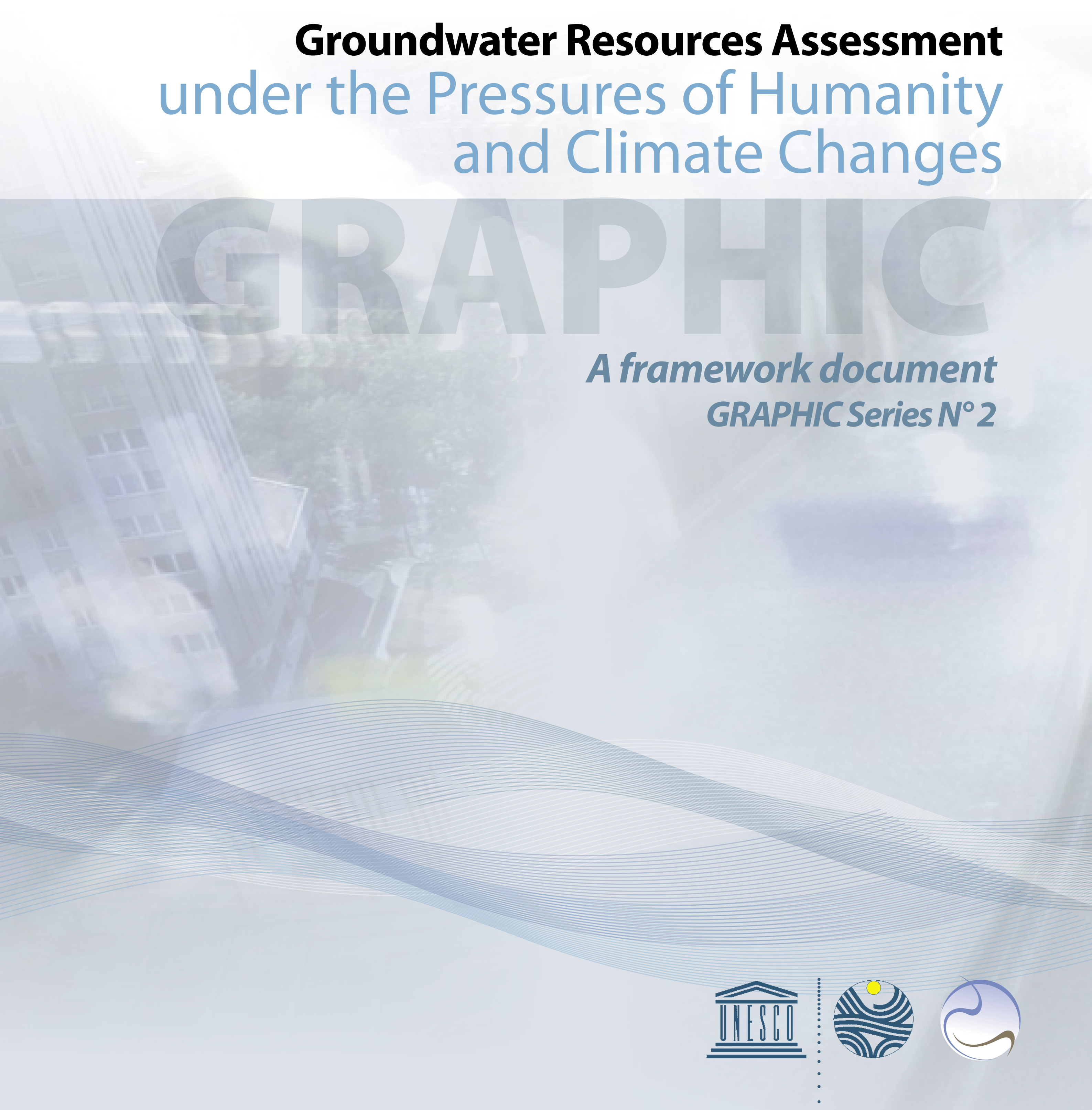
GRAPHIC

Groundwater Resources Assessment under the Pressures of Humanity and Climate Changes

GRAPHIC



A framework document

GRAPHIC Series N° 2

GRAPHICVision

GRAPHIC promotes and advances sustainable groundwater management considering projected climate change and linked human effects.

GRAPHICMission

GRAPHIC provides a platform for exchange of information through case studies, thematic working groups, scientific research, and communication.

GRAPHIC serves the global community through providing scientifically-based and policy-relevant recommendations. GRAPHIC uses regional and global networks to improve the capacity to manage groundwater resources.

Executive Summary

Given the vision and mission statements for GRAPHIC above, this document provides an updated framework for the GRAPHIC program. The approach to addressing global issues under the GRAPHIC umbrella involves case studies designed to cover a broad range of the identified Subjects, Methods, and Regions. Interdependencies of factors and processes affecting subsurface water are discussed first, followed by Subjects and Methods, including water quantity, water quality, geochemical indicators, paleo-indicators and proxy information, geophysical methods, remote sensing, information systems, simulation and modeling approaches, and management and policy implications, including feedbacks related to adaptation strategies. Finally, the GRAPHIC approach will be implemented using Case Studies of key aquifer systems and prototypes for investigations around the globe. Preliminary guidelines and criteria for selecting regional case studies are outlined. Thus, the framework for GRAPHIC is presented as a global collaborative effort in progress, where the stated Subjects and Methods of study will be adjusted to accommodate new partners and to firmly target the GRAPHIC vision and mission.

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GRAPHIC An introduction

Groundwater is an essential part of the hydrologic cycle and a valuable natural resource. More than 1.5 billion people worldwide rely on groundwater for their primary source of drinking water (Clarke et al., 1996). Groundwater also is important for sustaining agriculture, industrial uses, streams, lakes, wetlands, and ecosystems in many countries. The use of groundwater has particular relevance to the availability of many potable-water supplies. Groundwater enhances water supplies because it has a capacity to help meet water needs during periods of increased demand, particularly during drought and when surface-water resources are close to the limits of sustainability. However, global groundwater resources may be threatened by human activities and the uncertain consequences of climate change. Recent research has documented the effects of direct human activities, such as groundwater mining and contamination, on groundwater resources. The effects of climate change, whether caused by human activities or natural variability, on surface-water resources and associated ecosystems have been evaluated. However, little is known about how subsurface waters in the vadose zone and groundwater might respond to climate change and affect the current availability and future sustainability of groundwater resources (Green et al., 2007b). Thus, there are urgent and ongoing needs to address the expected coupled effects of human activities and climate change on global groundwater resources. To address these concerns regarding groundwater, UNESCO-IHP initiated the project Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC).

GRAPHIC seeks to improve our understanding of how groundwater interacts within the global water cycle, supports ecosystems and humankind and, in turn, responds to complex and coupled pressures of human activities and climate change. To successfully achieve these objectives within a global context, GRAPHIC was developed to incorporate a collaborative effort and umbrella for international research and education. GRAPHIC outlines areas of desired international investigations covering major geographical regions, groundwater resource topics, and methods to help advance the combined knowledge needed to address scientific and social aspects.

GRAPHIC Structure

GRAPHIC was designed with the understanding that groundwater resources can have nonlinear responses to atmospheric conditions associated with climate change and/or terrestrial-surface conditions associated with human activities. Thus, groundwater assessments under the coupled pressures of human activities and climate change and climate variability involve exploration of complex-system interactions. GRAPHIC incorporates a multidisciplinary scientific approach as the most rigorous platform to address such complexity. Furthermore, GRAPHIC extends investigations beyond physical, chemical, and biological interactions to include human systems of resource management, governmental policies, and economic considerations. The structure of GRAPHIC has been divided into Subjects, Methods, and Regions. The approach to addressing global issues under the GRAPHIC umbrella involves case studies designed to cover a broad range of the identified Subjects, Methods, and Regions.

GRAPHIC Subjects and methods

Groundwater is not an isolated or independent resource. It is a primary component of the hydrologic cycle and is connected to the land surface and terrestrial ecosystems. Current conceptualization of terrestrial water resources incorporates groundwater and surface water as a combined resource. Thinking holistically about groundwater systems in terms of connections to the hydrologic cycle illuminates a number of interdependencies that need to be considered when assessing groundwater availability and long-term aquifer sustainability. These interdependencies can exert substantial controls on the balance of in-flows and out-flows to the groundwater system (the groundwater budget), and the controlling factors can be greatly influenced by human activities at the land surface and effects of changes in climatic conditions (Healy et al., 2007).

The water fluxes affecting the groundwater budget include land-surface infiltration, evapotranspiration, flow within the vadose zone, flow into and through the saturated zone, aquifer losses to deeper strata, and the many forms of groundwater discharge or abstraction. Many factors influence water movement and the chemical quality of the resource in each of these compartments. Important controlling factors include local variations in climatic conditions, hydrogeologic setting (including vadose zone processes), vegetative cover, land use, and institutional approaches to water management. A holistic assessment evaluating changes in observed groundwater budgets over time is one approach for understanding of how human stresses and climatic changes may alter the balance of components of the system and ultimately influence groundwater recharge, groundwater storage, aquifer sustainability, and socio-economic stability.

Many of these factors vary over space and time, which makes quantifying the groundwater budget complex. The more carefully the interdependencies of each aspect of this system can be measured and understood, the more clearly the effects of human and climatic influences can be identified. GRAPHIC will aid transfer of the best available technology from all participating researchers so that state-of-the-art methodologies can be applied to understand the important interdependencies of the groundwater-climate-human system.

WATER QUANTITY
(Water Balance Components)

Groundwater recharge, discharge, and storage are discussed here in view of how climate change and human adaptation may affect each component of the water balance. Humans may abstract water directly from groundwater storage (internally), but climate change will act directly on surface boundary conditions to change recharge and discharge. Groundwater discharge and often recharge are affected by changes in storage, particularly when the water table approaches the land surface and plant roots.

Most estimates of freshwater resources have been based on mean annual river runoff (streamflow) without fully capturing ephemeral stormflow. Likewise, groundwater and soil moisture should not be neglected in light of the global use of groundwater and the importance of soils for seasonal water storage. Water beneath the ground surface provides an important reservoir for extraction by humans and plants during periods when water demands exceed supply. Groundwater also is an important component of the global water balance, where aquifer storage, groundwater discharge and recharge comprise the groundwater balance.

Groundwater Recharge

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

- Natural recharge
  - Diffuse (associated with surface infiltration in interfluvial areas)
  - Focused by subsurface preferential pathways
  - Focused by surface runoff to depressions, streams and lakes
- Artificial recharge
  - Intentional aquifer storage and recovery (ASR)
  - Excess irrigation that drains below the root zone

The key issues and research topics regarding groundwater recharge include:

- Spatial scaling from measurement to basin scales
- Further development of methodologies for predicting effects of climate change on recharge
- Process interactions and component/parameter interactions in complex models
- Model sensitivity to parameter uncertainty
- Quantifying stress responses of plants and potential species succession
- Hydrological interactions at groundwater recharge interfaces
- Changes in the spatial and temporal distributions of precipitation affecting hydrological fluxes at the land surface
- Fully coupled hydrologic-atmospheric processes
- Societal feedbacks

Aquifer recharge can be difficult to quantify because it can be affected by many different climatic and human factors, including the amount of precipitation; the density of streams that lose water to the aquifer; the ambient temperature, wind speed, and amount of solar radiation (potential evaporation); the type and amount of vegetative cover; the surface soil type and sub-surface geology; and depth to water. Human influences, such as disturbance of the natural soil structure, the type and intensity of land use (agricultural, urban, etc), or the amount and method of water application, also have important effects on groundwater budgets. The distribution and intensity of human influences are largely affected by spatial and temporal changes in climate.

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 replen-

ished by seepage (dry salt lakes), and transpiration by phreatophytic vegetation that draws water from the water table. Pumping activities by humans can be considered an artificial form of groundwater discharge.

The key issues and research topics regarding groundwater discharge include:

- Discharge response times
- Groundwater/surface-water interaction and coupled responses under climate change
- Spatial variability of discharge related to landform and vegetation patterns
- Chemical and nutrient fluxes to surface-water bodies
- Land subsidence and landslides
- Quantifying submarine discharge in space and time

Many interdependent factors control water movement within and out of an aquifer system. The factors include the permeability of aquifer sediments; amount and location of pumping wells; the topography and its intersection with the water table – where springs emerge; and the discharge of groundwater along streams, lakes and wetlands where groundwater supported baseflow and underwater discharge is critically important to the sustainability of aquatic ecosystems and endangered species.

Groundwater and Soil-Water Storage

Groundwater comprises approximately 30% of the Earth's freshwater resources and approximately 96% of liquid freshwater (excluding icecaps and glaciers). These numbers alone are meaningless without an understanding of the full water balance and sustainability, including water quantity and quality issues (next section).

As defined by mass balance:
Change in groundwater storage = Recharge – Discharge
Such conservation of mass holds for a defined aquifer volume, but the complexity lies in estimating fluxes and states over time and space to arrive at reasonable values of the three components. This equation also does not take into account soil-water storage. Soil-water storage comprises a much smaller portion of the global water balance, but water-limited agriculture is a major problem in semi-arid to arid regions where sustainable agricultural systems depend on seasonal storage of infiltrated rainwater in the soil profile. Errors in estimating total recharge and discharge for an aquifer may be greater than the change in storage over a period of time. Thus, computing this "simple" mass balance is not so simple.

Aquifers vary based on their geological structure and climatic conditions. Aquifer types include ephemeral perched water, unconfined, (semi)confined with direct recharge connections, and non-renewable and hydraulically isolated aquifers. The key storage issues that must be addressed for each of these main aquifer types are:

- Temporal dynamics of storage fluctuations
- Storage level triggers for management decisions
- Links to soil and vadose zone water

Will climate change augment or deplete soil-water and groundwater storage? Can we assess the current state of subsurface waters sufficiently to detect the effects of climate change on underground waters? While the concepts seem elementary, assessment remains a great challenge, which is essential for deriving adaptation strategies.

GROUNDWATER Quality

The groundwater science and management community faces many important challenges because climate change may affect groundwater supplies directly and indirectly, in ways that have been largely unexplored (Dettinger and Earman, 2007). In particular, the potential effect of climate change on the quality of groundwater resources has received relatively little attention to date compared with the potential effects on the quantity of water resources. The quality of groundwater is a function of the chemical, physical, and biological characteristics of the resource. Thus, groundwater chemistry can be expected to respond to changes in climate and linked human activities because of the influences of recharge, discharge, and land use on groundwater systems. Groundwater quality is a value-specific concept because the quality of water is important only in relation to specific water-use standards. Traditionally, the protection and enhancement of groundwater quality has been a high-priority environmental concern because of the direct implications for drinking water health standards (Alley, 1993). However, if groundwater becomes too saline because of rising sea levels, for example, the quality of the groundwater resource may be a limiting factor for other uses of groundwater, such as agriculture, industry, or ecosystem needs. Therefore, sustainability of water supplies under future climate change and human impacts is dependent on both the quantity and quality of groundwater resources.

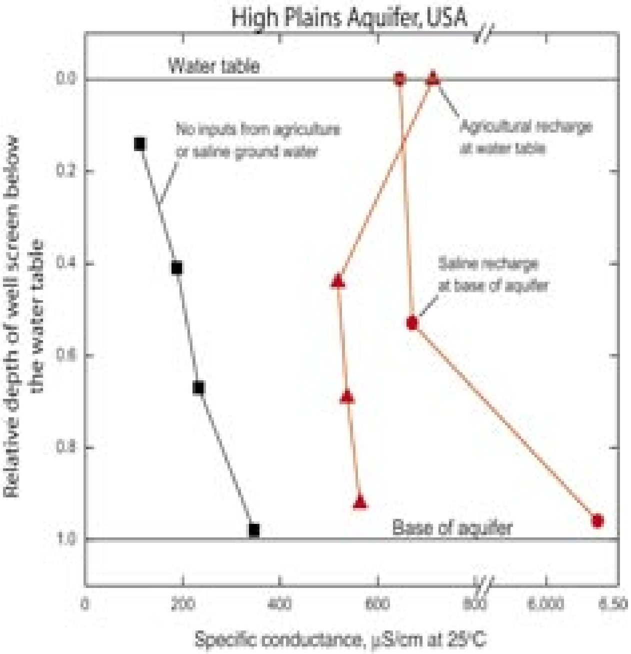

Figure 1. Specific conductance used as an indicator of agricultural and saline recharge to the High Plains aquifer. Irrigation pumping in parts of the High Plains aquifer induces upward flow of saline water from deeper aquifers. The magnitude and distribution of these recharge sources could change if land and water management practices are adjusted because of climate change.

The following are some important topics regarding groundwater quality that GRAPHIC will address to better understand the effects of linked human impacts and climate change on groundwater resources:

1. Because agricultural activities have the most ubiquitous effects on groundwater quality worldwide, and a changing climate may alter agricultural practices, research must address how changes to agricultural chemical inputs due to climate change may affect groundwater quality. For example, in agricultural areas, increasing air temperatures could lead to increased irrigation demand or possibly to a shift to more heat tolerant crops. Such changes could result in increased chemical loading to the water table or a change in the chemistry of agricultural recharge (Figure 1).
2. Subsurface thermal regimes have responded to land use and climate changes (Taniguchi et al., 2003). These changes in subsurface thermal regimes could alter chemical and physical processes in the soil and vadose zone, which could, in turn, affect groundwater quality. Examples include increased rates of weathering and mineralization of organic nitrogen that could increase chemical loading of dissolved solids and nitrate to the groundwater.
3. Climate change may alter spatiotemporal precipitation patterns, which, in turn, can mobilize previously immobile reservoirs of chloride (Figure 2) and other solutes that form naturally in the pore water of vadose zones in some semiarid and arid aquifers (Gurdak et al., 2007). Groundwater quality may be substantially deteriorated if these large chemical reservoirs reach the water table.
4. Global sea levels are forecasted to rise in response to climate change. Rising sea levels, land subsidence and over-abstraction may threaten the quality of groundwater in coastal aquifers and result in the loss of freshwater re-

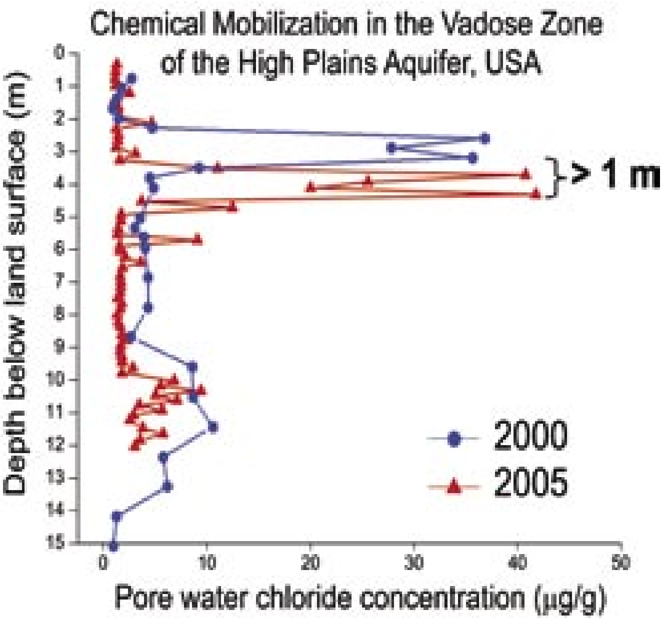

Figure 2. Downward mobilization of previously immobile pore water chloride reservoirs in the vadose zone of the High Plains aquifer, USA may occur in response to climate change (modified from Gurdak et al., 2007).

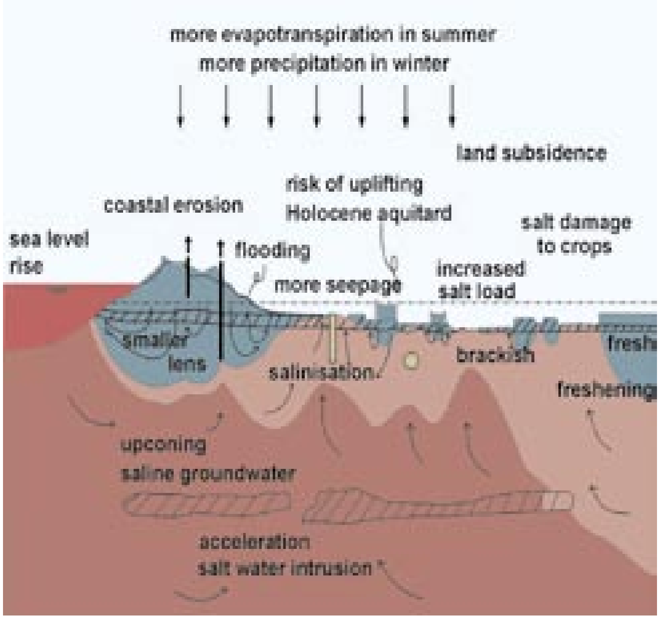

Figure 3. Coastal aquifers are susceptible to saltwater intrusion and may experience an acceleration of saltwater intrusion under future climate change and linked human abstraction (modified from Oude Essink, 1996).

sources. An acceleration of salt water intrusion into fresh groundwater resources (Figure 3) is to be expected (Oude Essink, 1996). Overpressures in the groundwater systems due to sea level rise may lead to the uplifting and cracking of the Holocene top layer. As the deeper groundwater is often brackish to saline in the coastal zone and nutrients are abundant, this may lead to a deterioration of the surface water quality. Due to increasing concentration of human settlements, agricultural development and economic activities, the shortage of fresh groundwater for domestic, agricultural, and industrial purposes becomes more striking in coastal low-lying deltaic areas like the Mississippi, Nile, Mekong, Ganges, Po and Rhine-Scheldt deltas.

5. Climate change and the global trend of increasing urbanization could increase flood vulnerability. Flooding in urban areas could increase loading of common urban contaminants like oil, solvents, and sewage to the water table.

GEOCHEMICAL INDICATORS OF CLIMATE and Linked Human Impacts on Groundwater

Potential geochemical indicators of climate and linked human impacts on groundwater are varied. Although some of these indicators are applicable to a broad range of hydrogeologic and land use settings, final selection of indicators should take into account local or regional characteristics and issues. Trend monitoring for some combination of these indicators in groundwater could provide timely warning of water-quality degradation that could inform the decision-making process related to water resource management.

1. Selected physical indicators
    a. Water temperature (controls on biological and abiotic reaction rates)
    b. Specific conductance (potential for continuous measurements)
2. Selected inorganic indicators
    a. Nitrate and ammonium
    b. Chloride
    c. Trace elements (would vary depending on site geology/issues)
3. Selected organic indicators
    a. Pesticides (would vary depending on land use/ crop type)
    b. Waste-water indicators (fecal bacteria and viruses, caffeine, hormones, pharmaceuticals)
    c. BTEX
    d. Common solvents (PCE, TCE, chloroform)
4. Other selected indicators (see proxy data below)
    a. H & O isotopes of water (source and timing of recharge)
    b. N & O isotopes of nitrate (sources and process information)
    c. Noble gases (recharge sources, temperatures, conditions)

PALEO-INDICATORS
of Environmental Changes

Past environmental changes, that were direct consequences of climate change, can be studied using proxies and old records of past hydrologic change. Several of the more common proxies in groundwater and selected sediments include:

Proxies in groundwater

The best environment for use of proxies is a confined aquifer with long known travel paths where several sampling points are found along the way. The following chemical and isotopic methods can be used:

- The isotopic ratio $\delta^{18}O/^{2}H$ of water indicates the source of water, amount of precipitation and evaporation, elevation and distance from the sea of recharge areas
- $\delta^{13}C$ of dissolved inorganic carbon identifies the type of vegetation (C-3 or C-4 plants) in recharge areas
- Dissolved Sr isotopes indicate sources of water and dust.
- Hydrochemical composition and ratios (e.g., a high SO_4 to carbonate ratio in water of the Negev and Sinai regions) may be used to estimate specific storm trajectories and paleo-geography.
- Some noble gases (e.g., ΔNe, Figure 4) provide in-

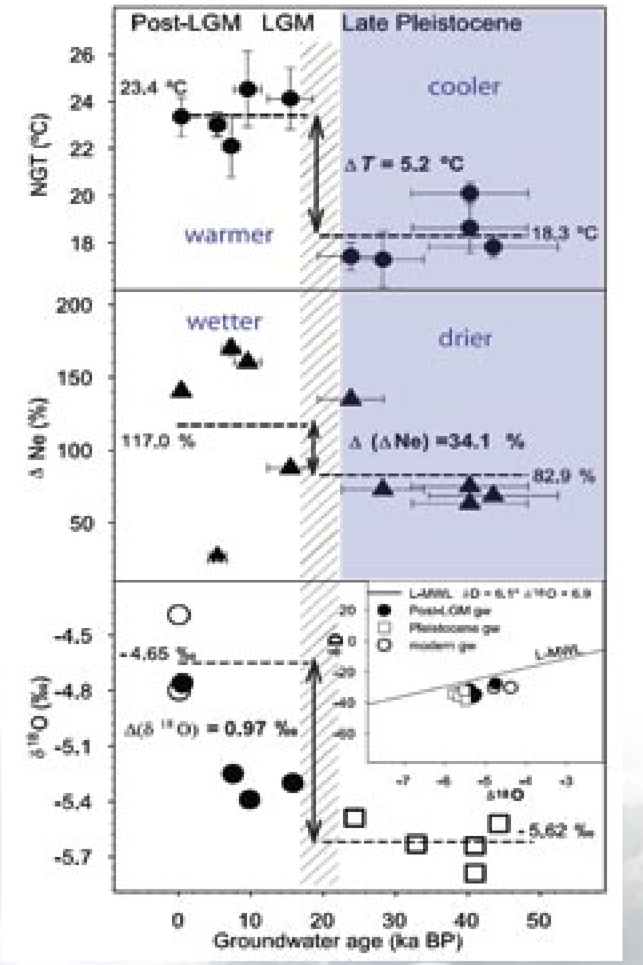

Figure 4. Paleo-climatic records according to the noble gases concentration and oxygen isotopes in groundwater from the Kalahari desert (after Kulongoski et al., 2004).

formation about the temperature of recharging water, sources of water, and possibly atmospheric moisture conditions (e.g. Beyerle *et al*., 2003). Noble gases (e.g. ^{3}He, ^{4}He) also serve as dating tools (see below). These and other age indicators (^{14}C, SF6, CFC, $^{3}H/^{3}He$) provide information on recharge rates and aquifer susceptibility to contamination.

Sedimentological Proxies

- Type of sediments – lake sediments indicate minimum water lake levels, while alluvial sediments indicate maximum levels, and shore sediment indicate exact levels. Relationships between lake levels and climate are not always clear. In general, higher lake levels imply higher recharge rates (runoff and/or groundwater), possibly due to higher precipitation and lower temperature.
- Isotopic signature in sediments – usually lake sediments, ocean bottom sediments and cave deposits such as stalagmites (Bar-Mattiews et al., 2003, Figure 5) are used. Isotopes in sediment ($\delta^{18}O$, $\delta^{13}C$ and Sr) and $\delta^{18}O/^{2}H$ in fluid inclusions reveal similar climate variations as noted above for groundwater. Trace elements can indicate sources and amounts of dust.

Biological Proxies

- These include pollens, types of vegetation, dendro-chronology and fossils.

Other Proxies

- Other sources of information for paleo-climate are paleosol (soil) profiles, archeological findings and historical records.

Response of hydrological systems to past climate changes

Hydrological records of past hydrological conditions could be used to forecast behavior of the same systems or others in the future.

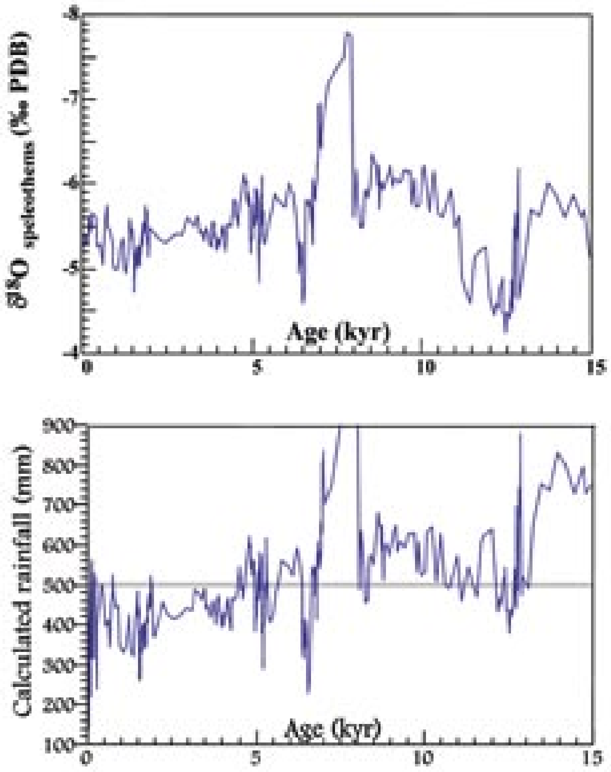

Figure 5. Paleo-climatic records according to the isotopic values in cave deposits in Israel (after Bar-Matthews et al., 2003). The lower graph of the calculated rainfall is based on the isotopic record of $\delta^{18}O$.

- Seawater intrusion due to past sea level rise; the hydrogeological configuration (e.g., connectivity of the different sub-aquifers to the sea) determines the rate of seawater intrusion into the aquifer in the past (e.g., Yechieli et al., 2001). Such information may inform the future aquifer responses to similar shifts in sea level.
- Recharge rates in the past can be calculated, provided accurate groundwater dating is conducted (McMahon et al., 2004, 2007).
- In some cases, a change in spatial precipitation may change the direction of groundwater flow.
- Studying the effects of extreme weather (such as El Niño phenomena) on groundwater systems will improve understanding of future responses to climate changes.
- Other environmental changes may include variations in wind direction and intensity, which may affect the quality of groundwater in specific areas.

Age Dating

Groundwater ages are estimated with several ra-

dioactive isotopes having different decay rates. ^{14}C, whose half life is 5700 years, is the most common tool for age dating in the range of approximately 100-30,000 years. This method is a relatively simple dating tool for sediment and wood. For groundwater dating, however, the technique is much more complicated because it requires several corrections to compensate for water-rock interactions. Other isotopes (e.g. ^{4}He, Ar, Kr), with different decay rates, can be used for dating at different time scales. Age tracers for short time processes (<50 years) include SF6, CFC, $^{3}H/^{3}He$.

GEOPHYSICAL Methods

There are several geophysical methods that can be used to evaluate the climate change/variations and related human activities on groundwater. Gravity, subsurface temperature, and electrical/electromagnetic methods are briefly described.

Gravity

Changes in groundwater storage can be detected using gravity measurements made *in situ* (gravity profiling). Pool and Eychaner (1995) undertook a temporal gravity survey to measure changes in aquifer storage and documented water-level variations in an aquifer and associated gravity variations. Changes in storage reflect variations in the volume of water stored in the subsurface. For an unconfined aquifer, storage change occurs primarily within the interval of water-level change. The change in density associated with the increasing or decreasing volume of stored water with time can be measured using relative gravity. Measured gravity changes of about 13 microgal represented storage changes of about 0.30 metres of water. Although this study was undertaken over a large area with station spacing on the order of kilometres, the details of the survey demonstrated that gravity meters are now sufficiently precise to measure variations in the gravitational attraction which are on the order of a few tens of microgals. As such, smaller study areas may be suitable for use of gravimetric methods. Relative gravity meters and absolute gravity meters are available to measure the gravity *in situ*.

Remote (satellite-based) gravimetry has also been employed to detect temporal changes in groundwater storage over large regions. This remote sensing technology is discussed in greater detail in the Remote Sensing section.

Subsurface Temperature

Temperature changes are fundamental to climate change. Shifts in surface temperature associated with shifts in air temperature can propagate into the subsurface, and can be detected by measuring ground temperatures either in the shallow subsurface or to

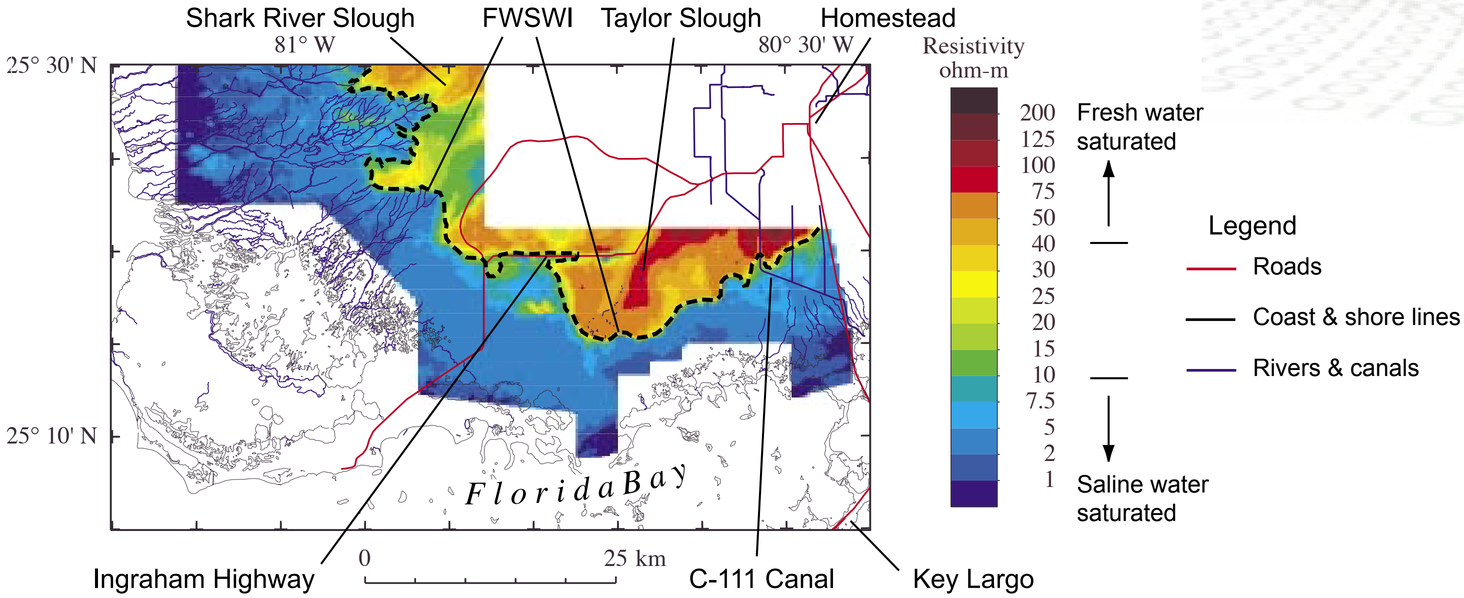

Figure 6. Groundwater salinity can be determined by mapping changes in electrical resistivity of subsurface rocks. Decreases in resistivity (measured in ohm-meters) correspond to the incursion of seawater beneath the Everglades. From Fitterman (1996).

greater depths (up to several hundred metres). Temperature-depth profiles collected in boreholes can reveal the surface temperature changes due to climate change and land cover change during a few to several hundreds years. Such borehole temperature profiles can be used to reconstruct past climate change and land cover change, because the history of the surface temperature is preserved in subsurface. For example, Lewis and Wang (1998), identified ground temperature anomalies and associated these with deforestation in Canada. Taniguchi et al. (1999) also examined these effects in Western Australia. The human impacts on subsurface temperatures, such as the «heat island effect», can also be detected from subsurface temperature (e.g., Taniguchi et al., 2007, Ferguson et al, 2007). Effects of global warming on subsurface temperature affect the ecology and water quality.

Electrical / Electromagnetic Methods

Saline water in aquifers can be detected using electrical or electromagnetic methods used in surface profiling and in downhole logging. Saline water can occur, for example, in coastal regions in association with seawater incursion, in arid areas due to salination from over-irrigation, as a consequence of road salt application in cold climate regions, near contaminated sites (such as landfills), and as a result of mixing of connate water (water that is entrapped in the interstices of sedimentary or igneous rocks at the time of deposition) with freshwater.

The detection of saltwater-freshwater contacts (e.g., a freshwater-saltwater mixing zone in a coastal area or a plume at a contaminated site) can be accomplished using resistivity methods, because the salinity of the groundwater increases the electrical conductivity of the pore fluids; conductivity is the inverse of resistivity. Figure 6 shows an electrical resistivity map for southern Florida near the Everglades. The effects of sea level rise on the groundwater, and saltwater intrusion due to pumping can similarly be detected by resistivity measurements. The location of the submarine groundwater discharge, which is reverse process of saltwater intrusion, can be aided by electrical methods.

Groundwater flow systems (such as recharge and discharge areas) can be detected by spontaneous potential (SP) measurements. The SP is relatively higher in the groundwater discharge area, and relatively lower in the recharge area. The SP shows the accumulated signal of

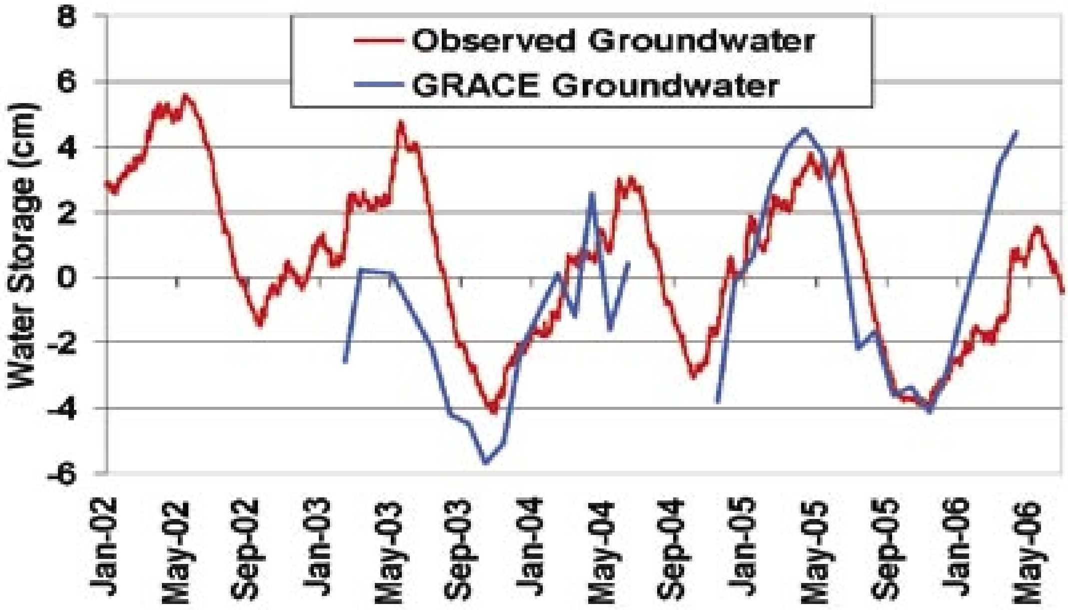

Figure 7. Time series of groundwater storage anomalies (deviations from the mean), as equivalent heights of water, averaged over the Mississippi River basin. The blue line depicts monthly groundwater storage anomalies estimated as the difference between GRACE-derived total terrestrial water storage anomalies and numerically modeled soil moisture and snow water storage anomalies. The red line is based on water level observations from 58 wells. Details are provided by Rodell et al. (2007).

the system at the concerning location, therefore the SP represents both regional and local groundwater flow systems which may be altered by climate change.

REMOTE Sensing

While hydrologists often consider in-situ measurements to be the most reliable form of observation, there are issues when it comes to regional to global scale monitoring. Installing and maintaining measurement systems, such as piezometers, can be expensive and labor intensive. Many regions are inaccessible due to environmental factors or political boundaries. Moreover, when an observation network does exist, the data records may not be digitized, centralized, and made readily available. There are also issues of data quality, and the need for metadata in order to properly interpret the observations. Finally, when the observed quantity such as groundwater exhibits significant spatial variability, an in situ measurement may not be representative of the surrounding region.

Satellite remote sensing has its own set of issues, but it offers the advantages of global coverage, availability of data, metadata, error statistics, and the ability to provide meaningful spatial averages. Several remote sensing technologies can contribute to groundwater monitoring activities. Landsat, the Moderate-resolution Imaging Spectroradiometer (MODIS), the Advanced Very High Resolution Radiometer (AVHRR), and certain other instruments can resolve the location and type of vegetation, which can be used to infer a shallow water table. Landsat imagery can also provide geological clues where not obscured by vegetation. Altimetry measurements and SAR over time can show where subsidence is occurring, which is often an indicator of groundwater depletion. Microwave radar and radiometry measurements can be used to estimate snow and surface soil water, which further constrain groundwater assessments. But perhaps the most valuable remote sensing technology for groundwater investigations is high-precision satellite gravimetry, as enabled by the NASA/German Gravity Recovery and Climate Experiment (GRACE).

GRACE, the first twin satellite gravimetry mission, is now being used to generate time series of total terrestrial water variations (Tapley et al., 2004), which can be used to assess groundwater storage changes.

Wahr et al. (1998) presented the first technique for deriving terrestrial water storage variations from global gravity field solutions delivered by GRACE. Rodell and Famiglietti (2002) showed in a pre-GRACE-launch study that interannual variations and trends in the High Plains aquifer water storage would be detectable by GRACE, pointing to new opportunities for groundwater remote sensing. Rodell et al. (2007) developed time series of groundwater storage variations averaged over the Mississippi River basin and its four major sub-basins using *in situ* data, and used these to verify GRACE-based estimates in which soil moisture and snow water equivalent fields output from a sophisticated land surface model were used to isolate groundwater from the GRACE terrestrial water storage data (Figure 7). At the smaller spatial scale of Illinois (145,000 km^2), Swenson et al. (2006) showed that GRACE captures the signal of changes in total water storage very well, while Yeh et al. (2006) showed that GRACE-based estimates of groundwater storage variations compared well with borehole observations on seasonal timescales. Swenson et al. (2008) used Oklahoma Mesonet data and local groundwater level observations to further refine methods to remove the soil moisture signal from the total water storage change signal recorded by GRACE. Strassberg et al. (2007) followed up on the work of Rodell and Famiglietti (2002) by presenting a post-launch assessment of GRACE capabilities to monitor groundwater storage variations within the High Plans aquifer.

GRACE has not yet been fully embraced by the hydrological community, owing largely to its low spatial and temporal resolutions and lack of information on the vertical distribution of observed water storage changes. GRACE can measure variations in equivalent height of water over regions about 200,000 km^2 or larger, with uncertainties on the order of a few centimeters (Wahr et al., 2006). Accuracy degrades rapidly as the spatial resolution increases. While this is sufficient for many large scale hydrological investigations, most water resources, meteorological, agricultural, and natural hazards applications require higher resolution data. Furthermore, GRACE launched in 2002 with an expected lifetime of nine years, while climate variability assessments require a longer, nearly continuous record. This emphasizes the importance of developing a follow-on gravimetry mission with advanced technology to increase spatial resolution while decreasing uncertainty. The monthly temporal resolution of GRACE is an issue for many applications, but it should be sufficient for regional groundwater assessments.

To address these issues, Zaitchik et al. (2008) used an advanced data assimilation approach to incorporate GRACE data into a land surface model, and hence merge them with other datasets and our knowledge of physical processes as represented in the model. In simulations over the Mississippi River basin, the GRACE-assimilation groundwater storage output fit observations better than output from the open loop (Figure 8), and they were of much higher spatial and

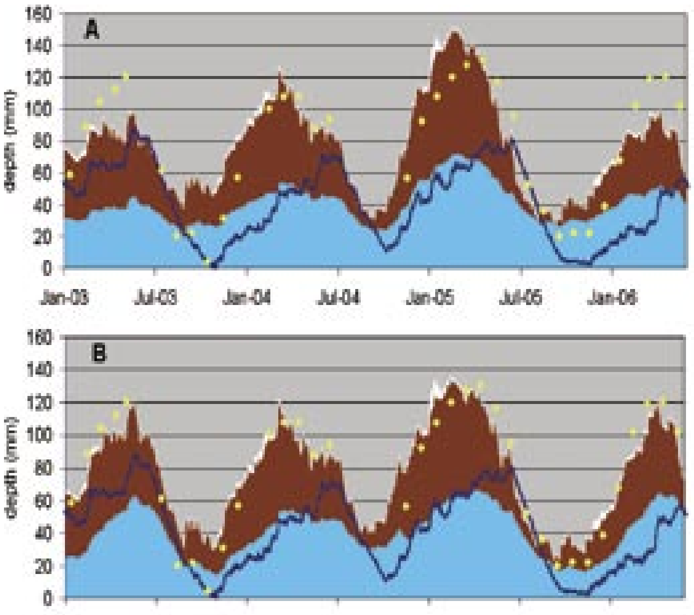

Figure 8. Groundwater, soil moisture, and snow water equivalent averaged over the Mississippi river basin from (A) open loop CLSM and (B) GRACE-DAS. Also shown are daily, observation-based groundwater and monthly GRACE-derived TWS anomalies. GRACE and modeled TWS were adjusted to a common mean, as were observed and modeled groundwater. The correlation coefficient between simulated and observed groundwater improved from 0.59 (open loop) to 0.69 (GRACE data assimilation), while the root mean square error decreased from 2.4 cm to 1.9.

temporal resolution than GRACE alone. This technique may be the key to maximizing the value of GRACE data for groundwater resources studies such as those fostered by GRAPHIC.

INFORMATION Systems

Information systems are defined by their content, the purpose (i.e. users) and the available technology (assuming that resources to build the system are provided). These three basic criteria are used below to depict a future GRAPHIC Information System.

A common GRAPHIC portal will be the main interface to the general public, policymakers and potential project contributors. It will contain a brief description of the GRAPHIC programme and a dynamic track of GRAPHIC activities. Many case studies and other GRAPHIC-related activities will have their own websites. The information harvesting technology will be used to ensure a constant flow of news from these websites to the GRAPHIC portal.

The portal will provide the links to various websites, databases, and knowledge banks comprising the GRAPHIC information system. Most of the databases and knowledge banks will be accessible only by specialists, although some could have additional interfaces for visitors. The GRAPHIC metadata database will be accessible to everyone. One part of the database will contain information about GRAPHIC people, organisations, projects, reports and the like (for example see the Meta Info Module at www.igrac.nl). The other part of the meta-database will be dedicated to spatial (geographically distributed) data. For this purpose an open source geospatial catalogue will be used (for example see http://geonetwork-opensource.org)

The diversity of GRAPHIC subjects and methods will certainly reflect the content of related databases and knowledge bases. Most of the GRAPHIC activities are interdisciplinary and international, carried out at the regional scale. Although the vast majority of current databases are neither interdisciplinary nor international, they will be a part of the GRAPHIC information system (even as a set of loose components). New technologies such as web map and feature services will be used to connect data from various sources into dedicated, distributed GRAPHIC service network.

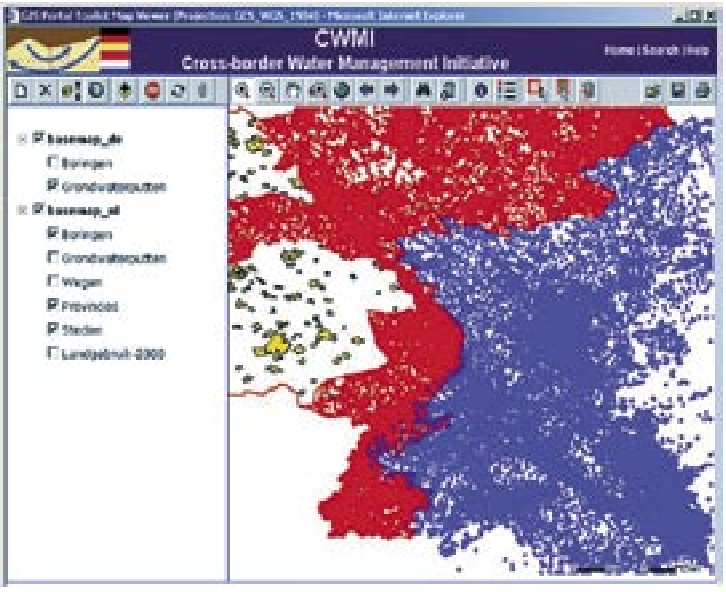

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Figure 9. Harmonised groundwater transboundary information available via a common portal (an example).

Joint visualization and processing of data residing in different databases often requires data harmonization. Despite advances made in international standards, this is a cumbersome process. For example, Figure 9 shows locations in the border region of Germany and the Netherlands containing harmonized and semantically translated borehole information (Kukuric and Belien, 2006).

Some GRAPHIC activities will require generation of specific data sets. Aggregated groundwater monitoring data for the purpose of regional and global studies is a good example of those sets (Figure 10). In such cases, development of a new dedicated application could be considered. GRAPHIC associates all over the world need to retain the full control over data and

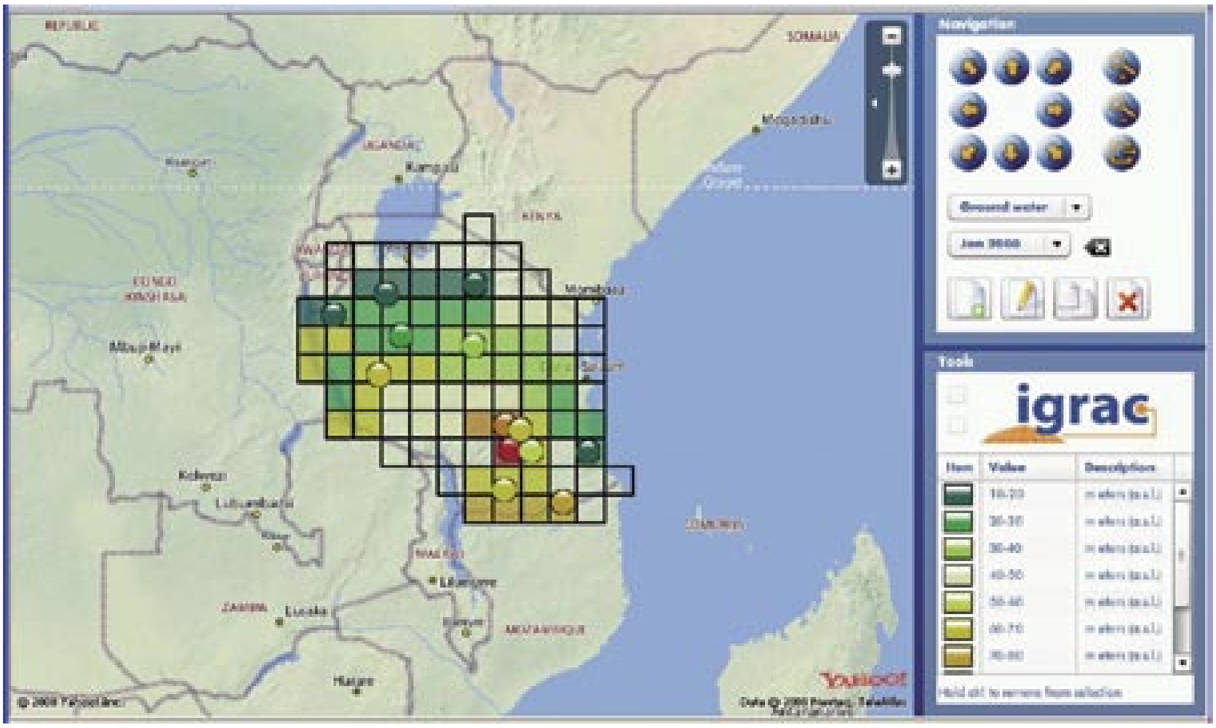


Figure 10. Aggregated groundwater monitoring data in the GGMN web-application.

information they provide and store in these applications. This feature is crucial to ensure participation and commitment of organisations and experts, especially in developing countries (Kukuric and Vermooten, 2007).

Both dedicated and independent applications will make up the GRAPHIC information system, accessible via the GRAPHIC portal. The portal will also have a collaborative environment in order to facilitate the GRAPHIC People Network. The People Network is crucial for development and use of the GRAPHIC Information System.

SIMULATION and Modeling

Modeling is an invaluable tool in hydrology. Mathematical models, encompassing numerical, analytical, statistical, and empirical approaches, enable one to test and thereby improve our understanding (i.e., conceptual model) of terrestrial hydrology for both individual and complex systems that often involve multiple, coupled (e.g., atmosphere-surface) processes. As such, modeling is an ideal tool for integrated water resource management and policy making.

Whereas our understanding of hydrological systems is developed from testing and integrating historical observations (i.e., *hindcasting*), management requires forecasting. The integration of science into policy is essential since management applications critically depend upon an effective representation of hydrological systems. However, evidence-based water management and policy methods require dedicated monitoring infrastructure to enable evaluations of the impacts of development and climate change. Monitoring networks generate critical observations to validate modeling efforts. 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, and the integration of socio-economic factors.

Modeling Software

A large suite of modeling software packages is available for GRAPHIC studies. In addition to groundwater models, which form the basis for groundwater assessment, other models include coupled land surface-atmospheric models, biogeochemical models, hydrologic (surface-water models), and coupled surface water-groundwater models, to name a few. Distributed groundwater models simulate flow in the subsurface, both in saturated and unsaturated conditions, and for porous and fractured media. Specialized software is used to simulate chemical processes, such as solute transport and reactions, heat transport, and density-dependent flow (e.g., for coastal regions). Lumped models use spatially distributed climate forcing data that is aggregated over the entire basin, while semi-distributed models aggregate data over sub-basins. The advantages and disadvantages of these various approaches require further investigation in respect of climate change modeling.

Differences in how the physical and chemical processes are represented in the model, along with the degree of complexity in subsurface and surface conditions, partially control the scale at which the models can be realistically applied and the type and scale of data required for driving or validating the models. Presently, process-based continental or global-scale hydrological models are rare, if not absent. Thus, most studies develop smaller scale models that are better constrained by available data and, thus, more easily calibrated. However, challenges remain for coupling predictions from global climate (or circulation) models (GCM) with hydrological models (Xu, 1999).

Coupling GCM Predictions with Hydrologic Models: Downscaling

Due to the coarse resolution of global climate models (GCM), climate data often must first be down-

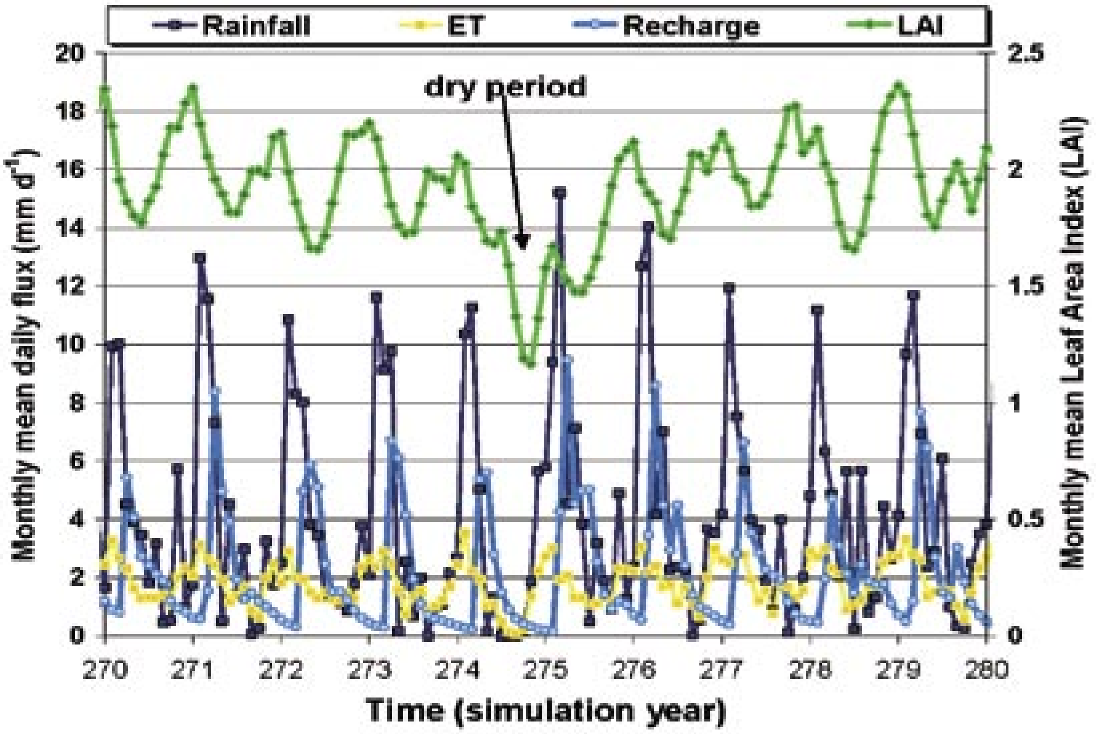


Figure 11. Example time series of simulated water fluxes (rainfall, evapotranspiration (ET), and recharge) and plant leaf area index (LAI) over a decade that includes an extended dry period (from Green et al., 2007a).

scaled to obtain climate data that are representative of smaller model regions. Two main downscaling approaches are commonly used:

- Dynamical downscaling (nesting of regional climate models in a GCM) and
- Statistical downscaling (based on historical records and GCM statistical characteristics)

While downscaling methods continue to improve, substantial challenges exist for generating representative climate data (particularly precipitation time series) for small regions. Consequently, different approaches have been developed and tested for overcoming downscaling problems (e.g., Vacarro et al., 1992; Bates et al., 1994; Bouraoui et al., 1999). One approach is to use a stochastic weather generator to generate a representative weather series and then apply shifts to that time series based on those predicted by either the downscaled or raw GCM data (e.g., Scibek and Allen, 2006). Green et al. (2007a) generated daily weather variables and simulated rainfall infiltration, variably saturated flow and evapotranspiration with dynamic plant growth and senescence values for various soil-vegetation environments. Figure 11 shows one decade of dynamic model output as a sample used to assess potential climate change effects on groundwater recharge from diffuse deep drainage.

Model coupling, either directly where one model is physically coupled to another one, or indirectly, whereby output from one is used as input to another, is increasingly used to assess land-use and climate-change effects. Groundwater systems are inextricably linked to surface hydrologic systems, which encompass both surface water bodies and the soil zone. Thus, the responses of these various systems will be spatially and dynamically impacted by changes in climate and land-use change. Consideration of the effects of climate change on surface hydrology, land use/land cover, etc., should be taken into account. For example, Scibek et al. (2007) considered effects to both streamflow and groundwater flow by modeling changes to stream discharge and groundwater recharge under future climate conditions and using these as input to a groundwater flow model to investigate climate change impacts on surface water-groundwater interaction. Figure 12 shows the temporal changes in groundwater level relative to current conditions for two future time periods. A shift in peak river flow by approximately one month earlier and a lower and longer baseflow period under future climate conditions lead to widespread shifts in the timing of the groundwater level response.

In addition, climate change is anticipated to result in more frequent extreme events (e.g., flooding, drought). Such extreme weather can lead to

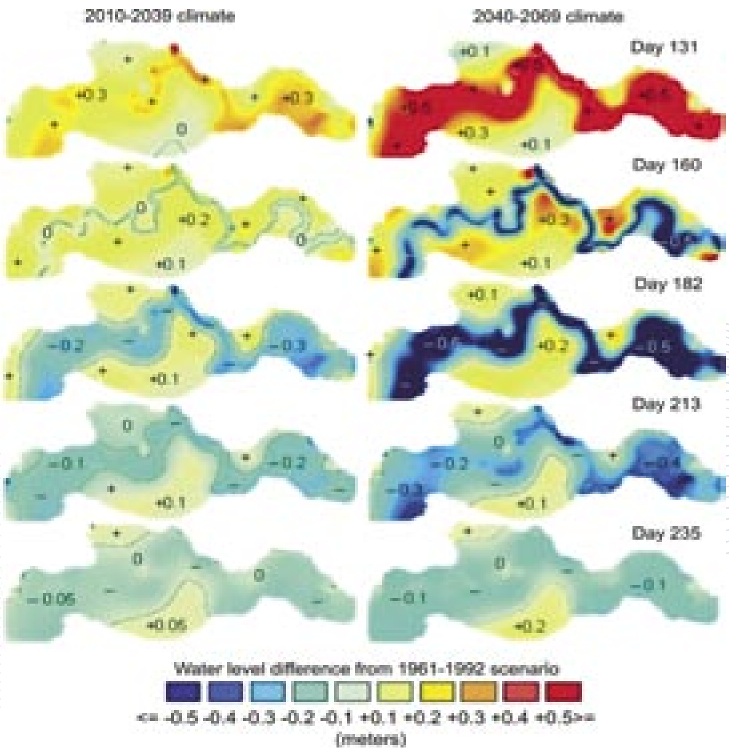


Figure 12. Water level differences (measured as head in layer 2 of the unconfined aquifer) between a) future (2010-2039) and present climate, and b) future (2040-2069) and present climate under pumping conditions. Maps by time step in days 131 to 235. Positive contours are shown at 0.1 m interval. The zero contour is a dashed line. Negative contours are not shown. Darkest blue colors indicate values < -0.5 m (along rivers only). At day 101 (not shown), difference map has values within 0.1 m of zero (from Scibek et al., 2007)

uncertain responses of groundwater systems. For example, while global scale predictions may suggest an increase in precipitation for a given region, if this precipitation occurs at a higher rate and over a shorter period of time, there may be less recharge to the groundwater system. Unfortunately, current recharge models are driven by daily weather series, which may not adequately capture the variability expected on shorter time scales. More research is needed to better understand and model the impact of extreme events on groundwater systems.

Uncertainty and Model Selection

At the root of all climate change assessments is the problem of model uncertainty. This uncertainty ranges from that of the GCMs themselves through to the physically-based process model. Uncertainty in GCMs arises from climate model parameter uncertainty and climate model structural uncertainty. Climate model parameter uncertainty can be resolved through multiple runs (e.g., QUMP). Structural uncertainty can be addressed by using output from a range of climate models (HadCM3, ECHAM4, CGCM2, CSIRO2 and PCM) under an ensemble approach (e.g., ClimGen). As well, 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, in particular, is poorly simulated because events such as thunderstorms occur at smaller spatial scale than the grid size of the GCM. Evapotranspiration is also not well represented in GCMs.

Selecting the appropriate climate model (or series of climate models) for undertaking climate change impacts assessments on groundwater can be an overwhelming challenge. Not only are there different emission scenarios (experiments) that provide alternative emissions trajectories spanning the years 1990 through 2100 for greenhouse-related gases (see Special Report on Emission Scenarios (SRES)) (Leggett et al., 1992), but there are also a wide range of climate models. These models are continually being updated and new experiments run.

In respect of physically-based process models that are needed to link climate to groundwater, the level of complexity of modeling is increasing. As a consequence, so are the data requirements needed to calibrate and validate the models. Often, there are insufficient monitoring data and a lack of measurements for the wide range of input parameters needed to run these models. This lack of information leads to high model uncertainty, which can translate into very uncertain representations of both the present day system and how that system may respond to climate change.

An overall modeling approach to overcome issues of uncertainty includes:

- Using 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.

- Addressing uncertainty:
  - estimate parameter uncertainty,
  - evaluate model sensitivity to parameters, and/or
  - estimate confidence intervals of model predictions/results.
  - perform scenario comparisons with different GCMs and/or
  - run perturbation experiments with transient GCM results.

- Identifying 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.

– Applying results to historical and paleo-data and records:
  - use hindcasting to test models and/or
  - extrapolate trends to aid forecasting.

MANAGEMENT and Policy

Groundwater is an important natural resource with more than 1.5 billion people worldwide depending on groundwater for their daily supply (Kemper 2004). Management practices that actively influence groundwater to a significant degree include groundwater pumping for irrigated agriculture, pumping for industrial and municipal supplies, supplementing streamflow during drought periods, dewatering areas for development, artificial groundwater recharge, and irrigation with treated water or water of variable quality.

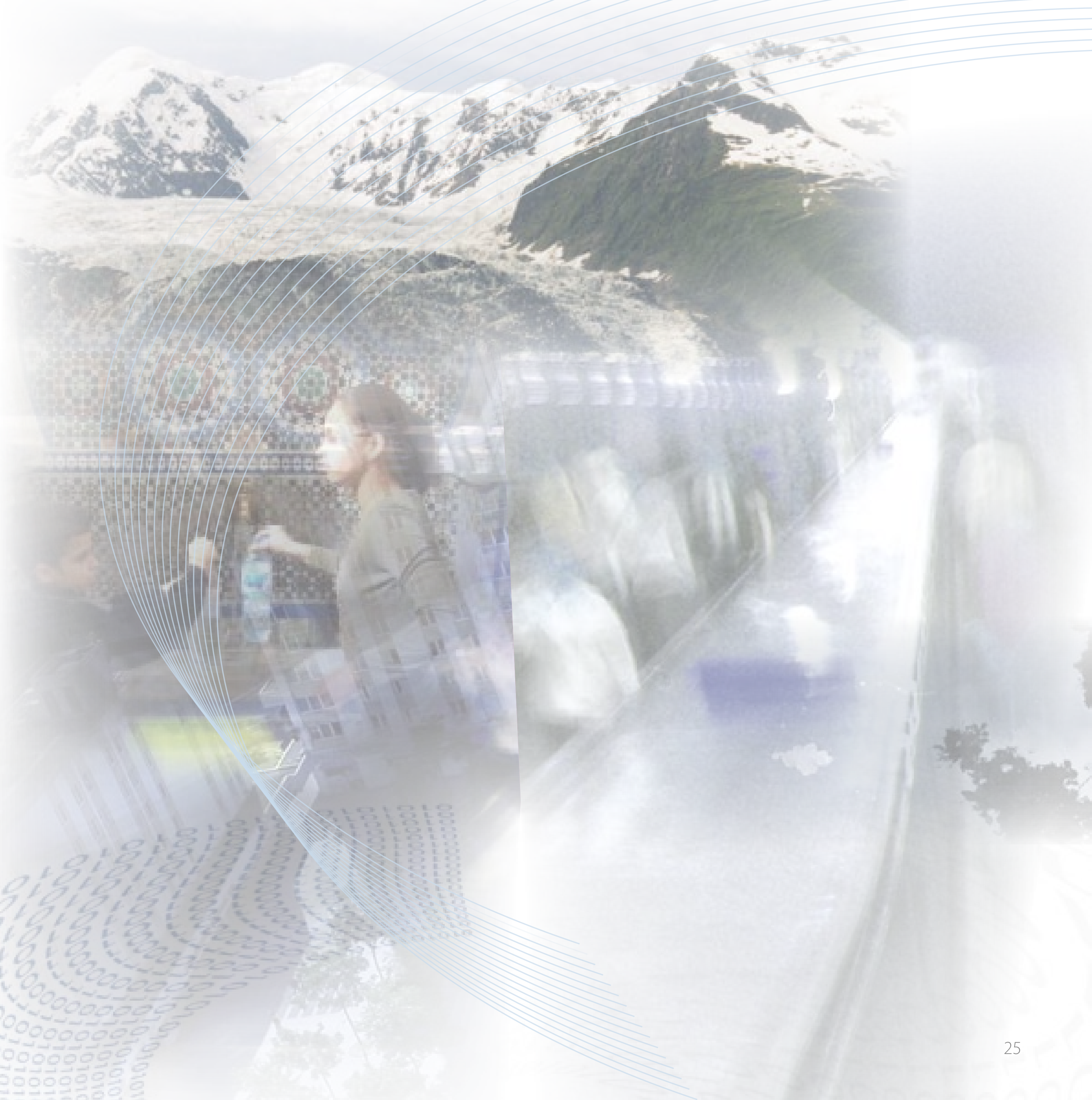
As a result of the growth in the global population, the demand for clean water is rising and the pressures on surface water and groundwater resources are increasing, particularly in semi-arid and arid regions of the world where useable water supplies are scarce. Climate change will exacerbate these pressures by affecting the frequency and rate of aquifer recharge as a function of changes in land use, soil and rainfall characteristics. For example, in rain-shadow areas adjacent to high mountain belts, the decrease of snow cover and glacier retreat will fundamentally alter surface water runoff and the recharge of alluvial aquifers that are often important for irrigated agriculture. Indirect effects of climate change include the potential expansion of bio-fuel crops which may cause further reductions in recharge and an increased risk of groundwater pollution from increased application of agricultural chemicals.

Groundwater has been poorly managed in the past due to low investment in scientific investigations at a time when intensive use of groundwater has placed groundwater resources under stress. To better manage groundwater, the vulnerability of groundwater resources must be assessed both now and in the context of climate change. Factors to be considered in groundwater vulnerability and risk assessments include drought, groundwater abstraction, chemical loading related to land use, and the local hydrogeological setting.. Furthermore, the natural functions of groundwater for river runoff and ecosystems must be investigated and safeguarded (Struckmeier et al. 2004). Current management practices are guided by policies at local, national and international levels, and policy decisions are usually made with long-term goals for economic or environmental improvement and sustainability.

The systematic analysis of stakeholder and groundwater-related policies is an important part of GRAPHIC.

Figure 13. Interconnections between the origin, characteristics and uses of groundwater resources and the threats to and opportunities for change presented by the good governance of groundwater.

An overall framework for studying management and policy interactions leading to good groundwater governance is given in Figure 13. Driving forces and development goals set the policy framework, while consultation with stakeholders leads to policy options that should reduce the effects of development in relation to the goals set. In this framework, sustainable, integrated water resources management must be informed by the collection and interpretation of groundwater data. This can be a challenge in areas with limited resources, and GRAPHIC draws attention to the need for increased institutional capacity that expands the knowledge base of existing resources so that innovative and flexible measures can be implemented to prevent further deterioration of groundwater resources.



CASE STUDIES and Regional Monitoring

One of the aims of GRAPHIC is the establishment of case studies in different countries and regions of the world that incorporate the philosophy and approach of GRAPHIC – to analyze groundwater sustainability under the impacts of human activities and climate change, identifying suitable measures of adaptation. Findings from those case studies will likely provide insights and comparisons for similar countries/regions, creating a global network of groundwater projects.

In keeping with the primary objectives of the GRAPHIC Project – understanding the impacts of human activities and climatic changes on groundwater availability and sustainability – encouraging and coordinating consistent regional monitoring efforts provides a means to achieve GRAPHIC objectives while broadening the impact and applicability of the GRAPHIC program.

Regional monitoring efforts within GRAPHIC case studies in different physiographic, climatic, and water use/management settings around the world will provide an opportunity to compare data among areas, and evaluate how controlling factors influence local water quantity and quality. A GRAPHIC program to develop and encourage application of a critical list of relatively low-cost and consistent sampling and analytical methods in all case-study areas would create a baseline and comparable dataset that would greatly enhance interregional comparisons.

Regional monitoring efforts would need to be carefully designed so that they are not cost-prohibitive, while still generating the critical data needed to accomplish primary GRAPHIC objectives. Monitoring would need to be designed around aquifers rather than political boundaries. Multiple nested studies that address both sub-regional variations and primary controlling processes enable up- and downscaling of interpretations.

Identifying a baseline set of critical data needed to participate in the GRAPHIC program does not preclude any case-study area from collecting additional data that might improve understanding or interpretations. Indeed, having this type of additional data collection might uncover important findings that could have high transfer value to other GRAPHIC study areas. Similarly, not currently having the critical baseline data does not eliminate any study area from becoming part of the GRAPHIC program. Part of the effort of the GRAPHIC leadership would be to assist selected case studies in securing funding and expertise to bring their regional monitoring effort up to baseline levels of data collection and quality.

Groundwater geochemistry can be a critical part of the baseline data collection. Although information on the basic elements of the local groundwater budget (precipitation, evapotranspiration, water-table fluctuation, water use) are necessary to understand current water availability and stresses on the aquifer system, chemical information can provide much insight to the past dynamics of the aquifer (paleohydrology), and can illustrate how the system has changed or responded to past fluctuations in human and climatic influences. This knowledge of historic responses to change can be the key to predicting how future changes could influence aquifer sustainability.

GRAPHIC promotes and creates linkages between case studies to achieve the objectives of the project. The description of each case study should include its geographic location, climatic conditions (humid, arid, semiarid, etc.), hydrogeology and soils, land use and land cover, methodology, subjects (issues covered), management systems, and knowledge gaps. The criterion for the selection of the case studies includes some of the following considerations:

1. Is the proposed case study applicable and relevant to the objectives and goals of GRAPHIC?
2. Are the methods, data, and approaches from the case study available and comparable to other GRAPHIC case studies?
3. Are lessons learned and findings from the case study transferable to GRAPHIC?
4. Are recommendations and findings from other case studies of GRAPHIC transferable to the proposed case study?

The existing GRAPHIC projects, presented at the last two expert committee meetings (Japan & USA) could be considered the initial case studies for GRAPHIC. Considering that they cover a wide range of conditions, they could serve as the starting point for future cases.

Two Regional Coordination Units (RCUs) have already been established within GRAPHIC (Australasia and Latin American/Caribbean (LAC)), and the establishment of new GRAPHIC RCUs for the other regions of the world (Asia, Africa, Europe, North America, Middle-East) will substantially increase the potential for the development of new inter-regional comparative studies. This will be facilitated by UNESCO-IHP, Paris, as a coordination office, with support of UNESCO's regional hydrologists and the countries' IHP National Committees.. The guidelines for inter-comparative studies and the establishment of new GRAPHIC RCUs are underway. The GRAPHIC team encourages broad international participation. Interested parties are invited to visit the GRAPHIC website (www.unesco.org/water/ihp/graphic) and contact UNESCO for information regarding upcoming meetings and activities.

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