the groundwater in the alluvial aquifer underneath the densely populated

Nile Valley and Delta is deteriorating due to domestic and agricultural pollution. Pollution of the shallow groundwater already poses a serious threat to the drinking water supply from handpumps in the rural areas. Also groundwater pumping stations for piped water supply systems may become affected.
- Surface water irrigation in the desert fringes along the Nile Valley and Delta has resulted in a groundwater flow to the lower delta, causing water logging and consequent increase of soil salinity (evaporation).
- Development of the fossil groundwater underneath the desert areas has resulted in substantial lowering of the water tables. The hydrographs in figure 3 illustrate that a rate of lowering of amounts to 0.5-1 meter per year and causes a serious threat to the yield of existing wells as is the case in the desert area bordering the Western Nile Delta (between Cairo and Alexandria). Also the groundwater salinity is expected to increase due to upconing of deeper brackish water.

Analysis of these problems reveals some typical key-issues, as often encountered in water resources management in developing countries:
- Increasing the amount of water for irrigation is the key issue in Egypt's national water policy. The MPWWR (formerly the Ministry of Irrigation) has to implement this policy, but is also responsible for overall water resources management in Egypt.
- There is little coordination between the MPWWR and other Ministries.
- Water for irrigation is provided almost free of charge and is not considered an economic good.
- Hydrogeological knowledge, especially related to the qualitative aspects and environmental impacts, is lacking.

There is a growing awareness in Egypt for the side effects of the national water policy. Within the framework of the national privatization process, discussion are being held about pricing of the water. The growing concern for environmental issues is illustrated by the establishment of the Egyptian Environmental Affairs Agency (EEAA) and the Egyptian Environmental Action Plan (EEAP) that was launched in april 1992. The EEAA will also become a platform for inter-ministerial coordination.
Water resources is one of the eleven sectors under the EEAP for which an action programme has been formulated and projects are identified in the field of water quality monitoring and for strengthening of the water planning in Egypt.

Netherlands support
The Egypt - Netherlands bilateral co-operation programme has been involved in the water sector in Egypt for twenty years (Royal Netherlands Embassy Cairo , 1992). In the seventies and eighties, most projects in the framework of this programme were concerned with the quantitative aspects of water resources development and management. In response to the water management problems ,the emphasis of this programme has shifted in recent years from quantity-oriented assistance to water quality and environmental issues and to planning of water resources.

In the groundwater sector this implied that the technical assistance has changed from technical hydrogeological studies towards assistance in an integrated approach of groundwater management with emphasis on water quality and planning aspects. Examples of recent activities are:

- Strengthening of the Research Institute for Groundwater (RIGW)in the field of groundwater quality monitoring and pollution control (project under the EEAP);
- Support for the establishment of monitoring networks for groundwater quality and drainage water quality (project under the EEAP);
- Environmental and economic feasibility study for the use of a coastal lake (Lake Burulus) for storage of Nile water (NEI, 1992);
- Study to control the water logging and soil salinization problems due to desert reclamation (RNE Cairo, 1992);
- Technical assistance to groundwater development study in the Western Nile Delta (RIGW/IWACO, 1990) and in the Eastern Nile Delta (Farid a.o.,1989);
- Organization of a workshop on the role of groundwater in integrated water resources management (RIGW/IWACO, 1992b);
- Organization of an international Round Table Meeting on the planning of groundwater resources in arid and semi-arid regions (RIGW/IWACO, 1992a);
- Support to the planning sector of the MPWWR (project under the EEAP) .

These projects have contributed to a better understanding of the role of groundwater in Egypt's national water management and have helped to improve the sustainable development of the Egypt's groundwater resources.

6 CONCLUSIONS

- Groundwater resources development without taking into account the scarcity of the resource may lead to negative side effects for other users and to a degradation of the resource.
- Integrated WRM (IWRM) is generally accepted to be right approach to sustainable development and management of scarce water resources
- Groundwater assessment is the basis for planning and development of groundwater resources. Hydrogeological studies are an important element of groundwater resources assessment. Hydrogeological tools and methods can also contribute to strengthen other components of the continuous IWRM process.
- International cooperation, such as the Egypt - Netherlands cooperation programme can help in introducing new concepts in water management practises in developing countries.

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INTERNATIONAL EDUCATION AND TRANSFER OF KNOWLEDGE IN HYDROGEOLOGICAL RESEARCH AND GROUNDWATER MANAGEMENT FOR EXPERTS IN DEVELOPING COUNTRIES

W. Spaans & W.A. Segeren

ABSTRACT

Population growth and higher standards of life have resulted in a still increasing demand for industrial products, agricultural production, physical infrastructure, energy and water. Over-exploitation of earth non-renewable resources has resulted in an irreversible depletion of minerals and ores, gas and oil, and geothermal energy. Mining of groundwater basins and waste leakage through dumps and surface water leads to a rapid deterioration of groundwater resources in quantity and quality.

Proper management of earth resources - and of groundwater in particular - is a prerequisite for a sustainable economic, environmental and social development on a regional and global scale. In this framework earth resources are defined as minerals and ores, groundwater, oil and gas and thermal energy. Basic needs for the set-up of a groundwater management infrastructure are:

- Skilled personnel, from observer to planning director.
- An efficient administrative well equipped organization.
- Information tools like field and laboratory equipment, computer models, databases and geographic information systems.
- Access to up-to-date applied technology and consultancy.

Developing countries - even when having access to modern techniques - in general are lacking this skilled manpower, equipment and information technology. National and regional based training from vocational institutes to universities is the backbone for a sustained development in applied education and research. Support by international institutes and international oriented universities substantially contributes to this development. Participation of technological institutes widen the scope of this international collaboration.

1 INTRODUCTION

Primary task of universities is the conduct of scientific educational and research programmes for national based students. The study leads to the B.Sc. and M.Sc. degree, while based on a sound scientific research the Ph.D. degree may be obtained. International collaboration of Netherlands universities is mainly related to institutional strengthening of universities in developing countries, and Central and Eastern Europe. The scientific and national oriented scope of universities and self-sufficiency in staff does in general not allow for a multidisciplinary problem-solving approach which is needed for - in particular but not only - engineers from developing countries. Moreover university B.Sc., M.Sc. and Ph.D. programmes are difficult to access because of language, cultural and administrative barriers.

Water research institutions and water consulting firms in general have a limited capacity to conduct international oriented training programmes for technicians and research engineers, based on the specific expertise and research field. Their strength in international education is the contribution to the conduct of courses and support of M.Sc. and Ph.D. research as conducted in the framework of post-graduate international education.

International Education (IO) institutes have a specific international oriented scientific approach to applied research and education. Their set-up allows to offer a wide range of post-graduate training programmes in the fields of earth sciences and (ground)water management. The involvement of lecturers from technical institutes, consultants and universities from all over the world safeguards an international applied problem oriented approach to education and research. It is the involvement of a variety of institutions and disciplines which makes these IO institutes unique in its international approach to education, research and capacity building. Post-graduate diploma and M.Sc. courses are practically and problem-solving oriented for B.Sc. holders with a relevant working experience. The duration of one year for diploma courses and maximum 16-20 months for M.Sc. courses allows a quick return to the job and prevents from braindrain.

The two major IO institutes in the Netherlands which jointly cover training, research and consultancy in the field of earth sciences - and in particular hydrogeology and groundwater resources - are the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE) and the International Institute for Aerospace Survey and Earth Sciences (ITC). The input-output relation of IO post-graduate training can be visualised as:

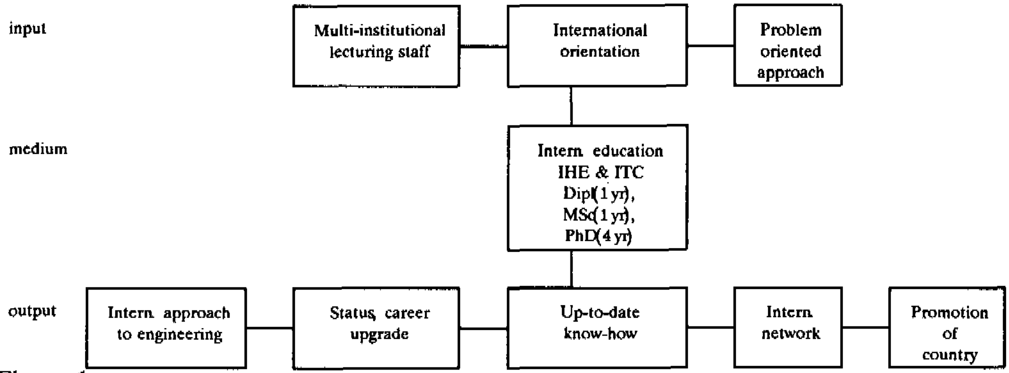


Figure 1

2 EARTH RESOURCES MANAGEMENT

Sustainable management and development of earth resources involves a number of distinctive steps from data collection to decision making. The various activity stages in the framework of earth resources (minerals and ores, groundwater, oil and gas, geo-thermal energy) management and development can be described as:

- Geo Information Survey: Geology, Geohydrology, Geochemistry, Exploration techniques, Geophysics, Remote sensing.
- Geo Information Management: Database management, Geographic information systems (GIS), Computer graphics.
- Geo Simulation and Prediction: Modelling flow, transport and pollution, Geostatistics, Reservoir operations.
- Geo Engineering: Exploitation techniques, resource manipulation, Geotechnics.
- Geo Decision Making: Economic, Social and Environmental assessment, Multi Criteria Analysis.
- Geo Resources: Decision Support Systems for Sustainable Development.
- Management legislation.

The realization of this overall framework requires a well structured organizational and administrative framework. This in return needs a well-founded educational framework in hydrogeology, which in IO respect is covered by the ITC and the IHE as:

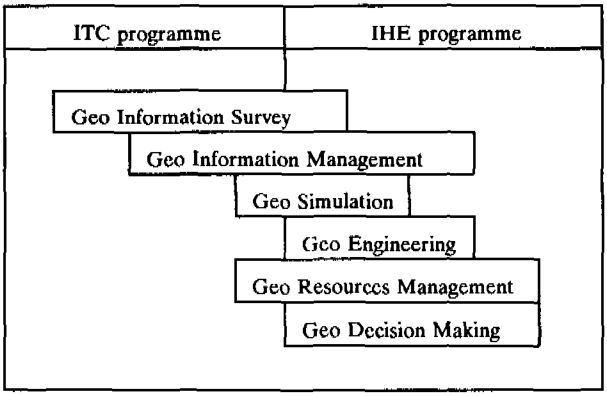


Figure 2 Earth resources scope and education

3 INSTITUTIONAL STRENGTHENING

International technical cooperation in the field of water and environment used to concentrate on the realization of engineering projects on groundwater and surface water development to satisfy agricultural (irrigation), municipal and industrial water requirements. Justification was mainly based on economic feasibility and strongly triggered by public opinion. Early eighties more attention was given to sanitation and public health projects regarding watertreatment, water distribution, and waste water collection. Also here economic and general social aspects were decisive in its justification. Social and environmental awareness together with community participation became vital items in project justification during the late eighties.

Transfer of knowledge through training and education, workshops and seminars, publications and pilot projects became a spearhead in sustainable institutional development. Substantial efforts have been and still are being made by bilateral, multi-lateral and international donor organizations and implementing institutions and universities. However, this has not really resulted in well established knowledge units embedded in the ministries, authorities, institutions and universities to safeguard a sustained support in - and development of - local know-how on the design, construction, operation and management of water resources systems.

Institutional strengthening and human resource development is given now top-priority by most international development institutions,including the Worldbank and UN organizations. This institutional strengthening involves capacity building on skilled manpower, organizational and administrative support, technical management and continuous education at various levels:

- National: Ministries, authorities involved in water sector master planning and Universities for education and applied research.
- District: Councils and water companies involved in regional planning and development and Vocational training centres for high/mid level technician training.
- Local: Local councils and projects, involved in local planning and operation and In-service training in the projects, and community participation.

Human resources development from mid-level technician to senior university researcher within the framework of continuous education and dissemination of knowledge involves:

- On the Job training and vocational training: In-service and abroad, for operators and high level technicians.
- Specialization programmes: Workshops, seminars, short courses.
- Dissemination of knowledge: Symposia, publications, manuals, newsletters.
- Post-graduate and M.Sc. courses and Research and Ph.D. programmes: In-country by universities. Abroad mainly by IO institutes.
- Educational capacity building programmes: In-country, supported by universities and IO institutes.

4 ON THE JOB AND VOCATIONAL TRAINING

On the job training involves practical training on the day to day work activities of mid-level and high-level technicians. In-service training is done by (expatriate) experts and devoted to a limited number of staff. Depending on the specific activity this training has a duration of one month to several years and in general is labour intensive. Often the upgraded staff obtains a better position elsewhere and is no longer beneficial for the project. Highly specialized training for promising staff can be given at specialized institutions or authorities abroad. Only in rare cases on the job training is devoted to graduate staff. Examples are training in hydrological observations, network loss determination, workshop management and computer data entry.

Training abroad is usually offered at specialized water boards and technological institutes like the Caribbean Meteorological Institute, Barbados. The ITC Diploma Course in Cartography is the only Netherlands regular technician course.

Vocational training is devoted to mid-level and high-level technicians. The training has a duration of two to three years and is on a regular base conducted at national or regional vocational training centres. Foreign support can be given by experts from technical colleges and water authorities. Examples are a training of geo-hydrological observer, workshop manager and geophysical operator.

The DGIS financed and NUFFIC based 'Financing Programme for Cooperation in Higher Education' supports this higher education of technical and professional staff.

5 SPECIALIZATION PROGRAMMES

Specialization programmes are devoted to specific problems in hydrogeology. The course programmes can be conducted worldwide and include problem oriented lectures in combination with hand-on practical workshops and fieldwork. These programmes are being carried out on a 'open registration base' on request of an international organization or 'taylor made' on request of a national authority or government. Depending on the target group the set-up of the programme will be:

- Course oriented with a substantial number of lecturing hours.
- Workshop oriented with a major emphasis on hands-on exercises.
- Fieldwork oriented, devoted to field investigations and its interpretation.
- Seminar oriented, where participants and invited experts present and discuss the specific topics.

The duration ranges from 1 week for seminars to 2 months for fieldwork.Examples of taylor made courses are a 6-weeks Course on Groundwater Management for the Ministry of Irrigation, Saudi Arabia and a two months course on Hydraulic Engineering for the Great Man-made River Project, Libya. The Short Course Programmes in Groundwater Modelling and Management as jointly conducted by the IHE and the International Groundwater Modeling Center (IGWMC) in Delft illustrates the 'open registration' courses. Although oriented to developed countries,this programme also includes a six week summer-course on Groundwater Modelling and Management for Developing Countries.

6 DISSEMINATION OF KNOWLEDGE

This involves the 'public domain' aspects of transfer of knowledge and includes:

- Symposia and conferences which deal with specific topics. Like the recent ICID conference held in The Hague and the Symposium on Hydro-informatics this year in Delft.
- Expert meetings as organized by international associations like IAH, IAHR and IHE/IGWMC.
- Public guestlectures, addressed in a Studium Generale or other events.
- Proceedings of the above mentioned meetings and symposia.
- Books, technical institute publications and lecture notes as distributed by ILRI, IHE, ITC, universities and others.
- Articles in technical periodicals as the Journal of Hydrology, Water Resources Research and Advanced Hydroscience.
- Handbooks and factsheets on specific topics as published by FAO and as planned by the IAH.

- Newsletters, information bulletins and annual reports from institutions and companies.

7 REGULAR POST-GRADUATE AND MSC COURSES RELATED TO HYDROGEOLOGY

Post-graduate international education in The Netherlands is accessible for mid-career B.Sc. holders from predominantly developing countries. Conditions for approval are a proven working experience in the field of study, a B.Sc. degree in engineering or earth science and financial support. As mentioned earlier, international post-graduate diploma and M.Sc. education in geology and hydrogeology is covered by two IO institutes:

- The International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), Delft. In the wide field of hydrogeology the IHE organizes one year post-graduate diploma courses in Hydrologic Engineering, Hydraulic Engineering and Sanitary Engineering. Out of the 270 annual participants, some 50 are being trained in groundwater related subjects. Successful students are admitted for the six months M.Sc. programme.
- The International Institute for Aerospace Survey and Earth Sciences (ITC) based in Enschede and Delft. In the field of hydrogeology the ITC offers post-graduate and M.Sc. courses in Geological Survey,Groundwater Resources Survey, Exploration Geophysics and Engineering Geology. Out of the 300 annual participants some 40 follow the groundwater related specializations.

The post-graduate diploma and M.Sc. courses are conducted by internal staff, supplemented by experts from national and international universities and scientific institutions. The M.Sc. programmes are supervised and evaluated by both internal and external senior staff.
The international M.Sc. programmes of the Agricultural University Wageningen and the International College Larenstein do not cover the fields of hydrogeology.

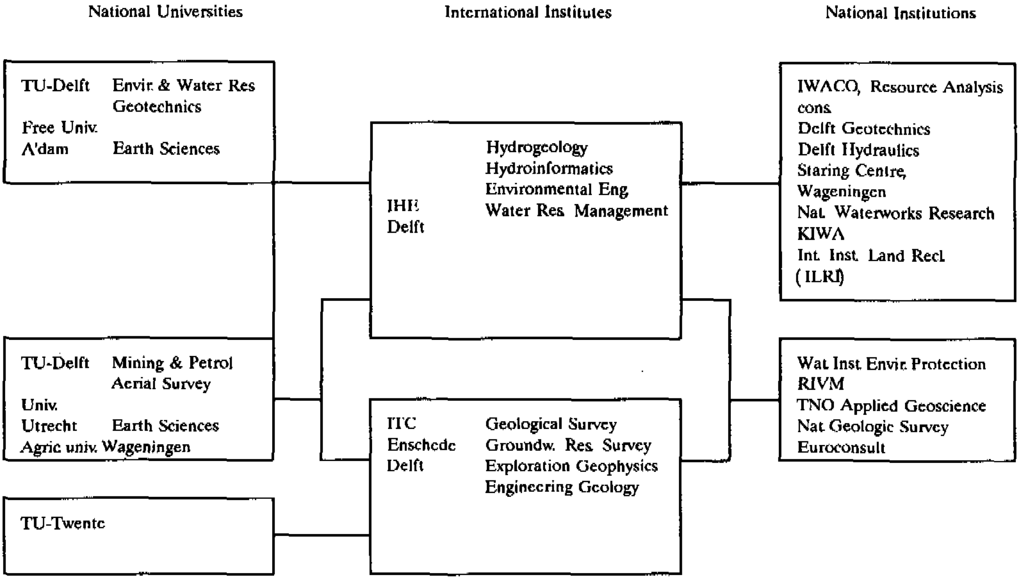


Figure 3 International hydrogeological education in the Netherlands (national involvement)

8 IHE COURSE ORGANIZATION

The post-graduate hydrogeological education at the IHE is primarily embedded in the Diploma Course in Hydrology. The course programme has the specialization branches Groundwater Hydrology, Water Resources Management and Surface Water Hydrology. Geotechnics is included in the Course in Hydraulic Engineering and Groundwater Recovery in the Course in Sanitary Engineering. All courses include economic and environmental topics. The course programme for the Course in Hydrology is outlined in annex 1.

The one year Diploma Courses are subdivided in two terms. The first term is mainly devoted to basic and applied subjects which are presented as lectures and related practical exercises and computer workshops. Major subjects are examined. The core of the second term is a groupwork where in a stepwise interactive approach an engineering design or masterplan is developed. During this term the lecturing programme consists of both compulsory and elective specializing subjects. A three week field programme is part of the programme. The final evaluation of the participant is based on the results of the examinations, the individual performance in the groupwork and a general final examination. On successful completion the Post-Graduate IHE diploma is awarded. Participants with a good study performance - average examination mark greater than 7.5 - are scientifically admitted to the M.Sc. programme. This programme has a duration of six months during which a sound piece of applied research must result in the presentations of a thesis. The research work is evaluated by internal and external professors and the Master of Science awarded.

The lecturing programme at IHE is conducted by some 65 internal IHE and some 450 external lecturers. The hydrological section at IHE consists of four hydro-geologists and five hydrologists. In addition some forty external guest lecturers contribute to the water resources programme.

9 THE ITC COURSE ORGANIZATION

The relevant course programmes include Geological Survey, Groundwater Resources Survey, Applied Geomorphology and Engineering Geology, and Exploration Physics. The set-up of the ITC post-graduate and M.Sc. courses is similar to the IHE courses. Major differences are that admission to the M.Sc. programme is decided at the start of the study and the inclusion of a lecturing cluster in the M.Sc. programmes.

The one year diploma course programme consists of two terms, the first term of four months being devoted to remote sensing, mapping and refresher subjects. The second term of seven months includes four months of specific course related subjects and three months of fieldwork. The M.Sc. programme has an additional duration of eight months, and includes a specializing lecturing programme and the presentation of a thesis or project work.
The lecturing programme at the ITC is mainly conducted by internal staff and a limited number of guestlecturers from universities and scientific institutions.

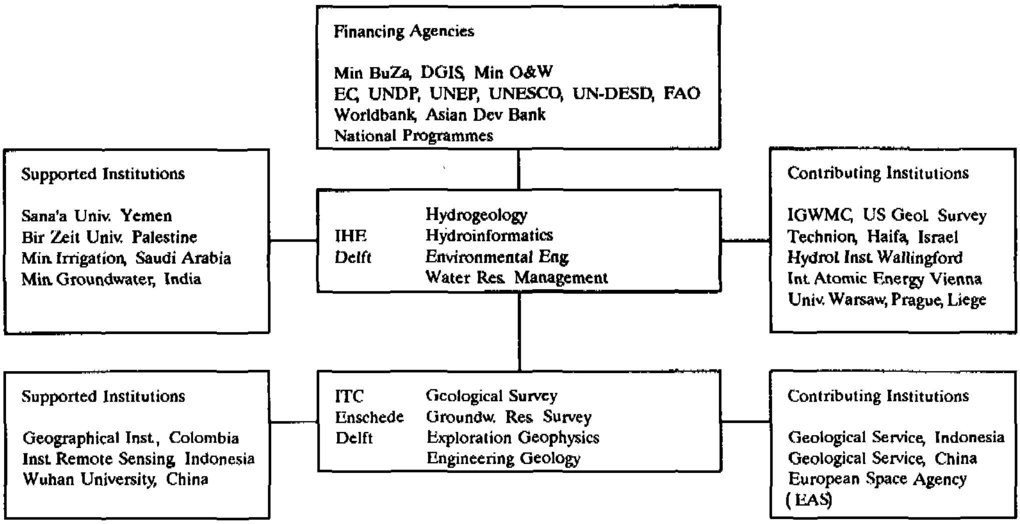


Figure 4 International relations in hydrogeology of IHE-Delft and ITC

10 PHD PROGRAMMES

Research programmes as well as advisory services are essential for strengthening the institutes expertise and safeguard the quality of the continuous changing educational programme. PhD research programmes are traditionally conducted at universities. Recently ITC and IHE have introduced PhD research programmes in cooperation with universities in The Netherlands and abroad, and institutes in developing countries. Often these programmes, with a minimum duration of three years, are conducted in a sandwich construction where the field research and preliminary report writing is done in the country and the actual thesis is prepared in the donor country. Examples of PhD research programmes are Sustainable use of arid and semi-arid zones, Groundwater exploration and exploitation in hard rock, Decision support systems for groundwater management and GIS as a toolbox for geo-hydrological engineering.

11 EDUCATIONAL CAPACITY BUILDING

National university and post-graduate education programmes are prerequisites for a sustainable development of a country or region, together with institutional strengthening. The IHE and ITC, as well as national universities, conduct capacity building programmes for the strengthening of the educational and research nucleus at universities all over the world. Technical research institutions like TNO-Geosciences, the IO institutes IHE and ITC, water authorities and private consultants conduct institutional strengthening for ministries and authorities in developing countries.

An illustrative project on Institutional strengthening and Human resources development is the IHE project 'Support Sana'a University, phase II', Yemen Republic. The project started with a demand from donor organizations for a founded in-country training of Yemeni water engineers. The first project phase started in 1989 with a post-graduate training programme in Water resources and Sanitary engineering, and the development of a water oriented curriculum development for the B.Sc. programme in civil engineering of the Faculty of Engineering. Some 100 professional engineers from all over Yemen were trained and the B.Sc. curriculum was approved by the university. The second phase has a duration of five years and started in 1992 with major aim to support the Civil Engineering Department in the implementation of the B.Sc. programme, the development and execution of an M.Sc. water programme, and the establishment of an applied research nucleus and centre. This support will be realized by providing long and short term foreign staff, training of five staff members for PhD in The Netherlands, Training of Trainers courses in The Netherlands and provision of equipment, computers and library extensions for the research nucleus.

Among the many ongoing projects are the collaboration programmes of the Free University with the Wuhan and Beijing Universities of Geosciences (China, staff exchange) and Western Cape University (South Africa, research and training)), the ITC support programmes with Colombia, Indonesia and China. Most recent is the support programme of the IHE with the Bir Zeit University, West Bank, Palestine.

12 INTERNATIONAL FINANCING

Financing of international education and research is done by many institutions by means of:
- Direct subsidies and donation to educational institutions.
- Providing fellowships for study and research in the region or abroad.
- Direct financing of total projects or of the educational component.
- Supporting dissemination of knowledge.

Relevant financing institutions in the Dutch IO framework are:

Netherlands	Min. Foreign Affairs, D.G. Int. Cooperation (DGIS) Min. Education and Science and Economic Affairs Min. Housing, Physical Planning and Environment
Europe	European Commission (EC) European Development Fund for Africa, Caribbean and Pacific EC-Asian Development Programme Bilateral organizations of Germany (GTZ), Denmark (DANIDA), et al
International	UN Food and Agricultural Organization (FAO), Rome UN World Meteorological Organization (WMO), Geneva UN Environmental Programme, Paris Int.Bank for Reconstruction and Devp / Worldbank, Washington, USA
Regional	Asian Development Bank, Manilla, Philippines African Development Bank, Nairobi

13 SYNTHESIS

The core of international transfer of knowledge and education for developing countries is largely based at the IO institutes IHE and ITC. Links with national and international educational and research institutes are indispensable for the conduct of a sustained educational and applied research programme. Scientific educational and research institutions strengthen the IO activities. Technological institutes and consultants complement the field of training and institutional strengthening for the water sector in developing countries.

The activities can be summarized as:

Institution		IO Activities
Tech. Univ. Delft	Dept. Civil Eng	University capacity building
	Dept. Mining	Ph.D. programmes
Free Univ. Amsterdam	Dept. Geosurvey	Guest lecturing IHE, ITC
Univ. Utrecht	Dept. Earth Science	Dissemination of knowledge
Agric. Univ. Wageningen	Dept. Earth Science	
	Dept. Hydrology	
IHE-Delft	Water Resources	Post-graduate courses
	Hydroinformatics	M.Sc. and Ph.D. courses
	Environm. Engineering	Specialization courses
ITC-Enschede,Delft	Water Resources Survey	Institution strengthening
	Engineering Geology	Dissemination of knowledge
	Exploration Geophysics	Guest lecturing
TNO Applied Geoscience, Delft		Institutional strengthening
Staring Centre, Wageningen		M.Sc., Ph.D. support and superv.
Nat. Inst. for Envir. Protection (RIVM), Bilthoven		Guest lecturing ITC, IHE
Nat. Geological Survey (RGD), Haarlem		Dissemination of knowledge
Nat. Inst. for Water Supply Research		In-house training
Int. Land Recl. Institute (ILRI), Wageningen		
Delft Geotechnics, Delft Hydraulics		
IWACO Consultants, Rotterdam		In-service training
Euroconsult, Arnhem		M.Sc. supervision
Resource Analysis, Delft		Guest lecturing IHE
Water companies, various		Dissemination of knowledge

INTERNATIONAL INSTITUTE FOR LAND RECLAMATION AND IMPROVEMENT/ILRI

ILRI'S MAIN OBJECTIVE IS TO COLLECT AND DISSEMINATE INFORMATION ON SUSTAINABLE DEVELOPMENT OF LAND AND WATER RESOURCES.

RESEARCH AND PUBLISHING

The research ILRI conducts is geared to rural development, especially in developing countries. Much of this work is focused on the development of land and water resources. Special attention is given to irrigated agriculture. Core research items are related to the drainage of irrigated land in arid and semi-arid areas to prevent or reduce salinization.
The results of ILRI's activities are published either in ILRI's own series of publications or as articles in international journals. A catalogue listing 52 currently available books will be sent on request.

ADVISORY SERVICES

ILRI makes its specialist staff available to assist in development projects abroad, in compliance with requests from The Netherlands Ministry of Development Cooperation, the Ministry of Agriculture, Nature Management, and Fisheries, the European Community, and international organizations such as the United Nations Food and Agriculture Organization, and the World Bank. This assistance takes the form of project identification, formulation, and evaluation. If necessary, ILRI recruits staff from other relevant Dutch institutes.

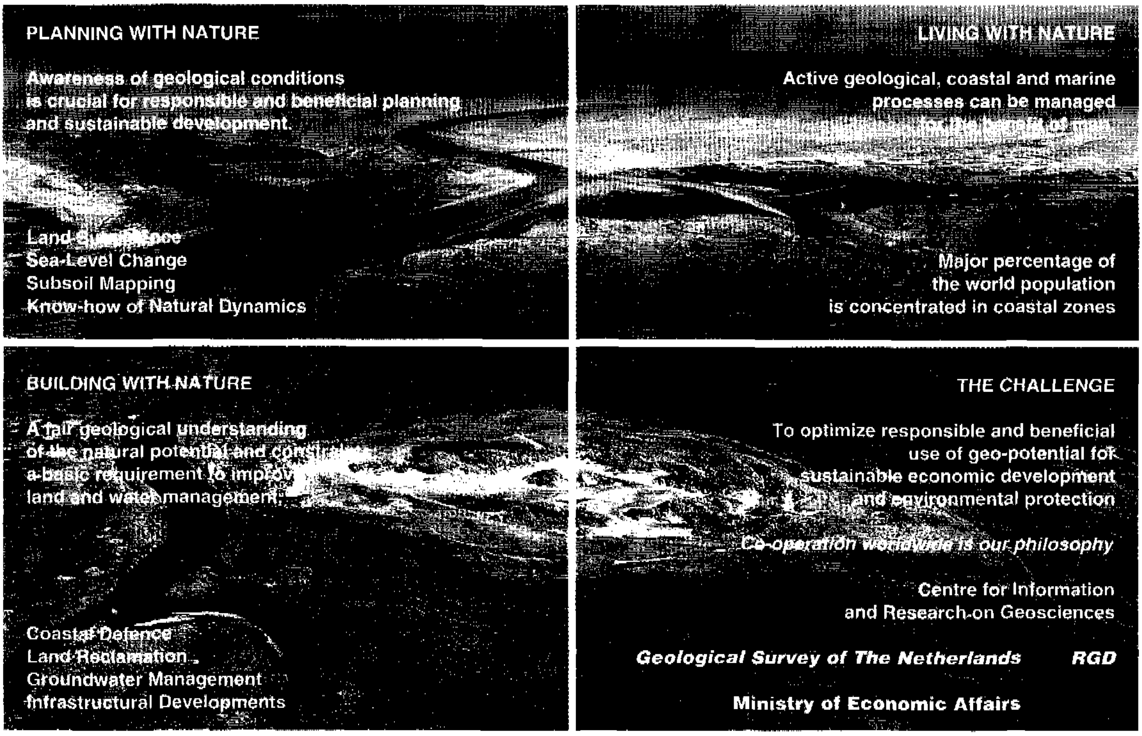
EDUCATION AND TRAINING

Each year, ILRI conducts an International Course on Land Drainage, which lasts three months. In 1993, ILRI initiated an International Course on Microcomputer Applications in Land Drainage and an International Course on Computer Applications in Irrigation.
Abroad, ILRI collaborates with universities and institutions to organize custom-tailored courses that meet local needs. Such courses have been held in Brazil, China, Egypt, India, Kuwait, Pakistan, Peru, and Sudan.

INFORMATION AND DOCUMENTATION

ILRI administers the Library of the Staring Building, which is the foremost library in The Netherlands for land, soil, and water research. The Library's collection contains some 50,000 books and 1500 journals on land and water management. Library services include document delivery and on-line literature retrieval from national and international data bases.

P.O.Box 45, 6700 AA Wageningen, The Netherlands, Tel ++31-8370-90144, Fax ++31-8370-17187



TNO Institute of Applied Geoscience

Institute
TNO Institute of Applied Geoscience is part of the Netherlands Organization for Applied Scientific Research, TNO (staff 4600). The institute is the central institute for groundwater research and the management of groundwater information in the Netherlands and the largest independent institute for geo-energy research in the country.

Mission
Through geoscience and related technological research the institute contributes to the sustainable management and use of the subsurface and subsurface natural resources.

Core Activities

- Research & Development, technical consultancy and transfer of expertise:
- Groundwater:
  - (Ground)water data acquisition and monitoring, data analysis and system assessment, water resources management, modelling and information management.
- Geo-energy:
  - Oil and gas exploration and production, geothermal energy and subsurface energy storage and information management

Type of Expertise

- Groundwater:
- R&D and Technical consultancies
  - Water resources management
    Groundwater resources assessment
    Water resources planning
    Water development planning
    Water use policy development
  - Information technology
    Groundwater information systems
  - Design of monitoring networks
    Groundwater quantity and quality
  - Water and environmental management
    Environmental impact assessment
    Eco-hydrology
- Training courses
- Project organisation and management in developing countries
- Institutional strengthening national/regional government and institutes

- Geo-energy:
- R&D
  - Geophysical software
  - High resolution seismic data acquisition and processing
  - Hydrocarbons exploration geology
  - Reservoir characterization/simulation
  - Exploration & production data-base
  - Geothermal potential
  - CO_2 storage in aquifers
- Technical consultancies
  - Seismic data acquisition, processing & interpretation
  - Reservoir geological modelling
  - Reservoir simulation studies
  - Well log and well test analysis
  - Customized data-base development
- Transfer of knowledge
  - Training courses
  - On-the-job training
  - Institutional support to ministries and national oil companies (establishment of knowledge/data/tool/infrastructure)

TNO Institute of Applied Geoscience has worked internationally since its inception in 1967. The institute has long standing experience in institution building and the transfer of know-how in developing countries.

TNO Institute of Applied Geoscience is member of GEONETH, a network of Netherlands geoscience institutes, universities, foundations and government agencies for international cooperation.

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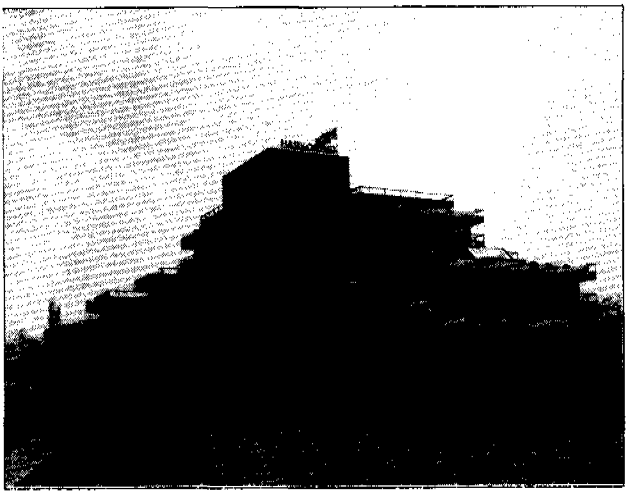

Head office, Nijmegen, the Netherlands

HASKONING Royal Dutch Consulting Engineers and Architects is an independent company of engineering consultants operating in the Netherlands and in more than forty other countries throughout the world.
When is was founded in 1881, HASKONING was the first independent private company of consulting engineers in the Netherlands.

HASKONING has approximately 650 employees. Highly qualified people, using the most up-to-date methods, working together to guarantee the success of a project.
As a multidisciplinary organisation, HASKONING can combine the various disciplines to offer clients tailormade solutions to every problem.

HASKONING's operations are organized in four divisions:

BUILDING
ENVIRONMENTAL AFFAIRS
INFRASTRUCTURE
INTERNATIONAL PROJECTS

The Divisions of Environmental Affairs and International Projects have ample experience in hydrogeological projects in the Netherlands and abroad. This experience ranges from hydrogeological reconnaissance studies to implementation of rural and urban water supply schemes. HASKONING works with nowadays techniques relevant hydrogeological studies, such as remote sensing, geophysical exploration methods, ground water flow and water quality monitoring and GIS applications. Institutional development is always a key element in our projects.

Branch offices in the Netherlands: Amsterdam, Rotterdam, Goes, Steenwijk, Wijnandsrade
Offices abroad: Bangladesh, Belgium, Botswana, Cameroun, Colombia, Ecuador, India, Indonesia, Morocco, Nigeria, Spain, Portugal, Thailand

NEDECO
Netherlands Engineering Consultants BV

Member of
ONRI

IWACO
Adviesbureau voor water en milieu

IWACO B.V. Consultants for Water and Environment

Hoofdweg 490
P.O. Box 8520
3009 AM Rotterdam
telephone: 010-4076543
telefax: 010-2201005

Offices in the Netherlands and Europe
Den Bosch, Groningen, Rotterdam, Belgium, Germany, Hungary

International Project Offices:
Bujumbura, Burundi
Cairo, Egypt
Dhaka, Bangladesh
Jakarta, Indonesia
New Delhi, India
Nouakchott, Mauretania
Ouagadougou, Burkina Faso
Paramaribo, Surinam
Quetta, Pakistan
Willemstad, Curaçao

International experience:
Netherlands Antilles, Bangladesh, Belgium, Burkina Faso, Burundi, Chad, Czech Rep., Egypt, Germany, Hungary, India, Indonesia, Jordan, Mali, Mauretania, Mozambique, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Philippines, Saudi Arabia, Senegal, Sierra Leone, Spain, Sudan, Surinam, United Arab Emirates, Yemen, Zambia

Managing Director:
N.A. Amesz

International Activities:
A. Leusink, Director
B. Blankwaardt, Africa & Rural Development
F.J.H. Dirks, Far East, Latin America & Environment
A.B.M. Lennaerts, Central and Eastern Europe
W.G.J. Overbeek, Asia & Institutional Development
A. Tuinhof, Middle East & Water Resources

General Description

IWACO B.V. Consultants for Water and Environment, is an independent consultancy firm qualified in water resources management and -studies, water supply and sanitation and integrated environmental studies. In these fields IWACO provides technical services as well as services in the fields of organization and institutional development, finance and economy, training and extension. Since its formation in 1969, IWACO has built up an extensive experience in the Netherlands, Europe and in developing countries in Asia, Africa and Central and South America.

Fields of specialization

Water resources
- Policy development: legislation, institution building, standards
- Planning & development: planning water systems, protection water systems, integrated WRM, monitoring
- Hydro(geo)logical studies: inventories, geophysics, remote sensing, well-field design, supervision drilling
- Eco-hydro systems: water quality, monitoring, hydrological system analysis
- Computer applications: groundwater models, quantity/quality models, GIS-applications, information systems
- Courses and training

Water Supply & Sanitation
- Rural water supply: technical, extension, institutional, organizational
- Urban water supply: technical, extension, financial, institutional
- Rehabilitation & maintenance: technical, management
- (Ground)water valorization: technical, extension
- Sanitation (rural/low cost): technical, extension, institutional, management
- WID, courses, computer models

Environment
- Policy development: legislation, institutional building, standards
- Planning/management: risk assessment, monitoring and information systems, regional environmental planning, waste management
- Protection measures: clean-up operations, environmental care systems, preventive measures
- Industrial processes: pollution abatement, waste recycling, clean technologies
- Investigations and impact appraisal: environmental profiles, environmental audits, EIA's
- Courses, software (MILWACO), contract research

Institutional Development
- Sector development: institutionalization, privatization PPP, legislation, policy issues
- Organizational development: managerial aspects, technical aspects, fin./adm. issues, public relations
- Human resources development: training needs analysis, training materials, training, manpower development
- Community related activities: sosec surveys, health education, environmental education, community participation
- Financial/economic analysis: economic analysis, financial analysis, loan doc's preparation, corporate finance
- Computer applications: GIS, MIS, CIS, financial models

The activities abroad are implemented under the authority of: AfDB, AsDB, DGIS, EC, IADB, IsDB, KfW, UNDP, WB, national governments and private companies.

Total Staff: 350

Department of Hydrogeology and Geographical Hydrology
Free University Amsterdam

The Hydrology Department of the Free University is part of the Institute of Earth Sciences. It is at present served by two full-time professors and six permanent academic staff. The number of undergraduate students majoring in hydrology currently approximates 60; these enter the 'doctorandus' (M.Sc) degree program in Hydrology after a two-year training in general Earth Sciences. Beyond this the degree courses cover a nominal period of two years and comprise a series of theoretical and practical subjects including field training in The Netherlands, N. Italy and S. Portugal. More than 20 Ph.D. students and post-docs are involved in the departmental research program, which encompasses a variety of fields and countries. The group's research profile is characterized by the themes:

- Groundwater resource exploration, evaluation and management.
- Catchment-scale environmental-hydrological studies.
- Hydrochemical and pollution transport studies.

The framework for this program is the hydrological cycle and its interaction with the lithosphere, the biosphere and the atmosphere. Major projects include hydrochemical process and transport modelling, hydro-environmental impact studies of de- and reforestation in humid-tropical areas, the use of satellite remote sensing for water and energy exchange modelling, groundwater recharge studies in semi-arid areas. External research project funds currently average US $ 1 million per year.

Inter-university exchange programs, within the framework of development cooperation, have been established with the University of Botswana, the University of Western Cape (South Africa), the China University of Geo-Sciences and the Gadja Mada University (Indonesia).

vrije **Universiteit** *amsterdam*

For more information please contact:
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IHE
DELFT

Infrastructure
Hydraulics
Environment

Education, Training, Research and Capacity Building for Development

Major Activities

- **Post-graduate education**
- **MSc and PhD programmes**
- **Tailor made and short courses**
- **Applied and scientific research**
- **Institutional strengthening**
- **Advisory services**

PhD Programme

IHE offers the possibility to conduct individual PhD research within its research programme, primarily to holders of the IHE MSc degree. The average duration of individual PhDwork is some 3 years. IHE encourages such work to be partly carried out in the participant's home country.

MSc/Diploma Programme

IHE's MSc programmes consist of a diploma course followed by individual thesis work. The diploma courses have a duration of 1 year. They are attended each year by some 300 professionals from all over the world. The subsequent MSc thesis work has a duration of 6 months. MSc/Diploma programmes are offered in the following areas:

Hydrologic Engineering
with specializations in Surface Water Hydrology; Groundwater Hydrology; Water Resources Management.

Water Quality Management
interdisciplinary training for monitoring and management of the quality of surface and groundwaters.

Environmental Sanitation and Management
emphasizes the consequences of industrial development on the environment.

Environmental Science and Technology
dealing with environmental problems in industrialized as well as in developing countries.

Sanitary Engineering
with specializations in Urban Water and Waste Water Engineering; Low-cost Water Supply and Sanitation; Anaerobic Waste Water Treatment.

Hydraulic Engineering
with specializations in River Engineering and River Structures; Coastal, Estuarial and Harbour Engineering; Land and Water Development; Hydroinformatics.

Transportation and Road Engineering
with specializations in Rural Highway and Road Engineering; Urban Traffic and Transportation Engineering.

Apart from organizing regular courses, IHE executes tailor made courses and assists governments and universities in the design and implementation of post-graduate training curricula and in institutional strengthening, capacity building and research in the fields of expertise of the institute.

International Institute for Infrastructural, Hydraulic and Environmental Engineering

Information
For all courses, please contact the IHE Registrar for detailed brochures, application forms and fellowships information.

IHE
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The Netherlands

Rector: Prof. Wil Segeren

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Telex : 38099 ihe nl
E-mail : ihe@ihe.nl

MASTERCLASS

GETTING GEO-INFORMED AT ITC!

Since its establishment in 1951, ITC has trained over 10,000 students from some [illegible] countries and carried out advisory and research work in some [illegible] projects in 70 countries. Courses are modular in structure to enable a multi-disciplinary approach: [illegible] informatics, land resource and urban sciences, and earth resources surveys. The training programmes offer some 40 different specialization courses, mainly at postgraduate, MSc and PhD levels.

Some 420 students are currently following courses at the International Institute for Aerospace Survey and Earth Sciences (ITC) in the Netherlands. An ITC "Masterclass" is mainly for mid-career people from developing countries, they have come to specialize in various aspects of aerospace surveys and the applications of remote sensing and geoinformation systems.

The purpose is to improve their understanding of the ever-advancing technology so urgently required for sustainable resource development and environmental planning and management. The knowledge thus gained is also a prerequisite for the modernization of institutes involved in the same type of work in their own countries.

The transfer of knowledge at ITC also encompasses advisory service activities. The institute is involved in some fifty projects per year around the world. These are tailor-made to deal with specific problems mainly in developing countries.

Supporting its training and advisory service activities, ITC carries out multidisciplinary and problem-oriented research focusing on strengthening surveying and environmental monitoring.

itc

GEOINFORMATION FOR SUSTAINABLE DEVELOPMENT
at the International Institute for Aerospace Survey and Earth Sciences (ITC)

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Telephone: (31) 53-874444,
Cable: Aersur Enschede,
Telex: 44525 itc nl, Fax: (31) 53-874400

geoneth
Geoscience network of the Netherlands for international cooperation

Why **geoneth**

Many problems for the rapidly growing population of the earth can only be solved with geoscience as a basis for e.g. coastal zone management, sustainable use of water, supply of energy and minerals, underground activities. The experience and know-how of geosciences concerning environmental and economic problems in the Netherlands are combined in **geoneth.**

geoneth is a cooperative association of Netherlands research, information and training institutes, foundations, university faculties and government agencies that share as a common field of interest the geosciences in the broadest sense. **geoneth** combines fields of expertise that originates from the Netherlands geographic and geologic environment, its historic traditions and its high standards of education and research with an international perspective.

geoneth operates on a world-wide basis in a wide spectrum of disciplines that are fundamentally related to the geosciences. The principal objective is to contribute to the environmentally sound and sustainable use of the earth' surface, subsurface and its resources.

geoneth has a structure of a foundation with the objective to foster international cooperation, in particular with the developing countries. The cornerstones of this objective are:
- contribution through geoscientific research and application to the proper management and use of natural resources and to the protection of the environment;
- promotion of knowledge and technology transfer by means of human resources through investing in education and training and institutional capacity build-up;
- provision of technical assistance, advisory and consulting services and project management.

geoneth can offer the following spectrum of key services:
- research and development
- regular and tailor made training and education programmes
- institutional capacity building
- consultancy and advice
- project organization and management

geoneth covers five main fields of interest:
- Water/Groundwater
- Soil
- Energy Resources
- Mineral Resources
- Natural Hazards/Environment

The six main disciplines of **geoneth** are:
- Geophysics
- Geochemistry
- Geohydrology
- Geo-engineering
- Geology
- Geomatics (geo-informatics and geostatistics)

APPLIED RESEARCH AND DEVELOPMENT INSTITUTES

RGD, Geological Survey of The Netherlands
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Winand Staring Centre for Integrated Land, Soil and Water Research
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TNO Institute of Applied Geoscience
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The Netherlands
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RESEARCH AND EDUCATION INSTITUTES

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IAC International Agricultural Centre
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The Netherlands
tel: +31 8370 90111 fax: +31 8370 18552

IHE, International Institute for Infrastructural, Hydraulic and Environmental Engineering
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tel: +31 15 151830 fax: +31 15 122921

ITC, International Institute for Aerospace Survey & Earth Sciences
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The Netherlands
tel: +31 53 8744441 fax: +31 53 874400

ISRIC, International Soil Reference Centre
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