# Groundwater monitoring in Denmark: characteristics, perspectives and comparison with other countries

**Lisbeth Flindt Jørgensen · Jens Stockmarr**

**Abstract** More than 99% of water use in Denmark is based on groundwater. Denmark has had a comprehensive national groundwater-monitoring programme since 1988 based on 74 well catchment areas and six small agricultural catchments with more than 1,500 screens at different depths for regular, mostly annual, water quality sampling. In addition, water samples from 10,000 abstraction wells are analysed every 3–5years. The water is analysed for main components, inorganic trace elements, organic micro pollutants, and pesticides and their metabolites. A unique feature is the 20-year time-series data of inorganic pollutants. Groundwater modelling supports traditional monitoring to improve the conceptual geological understanding and to assess the quantitative status and the interaction between groundwater and surface water. The programme has been continuously adjusted to incorporate new knowledge from research programmes and meet new policy demands, currently the European Union Water Framework Directive, particularly with respect to an increased focus on quantitative aspects and on the groundwater/surface water interaction. The strengths and weaknesses of the Danish programme are assessed and compared with other national groundwater-monitoring programmes. Issues discussed include: strategic considerations for monitoring design, the link between research and monitoring, and adoption of responses to climate changes.

**Keywords** Groundwater monitoring · Groundwater development · Groundwater quality · Denmark · EU water framework directive

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## Introduction

Groundwater is an extremely important resource for drinking-water production, irrigation and industry around the world. In Europe, about 75% of drinking water derives from groundwater, e.g. almost 100% in Denmark and Austria and more than 80% in Iceland, Switzerland and Italy (Quevauviller 2008a; Scheidleder et al. 2000).

Danish drinking water supply is based on a key principle of abstraction of pure groundwater or groundwater with very low impact from anthropogenic pressures. This translates into a practice where, after abstraction, the groundwater undergoes simple treatment comprising aeration and subsequent passage through a sand filter to remove precipitated iron- and manganese-oxides before distribution to consumers. In cases where groundwater has very low pH, the water is carbonated. Thus, the inherent quality of groundwater becomes critical, and surveillance of this through formal monitoring programmes has, since 1988, been of priority to the country (Danish EPA 1989; Stockmarr 2005).

In an international review of groundwater-monitoring programmes, Jousma and Roelofsen (2004) noted that national programmes differ significantly in objectives and design. A comparison of recent descriptions of national programmes (Onorati et al. 2006; van Geer 2005; Schwaiger 2003; Lee et al. 2007; de Caritat and Kirkhusmo 1995; He and Li 2006; Ward et al. 2004; Gosk et al. 2006; Stockmarr 2005) illustrate that they have developed differently, depending upon the differences in hydrogeological conditions as well as the socio-economic and political context under which they have been developed. This reflects that groundwater monitoring typically has been considered a national task with limited incentives to harmonise the differing approaches. In fact, Grath et al. (2008) state that as a wide variability in groundwater systems exist across Europe, a prescriptive approach is not appropriate or possible when setting up guiding rules on groundwater monitoring. Instead, a risk-based approach considering over-arching objectives and priorities as well as variations in hydrological and environmental factors is recommended.

Worldwide, groundwater is gaining increasing importance as a source of water supply. As an example, the European Union (EU) has within the last few years adopted new water

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management legislation with the Water Framework Directive (WFD; EC 2000) and the Groundwater Daughter Directive (GD; EC 2006). The WFD prescribes member states to ensure that all water resources, both surface and groundwater, within the union must attain good water status by 2015. The GD addresses the groundwater only and prescribes that member states actively must implement specific measures to prevent and control groundwater contamination. As a result, the European Commission recently has prepared guidelines for groundwater monitoring (EC 2007). This is probably the first comprehensive international guideline of its kind, although specifically addressing groundwater quality. There is therefore an admitted need to learn from national experiences and develop common recommendations for design and operation of groundwater-monitoring programmes, recognizing regional and national peculiarities.

The objectives of this report are (1) to describe objectives, background, methodologies and key results from the Danish Groundwater Monitoring Programme and to describe how the programme has adapted to changing objectives during the last 20 years; (2) to compare the Danish programme with other national monitoring programmes from other countries with water supply structures similar to that of Denmark but also countries with other drinking water sources than groundwater; and (3) to derive common experiences and guiding principles of relevance for meeting the challenges of groundwater monitoring in relation to the new European legislation (WFD and GD).

## The Danish Groundwater Monitoring Programme

### *Physiographic setting*

Denmark is a small country, about 43,000 km$^2$ with a population around 5.5 million. The landscape is cultural with hardly any pristine nature left as most of the land has been altered by man during the last centuries. Today, about two-thirds of the area is agricultural land, about 6% is urban and less than 20% is natural (wetlands, forest, etc.).

The topography is modest, the highest point being about 170 m above sea level. Undulating hills, modified by glaciers that have covered the country several times during the Quaternary, dominate the landscape, with flat outwash plains in the west arising from the melting of the latest glacier about 10,000 years ago. Thus, the uppermost sediments are predominately sandy and clayey tills and sandy or gravelly meltwater deposits allowing groundwater recharge in most areas. The Quaternary sediments are underlain by Tertiary and Cretaceous Limestone and Chalk in the eastern parts and by Tertiary sand- and clay-formations in the western parts of Denmark, of which the latter hold important, often deeper lying, aquifers. In the eastern parts, the top of the Limestone and Chalk often hold important groundwater resources in fractures originating from the pressure of the past glaciers. A simplified sketch diagram of the Danish geology is shown in Fig. 1.

Streams are mainly groundwater-fed and relatively small compared to European rivers, both in terms of lengths and discharge. The climate is coastal temperate and the average annual precipitation ranges between 600 mm/year in the south-east and 1,000 mm/year in the west.

As an example on how groundwater influences groundwater quality, Fig. 2 shows nitrate concentrations in groundwater across Denmark. The spatial distribution of nitrate in the aquifers varies according to the geology of the late Quaternary. West of the Weichselian glaciation borderline, the geology is dominated by shallow, unconfined aquifers overlying deeper, confined Quaternary and Miocene

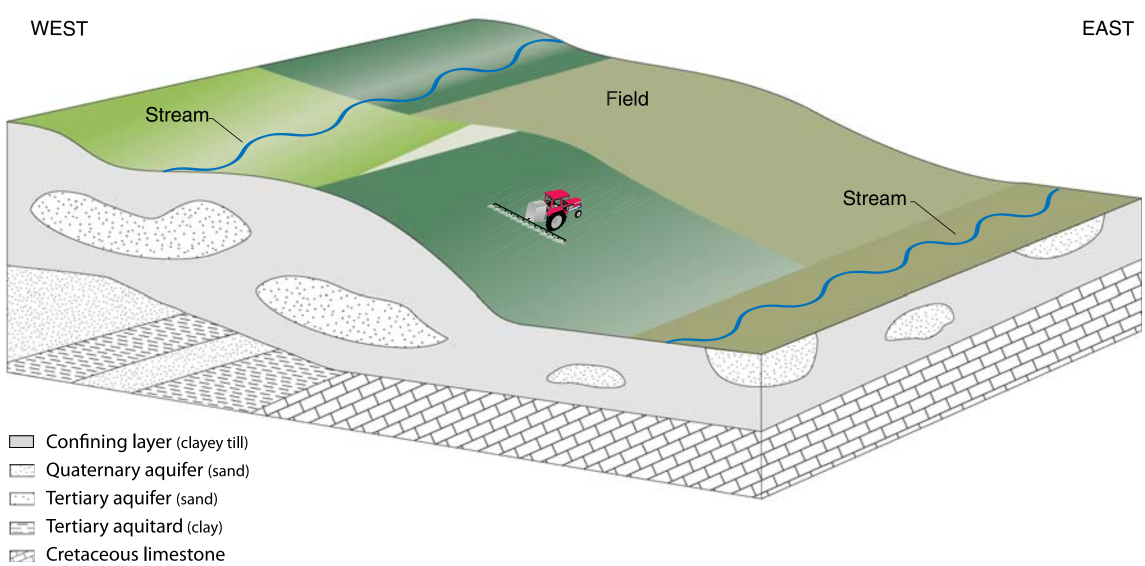


**Fig. 1** Simplified sketch of the Danish geology (not to scale). The tractor in the *middle* symbolizes agriculture

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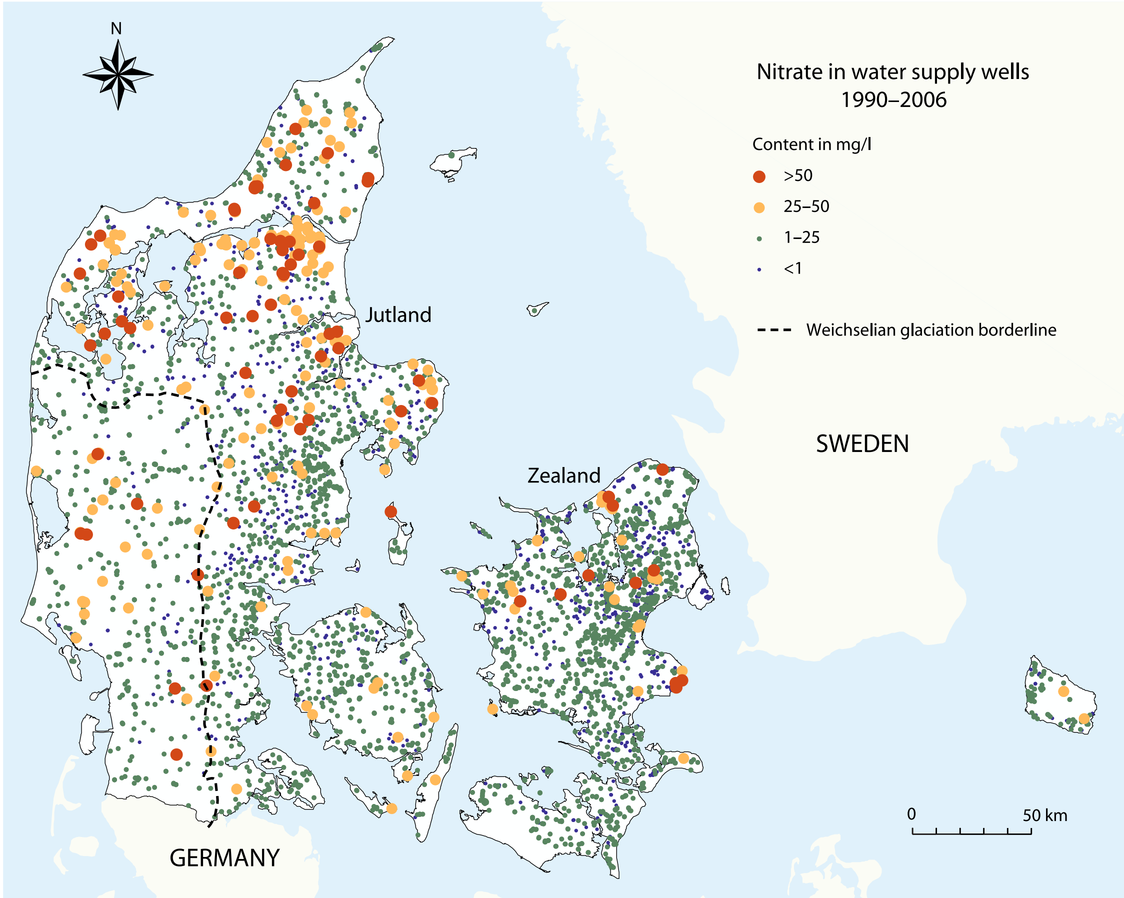


**Fig. 2** Distribution of nitrate in groundwater from abstraction wells for drinking water production (GEUS 2007)

sands. East and north of the glaciation borderline, aquifers based on sandy meltwater deposits and pre-Quaternary limestone are generally covered by clayey till, which either reduces or prevents nitrate infiltration to the major aquifers, except where the Quaternary cover is thin and overlies fractured chalk or limestone. This is especially the case in a NW–SE belt across northern Zealand over the central eastern and the northern part of Jutland, where nitrate levels are relatively high.

## Background

The Danish Groundwater Monitoring Programme is a part of the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environment, NOVANA (Svendsen and Norup 2005). The programme began in the late 1980s when oxygen depletion and fish kills (due to excessive nutrients leaching in the inner marine waters) caused a public debate. As a result, the first action plan on the aquatic environment was agreed upon in 1987 (Danish Ministry of the Environment 1987). Several measures to reduce diffuse and point sources of nutrients were introduced and monitoring programmes on coastal waters, surface water, groundwater, etc. were established. The main purpose of these was to follow the change in nutrient loads to the aquatic environment and to trace and record the effects of the implemented measures. The first comprehensive monitoring programmes were initiated in 1988 (Danish EPA 1989). However, at that time initial groundwater quality monitoring had already been established (Andersen 1987; Czakó 1994). A national groundwater-level monitoring network was initiated in 1951 but local targeted monitoring started much earlier; as an example Copenhagen Water Supply started monitoring groundwater levels back in the 1880s.

Groundwater sampling is carried out by regional authorities and analyses, according to international standards, are conducted by laboratories appointed by the Ministry of the Environment. The Geological Survey of Denmark and Greenland (GEUS) is in charge of the monitoring programme and has produced associated technical specifications and guidances on monitoring network design, well construction, sampling, analysis, etc. Groundwater data from the monitoring are gathered in a national public available database at GEUS and results reported annually.

The Danish Groundwater Monitoring Programme had an annual budget of 4.7 million € in the period from 1998–2003. From 2003, the budget was reduced to 3.3 million €, to 2.3 million € in 2007, and even future reductions have been notified.


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## Objectives of the programme

The Danish Groundwater Monitoring Programme was fully operational in 1989. It has been adjusted several times, partly due to new knowledge or emerging groundwater quality problems and partly due to revisions of the Action Plan on the Aquatic Environment, but still has the overall objectives to (Svendsen et al. 2005):

– Provide the necessary knowledge on the quantitative and qualitative status of groundwater and the trends and causes of changes therein. The overall aim is to ensure that there will be sufficient water of adequate quality to meet both society's water supply needs and that of natural habitats to achieve the desired environmental objectives
– Document the overall effect of the action plans on the aquatic environment, and other measures, on the quality and quantity of the groundwater resource, including whether the objectives are achieved
– Fulfil Denmark's obligations according to relevant European legislation and international conventions
– Help strengthen the scientific foundation for future international initiatives, national action plans, administration and other measures to protect and exploit the groundwater resource, including contribute to the development of various tools (e.g. models) and the achievement of a better understanding of the relationship between groundwater and surface water
– Regularly inform the public about the qualitative and quantitative status of the groundwater

## Monitoring design

*Groundwater-monitoring areas*

The Danish Groundwater Monitoring Programme comprises a network of 74 well catchment areas, dedicated to monitoring, spread almost evenly across Denmark, see Fig. 3. As the figure show, they are not restricted to the drinking water areas, where groundwater protection activities are concentrated. This is partly due to the fact that the drinking water areas were delineated later and party as the groundwater-monitoring areas are intended to represent all types of groundwater, geological settings and the different impacts of anthropogenic origin. Most of the

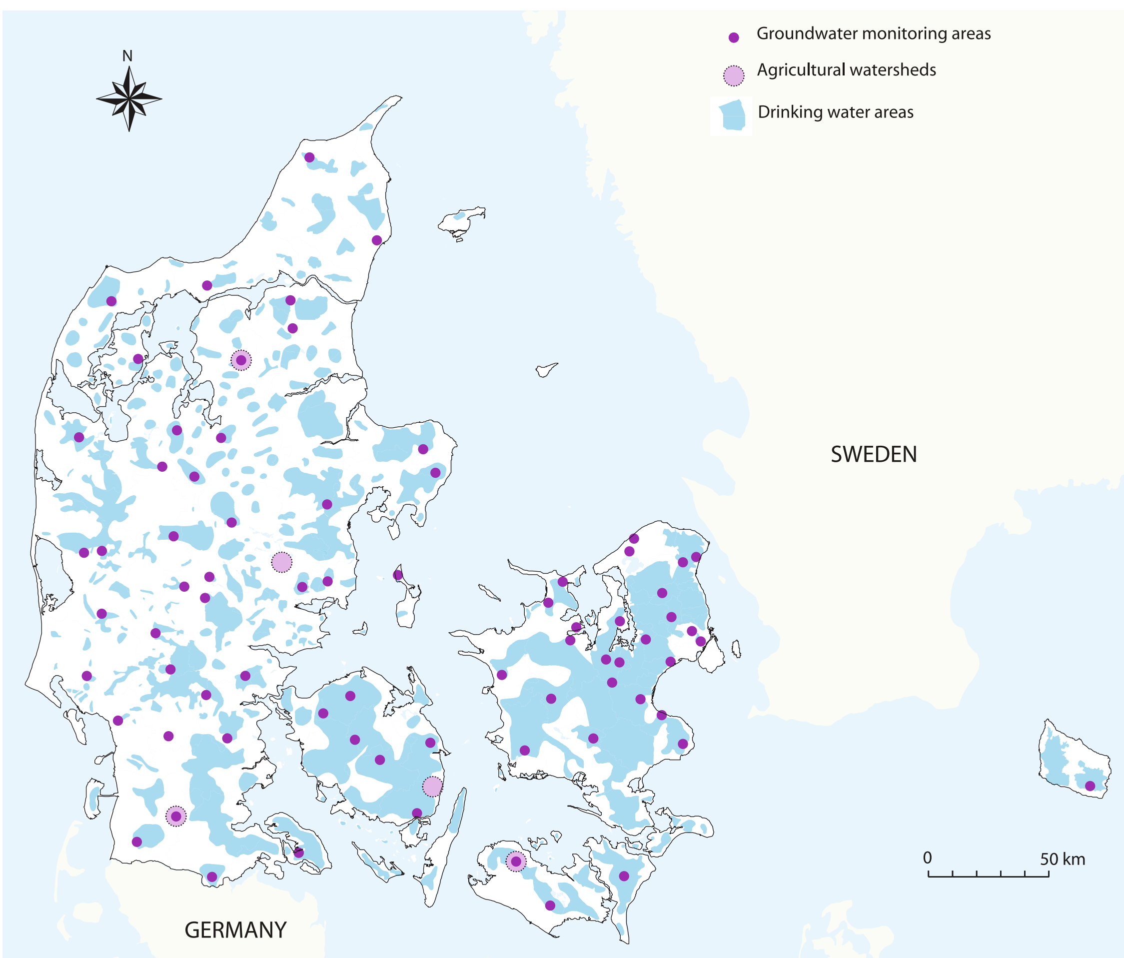


**Fig. 3** Groundwater-monitoring areas in Denmark


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monitoring areas are, however, situated in the countryside and only few in or close to cities, as the primary concern from the start of the programme was on agricultural nutrient pollution. The areas vary in size from five to 50 km$^2$ and each contains up to 25 monitoring wells. The wells are, as far as possible, established to allow surveillance of the water quality in both primary and secondary aquifers, see Fig. 4.

At the time of establishment, each area was delineated based on the catchment area of a central groundwater abstraction well for drinking water production. During the last 20 years, some of these abstraction wells, however, have been closed because of malfuncting or groundwater quality problems, thus changing the local flow scheme. However, groundwater monitoring has continued in most of the areas to follow changes in groundwater quality. The known extent of recharge areas have been adjusted during the last 10 years as a result of local modelling studies, resulting in closing of some wells and establishment of new. As shallow groundwater appeared to be underrepresented in the programme, new short wells have recently been established for monitoring younger groundwater that recharges to deeper aquifers.

Most wells are sampled every year and some several times a year (see Table 1). The parameters analysed are grouped into main components (such as chloride, nitrate, sulphate, ammonium and iron), inorganic trace elements (e.g. arsenic, copper and nickel), organic micro-pollutants (e.g. aromatic hydrocarbons, chlorinated solvents and phenols) and pesticides and their metabolites.

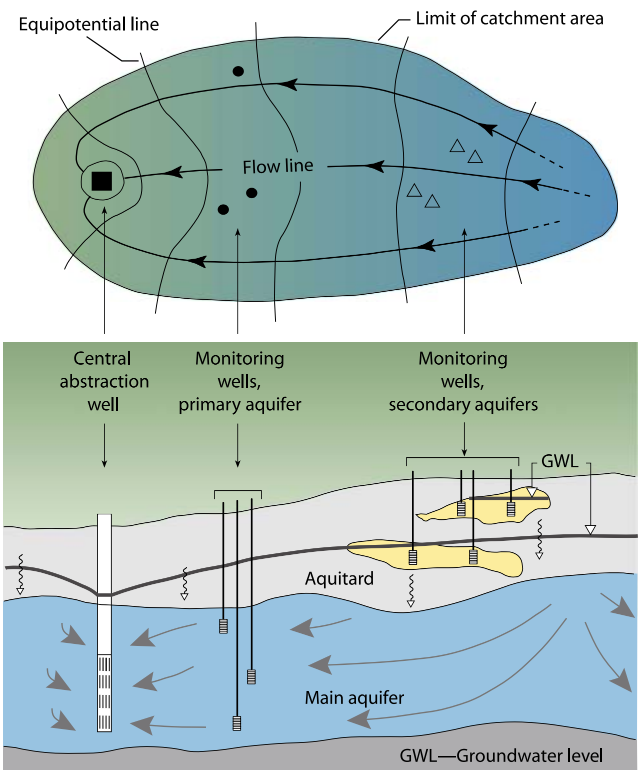


**Fig. 4** General outline of a groundwater-monitoring area seen from above and in cross-section

Figure 5 illustrates one of the results from the monitoring programme. Depth-specific nitrate concentrations from all wells in the monitoring programme, as well as from abstraction wells (see section Data from drinking water supply companies) are compared. Not surprisingly, the figure shows that nitrate occurs mainly in the upper layers, with more than 15% of the wells exceeding the quality standard for drinking water (50 mg/l) in the uppermost 10 m, but high nitrate concentrations are also found in deeper aquifers illustrating insufficient redox-capacities to remove nitrate.

### *Agricultural catchments*

In five agricultural catchments, 100 wells monitor the shallowest groundwater 1.5–5 m below the ground-surface, integrating the understanding of agricultural practice with the quality of soil water, groundwater, subsurface drains and streams. Agricultural practice on a field scale is recorded by interviews with farmers. The catchment areas are small, between 5 and 15 km$^2$. The fate of nutrients and, thus, the quality of the shallow groundwater below fields in common agricultural practice is recorded (Rasmussen 1996). Two of these catchments are situated in clayey areas, three in sandy. The wells are sampled 4–6 times a year (Table 1).

### *Multi-screened redox wells*

Six multi-screened wells each with about 20 screens at intervals of 0.5–1 m, reaching 30–45 m below surface, have been established to follow possible changes/migration in the oxidation/reduction front. This is particularly relevant for the fate of nitrate. The wells are sampled six times a year and analysed for at limited number of parameters (Table 1). Besides these wells, a system of eight multi-screened wells along a flow-line in a minor sandy catchment (Rabis Creek; Kristiansen et al. 1990) is sampled six times a year, also focussing on nitrate fate.

### *Groundwater level*

Quantitative monitoring was, until recently, carried out in a national network comprising 60 piezometric wells outside the groundwater-monitoring areas. Besides, most of the monitoring areas have one or more groundwater level monitoring wells. Other local project-related monitoring networks for specific purposes exist, but results from these are not a part of the national programme. A new national quantitative network is presently under establishment, based on delineation of groundwater bodies as prescribed by the WFD and GD. This delineation is derived from the national water resource model (see section Groundwater modelling).

### *Water quality parameters*

The selection of parameters to be analysed as part of the national groundwater-monitoring programme was origi-

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**Table 1** Monitoring frequencies etc. for different component groups in the Danish Groundwater Monitoring Programme

| Sampling and analysis frequencies | Programme elements | | | | | |
|---|---|---|---|---|---|---|
| | Groundwater-monitoring areas | | | | Agricultural catchments | Drinking-water supply abstraction wells |
| Monitoring elements | Young groundwater | Old groundwater | New wells | Redox wells | Groundwater | Groundwater |
| Main components | 1 per year | 1 per 6 years | 2 per year | 6 per year | 6 per year | 1 per 3–5 years |
| Inorganic trace elements | 1 per 2 years[a] | 1 per 2 years[a] | - | - | 1 per 3 years[b] | 1 per 3–5 years |
| Organic micro pollutants | 1 per 3–6 years | - | - | - | 1 per 3 years[b] | 1 per 3–5 years |
| Pesticides and metabolites | 1 per year | - | 1 per year | 6 per year[b] | 4 per year[b] | 1 per 3–5 years |
| No. of wells (main/inorg./org.) | 735/896/569 | 163/151 | 329/321 | 96/12 | 100/40/40 | ~10,000 |

[a] Different parameters in young and old groundwater respectively

[b] Only selected wells

Groundwater level is gauged in groundwater-monitoring wells before each sampling if the technical construction of the well allows. Automatic groundwater level gauges are usually installed in drinking water supply abstraction wells

nally described by a working group based on national and foreign experiences (Danish EPA 1987) and later revisions were subsequently based on both national and foreign monitoring campaigns and research. As an example, the list of pesticides started out in 1988 with the five most used pesticides in Denmark, but this number increased to 45 in the period from 1998–2003. These substances were selected among the most used or detected pesticides, based on literature studies or experiences in other countries and included a series of metabolites as well. The number was reduced to 34 from 2004, as some substances were never detected. On the other hand, new substances are included in the programme when necessary. Recently, a new substance, metribuzin, a potato herbicide, and its metabolites were included based on results from the Danish Pesticide Leaching and Assessment Programme (Kjær et al. 2005).

The development in the number of substances analysed is reflected in Fig. 6, which shows the detection of pesticides and metabolites in monitoring wells. The dramatic increase in detections from 1998 is mainly a result of the increase from ~8 to 45 substances rather than a sudden deterioration of the groundwater quality. On the other hand, there may still be relevant substance that are not yet included in the programme. The results from the last 3 years show that about every third well contains pesticides or metabolites at detectable levels, and that in about 10% of the cases the concentrations exceed the quality standard of drinking water (0.1 μg/l).

The groundwater quality monitoring data presented in this report reflects data collected until 2006 and includes analyses for a total of 97 chemical parameters, comprising 26 main chemical/physical elements, 14 inorganic trace elements (heavy metals, etc.), 23 organic micro-pollutants and 34 pesticides and metabolites. In some programme elements (see Table 1), however, not all parameters within each group are analysed, based on an assessment of actual and potential pressures. As an example, only inorganic trace elements that are expected according to the composition of sediments and redox conditions are analysed in old groundwater, while inorganic trace elements analysed in young groundwater have been selected to represent the pressures from the surface, e.g. impurities in fertilizers. Another example is that pesticides and metabolites are only analysed once in old groundwater, unless detected in the first test analysis.

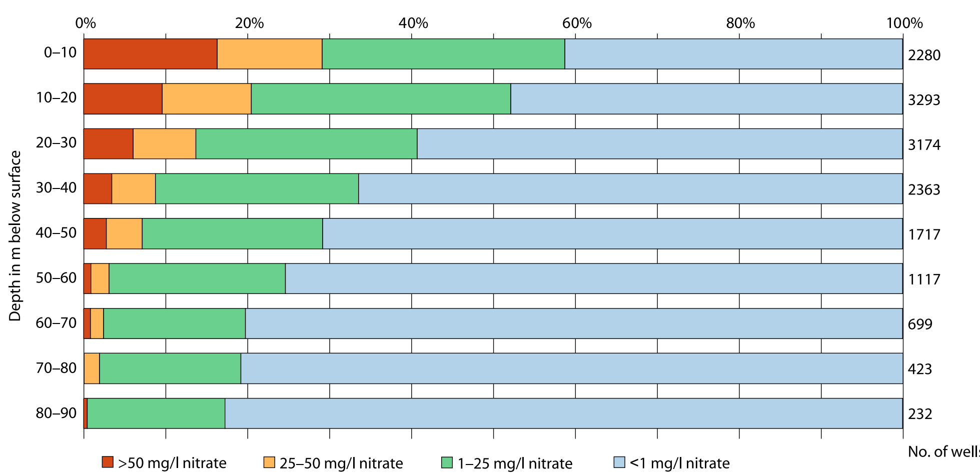


**Fig. 5** Distribution of nitrate compared to depth, 1990–2006 (GEUS 2007). Data are from both groundwater-monitoring wells and from groundwater abstraction wells for drinking water production. The number of wells analysed in each depths interval are indicated at the *right*

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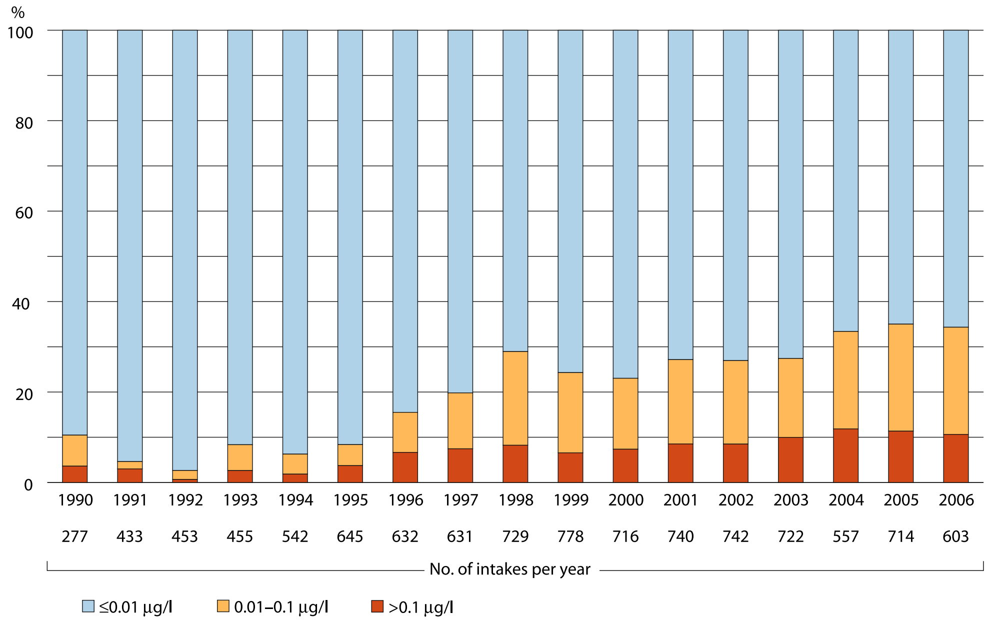


**Fig. 6** Detection of pesticides and metabolites in groundwater-monitoring wells each year from 1990 to 2006 (GEUS 2007). Total number of intakes analysed each year are indicated at the *bottom*

Groundwater age has been estimated in all monitoring wells based on CFC (chlorofluorocarbon) concentration as described by Busenberg and Plummer (1992) and Hinsby et al. (2008). With this method, groundwater recharged after 1940 can be dated and groundwater without CFC are generally characterised as "old". An example on how groundwater age data is used is given in Fig. 7. Here, average nitrate concentrations are compared with groundwater age in monitoring wells. Also presented is temporal development of the use of fertilizers (N) in Denmark. The figure indicates that the decrease in fertilizer use during the last decade as prescribed by the actions plans on the aquatic environment is mirrored by a decrease in nitrate concentrations in the young and shallow groundwater in the oxidised zone.

## Data from drinking water supply companies

Results from the compulsory quality control of groundwater carried out by the drinking water supply companies provide additional input to the Danish Groundwater Monitoring Programme. Groundwater abstraction wells for drinking water production are often quite deep, exploiting major aquifers with relatively good quality. Water samples from 10,000 abstraction wells are analysed every third to fifth year, depending on the amount abstracted, and hereby contribute to the picture of the status of Danish groundwater. This compulsory quality control monitoring programme comprises five microbiological parameters, 28 main chemical/physical elements, 16 inorganic trace elements, 30 organic micro pollutants and 23 pesticides and metabolites, but actual analyses carried out are based on a judgements of the local threats towards the water quality.

## Groundwater modelling

During the period 1996–2003, a national water resource model (DK-model) was constructed covering all of Denmark (Henriksen et al. 2003). The model is a numerical integrated groundwater–surface water model, based on the fully distributed physically based model system MIKE SHE/ MIKE 11 (Abbott et al. 1986). The main objective of the initial studies was to estimate the exploitable groundwater resource at national and sub-national levels. Previous estimates of the national water resource were based on relatively simple mass balance computations. A severe limitation of such simple computations is their inability to consider the entire freshwater cycle, the interaction between the different physical domains and the effect of different human pressures. Important aspects for the assessment of the sustainable exploitable resource are the effect of groundwater abstraction on nearby surface water systems, and the fact that not all water recharging the subsurface is suitable for drinking water because of contamination, predominantly in the shallow aquifers. Such factors limiting the exploitable resource were taken into account for the estimate based on the DK-model, where the qualitative policy considerations on sustainable development were translated into ensemble indicators, which could be evaluated on the basis of model simulations (Henriksen et al. 2008). Hence, the use of the comprehensive hydrological model nearly halved the exploitable resource in comparison to the earlier estimate (from 2 to 1 billion $m^3$/year), mainly because of inclusion of the above mentioned factors.

Following the DK-model study, it was decided to include a quantitative assessment by hydrological modelling in the national monitoring programme, allowing sub-national assessments. The DK-model is thus presently being refined and updated. Important for the subsurface system is the underlying geological model that has been updated,

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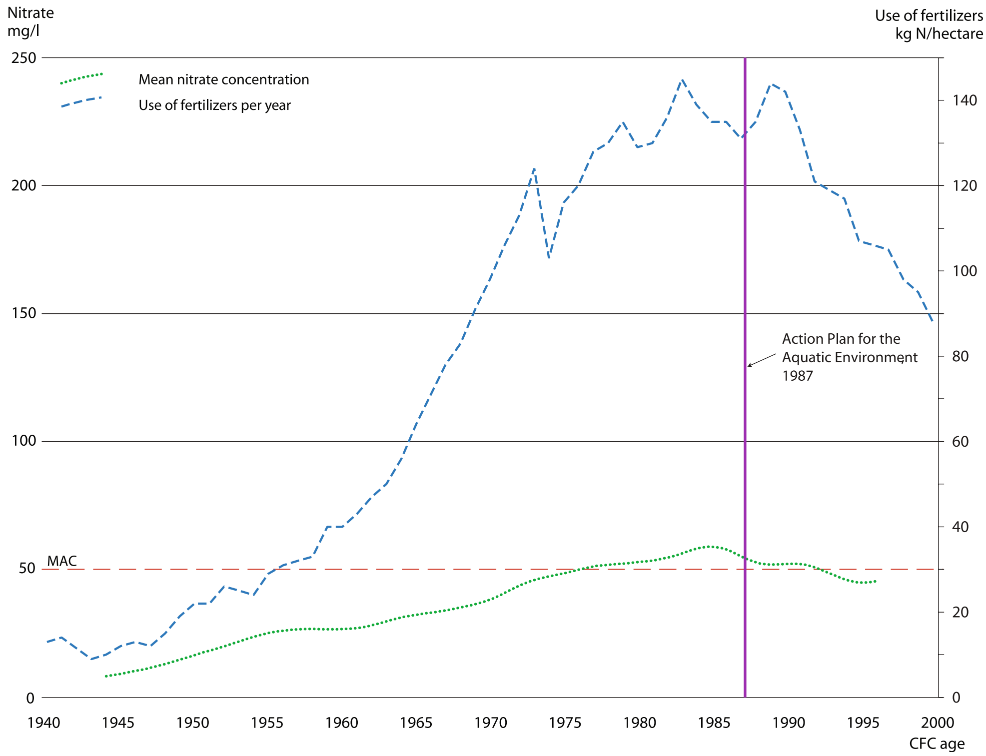


**Fig. 7** Fertilizer use and change of nitrate concentration in the oxidised zone, compared to groundwater age estimated by CFC content (modified from GEUS 2007)

based on extensive geological mapping carried out by the local water authorities in the past decade. Studies in near future are devoted to explore how the model and the national monitoring programme, on the quantitative status, can be linked more closely, e.g. to optimise the monitoring programme. In a longer perspective, the model's ability to supplement the monitoring of the qualitative status will similarly be studied.

## Data handling and reporting

All data collected within the Danish Groundwater Monitoring Programme are stored in a national database at the GEUS. Most data are transferred automatically and directly from the laboratory to the database, after electronic and in some cases manual quality control. Data are updated on a daily basis and freely available on the internet (GEUS 2008; Danmarks Miljøportal 2008) in line with the intentions in the Aarhus Convention (UNECE 1998) on public access to data collected via public funds.

Results from the Danish Groundwater Monitoring Programme have been reported annually since 1990. The main emphasis is on nitrate and phosphorus as wells as pesticides as a result of the documented diffuse agricultural impact on the water environment, including groundwater. Further, the concentration and trends of other parameters such as nickel, arsenic and organic micro pollutants are reported. Finally, all annual reports include an assessment of the use of water resources, split into the categories irrigation, industrial use, and domestic use. English abstracts from the latest reports are available electronically (see link at GEUS 2007) while Danish versions of the complete reports are available electronically for more years.

## Link with surface water monitoring

Although groundwater monitoring is an integral part of the National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environment, NOVANA (Svendsen and Norup 2005), the groundwater programme is, in reality, not well coordinated with the surface water programme, especially not with respect to water quality. This situation, however, has improved recently with regard to quantity by the establishment of the national groundwater model, because this model simulates the entire land phase of the hydrological cycle e.g. streamflow based on inputs of climate data.

## Quality of Danish groundwater

When illustrating results from monitoring analyses, it is extremely important to distinguish between data from abstraction wells for drinking water production and data from the Danish Groundwater Monitoring Programme. Abstraction wells are intended to provide clean groundwater that only has to undergo simple treatment to give drinking water of a proper quality. Thus, abstraction wells affected by pollution typically will be abandoned and new, and often deeper, wells drilled. As a result, groundwater quality assessed from abstraction wells generally will appear better than groundwater quality assessed from

 DOI 10.1007/s10040-008-0398-7

monitoring wells. Besides, abstraction wells generally have longer screens than wells for monitoring purposes, as abstraction wells usually are established in major and thus thicker aquifers; thus, groundwater from distinct levels of different quality can be mixed. So far, Danish water supply companies have succeeded in finding new groundwater resources of good quality and only in a few specific cases, temporary permissions have been granted by the Environmental Protection Agency to carry out advanced treatment of polluted groundwater for drinking water production.

The groundwater-monitoring wells, on the other hand, give a more detailed and accurate picture of the general status and changes in quality of Danish groundwater as these wells are monitored continuously. This is illustrated in Fig. 8, which shows mean nitrate concentrations in the monitoring wells as compared to abstraction wells. Not surprisingly, abstraction wells only have limited problems with nitrate as wells heavily affected by diffuse pollution are abandoned as mentioned above while 16% of the monitoring wells shows concentrations above the drinking water quality standard of 50 mg/l and only about half of the wells have no nitrate.

## Quantity of Danish groundwater

Groundwater levels are measured in a large number of wells spread throughout the country. These may give an indication of how groundwater levels fluctuate locally but do not give a sufficient description of the quantitative status at river basin level as required in the WFD. This is because the Danish geology is complex with often more aquifers overlaying each other, with individual groundwater levels. Each piezometric well has contact with a single of these and only represents this specific aquifer. Thus, to give an indication of the quantitative status, more piezometers are needed, both in different overlaying aquifers and in the single aquifers depending on the size and structure of the groundwater abstraction in the area. However, if a more knowledge-based estimate of the overall situation is required, model studies are essential.

As mentioned previously, attempts to assess the sustainable exploitable groundwater resources have been completed a couple of times. The last assessment was carried out by GEUS in 2003, based on monitoring data combined with modelling by the National Groundwater Model (Henriksen et al. 2008). The overall conclusion from this assessment was that the resource is sufficient at a national level, but not suitably distributed according to demands. Problems are especially associated with the major cities and to some extent with areas of high irrigation demands.

All abstraction of groundwater (and surface water) in Denmark is only allowed by licence acquired through municipalities. As a part of this licensing system, all users, from private, industries, agriculture and supply works, have to report their annually abstracted amounts. Thus, it is possible to follow the development of water use in Denmark closely (Fig. 9). The annual water use has decreased considerably during the last 20 years and is now more or less stabilised around 600–700 million $m^3$/year. This is mainly due to new water levies on abstracted water and intensive campaigns from water supply companies to reduce leakages. It is, however, evident that the amount of precipitation during spring and summer time is a decisive factor for the abstraction rate for irrigation as this account for 20–45% of the total abstraction, and a dry season increases abstraction considerably (Fig. 9).

It has been seen in several cases that groundwater abstraction causes streamflow depletion, as Danish streams are generally groundwater fed (Refsgaard and Hansen 1982; Christensen 1994). In some areas around the larger cities, it is often seen that wetlands suffer from a lowered groundwater table and that stream flows are low during summer time, mainly bearing treated waste water, and some actually temporarily run dry (Henriksen et al. 2008).

## International evaluation of the Danish monitoring programme

In 2002, the European Topic Centre on Water (ETCW/EEA 2002) was commissioned by the European Environment Agency to undertake an international evaluation of the Danish Aquatic Environment Monitoring and Assessment Programme on request from the Danish Environmental Agency. In this evaluation, the groundwater part of the programme was given quite fine remarks, both in terms of reaching its objectives and in the choice of parameters, locations and frequencies. Also, the data handling procedures

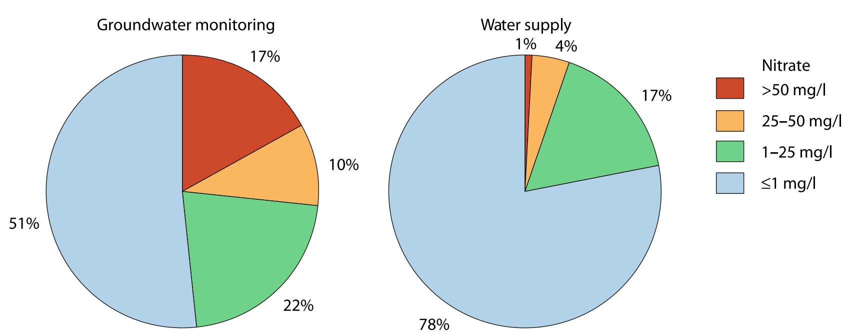


**Fig. 8** Nitrate concentration in the groundwater-monitoring wells as compared to groundwater abstraction wells for drinking water production, 1990–2006 (GEUS 2007)

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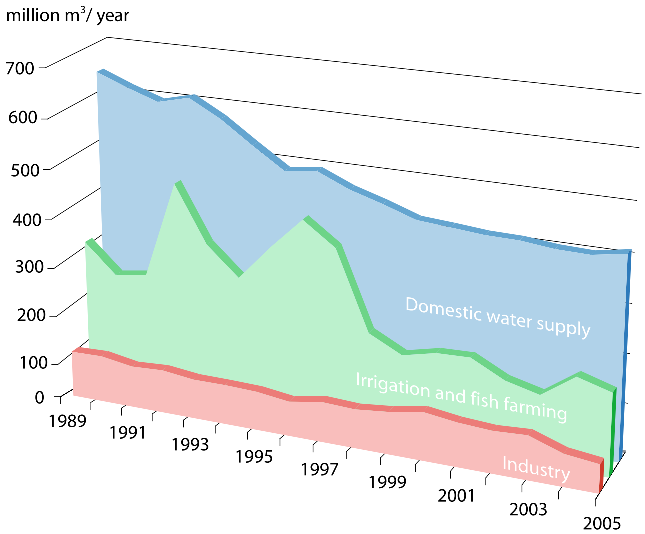


**Fig. 9** Groundwater abstraction in Denmark from 1989 to 2005 (GEUS 2007)

and the linkage to other sub-programmes were found adequate. Still, recommendations for further use of modelling were given. Besides, the evaluation panel was concerned that more than half of the budget is used for laboratory analysis and questioned whether this represents value for money.

## Groundwater-monitoring programmes in other countries

The most recent international review of groundwater-monitoring programmes was provided by Jousma and Roelofsen (2004). Their review was based on questionnaires disseminated worldwide to 180 countries, of which only 40 replied. The authors found literature on other programmes giving a total sample of 60 national groundwater-monitoring programmes. Their review concluded that programmes range from non-existent (especially countries in Africa and Central- and South America) to comprehensive national programmes (especially Europe, North America and Asia). The review also groups monitoring programmes into three categories, based on how extensive the programmes are and finally summarises limiting factors for improvements such as economics, political issues, etc. The review was mainly carried out to assess the actual situation with respect to groundwater monitoring and to identify needs for information and guidelines and did not, as such, compare programmes. An earlier similar survey was carried out by Koreimann et al. (1996) who gave an overview of 16 European groundwater-monitoring programmes. This overview is mainly a short description of each programme and also comprises a comparison of main features or principles and summarises differences and similarities.

To enable a comparison of the Danish Groundwater Monitoring Programme with similar programmes in other countries we have made a brief survey of peer reviewed literature on groundwater-monitoring programmes around the world. However, the amount of peer reviewed scientific literature on groundwater monitoring was surprisingly small. This may be explained by the fact that a national programme often provides input to national water management strategies and its results primarily are disseminated as national reports and relatively seldom published in scientific journals. Thus, the main part of our review is based on peer reviewed journal papers supplemented by a few national reports. The results are described below and a few characteristics from the eight national programmes found are summarised and compared to Denmark in Table 2.

The groundwater-monitoring programme in *Italy* (Onorati et al. 2006) was initiated in 2000 with the objective of fulfilling the requirements of the WFD. Italy is heavily dependent on groundwater, as 85% of the drinking water supply is based on groundwater and water from springs. As a result of high population density combined with widespread industry and agriculture, some regions suffer from overexploitation of groundwater resources and diffuse groundwater pollution. The Italian groundwater monitoring network is run by regional administrative bodies and has so far been established in 12 of 20 regions. Monitoring points are mainly existing abstraction wells and only a few are dedicated for monitoring purposes alone. Frequencies for quality monitoring are twice a year. The groundwater monitoring network has contributed to the development of River Basin Management Plans. In addition, the programme gives support to the implementation of the European Nitrates Directive (EC 1991) in some regions with high agricultural pressures.

In *The Netherlands* (van Geer 2005; Broers and van der Grift 2004; Broers 2002; Fraters et al. 2003), more than 60% of the drinking water derives from groundwater and the country has a long tradition of surveying groundwater both in terms of quantity and quality. Groundwater monitoring is carried out at different administrative levels—national, sub-national and local at well field scale. However, most data are fed into one national database and used for status evaluation on a national basis. The Netherlands Environmental Assessment Agency is responsible for the network, data interpretation and reporting. Frequencies for quality monitoring are usually once per year and the network focuses on nutrients from agricultural diffuse sources. Water production companies report annually on the quality of groundwater abstracted to the Ministry of Environment and the data management is carried out by The Netherlands Environmental Assessment Agency.

In *Austria*, (Schwaiger 2003) drinking water supply is based on fifty-fifty groundwater and spring water from karst areas. The national network for monitoring water quality was set up in 1991 to give comprehensive information on the state of the water environment in Austria, to establish the necessary databases in order to meet the national and the international demands, and for triggering and afterwards following progress of remediation

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**Table 2** Selected features of groundwater-monitoring programmes in nine countries

| Country | Groundwater share of public drinking water supply (%) | Focus of programme | Total country area ($km^2$) | No. of stations (quality/quantity) | No. of $km^2$ per station (quality/quantity) | Start of programme (quality/quantity) | Stations mainly only monitoring | Stations mainly abstraction or abandoned wells |
|---|---|---|---|---|---|---|---|---|
| Austria | 99 | Quality | 84,000 | 2,018/- | 42/- | 1991/- | | X |
| China | 20 | Quantity | 9,600,000[a] | -/23,800 | -/42 | -/1950 | | X |
| Denmark | 99 | Quality | 43,000 | 1,400/>60 | 31/< 720 | 1989/1950s | X | |
| Italy | 85 | Quality and quantity | 301,000[b] | 2,800/2,800 | 65/65 | 2000/2000 | | X |
| Latvia | >80 | Quality | 65,000 | 800/150 | 81/430 | 1990s/1970s | X | |
| The Netherlands | >60 | Quality | 42,000 | 2,300/25,000 | 18/< 2 | 1979/1940s | X | |
| Norway | <10 | Scientific | 324,000 | 45[c]/65 | 7,200/5,000 | 1977/1977 | X | |
| South Korea | 11 | Quality | 99,000 | 600/ 600 | 165/165 | 1995/1995 | X | |
| England and Wales (UK) | 35 | Quality and quantity | 151,000 | 3,500/7,300 | 43/21 | - | X | |

[a] The monitoring programme of China covers about 1 million $km^2$ of the country

[b] So far the monitoring programme covers 12 of 20 regions in Italy

[c] One-third of these are springs

programmes. Stations are a mixture of abstraction wells and wells dedicated to monitoring. Frequencies are from 2 to 4 times a year depending on the stresses from anthropogenic sources.

The share of groundwater for water supply is estimated to about 11% of the total water use in *South Korea* (Lee et al. 2007). The demand for water for drinking, agricultural and industrial uses is increasing and water shortage in a few years is foreseen. To forestall problems with unregulated groundwater abstraction resulting in land subsidence, saline intrusion, contamination etc., new regulations and initiatives for groundwater management have been developed and an advanced national groundwater-monitoring programme is one of the initiatives. Each station in the groundwater-monitoring programme consists of two separate wells dedicated to monitoring; one in shallow groundwater and another in deeper groundwater. Each well contains a data logger and a remote terminal unit and, every 6 h, water level, temperature and conductivity are measured and automatically transferred daily to a host server and stored in a central database. In addition, analyses of groundwater quality are performed twice a year. Demand for more stations to cover more aquifers and the necessity of including more parameters in the programme are foreseen by Lee et al. (2007).

In *Norway*, less than 10% of the drinking water derives from groundwater (de Caritat and Kirkhusmo 1995; Jæger et al. 2007). The groundwater monitoring network dates back to 1977, and consists of relatively few stations. Sampling frequencies are once or twice a year and only a few main components as well as 50 inorganic trace elements, mainly metals, are analysed. The network was designed to follow groundwater quality in areas without anthropogenic influences to follow baseline conditions and for process understanding, and stations with impact from human activities have been closed down. Thus, analyses for substances originating from diffuse sources are not included in the programme. Adapting the monitoring programme to fulfil the WFD is currently under consideration.

In *China* (He and Li 2006), especially in the north, groundwater is indispensable for socio-economic development as an important source of water supply, mainly for agricultural irrigation but also for drinking water. Groundwater exploitation has grown considerably since the 1970s and heavy abstraction has led to serious geo-environmental problems or even geo-hazards. Besides, aquifers close to bigger cities have been polluted to various degrees because of industrial and agricultural activities. Furthermore, groundwater with naturally high arsenic and fluorine and low iodine contents has caused endemic diseases in some regions. Regular groundwater monitoring has been carried out in China since the 1950s, especially on groundwater levels. The present programme covers one-ninth of the country, mainly the north. Most monitoring wells consist of existing boreholes, either abstraction wells or wells abandoned after groundwater investigations. Groundwater levels are measured with frequencies from every fifth to tenth day. Quality monitoring is carried out once or twice a year and includes 20 parameters; primarily main compo-

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nents, inorganic trace elements and some bacteria. The National Monitoring Institute under the Ministry of Land and Resources has recently established a framework for data collection, transmission, analyses, and results dissemination.

The use of groundwater for public drinking water supply varies remarkably between regions in *England and Wales* according to where the aquifers are, from more than 70% in the south east of England to only 3% in Wales (Ward et al. 2004; Environment Agency 2006a; Environment Agency 2006b). Sampling frequencies typically are once a year or once every second year. Parameters include a large number of metals, non-metal anions such as chloride and nitrate and more than 100 organic chemicals including pesticides and solvents. The UK Environment Agency has developed a strategic framework for groundwater quality monitoring. This framework recognizes the role of groundwater as a significant pathway for transport of diffuse pollution to surface waters. The framework currently is being implemented by a series of detailed regional programmes that are developed to provide background information at catchment scale to fulfil the requirements of the WFD.

In *Latvia* (Gosk et al. 2006; Gosk et al. 2007; LEGMA 2006), more than 80% of the drinking water supply originates from groundwater. Groundwater monitoring dates back to the 1970s, but until recently, quality monitoring only comprised a few parameters such as major ions and nitrogen compounds. However, additional data on especially shallow groundwater have been collected in a recent nation-wide project, giving input to a national qualitative monitoring programme on both deep and shallow groundwater as well as springs; the last being a quite important local source of drinking water in some areas. Diffuse pollution from agricultural activities is anticipated to be the main threat to the groundwater quality.

### *Comparison and distinct features of the programmes*

The structure and objectives behind the different national groundwater-monitoring programmes reviewed in this report differ considerably. When comparing the balance between quality monitoring and quantity monitoring, it is evident that most programmes focus on quality, a couple on both and only the Chinese programme primarily on quantity but with increasing focus on quality. These differences mainly reflect the challenges faced and the pressure on the groundwater resource. Where water shortage is an important issue, the main focus is, or has formerly been, on the quantity. But where groundwater quality constitutes a problem, either in terms of natural baseline quality that is health-threatening or in terms of anthropogenic pollution, quality inevitably becomes the main focus.

Where groundwater traditionally has been an important source for drinking water supply, extended and comprehensive monitoring programmes have often been operating for several decades. Countries like Norway and South Korea, with relatively low interest in groundwater for water supply, have the lowest density of stations (Table 2). At the other end, countries that almost entirely rely on groundwater for water supply, like Denmark and The Netherlands, have the highest density of monitoring wells. It should be noted that the density is not necessarily a quality indicator as the frequencies or number of parameters might be too low to give sufficient information. Very often, the spatial distribution of wells together with the frequencies and number of parameters have to be weighed against each other as all monitoring programmes are run with limited budgets. Thus, it is crucial to consider if it is possible to establish monitoring wells or areas that are representative of a given part of a country or region and to establish a comprehensive and sufficient monitoring network to describe processes and change in the groundwater system. The opposite strategy—scattering as many wells as possible around the country, analysing a few parameters at low frequencies—could also be chosen depending on the geology, response time, pressures, objective of the monitoring, etc.

Another interesting feature is the type of wells used for monitoring. In countries like Austria, China and Italy, existing wells constitute a considerable part of the monitoring network while the rest of the countries have established mainly new wells dedicated to monitoring. In this respect, the costs of establishing a new monitoring station may be a decisive factor as wells can be relatively costly. When choosing an existing well it is, however, essential to consider whether such a well is representative for the monitoring purpose and technically adequate for the intended sampling.

Some countries, like South Korea, China and The Netherlands have invested in automatic stations that transmit data continuously to a central database. This is an advance in data collection and a long-term cost-effective strategy that probably will develop and include more parameters and become common in more countries.

None of the national programmes appears to have explicit coordination with surface water monitoring programmes, and the use of groundwater models is not common as an integrated element of the programmes. Most European monitoring programmes are adapting to the requirements of the WFD (Quevauviller 2005). For some countries this implies the establishment of a new programme of a resource that has not been investigated or explored a lot. For others, already established programmes are being redesigned or extended. In a few cases, as the Danish, monitoring programmes are being reduced partly as a consequence of the Directive.

## Discussion

### *Lessons learned from 20 years of groundwater monitoring in Denmark*

Any monitoring programme needs to be tailored to the hydrogeological and socio-economic context. In this respect, the Danish Groundwater Monitoring Programme can be characterised by a full dependency of the Danish society on groundwater as its source of drinking water and

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by a high political will to protect groundwater resources from pollution. Since research results showed signs of groundwater pollution in the 1980s, the government has allocated substantial resources to research and monitoring.

*Highlights of the Danish monitoring programme*

When compared to other groundwater-monitoring programmes, the Danish programme can be characterised as follows:

- The Danish programme is solidly consolidated in terms of *technical specifications and guidance* for ensuring consistent and homogeneous sampling and data handling throughout the country
- *Data* from the Danish programme are, after quality assurance procedures, automatically stored in a large database with free, public access
- The programme has produced *longer time series* of a high number of parameters compared to most other programmes. In particular, the 20-year time series of inorganic pollutants appear to be almost unique
- The programme comprises a *large number of parameters*, including organic compounds such as a wide range of pesticides and their metabolites
- The programme is continuously adapted to *new perceived contamination* threats
- The monitoring wells are *clustered in monitoring areas*. This approach differs significantly from the common approach in other countries. The clustering approach has the advantage that the monitoring areas are investigated relatively thoroughly. The disadvantage is that the monitoring in between the monitoring areas is quite extensive. Therefore, the critical assumption is that the monitoring areas are representative for all the remaining areas. To what extent this assumption holds needs to be carefully examined when the monitoring has to be adjusted to the requirements of the Water Framework and Groundwater Directives in the coming years
- The wells used for sampling are established and used for *monitoring purposes only*. This is common but not standard in many of the other national programmes
- The monitoring of *water abstraction for domestic, industrial and irrigation purposes* provides a reliable and detailed picture of water use in the country. In spite of some uncertainty on the irrigation water use, which generally is calculated from electricity used for pumping, the record is rather unique
- The *conceptual understanding* of geology, geochemical processes and the contaminant fate is well developed. However, the need for conceptual understanding is not static, but heavily depends on the resource pressures and the policy context. This understanding has, as described above, been significantly improved since the initiation of the monitoring programme, and it needs further improvements during the coming years, especially with regards to groundwater–surface-water interaction and to the transport and fate of contaminants in the deeper part of the groundwater system
- Groundwater *modelling* has become an integral part of the monitoring programme. This is unique compared to other national programmes. This effort started about 10 years ago with the purpose of improving the conceptual understanding in the groundwater-monitoring areas. With the introduction of the national groundwater model, modelling is now also used for assessing the quantitative status of the surface water and groundwater resources, including groundwater recharge. Further integration of modelling and monitoring, as suggested by Højberg et al. (2007), is now being considered as part of the future revised programme
- The *coupling with surface water monitoring* is weak as in most other national programmes. Recently groundwater–surface-water interactions have been considered through the national scale hydrological modelling, but the monitoring is not yet fully consistent with this
- Unlike some other programmes, the Danish monitoring mainly *focuses on deep groundwater*. This is a recognised weakness, because deep groundwater is old, and the polluted, younger groundwater with maybe unknown characteristics has in most places not yet reached these lower depths. It is therefore interesting to monitor younger and near-surface groundwater to assess the possible movement of the pollution front and the long term threat to deeper groundwater. The present programme has some elements supporting this purpose such as the monitoring of very shallow and young groundwater in the dedicated agricultural catchments and the recently established 330 new shallow monitoring wells. However, this effort needs further strengthening
- The efforts on *quantitative monitoring are much weaker* than in most other national programmes. However, there are plans to amplify the national groundwater level monitoring programme considerably
- The Danish Groundwater Monitoring Programme is technologically less advanced than some of the other national programmes with respect to *automated monitoring stations* both for quantitative and qualitative monitoring. This weakness limits the benefits of coupling monitoring with modelling
- The Danish programme is not cost-effectively optimised with respect to *location and frequencies* of sampling. This probably is not the case with the other national programmes either. In this respect, approaches as suggested by van Geer et al. (2008) appear promising.

*Adaptation to new knowledge: link to research*

The development of the Danish Groundwater Monitoring Programme during the past 20 years illustrates the importance of linking monitoring and research activities. The programme has undergone substantial changes in content due to new knowledge that has emerged from parallel and associated research activities, much of it

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based on data and results from the monitoring itself. An example is the increasing monitoring of pesticides and their metabolites. Pesticide monitoring started in 1988 with only five substances in the programme; this rose to 45 in 1998 and was reduced to 34 relevant substances from 2004. Parallel to this, a major strategic research programme on pesticides in groundwater was undertaken between 1996 and 2000. Another example is the modelling activities, starting 10 years ago with local-scale modelling of the individual monitoring areas aiming at better estimates of recharge areas of the central abstraction wells. Following comprehensive research programmes on modelling, the programme has now been extended to include a national groundwater model aimed at an improving understanding of the conceptual geological model and an assessment of groundwater recharge and sustainable groundwater abstraction. Finally, it has been recognised that monitoring of young shallow groundwater was underrepresented in the programme resulting in the establishment of 330 new shallow monitoring wells.

Consequently it must be concluded that research and monitoring should be linked. This is also recognised by Quevauviller (2008b), both in terms of groundwater management in general and for groundwater monitoring specifically.

### *Adaptation to policy requirements*

The history of the Danish Groundwater Monitoring Programme illustrates how the programme during the years has been adapted to address policy needs on one hand and how the results of the programme have influenced policy decisions on the other. The programme was initially intended to monitor nutrients from diffusive pollutants. A few years later, it was realised from research results that pesticide leaching represented a serious threat to groundwater quality. As a consequence of this new knowledge, the monitoring programme was significantly expanded. Within the recent years, the monitoring programme is gradually adapting to the requirements of the new policies of the WFD and the GD.

Results from the Danish Groundwater Monitoring Programme have given input to the selection of additional parameters in the compulsory monitoring of groundwater for drinking water production. Also, the results have given input to national management strategies and investigations, e.g. an investigation of the quality of shallow groundwater used for drinking water production in small private water supplies (Brüsch et al. 2004) and the Danish Pesticide Leaching and Assessment Programme (Kjær et al. 2005). The new action plans on the aquatic environment have been adjusted according to results from the individual monitoring programmes on order to improve measures aiming at improved water quality. Also, initiatives of the action plans on pesticides aiming at a reduction in pesticide use have been implemented over the last 8 years. These plans aim at reducing the use of pesticides, both in terms of frequency and in terms of re-evaluation and possibly banning of already approved substances that are found in the groundwater.

## *Future challenges*

For most of the European countries, the WFD and GD place new requirements on monitoring. Thus, the present Danish water monitoring programmes, including the groundwater programme, will need to be gradually redesigned to fulfil the obligations of these directives. Because of the complicated Danish geology and the clustered design of the Danish groundwater monitoring network, many groundwater bodies are not monitored directly. To what extent this will call for a revision of the original monitoring design and objectives of the programme is not clear at the moment. However, an extension of the quantitative monitoring is foreseen as well as an incorporation of new emerging substances such as hormones, antibiotics, new pesticides, etc.

There will be a need to adapt the monitoring programmes to cope with the effects of climate change. There are two challenges in this respect. First of all, our present programmes assume that climate and groundwater are stationary, i.e. that their average conditions do not change with time. With climate change, this assumption will not hold, because, for instance, environmental pressures and temperature dependent water quality processes will change gradually. Secondly, monitoring the effects of a given measure will also become more difficult, because the effects of the measure now also need to be distinguished from the effects of climate change. Altogether, interpreting results from monitoring programmes becomes harder.

This report is based on results and programme content of the Danish Groundwater Monitoring Programme up to the end of 2006. From 2007, the programme budget was reduced resulting in lower frequency of data collection and fewer parameters, and even future reductions are noted. Thus, from a scientific point of view, it appears very difficult to fulfil all objectives within the programme itself as well as international requirements within the present economical frames of the Danish Groundwater Monitoring Programme.

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