Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark

R. Thomsen · V. H. Søndergaard · K. I. Sørensen

Abstract The water supply in Denmark is based on high-quality groundwater, thus obviating the need for complex and expensive purification. Contamination from urban development and agricultural sources, however, increasingly threatens the groundwater resource. In 1995 the Danish Government thus launched a 10-point plan to improve groundwater protection. In 1998 this was followed by a decision to instigate spatially dense hydrogeological mapping of the groundwater resource within the 37% of Denmark designated as particularly valuable water-abstraction areas. The maps will be used to establish site-specific groundwater protection zones and associated regulation of land use to prevent groundwater contamination. Traditional mapping based solely on borehole data is too inaccurate for this purpose. The work will take 10 years and cost an estimated DKK 920 million, equivalent to 120 million euro (€). To fund this, consumers will pay a € 0.02 surcharge per m^3 of drinking water during the 10-year period. This review of the Danish strategy to protect the groundwater resource demonstrates why dense mapping with newly developed geophysical measurement methods in large contiguous areas accords geophysics a highly central role in the forthcoming hydrogeological mapping. It is illustrated by examples of spatially dense, large-scale geophysical mapping carried out in the Aarhus area.

Résumé L'alimentation en eau au Danemark suppose une haute qualité des eaux souterraines, en éliminant ainsi le coûteux processus d'épuration. Néanmoins, la qualité des sources souterraines est menacée par la pollution provoquée par le développement urbain et agricole. En 1995 le gouvernement danois a lancé un plan en 10 points pour améliorer la protection des eaux souterraines. En 1999 ce plan a été suivi par la décision de promouvoir une cartographie hydrogéologique à grande densité sur 37% du territoire du Danemark où se trouvent des zones de captages importantes. Les cartes seront utilisées pour établir les zones de protection des eaux souterraines, en tenant compte des conditions locales du site ainsi que des règlements conjoints d'utilisation des territoires, afin de prévenir la pollution des eaux souterraines. La cartographie traditionnelle, basée seulement sur les données des forages, est trop imprécise pour ce but. Les travaux vont durer 10 ans avec un coût estimé à 120 millions d'euros (€). Pour ces travaux les consommateurs vont payer une surcharge de € 0.02 par m^3 d'eau potable, ceci pendant 10 ans. Cette révision de la stratégie du Danemark concernant la protection des ressources en eaux souterraines a démontré les raisons pour lesquelles on a accordé un rôle central aux nouvelles méthodes géophysiques dans la future cartographie hydrogéologique de vaste régions. On présente un exemple de cartographie géophysique réalisée dans la région d'Aarhus.

Resumen El abastecimiento de agua en Dinamarca está basado en agua subterránea de alta calidad, evitando de esta manera la necesidad de una purificación compleja y cara. Sin embargo, la contaminación a través del desarrollo urbano y de fuentes agrícolas, ha incrementado la amenaza para el recurso de agua subterránea. Entonces en 1995 el gobierno lanzó un plan de 10 puntos para mejorar la protección del agua subterránea. Este fue seguido en 1998 por la decisión para promover una cartografía hidrogeológica espacialmente detallada, para el recurso agua subterránea dentro del 37% de las áreas de extracción consideradas por Dinamarca con una importancia especial. Los mapas serán usados para establecer zonas específicas de protección para puntos de agua subterránea y una regulación asociada al uso del territorio, para prevenir la contaminación del agua subterránea. La cartografía tradicional basada exclusivamente en datos de la perforación es muy inexacta para este propósito. Este trabajo tomará 10 años y costará aproximadamente DKK 920 millones, equivalentes a 120 millones de Euros

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(€). Para financiar esto los consumidores pagarán un sobreprecio de € 0.02 por m^3 de agua potable durante un periodo de 10 años. Este análisis de la estrategia Danesa para proteger el recurso agua subterránea, demuestra porque la cartografía detallada, hecha con nuevos avances en métodos de medición geofísica, aplicados a grandes áreas aledañas, otorgan a la geofísica un papel altamente importante en el futuro de la cartografía hidrogeológica. Esto está ilustrado con ejemplos de cartografía geofísica a gran escala y espacialmente detallada, llevados a cabo en el área de Aarhus.

Keywords General hydrogeology · Geophysical methods · Groundwater management · Groundwater protection · Legislation

Introduction

In 1995, increasing problems with water quality in Denmark due to urban development and contamination from agricultural sources led the Minister for the Environment to approve a 10-point plan to improve groundwater protection. One of the major initiatives was to ban the use of pesticides which can contaminate the groundwater. Another was that the Counties (the regional authorities) should draw up new water-resource protection plans. By the end of 1997, the 14 County Councils had classified the country into three types of groundwater-abstraction areas: particularly valuable, valuable, and less-valuable water-abstraction areas (Fig. 1). This classification is based on an evaluation of the size and quality of all groundwater resources in the country.

In July 1998, the Danish Parliament adopted an ambitious plan to significantly intensify hydrogeological investigation to facilitate protection of the groundwater resource in order to meet future water-supply challenges. Parliament decided that, in addition to being responsible for water-resource planning, the 14 County Councils should also be responsible for ensuring spatially dense mapping and hydrological modelling of the water resources as a basis for establishing site-specific groundwater protection zones (Danish EPA 2000a).

The mapping and planning work is to be carried out over a 10-year period and encompasses all parts of Denmark classified as particularly valuable water-abstraction areas. Together, these cover almost 16,000 km^2 or 37% of the total area of the country. The total cost of this spatially dense mapping and planning work is estimated at around DKK 920 million, equivalent to 120 million euro (€, 2002 prices) or € 7,500 per km^2 for a programme encompassing geophysical profiling every 250 m, survey drilling every 4 km^2, water sampling and hydrological modelling. During the 10-year mapping and planning period, Danish consumers have to pay the County Councils a € 0.02 surcharge per m^3 of water consumed, i.e. about € 4 per family per year.

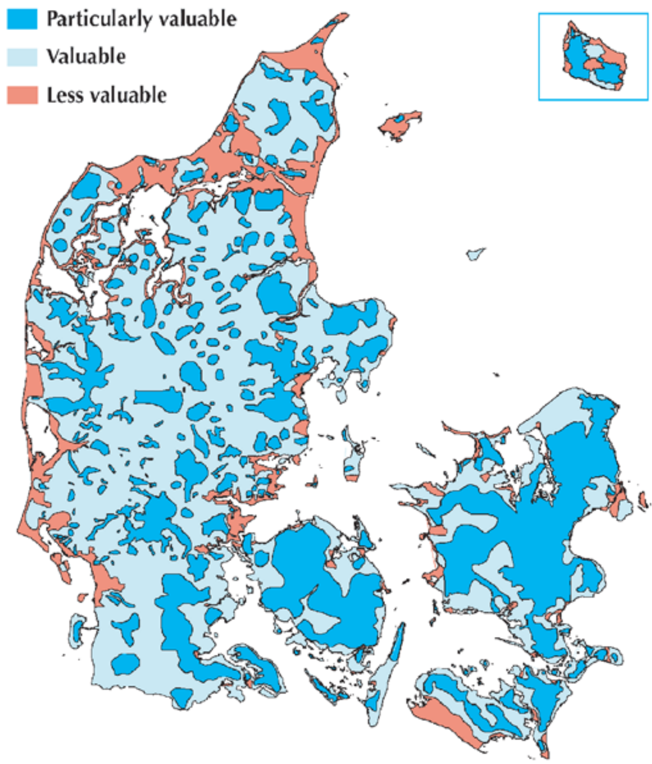

Fig. 1 Groundwater classification map showing subdivision of Denmark into particularly valuable, valuable and less-valuable groundwater-abstraction areas in 2001. The Danish island County of Bornholm, which is located far from the mainland in the Baltic Sea south of Sweden, is shown as an inset in the *upper right-hand corner*

Public Water Supply Administration in Denmark

Planning and public administration in Denmark is carried out at three governmental levels: State, county and municipal. Legislation is passed by the State. The 14 County Councils are responsible for overall administration of water-abstraction permits and protection of water resources against contamination. The Water Supply Act and the Environmental Protection Act require the use of groundwater and surface water to be regulated through integrated planning and comprehensive assessment and protection of the water resources while concomitantly ensuring water-supply needs and protection of nature and the environment. The administration of water-abstraction permits is regulated by the Water Resource Plan drawn up by each County Council pursuant to the Water Supply Act (Danish EPA 1999). The Water Resource Plan is the framework for the Water Supply Plan drawn up by each of the 275 Municipal Councils (Thomsen 1997).

Site-Specific Groundwater Protection Strategy and Action Plan

Groundwater protection in Denmark is based on the assumption that the physical environment provides some

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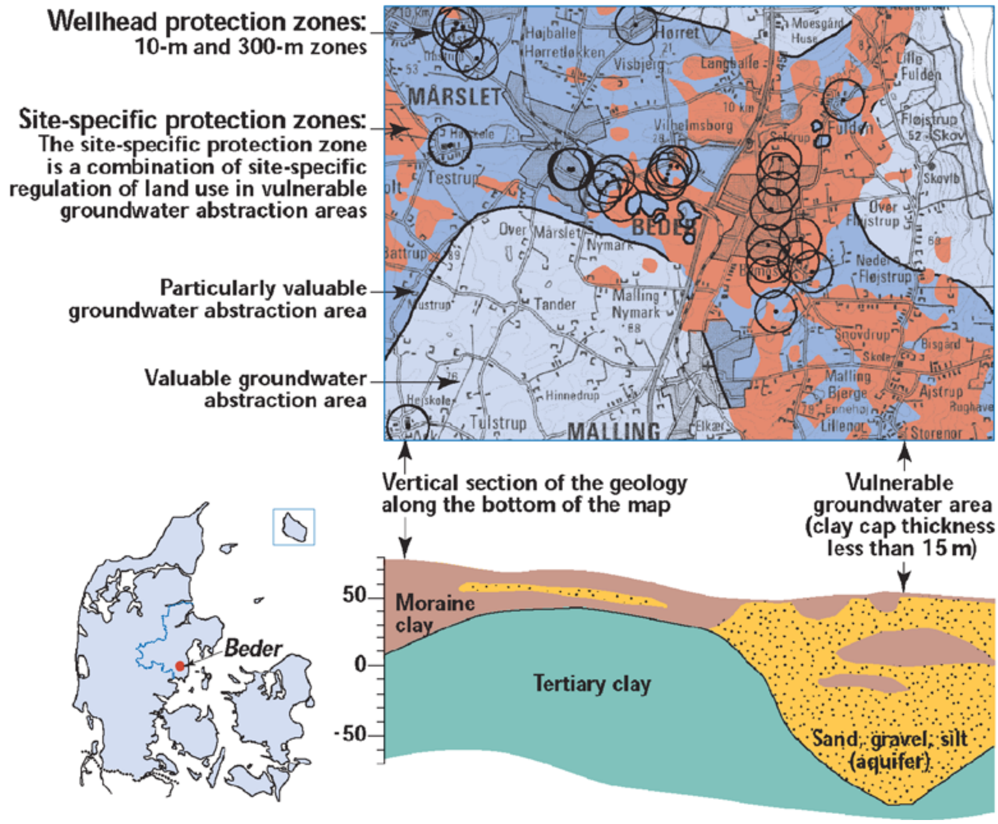

Fig. 2 Example of zoned groundwater protection at Beder abstraction site in Aarhus Municipality

degree of protection against anthropogenic pressures, especially as regards contaminants entering the subsurface environment. The fundamental concept of site-specific groundwater protection zones is that some areas are more vulnerable to groundwater contamination than others. The goal is thus the subdivision of a given area according to the different potential of the various sub-areas as regards specific purposes and uses. Assessment of groundwater vulnerability is described very comprehensively in the *Guidebook on mapping groundwater vulnerability* (Vrba and Zaporozec 1994). The guidebook specifies the uses and limitations of groundwater vulnerability maps.

The Danish site-specific groundwater protection strategy is based on three steps.

1. Spatially dense hydrogeological mapping based on new geophysical surveys, survey drilling, water sampling, hydrological modelling, etc., aimed at facilitating the establishment of site-specific protection zones. These zones are directed at both point sources and diffuse sources of contamination within the whole groundwater recharge area, and shall supplement the traditional protection zones around the wells. The vulnerability is interpreted in relation to the local hydrological and chemical conditions.
2. Mapping and assessment of all past, present and possible, future sources of contamination—both point-source and diffuse.
3. Preparation and evaluation of an action plan stipulating politically determined regulations for future land use within the site-specific groundwater protection zones. The action plan has to be evaluated through a public planning process with a high degree of transparency and public participation. Moreover, it must include a timetable for implementation, and a description of who is responsible for implementing the plan. The protection zones and guidelines will be used to prevent groundwater contamination from urban development and agricultural activities and for planning the remediation of contaminated sites.

This three-step protection strategy is based on previous experience with groundwater protection in Denmark and abroad. In some parts of Denmark, water-supply wells have been successfully protected using two-level protection zones directed at contamination from point sources. The protection zones encompass a 10-m-diameter protection zone around the well indicated by a fence, and a 300-m protection zone directed at point sources such as leaching of wastewater (Fig. 2). The well-site protection zones correspond to the protection zones which have been used for several years in countries such as Germany (DVGW 1995). In Germany, the well-site protection zones are established as concentric circles with a radius ranging from 10 m to 2–3 km around the well. These zones are based on experience with the dilution and degradation of contaminants from point sources, and the radius is fixed on the basis of the transport time and the hydraulic properties of the water-bearing layers in particular. In Denmark, the new site-specific protection

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zones shall encompass the whole recharge area, with particular emphasis on protection of the capture zones. The protection zones will be established on the basis of model calculations of groundwater flow, and calculations of the degradation of the contamination from point sources and diffuse sources, taking into account knowledge of the local geochemical conditions. The new type of protection zone ensures that the protection is now also directed at contamination from diffuse sources such as agricultural use of fertiliser and pesticides, which can cause extensive loading from large areas.

The establishment of protection zones of this type imposes demanding requirements as to mapping of the water resources, because the restrictions associated with the zones have to be set at property level. The Quaternary geology in Denmark is very complex, and the existing geological maps are largely based on geological information from wells. As a consequence, the maps are not sufficiently detailed and precise to enable delineation of the new protection zones. The new protection zones designated as a result of the new investigations are shown in Fig. 2. As a result of the delineation of the vulnerable areas in the town of Beder, no further expansion of the town will be permitted. At the same time, it was decided that future urban growth in the area should take place south of the town Malling in an area situated outside the particularly valuable groundwater recharge area. Within the Beder town boundaries, regular campaigns are made to curtail the use of pesticides. It is completely prohibited to use them on publicly owned land. In all areas designated as vulnerable, agreements have to be entered into with farmers to limit the use of fertiliser and pesticides.

Broad-Based Support

Active protection of the groundwater is accorded strong public support in Denmark, where there is a long tradition for public participation in the decision-making process. The public participates in the planning process and implementation of the groundwater protection strategy at several phases. The interest organisations are incorporated in the work in the drafting phase and, before the plans can be adopted, they have to be presented at public meetings according to a fixed timetable, with the possibility to submit comments before their final adoption by the County Council. Information, transparency and cooperation are accorded high priority throughout the whole process. Successful implementation of the plans necessitates that broad acceptance is attained during the process from among the most important actors affected by the plans, especially the agricultural sector, the waterworks and the Municipalities. Certain types of restriction on agriculture can be compensated for economically—this applies, for example, to reduced use of fertiliser and set-aside. This compensation is paid by the EU or by the waterworks which directly benefit from the protection.

At the government level, the new strategy is supported by all the major political parties. Moreover, the strategy is increasing the confidence of the water-supply utilities that they will be able to continue to furnish the Danish population with an ample supply of pure, minimally treated drinking water.

The agricultural organisations also endorse the new, spatially dense mapping initiative as a major condition for accepting protection zones and associated land-use restrictions. This is very important, as spatially dense mapping entails considerable traffic on farmland, and the consent of the farmers is necessary for access to the 16,000 km^2 which will be surveyed using boreholes and ground-based geophysical methods over a 10-year period.

The forest area in Denmark is to be doubled from 10 to 20% over the next 80 years. State subsidies will primarily be granted for forestation within the new groundwater protection zones. It is expected that the protection zones will substantially influence future urban development and land use in Denmark.

Initiation of Hydrogeological Mapping as a Basis for Establishing Site-Specific Groundwater Protection Zones in Denmark

The initial decision to initiate detailed hydrogeological mapping of much of Denmark to facilitate the establishment of site-specific groundwater protection zones dates back to 1998, to some extent in preparation for Danish implementation of the new EU Water Framework Directive. The steps in the process are outlined in the Appendix.

The Danish Hydrological Setting

Denmark occupies a total area of some 43,000 km^2. The country consists of mainland Jutland (30,000 km^2), which is contiguous with Europe, and nearly 500 islands, of which more than 200 are inhabited. Denmark has been continuously populated and cultivated for over 3,500 years. Agriculture is one of the most important industries, and dominates the landscape. Most of the country consists of Quaternary deposits overlying Cretaceous chalk, limestone and Tertiary sand and clay. The topography is low-lying, reaching a maximum of 172 m above sea level. The combination of low topography and widespread, consolidated and unconsolidated aquifers ensures a plentiful and easily accessible water resource. Groundwater recharge averages 100 mm per year, but can vary in the range 50–350 mm. Currently, approx. 800×10^6 m^3 of water is abstracted annually. Household consumption by the 5.35 million inhabitants amounts to approx. 250×10^6 m^3 per year. Of this, 99% derives from groundwater.

Groundwater quality in Denmark is generally good, thus obviating the need for complex and expensive water purification. Moreover, the Danish water supply is decentralised, thus rendering expensive, lengthy pipelines serviced by large, central water plants unnecessary.

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The drinking water is not chlorinated and is of bottle-water quality at the tap. Altogether, there are around 2,900 public water supplies and some 70,000 small, private water supplies (boreholes or dug wells). Two thirds of the water abstracted for the national water supply derives from 200 municipal waterworks, and one third from private cooperative waterworks.

At the national level, the most important source of information about the condition of groundwater and aquifers is borehole data. The national archive of borehole data at the Geological Survey of Denmark and Greenland contains information dating back to 1926 and has hitherto been the primary source of geological and hydrological information about aquifers. In Aarhus County, there are some 11,400 registered boreholes of relevance for groundwater mapping, some of which are poorly documented. The corresponding value for the country as a whole is more than 100,000 boreholes, corresponding to an average of approx. 2.5 boreholes per km^2. This data density, however, allows for only a very general description of the complex geological composition of Danish aquifers.

Spatially dense geophysical mapping in and around Aarhus County during the period 1994–1997 has revealed that traditional mapping based solely on borehole data is too inaccurate for establishing site-specific groundwater protection zones and regulating land use within them. According to the Danish EPA guidelines (Danish EPA 2000b), geophysical methods are expected to play an important role in hydrogeological mapping in Denmark. Experience with the application of geophysical methods to the mapping of large-scale geological structures around the city of Aarhus (see below) has been of great value. In recent years, new geophysical mapping methods have been developed through a collaborative effort by Aarhus County, the Public Utilities of Aarhus and the University of Aarhus. The aim was to upgrade and rationalise fieldwork as well as to standardise the use of the mapping methods in a region. These new methods are very important tools for carrying out the spatially dense mapping needed to determine the extent, vulnerability and water quality of Danish aquifers as the basis for delineating protection zones. The geophysical mapping methods are described below.

Mapping of Aquifer Vulnerability

Aquifers are recharged by water seeping down through overlying, covering layers. The complexity of the path followed by the water on its way to the deeper-lying aquifers used for abstraction varies. How fast the water seeps down through the earth and what changes take place in the composition of the water very much depend on the nature of the soil layers through which the water passes (Vrba and Zaporozec 1994). Generally speaking, the biological/chemical/physical processes which take place when water passes through clay purify water better than when water passes through sand. Danish experience is that the degradation of substances which can contaminate the groundwater is considerable in the plough layer, but that the thickness and the composition of the clay layers overlying the aquifers are the most important geological factors as regards protection of the groundwater against the types of contaminant which cause most problems in Denmark. It is therefore important to carry out spatially dense mapping of clay thickness and of the distribution and variation of sandy areas (windows) in the soil layers overlying the aquifers. The dense geophysical mapping is necessary because the complex geology makes it impossible to produce sufficiently detailed maps, as there are usually only very few boreholes per km^2 and the majority of the boreholes are not particularly deep.

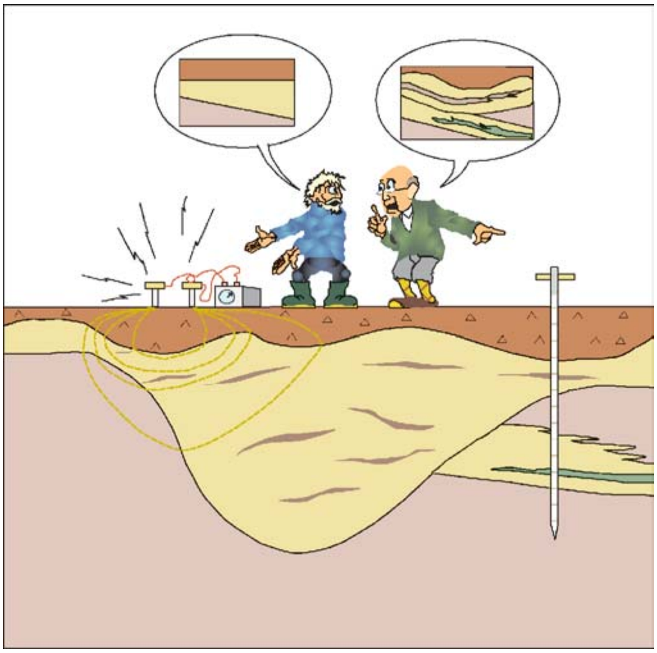

Fig. 3 The picture of the world is your own

As regards vulnerability mapping, the aim of the geophysical mapping is to determine the total clay thickness within the upper approximately 30 m of the subsurface, to delimit any sandy windows present in the upper clay layers, and to correlate the data with the information from the boreholes. Figure 3 illustrates the old problem that the interpretation of the surface geophysics reveals a simplified version of reality, while the boreholes reveal a wealth of detail which, however, represents only the actual site of the borehole. In Denmark it has long been tradition to primarily base mapping of water resources on geological interpretation of boreholes, and geophysics has only been used when it was in accordance with a previously established geological description.

Surface mapping with the new geophysical methods, combined with better interpretation programmes, has shown that it is time to do away with the old way of using geophysics. The quality with which water boreholes are described in Denmark varies considerably. Firstly, the choice of drilling method considerably influences the

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quality of the borehole samples which can be collected and, secondly, borehole drillers have only been required to have an education encompassing at least a minimum of geological knowledge since 2002. This means that a large number of borehole drillers are really good at drilling boreholes rapidly and cheaply but, unfortunately, also that they are less good at collecting geological information of reasonable quality. The borehole driller now has to send borehole samples to the national archive of borehole data at the Geological Survey of Denmark and Greenland for sample description, but many samples were previously only described by the borehole driller. It is now accepted in Denmark, however, that borehole data have to be viewed critically. In the future, therefore, geological interpretation must be based to a greater extent on all the available information, with the weight accorded to it being to a greater extent determined by its quality.

By carrying out measurements with pulled-array, continuous electrical profiling, it has been possible to map contiguous variations within the upper approximately 30 m of the subsurface which it would not be possible to map on the basis of borehole data alone. Based on combined interpretation of the geophysical measurements and the borehole information, it is possible to produce accurate maps of the total clay thickness within the upper approximately 30 m of the subsurface. Experience from investigations of water quality in particular has shown that if the total thickness of the clay layer within the upper 30 m of the subsurface comprises more than half of the total layer thickness at that depth interval, the groundwater is likely to be well protected against leaching of nitrate and most of the other contaminants which typically pose problems in Denmark. When the total clay layer thickness exceeds 15 m, it obviates the problem associated with fissures in the clay layer, as such fissures have not been observed to penetrate to depths greater than 7–8 m. The clay thickness maps correlate well with groundwater quality measurements, in that the composition of the groundwater in aquifers covered by more than 15 m of clay confirms that the clay layer offers good protection against contaminants such as nitrate leaching from the root zone.

The geophysical surface mapping was previously carried out using resistivity data in the Wenner configuration for 10-, 20- and 30-m electrode separations with manual electrode placement. That method is very expensive and time-consuming, and hence was only used for investigating small areas. In the early 1990s, Aarhus University developed the pulled-array, continuous electrical profiling method (PACEP) for obtaining electrical resistivity data in the Wenner configuration for 10-, 20- and 30-m electrode separations. The array pulled by a small caterpillar enables spatially dense measurements to be made along profiles (Fig. 4). The largest contiguous area in Denmark in which apparent resistivity has been measured (Wenner, a=30 m) is shown in Fig. 4. The majority of the pilot mapping studies carried out since the early 1990s are included in this figure.

Since the 1990s, the method has been improved to provide measurements at eight different electrode separations in the range 2–30 m, and is now known as the PACES method (pulled array continuous electrical sounding) with Pol–Pol configuration 2, 3, 4, 5 and 15 m as well as Wenner configuration for 10-, 20- and 30-m electrode separations (Sørensen 1996). Having more current electrodes, the new method provides better possibilities for interpreting in multiple layers. Fixed layer inversion for a selected depth of the top layer is used to determine the electrical resistivity and, hence, the presence or absence of protective clay covers. The acquisition of eight rather than three measurements at each location enables full, three-layer inversion of the data.

Further interpretation and data analysis are carried out using the programme package GGGWorkbench. The three Gs represent Geophysics, Geology and GIS. Geophysical processing and interpretation is carried out in a GIS environment integrating geophysical, geological and geographical data. The GGGWorkbench represents the newest generation of geophysical software from The HydroGeophysics Group (see the website http://www.hgg.au.dk). The GGGWorkbench operates on GERDA as its internal database for geophysical data. As mentioned above, GERDA is the national database for geophysical measurements (see the website http://gerda.geus.dk). This new tool enables far more comprehensive, geology-related interpretation of large amounts of geophysical data to be performed than has previously been possible (Fig. 3).

Aquifer Delineation

Aquifers in Denmark often occur as buried valleys eroded into the Tertiary clay substratum, and are usually interconnected to some degree. The buried valleys are often unrecognisable in the terrain. It is important to delineate the regional structures and their interconnectivity in order to be able to assess potential areas for water abstraction, to quantify regional resources, and to identify aquifers which are vulnerable due to the nature of their overlying soil layers. As the buried valleys are typically 200–300 m deep and often up to 1 km wide, they are difficult to delineate using boreholes, even in areas with a high borehole density. In Fig. 5, a small inset in the upper right-hand corner shows a map in which the course of valleys in the pre-Quaternary clay substratum has been determined solely from borehole data. Figure 6 shows two maps from the same small area illustrating the number and distribution of the boreholes down to different depths. Below this is a map showing the number of TEM (transient electromagnetic sounding) measurements in the same area. Within the map area, the borehole density is relatively high (three per km^2), and the quality of the description of many of the boreholes is reasonable (see upper map in Fig. 6). However, only 100 of the boreholes reach down to depths exceeding 50 m, corresponding to 0.6 boreholes per km^2 (see centre map in Fig. 6). Con-

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Fig. 4 Aquifer vulnerability. The *large map* (area 1,073 km^2) shows the apparent resistivity (Wenner, a=30 m) of the upper soil layers measured by pulled-array continuous electrical profiling (PACEP) or sounding (PACES). The individual profiles along which the measurements were made are indicated as *black lines*. Variations in the thickness of the clay cover are reflected as variation in resistivity. The clay content of the near-surface sediments is of great importance with respect to the vulnerability of the aquifers. These vulnerable areas are delineated much more accurately than can be determined from borehole data or other geophysical methods

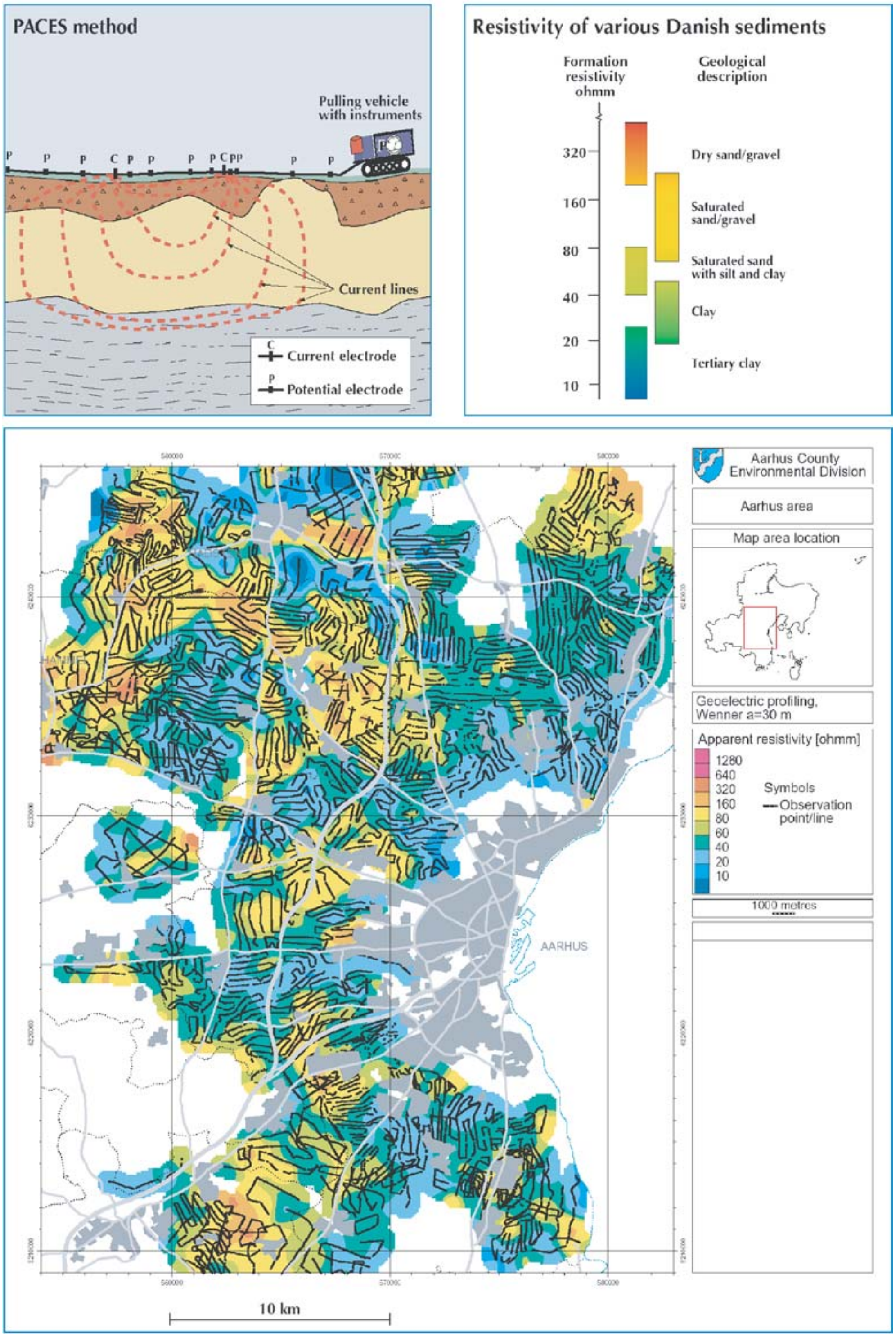

Fig. 5 Aquifer delineation. The *large map* (area 1,073 km^2), which is based on transient electromagnetic sounding (TEM) and pulled-array TEM (PATEM), shows the buried valleys in the pre-Quaternary clay substratum as *blue/green elongated areas* on the map. These comprise some of the most important aquifers. The *small map* in the *upper right-hand corner* shows the pre-Quaternary clay surface in the same area as the inset on the large map based only on data from boreholes. Observe the differences in detail between the two maps. Many of these complex and interconnected buried valleys were unknown before the TEM/PATEM studies, but have now been confirmed by new drilling surveys

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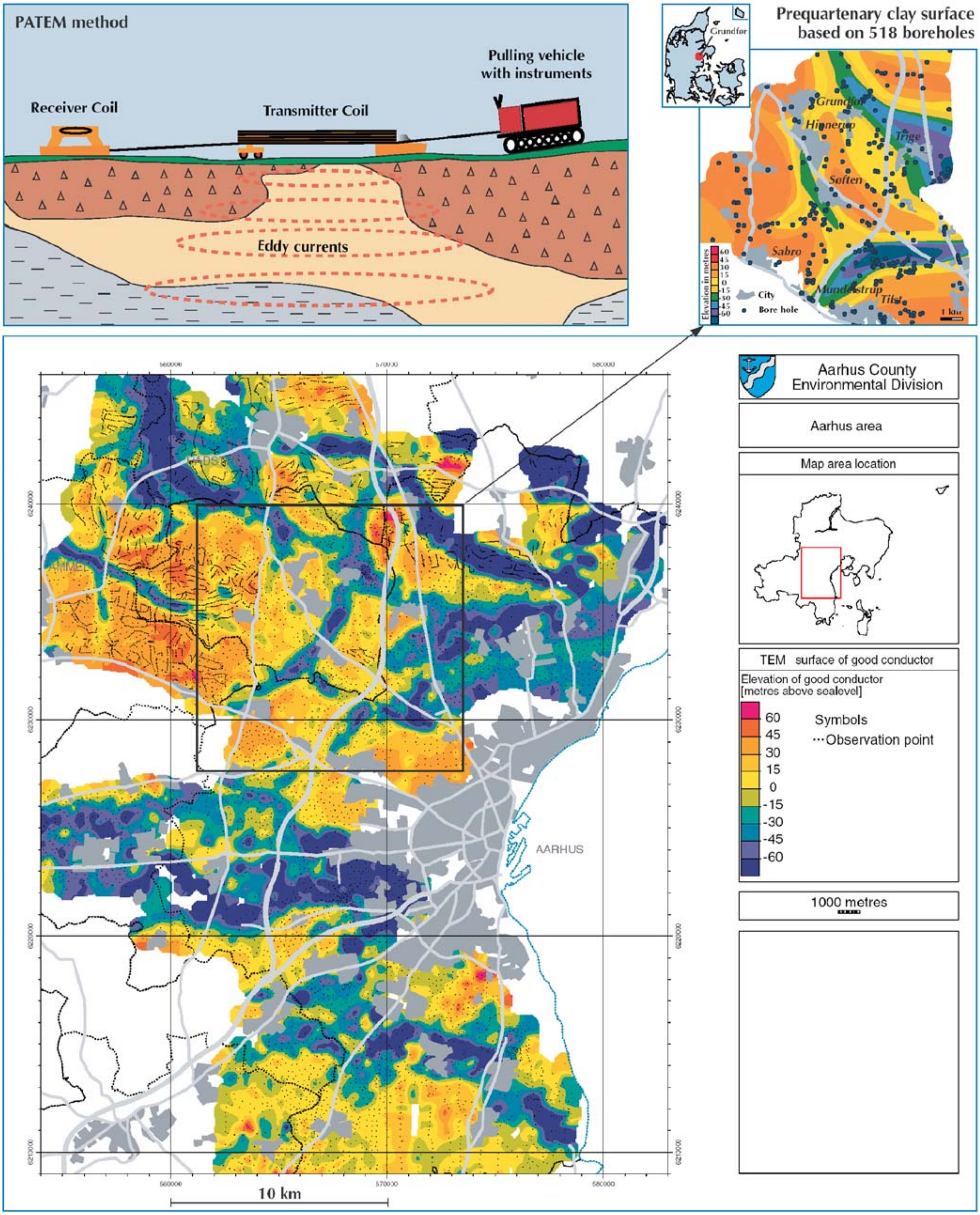

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siderable interpretation has therefore gone into the preparation of the contours of the valley shown in the upper inset in Fig. 5, where the valleys are more than 200 m deep. In comparison, the TEM measurement coverage is considerably greater (Fig. 6, lower panel). Traditional TEM requires a very large setup with a quadratic transmitter coil which transmits eddy currents down into the ground. A receiver measures how quickly the current dissipates. If the resistivity of the soil is high, e.g. as in sandy soil, the current dissipates rapidly, resulting in a rapidly dissipating measurement response. If the resistivity of the soil is low, e.g. as in clayey soil, the current remains longer, resulting in a slowly dissipating measurement response. The measurements enable the bed of the buried valleys to be determined and provide a rough measure of the extent to which the valleys are filled with sand or clay. To facilitate acquisition of high-density data, the University of Aarhus developed a continuous recording system known as the pulled array TEM (PATEM; Sørensen et al. 2000). The setup is illustrated in Fig. 5, which shows a TEM map of the largest contiguous area in Denmark hitherto mapped using the TEM method. In recent years, transient electromagnetic sounding (TEM) has been used extensively and successfully to delineate the layers of electrically conductive clay which border the aquifers (Christensen and Sørensen 1998).

Despite the fact that TEM has only been used in Denmark for a limited number of years, a large number of investigations have been performed. As of October 2003, the national geophysics database GERDA contained the more than 45,000 TEM measurements hitherto carried out in connection with the nationwide hydrogeological mapping of the water resources. The relatively few boreholes located in the mapped areas compared with the number of TEM soundings are in good agreement with the TEM interpretations with respect to the depth to the pre-Quaternary clay surface in particular, which is apparent in the TEM interpretations as a low-lying, particularly well-conducting layer. In Aarhus County alone, the TEM data have been confirmed using 150 new, deep, dedicated monitoring boreholes in addition to the existing boreholes.

High-quality interpretation of TEM data can reveal the major heterogeneities of most aquifers. However, high-density data are required to reveal coupling effects in the data due to man-made conductors (Sørensen et al. 2000). As the measured coupling effects have a considerably faster lateral variation than the effects of the geological variations in Denmark, spatially dense data will reveal

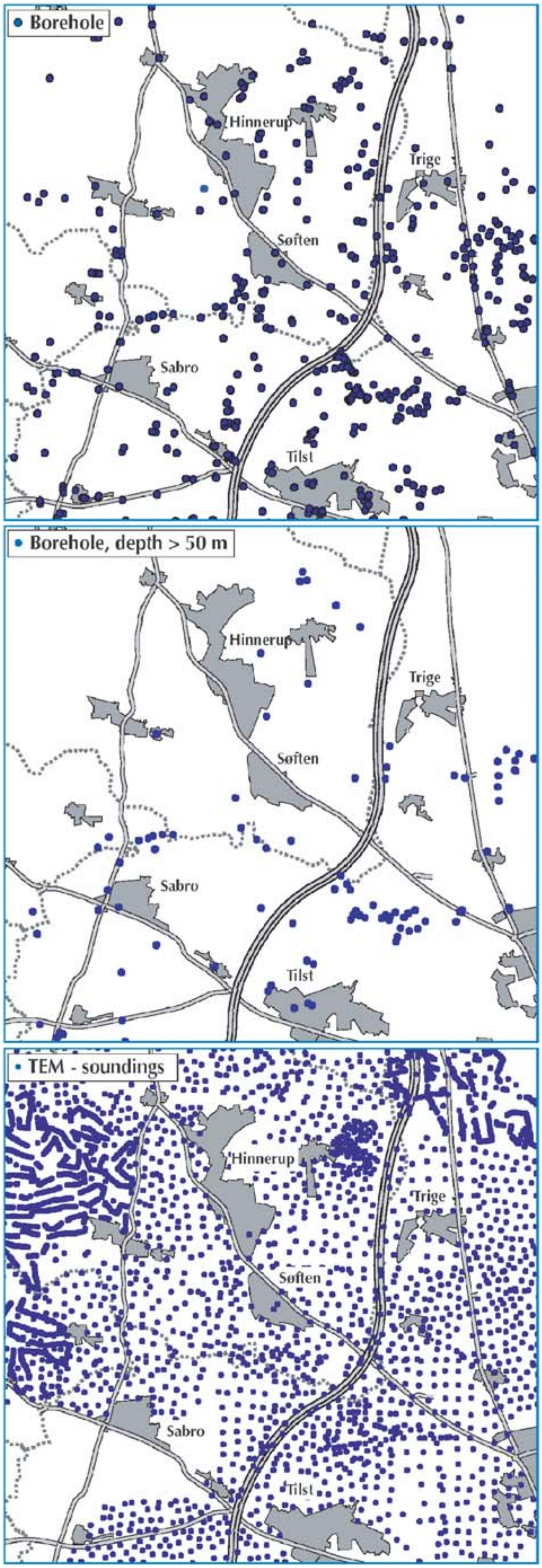

Fig. 6 The density of various types of data within the small inset shown in the *upper right-hand corner* of Fig. 5. The *upper panel* shows borehole density, which is three boreholes per km^2. The *centre panel* indicates those boreholes which are deeper than 50 m, which only applies to one in five of the boreholes in the area, corresponding to a density of only 0.6 boreholes per km^2, In comparison, the *lower panel* shows the density of TEM soundings in the area, which corresponds to 19 TEM soundings per km^2

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whether the variations in these are attributable to coupling effects.

Heterogeneities of the order of magnitude which can be mapped using the TEM method are of great importance to groundwater flow patterns within aquifers and, hence, to interpretation of measured groundwater quality at any given location. To ensure the quality of the data and their interpretation, it is necessary to perform laterally dense measurements along profiles or in grids. Measurements are acquired in profiles separated by an average distance of 250 m. Processing increases the data density within the profile to one sounding every 25–50 m, in contrast to a typical single-site density of 250 m between soundings.

As shown in Fig. 5, systematic spatially dense mapping with TEM reveals numerous structures of major hydrogeological importance, and delineates these structures and their interconnections. The small map in the upper right-hand corner of Fig. 5 shows that even in an area with a high borehole density (more than 500 in the area shown), the structural complexity is only weakly described by the borehole data compared to the remarkable level of detail revealed on the TEM map. The new structures identified have now been verified by survey boreholes. Note the very small valley in Fig. 5 which can be seen just outside the left side of the inset indicated on the large map. This valley is approx. 600 m wide and has been shown to be 110 m deep, possibly even deeper in some parts. This valley has now been verified by four boreholes. The valley was previously unknown, and there are no visible signs in the present terrain to indicate the presence of a buried valley. It would have taken a large number of boreholes to reveal this buried valley with the aid of boreholes alone, as it is markedly cut down into an otherwise flat, pre-Quaternary clay plateau.

In 2002, the HydroGeophysics Group further developed the TEM method into the SkyTEM method, with greater transmitter strength and a 12×12 m transmitter coil which can be mounted beneath a helicopter. The first experiments indicate that the airborne measurements are of the same quality as those made on the ground using PATEM equipment (Sørensen and Auken 2003).

Mapping of Groundwater Quality

The Danish drinking-water strategy aims to obviate the necessity for purification of raw water at waterworks. Detailed knowledge of the quality and the variation in quality of the water in aquifers is thus essential. For economic and practical reasons, however, it is impossible to acquire such detailed information by means of traditional drilling techniques.

The Ellog auger drilling method (Sørensen and Larsen 1999) was developed to rapidly, inexpensively and relatively unobtrusively collect water samples and measure the electrical resistivity of the subsurface. With this method, electrical resistivity and gamma logs are recorded continuously during drilling with an auger drill which also

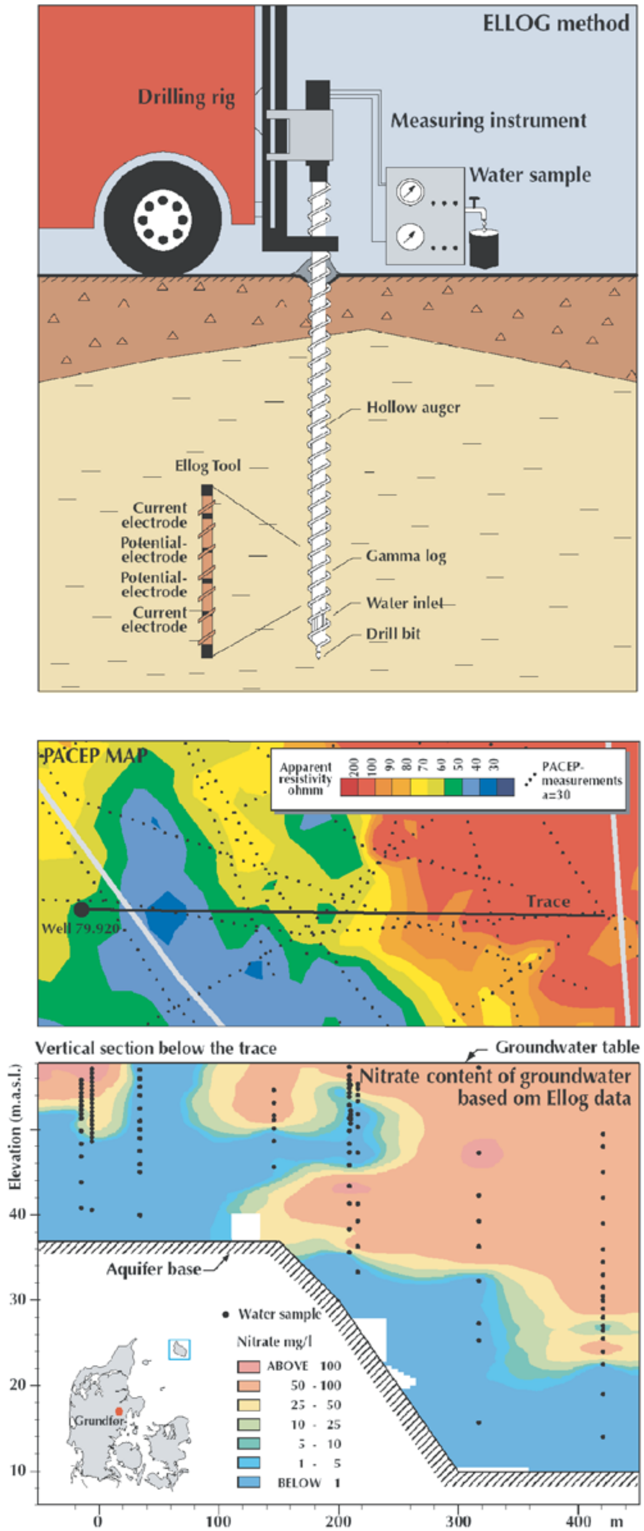

Fig. 7 Aquifer water quality. Pulled-array continuous electrical profiling (PACEP) reveals areas of high resistivity (and thus of low clay content), indicating vulnerability to nitrate leaching. The high nitrate content in the deeper parts of the aquifer below the high-resistivity area shown on the PACEP map (*centre panel*) is documented in the *lower panel*, which shows the nitrate concentration determined from Ellog data for a vertical section along the profile indicated on the PACEP map

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enables undisturbed groundwater samples to be collected at selected levels (Fig. 7). Using the method it is possible to drill to a depth of 60–80 m, depending on the geological conditions. Because the water is sampled at the same level as the geophysical measurements, the Ellog method enables the variation in water quality to be correlated with the geophysically interpreted lithology.

Ellog data can be correlated with the surface geophysical data to develop a complete picture of water quality in an aquifer (see, for example, Fig. 7). The PACEP map reveals the variation in the resistivity of the upper 30 m of the subsurface. Areas with an apparent resistivity greater than 50–60 ohm metres are predominantly sandy and comprise “windows” whereby contaminants such as nitrate can leach to the groundwater. The lower part of Fig. 7 is a vertical section along the profile shown on the PACEP map. The nitrate content in the groundwater was determined by analysis of the Ellog water samples. Comparison of the two parts of the figure reveals that the nitrate concentration of the groundwater was much higher, and the nitrate contamination penetrated to much greater depths beneath the sandy areas than beneath those protected by clay. The Ellog measurements are used to support interpretation of vulnerability to contamination and to prepare the clay thickness maps.

Combined Interpretation of Data

The new mapping initiative includes setting up conceptual geological models and hydrological models for use in analysing the geological information and determining the water balance, the effect of climatic change, the extent of river basins, the capture zone of water-supply wells and the contamination risk. Particle path calculations in particular have been used to delineate the capture zone. For the past 15 years, Aarhus County has used the MIKE-SHE model programme package to model major areas of up to 1,600 km^2 (see http://www.dhisoftware.com/mikeshe). Model resolution is normally 250×250 m (corresponding to the average distance between the geophysical measurement lines). In recent years, smaller areas have also been modelled using the programme package Groundwater Vistas (see http://www.groundwatermodels.com), which is based on the MODFLOW code developed by the US Geological Survey (see http://water.usgs.gov/nrp/gwsoftware/modflow.html) and, to a lesser extent, Processing Modflow (see http://www.pmwin.net). The model calculations are in turn used to draw up site-specific groundwater protection maps and to establish protection zones.

During the past four years, all the major water utilities in Denmark have gained experience in all the aspects of spatially dense hydrogeological mapping. The cooperation between the HydroGeophysics Group at Aarhus University and the Counties is very important for ensuring high quality in the collection and interpretation of geophysical data. The HydroGeophysics Group at Aarhus University works intensively to continually improve the measurement methods and data interpretation. The extensive measurement campaign has shown that geophysics is presently a cheap and effective method to fill in the geological picture between boreholes. The practical work of undertaking the geophysical measurements and interpreting the results has been carried out by private consultancy firms. The quality-assurance procedures for the geophysical measurements and the programming of interpretation programmes are paid for by the Counties and the University. The work is carried out by the HydroGeophysics Group and made available free of charge to the consultants. Measurement data have to be submitted to the national geophysics database GERDA. The cost of carrying out the geophysical measurements in Denmark has now reached a stable level. The following price examples encompass measurement, interpretation and comprehensive reporting with various theme maps. The costs are based on mapping tasks encompassing an area of at least 10 km^2, and include 25% Danish VAT. Providing these assumptions are met, a single TEM sounding will cost € 140, with 16 soundings normally being made per km^2. PATEM will cost € 750 per linear km, with four lines needed per km^2, while PACES will cost € 550, with four lines needed per km^2, and Ellog drilling will cost approx. € 125 per drilled metre.

Experience with Groundwater Protection in Aarhus County

The establishment of site-specific protection zones, with regulation of land use within them, has proven successful at a waterworks on the island of Tunø within Aarhus County (Aarhus County 2001; Thomsen 2003). About 12 years ago, the only aquifer on the island was highly contaminated with nitrate, and measures needed to be taken to rectify the situation. It was calculated that the establishment of protection zones and associated regulation of land use would be cheaper than the introduction of water treatment. The effect of the site-specific protection zones has been monitored since 1990, and the nitrate content of the water in the upper layers of the aquifer has declined to a level below the EU limit value. In a few years time, water quality is expected to be acceptable in the whole aquifer.

The success of this and other attempts to protect groundwater is partly due to the fact that they were based on spatially dense geological and hydrological mapping combined with modelling of the hydrological system. The models have been used to delineate the capture zones feeding the aquifer and determine the effect of sources of contamination. The land-use regulations imposed were specific to these protection zones and were accepted by the landowners because of comprehensive documentation.

In Aarhus Municipality, the total thickness of clay layers above the aquifers has been determined by combined interpretation of geophysical and geological data. Groundwater protection zones are now being established in the particularly valuable water-abstraction areas, on the

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basis of the spatially dense geophysical mapping and hydrological modelling. After negotiation with Aarhus County, Aarhus Municipality has accepted the importance of active protection of the groundwater resources as a basis for ensuring a future drinking-water supply of good quality. All new urban development around the city of Aarhus must take groundwater interests into consideration, and urban development will not usually be permitted in areas where natural protection of the groundwater is poor. Moreover, plans to develop 1,000 ha of land designated for urban development have been abandoned in 2001 as a result of the new information. In 1997, Aarhus County Council decided that no new areas could be designated for urban development before spatially dense hydrogeological mapping of the areas in question had been carried out. It is estimated that the groundwater is protected by clay layers in 50% of Denmark.

The Water Framework Directive and the European Community

European Community waters are under increasing pressure from the continuous growth in demand for sufficient quantities of good-quality water for all purposes (Thomsen 1993; European Environment Agency 1995, 1999, 2000, 2001). An EU directive establishing a framework for Community activity in the field of water policy was thus enacted in 2000 (EU 2000). The main aspects of this innovative approach to protection of the aquatic environment are outlined in the Appendix.

With respect to groundwater, the Directive specifically requires Member States to implement the measures necessary to prevent, limit and remediate contamination of all bodies of groundwater in order to reduce the level of purification required to ensure the drinking-water supply, among other means through the establishment of "safeguard zones" for those bodies of groundwater. The good experience with the new geophysical methods shows that it is possible to carry out the task without imposing major additional costs on consumers.

Conclusion

It is expected that the site-specific groundwater protection zones currently being established to ensure the future water supply in Denmark will substantially influence future urban development and land use. It is thus important that the protection zones are based on spatially dense hydrogeological mapping encompassing geophysical and geochemical data. The geophysical mapping will be performed using PACES and PATEM (now SKYTEM) combined with Ellog auger drilling studies. The site-specific protection maps designating the protection zones and associated regulation of land use will be used to prevent groundwater contamination from urban development and agricultural activities, and for planning remediation of contaminated sites. Mapping and establishment of the groundwater protection zones will take place over a 10-year period at a total cost of around € 120 million. During the 10-year period, consumers will pay the County Councils a € 0.02 surcharge per m^3 of water consumed, i.e. less than € 4 per family per year. This ongoing Danish initiative to draw up spatially dense hydrogeological maps of the 37% of Denmark designated as particularly valuable water-abstraction areas will have to be adjusted to the new EU Water Framework Directive, as the latter encompasses all water bodies.

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Appendix

Chronology of Dense Hydrogeological Mapping in Denmark

- December 1998: the Danish Parliament decided that the County Councils should be responsible for detailed mapping of the water resources within a combined area equivalent to 37% of Denmark.
- August 1999: the County Councils established a technical advisory group responsible for coordinating the groundwater protection scheme. Three subgroups were established to solve practical problems within geophysical mapping, hydrological modelling and geochemistry respectively. The County Councils signed a five-year contract with the Department of Geophysics, University of Aarhus, called HydroGeophysics Group, to enhance geophysical data acquisition and interpretation through workshops and the development of improved quality assurance procedures for measurement of geophysical data, data processing, modelling and analysis software. See the website http://www.hgg.au.dk
- March 2000: the County Councils signed a contract with the Geological Survey of Denmark and Greenland for constructing and managing the national geophysical database. The mapping data can be transferred to and from the database via Internet. Together with the software company NetNord, Aarhus County Council, the University of Aarhus, the Geological Survey of Denmark and Greenland and the Spatial Planning Department developed the geophysical database system known as GERDA. See the website http://gerda.geus.dk
- May 2000: the County Councils signed a contract with the Geological Survey of Denmark and Greenland to provide instruction in the use of hydrological modelling. See the website http://vandmodel.dk/
- June 2000: the Minister for the Environment issued a statutory order stipulating how the County Councils are to implement the groundwater protection scheme (Danish EPA 2000a).

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- August 2000: the Danish EPA published guidelines for the detailed mapping work and establishment of groundwater protection zones (Danish EPA 2000b).
- 2001: the County Councils established action plans including a timetable for implementing the measures necessary to protect the groundwater.
- 2000–2010: detailed mapping and groundwater protection plans to be developed for 37% of Denmark.
- 2000–2015: EU Water Framework Directive to be implemented.
- 2001: the County Councils signed a five-year contract with the Department of Geology, University of Aarhus, to ensure development of new methods, among other things for the identification of Quaternary meltwater sediments.

The EU Water Framework Directive

In summary, the new Directive

- protects all waters—rivers, lakes, coastal waters and groundwaters,
- sets ambitious objectives to ensure that all waters meet "good status" by 2015,
- sets up a system of management within river basins,
- ensures reduction and control of pollution from all sources such as agriculture, industry, urban areas, etc.,
- ensures active participation of all stakeholders, including local communities, in water management activities, and
- requires water-pricing policies and ensures that the polluter pays.

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