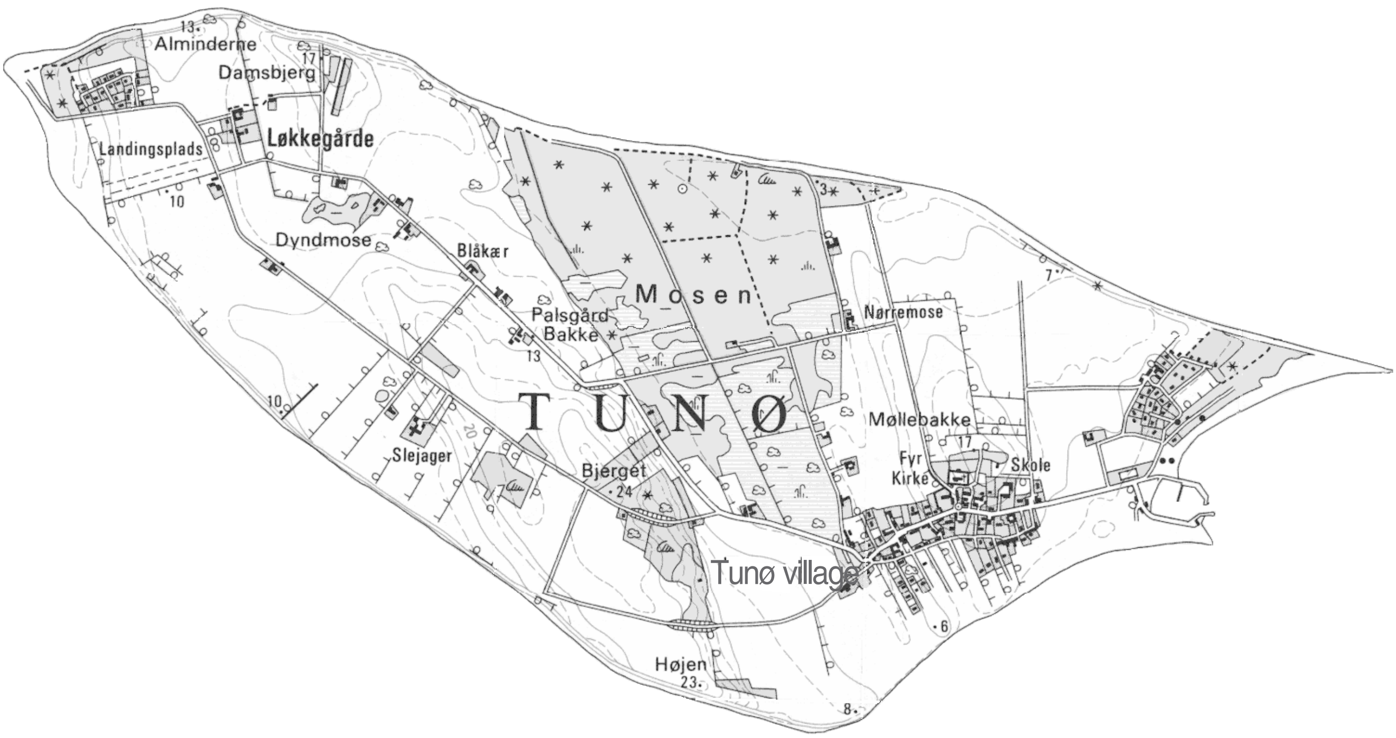
TECHNICAL REPORT



TUNØ

STATUS REPORT 1989–1999

AUGUST 2001

AARHUS COUNTY
ENVIRONMENTAL
DIVISION

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Contents

Introduction

Planning and public administration in Denmark is carried out at three administrative levels: Central government, County Councils (14) and Municipal Councils (275).

Laws and legal instruments are prepared by the State.

The County Councils are responsible for the overall administration of water abstraction permits and for protecting water resources against contamination.

As more than 99% of the drinking water supply in Denmark derives from the naturally pure groundwater, protection of the groundwater resource from industrial and agricultural contamination is accorded high priority. One means of doing so is the establishment of protection zones in the vicinity of the water abstraction wells.

The present project is the first in Danish water supply history in which it has been possible to protect the groundwater from the effects of agriculture. As experience with groundwater protection zones was very limited ten years ago, the project involved extensive water quality monitoring in order to determine the effects of the protection zones.

Agriculture can considerably deteriorate the quality of the groundwater. On sandy soils and in areas where groundwater is abstracted from aquifers close to the surface, nitrate leaching in particular has caused problems for many waterworks. In Aarhus County alone, more than 100 waterworks have closed down due to high nitrate levels in the groundwater.

The essence of this project was the establishment of protection zones surrounding the waterworks. Closest to the waterworks there was to be permanent grassland that was neither fertilized nor sprayed with pesticides. In the outer protection zone, the goal was to reduce leaching by adjusting the fertilizer application rate to crop needs. The measures implemented were to be regularly evaluated through systematic monitoring activities.

The project was centred around Tunø Waterworks on the island of Tunø in Aarhus Bay. The waterworks abstracts water from the only water resource of significance on the island.

Tunø has a permanent population of approx. 90 persons. During the summer months, in addition, there is a considerable flux of tourists to the summer cottages and in particular to the marina. The majority of the inhabitants and tourists are supplied with water from Tunø Waterworks.

During the course of the 1980s, the nitrate content of the drinking water increased so much that action was needed to ensure that the quality of the water complied with the limit value stipulated in the Statutory Order on drinking water.

On the initiative of Richard Thomsen, Aarhus County, a working group was therefore established in 1986 charged with the task of drawing up a strategy for safeguarding the drinking water supply on Tunø. The working group consisted of representatives from:

- Aarhus County
- Odder Municipality
- Danish Environmental Protection Agency
- Spatial Planning Agency
- Centre for Soil Ecology (now National Environmental Research Institute)
- Department of Agricultural Law, Danish Agricultural Advisory Centre
- Department of Plant Production, Danish Agricultural Advisory Centre
- The agricultural advisor for Tunø and Samsø

On June 20 1988, Aarhus County and Odder Municipality after reviewing several possible solutions decided to safeguard the water supply on Tunø by establishing protection zones such as suggested in the report "Water supply on Tunø – 1987" (1) (see Annexe 1). This report demonstrated that the establishment of protection zones is both the simplest and cheapest means of safeguarding the future quality of the drinking water. The report also provides a detailed description of the geological conditions and water supply situation on Tunø.

In spring 1989, two protection zones were established: an inner protection zone of approximately three hectares with permanent grass immediately surrounding the abstraction wells, and an outer protection zone extending to a radius of 300 metres in which the land was subject to a field management system and other agricultural measures.

The first status report on the Tunø project was published in December 1989 (2). This describes the decision-making process and the practical implementation of the protection measures.

The area of the inner protection zone was doubled in summer 1991 as the effect of the agricultural measures in the outer zone proved insufficient.

The next status reports were published in December 1991 (3) and May 1994 (4). These presented the results of the first monitoring work, including the technical investigations of the soil's properties. The findings indicated that the inner protection zone was too small. The reports describe the additional measures implemented.

The present status report reviews the first ten years of experience with the protection zones. The establishment of permanent grass rapidly and effectively reduced nitrate leaching. However, the field management system implemented did not have the expected effects, chiefly because of the special crop mix farmed on Tunø and the very low level of net precipitation.

By January 1994, the nitrate-free water from the inner protection zone had reached the groundwater table. By New Year 2000, the upper nearly two metres of the grundwater was good-quality drinking water. At the time of writing, the nitrate concentration of the abstracted water is around the limit level, with further improvement on the way.

All the above-mentioned reports were prepared by the Environmental Division, Aarhus County.

Tunø Waterworks was privatized on January 1 1994, and is no longer one of the Odder Municipality waterworks. On that occasion, Tunø Waterworks took over the land in the inner protection zone and hence responsibility for maintenance of the permanent grasslands.

The chief participants in the "Pure water on Tunø" project as per 1 January 2000 are:

- Environmental Division, Aarhus County
- Odder Municipality
- Tunø Waterworks
- Department of Plant Production, Danish Agricultural Advisory Centre

and not least:

- The farmers and vegetable growers with land in the protection zone, namely Valdemar Borggård, Oluf Theilgård and Mogens Deigård.

Conclusions

Protection zones can ensure pure groundwater. Permanent grass reduces nitrate leaching rapidly and effectively. After just one year, the nitrate concentration in the new groundwater formed under the grassland remains at around 1 mg/l.

Monitoring is necessary in order to be able to rapidly focus efforts so as to ensure the necessary improvement in water quality.

It took five years for the pure groundwater to reach the water table. After ten years, the upper metres of the grundwater below the inner protection zone are now completely pure. It is anticipated that it will take a further five to ten years before the improvement in water quality is detectable in the water abstracted by the waterworks (Figure 1).

The level of net precipitation on Tunø is low, in the range 100–150 mm/year. This makes great demands on the field management system as nitrate leaching has to be kept below approx. 25 kg N/ha in order to ensure compliance with the limit level for nitrate in drinking water. The field management system could not meet these strict demands, and it was therefore necessary to extend the inner protection zone in 1991.

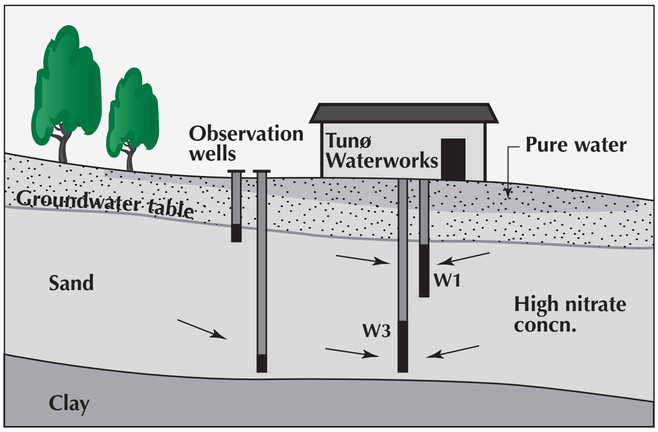
Even with a relatively simple groundwater aquifer such as that on Tunø, geological studies are necessary in order to be able to determine how groundwater recharge takes place.

Since 1992, virtually the whole of the capture zone has contributed in some way to the formation of groundwater with a low nitrate concentration, thus allowing agricultural production to be continued in the remainder of the capture zone beyond the inner protection zone. The agricultural area should not be expanded, though, until leaching has been reduced significantly on that part of the land that is cultivated with leeks in rotation.

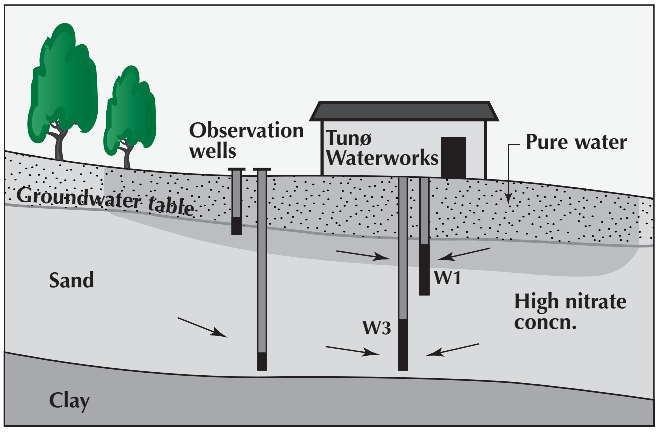
Implementation of the project "Pure water on Tunø" involved numerous parties, including authorities responsible for groundwater resources in the county and municipality, the farmers unions, state agencies and research institutions and – not least – the local farmers and vegetable growers. Without the good will of all parties, implementation of the project would not have been possible.

At the present time there are good grounds to believe that it will soon be possible to supply drinking water of really good quality to the consumers on Tunø.

1990: The pure water is present in the upper layers of soil



2000: The pure water has reached the upper groundwater



2010: A permanent solution has been achieved – pure water for consumers

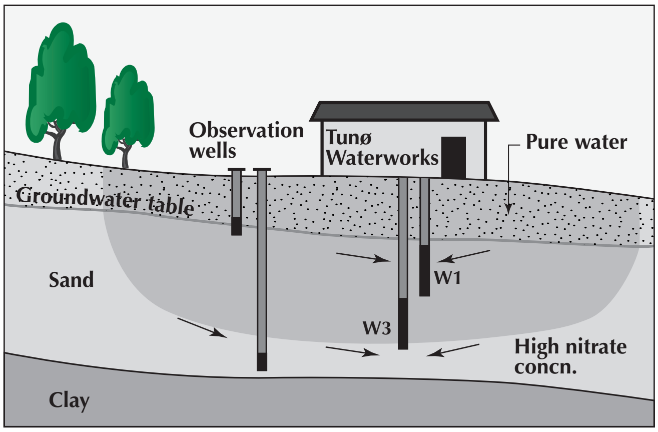


***Figure 1:** Downwards progression of the pure water front*

Project description

The Tunø project is founded on two principles:

- ▶ Groundwater protection
- ▶ Monitoring

The project for safeguarding the water supply on Tunø has been implemented through a number of activities as described below. The land involved and the location of the various monitoring activities are shown in Figure 2.

1. Establishment and upkeep in the inner protection zone
In the inner protection zone, the agricultural land in the immediate vicinity of the waterworks has been withdrawn from crop rotation and sown with grass, which is cut once a year. The area is presently 6.5 hectares.

2. Field management system in the outer protection zone
During the initial years of the project, land use in the outer protection zone was regulated using a field management system based among other things on analysis of the soil nitrogen content. This was changed following the introduction of stricter Danish regulations on agricultural nitrogen budgets, though (see the chapter entitled "Protection zones").

In addition, work was undertaken on other agricultural practices such as the application of fertilizer in the rows of vegetable crops using a special fertilization applicator.

The outer protection zone extends 300 metres beyond the waterworks and covers approx. 25 hectares. The western part of the area covering a total of seven hectares has been set aside for the period 1992–2017 under the EU set-aside scheme.

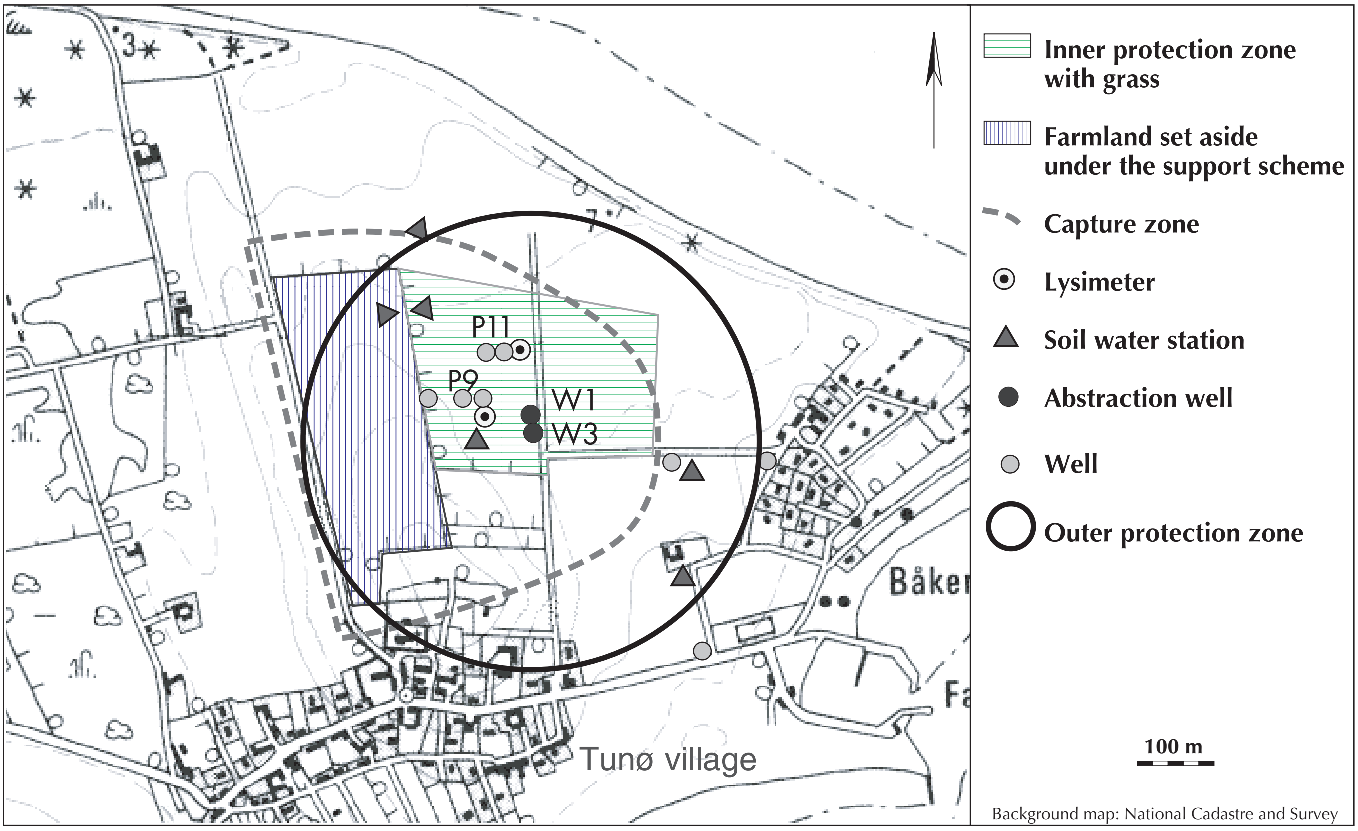


Figure 2: *Map of the area around Tunø Waterworks. The map shows the inner and outer protection zones as well as the farmland west of the waterworks that has been set aside. The estimated capture zone from which water is abstracted is also indicated.*

3. Monitoring of leaching from the root zone

Suction cells have been established at six locations for monitoring the nitrate content of the water percolating from the root zone down towards the groundwater. Of these, two are located in the inner protection zone, one in the set-aside land and three in the cultivated areas.

4. Monitoring of groundwater quality

The quality of the groundwater is followed in nine monitoring wells. Two of these wells located in the inner protection zone are specially equipped for monitoring the quality of the water in the unsaturated zone above the water table.

5. Control of the drinking water

A central aspect of the project is to control the quality of the drinking water both at the waterworks and in the households.

6. Nitrogen and water balances

Groundwater recharge is measured so as to enable calculation of the water balance and to establish a model for the mass balance of nitrogen within the area. The groundwater table in the wells is measured during each sampling session. These data and those from the geological investigations are used to determine the actual capture zone.

Geology

The geological conditions on Tunø were described in a report published in 1979. At that time it was already clear that there is only one aquifer from which Tunø Waterworks can abstract groundwater for the drinking water supply. Prior to initiation of the project on active groundwater protection on Tunø, Aarhus County published a more detailed report: “Water supply on Tunø”, Aarhus County, April 1987. This report provides a more comprehensive examination of the geological and hydrological conditions of significance for the future abstraction of groundwater.

Since practical implementation of the project in 1989, a number of more specific hydrogeological studies have been undertaken. These have further contributed to the understanding of the geological structure of the aquifer at Tunø village and the possibilities for continued abstraction of good-quality groundwater. The results from the geophysical measurements and the monitoring wells will be briefly described below.

Geophysical measurements

In spring 1989, geoelectrical linear profile measurements were made in an area slightly greater than the two original protection zones. The purpose of the measurements was to provide information about the character of the top layers overlying the aquifer and about the upper parts of the aquifer itself. The measurements were also expected to contribute to more accurate delineation of the extent of the aquifer.

A map reflecting the variation in electrical resistivity caused by differences in the clay and sand content of the soil layers in the upper 5–15 metres below ground level is shown in Figure 3. The resistivity is highest in areas where this depth interval predominantly consists of sandy deposits, i.e. where the upper moraine clay layer covering the aquifer is rather thin. The resistivity is lowest in areas where the clay cover is thicker or where there is no aquifer, but only clay.

The rather distinct boundary of the aquifer towards the west is reflected in the geoelectrical linear profile measurements in the form of a sudden switch to low resistivity west of a virtually longitudinal line running north from Tunø lighthouse. The relatively high resistivity east of this line shows that the aquifer here can extend all the way to the northern, eastern and southern coasts.

Groundwater recharge is greatest in areas where there is little or no clay cover above the aquifer. This is the case in those parts of the area where the highest resistivity is measured, as seen in Figure 3. In these areas, the rainwater will seep directly through the sand layers and will be the first to reach down to and become groundwater.

Monitoring wells

In 1988-89, three wells were drilled using a newly developed special drilling method termed hollow auger drilling. With this method, the resistivity of the undisturbed soil layers is measured during the drilling process, thereby providing information on the variation in the composition of the soil layers drilled through. In 1993, two additional wells were drilled. By that time the method had been further developed to allow measurement of the natural gamma radiation of the

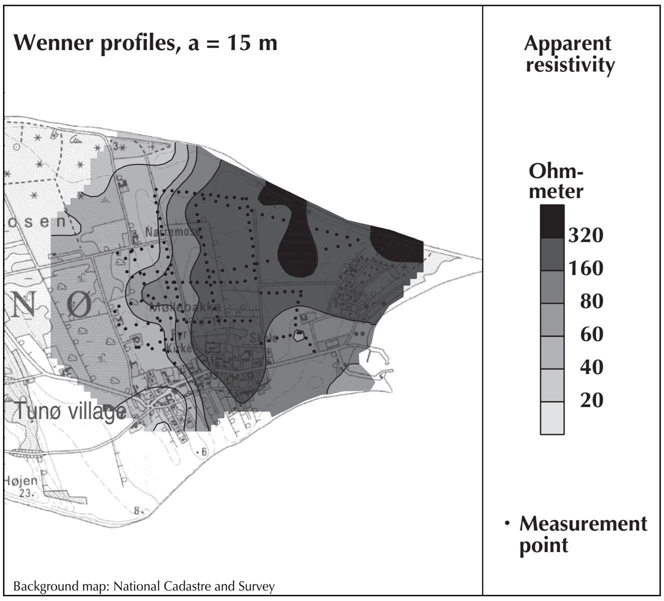


__Figure 3:__ Geoelectrical linear profile measurements on Tunø. The resistivity is lowest where clay deposits dominate. The resistivity is highest above the aquifer, where the deposits mainly consist of sand, and where groundwater recharge is therefore greatest.

soil, which particularly reflects the variation in the clay content of the soil layers. This information improved the possibilities for the precise positioning of short filters in the sandy deposits for the collection of water samples for analysis. In the latter two wells, suction cells have been mounted on the lining tubes to enable samples to be collected in the unsaturated zone of the water that is on its way down to the groundwater (see page 18).

The aquifer

The five hollow auger wells have further substantiated the view that the aquifer consists of rather inhomogeneous glacial material largely comprised of sandy and silty layers, but with some layer sequences mainly consisting of clay. The extent and interrelationship between these clay deposits are so complex that it is prohibitively expensive to fully determine their extent. The clay horizons influence the pattern of water flow above as well as in the aquifer. Thus secondary aquifers are occasionally present having a local groundwater table. A further consequence of these relatively thin clay layers is that the time that it takes the precipitation (for example with a low nitrate content) to seep down to a particular depth can differ in different parts of the aquifer.

A cross-section through a number of the wells along a trace from west to east through the aquifer is shown in Figure 4. The location of the cross-section is shown on the map in Figure 5.

Groundwater level

The groundwater level in the vicinity of Tunø Waterworks is determined by means of water-level readings of all available wells. A good knowledge of the groundwater level is a precondition for being able to determine the capture zone from which the waterworks abstracts its water. Demarcation of this capture zone is in turn necessary in order to be able to establish the protection zones in the right places so that the protection measures implemented in these zones can lead to an improvement in groundwater quality.

In all, ten wells are available for determination of the groundwater level in the Tunø aquifer. Figure 6 shows a momentary representation of the groundwater level. The measurements on which this representation is based were made on April 22 1999 in the case of seven of the wells and on February 22 1999 in the case of the other three wells. The groundwater table in the most westerly part of the aquifer is approximately one metre above sea

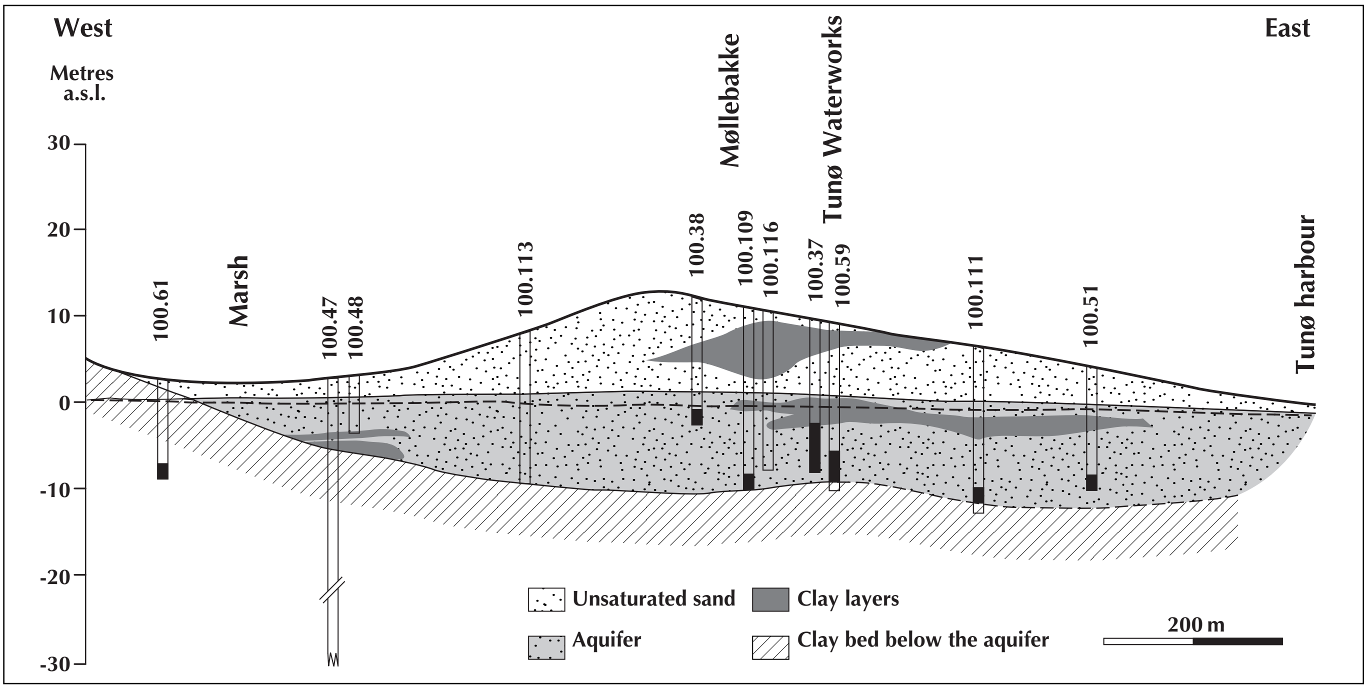


***Figure 4:** Simplified geological cross-section from west to east through the aquifer and the wells along the trace shown in Figure 5.*

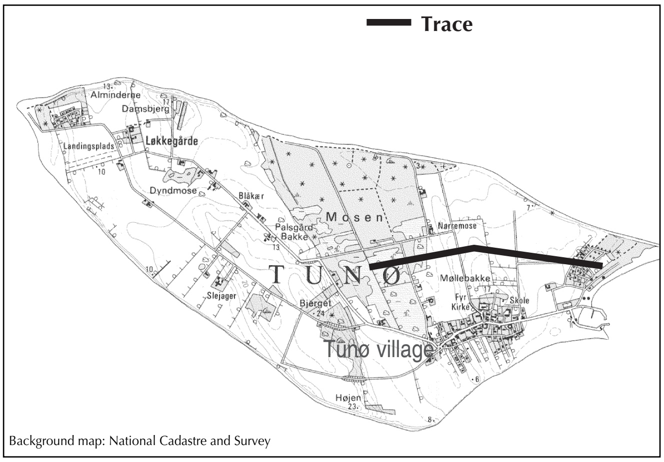


Figure 5: *Trace of the geological cross-section through the Tunø aquifer shown in Figure 4.*

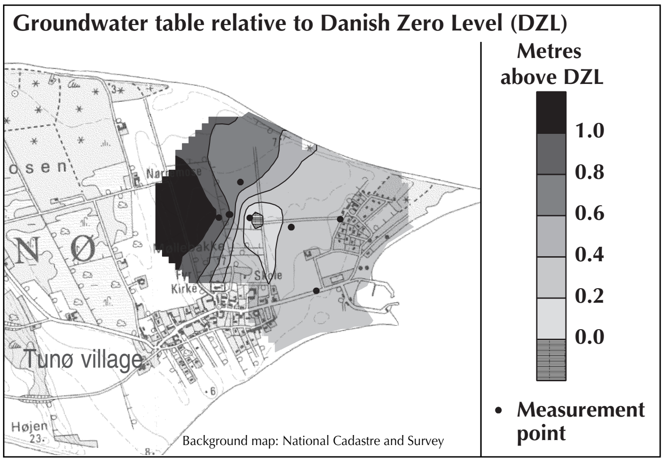


Figure 6: *A snapshot image of the groundwater table in the aquifer near Tunø Waterworks. The map is based on a survey undertaken in spring 1999 in the deepest filters in the accessible wells in the area. Note that the groundwater table is at approximately Danish Zero Level near the waterworks.*

level. From there the level of the groundwater table falls towards the east down to around sea level near the well field. The groundwater thus flows in an easterly direction down towards the waterworks from the area north of Tunø village. In the area around the well field itself, groundwater flows towards the wells from all directions.

The water-level readings made in spring 1999 thus showed that at that time, the groundwater level within the area varied from only one metre above sea level to eight cm below sea level. When the level of the groundwater table falls below sea level, the water pressure is lower in these areas than in the sea. Seawater might therefore be able to infiltrate the aquifer and contaminate the fresh groundwater if the groundwater table is permanently below sea level. A precondition for preventing the destruction of the groundwater resource is therefore to careful monitor the groundwater level and refrain from abstracting too much water in order to avoid a groundwater table permanently below sea level.

The problem of a very low groundwater table and the consequent risk of saltwater infiltration in connection with a slightly increased level of abstraction is a well-known phenomenon on many small islands. The positive aspect is that a monitoring programme has now been established on Tunø that enables this problem to be taken into account.

Protection zones

Work on establishing the protection zones was initiated in 1989. At that time the extent of the actual capture zone was unknown and the protection zones were therefore established within the area radiating 300 metres from the waterworks' main well (W3 on Figure 2).

The inner protection zone

Agriculture ceased in the inner protection zone in 1988. In September 1989, three hectares of land around the waterworks were ploughed, harrowed and sown with red fescue grass. The land had been set aside the preceding year. Prior to that it had been cultivated with leeks and cereals. The boundaries of the area follow the original field boundaries.

In summer 1991 the inner protection zone was extended by 3.5 hectares towards the north. Prior to and including 1990, the area was under intensive cultivation with leeks in rotation with cereals. In spring 1991, the land was sown with barley undersown with grass. The field was not ploughed after harvest, thus resulting in the establishment of permanent grass, which became efficient from 1992.

The grass in the inner protection zone is cut once yearly. The application of fertilizer or pesticides in this zone is prohibited.

Odder Municipality purchased the land at the beginning of the project, and the requirement for it to be farmed was rescinded. The land was handed over to Tunø Waterworks in January 1994 in connection with the privatization of the waterworks. Operation of the waterworks presently entails not only the traditional tasks associated with a waterworks, but also the maintenance of the inner protection zone.

The outer protection zone – establishment phase

When the outer protection zone was established, nitrogen budgets were not required on purely arable farms because the existing measures concentrated on livestock farms and green fields. During the period 1989–95, Aarhus County and Odder Municipality thus paid to have fertilizer use regulated using field management plans based on soil analyses where the plant-available nitrogen is determined. Soil samples were collected from the fields in the outer protection zone on several

Photo: Per Misser

Figure 7: *View of the inner protection zone with Tunø Waterworks on the left.*

occasions during the growth season. The samples were analysed by the environmental consultancy company Hedeselskabet using the N-min method and processed by the Department of Plant Production, Danish Agricultural Advisory Centre. Based on these measurements, the agricultural advisor advised on the economically optimal nutrient supply taking into consideration the amount of plant-available nitrogen.

A special fertilizer applicator was purchased in 1990 for use in the leek fields. This places the fertilizer close to the plant roots and can be adjusted to deliver precisely the amount of fertilizer stipulated in the field management plans. This avoids fertilizing between the crop rows, where the roots cannot reach it, thereby saving on costs and protecting the groundwater against nitrate contamination due to the application of excess fertilizer.

The machine was purchased by the Spatial Planning Agency and handed over to Tunø Family Farmers Association on the condition that during the initial trial period, it was only to be used in connection with leek production within the protection zone. The machine is still in use and thus still helps to reduce nitrogen leaching.

Other agrotechnical measures employed to improve nitrogen utilization included a change in the temporal pattern of nitrogen fertilizer application during the course of the year on the leek fields, a change in the crop rotation rhythm, and loosening the soil by deep grubbing.

Land use	*% Before 1989*	*% 1989-1991*	*% After 1992*
Not in agricultural use	**7**	**7**	**7**
Permanent grass, inner protection zone	**0**	**10**	**34**
Permanent grass, with horses	**6**	**6**	**36**
Barley and wheat	**31**	**31**	**1**
Leeks in rotation	**56**	**46**	**22**

Table 1: *Land use in the capture zone of Tunø Waterworks. The capture zone encompasses 20 hectares due to uncertainty as to the extent of the capture zone. Adapted from Roorbach, 1993 (5).*

Seven hectares in the western part of the outer protection zone have been set aside from September 1991 to 2017 under the EU set-aside scheme. The area has been sown with grass and clover and is grazed by a couple of horses.

The actual capture zone has been delimited by surveys and geophysical studies (Figure 2 and 4). It lies slightly more westerly than the outer protection zone and is so

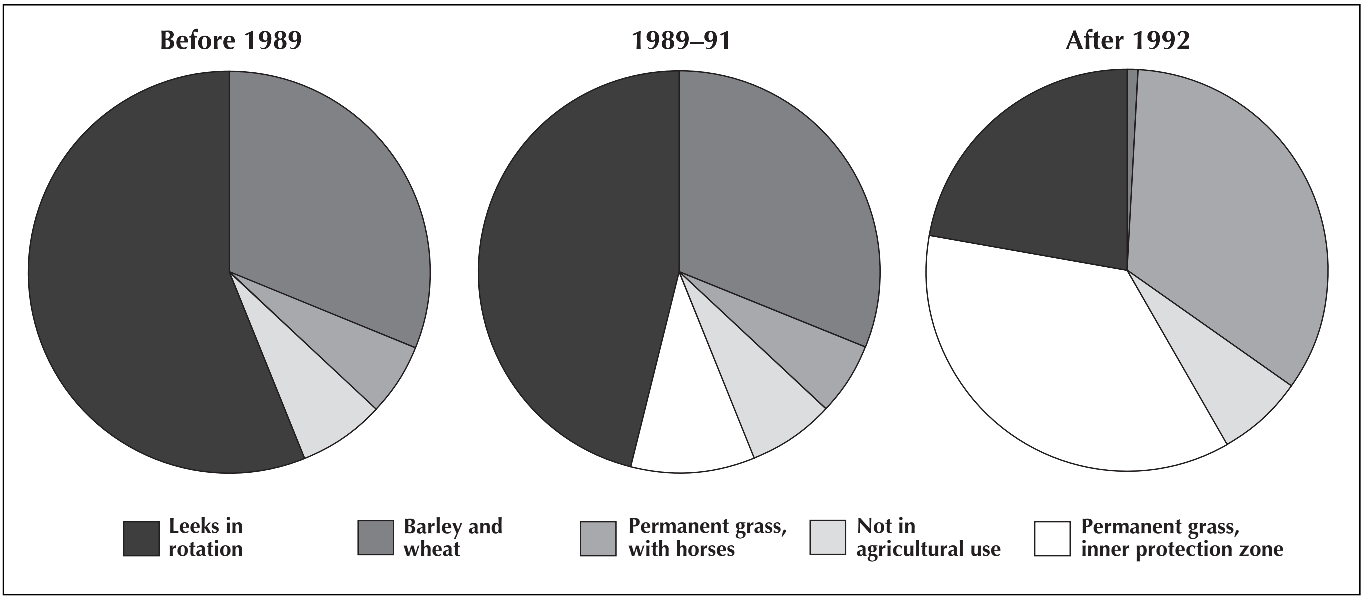


Figure 8: *Development in land use in the capture zone of Tunø Waterworks resulting from the implementation of groundwater protection (illustration of data in Table 1).*

large that it can outweigh uncertainty concerning variation in geology, precipitation and water consumption. Delimitation of the capture zone has not led to any changes in the area of land encompassed by the project.

The percentage of the capture zone under ordinary agricultural practice has decreased during the course of the project (Table 1) (5). From Figure 8 it can be seen that since 1992, only approx. 25% of the waterworks' capture zone has been farmed.

The outer protection zone – results and future

Despite efforts to reduce leaching in the outer protection zone, leaching was not reduced sufficiently. Nitrate leaching under the cultivated areas measured in suction cells at a depth of one metre averaged 150–250 mg/l (see Figure 12).

The field management system was not completely without effect, however. Thus whereas the nitrate concentration in the soil water beneath vegetable crops was often 500–600 mg/l in the first years, such high levels of leaching are rarely encountered now. In fact, nitrate leaching from cereal fields is occasionally even as low as 50–75 mg/l.

The continued presence of very high nitrogen concentrations under the cultivated fields necessitated extending the inner protection zone in 1991. Moreover, the fields that had been set aside in the western part of the area cannot be cultivated again without new measures being taken to reduce leaching.

During the project period, increasingly strict Danish requirements have been introduced concerning nitrogen utilization in agriculture. The measures of greatest significance for Tunø, where mainly vegetables and cereals are cultivated, are outlined in the box opposite.

The introduction of centrally dictated nitrogen norms for the individual crops made continued use of the field management system included in the original project superfluous.

Calculations made in 1995 by the Department of Plant Production, Danish Agricultural Advisory Centre, show that it is possible to grow crops and have low leaching at the same time, but that this would necessitate considerable changes in crop rotation combined with, for example, the ploughing in of straw and the use of catch crops. If these initiatives are to be implemented it will be necessary to provide financial compensation to the farmers and vegetable growers in the area at a level exceeding the existing framework for agri-environmental support schemes in the so-called "environmentally sensitive agricultural areas". The project group decided not to implement these measures on the grounds that continued operation of the outer protection zone should be exclusively regulated within the framework of the existing legislation and support scheme structure. For the same reason, support has not been provided for field management in the outer protection zone since 1995.

Major legislative changes of relevance for the Tunø project

1987, Action Plan on the Aquatic Environment I (from autumn 1990)

- **Requirement for winter green cover on at least 65% (easily fulfilled as leeks come in under green cover).**

1991, Action Plan for Sustainable Agriculture (from harvest year 1994)

- **Fines for exceeding the maximum permitted norms for application of nitrogen.**
- **Requirements for fertilization budgets. Introduction of centrally dictated fertilization norms.**

1998, Action Plan on the Aquatic Environment II

- **10% reduction in nitrogen norms. Fines for norm exceedence.**

Monitoring

The objective of the monitoring activities on Tunø is to assess whether the protection zones have the desired effect with respect to improvement in groundwater quality, while at the same time providing an estimate of how long it will take before the waterworks is once again able to supply water of satisfactory quality. A further objective is to survey the quality of the groundwater in the area. This is achieved by following the water from the time it leaves the root zone, down through the unsaturated zone and until it ends up in the groundwater.

The location of the various monitoring activities is indicated in Figure 2. Monitoring was started at the beginning of the project in 1988/89 and in November 1993 was supplemented with two wells enabling the clean water from the inner protection zone to be followed on its way down through the unsaturated zone.

The technical details from the establishment of the monitoring activities on Tunø are described in "Status report – Tunø 1989" (2).

Net precipitation

That part of the precipitation that ends up in the groundwater is termed the net precipitation. The net precipitation is measured in the inner protection zone using two lysimeters. These are placed under grassland, cover an area of approx. 1.33 m^2 and collect water at a depth of approx. 1.25 metres. The lysimeters are emptied in connection with the other sampling activities in the area. They provide a measure of the amount of water leaving the root zone during the course of the year.

Soil water

The quality of the water that leaves the root zone is followed at six soil water stations. Two are located in the inner protection zone and four in the outer protection zone, one of which covers the part of the zone that has been set aside. Each soil water station consists of 12 suction cells situated at a depth of approximately one metre, from where water samples are collected. In the first years the water was analysed for nitrate approx. 12 times annually. Since 1994, it has only been analysed approximately six times annually.

Unsaturated zone

In November 1993, two wells each containing six suction cells were drilled down through the unsaturated zone. Both wells are located in the inner protection zone, one in the new part and one in the old part. In order to prevent the wells functioning as drains allowing the surface water to rapidly flow down to the groundwater, clay plugs have been inserted in the bore hole between the suction cells as well as at ground level. The suction cells are located in a mixture of silica flour and quartz sand. The water samples from the unsaturated zone are analysed for nitrate. Sample collection in the unsaturated zone is undertaken twice yearly.

Groundwater

The groundwater is monitored in five dedicated monitoring wells as well as in the waterworks' abstraction wells and survey wells. A total of 12 filters in the area are monitored. Samples are collected from the groundwater twice a year and analysed for nitrate, nitrite, manganese, oxygen, pH and conductivity.

Groundwater table

Each time samples of the groundwater are collected the depth of the groundwater table in the well is measured, thereby enabling determination of the direction of the groundwater flow and the extent of the capture zone. Another aim is to determine the risk of influx of salt water from the surrounding sea during periods of very low precipitation, as can happen if the groundwater table falls below sea level.

Land use

Land use at the six soil water stations is known from the field management plans, etc. This is shown in detail for the duration of the project in Table 2. Note that in the early years of the project, the fields used for cultivating

Year	*Plot 1*	*Plot 2*	*Old inner p.z.: Plot 3*	*New inner p.z.: Plot 4*	*Plot 5*	*Plot 6*
1988	**Carrots**	**Leeks**	**Spring barley**	**Leeks**	**Spring barley**	**Spring barley**
1989	**Leeks**	**Spring barley**	**Set-aside**	**Spring barley**	**Spring barley**	**Leeks**
1990	**Spring barley**	**Leeks**	**Grass**	**Leeks**	**Winter rye**	**Spring barley**
1991	**Winter wheat**	**Winter wheat**	**Grass**	**Spring barley undersown with grass**	**Winter rye**	**Leeks**
1992	**Leeks**	**Leeks**	**Grass**	**Grass**	**Clover grass**	**Winter wheat**
1993	**Spring barley**	**Spring barley**	**Grass**	**Grass**	**Clover grass**	**Leeks**
1994	**Leeks**	**Oats**	**Grass**	**Grass**	**Clover grass**	**Oats**
1995	**Barley**	**Leeks**	**Grass**	**Grass**	**Clover grass**	**Parsley root**
1996	**Leeks**	**Spring barley**	**Grass**	**Grass**	**Clover grass**	**Spring barley**
1997	**Barley**	**Barley**	**Grass**	**Grass**	**Clover grass**	**Leeks**
1998	**Wheat**	**Parsley root**	**Grass**	**Grass**	**Clover grass**	**Barley**
1999	**Wheat**	**Parsley root**	**Grass**	**Grass**	**Clover grass**	**Wheat**

Table 2: *Land use at the soil water stations on Tunø 1988–1999.*

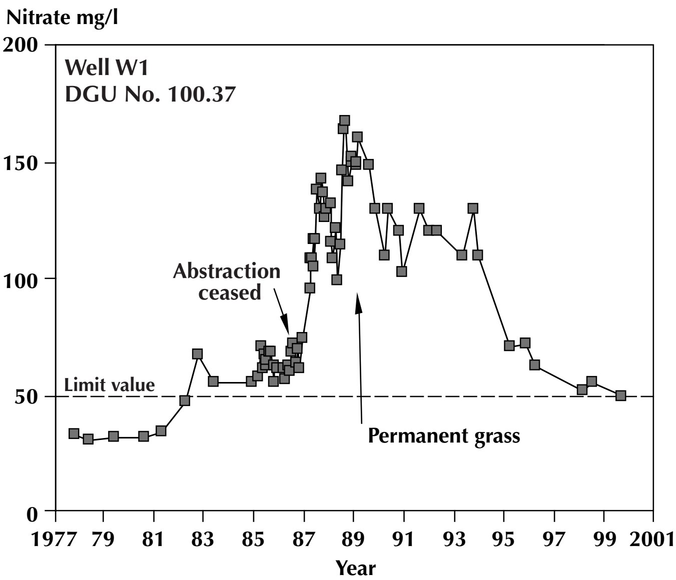
leeks were under biannual crop rotation with leeks. The longer crop rotations in the subsequent years are the result of implementation of the field management system.

Nitrate content of soil water and g

Water supply wells

The development in nitrate concentration in the waterworks' two abstraction wells, W1 and W3, is shown in Figure 9.

Well W1 served as an abstraction well until approx. 1987. Since then it has served as a reserve well. The nitrate content of the abstracted water was around 30 mg/l in the 1970s, but increased to around 60 mg/l in the 1980s. After operation of the well ceased, the nitrate content increased further to around 125 mg/l. Since the mid 1990s the nitrate concentration has been falling again in this well, the filter of which is located in the upper groundwater.



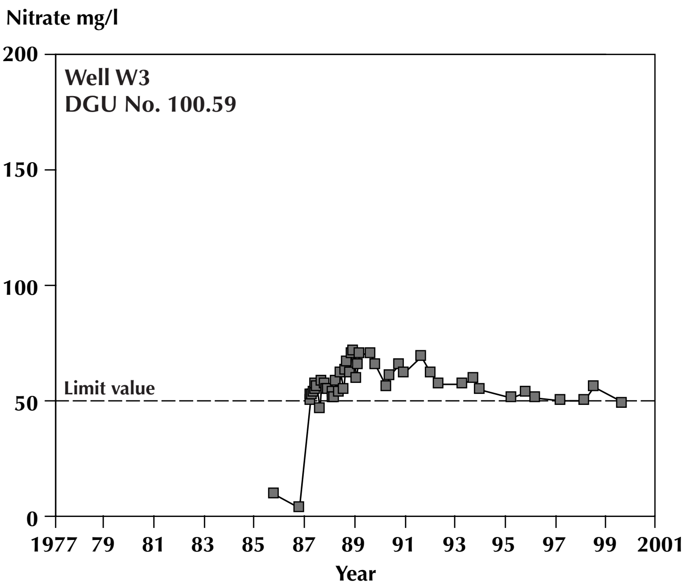


Figure 9: *Nitrate content of the abstraction wells W1 and W3.*

The waterworks attempted to solve the nitrate problem with a new abstraction well. In 1985, well W3 was therefore established next to W1 with the filter located in the lower part of the aquifer. At that time the nitrate content was less than 10 mg/l. Once the well started operation, though, nitrate-containing water was drawn down into the filter. Over the course of a few weeks the nitrate content increased to around 60 mg/l, which is above the limit value of 50 mg/l. As is apparent from Figure 9, the nitrate concentration has been falling slightly in recent years and is now around 50 mg/l.

The fact that the quality of the water in W1, which is abstracted from the uppermost oxygenated groundwater, complied with the 50 mg/l limit value for nitrate in drinking water until the end of the 1970s shows that the occurrence of very high nitrate concentrations in the groundwater on Tunø is a recent phenomenon. Over the past five years the nitrate content has fallen considerably, probably because abstraction draws pure water from the uppermost groundwater under the protection zone down into the filter. The resultant water quality is thus a mixture of old water with a high nitrate content from the time before establishment of the protection zones and younger pure water from the areas of permanent grass.

Net precipitation and water consumption

Measurements of net precipitation in the inner protection zone have revealed considerable variation over the past ten years, ranging from as little as approx. 75 mm/yr in dry years to as much as 325 mm/yr in more wet years. Average net precipitation was approx. 150 mm/yr (see Figure 10).

Water consumption has been stable since 1990 at around 11,000 m^3/yr. The permitted level of abstraction is 13,000 m^3/yr. Apart from two years with particularly high consumption, inter-annual variation in water consumption has been less than 10%.

groundwater

The formation of the 11,000 m³/yr required by the waterworks necessitates a groundwater capture zone of 7.3 hectares assuming a net precipitation of 150 mm per year. The marked variation in precipitation means that the size of the groundwater capture zone can vary considerably from year to year. Thus over the past ten years the size of the necessary groundwater capture zone has varied between 4 and 16 hectares. If more permanent changes in precipitation or water consumption occur on the island, it could prove necessary to adjust the size of the protection zone or the water consumption.

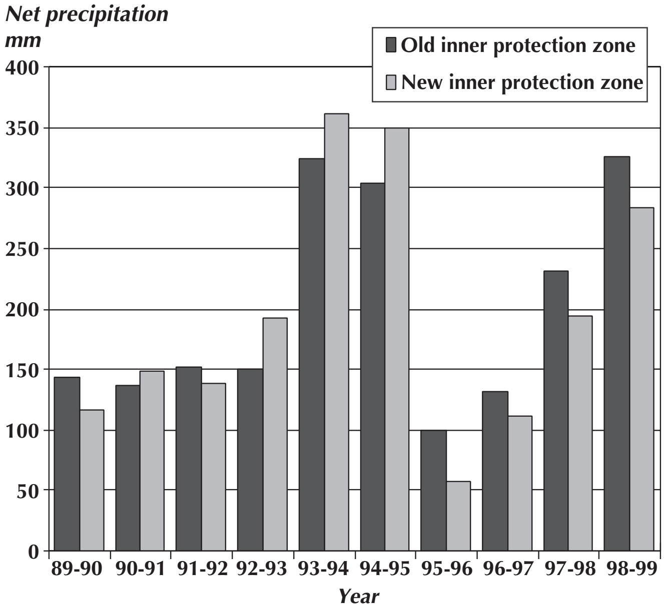


Figure 10: Groundwater recharge in the inner protection zone 1989/90–1998/99.

Soil water

The water that leaves the root zone to subsequently become groundwater is collected in the unsaturated zone in suction cells located approximately one metre below ground level. The water samples indicate what the maximum nitrate concentration will be in the future groundwater. A smaller part of the nitrate in the soil water will be removed during transport or taken up by particularly deep plant roots.

The development in nitrate leaching under the fields that are no longer cultivated is shown in Figure 11. Plots 3 and 4 are located in the inner protection zone. As indicated by the figure, leaching of nitrate in the inner protection zone is insignificant as the nitrate concentrations in the soil water are around 1 mg/l. It

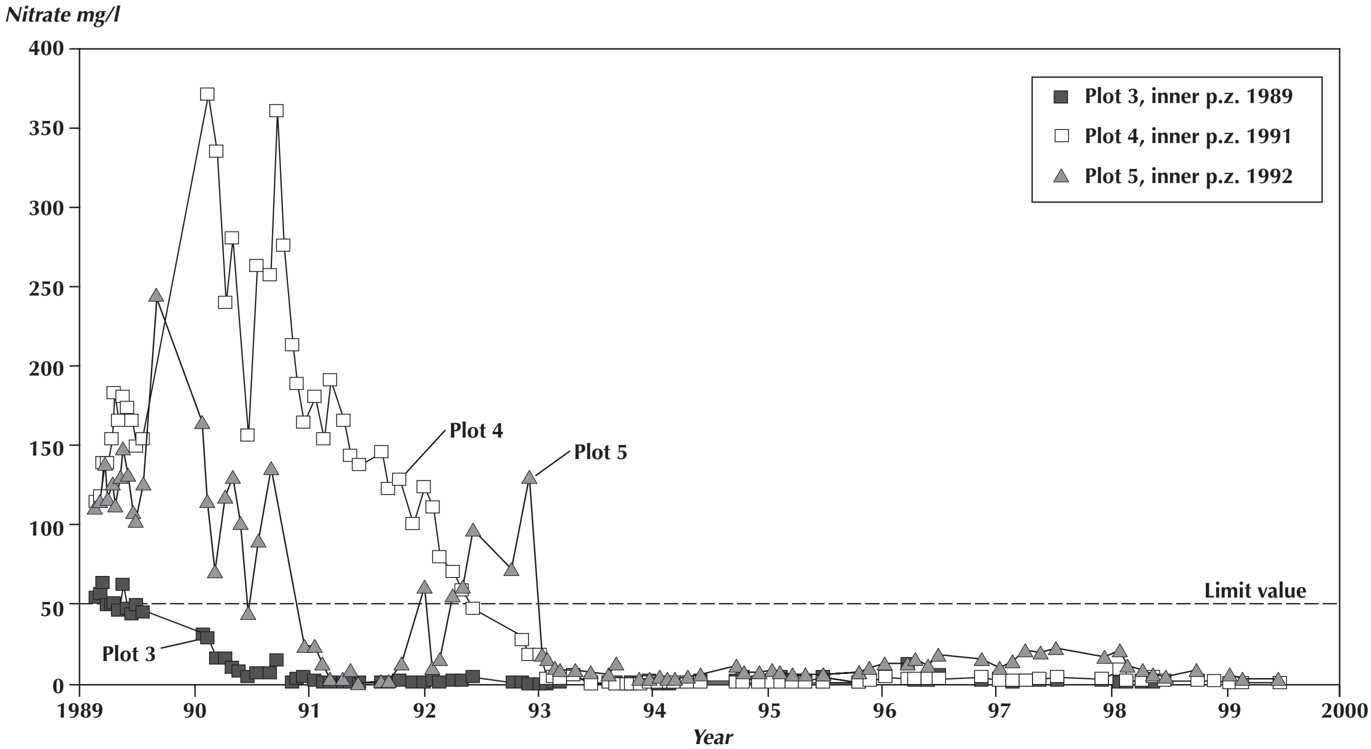


Figure 11: Development in nitrate concentration in the inner protection zone (p.z.) and on the set-aside farmland. Plot 3 has been within the inner protection zone during the whole period, whereas Plot 4 was cultivated with leeks in rotation until 1991. The set-aside land, Plot 5, has been planted with grass and clover since 1992 (see Table 2).

transpires that it only takes one year following the establishment of permanent grass before leaching of nitrate is curtailed. This is quite remarkable, not least in Plot 4, where nitrate leaching exceeded 100 mg/l with an average in individual months exceeding 300 mg/l before the grass was sown.

Experience from the oldest part of the inner protection zone shows that nitrate leaching remains very low even under variable climatic conditions. Root counts in the inner protection zone undertaken in 1990 (3) indicate a well-developed root system down to a depth of 1.5 metres under the permanent grass that is able to take up nitrate in step with the mineralization of organic nitrogen in the soil.

One can reasonably talk about pure water being "cultivated" in the inner protection zone.

Before the field at Plot 5 was set aside, the nitrate level was lower than in the other cultivated plots. Vegetables had not been grown in that field and the farmer volunteered the information that he had applied less fertilizer than recommended by the agricultural advisor. After having been set aside, the land was sown with grass and clover. It can be seen that in contrast to the situation with red fescue grass, measurable leaching of nitrate takes place from grass containing clover, yielding a soil water nitrate concentration of approx. 10–15 mg/l.

Nitrate leaching from the cultivated Plots 1, 2 and 6 is shown for each year of the project period in Figure 12. The annual median values are used in order to attenuate the effect of individual very high nitrate measurements. Contrary to expectation, there is no evidence of any systematic pattern of annual variation in the soil water nitrate concentration.

As is apparent from the figure, the nitrate content of the soil water under the three fields where leeks have been cultivated in rotation during the whole project period has been at a constantly high level of approx. 150–250 mg/l. In a few cases (not shown), values as high as 500 mg/l were measured. The magnitude of leaching has been independent of whether the fields were cultivated with leeks or cereals during the year in question. This could be attributable to the marked climatic fluctuations that characterized the period, with both very warm and dry years and years with unusually great precipitation and cool weather.

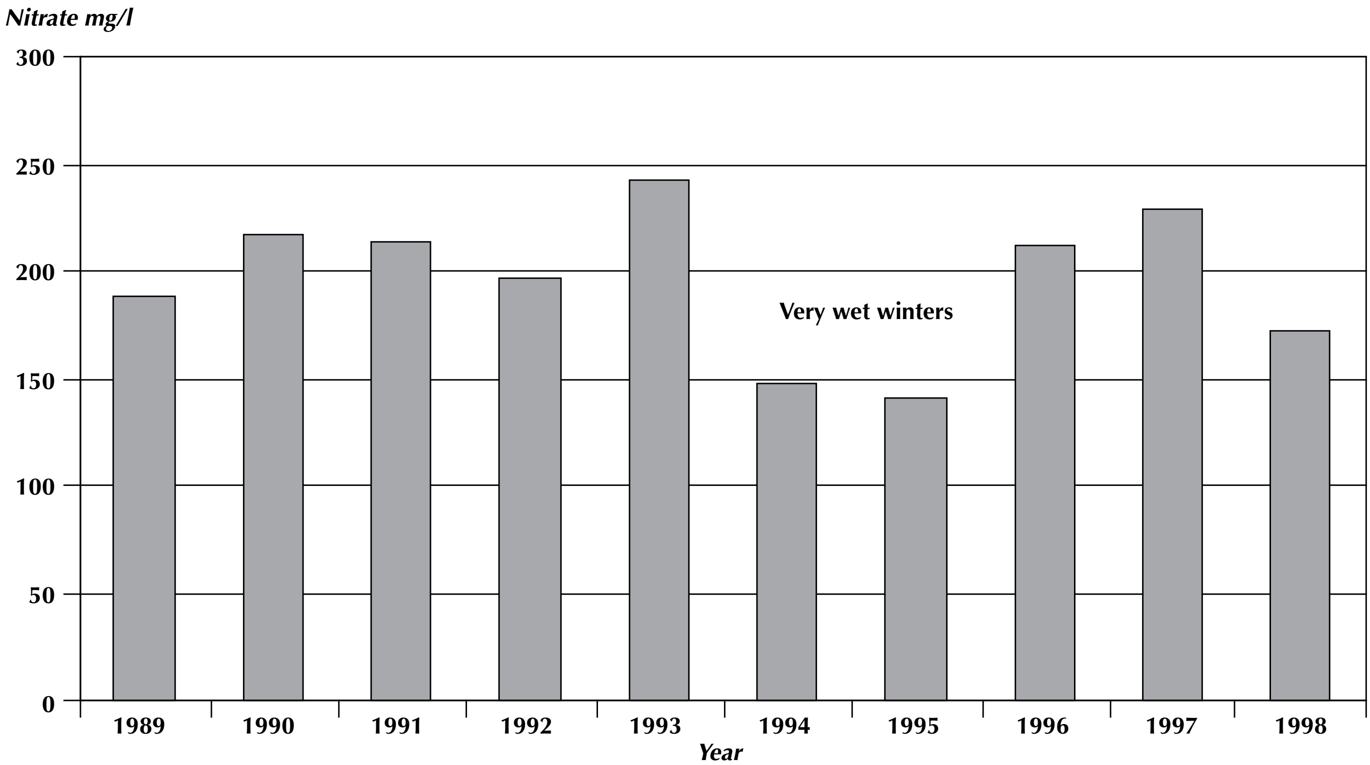


Figure 12: *Soil water nitrate concentrations measured under the cultivated fields in Plots 1, 2 and 6. The values are the medians for each year during the project period.*

The resulting groundwater quality under the field at Plot 2 can be seen in well P6.2, the filter of which is located in the upper groundwater. Here the nitrate content of the groundwater is approx. 200 mg/l, which is in good agreement with the concentration in the soil water (150–250 mg/l). This shows that virtually all nitrate leaching from the fields can be found in the groundwater.

Despite the field management measures, nitrate leaching from the cultivated areas has not changed appreciably since the project began.

The unsaturated zone

In order to determine when the pure water from the inner protection zone will reach the groundwater, two wells fitted with suction cells were drilled down through the unsaturated zone and uppermost groundwater in autumn 1993.

Nitrate concentration is shown as a function of depth and number of years since the establishment of permanent grass cover in Figure 13. The two lowermost samples in each well are from below the groundwater table.

As is apparent from the figure, the pure water from both the new and old parts of the inner protection zone has migrated down through the whole of the unsaturated zone and into the upper metres of the groundwater. It took the pure water approximately five years to reach the groundwater. Note that the nitrate concentration one metre down into the groundwater has fallen from over 100 mg/l to around 10 mg/l. This is in good agreement with the fact that the effect of the inner protection zone is also detectable in other wells (see Figure 15). The difference between the two wells is partly attributable to differences in the composition of the soil layers.

The pure water derived from the whole of the protection zone has now reached the upper groundwater. In the course of a few years it can be expected to reach deeper into the groundwater, and hence to the waterworks.

Groundwater

Figure 14 shows a map summarizing the nitrate content of the wells around Tunø waterworks in 1999. Each well has had a characteristic nitrate concentration throughout the project period except the wells with

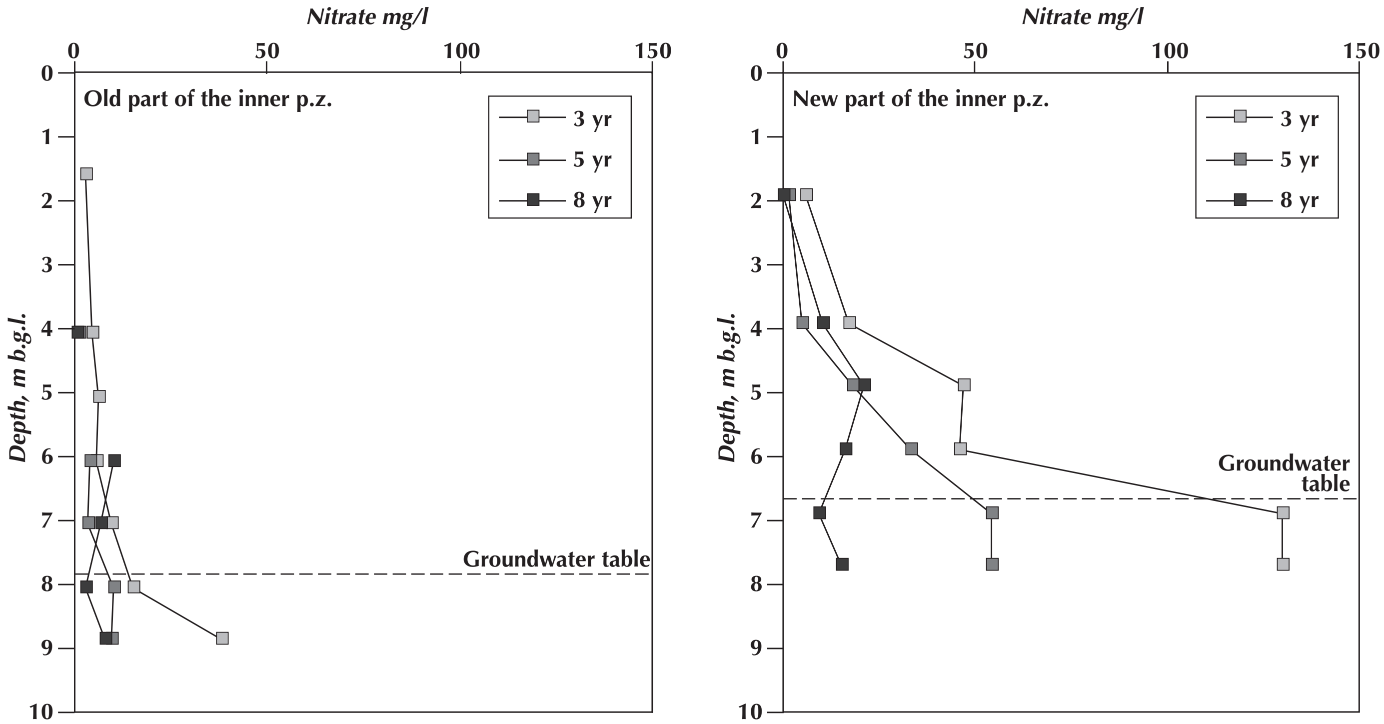


Figure 13: Nitrate concentration down through the unsaturated zone under the old and new parts of the inner protection zone (p.z.). The curves show nitrate profiles 3, 5 and 8 years after establishment of permanent grass.

filters in the uppermost groundwater within the protection zone (see Figure 13).

The survey of groundwater quality on Tunø has shown that there is no nitrate-free groundwater. In the wells where the filters are placed deeper than four metres below the groundwater table, nitrite occurs in groundwater because oxygen is absent. The presence of nitrite shows that nitrate reduction takes place since nitrite is an intermediate product in the reduction of nitrate to free nitrogen: ($NO_3^- \rightarrow NO_2^- \rightarrow N_2$).

The nitrite-containing groundwater that is abstracted at the waterworks does not cause problems of compliance with limit values. The abstracted water is oxygenated to remove manganese. During the process, nitrite is oxygenated to nitrate.

Even though the presence of nitrite shows that nitrate reduction takes place in the lowermost part of the aquifer, the reaction rate is far too low to result in any appreciable removal of nitrate.

The only way to ensure a low groundwater nitrate content in the aquifer at Tunø Waterworks is therefore to ensure the input of pure water from above, such as it has been the case in the inner protection zone.

Another effect of the variable precipitation conditions is that the groundwater table has fluctuated by up to almost one metre. Over the past five years, the same filter can therefore have monitored different layers of the groundwater. The relationship between the depth of the filter below the groundwater table and the well nitrate content is shown for the three uppermost filters in the groundwater in the old and new parts of the inner protection zone in Figure 15. As is apparent from the figure, the low nitrate concentration reaches a depth of approx. 1.5 metres below the groundwater table, corresponding to approximately ten metres below ground level in the old part of the inner protection zone. In contrast, the pure water in the new part of the zone reaches just approx. 0.75 metres down into the groundwater. Approximately three metres below the groundwater table the nitrate concentration is still approx. 100 mg/l.

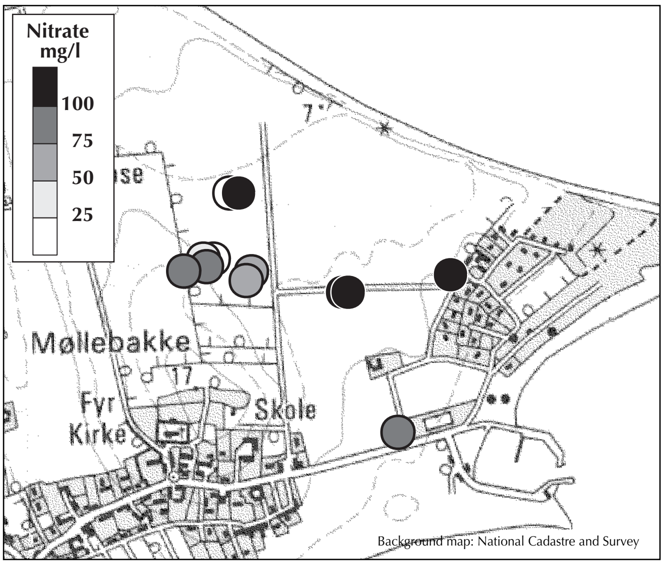


Figure 14: *Groundwater nitrate concentration on Tunø 1999.*

Future prospects

In order to be able to reasonably predict how long it will be before the waterworks can pump pure water from the protection zone to consumers, the groundwater in all the monitoring wells has been dated using the CFC method. For technical reasons, it proved impossible to date the water in the abstraction wells.

The relationship between the age of the groundwater in years and the distance below ground level is illustrated in Figure 16. As is apparent from the figure, the uppermost groundwater is approx. 8–10 years old, which is in accordance with the fact that it derives from the wells where the pure water from the protection zone is found.

The oldest water from the deepest wells is approx. 30 years old and can be expected to have been replaced by water formed at the beginning of the project in approx. 20 years time. In general, the age of the groundwater increases by approximately one year per 50 cm depth.

This is comparable with the estimate obtained based on the groundwater recharge.

If it is assumed that net precipitation averages approx. 150 mm/yr and that the average effective porosity is 20%, the aquifer will receive 75 cm of new groundwater each year.

Part of this water will flow out to the sea so that the actual contribution of one years' precipitation to the groundwater in the centre of the island will be less than 75 cm. To this should be added the uncertainty with respect to the effective porosity which, depending on grain size distribution in the soil layers in question, will vary between 10% and 40%. This will halve or double the extent to which the new groundwater penetrates into the aquifer. All in all, though, there is good agreement between the 50 cm/yr determined by dating and the approx. 75 cm/yr minus runoff calculated on the basis of average net precipitation.

Figure 16 also indicates the location of the abstraction well filters. Based on the dating in Figure 16 it seems probable that part of the fall in nitrate in abstraction well 1 is attributable to the pure water from the protection zone being drawn into the filter because of the high abstraction rate.

It can also be seen that the water in the layer at the bottom of abstraction well 1 is approx. 20 years old and can therefore be expected to have been replaced by the first water from the inner protection zone in approximately ten years time. In that case, the well should be put into operation again.

The pure water from the protection zone can be expected to be supplied to consumers within the next ten years.

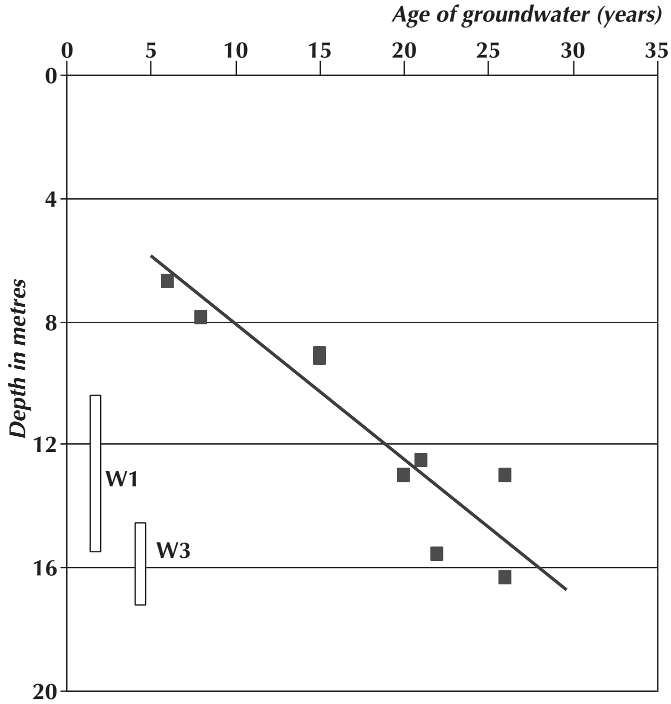


Figure 16: Age distribution of the groundwater with depth in metres below ground level. The depth distribution of the abstraction well filters is indicated for comparison.

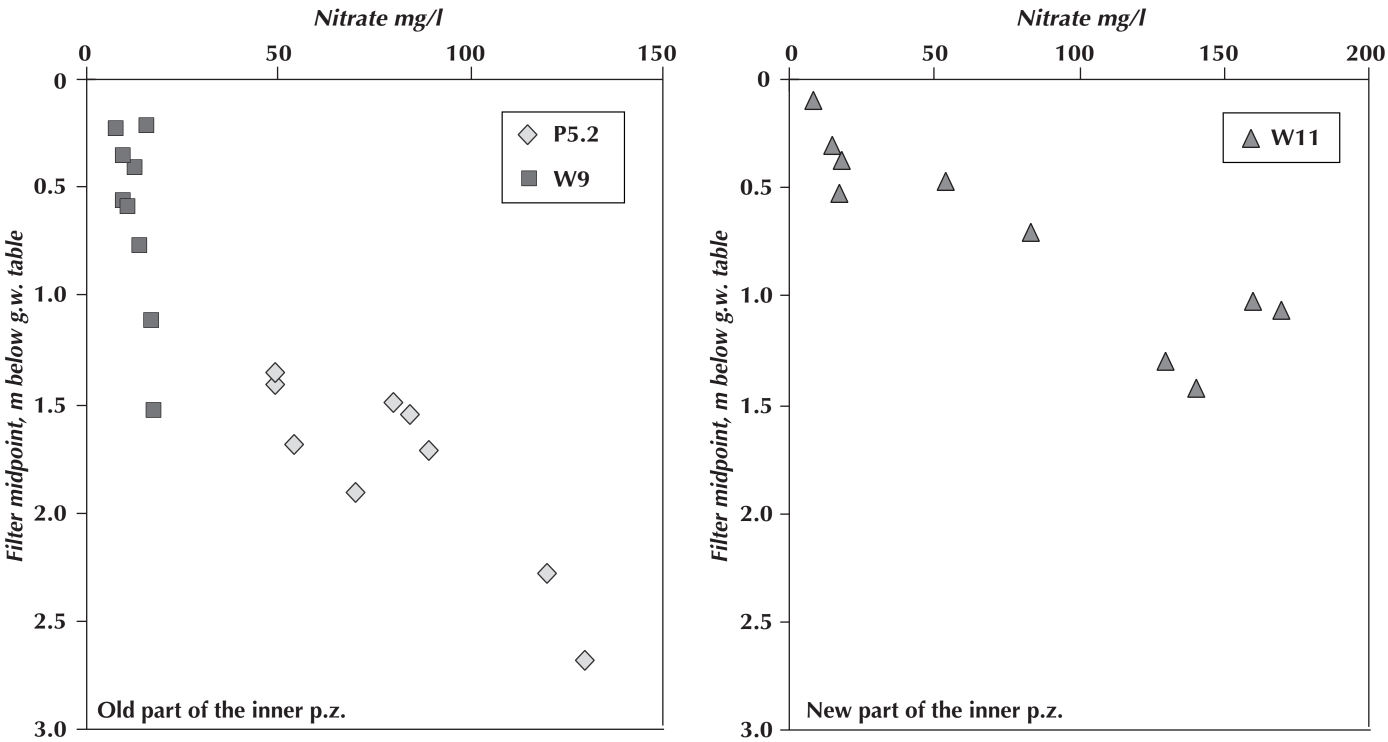


Figure 15: Nitrate concentration as a function of filter location in the groundwater for a period with variable groundwater table 1995–98. From the figure it can be seen that the low nitrate concentration reaches approx. 1.5 m below the groundwater table, corresponding to approx. 10 m below ground level in the old part of the inner protection zone (p.z.), while the pure water has only reached approx. 0.75 m down into the groundwater in the new part.

Perspectives

The monitoring data can be used to predict the future quality of the water. How long will it take before the pure water reaches the abstraction wells and is the protection zone sufficiently large?

Considerable improvement in water quality can be expected at the waterworks within the next ten years. Within the next few years, moreover, it should once again be possible to supply water that complies with the limit value for nitrate. Analysis of samples from the waterworks' two abstraction wells for 23 pesticides undertaken in 1998 revealed that the water did not contain pesticide residues.

Tunø Waterworks was privatized in 1994 and in future might be merged with the small waterworks Stenkalven. Water consumption is approx. 11,000 m^3/yr while that at Stenkalven is maximally 2,000 m^3/yr. With a net precipitation of 150 mm/yr, the abstraction of 13,000 m^3/yr would theoretically necessitate a capture zone of approx. 8.6 hectares.

The current size of the inner protection zone is 6.5 hectares. Thus nitrate leaching could only occur in a minor part (approx. 25%) of the capture zone. The fields in the capture zone south and west of the inner protection zone are grazed by horses, thus leading to very little nitrate leaching. Leaching is very low in a total of approx. 13 hectares in the vicinity of the waterworks. Despite a certain degree of uncertainty about the actual extent of the capture zone, it can be assumed to be adequate.

It is important that leek production, which we found can result in 200 mg/l nitrate in the groundwater, is not resumed on the fields around the waterworks to any greater extent than at present without prior careful consideration. If leek production is resumed on all the fields outside the protection zone, the waterworks would once again find itself in a critical situation.

Leaching from leek fields is not considerably greater than from other Danish agricultural areas. With a net precipitation of 150 mm/yr, the 200 mg/l in the soil water corresponds to leaching of approx. 75 kg N/ha. Leaching of this magnitude has been measured in many places in connection with the Agricultural Catchment Monitoring Programme (6).

The following calculation can be made:

- **The leek fields give approx. 200 mg/l nitrate in the oxidized groundwater.**
- **The inner zone gives approx. 0 mg/l.**
- **The permitted abstraction is approx. 13,000 m^3/yr. With a precipitation of 150 mm the capture zone is 8.6 ha.**
- **6.5 ha capture zone with 0 mg/l and 2.1 ha capture zone with 200 mg/l yields a water quality of 49 mg/l.**

- **This means that the limit value is exceeded if leaching is just a few percent greater or if abstraction increases or if net precipitation decreases (see Annexe 2).**
- **The current abstraction level of 11,000 m^3/yr yields a calculated water quality of 22 mg/l nitrate.**

Future plans

In the coming years, monitoring of the soil water, unsaturated zone and groundwater will continue. In view of the very convincing and stable results, monitoring intensity will be reduced.

The monitoring activities will be continued until the water at the waterworks is completely pure.

During the time that monitoring has been undertaken, the field management measures seem to have only slightly reduced nitrate leaching. However, assessment of the possibilities offered by field management shows that with the present support structure, it cannot pay to take further measures even though the land in question is designated as "environmentally sensitive agricultural areas", and hence entitled to the maximum possibilities for support.

The good experience gained at Tunø should be incorporated in future action plans for threatened waterworks.

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Annexe 1

Economic preconditions for choice of solution

With the aim of drawing up a strategy for safeguarding the water supply on Tunø a working group was established on May 5 1986. The working group originally consisted of representatives of Aarhus County, Odder Municipality, the Danish Environmental Protection Agency, the Centre for Soil Ecology (now National Environmental Research Institute), the Department of Agricultural Law, Danish Agricultural Advisory Centre and the agricultural advisor for Tunø and Samsø. At that time, Tunø Waterworks was a municipal waterworks run by Odder Municipality. The composition of the working group has changed over the years, in particular with the involvement of the Department of Plant Production, Danish Agricultural Advisory Centre, in drawing up the final project. In addition, local farmers have been provided the possibility to express their views.

Prior to deciding to establish the protection zones around Tunø Waterworks, the working group examined a number of different solutions ranging from water treatment to the import of drinking water to actual groundwater protection.

The economic consequences of the establishment and operation of each of these solutions were calculated. These are presented below in 1986 prices.

The details of the various proposed solutions are described in the report "Vandforsyning på Tunø (Water Supply on Tunø)", Technical Report by Aarhus County, April 1987.

Solution	*Establishment*	*Annual running costs*
Protection zones	**200,000 DKK**	**ca. 2,000 DKK**
Monitoring	**400,000 DKK**	**80,000 DKK**
Water treatment	**1.5–2 mill. DKK**	**ca. 200,000 DKK**
Import of water in tankers	**65,000 DKK**	**ca. 265,000 DKK**
Import of water by pipe	**3.6 mill. DKK**	**ca. 400,000 DKK**

Table 1: *Cost of solving the nitrate problem on Tunø.*

Three main solutions were proposed:

1. The establishment of protection zones involving regulation of land use and associated monitoring with the aim of restoring good groundwater quality.

2. The establishment of advanced water treatment systems such as reverse osmosis or denitrification.

3. Import of pure drinking water, either via a pipeline from the mainland or using road tankers.

The technical and economic advantages and disadvantages of each solution were calculated. In 1987, the working group concluded that from both the technical and economic viewpoints, groundwater protection was the most appropriate solution (see Table 1). The only other solution that was economically similar to the establishment of groundwater protection zones was the import of water in road tankers. The latter solution would entail considerable daily practical nuisance for the consumers, however.

Annexe 2

Sensitivity analysis of groundwater recharge and abstraction volume

The size of the inner protection zone was set in accordance with the present abstraction volume and the average net precipitation over the preceding 10-year period.

The possibility cannot be excluded, though, that abstraction needs at Tunø Waterworks might change in the future. Similarly, it is known that the climate can change considerably over the course of a century. During the past 30 years, net precipitation has been unusually high compared with 100 years ago. (Thomsen R. (1993) Future Droughts, Water Shortages in Parts of Western Europe, EOS, Transactions, American Geophysical Union, Vol. 74 pp. 161–165).

In making the calculations it is assumed that leaching from the cultivated fields was around 200 mg nitrate/l and that the land within Tunø waterworks' capture zone that is not presently farmed would not be farmed in the future.

The average nitrate concentration in the abstracted water is shown as a function of the amount of water abstracted and the net precipitation in Figure 1.

The figure shows that at a net precipitation of 150 mm, up to approx. 13,000 m^3/yr can be abstracted before the average nitrate concentration exceeds the limit value for nitrate in drinking water.

Conversely, the figure also shows that if the climate becomes slightly drier and net precipitation falls by for example 16% to 125 mm, it will not be possible to abstract more than 11,000 m^3/yr if the limit value for nitrate is to be complied with.

The sensitivity analysis shows that it could become necessary to adjust the size of the protection zone if the current assumptions with regard to precipitation and abstraction change. It should be noted that if leaching of nitrate under the cultivated fields decreases, this will also affect the resultant quality of the water from Tunø Waterworks.

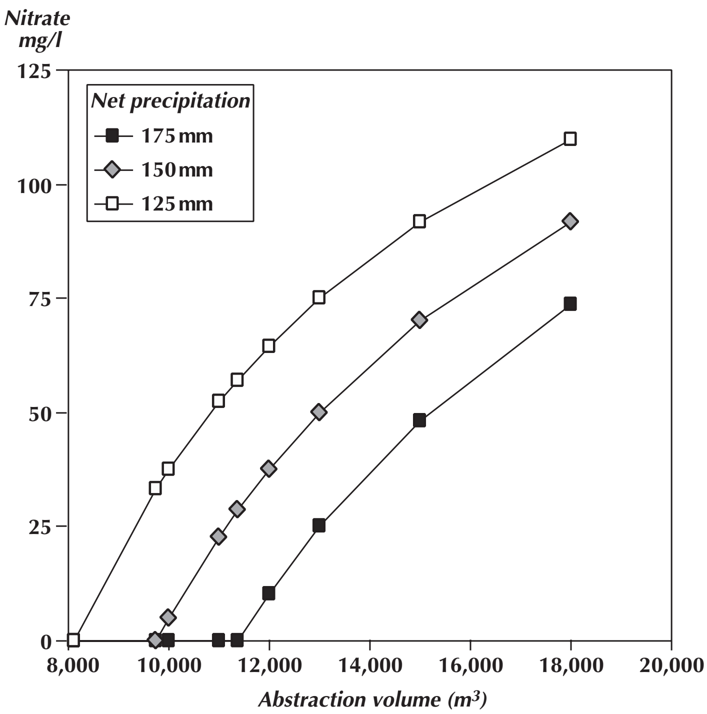

Figure 1: *Nitrate concentration as a function of abstraction volume at Tunø Waterworks at various levels of precipitation.*