Groundwater Resources Assessment
under the Pressures of Humanity and
Climate Changes

GRAPHIC

Preface

Groundwater is a valuable natural resource providing a primary source of water for agriculture, domestic and industrial purposes and accounts for 95% of readily accessible freshwater. Subsurface resources are challenging to evaluate; however, there is a growing awareness of their importance in global environmental cycles. Thus, UNESCO's initiative GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Changes) addresses the paucity of data on groundwater and investigates the effect of climate change and human activities on groundwater. This brochure contains a brief summary of our current activities and the methodologies used to evaluate the impact of human and climate stresses on groundwater resources and provides information about our upcoming pilot programmes for groundwater evaluation.

UNESCO-IHP activities in groundwater resources

IHP seeks to address the impact of global change (e.g. climate change and human pressures) on the water cycle. Through the Programme, UNESCO serves its Member States by addressing regional needs through global coordination. It also provides opportunities for knowledge-sharing through thematic regional networking.

In many nations, unsustainable groundwater management practices are contributing to significant and irreversible damage of the resource base. IHP builds capacities for improving integrated groundwater resources management at national and international levels. To achieve this, IHP compiles and makes available reliable global data and information on groundwater resources, including aquifer locations and characteristics, to the international scientific and management community. At the regional level, in response to specific needs IHP prepares and publishes regional case studies and organizes regional workshops and training courses on various themes. A broad range of groundwater studies and training material are published and made freely available through UNESCO's Water Portal (http://www.unesco.org/water). In the arid regions, water-scarce zones and on small islands, groundwater is often the only freshwater resource. Thus the hydrological processes in these vulnerable environments must be well understood in order to ensure that the resource is developed sustainably.

IHP develops integrated basin or watershed approaches to land, surface and groundwater management. IHP also investigates measures to minimize threats to vulnerable water resource systems. The Programme also promotes the rational use of groundwater in response to emergency situations like floods and droughts. For example, this is accomplished by preparing an inventory of groundwater basins resistant to natural and human impacts in pilot regions and by developing guidelines on groundwater use in emergency situations. Beyond these population demands, IHP also recognizes the importance of groundwater in supporting ecosystems such as in wetlands and lakes.

High priority is given to managing water as a scarce resource for human needs, particularly in developing countries. IHP develops regional networks to improve national and regional capacity to manage water resources, especially in arid and semi-arid lands and in urban areas. Work on shared groundwater resources is carried out through the International Shared Aquifer Resource Management (ISARM) initiative, which aims at identifying and characterizing transboundary / shared aquifers at the regional level to enable their sustainable management, including the legal and institutional aspects.

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1. **Introduction**

Global environmental studies typically focus on the environmental issues above the ground's surface such as air and seawater pollution, global warming and decreases in biodiversity. However, subsurface phenomena make an important contribution to environmental cycles. Subsurface conditions are challenging to evaluate but are essential for a more complete understanding of global environmental change.

Groundwater is a valuable natural resource providing a primary source of water for agriculture, domestic and industrial purposes in many countries. The importance of groundwater resources is highlighted in global environmental studies, including those of the IPCC (Intergovernmental Panel on Climate Change):

> "Despite the critical importance of groundwater resources in many parts of the world, there have been very few direct studies of the effect(s) of global warming on groundwater recharge." (IPCC 1996, p. 336)

> "Although the effects ... on groundwater resources are not adequately understood at present, they cannot be ignored." (IPCC 1998, p.122)

> "Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change." (IPCC 2001, p. 199)

The last three reports of the Intergovernmental Panel on Climate Change emphasize a continuing need to assess the potential effects of CO2-altered climates on aquifer recharge. The IPCC (2001, p. 200) concludes: "In general, there is a need to intensify research on modeling techniques, aquifer characteristics, recharge rates and seawater intrusion, as well as on monitoring of groundwater abstractions. This research will provide a sound basis for assessment of the impacts of climate change and sea-level rise on recharge and groundwater resources." Furthermore, the dynamics of groundwater systems in response to human and climatic stresses require further attention.

2. Objectives and structure of the GRAPHIC Project

Objectives of GRAPHIC

The GRAPHIC project seeks to improve our understanding of how groundwater contributes to the global water cycle and thus how it supports ecosystems and humankind. In recent years, the demands of a growing population have seriously degraded groundwater resources. In addition to this, global warming will cause changes to groundwater recharge rates, and rising sea levels will cause saltwater intrusion. These two influences decrease the amount of usable groundwater. Thus, a comprehensive understanding of groundwater resources is needed for their sustainable use. Specifically, an evaluation of the changes to groundwater composition, storage and groundwater flux (recharge and discharge rates) should be made. This project will deal with groundwater resource assessment and future forecasting under various population pressures and climate change scenarios.

Structure of GRAPHIC

The structure of the GRAPHIC project has been divided into:

(a) **Subjects** – thematic, cross-regional issues: (i) recharge, (ii) discharge, (iii) storage, (iv) quality and (v) management;

(b) **Methods** – methodological approaches: (i) database and monitoring, (ii) satellite GRACE (Gravity Recovery and Climate Experiment), (ii) modeling and simulation and (iv) paleohydrology; and

(c) **Regions** – representative geographical areas, where pilot studies will be carried out: (i) North and South America, (ii) Europe and Russia, (iii) Asia and Oceania and (iv) Africa.

Figure 1illustrates the structure of the GRAPHIC project.

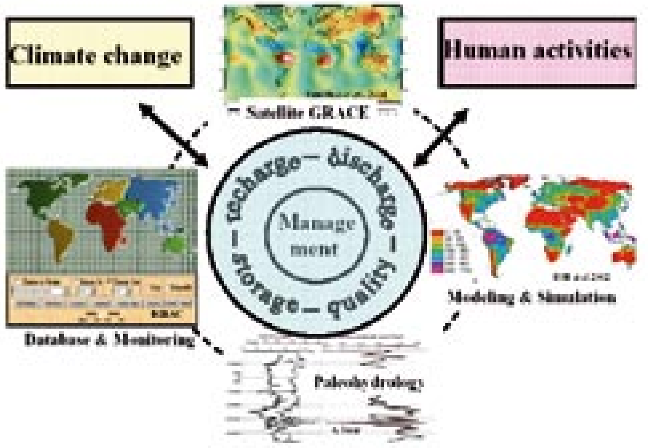

Figure 1. Structure of the GRAPHIC project.

3. Subjects

The GRAPHIC project investigates physical fluxes, state variables and their interaction with the human management of groundwater systems. The subjects addressed by the GRAPHIC project are groundwater recharge, discharge, storage, quality, and management. Figure 2 shows the components of a groundwater system with fluxes (recharge and discharge) and state variables (water quality and storage), where all physical components affect each other. Thus, management of the system plays a critical role in the mass balances of the water and chemical constituents. All components of the system can be affected by changes in both climate and population pressures. Although management effects fall within the Pressures of Humanity in GRAPHIC, management and policy are dealt with separately further on (see Subject 5).

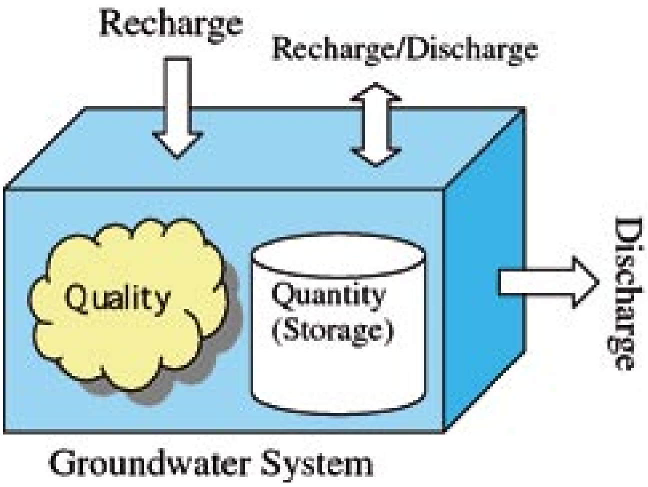

Figure 2. Schematic diagram of a physical groundwater system with inputs (recharge), outputs (discharge), and internal state variables (quantity and quality).

Subject 1: Groundwater Recharge

Groundwater recharge is defined as any influx of water entering a groundwater system at any of its defined boundaries. However, the water table boundary can vary in space and time. The different modes of groundwater recharge to be investigated will include:

1. Natural recharge
    a. Diffuse infiltration (from interfluvial areas)
    b. Focused by subsurface preferential pathways
    c. Focused by surface runoff to streams and lakes
2. Artificial recharge
    a. Intentional aquifer storage and recovery (ASR)
    b. Excess irrigation

For both human water supply and environmental issues, the hydrological fluxes of interest include spatial and temporal groundwater recharge rates. Emphasis is given to the timing and location of recharge in addition to the net recharge integrated over time and space. This is because gradients in water potential and quality affect the movement of water and its chemical constituents. Although the importance of the quality of water recharging an aquifer is noted, most studies to date have focused on water quantity issues. Indeed, changes in quantity alone can be extremely difficult to predict.

There is a basic need to identify the sensitivity of groundwater recharge to climate variability and change. Vaccaro (1992) used a relatively simple energy-soil-water balance model to estimate recharge with daily historical climate and GCM (general circulation model) generated climates for double-CO_2 conditions, including predevelopment and current (1980s) land use conditions. Vaccaro's study thus demonstrated the importance of investigating the joint pressures of population and climate on groundwater.

Plant water use (transpiration) is an important component of the water budget needed to compute groundwater recharge. Dooge (1992) noted that "meaningful scenarios of hydrologic prediction and climate prediction are not possible without an understanding of vegetation response." Green et al. (1997a,b) presented an approach to simulating the potential effects of a double-CO_2 climate change scenario. Simulated recharge varied dramatically, where the magnitude and even direction of change depended upon the particular combination of soil, vegetation and climatic region (Figure 3). Conversely, Eckhardt and Ulbricht (2003) simulated relatively small effects on mean annual recharge in central Europe using the Soil and Water Assessment Tool. Even so, the seasonality of groundwater recharge and stream flow were sensitive to climate change. Both studies included the joint effects of atmospheric CO_2 concentrations on carbon assimilation rates and the stomatal conductance of plants. These are essential for testing sensitivity to climate change, and more could be done to determine the effects of changes in plant communities (e.g. succession) under changes to both the mean and variability of climates.

The GRAPHIC project has identified the following problems and research needs related to groundwater recharge:

1. Diffuse recharge is a residual of two large factors (rainfall and evapotranspiration [ET]), resulting in large uncertainty, which must be quantified;
2. Surface runoff and other lateral flow processes can focus recharge, particularly beneath streams in arid regions, which requires improved coupling with hydrological models;
2. Inference from historical measurements must be combined with process simulation to evaluate potential sensitivity of recharge to climate change;
3. Spatial variability and interactions between land areas require improved upscaling methods; and
4. Uncertainty in climate variability/change scenarios may be addressed in part using ensemble methods..

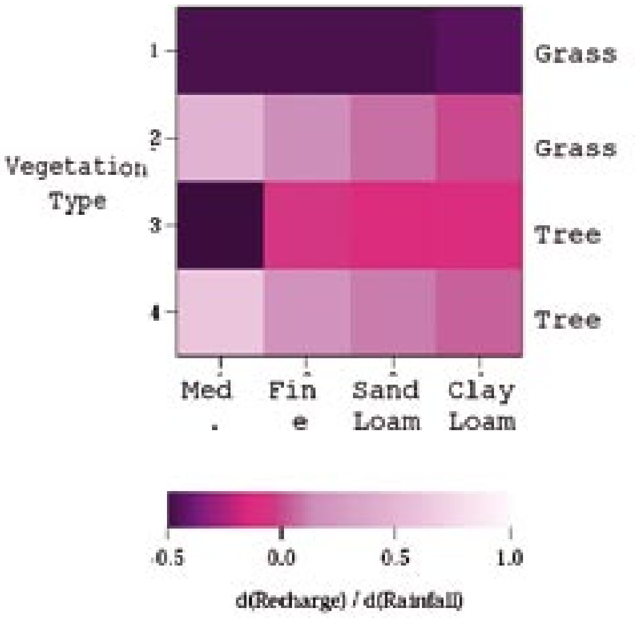

Figure 3. Simulated change in recharge per unit change in rainfall under a double-C02 climate change scenario in Western Australia (Green et al. 1997b). Grasses 1 and 2 are perennial grasses and Trees 1 and 2 represent pine and eucalyptus canopies with different model parameters for optimal temperature ranges, carbon assimilation, stomatal conductance, etc.

These problems involve several major research issues:
(i) point- to basin-scale processes and perspectives, with rigorous spatial scaling;
(ii) complex model structures and component interactions;
(iii) identification of model sensitivity to parameter uncertainty;
(iv) quantitative plant physiology and succession for environmental stress responses;
(v) hydrological boundary conditions affecting recharge;
(vi) feedbacks associated with societal adjustments in land/water resource management; and
(vii) coupled hydrologic-atmospheric processes.

The impacts on groundwater recharge cannot be studied in isolation, as various interactions in the hydrological cycle will be critical to our understanding of the land-atmosphere coupling. It is predicted that the response of the world's groundwater systems to global change is likely to include trigger factors and threshold phenomena.

Subject 2: Groundwater Discharge

Groundwater discharge is an important element of the hydrological cycle that describes the loss of water from the groundwater compartment to surface water, the atmosphere and the ocean. Groundwater discharge includes springs, diffuse seepage into drainage systems (both natural and man-made) and lakes, diffuse and localized discharge through the seafloor, evaporation of soil moisture that is replenished by seepage (dry salt lakes) and transpiration by phreatophytic vegetation that draws its water from the water table. Pumping activities by humankind can be considered an artificial form of groundwater discharge.

Groundwater discharge is a key factor controlling water table conditions, surface and groundwater quality, lake levels, baseflow of rivers and streams, and terrestrial and aquatic ecosystems, notably in riparian zones and wetlands. Enhanced groundwater discharge by abstraction and land drainage can moreover lead to land subsidence, which is particularly a concern in low-lying coastal areas. Climate change affects groundwater discharge primarily in indirect ways through alterations to recharge conditions. By contrast, human activities can exert a direct influence on groundwater discharge through groundwater extraction and artificial control of surface water levels in discharge areas. In addition to these direct influences, humankind also exerts an important control on recharge via land use and to some extent via artificial infiltration.

Key groundwater discharge issues relate to the measurement and quantification of discharge and associated aspects of scale (spatial and temporal variability), and reduced baseflow of river systems. Other key issues include the role of vegetation in groundwater discharge and the importance of groundwater discharge as a vehicle for the transport of nutrients and contaminants to the surface environment, including estuaries and the sea.

Potential issues to be addressed in GRAPHIC are the impacts of human pressures and climate change on:
1. Baseflow of groundwater to river systems.
2. Groundwater discharge to and through lakes.
3. Other terrestrial groundwater discharge (e.g. wetlands).
4. Submarine groundwater discharge.

In every case, there is a need to separate the effects of climate change from human pressures. Human pressures of interest to this project are de/reforestation, land-use, groundwater abstraction, specific water management practices, precipitation and/or temperature change and changes in climate variability (storminess, seasonality) etc.

Various questions will be addressed, such as:
- What is the time lag in discharge response to periods of drought and damping?
- Are nonlinearities due to discharge-induced changes in drainage levels important?
- What changes in the water quality of exfiltrated groundwater may be expected when groundwater flow patterns (systems) are modified by these pressures (e.g. exfiltration of different groundwater bodies and/or induced water-mineral reactions such as changing arsenic concentrations)?

Measurement of submarine groundwater discharge is notoriously difficult (see www.old.nioz.nl/loicz/res.htm) and historic records are lacking. Thus monitoring of future change in selected areas and predictive modeling may be most appropriate to address these challenges. Modeling has to account for variable-density flow (Figure 4.). Potentially, coastal zones with well-documented cases of seawater intrusion may provide the most promising study areas.

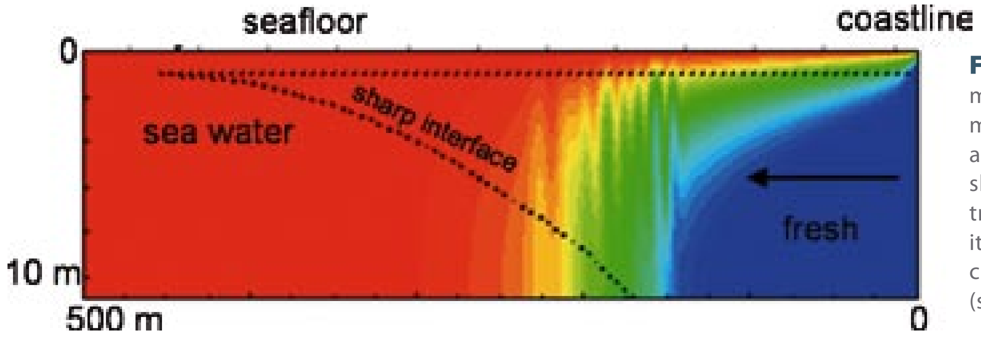

Figure 4. An example of submarine groundwater discharge modeling – accounting for variable-density flow. These models should be coupled with reactive transport to assess water quality issues associated with climate change and human pressures (see Subject 4).

Subject 3: Groundwater Storage

Storage of groundwater refers to state variables rather than the fluxes across system boundaries as found in the previous subjects. The state variables are important direct indicators of groundwater resources. Present or expected undesired values of these state variables trigger management decisions (e.g. artificial recharge and groundwater [quality] protection).

Groundwater storage is affected by both recharge and discharge with a simple mass balance, but the factors that influence it may be quite complex. Topics of interest include artificial and induced recharge (e.g. by irrigation). It is important to identify and consider the functions of the specific bodies of groundwater in storage (source of water for abstraction, ecological factors, environmental factors determining the stability of the land surface, etc.).

It is also important to understand where non-renewable groundwater is located and which of these sites should be developed. GRAPHIC may respond to these questions by making an assessment of expected types of impacts of human activities on non-renewable resources. Direct impacts of climate change on groundwater storage are expected to be negligible on the time scales relevant for contemporary planning, but propagation of pressure waves in confined aquifer systems may lead to changes of practical significance (e.g. reappearance of springs that have dried up) within a few decades. The time scales for responses of groundwater systems under different climatic conditions (arid to humid) can be investigated under the subject of storage. Groundwater storage is variable in space and time and is also linked to contamination, as contamination and saltwater intrusion decrease the amount of useable groundwater (see Figure 5.).

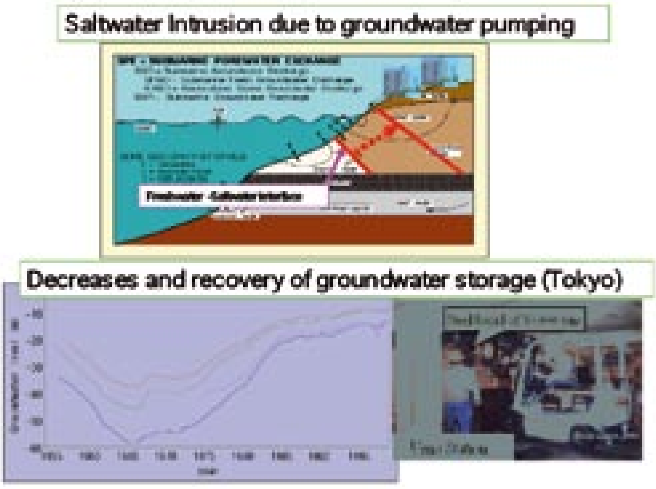

Figure 5. Changes in groundwater storage.

In order to target GRAPHIC toward the most relevant issues and geographical areas, we may identify the most endangered zones (resulting from a combination of vulnerability assessment and prognosis on changes in climate and human pressures). As a result, GRAPHIC can focus on marginal zones where the most problems are expected, or to zones where new opportunities develop as a result of changing boundary conditions.

Subject 4: Groundwater Quality

In addition to water quantity, the thermal and chemical properties of groundwater are affected by human activities and climate. Taniguchi and colleagues (e.g. Taniguchi et al. 2003) have identified changes in subsurface temperature regimes in response to changes in land use and climate. Glassley et al. (2003) simulated reactive chemical transport in a deep vadose zone, and identified thermal impacts of radioactive waste emplacement similar to those expected to result from climate change. Siegel et al. (2002) identified a carbon feedback between pore water in peatlands and the atmosphere, where fluid flow direction through the peat may be intermittently reversed in response to short-term climatic fluctuations; while longer-term changes in hydrology can affect fluxes of dissolved organic matter through the deeper peat. These hydrochemical feedbacks and other important water quality issues can only be predicted with an improved understanding of the spatial and temporal dynamics of groundwater recharge and discharge.

To determine groundwater quality, it is necessary to identify the most obvious changes expected from changes in climate and in human pressures. Given that many projects and groups already concentrate on pollution and other human-induced changes in water quality, GRAPHIC focuses on the climate change impacts on groundwater quality.

To adequately determine the effects of climate change, longer time series than those currently available are needed. However, these time series may be compensated to some extent by transposing contemporary data from one zone to those zones with climatic conditions similar to the expected future climate. Climate classifications and climate indicators (e.g. the aridity index) may be helpful in this respect.

Aquifers may be further classified by the sensitivity of different aquifer types to an expected response to a "unit change" in a given climate variable, or to given scenarios of climate change considering the variables to be coupled. Here, the emphasis is on water quality rather than quantity, but both storage and water quality can be studied in tandem to address societal feedbacks under climate change.

Subject 5: Management and Policy

In the model, management refers to active human pressures on groundwater systems. Management practices that actively influence groundwater to a significant degree include groundwater pumping for irrigated agriculture, pumping for industrial and municipal supplies, supplementing stream flows during drought periods, dewatering areas for development, artificial groundwater recharge, and irrigation with treated water or water of variable quality. These management practices are guided by policies at local, national and even international levels, and policy decisions are usually made with long-term goals for economic or environmental improvement and sustainability. Thus, the outcomes of GRAPHIC-type investigations may influence management policies.

Systematic analysis of stakeholder and groundwater-related policies is a crucial part of GRAPHIC. A chain of social interactions and feedbacks for groundwater systems under the influence of climate change may be written as:

Driving forces and development goals –> policy framework –> stakeholders –> policy options –> impacts –> relation to goals

The overall framework for studying management and policy interactions is given in Figure 6.

Groundwater management is typically characterized by many variables that are known with a low or very low level of certainty. Those variables are strongly interconnected, and belong traditionally to different scientific disciplines (chemistry, biology, engineering, socio-economics, etc.). Consequently, a mathematical approach that can handle many highly uncertain, interconnected, multidisciplinary variables is needed. The model must be built upon a mixture of exceedingly diverse types and qualities of information from the different components of the system. This information must then be organized and structured so as to allow systematic analyses.

The Bayesian network approach enables systematic analysis of such problems. It supports a learning process from scattered, scarce, inconsistent, and subjective information toward a transparent, consistent, casually structured and communicative model that allows the analysis of policy-related scenarios and can be used as a tool for decision analysis. The underlying mathematical approach is probabilistic and risk-analytic. This model is developed through interconnecting semi-qualitatively defined variables, which are expressed in relative scales.

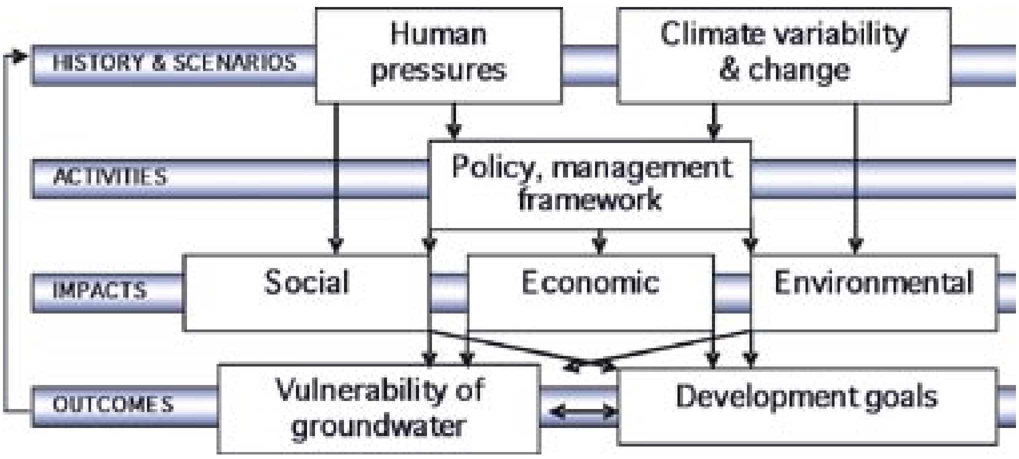

Figure 6. A framework for management and policy interactions influenced by a combination of human pressure and climate change.

4. **Methods**

Method 1: Database and monitoring

Baseflow records may be augmented with paleorecords of river discharge using sedimentological indicators. Also, depending on the river type, records of periodic no-flow conditions may be used (e.g. Yellow River in China). Because baseflow integrates discharge over the entire upstream part of the drainage basin, basins with a dense network of gauging stations are essential to address variability within a given basin and to account for possible discharge and recharge reaches of river systems. Additionally, satellite altimetry of river stages may be used to extend the spatial coverage of flow conditions. The baseflow records should be linked to meteoric and paleoclimate records, land use records (remotely sensed data) and piezometric level records of groundwater conditions. Process-based interpretation requires conjunctive use of SVAT (Soil Vegetation Atmosphere Transfer) with groundwater and surface water models. Finally, apart from using existing records, dedicated monitoring may have to be set up in strategically located basins.

The GRAPHIC project plans to use and link to existing groundwater-related databases. For the specific purposes of GRAPHIC and its case studies, it plans to cooperate with existing monitoring and database development projects. Cooperation is especially planned with the International Groundwater Resources Assessment Center (IGRAC) detailed in figure 7 (facing page). IGRAC develops and maintains a Global Groundwater Information System, which contains as one module a worldwide overview of selected groundwater-related attributes. The spatial and global aspects of changes in groundwater and groundwater problems will play a key role in the database and monitoring method of GRAPHIC. The goal of GRAPHIC is to use the case studies to analyze the observed local effects, and then use these results in assessing the probabilities of regional effects and, finally, use these for inter-regional assessments. The project will utilize GIS technology and the latest results of geoinformatics and spatial science to achieve this goal.

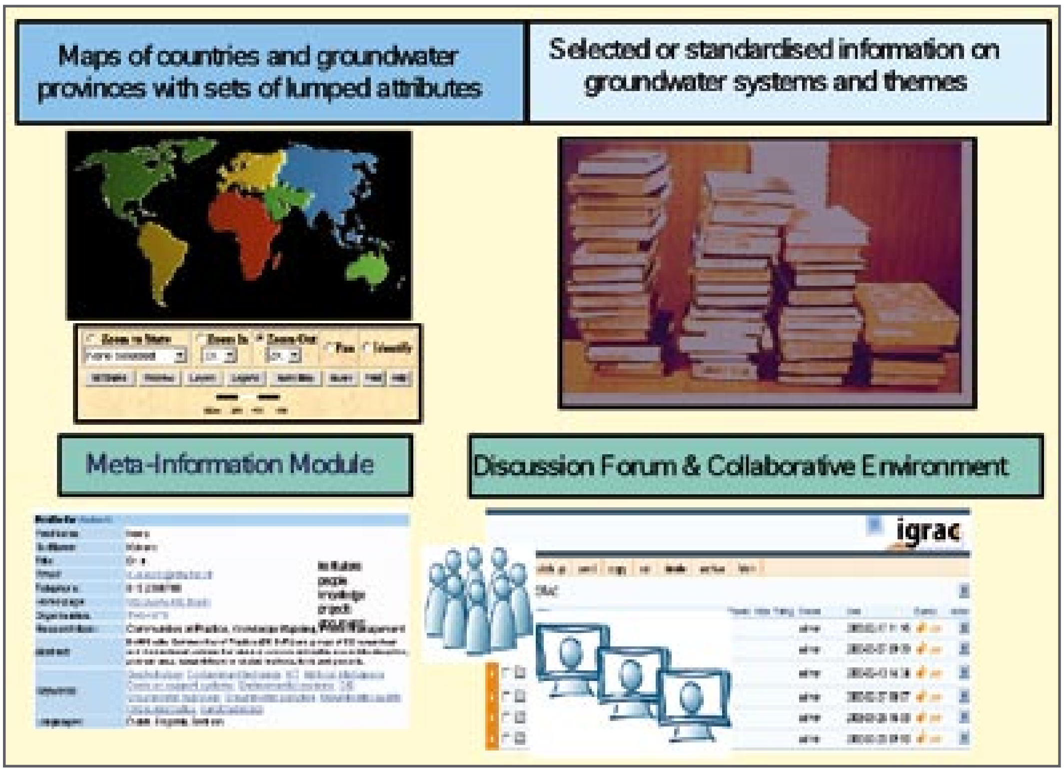

Figure 7. Portal for global groundwater information system (IGRAC) at http://www.igrac.nl

Method 2: Satellite GRACE

The scientific context

Continental water resources play an important role in economic development, as well as having an impact on climate change. Unfortunately, no complete global and accurate database of in situ measurements of water table variation exists. An alternative solution to this problem is found with new satellite data that offer systematic and global coverage mapping of the Earth's surface properties, such as the monitoring of continental water levels of rivers, lakes and flood plains by radar altimetry and detection of water mass storage changes using accurate GRACE (Gravity Recovery and Climate Experiment) gravimetry. Successfully launched in mid-March 2002, the goal of the GRACE satellite mission is to measure the spatio-temporal variations of the Earth's gravity field to a high accuracy (~1 cm in terms of geoid height) and a spatial resolution of ~200-300 km for a nominal period of five years. For the first time, GRACE provides global monitoring of the tiny time variations of the gravity field that are due to the redistribution of fluid masses on the Earth's surface. However, the classical inverse problem of gravimetry is that GRACE measurements represent the sum effects of all the water mass/solid Earth contributions, and therefore cannot distinguish between the different sources of gravity anomaly, especially those of the continental waters.

The strategy for extracting the continental waters variations from GRACE data

Recently, a new inverse approach for separating the different hydrological contributions of the main water reservoirs (atmosphere, oceans and continental waters) from monthly GRACE geoids has been developed. This linear least-square method provides estimates of spherical harmonics of the geoid for each reservoir, by using a priori information from global model outputs to build covariance matrices describing the dynamics of water mass. Moreover, it takes a priori GRACE errors and model uncertainties into account as well as elastic compensation of mass by the Earth's surface. The continental water solution is converted into surface density expressed in terms of equivalent-water thickness by filtering the estimated geoid coefficients. Details of this inverse approach are given in Ramillien et al., 2004.

Solutions for continental water have already been derived from the available series of monthly GRACE geoids for the period 2002-2003 (Figure 8.). Unfortunately, the presence of important noise on observed harmonic degrees up to 15 still limits the recovering to spatial wavelengths greater than ~2000 km. At this resolution, a posteriori uncertainties are less than 20 mm of equivalent-water height since the amplitude of water mass variations reaches 200-300 mm in large river basins.

How to estimate global spatio-temporal variations of the groundwater?

A similar inverse approach can easily be applied to efficiently extract the groundwater component from the total continental water storage from GRACE, but only if enough a priori information about groundwater alone is available.

Obviously, in a large desert zone where the effects of river stream and vegetation can be neglected, GRACE Land Water solutions (LW) directly reflect the variations of water mass of large-scale aquifers. In this very particular situation, sparse surface measurements of the water table variations would help directly validate these GRACE solutions. Collaboration with GRAPHIC members would be the first task to demonstrate the ability of the GRACE mission to recover groundwater signals.

A second task would be to develop a robust matrix approach for estimating spatio-temporal variations of groundwater by combining these different types of information when there are enough observations available.

Possible hydrological parameters, and their uncertainties, for isolating groundwater signals could be:

- snow thickness and soil moisture prognostics provided by global models such as GLDAS (Rodell et al., 2004) LaD and GSWP, variations of these parameters are also measured by present (e.g. AMSR) and future satellite missions (e.g. passive interferometry SMOS [Soil Moisture and Ocean Salinity] scheduled for 2005).
- surface water flows (lakes, rivers, flood plains) for which local time-series of levels are measured by tide gauges and/or by satellite altimetry (e.g. Topex/Poseidon, ERS-1 & 2, ENVISAT, Jason-1).

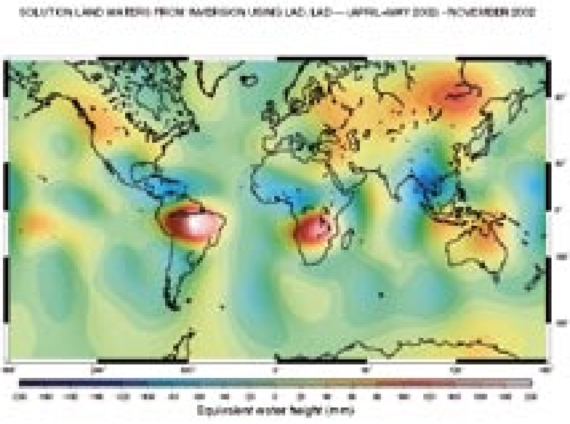

Figure 8. Seasonal variations of the total continental waters estimated from GRACE geoids (i.e. May, 2002, minus November, 2002) by using the inverse method developed at LEGOS (Ramillien et al., 2004). Note the important water mass variations in large drainage basins (the Amazon and the Congo) as well as the signature of the monsoon near India.

Method 3: Modeling and simulation

Numerical simulation (i.e., modeling) is an invaluable tool in hydrology. It provides a method to improve understanding of processes, for both individual and also for comprehensive systems involving multiple coupled processes. Additionally, modeling is increasingly required as a tool for integrated water resource management and policy making. While science applications rely on explaining and integrating observations and, therefore, inherently emphasize validation and testing of models by *hindcasting*, management requires *forecasting*. In spite of these key differences, science and policy applications are becoming more integrated and must be developed in concert, since management applications critically depend on appropriate process representation. Water management and policy methods also require a dedicated monitoring infrastructure to allow evaluation and impact assessment. This monitoring generates key data sets to further the scientific approach. GRAPHIC highlights this synergy of science and policy objectives. GRAPHIC advocates an integrated modeling approach that includes modeling at different scales, coupling of atmospheric, surface and groundwater models, as well as coupling with socio-economic factors.

A large suite of groundwater modeling codes can be used for the GRAPHIC project. All of these are based on Darcian flow. However, some are more appropriate for coastal zones (variable-density flow), water quality issues (reactive transport), and unsaturated zone representation. Differences in the detail of process representation, representation of subsurface properties and boundary conditions control, to some extent, the scale at which the codes can be realistically applied as well as the type and scale of data required for driving or validating the models. Process-based continental or global-scale hydrological models are rare if not absent at present. Coupling to surface hydrological process models – mainly to generate recharge boundary conditions for the groundwater models – is essential for assessment of land-use and climate change impacts. These models also differ in the detail and scales of process representation, hence judicious selections must be made. SVAT (Soil Vegetation Atmosphere Transfer) models are most suitable for hillslope scale simulations, DHM (Distributed [physical] Hydrological (parameter) Models) for catchment scale modeling, and SWAT (Soil Water Assessment Tools) for catchment to continental scale modeling.

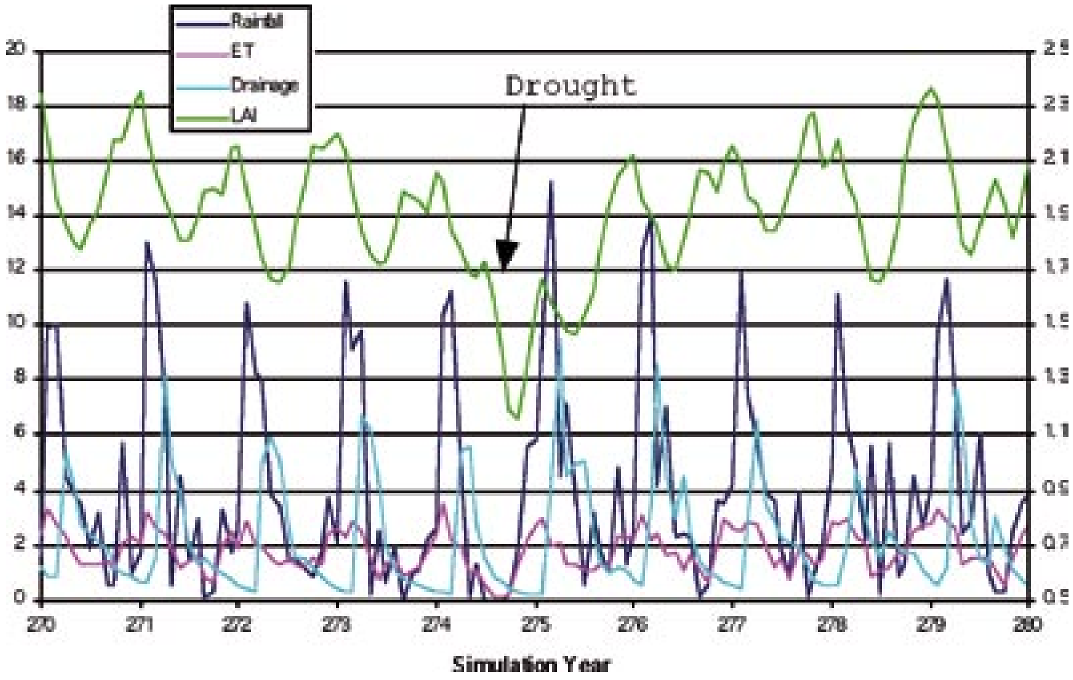

Figure 9. An example of simulated water fluxes (rainfall, evapotranspiration (ET), and deep drainage (or recharge) and plant leaf area index (LAI) over a decade that includes a drought period.

Several studies have already coupled GCM predictions with coupled surface and groundwater hydrological models. However, these remain mainly illustrative. Attention to uncertainty can greatly be improved.

Problem of gaps in coupling GCM predictions with hydrological models (Xu, 1999).

1. GCM accuracy decreases at increasingly finer spatial and temporal scales, while the needs of hydrological impact studies conversely increase with higher resolution.
2. GCM accuracy decreases from free tropospheric variables to surface variables, while the latter are key inputs in water balance computations. Accurate prediction of variability at the daily time scale is essential because of the strong non-linear dependencies of recharge on the parameters.
3. GCM accuracy decreases with climate-related variables, i.e., wind, temperature, humidity and air pressure. Precipitation, evapotranspiration, runoff, and soil moisture are key climate-related variables in hydrologic regimes.

Land phase parameterizations in current GCMs do not yield consistent predictions of most hydrological variables. It is known that the higher the altitude, the better prediction expected from GCMs, but the less correlation with ground surface variables. Precipitation is poorly simulated because events such as thunderstorms occur at smaller spatial scale than GCM's grid size. Evapotranspiration is also not well represented in GCMs.

Prediction of changes in recharge requires downscaling of GCM predictions.

Different approaches include:

- Dynamic downscaling (nesting; regional model from GCM) and
- Statistical downscaling based on historical records and GCM statistical characteristics using weather simulators (e.g. Vaccaro, 1992; Bates et al., 1994; Bouraoui et al., 1999).

An example of such methods from Green et al. (1997a) involved the generation of daily weather variables using a stochastic daily weather generator, followed by a numerical simulation of rainfall infiltration, variably saturated flow and evapotranspiration with dynamic plant growth and senescence values for various soil-vegetation environments. Figure 9 shows one decade of dynamic model output as a sample used to assess potential climate change effects on groundwater recharge from diffuse deep drainage.

Overall modelling approach:

- Use different scale models:
  - apply models at the scale of interest for a given problem,
  - develop methods for transferring results across a range of spatial scales, and/or
  - regionalize (upscale) or localize (downscale) model predictions.
- Address uncertainty:
  - estimate parameter uncertainty,
  - evaluate model sensitivity to parameters, and/or
  - estimate confidence intervals of model predictions/results.
- Identify different levels of process representation and coupling:

  - compare model constructs from the simplest to the most complex,
  - consider model uncertainty in overall uncertainty (above),
  - identify dominant process feedbacks, and/or
  - recommend appropriate levels of complexity for different problems.
- Multiple GCM predictions required:
  - perform scenario comparisons with different GCMs and/or
  - run perturbation experiments with transient GCM results.
- Application to historical and paleo-data and records:
  - use hindcasting to test models and/or
  - extrapolate trends to aid forecasting.

Method 4: Paleohydrology proxy

While the investigation of contemporary climate change is based on direct data – such as air and sea temperatures, atmospheric pressures, wind directions and velocities – investigation of climate change in the past is based on proxy data derived from geology (the nature and distribution of sediments), geochemistry (chemical and isotopic composition of strata), biology (botanical and faunal assemblages, tree rings). Other sources, such as archaeology (material remains of past cultures) and historical records, are also important.

Oxygen and hydrogen isotopes can serve as a "finger print" for deciphering the characteristics of the paleo-climatic conditions and their influence on the hydrological system. This is because oxygen 18 (^{18}O) and deuterium (D or ^{2}H), whilst constituting a small proportion of the total mass of water, nevertheless affect its thermodynamic character. Thus, when water evaporates, a higher proportion of ^{1}H^{216}O atoms will leave. This causes the water vapor to be lighter isotopically than the mass, which remains as liquid water. Consequently, the vapors, and later the precipitation, contain less heavy isotopes than the ocean water. However, the composition of the vapor depends upon the temperature of the water from which evaporation started, as well as its isotopic composition. In general, water evaporating from warm ocean water will be heavier that that of cold regions. When condensation takes place the heavier water atoms, composed of the heavier isotopes, will condense first and fall down as precipitation. Thus, rain in the coastal areas is the heaviest and becomes lighter as the clouds travel inland. This is referred to as the "continental effect". The same happens with precipitation caused by adiabatic cooling when the clouds ascend a mountain barrier. The higher they climb, the lighter the precipitation. This is referred to as the "altitude effect." Also, the cooler the temperature, the higher the rates of condensation, and thus the lighter the rain becomes, isotopically. The opposite trend is seen in the isotopic composition of the water bodies, which undergo evaporation and are not replenished. The more evaporation the water undergoes, the heavier is its isotopic composition. A worldwide survey of isotopic composition of precipitation, carried out by the International Atomic Energy Agency in Vienna, has shown that on a global scale the ^{18}O/D composition of the precipitation, correlated with the Standard Mean Ocean Water (SMOW), falls along a certain line called the "global meteoric line". In contrast, the contemporary isotopic character of the precipitation of the Mediterranean region falls on another line, denoting heavier composition. This is due to the special marine and atmospheric regime of the Mediterranean Sea.

Another isotope, which serves as an environmental indicator, is ^{13}C. Soil moisture in forested areas is relatively depleted in this isotope whereas areas covered by grasses and bushes are characterized by a higher ratio of the isotope. Thus, under normal Mediterranean climate conditions, the vegetation during colder and wetter conditions is that of woodlands, and the water percolating into the subsurface is depleted in both ^{13}C and ^{18}O. The opposite is seen in warm and dry periods.

Isotopic time series can be derived from sea and lake sediments and fossil skeletons, cave speleothemes (especially stalagmites) and fossilized wood. Proxy data derived from ancient lake and sea levels is of great importance in establishing paleoclimatic and hydrologic scenarios. Its value, however, has limitations in that its markers are confined to extreme points, i.e. highest or lowest levels. Traces of intermediate levels have a high chance of being abraded by the water mounting or retreating to these extreme levels.

Pollen time series showing changes in vegetation can be a result of human activity, like the cutting or planting of trees. Yet this human activity in itself can be a result of climate change. Thus the interpretation of ancient pollen assemblages must also be compared with other time-series of proxy data. Also important is the dendro-chronological (tree ring character) method for identifying climate changes according to the rate of growth of the tree. The types of trees found in archaeological excavations provide information equivalent and complimentary to pollen series. In these investigations the remains are dated using radiometric methods, while the type of wood is identified by comparing the microscopic structure of the woody material of the ancient sample with that of modern trees. The isotopic composition of the wood changes according to the environmental conditions, which is a function of the climate.

It should be stressed that the interpretation of proxy-data time series must be done in an interdisciplinary way combining the results of research of the proxy date mentioned above as well as archaeological and historical data and vice versa. For example, archaeologists learnt from the lists of donations to the temples about a shift from wheat to barley about 4000 years ago in Mesopotamia. As barley is more tolerant to salt the archaeologists came to the conclusion that the ancient Mesopotamians over-irrigated their lands causing problems of drainage and thus salinity. A correlation with all the other time series of proxy data shows that during the same period the climate became warm and dry, which reduced the quantities of water available for irrigation and flushing of salts from the soils.

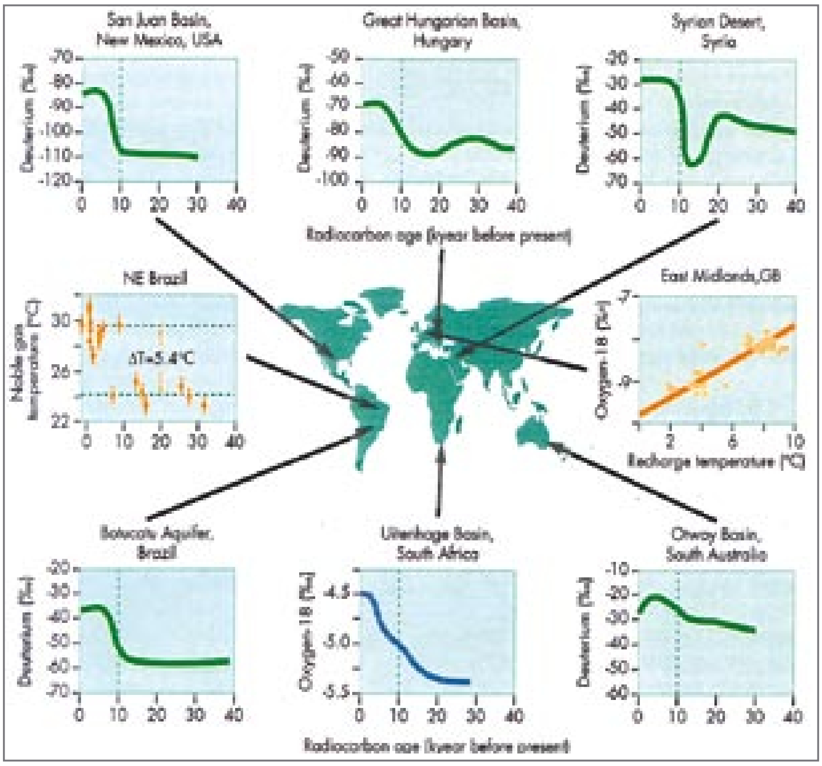

Figure 10. Climate reconstructions during the last 40 000 years from proxy data in major aquifers (IAEA, 1995).

When interdisciplinary correlation of time series of the proxy data is carried out, the dating method should also be taken into consideration. The archaeological sites are in most cases dated by the carbon radiometric age determination method, i.e. ^{14}C or radiocarbon. This element, produced in the upper atmosphere by the bombardment of cosmic rays, decays exponentially, its half-life being about 5570 years. By modern methods of enrichment and by using a nuclear accelerator, the dating range approaches 75,000 years. The constraints of the ^{14}C method are a function of errors arising from accuracy limitations of the laboratory methods, the range of which may span over decades or a few centuries, depending on the method of sampling and measurement, the time scale of the dating, and sample contamination. This range of error is given when the data are presented. Secondly, the amount of radioactive carbon in the atmosphere has not been constant during the last 12,000 years. In order to overcome this limitation, calibration curves were produced in which the measured radiocarbon ages were corrected according to absolute ages obtained from counting the rings in tree specimens.

The U-Th isotope age determination method is based on measurement of the decay of uranium ^{238}U into ^{234}U into thorium ^{230}Th. The dating range is from a few years to 350,000 years. The accuracy of dating stalagmites depends on the determination of the initial isotopic concentrations and on the assurance that the thorium in the sample is only the product of the decay and has not been enriched from external sources like organic debris.

5. **Project implementation**

Pilot Study in Japan

This pilot study will assess the effects of climate change and human activities on the subsurface environment, providing important information for the management of this resource. As the utilization of subsurface resources has rapidly accelerated in Asian coastal cities, they provide an excellent study site. The primary goal of the pilot study is to evaluate the relationship between the developmental stage of cities and various subsurface environmental problems, such as extreme subsidence, groundwater contamination, and subsurface thermal anomalies. We will focus on the evaluation of: (i) degradation of subsurface environments and changes to reliable water resources, (ii) accumulation of materials (contaminants) in subsurface environments and their transport from land to ocean, and (iii) subsurface thermal anomalies due to global warming and the heat island effect. Finally, we will address the challenge of the sustainable use of groundwater and subsurface environments toward improving development decisions for future generations.

In many Asian cities changes to reliable water resources depend on the development stage of urbanization. Although surface water is relatively easy to evaluate, changes in regional groundwater storage remains a difficult task. New techniques using Satellite GRACE (Gravity Recovery and Climate Experiment) and isotope data to evaluate groundwater flow systems may assist in evaluating the regional scale of processes affecting groundwater dynamics.

Material (contaminant) transport to the coast through direct groundwater discharge has recently been recognized as a significant water and material pathway from land to ocean (Taniguchi et al., 2002). Many major Asian cities are located in the coastal zone so material and contaminant transport by groundwater is a key to understanding coastal water pollution and its effects on associated ecosystems. Previous studies have shown some relationship between direct groundwater discharge and coastal ecological problems such as harmful algal blooms.

Recent global warming is considered a global environmental issue only above the ground. However, subsurface temperatures are also affected (Huang et al., 2000). In addition, the heat island effect due to urbanization creates a subsurface thermal anomaly in many cities. The combined effects of heat island and global warming can reach to more than 100 meters below the surface, and the increased rate of subsurface temperatures in cities by the heat island effect is much larger than that of global warming.

In this pilot study, four different methods (database and monitoring, satellite GRACE, modeling and simulation, and paleohydrology) will be applied to the five subjects (recharge, discharge, storage, quality and management) in the Tokyo area to evaluate both the effects of climate change and human activity on groundwater, and then we will extend the results to other geographical and climatic regions.

Plans for extending to other geographical and climatic regions

The GRAPHIC project will be extended to other pilot studies under different climates (humid, tropical, temperate, dry (for example the pilot project in Israel would cover a desert environment), different hydrogeology (karst, delta, tertiary sediment, fractured rock, etc.), different land-use (urban, agricultural, etc.), different human pressures (population, megacities, groundwater use by sector, etc.) and different geographical regions. Results of these pilot studies using the five subjects and four methods will be combined to assess the current situation of groundwater resources and for future forecasting under various human pressures and climate change scenarios.

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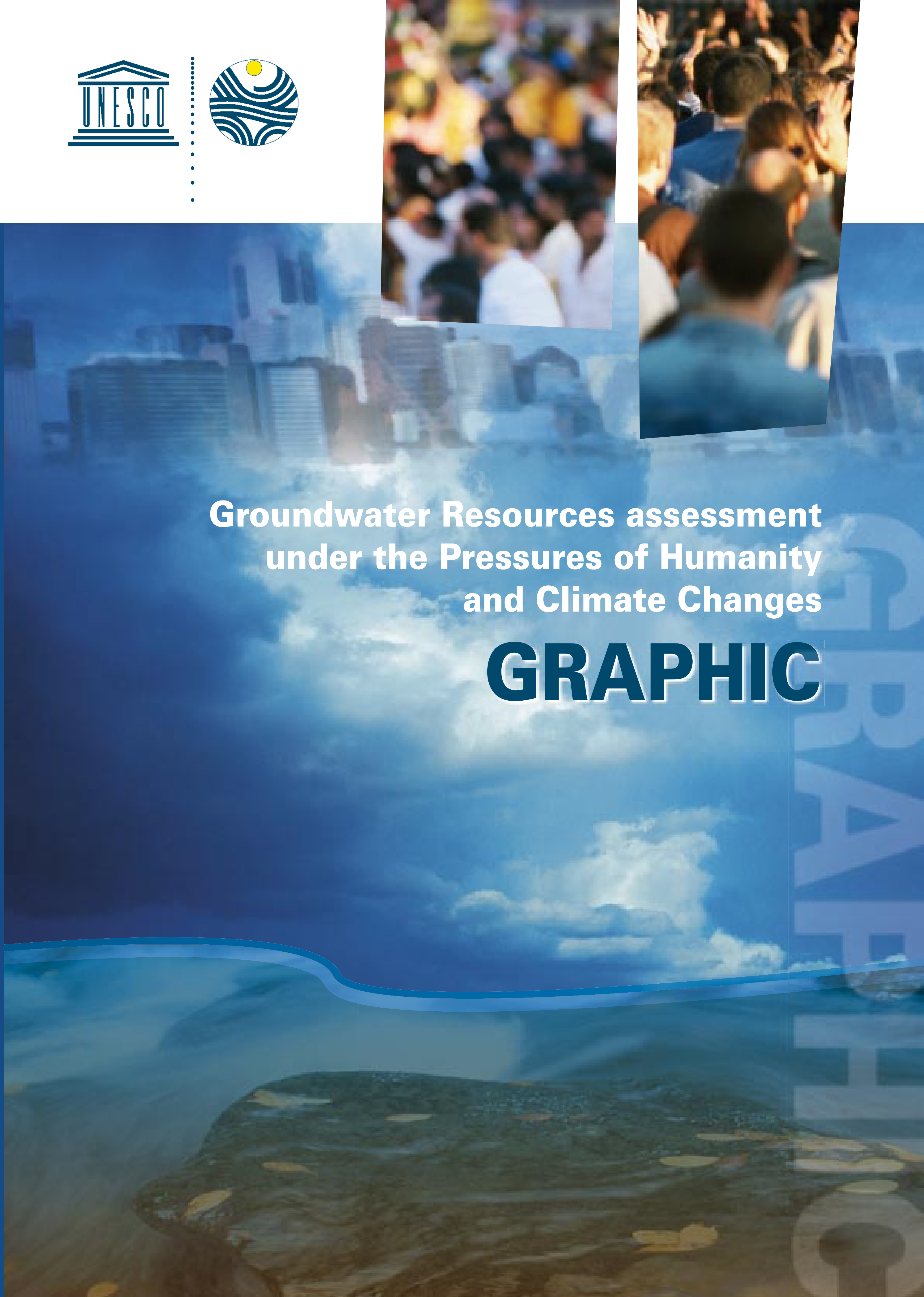

Groundwater Resources assessment under the Pressures of Humanity and Climate Changes

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