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white paper

Greater water security with groundwater

Groundwater mapping and sustainable groundwater management

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Version 1.0

About this white paper
This white paper is developed by the Rethink Water network in Denmark. The network consists of more than 50 technology and consulting companies, water utilities, water organisations and public authorities. It was established to support our partners internationally in developing the highest quality water solutions.

Frontpage picture
Groundwater survey in Colorado, USA

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Executive summary

We must manage groundwater resources in order to be able to meet the needs of future generations. Good decision-making tools are key in taking the right decisions to protect our groundwater

IDA AUKEN
Minister for the Environment
DENMARK

Providing enough fresh water for a growing population and for increasing industrial production is a critical issue in many countries. Climate change is affecting global rainfall patterns and water distribution. Since there is approximately 100 times more groundwater on Earth than surface water, it makes sense to exploit groundwater as a source of water. In many parts of the world, especially in arid or seasonally dry regions, groundwater can provide a stable and sustainable source of high quality water.

Failed investments

There is a history of many failed investments in dams or groundwater well fields. The most important cause has been the difficulty in assessing project feasibility and sustainability due to inadequate knowledge, data and tools. Sustainable exploitation requires that the main recharge areas are protected to ensure that aquifer replenishment comes from clean water.

Efficient methods and tools exist

Because of a historical shortage of surface water, Denmark has always relied heavily on groundwater. Danish companies are now among the world's leading experts in exploiting this resource. Groundwater can be located very efficiently, and groundwater management made sustainable with modelling and monitoring systems. Today there is great demand around the world for this expertise and the associated technologies, which include surveying techniques, integrated water resource modelling and decision-making systems.

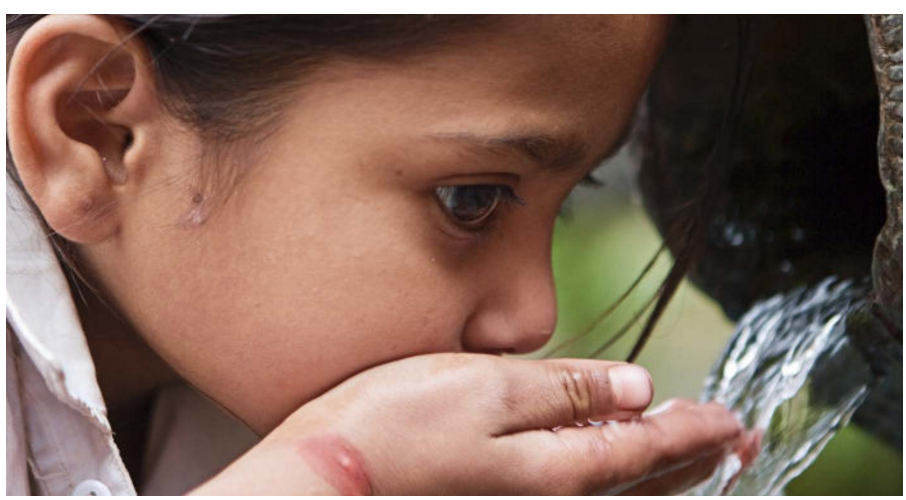
Multiple benefits from groundwater use

Groundwater is less exposed to pollution than surface water, the water quality is higher and it requires less treatment. Moreover, water utilities can benefit from planning long term. They can avoid major investment linked to surface water infrastructure and enjoy a higher level of water security. Groundwater mapping and sustainable groundwater management ensure improved knowledge of the availability of water resources, a critical factor in attracting new companies and industry. By investing in groundwater usage local business partners will develop their competence through knowledge transfer from international experts. This creates a strong platform for expanding the local water business to other regions.

Management must be integrated

It is important to understand that it only takes a few contaminants and/or an unbalanced approach to utilisation for groundwater resources to be damaged forever. Some of the critical issues or barriers can be addressed or resolved by accurate groundwater mapping and sustainable groundwater management, or with integrated water resources management. Groundwater is an important part of the hydrological cycle and should be managed in an integrated way with other water resources.

National pilot study, India *In 2013, a pilot study in India will map groundwater aquifers in six different regions representing the complexity of Indian hydrogeology. The study is funded by the World Bank and the Indian Ministry of Water Resources. The goal is to develop a cost-effective approach to the exploration and management of the country's groundwater resources. If the pilot is successful, the project will be extended across India. Danish scientists and companies will be supporting their Indian colleagues in the collection, processing and interpretation of vast amounts of data and in building the tools for the sustainable management of India's groundwater resources. (Courtesy: Aarhus University, HydroGeophysics Group, and SkyTEM Surveys).*



1. The right knowledge makes groundwater last forever

Groundwater resources are often overlooked. But for many countries groundwater exploitation can be carried out sustainably, and provide a reliable supply of water for current and future generations

RICHARD THOMSEN
Geophysicist and Hydrologist
GEUS GEOLOGICAL SURVEYS OF DENMARK AND GREENLAND

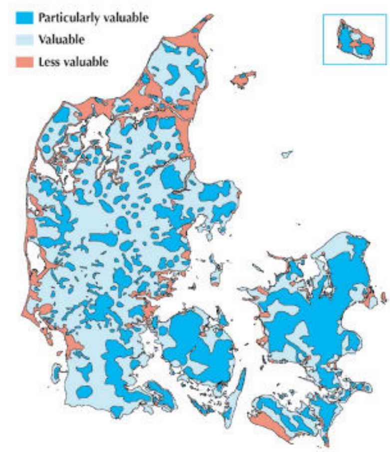
Providing enough fresh water for a growing population and for increasing industrial production is a critical issue for many countries. Climate change is affecting global rainfall patterns and water distribution. Since there is approximately 100 times more groundwater than surface water on Earth, it makes sense to exploit this important source of water. In many parts of the world, especially in arid or seasonally dry regions, groundwater can provide a stable and sustainable source of high-quality water.

Sustainable groundwater exploitation

Groundwater can be located very efficiently with advanced airborne geophysical mapping methods, and groundwater management can be achieved sustainably with groundwater modelling technologies and monitoring systems. The key is a credible groundwater model, which guards against over-extraction from the wells. Over-exploitation of the resource will come at the expense of future generations.

Mapping programme in Denmark

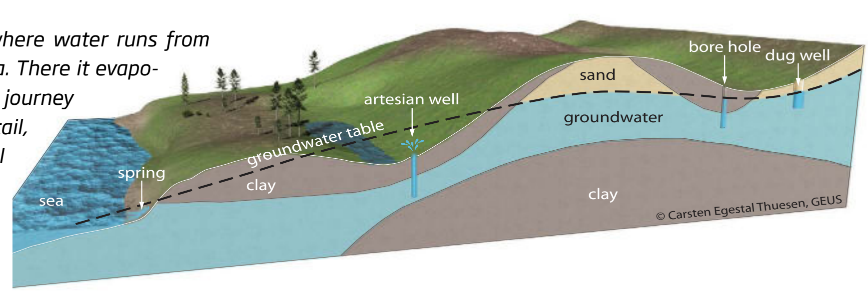
An ambitious groundwater mapping programme laid the foundation for the groundwater expertise of Danish companies. Today this expertise, which includes surveying technologies, software tools for integrated water resource modelling and decision-making systems is in global demand. The programme began in 1998 when the government adopted a plan for hydrogeological investigation. The aim was to produce an accurate picture of Danish aquifers with respect to their location, distribution, extension and interconnection and to produce maps identifying the weak points in the system. Site-specific groundwater protection zones were established to prevent groundwater contamination from urban development and agricultural sources.



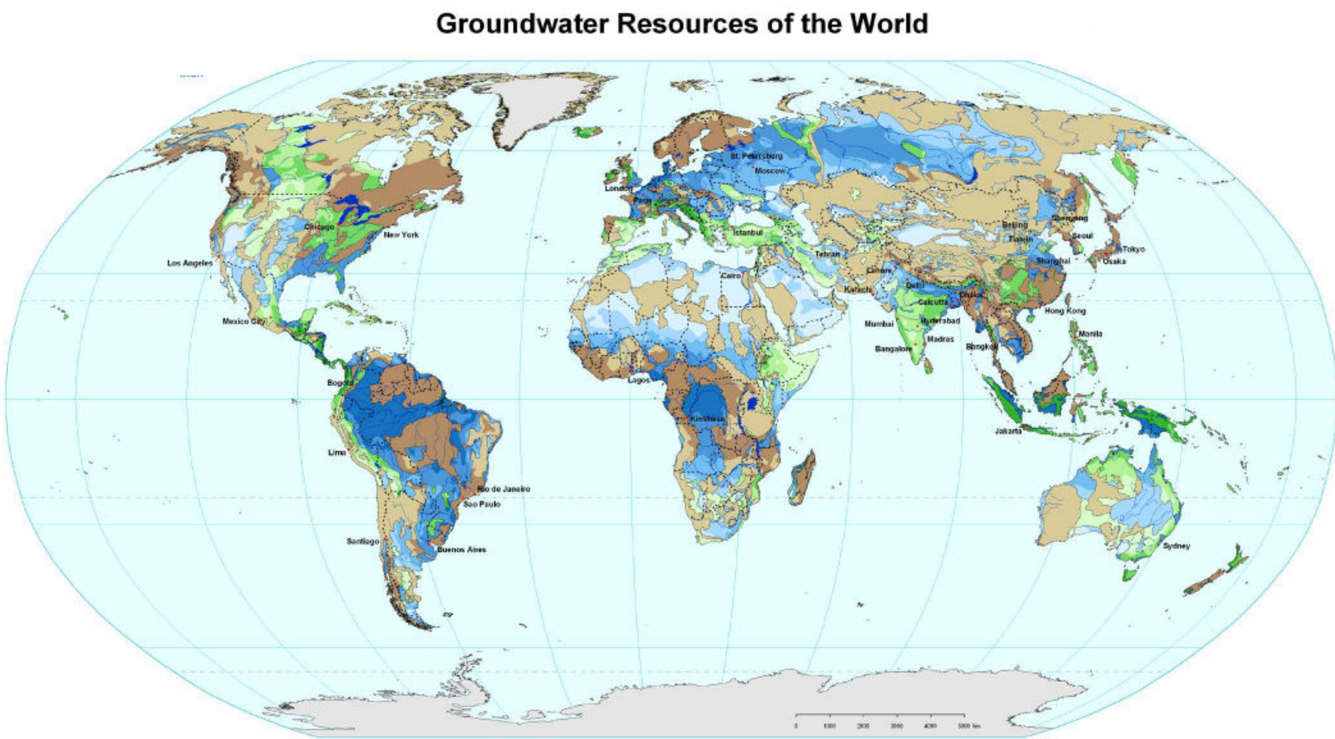
Classification *Groundwater classification map with subdivision of Denmark into highly valuable, valuable, and less valuable groundwater-abstraction areas. (Courtesy: GEUS).*

Summary of the Danish site-specific groundwater protection strategy:

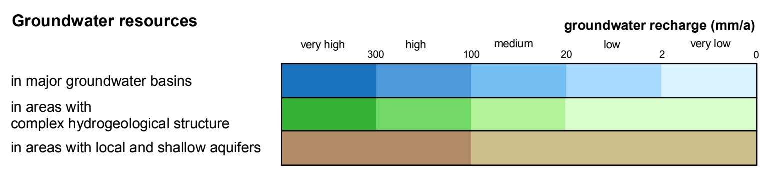
1) Spatially dense hydrogeological mapping based on existing data supplemented with new geophysical surveys, drilling surveys, water sampling and hydrological modelling. The mapping is aimed at establishing site-specific protection zones. Vulnerability is interpreted in relation to the local hydrological and chemical conditions.



Water cycle *The water cycle is an endless cycle where water runs from layers in the ground towards rivers, lakes and the sea. There it evaporates, falls from the sky as rain or snow and begins its journey again into the ground. To understand this process in detail, it is necessary to understand the factors that control the flow of water. Efficient mapping of groundwater and of the protection it needs are essential for optimal management of the resource. (Courtesy: GEUS).*



Groundwater recharge *The UNESCO Worldwide Hydro Geological Mapping and Assessment Programme has developed this map showing groundwater recharge in millimetres per year around the world. In areas where groundwater recharge is limited, and the geological conditions particularly complex, groundwater mapping and management based on hydrological models is essential for sustainable groundwater exploitation. (Source: www.whymap.org)*



2) Mapping and assessment of all past, present, and possible future sources of contamination – both point sources and diffuse sources.

3) Development of an action plan with legally binding regulations for future land use in the groundwater protection zones.

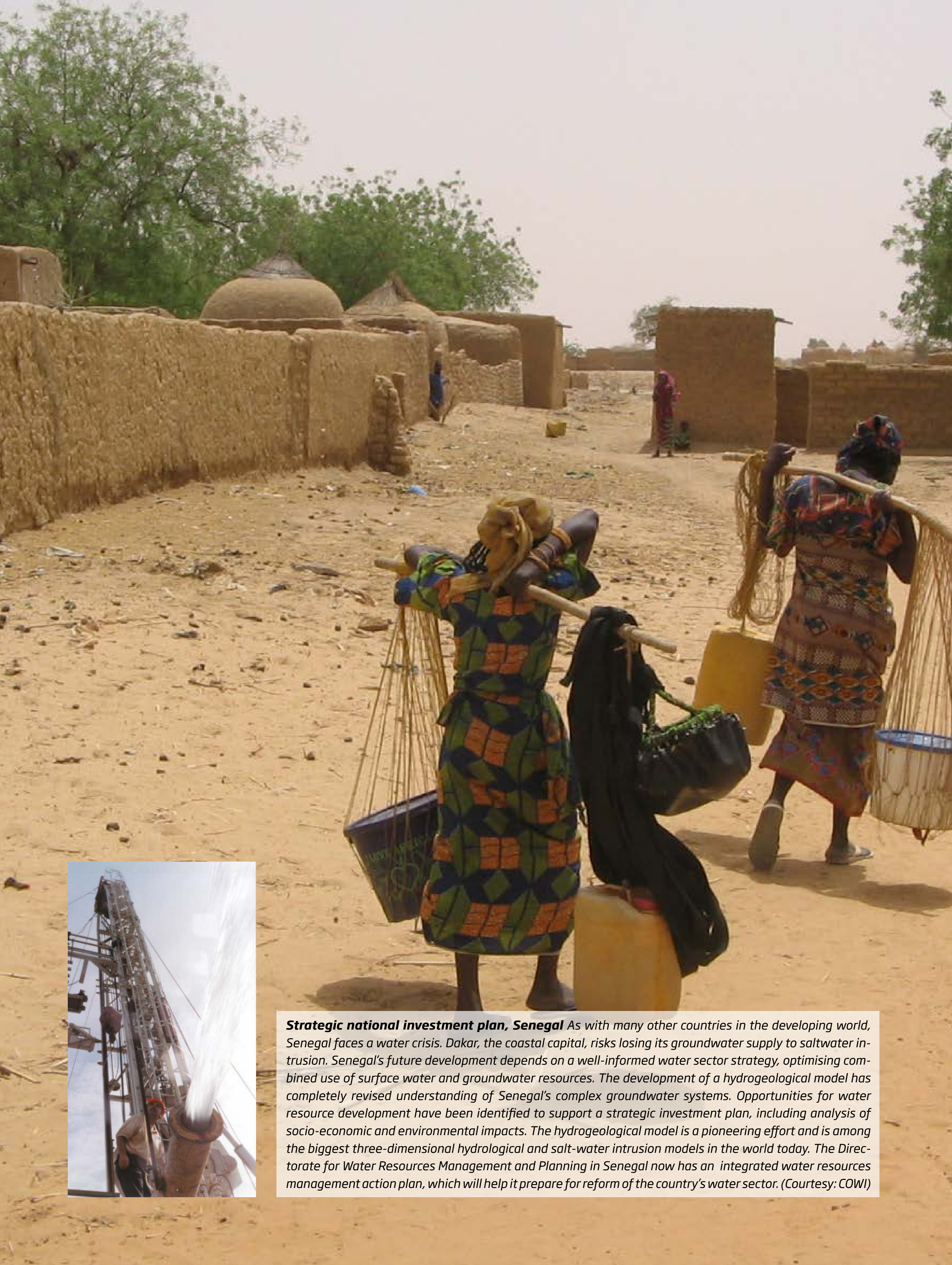
Water vital for growth and welfare

The groundwater mapping programme in Denmark is financed directly by those using the water. Public and private water consumers pay an additional 0.04 euros per cubic metre of water (0.2 dollars per 1,000 US gallons). In 2015, when the programme ends, the total cost will have been around 250 million euros (325 million dollars) with more than 25 percent of the money spent on geophysical mapping. Other countries may not be equally ambitious, but investing in some sort of scheme for groundwater or surface water development is essential when facing constraints on water resources. An unreliable water supply will have a negative impact on a country's growth and welfare opportunities, since these are very closely correlated with water security.

Failed investments historically

Historically, there have been many failed investments in dams and groundwater well fields. The most important cause has been the difficulty in assessing project feasibility and sustainability due to inadequate knowledge, data and tools. Since groundwater development and exploitation requires sizeable, long-term investment, there has to be a strong platform enabling a country or region to take the best decisions. Investments include the infrastructure around groundwater abstraction, and water treatment plants. The correct location of these facilities – taking into account the distribution of the groundwater, the consumers and the environment – is essential.

In addition, a groundwater aquifer responds very slowly to outside impacts. Sustainable exploitation requires that the main recharge areas are protected such that replenishment of the aquifer comes from uncontaminated water. To avoid unforeseen negative impacts or insufficient yields, an analysis of long-term development and variability of the climate and the hydrological system is required. It must include both the aquifers as they are and how they are likely to develop over time, as the groundwater is exploited. Furthermore, recharge areas must be mapped and included in future land planning to avoid contamination of the resource. Based on data collection, mapping, analytical tools and models, the resource availability and possible impacts are assessed to support groundwater development and decision making.



Strategic national investment plan, Senegal *As with many other countries in the developing world, Senegal faces a water crisis. Dakar, the coastal capital, risks losing its groundwater supply to saltwater intrusion. Senegal's future development depends on a well-informed water sector strategy, optimising combined use of surface water and groundwater resources. The development of a hydrogeological model has completely revised understanding of Senegal's complex groundwater systems. Opportunities for water resource development have been identified to support a strategic investment plan, including analysis of socio-economic and environmental impacts. The hydrogeological model is a pioneering effort and is among the biggest three-dimensional hydrological and salt-water intrusion models in the world today. The Directorate for Water Resources Management and Planning in Senegal now has an integrated water resources management action plan, which will help it prepare for reform of the country's water sector. (Courtesy: COWI)*

2. Methods and tools for mapping and hydrogeological modelling

Airborne data sampling can now generate a detailed 3D-picture of subsurface structures. But just as 3D brain scans require detailed analysis by experts, so airborne geophysics needs analysis and interpretation of data by professionals, in order to fully understand the geology

VERNER SØNDERGAARD
Research Geophysicist
GEUS GEOLOGICAL SURVEYS OF DENMARK AND GREENLAND

The Danish government's decision to protect and secure Denmark's groundwater for future generations has led to new innovative methods and tools that today constitute a proven setup for conducting groundwater mapping on a large scale. Developments include new geophysical mapping methods, a unique geophysical database, world-class data processing tools and innovative 3D geological modelling software. The advanced methods and tools are all scientifically and internationally documented and are continuously being improved through different tests and the establishment of new boreholes.

Mapping using two data sources

In most parts of the world groundwater mapping is based only on one data source: drilling information. However, low borehole density means that this strategy often leaves many uncertainties in the models. In Denmark, and a few other countries, geophysical measurements are used in conjunction with drilling to map aquifers. Intensive, large-scale use of geophysical methods, particularly airborne electromagnetic surveys in an integrated workflow together with drilling, makes mapping results more accurate and reliable.

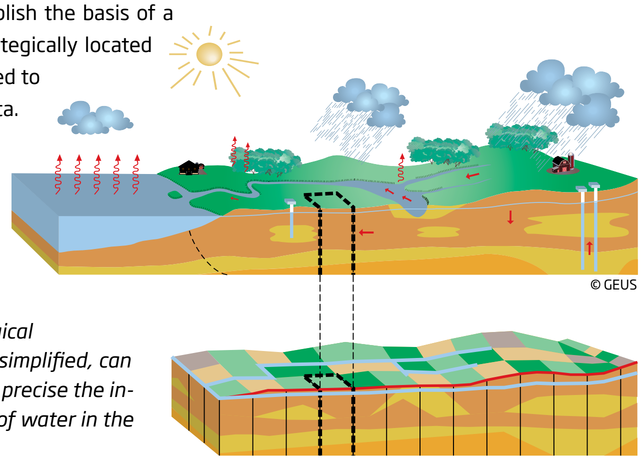
Borehole data contributes significantly when mapping overall geology, but inevitably the density is low and most boreholes are quite shallow. Spatially dense geophysical measurements can be used to establish the basis of a hydrogeological model. Strategically located boreholes may then be drilled to confirm the geophysical data.

They provide critical information for translating interpretations of the geophysical data into a geological model. Used together, the two datasets multiply their respective descriptive and modelling capabilities.

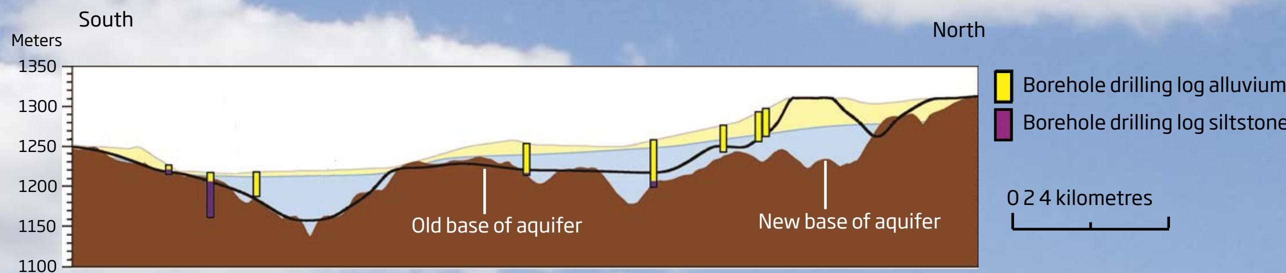
Two methods – the electrical and the electromagnetic methods – are particularly useful among the geophysical methods since there are strong correlations between both the measured resistivity and the lithology of the subsurface, and between the resistivity values and water salinity. Thus, airborne mapping with electromagnetic methods provides detailed area-covering input for a geological model of the subsurface, at basin scale. The data density obtained over large areas using airborne surveys is many times greater than can be achieved with ground-based surveys, and magnitudes larger than that of drilling surveys.

Transient electromagnetic measurement

The SkyTEM system, developed in Denmark, is recognized as one of the best airborne transient electromagnetic measurement systems in the world, and the only system developed specifically to meet the high data quality requirements of hydrological mapping. Airborne survey methods produce data sets with a high lateral density. Typically, a survey is flown with parallel lines at a distance of 100-500 metres (one metre equals 40 inches), depending on the target



Groundwater model *A hydrogeological model is a simplified description of a real geological system. Creating a perfect replica of the geology is impossible using only geological and geophysical surveys and drilling, because a geological system is extremely complicated. But creating a groundwater model, though simplified, can support decision making in groundwater management. The more detailed and precise the input data is, the more realistic and useful the calculations of flow and storage of water in the underground system will be. (Courtesy: GEUS).*



Airborne survey in one region of the USA *In the Platte River area in Western Nebraska, in the US, ground and surface water management is needed due to a large demand for irrigation. Over several years, the United States Geological Survey contracted and oversaw airborne electromagnetic data acquisition and processing. Important parts of this process were carried out by Danish companies. The black line on the illustration shows what was estimated to be bottom of the aquifer bedrock prior to the airborne electromagnetic survey. After the survey a more accurate groundwater model was made and five million cubic meters of previously undetected groundwater was found. (Source: USGS Scientific Investigations Report: 2011-5219).*

> It is our experience that the acquisition of dense, accurate geophysical data, that is followed by rigorous processing procedures, adds valuable information to the existing knowledge of the hydrogeology and towards better management of the resources
>
> **ANDREA VIEZZOLI**
> **Director**
> **AARHUS GEOPHYSICS**

and the complexity of the geology. The in-line sounding distance is typically 20-40 metres with a depth of investigation around 300 metres below the surface. The standard output is therefore a 3D description of the subsurface, from the surface to a depth of 300 metres, based on hundreds of data points per square kilometre. Alongside the development of the SkyTEM system a dedicated data processing, inversion and visualisation system has been built, called the Aarhus Workbench.

Other geophysical methods

In order to improve the models, the airborne measurements are often supplemented by other measures, such as seismic measures to supply detailed structural information not obtained by the airborne methods, or the magnetic resonance sounding (MRS). Magnetic resonance sounding measures water content directly, and can distinguish salty groundwater from heavy clay, for example.

Other important mapping methods

Geophysical data is typically supplemented by other data. This includes new boreholes, pumping tests, groundwater head mapping, water mapping and soil chemistry mapping. New boreholes are drilled in areas where precise knowledge about the geological structure of the groundwater system is lacking. Pumping test analyses give valuable information about the hydrogeological structure of the system. Systematic mapping of the groundwater head is used to determine flow patterns and the interaction between multiple aquifer systems and surface water systems. Groundwater chemistry mapping based on water samples from multiple boreholes provides information that can help with groundwater protection and may help shed light on the subsurface structure, thus helping with the interpretation of data from other sources.

Modelling

Geological, hydrogeological and hydrological as well as groundwater chemistry models are needed to identify groundwater protection areas, optimum well locations, sustainable water extraction levels and so on. These models are developed by combining airborne measurements, ground-based geophysical measurements and data from boreholes using a 3D modelling tool. This requires a multitude of skills and the experienced geological modeller combines an understanding of geophysical data, a knowledge of geological development processes and history, and a practical understanding of the nature of rock and soil. To facilitate model building, new geological modelling software has been developed, called GeoScene3D.

A consistent, documented and retraceable path leads from the first well drillings and airborne survey and groundwater chemistry data, through the processing and analysis, to the final model. It is crucial that the entire workflow, from collection of the electromagnetic measurement data to generation of the groundwater model, is carried out to the highest technical level and with the highest possible degree of accuracy, transparency and documentation.

Figure 1 - Map based on 518 boreholes

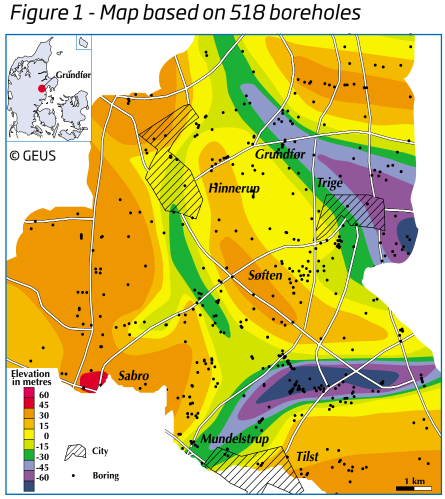
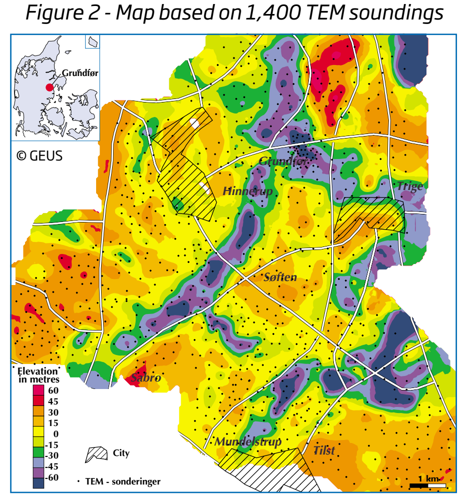
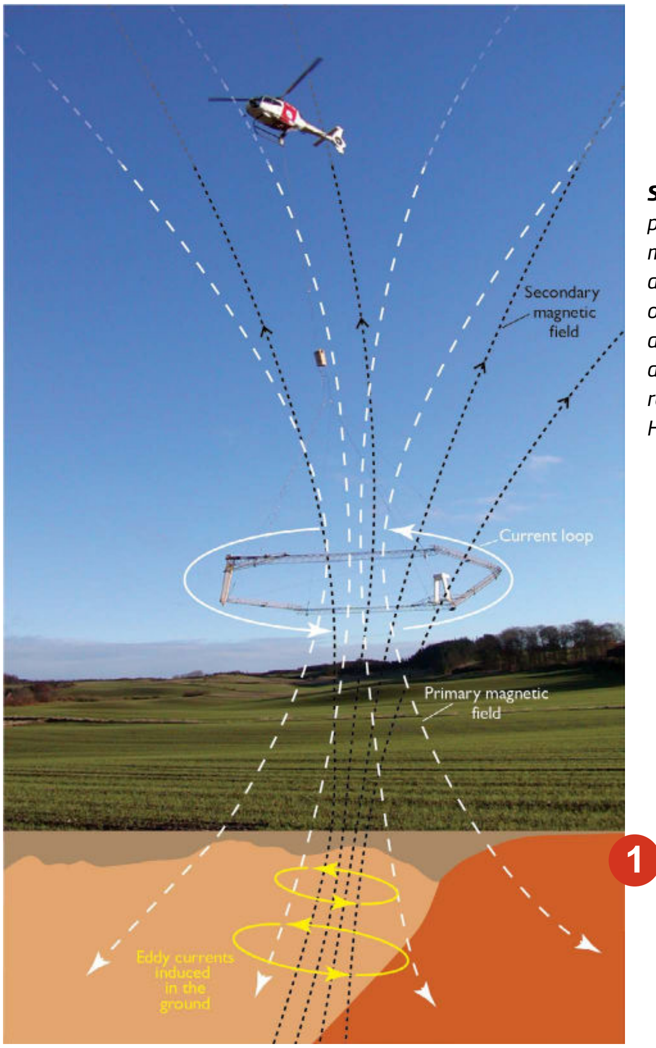


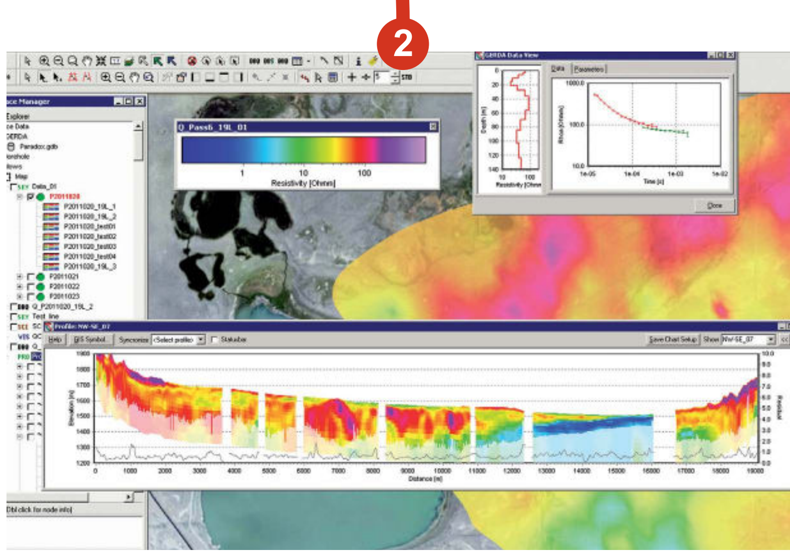
Figure 2 - Map based on 1,400 TEM soundings



Accuracy of mapping *This diagram shows our understanding of the aquifer structures before and after geophysical mapping based on airborne transient electromagnetic measurement in an area of Denmark. The survey revealed completely unknown aquifers in the area. Figure 1 shows our understanding of the aquifers based solely on well drilling. The dark blue areas are thick aquifers; red colours show areas with no aquifer or a thin aquifer. Figure 2 shows the same area after geophysical mapping by ground based TEM. The revised interpretation shows substantial differences in aquifer location, which have subsequently been verified by new boreholes. (Courtesy: GEUS).*



Step 1 *The SkyTEM airborne survey system has proved to be an invaluable aid in the large-scale mapping of groundwater resources in Denmark, and other countries, through the detailed mapping of the subsurface resistivity. The system transmits an electromagnetic signal towards the ground, and translates the signal it receives back into a resistivity model. (Courtesy: Aarhus University, HydroGeophysics Group and GEUS).*



Step 2 *The Aarhus Workbench software allows geophysicists to turn the SkyTEM raw data into accurate, transparent and well-documented 3D resistivity models of the subsurface, which are the geophysical basis for the groundwater mapping programme. The software is unique, as it was developed specifically for the hydro-geological application of airborne geophysical data. It incorporates tools for applying data processing and modelling protocols to ensure the results meet the quality required in ground-water mapping. (Courtesy: Aarhus Geophysics).*

***Step 3** When the geophysical data has been processed, and interpreted, specific structures in the subsurface can be identified. The task is to identify different layers and structures based on differences in electrical conductivity. Knowledge about the electrical properties of different sediments is crucial to distinguishing the various geophysical structures. This step relies heavily on information from boreholes in the area. Once the structures have been identified, geological modelling can be carried out, using the GeoScene3D tool. (Courtesy: GEUS).*

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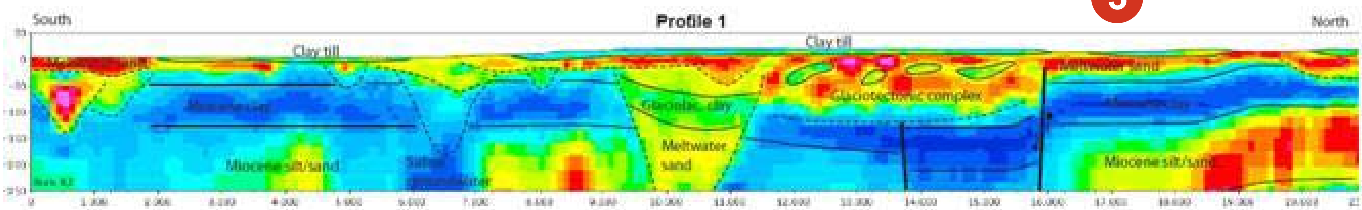

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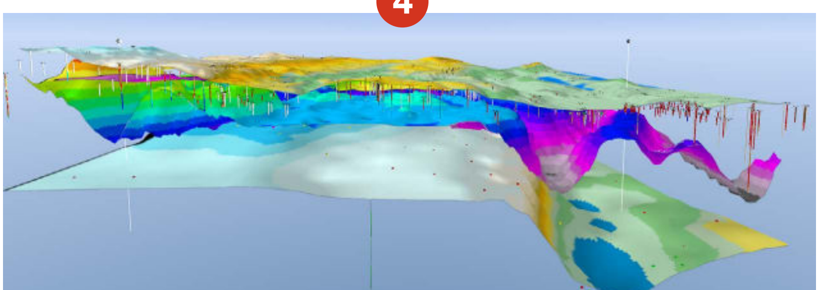

***Step 4** In GeoScene3D both airborne and borehole data is collated in a 3D environment. The geologist, in collaboration with the hydrogeologist and hydrochemist, can now develop a geological model for the area being studied. The result is a model that can be used in groundwater flow calculations by applying hydrological modelling software, such as MikeShe, Modflow or FeFlow. (Courtesy: I-GIS).*

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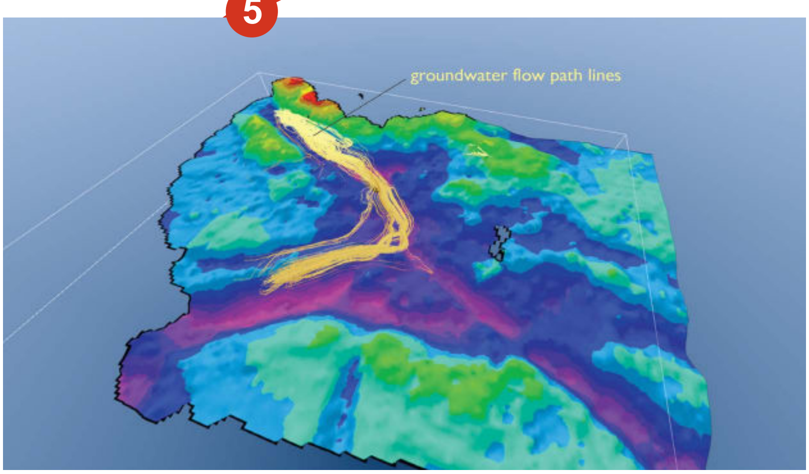


***Step 5** A groundwater model reveals how groundwater flow is determined by geological structures. All the necessary details for the groundwater model are exported directly from GeoScene3D into the hydrological modelling software. Calculations of groundwater flow path lines, to mention one example, are completely dependent on the quality of the input from the geological model especially when it comes to more complex subsurface geological structures. An example would be the incised valleys shown in the example here. (Courtesy: GEUS).*

3. Policies and administration of groundwater resources

Groundwater mapping is the first step to a stable and sustainable water supply. But mapping requires good data collection and secure data management. More importantly still, there has to be the political will to protect groundwater resources.

JAN REISZ
Head of National Groundwater Mapping Office
DANISH NATURE AGENCY

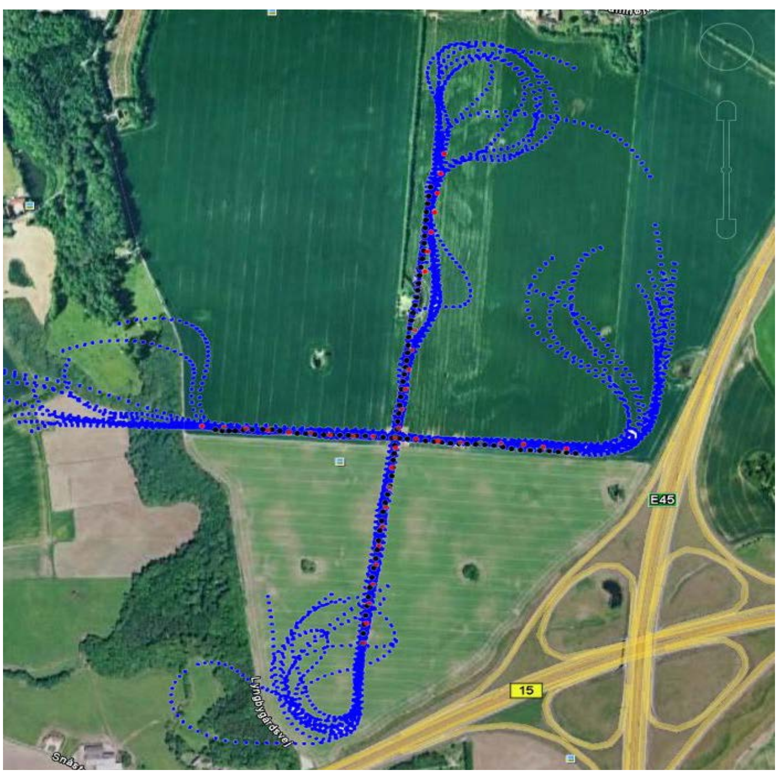
In order to obtain the best results, groundwater exploitation should always form part of a long term strategy, with sustainable groundwater supply a political priority and with the necessary resources allocated. In Denmark, both public and private water consumers pay 0.04 euros per cubic metre of water consumed (0.2 dollars per 1,000 US gallons). This money funds the groundwater mapping and management programme. Public entities have been appointed to ensure that the results of groundwater mapping are used to the best effect, and interpreted within a wider context.

Administration and management

Before initiating a groundwater mapping programme it is important to consider what the results will be used for, and how they will be used in management of the water resources. It is particularly important to allocate resources for an administration that will ensure data collection and interpretation, and determine which public authorities will be responsible for the administration.

National databases and standards

In order to draw the necessary conclusions from survey data, the data must be available, reliable and accurate. National databases are essential for storing data and results securely. If they are made easily accessible they can also be of great value in the future. Data has to be stored in a well-documented and consistent manner. Uniform standards and guidelines exist and should be referred to, to ensure the quality of the data before it is put into the databases.



System verification *To make sure that geophysical survey equipment is working properly, it is important to have test sites. The national Danish test site for airborne and ground-based TEM instruments is situated west of Aarhus. Testing and calibration of the SkyTEM system is regularly carried out at different altitudes. The results are compared with ground-based TEM measurements in order to ensure a consistently high quality of data collection. (Courtesy: Aarhus University, HydroGeophysics Group).*

National pilot study, Thailand *In 2011, the Thai Government initiated a pilot study about 350 km north of Bangkok led by the Department of Groundwater Resources in Bangkok. The aim of the study was to map aquifers in a test area of 1000 square kilometres with assistance, knowledge transfer and training in geological modelling contributed by the Danish engineering and software companies EnviDan, SkyTEM Surveys and I-GIS along with GEUS. GEUS also assisted with the supply and implementation of a geophysical database.*

A close and professional collaboration between public authorities, universities and consulting companies means that Denmark has developed excellent expertise in sustainable groundwater supply

PETER THOMSEN
Project Manager and Geophysicist
RAMBØLL

The Danish Government has prioritised data security ever since initiating the national groundwater mapping programme in 1998. GEUS Geological Surveys of Denmark and Greenland has established national databases for all geophysical data, data from both pre-existing and new wells, water chemistry and hydraulic data. Uniform standards and guidelines are in place to ensure that the primary data is comparable and quality assured. This is essential for further processing of the data. In addition, databases for the geological and hydrogeological models, and for all reports on groundwater mapping, have been developed. A set of integrated software products, making the data easily available and the data processing uniform, has been developed in Denmark and supports efficiency.

Groundwater: a political priority

Effective use of data is essential for successful groundwater mapping, but interpretion of data alone is not enough. The results of groundwater mapping must eventually be used for the management and protection of aquifers. This requires that groundwater be placed higher on the political agenda and that administrative units, responsible for the future use of mapping results, be designated. Public entities should also be designated to monitor the groundwater resources that have been mapped and ensure that they are protected.

Regional mapping, Malaysia *New technology makes it possible to map water and minerals from the air. In Southeast Asia, in Malaysia, airborne technology has been used for very large geophysical surveys of groundwater. These involved flying over 15,000 km in 30-40 km long parallel tracks, covering an area of 3000 square kilometres. Several Danish companies worked together in order to carry out drilling, down hole logging, water-quality testing, well field design, geological and hydrological modelling. Today the region is supplied with 500 million litres (130 million US gallons) of groundwater per day. (Courtesy: SkyTEM Surveys and EnviDan International).*

4. The benefits of investing in groundwater supply

Groundwater can provide a stable supply of water for industry. If used sustainably, groundwater can contribute positively to economic growth and development

JENS DYRBERG
Project Manager
ENVIDAN INTERNATIONAL

A key argument for using groundwater – besides the obvious argument of there being a shortage of surface water – is that groundwater is better protected from contamination than surface water. The quality is higher and the water requires less treatment. It is important to take care that aquifers do not get contaminated, which can lead to high clean up costs. Otherwise, in many places,, using groundwater can be economically beneficial and secure a safe and stable water supply across both public and commercial sectors.

Postponing investments

There are potential financial benefits for water utilities who supplement a water supply based on surface water resources with new groundwater resources. They may be better able to plan long term. They may also be able to postpone major investments in surface water infrastructure, or in assuring a higher level of water security. The treatment process for groundwater is simpler and cheaper compared with that for surface water, and increasing the volume of supply is much easier, since there is no need to build dams.

Addressing the needs of industry

Groundwater mapping and sustainable groundwater management provide better knowledge of the availability of water resources, a critical factor in attracting new companies and industry. Companies can benefit from improved water efficiency, better water quality and supply security. Mines, the food and beverage industries and the agricultural sector often fight over water with other sectors or groups. Groundwater may provide the solution. Moreover, groundwater extraction leaves a smaller footprint on the environment if managed properly. All of the above contribute to boosting economic growth.

Knowledge transfer to local partners

Investment in groundwater mapping and sustainable water management has the additional benefit for local business partners of teaching them new skills. The Danish experience of cooperating with other countries is that knowledge transfer from international experts creates a strong platform for expanding the local water business to other regions.

Avoiding saltwater intrusion, Vietnam *Part of the water supply to Ho Chi Minh City in Vietnam comes from groundwater. Since saltwater is present deep down in the aquifers, a project was formed and Danish experts were asked to carry out a geophysical survey using ground-based transient electromagnetic measurement (TEM) to reveal the depth of the freshwater/saltwater interface and avoid intrusion of saltwater into the extraction wells.*
(Courtesy: ALECTIA).

Groundwater action plan, Vietnam *A key element in the development of a Water Resources Action plan for the 12,300 square kilometre Upper Srepok River Basin in the central highlands of Vietnam was to assess the groundwater resources in the area and to explore the possibility of using groundwater for irrigation and urban water supply. The investigations included geological, hydrogeological and hydrological modelling to 1) evaluate the effect on irrigation demand of changes in crops cultivated in the basin and 2) to assess the safe yield from groundwater resources should higher demand for water in the future should be met using groundwater. The Water Resources Action Plan was developed in 1993 - 1994 and updated in 1995 – 1997. It laid the foundation for the Central Highlands becoming a major coffee producer. Implementation of two priority rural development projects 1997 - 2001 were aimed at improving living standards in rural areas in general and among poor and ethnic minority communities in particular. (Courtesy: COWI)*

5. Avoiding problems with groundwater

Problems associated with groundwater exploitation can often be resolved with accurate groundwater mapping and sustainable management.

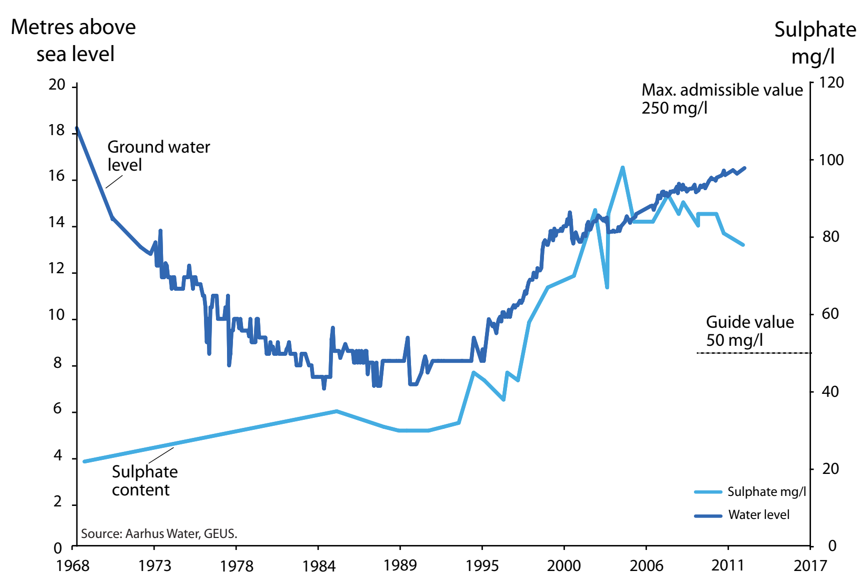
FLEMMING PEDERSEN
Head of Department, Geophysicist
ALECTIA

It only takes a few contaminants and/or an unbalanced approach to utilisation for groundwater resources to be damaged forever. Some of the critical issues can be resolved through accurate groundwater mapping, sustainable groundwater management and with integrated management of water resources. This topic will be introduced in the next chapter.

Here are some of the main challenges and how they can be resolved:

- Saltwater intrusion can be avoided by mapping the freshwater and groundwater interface and by revealing previously undetected freshwater aquifers in coastal areas
- Land subsidence in cities is a risk that can be addressed by tapping into groundwater resources outside cities. This ensures that well fields are located in more remote areas or in areas less vulnerable to land subsidence
- Poor water quality can be an issue, even with groundwater. Groundwater mapping means that better decisions can be taken on where and how deep to sink wells, away from pollutants or poor natural chemistry
- Even if previous wells have yielded disappointing results, improved mapping can lead to better well locations, revealing a potential for successful wells
- Poor administration of groundwater resources may have caused severe problems in the past. Better knowledge about aquifers provides the basis for implementing the necessary administrative structure
- If faced with a deteriorating quality in existing wells, groundwater mapping and modelling can improve understanding. It can create a platform for sustainable exploitation of the groundwater resource in the future

__Sustainable yield, Denmark__ The capacity of a water pumping station in Beder in Denmark was originally calculated using traditional hydrogeological analysis of the borehole data, combined with a short-term pumping test. These methods provided an incomplete understanding of the complexity of the aquifer dynamics, and as a result the capacity of the pumping station was overestimated. After pumping began in 1968 the water table fell by over 10 metres and the sulphate concentration increased. Based on advanced geophysical mapping and 3D hydrological modelling the sustainable yield estimate was reduced in 1990 by 35 percent. The water table has now risen to a sustainable level and the sulphate content has stabilised. (Courtesy: GEUS)

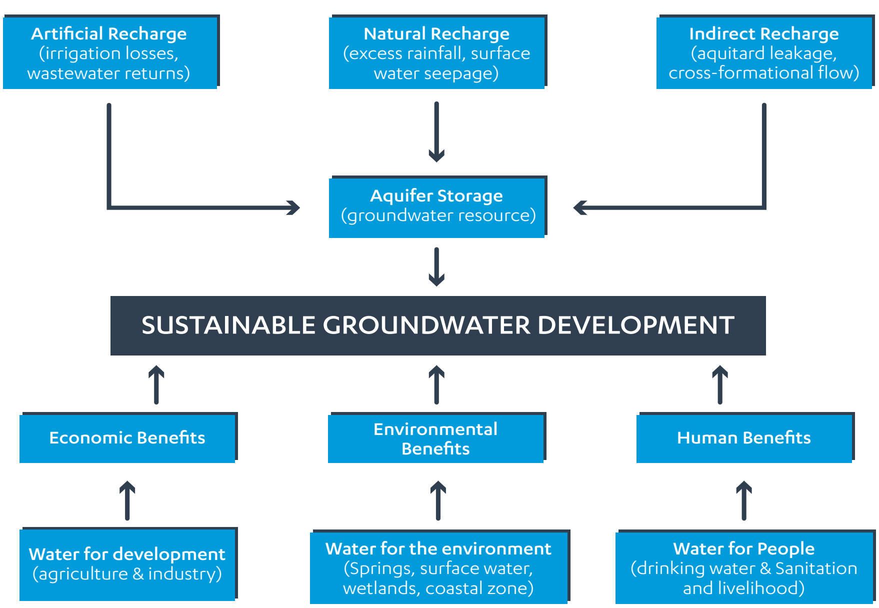


6. Groundwater as a part of integrated water resources management

Groundwater can be exploited across large areas to meet local demand and affordability. In a healthy aquifer it can be transported over huge distances free of charge and without evaporation losses. However, balancing recharge against abstraction is essential.

ANDERS REFSGAARD
Project and Market Director
COWI

Groundwater is an important part of the hydrological cycle. Groundwater is interconnected with surface water and form *one* resource, hence groundwater and surface water should be managed together in river catchments. Groundwater use must therefore be evaluated with respect to its impact on both surface water (e.g. wetland and stream depletion) and the aquifer. Also, the risk of salinity intrusion in river deltas and coastal areas increases with groundwater pumping as flow between aquifers and surface water bodies are altered. Groundwater protection and contamination control is closely connected to surface activities and land use management. Consequently, groundwater management, utilisation and sharing should take surface water impacts into account and comply with the Integrated Water Resources Management (IWRM) guidelines. These guidelines promote the co-ordinated development and management of water, land and related resources in order to maximize the economic and social welfare without compromising the vulnerability of vital ecosystems.



Assuring sustainable groundwater use

Making reliable recharge estimates for aquifers requires a geological model and the assessment of distributed hydrogeological properties. It also involves accounting for the interaction between surface water and groundwater. Balancing groundwater recharge against groundwater abstraction is essential to achieving sustainable groundwater use. In water scarce, arid environments artificial recharge of aquifers at farm scale or at aquifer storage and recovery sites (ASR) may be a feasible solution. However, at the risk of polluting the aquifer unless adequate precautions are taken.

Planning and management

Integrated Water Resources Management, IWRM, is an accepted framework for water planning and water resource management. It encourages a holistic, multi-sector, participatory process focusing on river catchments and shared use of water. Groundwater development and exploitation should be viewed in this overall context. The IWRM approach promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social benefits in an equitable manner without compromising the sustainability of vital ecosystems. This includes more coordinated development and management of land and water, surface water and groundwater, the river basin and its adjacent coastal, marine environment and upstream and downstream interests. However, integrated water resources management is not just about managing physical resources, it is also about reforming human systems to en-

Sustainable groundwater development

Illustration of sustainable groundwater management balancing recharge and water use (modified from Hiscock, K.M., Rivett, M.O. & Davison, R.M. 2002, Sustainable Groundwater development).

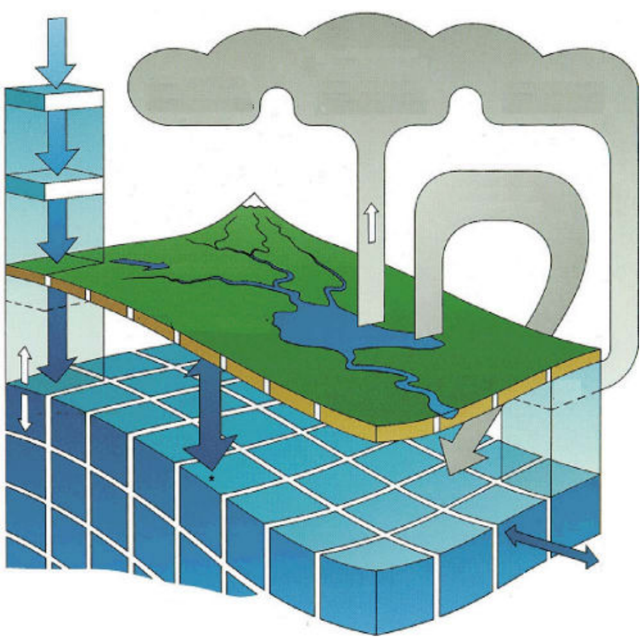
A growing demand for water from agriculture and industry places stress on freshwater resources. Groundwater exploitation must form part of an integrated water management plan

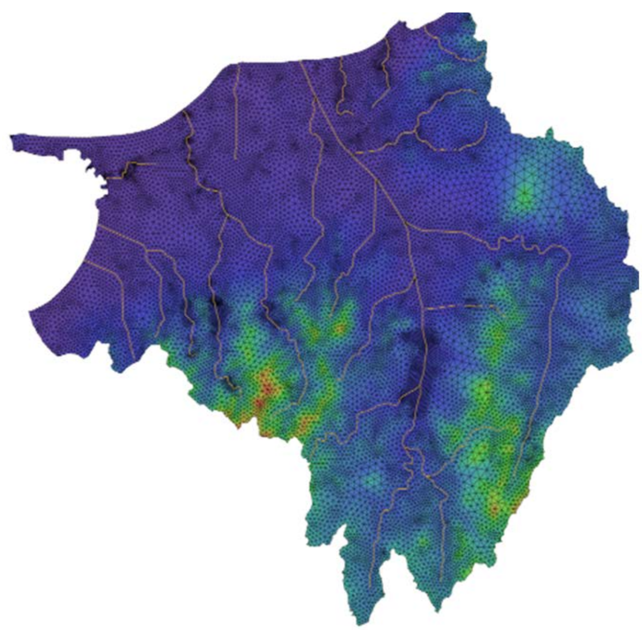
TORSTEN V. JACOBSEN
Hydrologist, DHI

able people, both men and women, to benefit from those resources. At its simplest, IWRM is a logical and appealing concept. It is based on the idea that the many different uses of water resources are interdependent.

Avoiding an unsustainable approach

In many countries, the need for groundwater has increased in response to overexploitation and contamination of surface water resources. As the groundwater table has fallen, wells have been deepened, leading to continued groundwater mining, dried out wells, depleted rivers and wetlands and deteriorating water quality. Signs of an imbalance and unsustainable water use initially become visible in dry years, in the form of dried-out wells, river beds and wetland. Continued extraction will eventually reach a level from which it will take decades to recover at low natural recharge rates. As the cost of pumping increases with depth, the alternative may be to move well fields to newly developed aquifers and invest in pipelines. Insufficient, inefficient or costly water supply has profound impacts on production and livelihood. Shortfalls, water stress and unreliable supply are likely to become increasingly common with climate change. The higher population pressure underscores the need to address both present problems and future scenarios. Appropriate groundwater management, monitoring and regulation from a solid knowledge base is part of the solution. Acknowledging the integrated nature of water resources will help secure both the resource and any investments in water infrastructure in the long term.





Comprehensive water management *Along the coast of Eastern China, between Weifang and Yantai, the water supply from groundwater is under threat. An unsustainable level of pumping has led to severe problems in relation to both the water quantity and quality. This has had a negative impact on both regional economic development and the environment. Progressive intrusion of seawater into the aquifer has been observed during recent decades with elevated salinity concentrations now extending more than 10 km from the coastline. Attempts to artificially increase the groundwater recharge from surface water reservoirs have not effectively pushed back the interface between fresh and saline water. A comprehensive water management project was undertaken and different management scenarios were analysed. Results showed that the salinity intrusion could be counteracted by adjusting re¬charge and pumping levels by 25 percent of the current levels, thereby avoiding high salinity concentrations at city well fields. In this work the MIKE software developed DHI is an important tool for integrated surface water and groundwater modelling and in assessing groundwater resources and impacts. DHI integrated management modelling concepts was implemented using FEFLOW, MIKE SHE and MIKE11. (Courtesy: DHI).*

Denmark knows water

Danish water companies have shown their courage and drive by working with their competitors in order to create the Rethink Water platform. They are showing the world that Denmark is ready to take responsibility and contribute to finding solutions to the major water challenges the world faces.

IDA AUKEN
Minister for the Environment
DENMARK

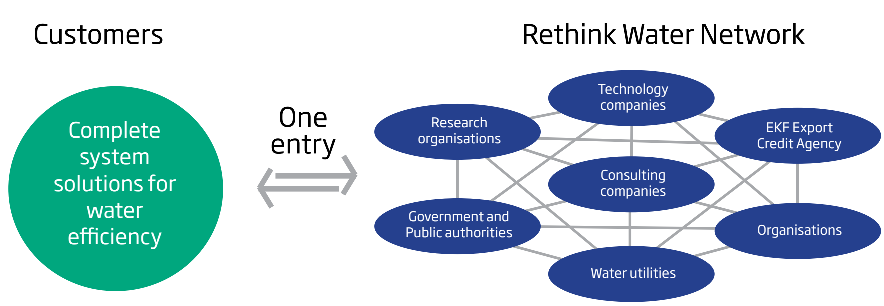
Selvom Danmark kun er en lillebitte kalkaflejning på den nordlige halvkugle, har vi én af Europas længste kystlinier, er verdens største søfartsnation og har noget af verdens reneste vand i hovedstadens havn, som vi svømmer i. Det skyldes ikke tilfældigheder, for Denmark knows water. Helt tilbage fra dengang vi var vikinger og spredte frygt og rædsel på havene. Nu er det noget helt andet, vi ønsker at sprede: Viden og samarbejde om vandeffektivitet.

Danmark er ikke magtfuld, men viden er magt. Noget af det, der kendetegner Danmark er, at vi er gode til at skabe internationalt samarbejde i fredelige og lydhøre rammer. Vi ved, hvordan man når til effektive løsninger med respekt for forskellige agendaer og synspunkter. Danmark er bygget på samarbejde og tillid om konkrete forbedringer af vores livskvalitet som mennesker.

Denmark knows water, men vi bilder os ikke ind, at vi har alle svarene på de mange vandudfordringer, som verden står overfor. Men da Danmark historisk aldrig har haft rige naturlige ressourcer og er mange mennesker på et lille areal, har skiftende regeringer altid fokuseret på effektivt ressourceforbrug og et godt, sundt og sikkert miljø at leve i. Derfor ved vi en masse om vandeffektivitet. Ikke af akut nød, men fordi vi er et lille effektivt og samarbejdende folk.

Denmark knows water. Vi er et netværk af over halvtreds danske virksomheder, institutioner og organisationer med ekspertise i vandeffektivitet. Det netværk kalder vi Rethink Water. Vi samarbejder om de løsninger, det er vigtigt at finde i fællesskab og ikke opgive på grund af egoistiske hensyn. Vi er noget så sjældent og værdifuldt som konkurrenter, kunder, forskere og myndigheder, der deler viden og hjælper hinanden med at udbrede vores viden om water efficiency til hele verden.

Hvis dit mål er water efficiency er Danmark parat til at blive din partner. Vi er parate til at dele vores viden om vand med verden og lade den sprede sig som ringe i vandet. Èt land kender opskriften på samarbejde for vandeffektivitet: Denmark knows water.



The Rethink Water group of companies, research institutes, organisations, utilities and public authorities:

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State of Green
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