

THE SOUTH AFRICAN GROUNDWATER MAPPING AND ASSESSMENT APPROACH (SAGMAA)

GUIDELINE: Appendices

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Appendix A



water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA



The Danish groundwater mapping approach

1. BACKGROUND

Nearly 100% of Denmark's water supply is based on groundwater. Traditionally, the water supply has been focused on a simple treatment process consisting of aeration and simple sand filtration. As the water supply was entirely from high quality groundwater, other treatments, such as chlorination, reverse osmosis, activated carbon, or advanced filtration, were not needed. However, particularly during the 1980's and 1990's, Denmark began to monitor for a wider range of pollutants in the drinking water, which were found. Thus, it was realised that protective measures were needed to maintain high-quality groundwater for future generations.

The Danish Groundwater Mapping Program has its roots in 1995, when the Danish Minister of Environment and Energy asked the country's 14 counties to designate areas of special drinking water interest. These areas were designated to secure a groundwater-based water supply, with simple treatment, for future generations. The total area designated as special drinking water interests covers approximately 40% of Denmark's total area. The funding for the groundwater mapping program was agreed upon in 1999 with the establishment of the drinking water levy. The agreed levy funded the program from 2000 to 2015.

The Groundwater Mapping Program's primary focus was on the protection of the groundwater resources within the areas of special drinking water interests (SDWI) ("områder med særlige drikkevandsinteresser", OSD), as designated by the counties. These areas are equivalent to Strategic Water Source Areas in South Africa. The counties were responsible for designating groundwater vulnerability areas within the SDWI, considering potential sources of contamination, both human and natural. Thereafter, the counties were required to develop groundwater protection plans to ensure groundwater quality.

In 2007, Denmark undertook a structural reform where, amongst other regulatory and institutional changes, the counties were dissolved. At this time, the responsibility for the Groundwater Mapping Program was transferred to the state, coordinated by the Danish Nature Agency, and, after the designation of groundwater vulnerability areas, municipalities were required to develop and maintain groundwater protection plans at the local level.

At the end of 2015, the original levy expired. At this time, all areas of special drinking water interest and the waterworks catchment areas outside these areas had been mapped, and the vulnerable areas requiring action had been designated. However, during the course of the Groundwater Mapping Program, it was realised that the conditions are not static, and that the program needed to continue to take into account the changing water supply structure, including increases/decreases in groundwater abstraction, new wells, wells taken out of production, as well as new information on the geology and hydrology since the original groundwater mapping had taken place. Thus, in 2015, the drinking water levy was renewed in a new Act, continuing the program with a focus on updating the groundwater mapping. In these cases, municipalities request an update to the groundwater mapping when they have changes in their water supply structures or new information affecting the designation of groundwater vulnerability areas they need to protect.

2. THE DANISH SETTING

2.1 Danish legislation

This section provides a brief description of the relevant laws governing the administration of the groundwater resources in Denmark.

The Danish Water Supply Act was drafted to secure the use and protection of Denmark's groundwater resources based on a unified planning and quality limits for drinking water. It is this Act that gives the basis for the Danish Groundwater Mapping. Here, the Danish EPA is required to designate areas of special drinking water interest, define drinking water catchment areas, designate areas particularly vulnerable to different types of pollution where groundwater protection plans need to be developed, and designate well-head protection areas. Other relevant paragraphs of the Act include:

- Municipalities are required to create groundwater protection action plans.
- Municipalities are required to develop water supply plans.
- Municipalities have the authority for abstraction permits
- Municipalities are required, once a year, to submit abstraction and water quality data to the national groundwater database, Jupiter.
- Municipalities have the responsibility to make sure that the waterworks are meeting the water quality and reporting demands.
- All water wells need to be reported to the Geological Survey for Denmark and Greenland, including all geological and hydrological data collected under the establishment of the well.

Under the umbrella of the Danish Water Supply Act, there are several auxiliary Acts, where the ones relevant to groundwater protection include:

- The Water Levy Act, which provides the funding for groundwater mapping in Denmark. The Act states that every waterworks supplying drinking water to more than 10 households pays a levy, per cubic meter, specifically earmarked for groundwater mapping and assessment.
- Act on the assessment of well-head protection areas, where the municipalities evaluate the vulnerability of these areas with respect to nitrate and pesticides, and whether or not restrictions in these areas need to be taken.
- Act on water quality and control at the waterworks, which sets the drinking water limits and dictates the control program that the waterworks are required to conduct.
- Act on groundwater protection action plans, which provide the requirements of the contents and details of the plans which the municipalities are required to produce.
- Act on water well drilling and decommissioning, which directs how wells are to be safely drilled or plugged, preventing pollution from reaching a deeper groundwater aquifer through a leaking borehole.

The Environmental Protection Act provides many of the teeth for groundwater protection. The Act provides municipalities with the authority to restrict or prohibit activities that could endanger the water quality in current or future water supply wells. The Act can be used to implement groundwater protection action plans regarding nitrates and pesticides. The Act requires voluntary agreements, but if that is not possible, the municipality can issue an injunction to compel an agreement. The Act requires that all affected parties be fully compensated for any monetary losses.

The Soil Pollution Act was drafted to prevent point source pollution from negatively affecting groundwater quality, human health, and the environment.

As governed by Danish legislation, the different responsibilities for groundwater protection are shown in Figure 1.

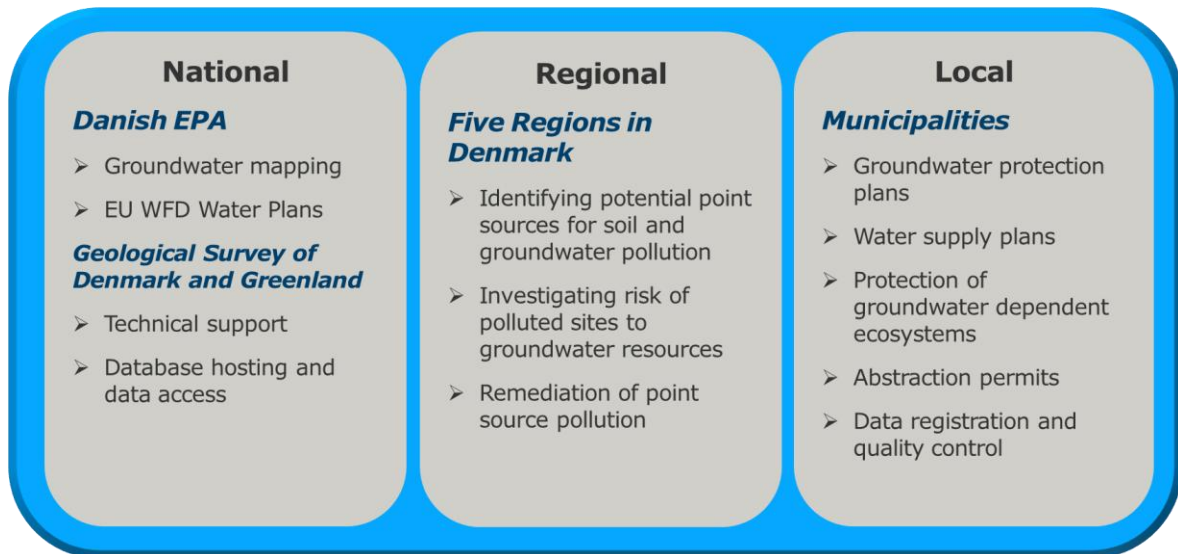


Figure 1 Responsibilities for groundwater protection on the national, regional and local levels.

2.2 Water supply and distribution

In Denmark, the government owns the rights to the groundwater resources, and thus any utilisation of groundwater requires a permit. The only exception to this is for single households, who can establish their own well, provided they are not connected to a water supply distribution network. Groundwater use is generally divided into the following categories:

- Municipal and private waterworks, supplying more than 10 households,
- Smaller waterworks supplying 3 – 9 households
- Single households
- Industry
- Institutions, including day care, schools, hospitals, etc.
- Agriculture, including field irrigation, plant nurseries, orchards, vineyards, etc.

Only municipal and private waterworks have to pay the drinking water levy. The other users only have to pay for production and distribution costs.

According to national statistics, in 2019, 708 million m³ of groundwater were withdrawn, of which 59% were used for municipal and private water supply, 32% for agriculture, and 9% for industrial use.

The municipalities are responsible for the permits. During the permitting process, the municipality considers the required water quality, the amount requested with respect to groundwater recharge (sustainable use), impacts on groundwater-dependent ecosystems, and impacts on existing groundwater abstraction.

The drinking water supply in Denmark is decentralised, with both private and municipal water supply companies. Private water supply companies tend to be smaller waterworks with production of less than 200,000 m³/year, serving smaller towns and villages. The municipalities own the municipal water supply companies; however, they are operated independently. Municipal water suppliers tend to be larger, generally with production over 200.000 m³/year. In recent years, there has been a trend of smaller waterworks merging or being taken over by municipal water supply companies.

Each water supply company, whether private or municipal, has its own distribution area, where it is responsible for supplying water to all residents who want to connect to its distribution system. Municipalities define the boundaries of water distribution areas in municipal water supply plans. The water supply companies are independent of each other; however, most have auxiliary connections with neighbouring waterworks, where both treated and untreated water can be exchanged. These connections are important when a waterworks cannot supply the required drinking water itself.

The responsibility for controlling the waterworks to maintain drinking water quality and to meet the terms of their water permits falls on the municipalities. All waterworks are required to report the volume of water they have pumped each year. In addition, they are required to measure water levels in their wells and collect water quality samples directly from those wells. The time interval for these measurements varies depending on the waterworks' size and the terms of their permit. The waterworks send all collected measurements to the municipalities, who then approve the data, report it to the Danish EPA, and enter it into the national groundwater database.

2.3 Geological and hydrological setting

The Danish geological setting consists primarily of Quaternary sediments underlain by Tertiary to Cretaceous sediments. The Quaternary sediments were primarily deposited during several episodes of advancing and retreating of the Scandinavian ice sheet. This has resulted in a complex structure of unsorted clayey tills with lenses of outwash sands and gravels, with the sediments from older glacial events being overrun or eroded by the advancing ice sheets. This has created a setting in which you have sand and gravel aquifers of varying thickness and area, surrounded by clayey till aquitards. The thickness of these lenses tends to be 2 to 10 meters, but can reach 20 to 50 meters. The last ice advance did not cover the south-western part of the country and consists of a large outwash plain from the melting ice sheets. Here, the unconsolidated sands and gravels are right at the surface, often over 50 meters thick. In addition to the glacial sediments, there are also locally interglacial and post-glacial sediments. These tend to be marine and lake bottom sediments. The thickness of the Quaternary sediments varies widely, from just under 2 meters in the eastern part of Zealand to about 120–150 meters in the central part of the country.

The Pre-Quaternary sediments include the Miocene sandstones and shales, Oligocene shales, Eocene diatomite and shales, Palaeocene shales, marls and limestone, and Cretaceous Chalk. The Miocene sandstones form the Pre-Quaternary aquifer in southern Jutland. In contrast, the fractured limestones form the Pre-Quaternary aquifers in northern Jutland and the islands of Central and Eastern Denmark.

The island of Bornholm in the Baltic Sea has a unique geological setting compared to the rest of Denmark. The island lies within the Sorgenfrei-Tornquist tectonic zone, which marks the boundary between the Scandinavian shield and the deeper basins to the west. The northern two-thirds of the island consists of granite and gneiss, whereas the southern third contains a range of sediments, including Cretaceous limestones, sands, and shales; Jurassic, Triassic, Silurian, and Ordovician limestones and shales; and Cambrian sandstones and shales. The overlying Quaternary sediments are, in general, under 20 meters thick and more often than not, less than 10 meters. As the island lies in the tectonic zone, it is heavily faulted, particularly in the Mesozoic and Palaeozoic sediments. In the granite and gneiss, the aquifers lie in the faulted fracture zones. In the southern portion of the island, the aquifers are predominantly fractured sandstones, with some production also occurring in fractured shales. In the south-western part of the island, there is some abstraction from Cretaceous sands and fractured limestones.

Figure 2 shows an illustration of a typical geological setting in Denmark, where you have 30 to 120 meters of unconsolidated Quaternary sediments, predominantly glacial clayey tills and lenses of outwash sands and gravels, overlying the Pre-Quaternary sediments.

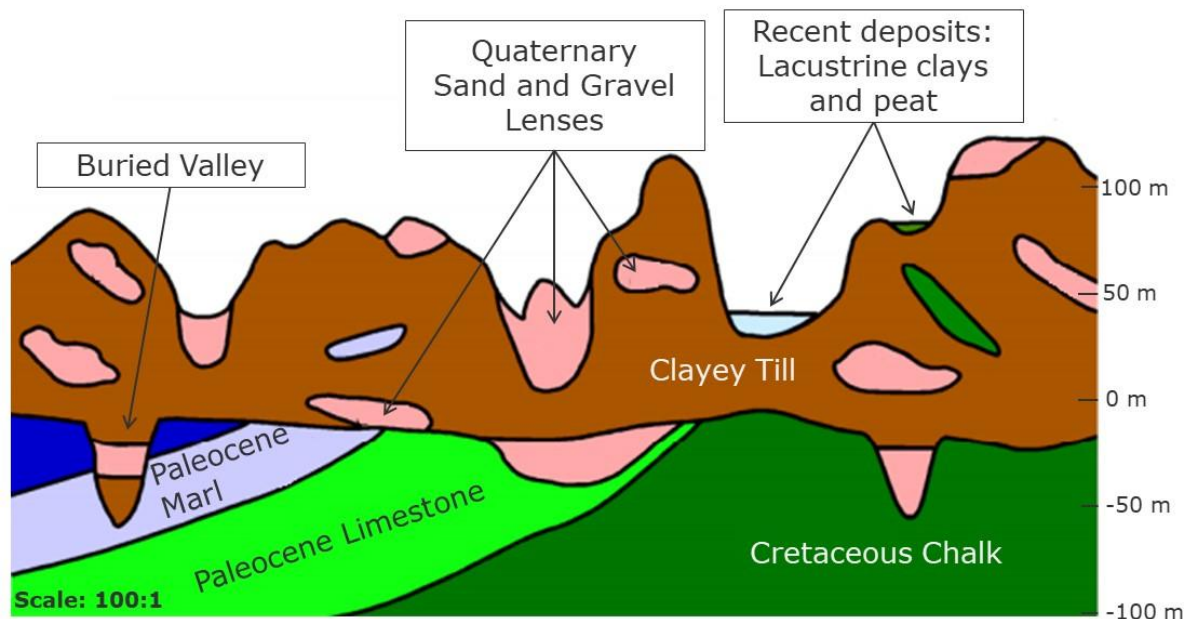


Figure 2 A regional cross-section illustrating the typical geological setting in Denmark, excluding the island of Bornholm. The figure shows the Pre-Quaternary sediments overlain by glacial sediments, predominantly clayey till with lenses of outwash sands and gravel, and post-glacial lacustrine clays and peat at the surface.

Precipitation in Denmark varies from over 900 mm/year in southern Jutland, to just under 600 mm/year in much of Zealand, Lolland, Falster, Møn and Bornholm. Figure 3. However, most of the country is seeing a long-term increase in precipitation. Of the precipitation, between a third and a half of it infiltrates into the saturated zone, ranging from just over 400 mm/year in southcentral Jutland to 150 – 200 mm/year on parts of Funen, Zealand and the other eastern islands, see Figure 3. The pattern of infiltration is dependent not only on precipitation but also on soil type, with clayey soils in the eastern half of the country having a higher runoff potential, better agricultural soils, and thus higher evapotranspiration rates.

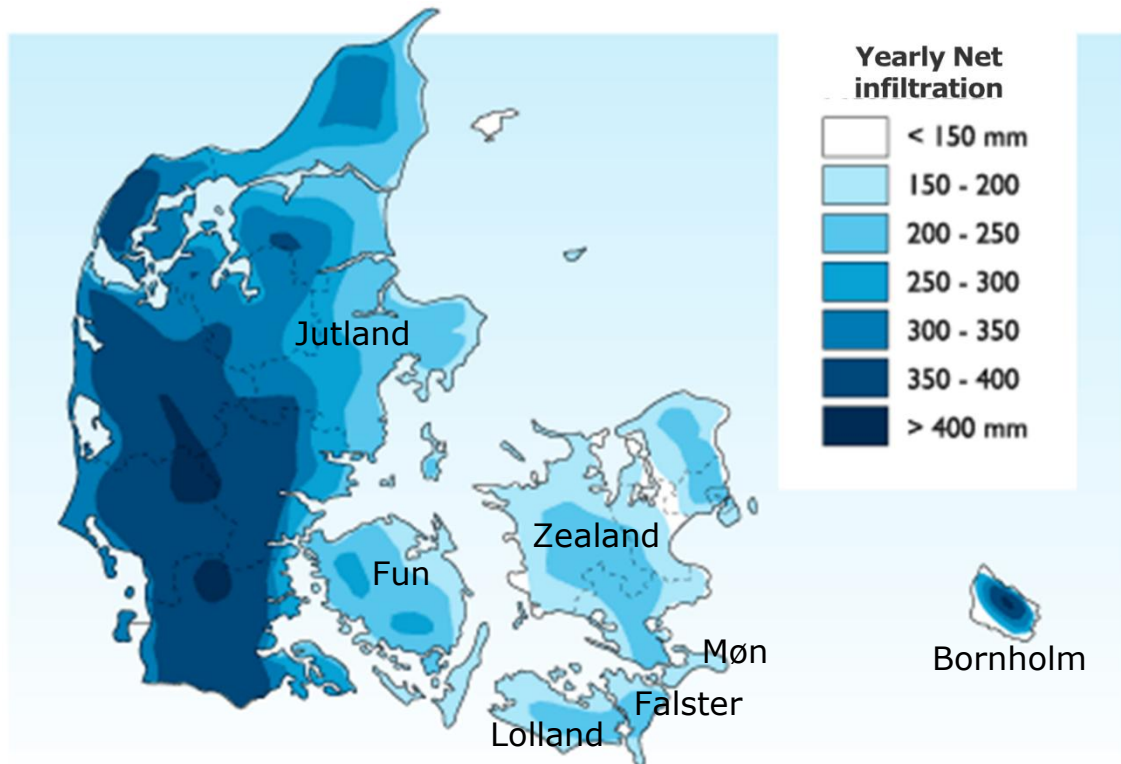


Figure 3 The yearly net infiltration to the saturated zone. Source: GEUS - <https://www.geus.dk/udforsk-geologien/viden-om/viden-om-grundvand/vandets-kredsloeb>.

2.4 Challenges and threats

In general, groundwater in Denmark is of high quality; however, several challenges and threats remain, including naturally occurring pollutants and those from human sources. These affect water quality and can influence the resource's quality for future generations.

The naturally occurring pollutants that influence Danish groundwater quality come from sediments that form the aquifers and aquitards. Groundwater abstraction from the fractured chalk and limestone aquifer often has high concentrations of arsenic, strontium, fluoride, non-volatile organic carbon, and saltwater. These come from the natural minerals within the sediments or from residual seawater that remained in the limestone and chalk matrix when the sediments were formed. High levels of arsenic are also observed in the Miocene shales, which can seep into the Quaternary aquifers, where buried paleochannels eroded through the Miocene sediments. Concentrations of these naturally occurring pollutants can increase with over-abstraction (unsustainable groundwater use), degrading groundwater quality. In the Quaternary sediments and limestone aquifers near the surface, there are also areas with high nickel and arsenic concentrations. This generally results from a lowering of the groundwater table, during which pyrite becomes particularly oxidised. When the water table rises again, arsenic and pyrite are released into the groundwater, raising concentrations. On the smaller islands and near the coasts, groundwater abstraction can also induce seawater intrusion into the groundwater aquifer, degrading water quality.

The primary source of pollution from human activities is agriculture. Denmark is the most agriculturally intensive country in Europe, with over 60% of its total area used for agriculture. Here, it is nitrates from fertilisers and pesticides that pose the largest problem. Areas with sand and gravel at the surface and little clay layers are particularly vulnerable to nitrate leaching from the farm fields, as there is little chance for nitrate to be reduced before it gets

to the aquifer. Pesticides also pose a problem, as they are also found to leach into the groundwater. In general, only pesticides that degrade in the soil are approved for use in Denmark, and it is now banned pesticides that make up the largest share of pesticides found in groundwater today. These pesticides were banned precisely because they are too mobile and pose a significant threat to the groundwater resources. However, approved pesticides are still observed in some areas.

In addition to agricultural pollutants, industrial and landfill sources also pose a threat to groundwater resources. These are often point-source pollution from single sites where there were spills or have been leakage over longer periods. The most significant pollutants include chlorinated solvents, but heavy metals and BTEX can also pose a threat.

3. CONCEPT AND STRUCTURE OF GROUNDWATER MAPPING

The current assessment and protection of groundwater resources in Denmark are governed by three parallel processes: Groundwater Mapping, the EU Water Framework Directive (WFD) Water Plans, and the regions' strategies for cleaning up point source pollution sites.

The primary focus of groundwater mapping is to actively protect groundwater quality and secure clean drinking water for future generations. The focus of groundwater mapping activities is to determine where current and future groundwater resources are and, thereafter, identify where these resources are vulnerable and the actions needed to protect them. The focus of groundwater mapping is on the local scale.

The focus of the WFD Water Plans is to determine the quantitative and qualitative conditions of the different regional aquifers. The WFD requires groundwater to be in good quantitative and qualitative condition. The Water Plans do not just cover groundwater but also surface water and water ecosystems. Thus, a primary consideration for the quantitative status is sustainable abstraction, which determines how all groundwater uses affect groundwater dependent ecosystems. The focus on these calculations is on the regional scale.

The focus of the point-source pollution program is to identify potential pollution sites and assess the extent to which they threaten groundwater quality in the area's aquifers. If the sites are determined to be a significant threat to groundwater resources, then remediation activities to remove both the source and clean the polluted groundwater are undertaken. The Danish Regions conduct these activities, and municipalities use the studies' results in their water planning and permitting.

Figure 4 shows a diagram illustrating the three separate processes for groundwater mapping and assessment in Denmark. The Danish EPA runs the first two programs, whereas the Danish Regions undertake point source pollution programs. The end recipients of the results of all processes are the municipalities, which are required to take the necessary measures to protect groundwater. Results from all processes are implemented across the different protection plans and permits to ensure that groundwater quality, quantity, and groundwater dependent ecosystems are protected.

In this section, a detailed description of these three programs is provided.

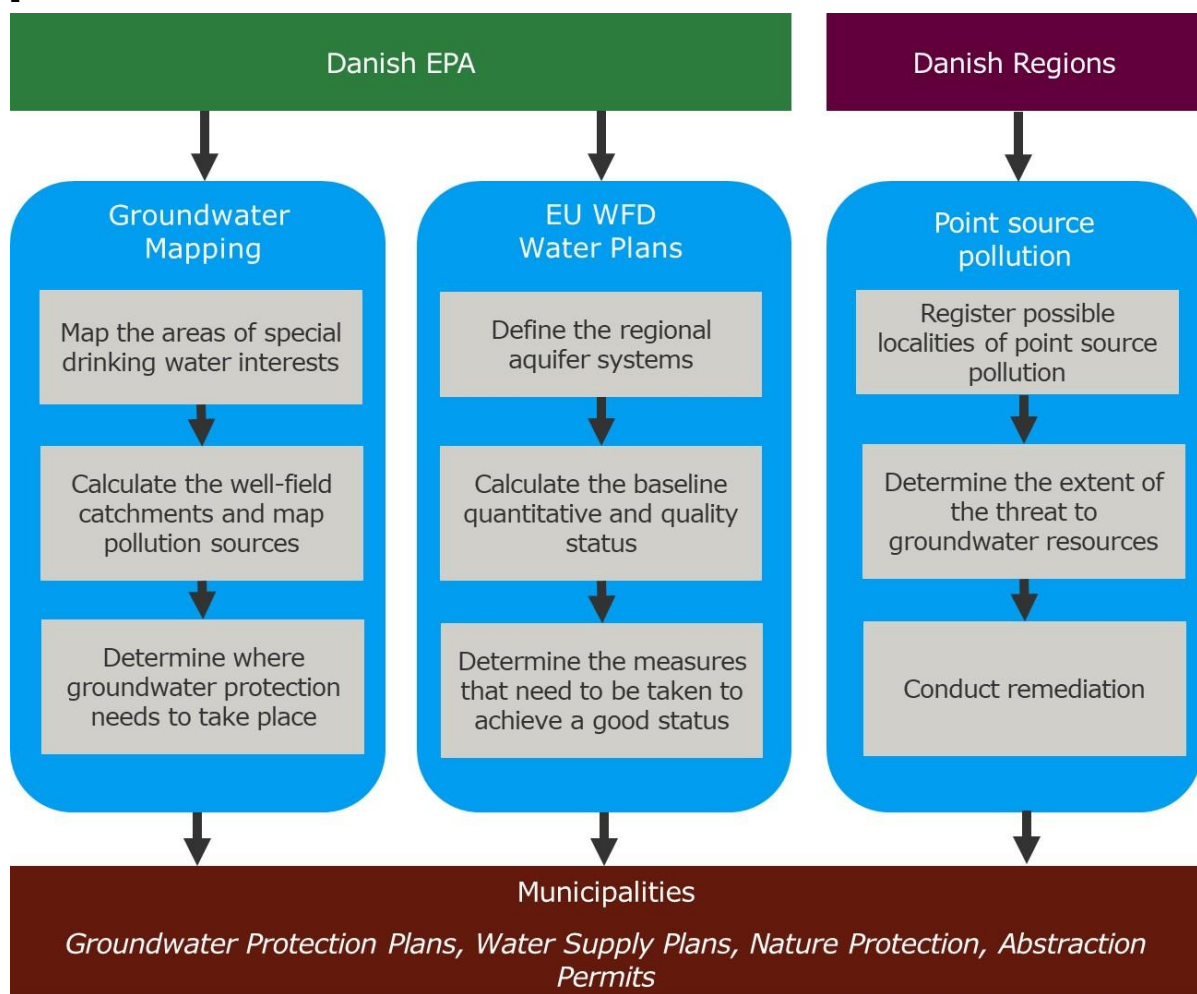


Figure 4 Diagram outlining the two parallel processes for groundwater mapping and assessment in Denmark.

3.1 Groundwater Mapping

The Danish Groundwater Mapping Program has been conducted in two phases: the first from 2000 to 2015, and the second from 2016 onward (Danish EPA, 2022a). During the first phase, the primary focus was on mapping all areas of special drinking water interest, covering about 40% of Denmark’s total area. In addition, wellfield catchment areas outside of these areas were also mapped. In 2016, the focus shifted to updating the existing mapping in areas where the location or amount of groundwater abstraction by the waterworks changed, or where new information could influence the designation of groundwater vulnerability areas for which municipalities must develop groundwater protection action plans.

Although the focus between the two phases has shifted from mapping all areas to updating only areas that have changed, the actual mapping process remains largely the same. The process involved is illustrated in Figure 5.

The process includes the following five steps:

1. Screening
2. Start
3. Data
4. Results
5. Completion

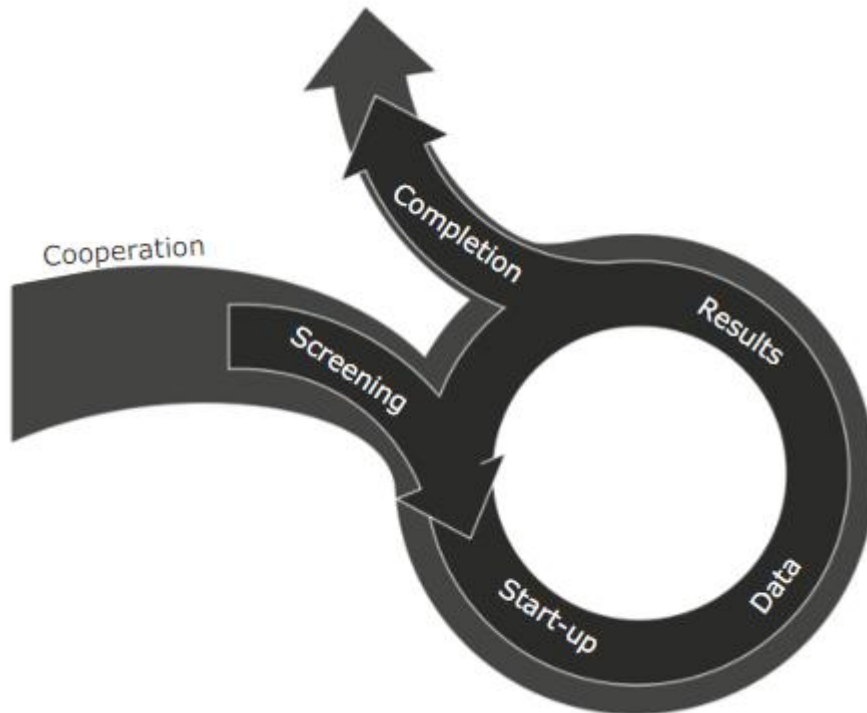


Figure 5 Diagram illustrating the processes involved in groundwater mapping. Modified from Danish EPA (2022a).

The diagram is drawn as a circle in the middle to illustrate that groundwater mapping can be an iterative process. The ideal succession is to go through Screening, Start-up, Data and Results, and end with the Closing phase. However, during the Results phase, it may be discovered that important information is missing and that certain parts of the mapping need to be revisited. It doesn't mean that the entire process needs to be redone, but that the considerations along the mapping process are re-evaluated. Then, when the process is completed to the needed quality, the mapping is closed.

3.1.1 Screening

The groundwater mapping process begins with a dialogue between the Danish EPA and the municipalities. When municipalities determine they need a new mapping, they submit a request to the Danish EPA. These changes can include increases or decreases in one or more waterworks permit amounts, new wells drilled or wells taken out of production, or new data or information that could affect the results of the groundwater mapping from the first phase. These submissions are then prioritised by the Danish EPA based on the type of request submitted and the resources available to conduct the new mapping activities. Once the submissions are prioritised, the municipalities are notified of the screening results and the start date for the new mapping activities.

3.1.2 Start-up

Start-up begins directly after the screening process. This consists of a desktop study, the primary purpose of which is to obtain a detailed overview of existing data, models, and previous groundwater mapping activities. These data, models, and activities are then reviewed and analysed to identify gaps to be addressed in the next phase of groundwater mapping, which occurs during the Data phase of the project. The start-up concludes with recommendations for filling these data gaps, taking into account the objectives of the specific groundwater mapping area.

The first step in Start-up is to collect all existing data, models, and reports. This includes:

- Waterworks data, including abstraction rates, active wells, and monitoring wells.
- Geophysical data, including all studies conducted in the area. These can be resistivity surveys, areal electromagnetic surveys, magnetic resonance surveys, seismic lines, and borehole geophysical logs.
- Geological data, particularly from boreholes, maps and reports/articles.
- Water quality data.
- Hydrological data, including water level measurements, aquifer potential maps, pumping tests, measurements from data loggers, and stream measurements.
- Reports and databases from previous groundwater quality studies.
- Existing 3D digital geologic and hydrostratigraphic models, with the documentation.
- Groundwater and hydrological models, with the documentation.
- Land use data and mapped polluted localities.
- Any relevant reports on studies conducted in the mapping area.

Once the data is collected, it is evaluated for quality and spatial coverage. For example, the geophysical data is evaluated with respect to the age of the data and how well the results can reveal the geological formations in the area. The spatial coverage is then evaluated based on the presence of good, moderate, poor, or no data. Once the quality and special coverage of each data type have been evaluated, the data gaps are identified, and recommendations for further data collection are made. This could take the form of synchronous water-level measurements across the area or the collection of additional geophysical data.

For groundwater quality, the reports are reviewed to determine the state of the aquifers at the time they were mapped. This is then evaluated against the parameters and techniques used today to determine whether any gaps need to be filled. For example, several new pesticides are analysed today compared with those studied 10 years ago. In addition, the results from the previous studies are compared with newer results to determine how much has changed. Based on this, recommendations are provided on which water quality parameters should be addressed in the new mapping.

Geologic and hydrostratigraphic models are evaluated on two different levels. The first is an evaluation of how well they still fit the evolving conceptual geological model of the area. Since the geologic or hydrostratigraphic model was produced, additional studies may have changed the understanding of the area; for example, new faults, buried valleys, or additional aquifers may have been mapped that were not included in the existing geological or hydrogeological model. The second level is how well the existing digital model fits the collected data. New data will often have come in since the geologic or hydrostratigraphic model was constructed. The model is therefore evaluated against the collected data to assess its quality. Based upon the two levels of evaluation, recommendations for updating or creating a new geologic or hydrostratigraphic model are made.

Groundwater and hydrological models are evaluated for their quality and ability to simulate the groundwater flow system in the mapping area. This includes an evaluation of their

hydrostratigraphic framework, how well they simulate water levels (both in boreholes and on potentiometric maps), and the geographic distribution of errors and surface water. From this, recommendations are made on whether the model can be used as is, needs updating, or a completely new model should be set up.

The final evaluation in Start-up looks at the designation of groundwater vulnerability areas. During the course of the groundwater mapping program, the methods for designating groundwater vulnerability areas varied from county to county, becoming fully standardised only in 2012. Thus, these primarily evaluate the groundwater vulnerability areas designated in the specific mapping area, focusing on the methods used in the designation and how well they align with the current approved standards. Recommendations are then made on whether the groundwater vulnerability areas need to be updated in the new mapping.

The final product from Start-up is a summary of recommendations for the tasks to be conducted during the Data phase of mapping. Start-up produces a full list of tasks categorised as essential or non-essential. For non-essential tasks, an evaluation of how they can improve the overall results of the groundwater mapping is provided, so that decisions can be made about whether there is time and resources to conduct them.

3.1.3 Data

The Data phase of groundwater mapping consists of activities needed to fill the gaps identified during Start-up. The activities conducted are determined at the beginning of the Data phase of the project, considering the primary objectives of the groundwater mapping, available time, and, particularly, available budget.

There are four overarching tasks under the Data phase: supplemental data collection, geological modelling, groundwater quality modelling, and groundwater modelling. The tasks, workflow and data exchange for the Data phase are presented in Figure 6. In the figure, the numbers show the overall workflow, though there can be overlap between the start and finish of the different tasks. In addition, when updating a mapping area, it may not be necessary to complete all of the tasks, as determined in the Start-up phase.

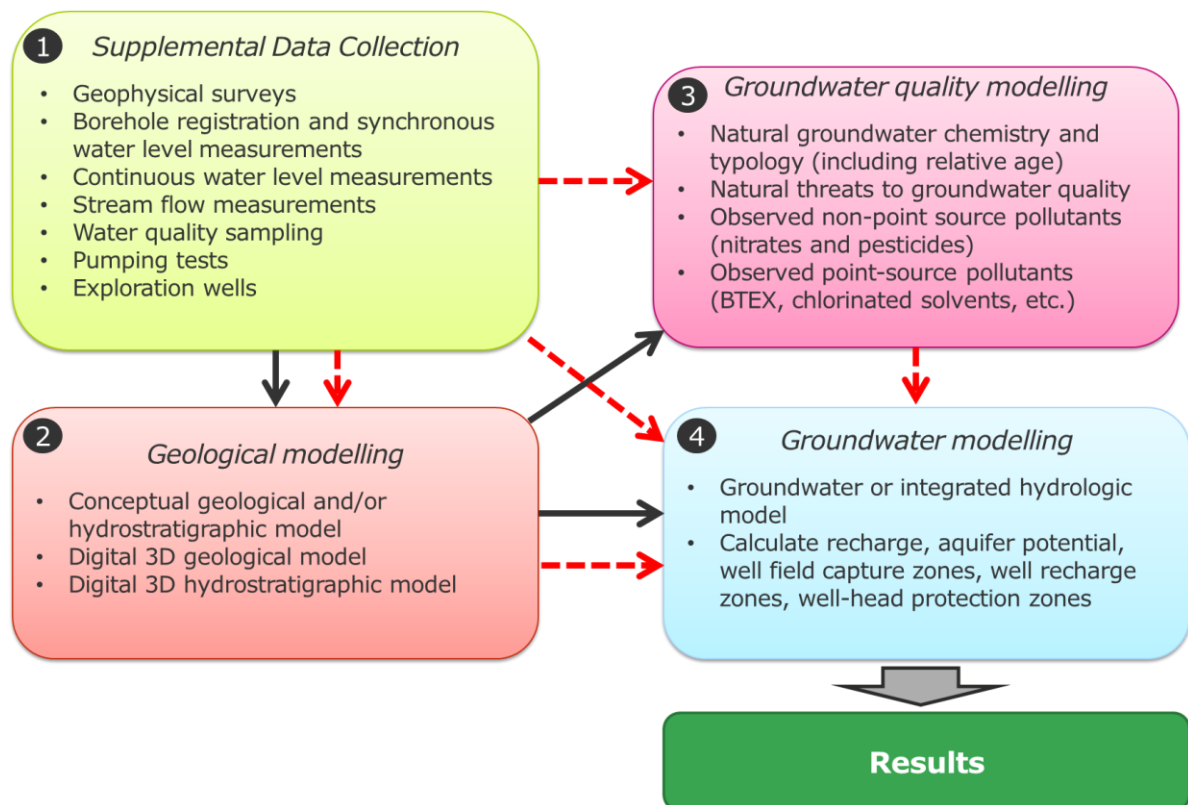


Figure 6 Illustration of the four tasks included in the Data phase of groundwater mapping. The black arrows illustrate the workflow, and the red dashed arrows show the data flow between the four steps.

Supplemental data collection:

The collection of supplemental data fills in the identified gaps. The typical types of supplemental data include:

- Geophysical surveys
- Borehole registration and synchronous water level measurements
- Continuous water level measurements
- Stream flow measurements
- Water quality sampling
- Pumping tests
- Exploration wells

In the Start-up phase, data gaps are identified and prioritised based on their criticality for completing the mapping objectives. Not all data types listed will be collected in a specific mapping project, as there can already be adequate data coverage or simply not be enough funds or time to collect the data. In addition, only a portion of the mapping area may need to be collected.

Geophysical surveys used in groundwater mapping include:

- Resistivity methods, such as aerial electromagnetics (AEM), transient electromagnetics (TEM), multi-electrode profiling (MEP), and single point electrode profiling (Wenner and Schlumberger).
- Seismic surveys
- Magnetic resonance sounding (MRS)
- Borehole logging.

Resistivity methods are used to aid interpretation of the area's geology. They are particularly useful when there are high resistivity contrasts in the sediments. In Denmark, this is typically used to distinguish between clayey units (low resistivity) and sand and gravel or limestone units (high resistivity). On Bornholm, resistivity can be used to identify bedrock, including granite, gneiss, quartzite, and sandstones, which tend to have a very high resistivity compared to the overlying clayey tills. In addition, resistivity can be used to assess saltwater intrusion, as it decreases with increasing salinity in aquifers. Generally, the depth of investigation varies from around 50 to 80 meters in MEP and towed-TEM to up to 500 meters with AEM and single point electrode profiling; the total depth of penetration is dependent on local geological conditions and groundwater salinity. Each type has certain advantages; for example, AEM, which is flown by helicopter, can cover large areas quickly; however, it is more expensive and is generally restricted to larger projects. MEP and towed-TEM are conducted along lines that provide high resolution 2D sections. Figure 7 shows an example of resistivity data from an AEM survey, with the interpreted geology. The geology along the cross-section can be interpreted using the changing colours, which represent resistivity (low resistivity in blue, progressively higher in green, yellow, and orange, with the highest resistivity in red). In this case, the resistivities clearly show the Danian Limestone in the lower part of the figure, which is a fractured limestone aquifer with fresh water.

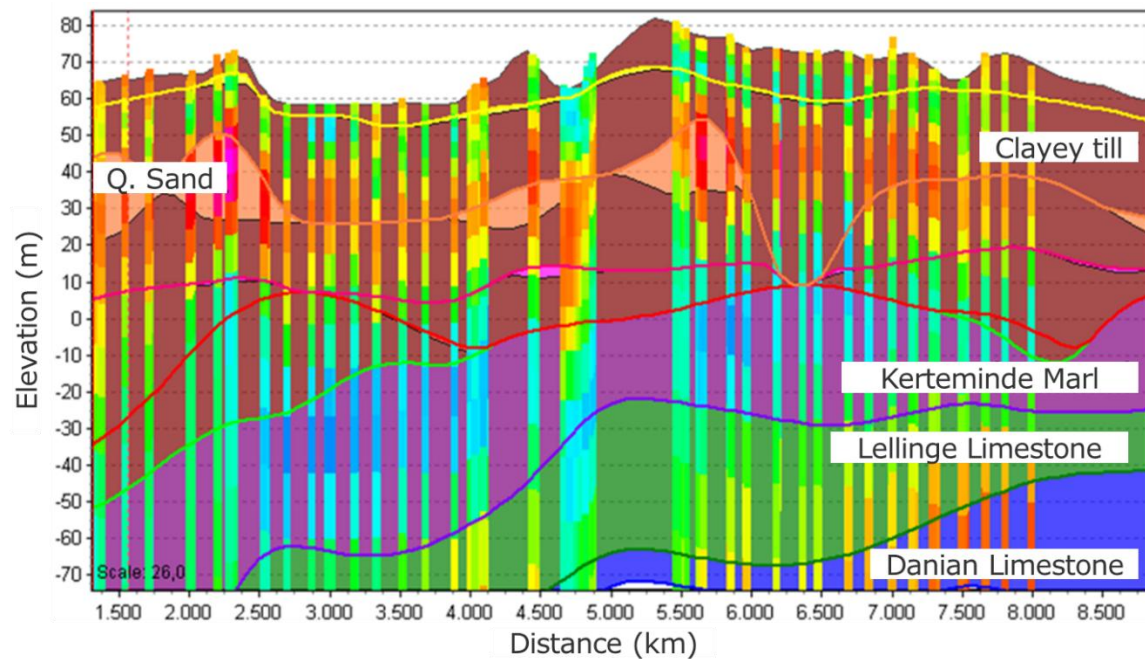


Figure 7 Example of the interpretation of AEM resistivity data. On the figure, the red colours show the more resistive units, including sands and gravels and the fractured limestone aquifers. The light orange, yellow, and green colours show the clayey till; the higher the clay content, the bluer the colours will be. This cross-section is in an area where there is no borehole data within 500 m of the cross-section line.

Seismic surveys are used in Denmark to map fault locations and buried valleys. A vibration seismic survey, consisting of a truck-mounted vibrator followed by an array of geophones up to 200 meters long, can map reflective surfaces to depths of up to 1000 meters. Magnetic resonance sounding (MRS) is a method that can be used to estimate water content and permeability in different units to depths of up to about 100 meters. MRS uses the same technology as MR scans used in hospitals. Borehole logs provide detailed information on the geology of a well, as well as on borehole construction and quality (e.g., identifying possible

leaks). Flow logs are used to identify where groundwater is entering through the screened interval, which is very useful in fractured aquifers.

The primary purpose of borehole registration is to accurately locate the boreholes that can be used for water level measurements, groundwater sampling and borehole logging. In this task, the boreholes are localised and measured with GPS to obtain accurate coordinates. In addition, the overall borehole quality is assessed, and, where possible, leakage from the surface to the aquifers through the boreholes is recorded. The borehole at the surface is also typically photographed, with the water level measuring point identified and registered so that the same point can be used in the future.

Often, in conjunction with borehole registration, synchronous water-level measurements are also conducted across the mapping area. The measurements, often of over 100 wells, are conducted within 14 days to provide a real-time picture of groundwater potential in the aquifers. This allows the construction of groundwater potential maps that can then be used to validate groundwater models.

To supplement water level measurements, data loggers are installed in boreholes to provide a continuous record of groundwater levels. This provides high-resolution data, allowing seasonal variations in groundwater potential to be easily observed and the aquifer to be seen responding to precipitation events. Typically, data loggers are installed for a year or more to cover a full season. The data is then used to validate the seasonal variation in groundwater levels simulated with the groundwater model.

Stream flow measurements are used to quantify stream runoff and are directly incorporated into integrated hydrological models. In Denmark, there is an established network of streamflow monitoring stations that provide continuous measurements for model use, so this task is not often needed.

Water quality sampling is conducted in areas where there is either a spatial or temporal gap in the available data. As all waterworks are already required to conduct regular water well sampling, groundwater sampling conducted during groundwater mapping will likely come from private boreholes for individual households, irrigation wells, or industrial wells. The wells that can be sampled are identified during the borehole registration. The sampling can be broad, covering a wide range of parameters, or specific to a particular parameter important for groundwater quality modelling in the mapping area.

Pump tests are conducted in areas where there is a need to determine an aquifer's transmissivity. This provides direct input to the hydrological model. Long-term pump tests can also be conducted to determine the distance to hydrological barriers, which can aid hydrostratigraphic modelling, particularly in areas with buried valleys cutting the Pre-Quaternary units or areas faulted.

Exploratory boreholes are established in areas with few boreholes, providing limited knowledge of geology, water levels, and water quality. In general, borehole data coverage in Denmark is relatively dense. This, combined with the high costs of establishing a new borehole, means this task is not often utilised in groundwater mapping.

Geological Modelling:

In this step of groundwater mapping, the aquifers and aquitards of the mapping area are defined and mapped. This is accomplished in a three-step process:

1. Development of a conceptual model
2. Development of a 3D geological model
3. Development of a 3D hydrostratigraphic model

The conceptual model is the process by which an overview of the area's geology is obtained and presented. It is in this stage that the mapping of areas, aquifers, and aquitards is defined. This is conducted by reviewing previous reports, articles, and maps, as well as primary data from key boreholes. In this stage, the general geology of the area, including stratigraphy, structures and depositional environments, is described and presented in illustrative cross-sections or sketches. Figure 8 shows a typical cross-section illustrating the conceptual model for a mapping area in central Jutland. The figure shows that the area's geology includes Eocene, Oligocene, and Miocene units composed of interbedded shales and sandstones, overlain by Quaternary outwash sands and gravels and clayey tills. An important point in the conceptual model is the presence of buried valleys in the area, where streams from the Quaternary period have cut into the Pre-Quaternary units, and later filled with sands and gravels or clayey till. This provides critical input to the creation of the 3D geological and hydrostratigraphic model, as it shows the different units and structures that must be accounted for when developing the model.

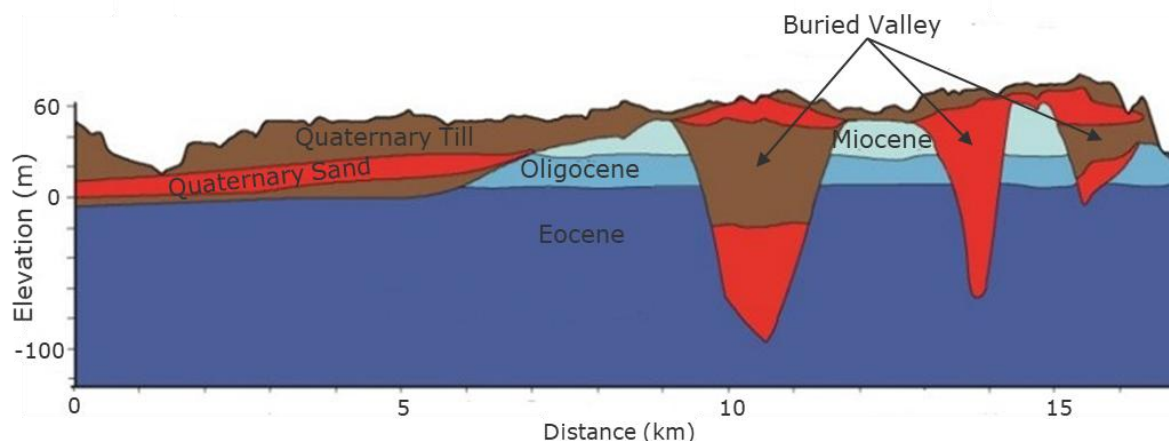


Figure 8 Conceptual cross-section of a mapping area in central Jutland. On the profile, the general geological layers are shown, including the Pre-quaternary units in blue, and the Quaternary glacial sediments shown in brown (clayey till) and red (outwash sands and gravels). The presence of buried valleys is illustrated on the cross-section.

The second step in the geological modelling process is the development of a digital 3D geological model. The model is based upon the conceptual model developed in the first step, while integrating all available data, including maps, borehole data and geophysical data. The model is set up using geological modelling software, such as Leapfrog or GeoScene3D, the latter of which has been partly funded by the Danish groundwater mapping program and is by far the most widely used geological software in Denmark. The geological model includes the modelling of the different formations and ages, and takes into consideration the depositional, structural and tectonic history of the mapping area. For example, in Denmark, the geological model divides the Quaternary deposits into multiple glacial advances and retreats. The geological model does not necessarily divide units into distinct aquifers and aquitards. For example, as shown in Figure 8, the Miocene, Oligocene and Eocene units are

mapped out as individual formations, but within these units will be both sandstone aquifers and shale aquitards.

The third step in the geological modelling process is the development of a digital 3D hydrostratigraphic model. This is based on the digital 3D geological model, in which the geological units are divided into aquifers and aquitards based on their hydrogeological properties. In some cases, this may involve further division of the formations mapped in the geological model, while in others it may involve simplification, grouping several formations. For example, in the case of the Pre-Quaternary units shown in Figure 8. They can be further divided into mapable sandstone aquifers and shale aquitards, which may also extend across their geological boundaries. An opposite example in Denmark is from the island of Zealand, where the Quaternary sand lenses are simplified to four units: at the surface (Sand 1), shallow (Sand 2), intermediate (Sand 3), and deep (Sand 4). In the hydrostratigraphic model, the geological units can also be divided into fractured zones with higher hydrologic conductivity (both horizontal and vertical).

In Denmark, a national hydrostratigraphic model has now been developed that covers the entire country, except for the island of Bornholm and a few smaller islands. Therefore, the process for geological modelling has, in general, been simplified to an updating of the existing hydrostratigraphic model. In the Start-up phase, the existing model and supporting documentation are reviewed and evaluated, with recommendations presented. Based on these recommendations, the hydrostratigraphic models are updated using new borehole data and geophysical data not included in the original model, and errors in the models are corrected. In this way, the existing national hydrostratigraphic model is not static but is continuously improved with each subsequent groundwater mapping project.

When the hydrostratigraphic model is completed and updated, the mapped units provide the geological framework for the groundwater models and an assessment of the geological vulnerability of the aquifers.

Groundwater Quality Modelling:

The purpose of the groundwater quality modelling is to describe the groundwater chemistry observed in the mapped aquifers, including the geochemical processes and conditions, and describe how this changes geographically.

The steps in the groundwater quality modelling include:

1. Determine the processes and parameters to be analysed
2. Preparation of the groundwater quality data
3. Analysis of the important processes and water quality parameters
4. Analysis of the geographical variation of the processes and quality

The first step is to define the objectives of the groundwater quality modelling. In the Start-up phase, several recommendations are provided; however, the final decisions as to what should be completed are often dependent upon several factors that are also part of the mapping process, including (but not restricted to) whether or not new water samples will be collected, whether or not there will be a new vulnerability assessment, or the available resources to conduct the modelling. Through discussions between the Danish EPA and stakeholders, the objectives of the water quality modelling are determined.

The second step is preparing the groundwater quality data. As a starting point, the groundwater quality data is downloaded from the national borehole database, Jupiter. Almost all available water quality data will be in the Jupiter database, though additional data may be

available from regions, municipalities, or waterworks. Once the data is downloaded, it undergoes quality control to identify potential sample errors. This is done by examining the balance between cations and anions in the water sample. If the error exceeds 15%, the sample is marked as uncertain. The parameters are then examined more closely to determine why the difference is so large and whether the water sample can be trusted. Data with large unexplained errors are either removed or marked as uncertain. The final step is to assign the samples to a specific aquifer. This is based on the placement of the borehole's screen relative to the aquifers mapped in the hydrostratigraphic model. In this manner, the groundwater quality can be analysed for each specific aquifer.

The analysis of the important groundwater chemistry processes is the foundation for the groundwater quality model. Looking at these processes provides fundamental information on the relative age of groundwater in each aquifer, how much surface activities influence it, how the aquifer is being impacted by groundwater abstraction, and how these processes are changing over time. The primary processes that are typically analysed include:

- Groundwater oxidation state, where oxidised groundwater indicates younger, more vulnerable aquifers, and strongly reduced groundwater indicates older, less vulnerable aquifers;
- Pyrite oxidation state, where groundwater that shows an influence of pyrite oxidation is younger and can indicate nitrate leaching from the surface;
- Sulphate reduction, where aquifers showing sulphate reducing conditions have older groundwater, indicating a relatively well-protected aquifer;
- Ion exchange, particularly the ratio between sodium and chloride ions, which provides information on whether the aquifer is undergoing seawater intrusion, freshening or mixing, as well as a relative age (a high sodium to chloride ratio generally indicates old groundwater);

The results from these processes are used directly in the overall aquifer vulnerability assessment conducted in the Results phase of groundwater mapping.

The final step is to examine the geographical variation in both water quality and the processes that drive it. This is an important step in the geochemical modelling of groundwater properties to create a zoning of the predominant processes and the overall groundwater quality of the mapped area. This provides critical information on where aquifers are susceptible to surface pollution and allows identification of regions where groundwater quality is being degraded by pumping.

Groundwater Modelling:

For each mapping area, a groundwater model is developed. The primary objective for the modelling is:

- to calculate the well field capture zones (“indvindingsoplade”)
- to calculate well head protection zones (“BNBO”)
- Simulate groundwater potential for each aquifer
- calculate groundwater recharge, both to the saturated zone and the aquifer specifically.

Both integrated hydrological models and groundwater models simulating only the saturated zone have been used in groundwater mapping. The integrated hydrological models have both groundwater and surface water components, with model inputs including climate data such as temperature, precipitation, and evapotranspiration (based on land use). Groundwater models simulate only the saturated zone, and recharge to it typically comes from the Danish national water resource model. This integrated hydrological model covers the entire country.

Both dynamic and stationary models have been used in mapping. Generally, dynamic models are preferred, but there may be local areas where there is insufficient data, either in the number of time series or in geographical coverage, to develop a robust dynamic model.

The models are set up, calibrated and validated specifically with respect to the four objectives stated above. The models are typically calibrated using aquifer specific groundwater level measurements and streamflow measurements. The guidelines for hydrological modelling specify the criteria that must be met before a model is considered calibrated or validated.

Once the model is validated, different scenarios are simulated. At a minimum, a scenario with the maximum allowed abstraction/pumping is run (the permit scenario). Dependent upon the mapping area and the stakeholders involved, other scenarios, including no abstraction or actual/historical abstraction rates, can be run. Additional scenarios to test the importance of non-calibrated input parameters, such as effective porosity, are also sometimes conducted.

The permit scenario is the model run that provides the results for the Results phase of the project. In the permit scenario, the administrative well field catchment areas and the wellhead protection zones are delineated. In addition, aquifer specific recharge and potential are calculated using the permit scenario. The well field catchment areas are calculated using the particle tracking module in the models. The particle tracking module traces the movement of water from the ground surface to the well. The metadata for the particles contains the simulated travel time from model start to when the particle reaches the water well. Using this, the areas where water infiltrates at the surface and ends up in an abstraction well, as well as the simulated transport time (indicating groundwater age), can be mapped. The age of the groundwater reaching each well can be calculated and plotted.

Finally, the model is quality controlled by comparing simulated data with real data. This includes checking the simulated potential against aquifer potentiometric maps and simulated stream flow against measured flow. In addition, the modelled groundwater age in the abstraction wells is compared with water quality samples to determine whether the calculated age matches the observed age estimated from groundwater chemistry. In some cases where modelled areas show significant differences between calculated and simulated flow direction or age, the model is re-examined to determine whether these issues can be explained or whether the model should be reopened for a new calibration. Thus, groundwater modelling is often an iterative process.

3.1.4 Results

When the Data phase is complete, the groundwater mapping enters the Results phase. The geological, groundwater quality, and hydrological model provides the basis for the different designations that are emerging from the groundwater mapping. These designations include:

- Well field capture zones
- Well head protection zones
- Adjustments to the areas of special drinking water interests
- Vulnerability assessments

The delineation of the well field capture zones and the well head protection zones is essentially complete based on the groundwater modelling conducted in the Data phase. The only activity is preparing the GIS polygons with these designations for submittal in the Closing phase. The other two activities, adjustments to the areas of special drinking water interests and vulnerability assessments, combine the results from the three Data modelling activities, geological modelling, groundwater quality modelling, and groundwater modelling, in the assessments. This process is described in detail in the sections below.

Areas of Special Drinking Water Interests:

The areas of special drinking water interests (SDWIs) were first designated in 1997 and then revised in 2005. This area covers approximately 40% of Denmark's total land area and is required to secure the Danish drinking water supply for future generations. These areas are, in principle, fixed; however, there is an opportunity to make minor adjustments based on results from groundwater mapping efforts.

As a guiding principle, the DSWIs were defined as areas with high quality, suitable sized aquifers. In addition, groundwater flow in the aquifers should always be from within the DSWI to outside, rather than from outside the DSWI to within it. As new information from the Data phase of groundwater mapping is obtained, adjustments to the DSWIs can be made. The adjustments can include adding areas if a new aquifer with high groundwater quality is mapped. Some areas can be removed if groundwater mapping shows that groundwater quality is so poor that it cannot be remediated and thus cannot be used for drinking water, or if new studies show that there is no longer a viable aquifer at that location. The boundaries can also be adjusted to prevent groundwater from outside the DSWI from streaming into the DSWI. Results generally make these adjustments from the groundwater modelling.

Vulnerability Assessment:

The ultimate objective of Danish Groundwater Mapping is to identify areas vulnerable to non-point source pollution. The vulnerability assessments are conducted in all areas within the designated special drinking water interests or within a well field catchment zone outside these interests.

One of the primary focuses of the Danish Groundwater Mapping and Assessment program is protecting existing groundwater resources. In Denmark, this focus has been in areas with special drinking water interests, as well as in the wellfield catchment areas outside these interests, which comprise just over 40% of Denmark's land area. Given that intensive agriculture covers much of this area, the assessment in Denmark focuses on nitrate and pesticide pollution. This is in contrast to South Africa, where, in addition to agricultural sources, pollution from mining and other industrial sources also impacts groundwater quality. Although there are differences between Denmark and South Africa, both in size (see Figure 9) Given the geological complexity and the various threats to groundwater quality, aspects of the groundwater mapping and assessment program in Denmark can be effectively applied to groundwater protection in South Africa.

In Denmark, groundwater vulnerability assessments are conducted at the local to smaller regional scale (maximum 1,000 km²).

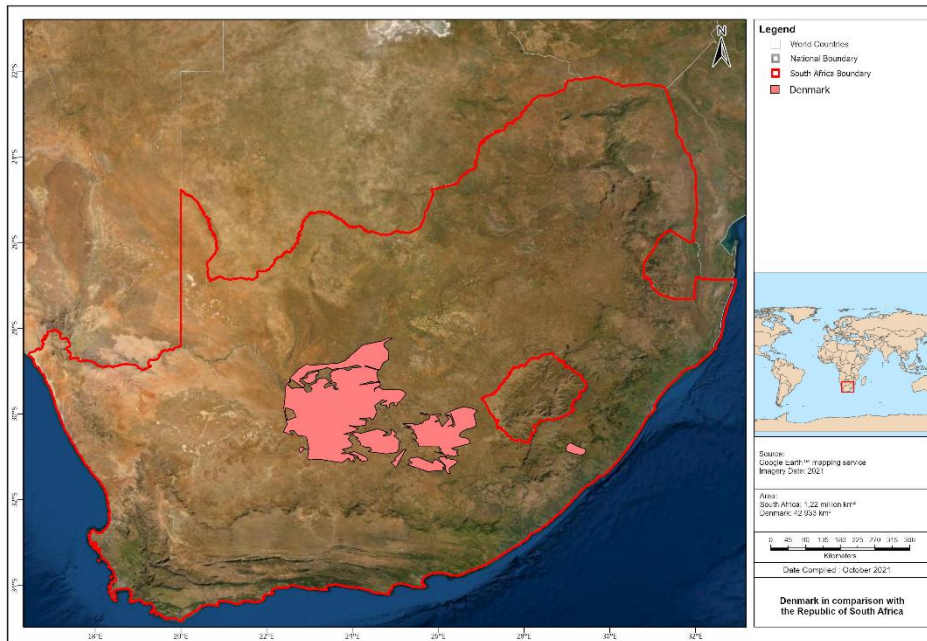


Figure 9 Map showing Denmark's relative size compared to South Africa.

As stated in Section 0 The two primary non-point source threats to the Danish groundwater resources are from nitrates and pesticides. Over the last 30 or so years, extensive research has examined how nitrates and pesticides leach from agricultural soils into the saturated zone and then flow into aquifers used as sources of drinking water. The results of these studies provide the basis for designating areas particularly sensitive to nitrates and pesticides, and for subsequently identifying areas where groundwater protection plans need to be developed.

Vulnerability with respect to nitrate

Designating the areas in which action plans need to be developed is a three-step process, as outlined in the guidelines from the Danish EPA (2000) and (2021), which include:

1. Determining the aquifers' vulnerability to nitrates
2. Designating the areas that are sensitive to nitrate leaching
3. Designating the areas where groundwater protective actions need to be taken.

The first step, a vulnerability assessment regarding nitrates, is based on the sediment's natural reduction capacity. Particularly, the presence of organic matter and pyrite in the aquifers and the sediments overlying them will reduce nitrate levels as the flow through the sediments to the aquifers. In Denmark, it is mainly the reduced clayey sediments that have a relatively high pyrite content, available to reduce leached nitrates. The outwash sand and gravel are relatively clean and will have only a limited reduction capacity. The Pre-Quaternary sediments can also contain both pyrite and organic matter that can reduce nitrates; however, the nitrate reduction capacity in these sediments is often spatially variable.

As a starting point, the determination of an aquifer's vulnerability with respect to nitrates is based on the thickness of reduced clay sediments overlying the aquifer. Studies on clay sediments in Denmark showed that the thicker the accumulative clay sediments over the aquifer, the greater the reduction capacity and thus the better the aquifer is protected. The thickness of the reduced clay is calculated by summing the thicknesses of the clay layers over the aquifers from the hydrostratigraphic model, and subtracting the oxidised clay as observed in the geological descriptions from the borehole logs, or the unsaturated clays. In general, if there is less than 5 meters of accumulated reduced clays, there is only a limited

capacity to reduce nitrate. The aquifer has a high vulnerability. If there are 5 to 15 meters of reduced clay, there is moderate vulnerability; if there are more than 15 meters, there is a strong reduction capacity in the sediments. Thus, the aquifer is low in vulnerability to nitrates.

There is, however, uncertainty in calculating the thickness of reduced clays, as there can be long distances between data points (borehole information) and unmapped geological windows within the clay layers, which provide shortcuts through the protective clays and reduce the reduction capacity. Therefore, groundwater quality is also used in the vulnerability assessment. In this case, the presence of oxidised groundwater containing nitrates indicates that the aquifer's groundwater is highly vulnerable. The presence of high and/or increasing concentrations of sulphate indicates that pyrite reduction is occurring in the sediments, that the reduction capacity within the clay layers is being depleted, and that the aquifer is highly or moderately vulnerable. On the other hand, strongly reduced groundwater with low and stable sulphate concentrations, often with ammonium and methane, indicates very old groundwater, and the vulnerability will be low.

Table 1 illustrates how groundwater nitrate vulnerability is determined. Here, the thickness of reduced clay is compared to the groundwater quality. If there is agreement between these two parameters, the vulnerability is set. However, there are situations where agreement between the two parameters is not reached, and an individual assessment is required. For example, there can be areas with over 15 meters of reduced clay, but one or more wells show oxidised groundwater. In this case, a closer evaluation of groundwater quality will be conducted to assess whether oxidised groundwater results from leakage from the surface through a damaged borehole or from a poorly constructed casing. The thickness of the clay layer will be assessed to determine whether it is consistently greater than 15 metres or whether there is a possibility of a geological window through the clay in the area. Three-dimensional flow paths from the groundwater model are also utilised to evaluate whether the observed groundwater chemistry results from oxidised groundwater flowing in from a different area where the clay layer is much thinner. A final decision on the vulnerability will be made based on this evaluation. The result is a mapping of groundwater vulnerability to nitrate, with each aquifer assigned a level of high, moderate, or low.

Table 1 Designation of the aquifer's vulnerability with respect to nitrate.

| Thickness of reduced clay | Groundwater quality | Vulnerability |
|---------------------------|--|---------------|
| 0 to 5 meters | <ul style="list-style-type: none"> Oxidised groundwater Weakly reduced groundwater with a high sulphate content (over 70 mg/l) | High |
| 5 to 15 meters | <ul style="list-style-type: none"> Weakly reduced groundwater, sulphate over 20 mg/l | Moderate |
| Over 15 meters | <ul style="list-style-type: none"> Strongly reduced groundwater, sulphate is under 20 mg/l (under sulphate reducing conditions), often with methane | Low |

As an alternative to using the thickness of reduced clay sediments to determine vulnerability, a calculation of the aquifer's natural reduction capacity can also be made. This is particularly evident on the island of Bornholm, where Quaternary clay deposits tend to be thin. At the same time, the Mesozoic and Palaeozoic sedimentary rocks have a natural capacity for reducing pollutants. To determine vulnerability, the nitrate reducing capacity can be calculated from the fraction of organic material and the presence of pyrite in samples taken from boreholes drilled. This is thereafter compared with the water quality. If nitrate is present in groundwater, the aquifer's natural reduction capacity is limited or exhausted, and its vulnerability will be high. On the other hand, reduced groundwater without nitrate indicates a

natural reduction capacity, and, depending on the amount present, the vulnerability will be low or moderate.

The second step in the overall vulnerability assessment is to designate the areas where the aquifer is sensitive to nitrate leaching; this is basically determining where nitrates pose a threat to groundwater quality for the specific aquifers. This evaluation concerns aquifers that are either already used as a source for municipal drinking water supply or identified as future reserves for the drinking water supply.

Identifying sensitive areas for nitrates involves evaluating areas with high or moderate vulnerability. Areas with low vulnerability are considered adequately protected against nitrate leaching. The assessment first examines groundwater recharge calculated by the groundwater model. Areas with no groundwater recharge, regardless of the aquifer's vulnerability, will not be sensitive to nitrate leaching. Areas with groundwater recharge and high vulnerability will be sensitive to nitrate leaching. In areas with groundwater recharge and moderate vulnerability, a closer evaluation of groundwater sulphate concentrations is undertaken. If the sulphate is low (under 50 mg/l) and stable over time, then the area is determined not to be sensitive to nitrate leaching. However, if the sulphate is high (over 50 mg/l) or shows an unstable or increasing trend over time, the area is considered sensitive to nitrate leaching.

provides an overview of how the areas sensitive to nitrate leaching are determined.

Table 2 Determination of the areas that are sensitive to nitrate leaching

| Vulnerability | Recharge | Groundwater quality | Sensitive to nitrate leaching? |
|---------------|----------|---|--------------------------------|
| High | No | -- | No |
| | Yes | -- | Yes |
| Moderate | No | -- | No |
| | Yes | High sulphate, unstable or increasing sulphate concentrations | Yes |
| | Yes | Low sulphate (under 50 mg/l) with stable concentrations | No |
| Low | -- | -- | No |

The third step in the process is to designate groundwater protection areas, where actions must be taken to protect groundwater resources from nitrate leaching. This is done by assessing the land use in the areas designated as sensitive to nitrate leaching. If the land use in these areas is already protected or where fertilisers are not applied, no protective measures regarding nitrates are required. This includes protected areas such as meadows, heath, bogs, grasslands and forested areas under long-term or no cultivation. All remaining nitrate sensitive areas, including agricultural, recreational, and urban areas, are designated as requiring actions to prevent nitrate leaching into aquifers.

Figure 10 shows an example of the mapping results. Note that there are large areas with high or moderate vulnerability that are not designated as sensitive to nitrate leaching. These are the areas where no groundwater recharge reaches the aquifer. There are also significant areas sensitive to nitrate leaching that are not designated for groundwater protection. These are areas that are already protected from groundwater leaching (either wetlands or protected forests).

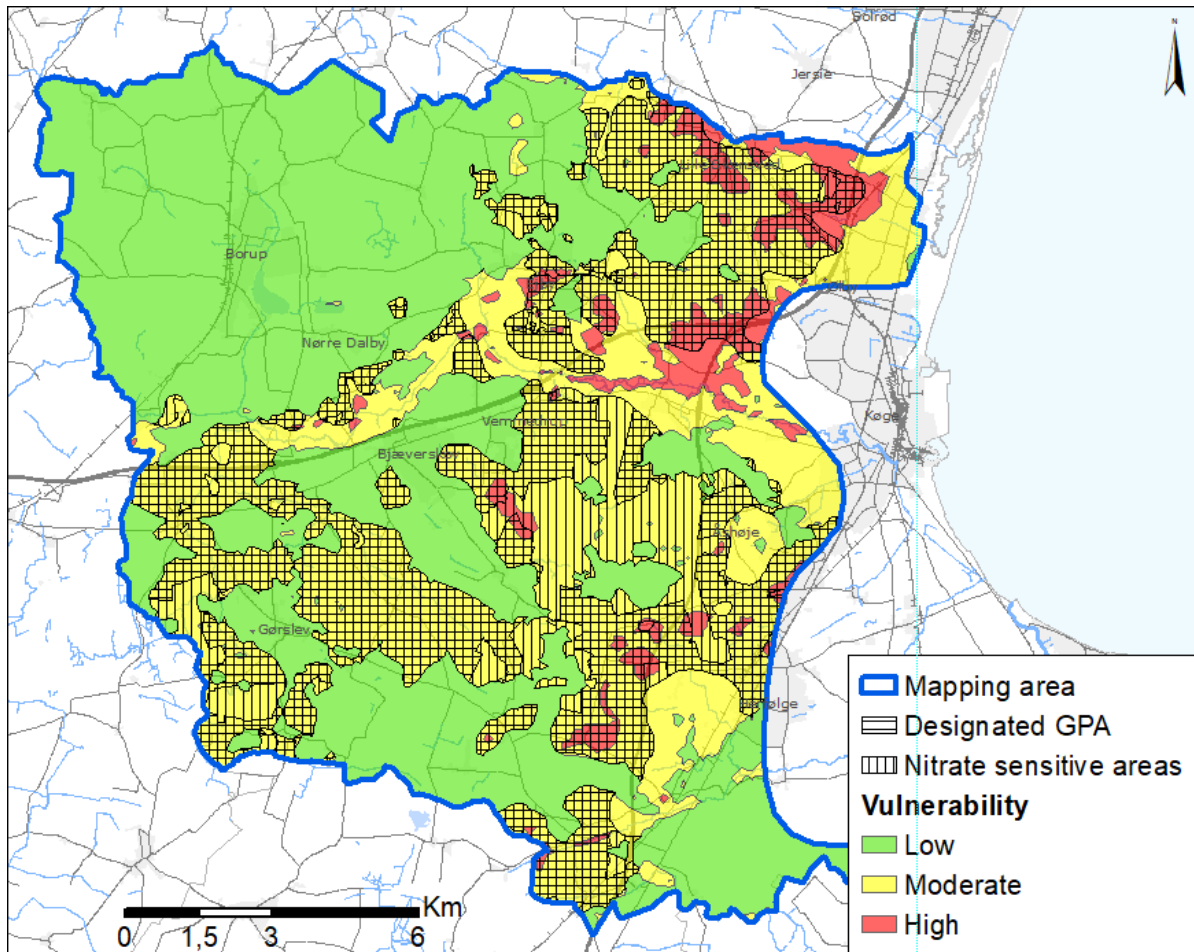


Figure 10 Example of the results from the groundwater mapping (Danish EPA, 2022a). The colours represent the mapping of vulnerability to nitrates; the vertical lines show the nitrate-sensitive areas; and the horizontal lines (forming cross-hatching) show the areas designated as groundwater projection areas (GPA).

Vulnerability with respect to pesticides

In contrast to nitrates, research conducted on the mobility and degradation of pesticides in Denmark did not produce clear cut results in determining aquifer vulnerability to the leaching of pesticides that could be used in all of Denmark. The studies have shown that, for sandy soils, vulnerability can be assessed based on the volumes of humus and the clay and silt fractions (Danish Nature Agency, 2015). However, for clayey soils with clay content greater than 10%, no determination could be made, and these soils are not assigned a vulnerability.

For sandy soils with clay content less than 10%, vulnerability is assessed based on the fractions of humus, clay, and silt. This relationship is shown on Figure 11. Based upon these fractions, the soils are divided by the researchers in four categories: Highly vulnerable (low humus and coarse grain content – cut-off shown by the red line), potentially vulnerable (soils that fall between the red and orange line), slightly vulnerable (between the orange and yellow line) and not vulnerable (soils with high humus and/or high fine grain content – soils that fall above the yellow line). From this relationship, the soil types found in Denmark are categorised into these vulnerability categories. Thereafter, maps covering Denmark can be used to designate the relative vulnerability to leaching of pesticides.

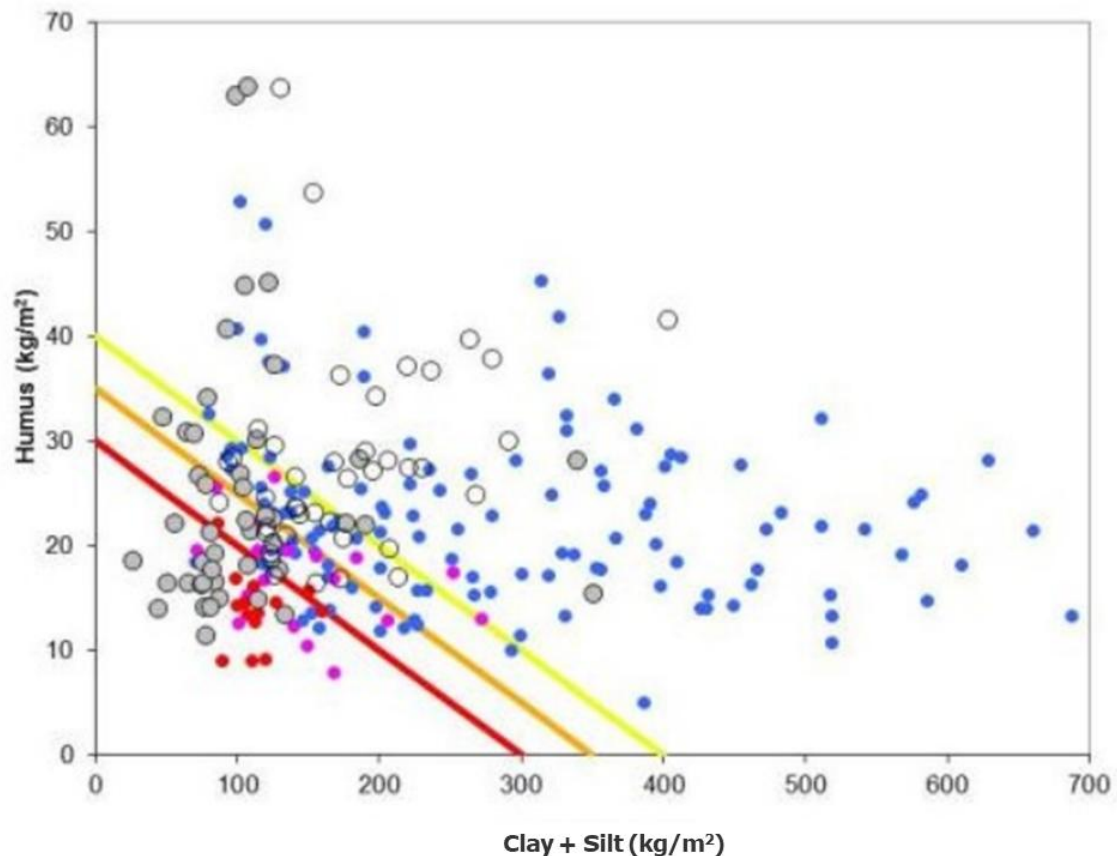


Figure 11 Relationship of the vulnerability to pesticide leaching (Danish Nature Agency, 2015). Soils that fall below the red line are highly vulnerable; those between the red and orange lines are potentially vulnerable; those between the orange and yellow lines are slightly vulnerable; and those above the yellow line are not vulnerable.

Once the vulnerability to pesticide leaching has been determined, the groundwater protection areas for pesticides are identified. These areas include all highly and potentially vulnerable soils that fall within areas of specific drinking water interest or within a well field catchment zone for a municipal water supply. For areas with soils that are slightly vulnerable or not vulnerable, or with little risk of pesticide leaching, including urban areas, roads and railroads, parks, cemeteries, beaches, and grasslands, no groundwater protection areas for pesticides are designated. It should be noted that for soils with a clay fraction greater than 10%, the results are inconclusive. Although no groundwater protection areas for pesticides are designated on these soils, this does not mean the aquifers are protected from pesticide leaching. It means that the leaching potential in these soils could not be described, and that the soils may or may not be vulnerable to pesticide leaching.

3.1.4 Completion

The final stage of groundwater mapping is Completion. Upon completion of the Results phase, the four different designations are prepared and submitted to the Ministry of Environment for official acceptance. The first step includes a quality control of the submitted files. Thereafter, the designations go through an 8-week public hearing process, during which all stakeholders and the public at large can review and comment on them. The Danish EPA then addresses the comments. Thereafter, the designations are sent to the Minister of Environment, who then makes the designations official.

In addition, the Completion phase includes collecting and storing data from the groundwater mapping process. The results from the Data and Results phase are entered into a GIS template, where the data are stored with relevant metadata and are subsequently publicly available. The different reports and primary data are stored in national databases, and the geological and groundwater model is uploaded to the national model database for general public access.

3.2 EU Water Framework Directive Water Plans

The EU Water Framework Directive (WFD) was implemented in Denmark in 2000 to address environmental threats to the member state's water bodies, including streams, rivers, wetlands, marine and groundwater bodies and their associated ecosystems (Danish Ministry of the Environment, 2022). The ultimate goal of the WFD is for all bodies to achieve a good status. The WFD mandated that all countries conduct a baseline analysis, create and implement a water plan by 2015. Then, every six years, a new baseline analysis is to be conducted, and the water plans are to be revised. Denmark is currently developing the next water plan for the period 2021 to 2027.

The driving force for the WFD is to protect the EU's water bodies, ensuring that both freshwater and marine ecosystems remain/become healthy, and to secure clean, plentiful water resources for future generations (European Commission, 2022). Groundwater is recognised as a critical source of drinking water, supplying around 75% of the EU's and 100% of Denmark's drinking water. In addition, groundwater is also recognised as an important component of freshwater ecosystems, providing baseflow of clean, cool water to streams, wetlands, lakes, and coastal marine environments. Groundwater can also serve as a pathway for the transport of pollutants, such as nitrates and pesticides, that can affect these environments. It is on this background that groundwater is an important component of the WFD water plans developed by each country.

The WFD states that groundwater bodies should be assessed and managed at the river basin scale, rather than along political boundaries (European Commission, 2022). In Denmark, groundwater bodies have been divided into 23 basins based on the larger stream or fjord catchment areas. As Denmark has only a relatively short boundary with one neighbouring country, namely Germany, and only one international groundwater basin, the administration is shared between Denmark and Germany. For each groundwater basin, three groundwater bodies have been identified: near surface aquifers, regional aquifers, and deep aquifers. The near surface aquifers are in direct contact with the surface and consist primarily of shallow Quaternary sand and gravel, with fractured bedrock on the island of Bornholm. The regional aquifers are larger sand and gravel deposits, as well as fractured limestone, chalk, and bedrock, that are deeper than the shallow aquifers but still in hydrological contact with surface water bodies. The deeper aquifers, which include fractured limestone, chalk, and sandstone, are deep enough that there is only limited hydrological contact with surface water.

The process for each 6-year plan period includes two steps:

1. Baseline analysis
2. Development of the water plans

The purpose of the baseline analysis is to determine the current status of the groundwater bodies, both the quantity and quality. For the quantitative analysis, risk is determined through a water balance, comparing groundwater recharge reaching the aquifer with the amount abstracted from it. Taking into account the needs of groundwater dependent ecosystems, it is considered that if groundwater abstraction exceeds 30% of recharge to the specific groundwater body, there is a risk that a good quantitative status cannot be achieved.

However, if abstraction falls below 30% of groundwater recharge, then there is a risk that a good quantitative status cannot be achieved.

The water balance is calculated using the national water resource model set up and run by the Geological Survey of Denmark and Greenland (Danish Ministry of the Environment, 2022). The model is a dynamic, integrated hydrological model that includes climate data and surface water and groundwater. The model is divided into 7 sub-models, with the smallest being the island of Bornholm, covering 589 km², and the largest, mid-Jutland, covering 11,551 km². The hydrological models are based on the national hydrostratigraphic model, which is continuously updated from geological modelling activities through groundwater mapping. The model includes all reported groundwater abstraction and abstraction permits and is calibrated against water level and stream discharge measurements from national databases.

Figure 12 shows an example of the baseline assessment of the regional aquifers near Copenhagen. In this case, the regional aquifer north of Copenhagen (København) consists of thicker deposits of Quaternary sand and gravel, whereas in Copenhagen and extending to the southwest, the regional aquifer consists of fractured limestone.

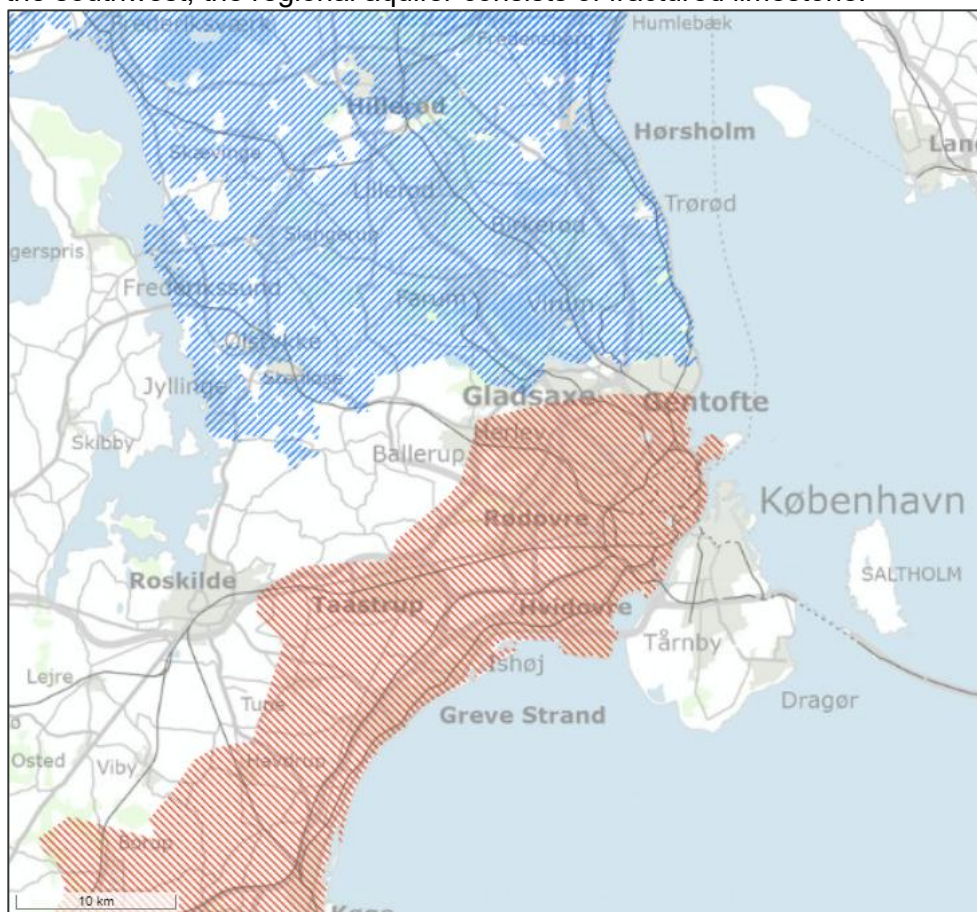


Figure 12 Quantitative baseline analysis for the regional aquifers near Copenhagen. The regional aquifer north of Copenhagen, consisting of sands and gravels, has a good quantitative status (blue), whereas the regional aquifers in and southwest of Copenhagen, consisting of fractured limestone and chalk, are at risk of not achieving good status. From the Danish Ministry of the Environment, 2022.

The results of the baseline assessment show that the Quaternary sand and gravel aquifer to the north has a good quantitative status (blue colour), whereas the fractured limestone has a risk of not achieving good status (red colour).

The calculation of the quantity status is conducted for the groundwater bodies as a whole, which contain the different aquifers. In the case near Copenhagen, both groundwater bodies cover an area of over 350 km² and do not account for local variations in groundwater abstraction. Thus, when abstraction exceeds 30% of recharge in a given groundwater body, there may be local areas where abstraction is less concentrated, allowing further abstraction without harming freshwater ecosystems.

The groundwater quality status looks at the broader water quality of the aquifers. To achieve a good status, the groundwater body should not show degradation due to saltwater intrusion or exceed groundwater quality limits. In addition, groundwater bodies should be of sufficient quality not to affect groundwater dependent ecosystems or degrade water quality in connected water bodies, including streams, lakes, and coastal marine environments.

Like for the quantitative status, the quality status is determined for the groundwater body as a whole. For example, if the groundwater body has one borehole where nitrate exceeds the water quality limit of 50 mg/L, it is considered to pose a risk of failing to meet the high standard. In these cases, a specific evaluation of groundwater quality in the groundwater body is required.

Once the quantitative and qualitative baseline is established, the water plans are developed. This includes formulating the specific objectives to meet. In the water plan for 2015 to 2021, the objectives for groundwater included:

- Quantitative:
 - Abstraction over longer periods may not exceed the long-term available groundwater resource (water balance);
 - Water level cannot be reduced so that the surface water bodies cannot meet their objectives or degrade the ecological status of these or groundwater dependent ecosystems;
 - Abstraction may not result in saltwater intrusion.
- Quality:
 - Electric conductivity measurements should not indicate saltwater intrusion or other human-caused effects;
 - EU water quality limits should not be exceeded;
 - The quality should be maintained so that the surface water and groundwater dependent ecosystems are not degraded or prevented from meeting their objectives
 - Pollutants posing a threat to groundwater quality should be limited or prevented, so that groundwater quality is improved or the long-term trend does not exceed 75% of the EU water quality limits.

Actions taken to meet the objectives fall primarily to the municipalities. This is primarily through new abstraction permits. The municipalities may not issue new permits, so the objectives cannot be met. This includes an evaluation of how the new permit will affect surface water- and groundwater dependent ecosystems and ensure that groundwater quality in the aquifers can be maintained. In areas where abstraction exceeds recharge, groundwater use can be prioritised, with drinking water given the highest priority. The Regions are responsible for determining the source of and eventual remediation of pollution from such.

In connection with the water plans, the Danish EPA monitors water levels and quality in groundwater bodies through a national groundwater monitoring network. In addition, the state will continue to acquire new knowledge about the effects of groundwater abstraction on freshwater and groundwater dependent ecosystems.

3.3 Assessing point source pollution

Since 2007, the Danish Regions have been responsible for mapping and assessing point source pollution in Denmark. This includes mapping all potential and actual soil pollution sites and evaluating the risk to both the surface water and groundwater resources (Danish Regions Center for Environment and Resources, 2022).

The process the Danish Regions conduct consists of three steps: mapping all possible sites that may contain soil pollution, determining the extent of the pollution and the threat to groundwater resources, and remediation of sites that pose a threat.

The first step is to map all possible sites that may be polluted. These sites can be old or active landfills, old industrial areas, leaking oil and gas tanks at petrol stations or chemical storage depots. This step primarily involves reviewing historical business registries to identify businesses that may have conducted activities that led to chemical spills. This can include, for example, old factories, laundries, or workshops where chlorinated solvents were used or stored, old service stations where a buried oil or gas tank may have been, or an old landfill that is now covered. In addition, the Regions can receive submittals from municipalities, private entities, or the general public regarding other potential pollution sources. These can include, for example, old depressions in the landscape, gravel or clay pits that were used as unregistered landfills and subsequently covered over. These unregistered landfills can pose a particular threat as they are often covered over by the farmers after they have been filled up with containers containing chemicals and pesticides, covered with soil, and are now used for growing crops or grazing.

The second step is to determine the threat that the polluted sites pose to the groundwater resources. This is done through site studies, during which soil, pore water, and groundwater samples are collected to determine whether pollutants are present. This step may include supplemental geophysical studies, detailed geological mapping, and/or solute transport modelling, depending on the site. The product is a report which determines:

- Whether or not the site is polluted;
- The types and concentrations of the different pollutants in the soils, porewater and groundwater;
- Assessment of whether or not the pollutants at the site pose an actual threat to the groundwater resources.

In cases where a point source of pollution poses a threat to groundwater resources, the Danish Regions can intervene and initiate remediation activities to remove the source and clean the groundwater if it is already polluted. However, as remediation is often very expensive, sites are prioritised for remediation. Often, sites are prioritised based on the degree of threat to groundwater resources, the degree of observed pollution, the extent to which the pollution poses a risk to a municipal water supply, and whether there are alternative sources of clean groundwater for the affected waterworks. The actual prioritisation, though, will vary across regions.

The results of the mapping of point source pollution at all three stages are utilised by municipalities in their groundwater protection plans and permitting. Many municipalities include point source pollution sites in their groundwater action plans to continue a dialogue with the region on the evaluation and remediation of particularly vulnerable groundwater resources. In addition, municipalities will use knowledge of the potential and actual polluted sites when issuing groundwater abstraction permits. For waterworks permits, municipalities will assess the possibility that pollution could be mobilised and reach the drinking water well. Alternatively, the municipalities could use the results to prioritise placing abstraction that does

not require drinking water quality near the sites to help prevent the further spread of pollution in the groundwater system.

3.4 Data flow

The data produced by the groundwater mapping and assessment programs are publicly available and stored in various publicly accessible databases. The data in these databases are also directly utilised by the three programs and by municipalities in their groundwater management and protection activities and plans. This provides for a complex relationship among these four activities, where each provides certain information and utilises information from the other programs. Figure 13 illustrates the relationship in the data flow between the programs. This flow is also described in the text below.

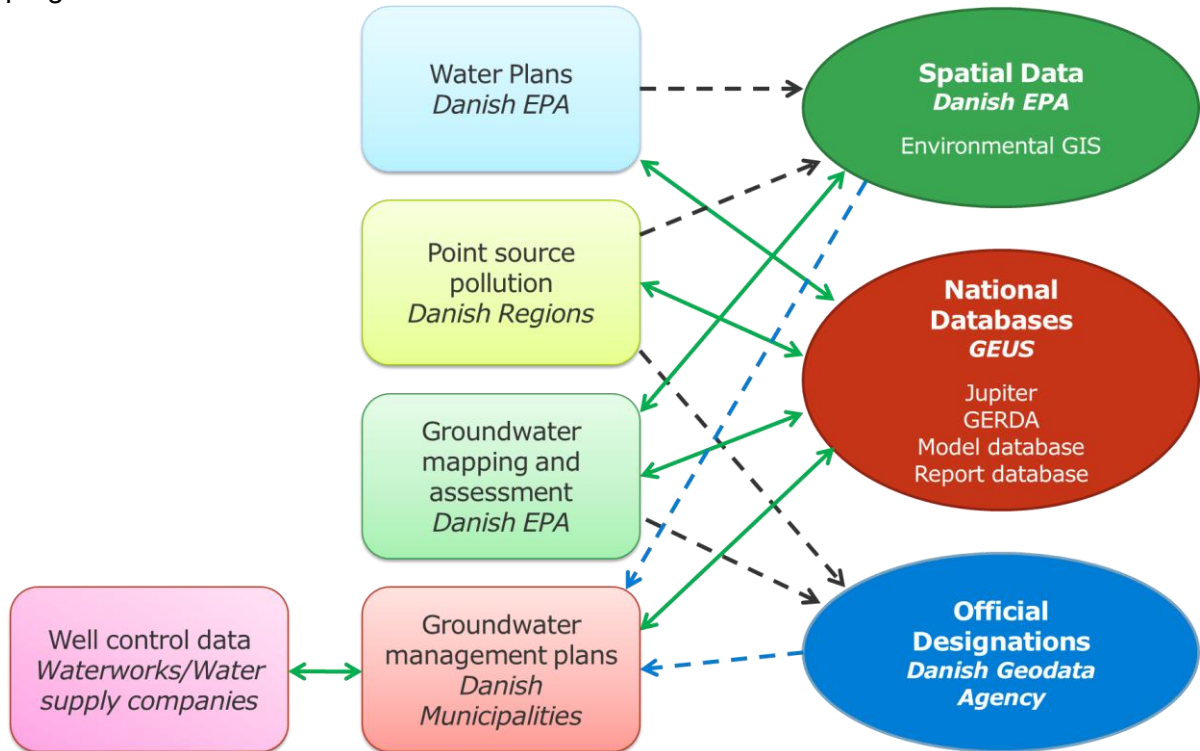


Figure 13 Diagram illustrating the data flow between the different groundwater mapping, assessment and protection programs and the different databases in Denmark. The dashed lines show a one way relationship, where black dashed lines show where data are provided, and blue dashed lines show where data are used. The solid green double arrows show where data is both provided and used. See text for a full description of this interaction.

As authorised by the Danish legislative initiatives, data and information on groundwater are collected through programs run by the Danish EPA, the Regions and municipalities in Denmark, as well as the waterworks and water supply companies. As illustrated in Figure 13, all the entities are both consumers and providers of the groundwater data.

Starting with the water supply companies, as part of the permits issued by the municipalities, they are required to collect data from their abstraction and monitoring wells. This includes regular water level measurements, groundwater quality, pumping amounts and results from pumping tests. They can also conduct synchronous groundwater level measurements in cooperation with other nearby waterworks, stakeholders and even the municipality. All data collected from the waterworks is thereafter sent to the municipality for approval, which then submits it to the Jupiter database. The Danish Municipalities frame the activities of the water works through their different groundwater management plans and often assist the water works in accessing and using the data stored in databases when determining groundwater

protection, abstraction strategies, or the location of new wells. However, the waterworks can, and often do, access these data and models directly from the databases.

For the development of the Water Plans, the Danish EPA, supported by the Geological Survey of Denmark and Greenland (GEUS), uses data from national databases, particularly Jupiter, to develop its national water resource model (GEUS, 2022). In particular, the water levels, pumping volumes, and water quality collected by waterworks and municipalities provide critical data. In addition, they use geological and hydrological data collected and submitted through the groundwater mapping and assessment program. The results of the model work are made available through the Environmental GIS platform and the models, and any extra data collected is made available through the national databases.

The Danish Regions, which work on the study and remediation of point source pollution, rely on data from national databases and the Environmental GIS. This serves both to prioritise their activities and to assess the threat to groundwater resources. The data collected is thereafter made available in the different databases, as well as the status of the different pollution sites in Environmental GIS. The collected data include new monitoring wells, water level and water quality measurements, and geophysical studies.

The Groundwater Mapping and Assessment Program, run by the Danish EPA, is both a significant consumer and producer of data in the different databases. Their use of data includes all available data, collected by the different programs and from earlier groundwater mapping and assessment activities. When groundwater mapping is completed, they make all data available, including geophysical data collected, hydrological data, groundwater quality, hydrostratigraphic models, groundwater models, and simulation results. In addition, the groundwater vulnerability designations are also made available.

The Danish Municipalities are primarily consumers of the data. The data from the above-mentioned programs provide the foundation for the development of their respective groundwater management plans and permitting procedures. As described before, they also provide data to the national databases, but this data primarily comes from the waterworks, which the municipalities approve and submit to the different databases.

4. SUPPORTING INFRASTRUCTURE

A supporting infrastructure was developed to assist with national groundwater mapping and assessment activities as outlined in Danish legislation. The groundwater mapping and assessment activities could be accomplished without the supporting infrastructure; however, it would not have been possible to carry out the activities to the detail or consistency with which it is done today. The supporting infrastructure comes in four forms:

- Establishment of national programs dedicated to groundwater mapping and assessment activities,
- development of guidelines,
- establishment of databases, and
- the development of specialised tools.

One of the most critical infrastructure developments is the establishment of programs with dedicated resources and personnel for groundwater mapping and assessment. This includes Danish Groundwater Mapping and Assessment and the Water Plans (EU Water Framework) run by the Danish EPA, and the Danish Regions, looking at point source pollution. Thus, the establishment of these programs provided the framework for dedicated resources and staff

specific to groundwater mapping and assessment; something which may not have otherwise occurred at the same scale.

To support groundwater mapping and assessment efforts, several technical guidelines were developed. Early on in the program, each county responsible for the mapping activities was conducting the mapping efforts individually. Here, it was realised that it would be beneficial to have a number of technical guidelines that could provide an outline of what analysis could be done and recommendations for the methods that could be used in order to assure that the mapping and assessment activities maintain a high quality. Utilising funding from the groundwater mapping and assessment program, a number of technical guidelines were developed. These include:

- Soil sampling and establishing groundwater wells,
- Geological and hydrostratigraphic modelling,
- Water level measurements and groundwater potential maps,
- Groundwater chemistry analysis,
- Hydrological modelling and calculating wellfield catchment areas
- Determining groundwater vulnerability to nitrate.

These guidelines are available on the Danish EPA's website (Danish EPA, 2022b)

An integral part of the infrastructure for groundwater mapping and assessment is the various databases established (GEUS, 2022). These databases include:

- Jupiter database, which stores all borehole related data, including location, ownership, use, construction, geology (well completion reports), water level measurements, and water quality measurements as well as information on waterworks, including permits, abstraction and water quality delivered to the consumer.
- GERDA database, which holds data from geophysical surveys and borehole logs.
- Model database, which contains 3D geological and hydrostratigraphic models and groundwater models.
- Report database, which contains all reports for groundwater studies completed in connection with groundwater mapping and assessment, as well as many other reports completed from other projects.
- Environmental GIS database, containing a large amount of the spatial data and results from groundwater mapping and assessment, as well as data on point source pollution collected by the Danish Regions.

These databases provide an integral repository of all publicly collected data and some privately collected data, open to all for use. This has created a platform where information can easily be shared, and everyone is working with the same data pool for their evaluations. As illustrated on Figure 13, all the different programs utilise the data stored in these databases.

During the groundwater mapping and assessment program, funds have been made available to support the development of several tools to assist in the mapping and assessment process. These tools have been in the form of support in the development of aerial electromagnetic surveys (SkyTEM), allowing for the rapid collection of resistivity data over large areas, as well as the development of software for processing of geophysical data and geological modelling.

Appendix B



water & sanitation

Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA



South African groundwater mapping and assessment approach

1. BACKGROUND

Nearly 77% of South Africa's water supply comes from surface water. Estimates of groundwater use in South Africa suggest that about 15% of the total volume of water used in the country is groundwater. Historically, groundwater has been a standalone or site-specific resource, never a regional bulk water supply. Because of increasing socio-economic pressures on urban water resources, groundwater is increasingly being considered an alternative water source for urban settlements. The National Department of Water and Sanitation has the primary responsibility for managing and protecting all water resources. Groundwater was a private entity and became publicly owned after the promulgation of the National Water Act 36 of 1998 (NWA).

Traditionally, the water supply has been focused on a treatment process consisting of filtration and chlorination. Other treatment methods, such as reverse osmosis, active carbon, advanced filtration and ozone, are also used where unsuitable source water quality and pollution of water resources have been identified. Surface water and groundwater used for water supply are tested to determine whether their quality is suitable for drinking and domestic use.

Full integration of groundwater into water resources management cannot yet be considered complete. The first edition of the National Water Resource Strategy (NWRS) from 2004 did not see groundwater as a separate resource requiring special focus and, where necessary, separate strategic plans. The national groundwater mapping program (GRAI, 1997-2000, and GRAII, developed from 2002 to 2004) produced high quality groundwater information that could be used for the management of the resource. It recognised groundwater as part of water resources and national water resources planning. The National Groundwater Strategy was finalised in 2016. This strategy is required to unleash the full potential of groundwater for water security in South Africa, to establish a framework within which stakeholders at all levels become part of groundwater governance, and to initiate a long-term process of rolling out sustainable groundwater utilisation.

The National Department of Water and Sanitation (DWS) currently has a rollout plan for the 2016 National Groundwater Strategy. After the roll-out, planning will be initiated for the national groundwater mapping program for which the National Department of Water and Sanitation is responsible.

Groundwater protection plans in response to current and future water supply threats are primarily developed at the national and regional levels. Water safety plans are developed at the municipal level.

The threat to future water supplies is the destruction of natural ecosystems, deforestation, surface water and groundwater depletion, land degradation, and pollution, for example, from anthropogenic sources and chemical and agricultural waste. Environmental damage contributes to increased natural disasters, climate change, and water attenuation. Increased pressure is placed on groundwater resources due to overabstraction in the agricultural, industrial, and municipal sectors. The decanting of old mine works, unknown hazardous waste storages, poorly sited cemeteries, landfill sites and dysfunctional wastewater treatment works are among the threats to groundwater pollution.

Municipalities can apply to access bulk water infrastructure grants for funding surface water and groundwater infrastructure and maintaining it. Raw water levies and water resources

management charges payable to DWS by registered, authorised and licensed water users and other sources, such as taxes, are used by the Catchment Management Agency (CMA) or Proto-CMA to manage all the water resources within the catchment. Households do pay municipalities for the volume of water used, which also includes levies, as supplied to them by municipalities and or water service providers. However, domestic water users are not charged when groundwater is abstracted from a borehole or well situated on their property, except for levies that some municipalities charge on those properties for boreholes or wells. Poor communities receive a certain volume of water for free (free basic water – FBW) before any payment is required to municipalities.

2. THE SOUTH AFRICAN SETTING

2.1 South African legislation

This section provides a brief description of the relevant Acts and/or strategies governing the administration of surface and groundwater resources in South Africa.

The second National Water Resource Strategy (NWRS II) of 2013 is an expansion of the National Water Act of 1998 (Act 36 of 1998) (NWA) and provides a framework for the protection, use, development, conservation, management and control of water resources. It also provides the framework for managing water at the regional or catchment level within defined water management areas. The National Water Resource Strategy is binding on all authorities and institutions exercising powers or performing duties under the NWA.

The ultimate goal of the National Groundwater Strategy (NGS) of 2016 is to ensure sustainable, accessible, and cost-effective supplies for human survival and socio-economic development, while maintaining the environmental services that groundwater supports, in an integrated development approach. The development of effective approaches requires a long-term process through which viable national, regional and local systems can evolve. Including a long-term process of rolling out sustainable groundwater utilisation within integrated water resources management.

Before each National Water Resource Strategy (2004 and 2013), Groundwater Strategies (2004 and 2010) were developed as input to the NWRS, providing detailed strategic action plans. The National Groundwater Strategy of 2016 will thus serve as input to the current NWRS III, which is being developed.

The South African Water Related Laws were compiled to secure the protection, use, development, conservation, and management of water in a sustainable and equitable manner. There are no specific laws for groundwater mapping; however, the National Groundwater Strategy of 2016 mentions that the rollout planning for the national groundwater mapping program will be initiated at a later stage.

The DWS designate Water Management Areas (WMA). Within these water management areas, there are quaternary drainage areas. Quaternary drainage regions are hydrological units that are hierarchically nested from the primary drainage basin down to secondary, tertiary, and quaternary levels. The 1875 quaternary drainage regions are on average 650 km² in size (48 to 18096 km²). A groundwater reserve is determined for each quaternary drainage region for groundwater allocation purposes. The delineation of these quaternary drainage regions was based on surface water catchments. Aquifers do not necessarily follow surface water boundaries and manmade boundaries.

The National Groundwater Strategy of 2016 proposes the following stakeholder participation and collaboration:

- Aquifer management – joint management of shared aquifer resources by stakeholders organised in appropriate local management bodies within available plans, regulations, and guidelines.
- Action by municipalities – a professional groundwater supply service and source protection.
- Action from utilities - source protection, wastewater management.
- Farmers and larger agricultural ventures – institutionalised good practices.
- Mines / Energy producers / Industries – institutionalised good practices.
- Civil Society – raising public awareness, taking community initiatives and acting as watchdog.
- Media – Unique communication role in society; creates public discussion.

As governed by the South African legislation, the different institutional arrangements for water are shown in Figure 14. The different actors and their roles are described in the section below.

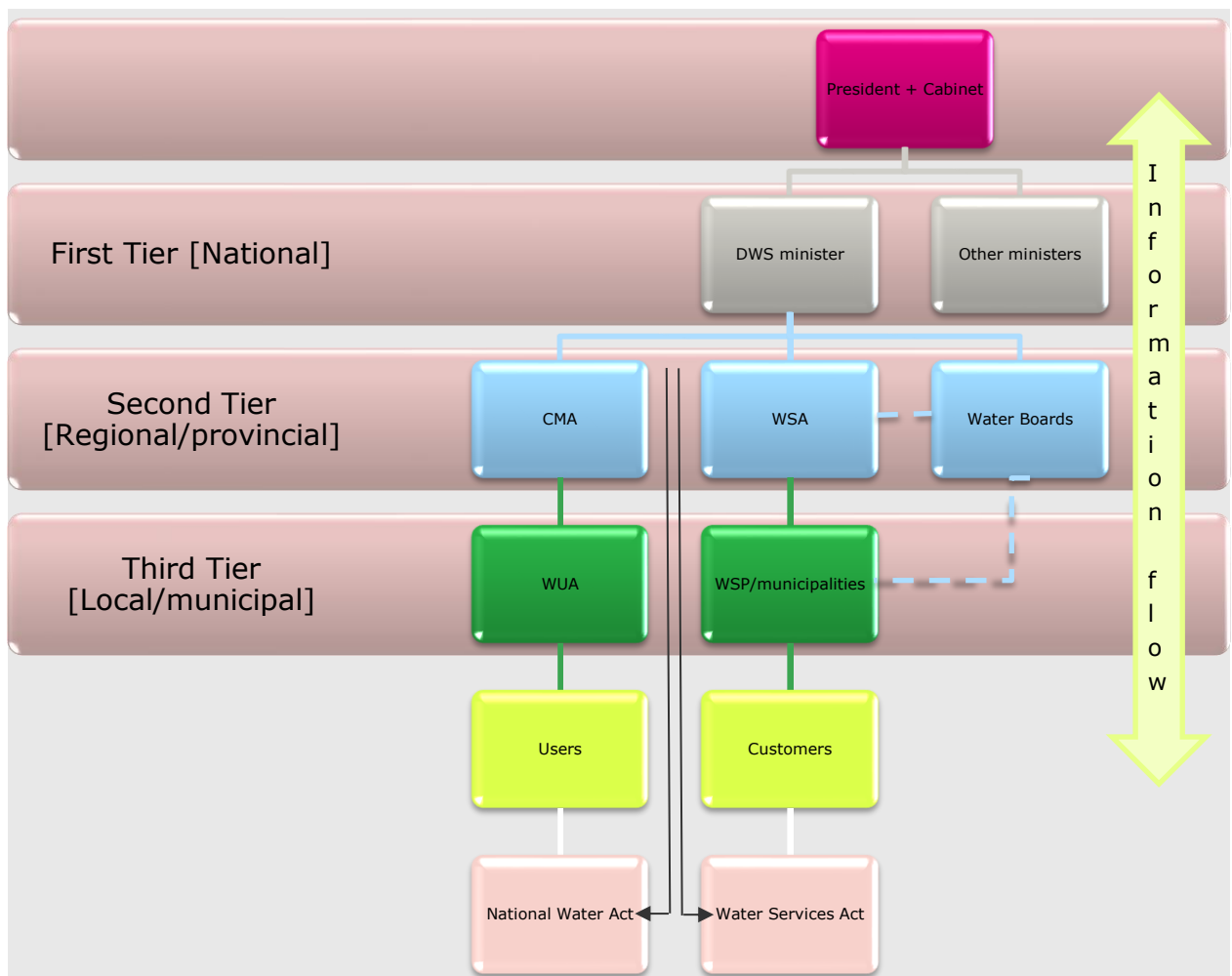


Figure 14 Responsibilities for groundwater protection at the national, regional, and local levels, adapted from Kelbe and Rawlins (2004).

2.2 Water supply and distribution

Water is a shared resource that is part of a continuous cycle and thus a common good that belongs to all. The minister at the head of the Department of Water and Sanitation is the

custodian of water resources in South Africa, managing them on behalf of the country's people. It is managed by the Department of Water and Sanitation on the day-to-day functions. Allocations are made through different forms of authorisation:

1. Schedule 1 use covers reasonable domestic use, watering of a garden and water for animals not in a feedlot.
2. Existing Lawful Use is linked to historical water use that must have been exercised before a certain date linked to the transition to the NWA.
3. General Authorisation is awarded where the impact of the water use is small enough that it does not require a full licence.
4. Water Use Licence is a water use that has a significant impact and comes with certain requirements.

DWS is the bulk raw water supplier to a large number of municipalities, agriculture, certain industries and mines. Where Catchment Management Agencies (CMAs) are established, they are responsible for performing certain functions as agents of DWS, such as issuing water use authorisations and collecting raw water tariffs. DWS provides bulk raw water from dams and other surface water systems to municipalities and other water users. The raw water tariffs are used to fund the work of the CMAs (and in the absence of a CMA, the branch in DWS that is responsible for managing the Water Management Area (WMA), known as the Institutional Establishment or proto-CMA), which is responsible for the management of the bulk schemes in conjunction with DWS. Proto-CMAs were established in each regional/provincial office (where CMAs have not yet been established) to ring-fence staff and functions that would later be transferred to CMAs when they are established. The raw water tariff includes groundwater, as the management of groundwater resources is the responsibility of the national DWS.

The Water Service Authority (WSA) is a municipality that is responsible for managing the water treatment schemes, i.e. that raw water is treated to potable standards. The treatment of groundwater will depend on its natural quality. The WSA may carry out the services of a water services provider (WSP, see below) or may enter into a contract (service delivery agreement) with another water services provider.

The Water Services Provider (WSP) is the entity that physically provides water supply and sanitation services to consumers under contract to the Water Services Authority (WSA). WSA can be a municipality, Water Board, Non-Government Organisation (NGO), Community-Based Organisation (CBO), or a private sector company. They maintain the reticulation infrastructure, treat raw water to potable standards at water treatment plants, and distribute it to users. Water users within municipal boundaries – domestic, commercial, and industrial – only have to pay for the costs of production, distribution, and maintenance of reticulation infrastructure.

Water Boards, i.e., Umgeni Water, Rand Water and Bloem Water, are private entities that provide treated water to the municipalities. Water boards are public (regional or bulk) water service providers that supply water to other water service institutions. They are established and regulated by DWS under the terms of the Water Services Act and also regulated by the National Treasury (NT) under the terms of the Public Finance Management Act (PFMA). They may supply water to more than one municipality. The municipalities need to pay for the services provided. Where Local Municipalities act as both WSA and WSP, that process is simpler. Responsibilities of the WSA and WSP overlap depending on the local structure, i.e. where the local municipality fulfils both functions.

Groundwater management has not been delegated to the local level of government, but is the responsibility of DWS and the CMA. Municipalities can only manage groundwater within

the constraints of their own water use authorisation. The Catchment Management Agencies (CMAs) are responsible for issuing water use authorisations. During the authorisation process, the CMA/proto-CMA considers the required water quality, the amount requested for groundwater recharge (sustainable use), impacts on groundwater dependent ecosystems, and impacts on existing groundwater abstraction.

The drinking water supply based on surface water is highly centralised and managed at different levels of government. Each municipality or water service provider has its own distribution area, where it is responsible for supplying water to all residents who want to connect to the distribution system. Groundwater supply systems are managed by municipalities (Local or District Municipalities) or water boards, which must comply with licence conditions and report to DWS.

The oversight of ensuring that the quality of drinking water supplied to customers by municipalities is maintained and that it meets the terms of their water authorisations falls to the CMAs and, ultimately, to DWS. They also have to manage the quality of the source water. Ensuring that drinking water quality demands are met is the responsibility of the municipality or the Water Board. All water use licence holders, including farmers, industries, municipalities, and water boards, are required to report the amount of water they abstract each year. In addition, they are required to measure water levels in their wells and collect water quality samples directly from the wells. The time interval of these measurements varies dependent upon the requirements of their Water Use Licence. All of the collected measurements are sent by the municipalities to the CMA/proto-CMA and DWS, who enter it into the national groundwater database.

There are some deviations from this structure, with a few examples below:

Victoria West within the Northern Cape province:

- Farmer is WSP. Supply water to the reservoir from a private well field, where the municipality pumps the water and augments it with their own sources.

Kenhardt within the Northern Cape province:

- Incentive for groundwater from a private farm for servitude and land management that is provided by the farmer.

Bloem Water within the Free State province:

- The water board took over the responsibility of maintaining and operating the municipal wellfield. Water is now supplied to the municipal reservoir from where the municipality is responsible for distribution. Additional wellfields are developed under a private agreement between the water board (Private Service Provider) and landowners and are now handled by the water board.

Agricultural water use is managed through Water Users Associations (WUAs) or Irrigation Boards (IBs), which must report to the CMAs. South Africa is in the process of transforming the long standing IBs into WUAs. The process started with the de-establishment of the IB's and was followed by the establishment of the WUA. The transformation process is a long administrative and stakeholder engagement intensive process. A very low number of WUAs are already established, although many IBs have already been de-established.

2.3 Geological and hydrological setting

The South African geological setting is very complex (Figure 15) and consists of alluvial sediments and coastal dunes systems overlying shale of the Malmesbury Group and granite intrusions of the Cape Granite Suite, quartzitic sandstone that makes up the Cape Fold belt from the Table Mountain Group – part of the Cape Supergroup, followed by the Karoo Supergroup, consisting of interbedded sandstone and shale with dolerite intrusions, basalt and granite of mountains in and around Lesotho, the igneous basement complex in Limpopo

in the north of the country and the Kalahari Sands. Figure 16 provides a cross section showing the geology from George on the southern Cape coast to Johannesburg in the north.

The sedimentary strata of the Main Karoo Basin range in age from the Late Carboniferous to the Early Jurassic. It has a cumulative thickness of about 12 km in the basin's southern part. Outcrops of the Karoo strata cover an area of approximately 700 000 km² – more than half of South Africa's land area (Woodford and Chevallier, 2002).

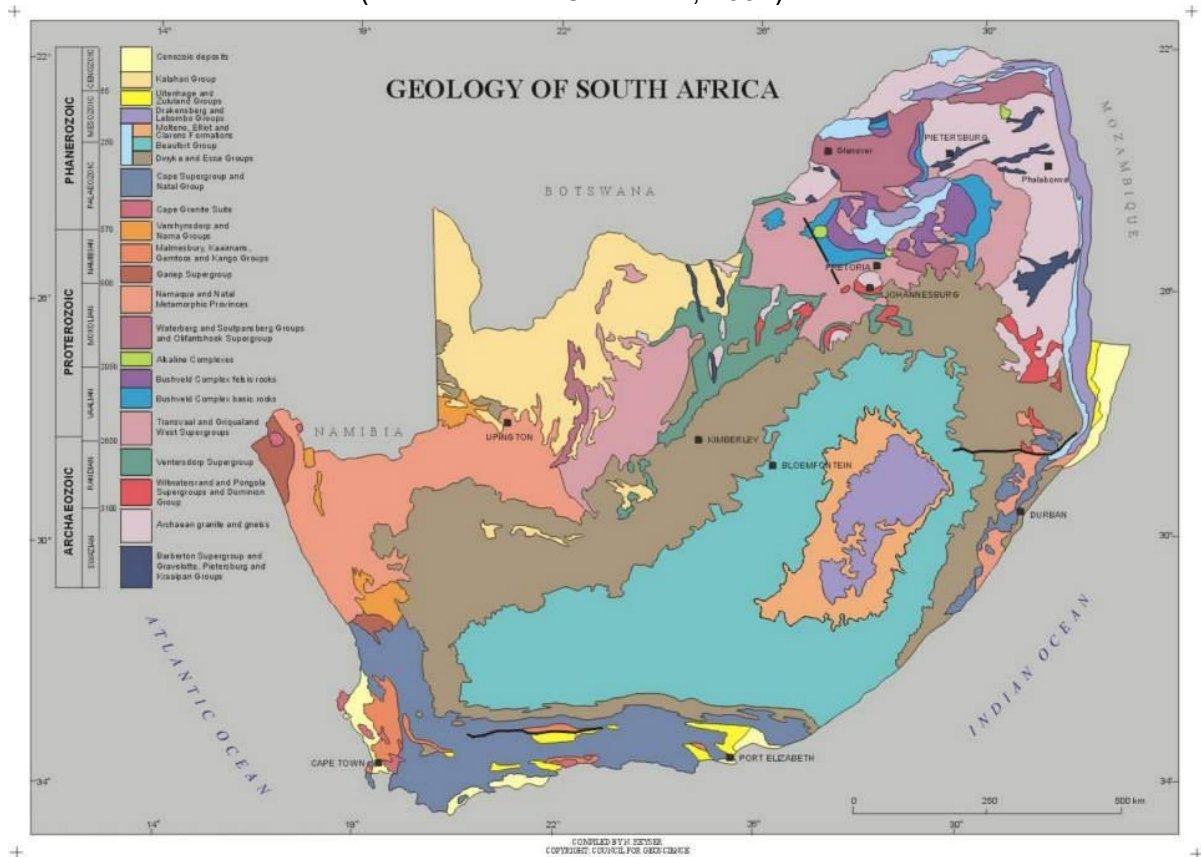


Figure 15: Simplified geological map of South Africa (CGS, 1997)

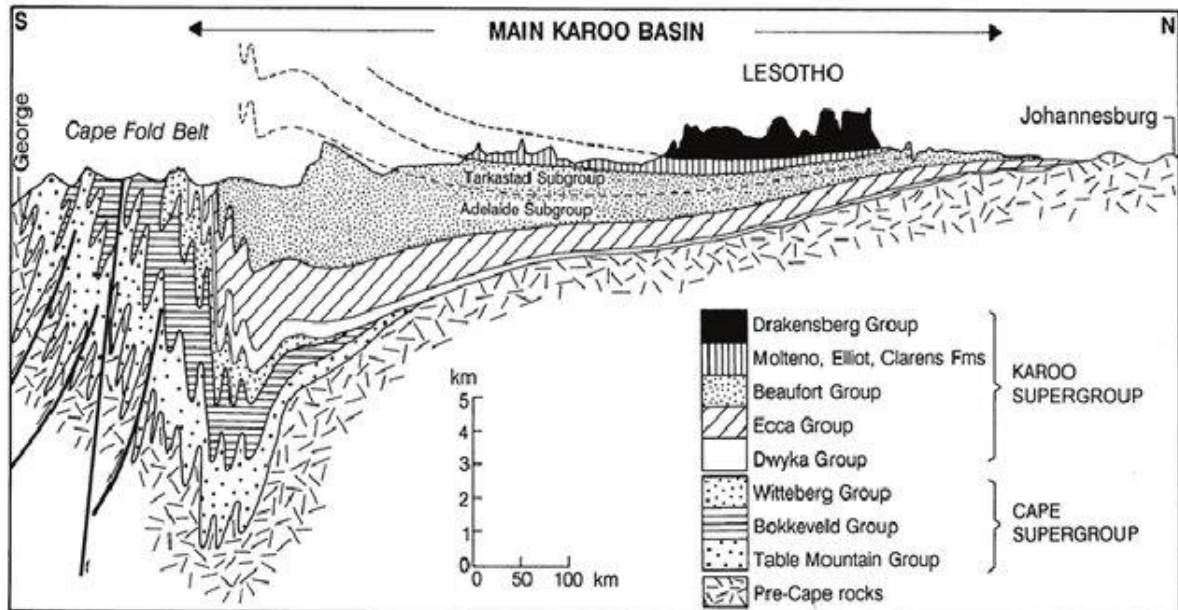


Figure 16: A simplified cross section of the main Karoo Basin from George in the south to Johannesburg in the north (Woodford and Chevallier, 2002).

About 90% of the aquifers in South Africa are hard-rock fractured aquifers, with the Karoo aquifers of sandstone, shale and mudstone making up the largest group (See Figure 17). Basement aquifers, quartzitic sandstone aquifers, karst aquifers and aquifers in igneous rocks complete the hard rock aquifers. Coastal aquifers and other porous aquifers make up the remaining 10%. They are nevertheless important as a source of groundwater for the local water supply. Geology determines the characteristics of the various aquifers, including recharge potential, flow, and quality.

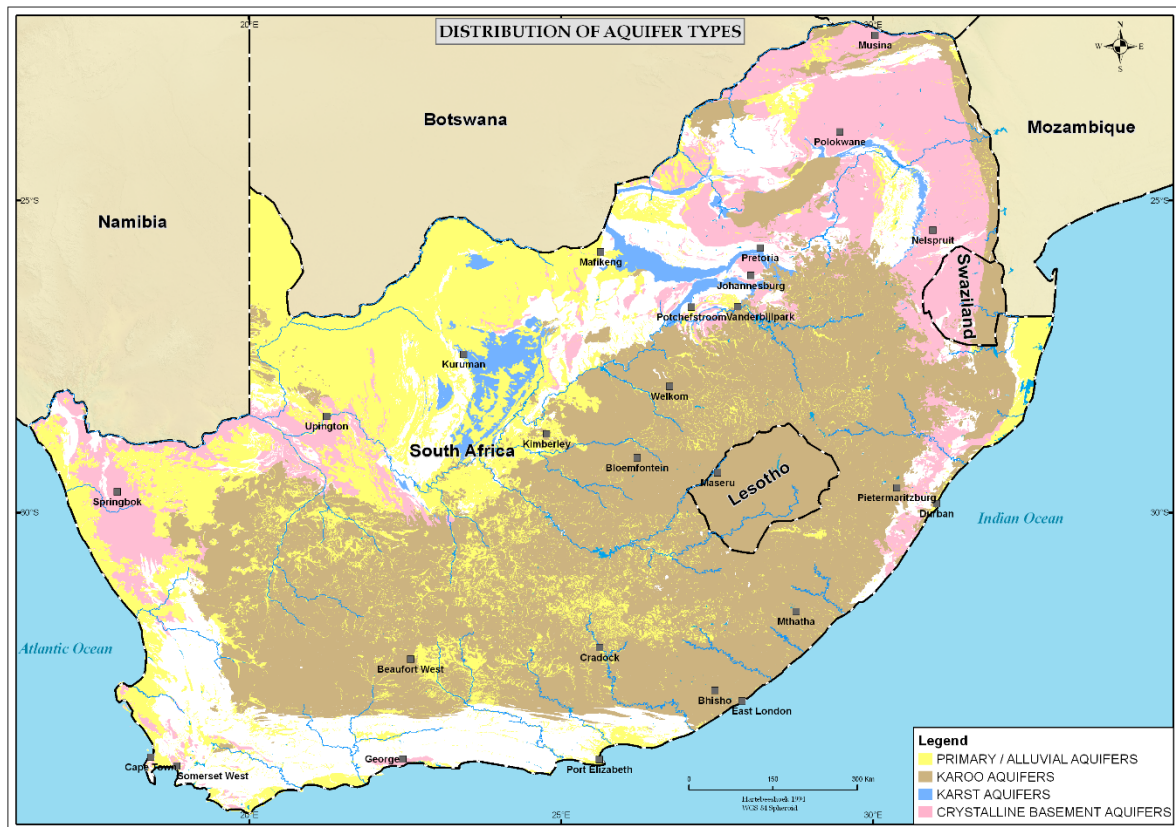


Figure 17: Distribution of aquifer types in South Africa.

Precipitation in South Africa varies from less than 100 mm/year on the northern West Coast and along the lower Orange River, to more than 1200 mm/year along the East Coast and some of the high mountains in the Western Cape and Mpumalanga (Figure 18). The country's mean annual precipitation is far below the world average, which earns South Africa the designation of a semi-arid to arid country. The pattern of rainfall infiltration into groundwater recharge depends not only on precipitation but also on soil type, geology, land use, temperature, and evapotranspiration.

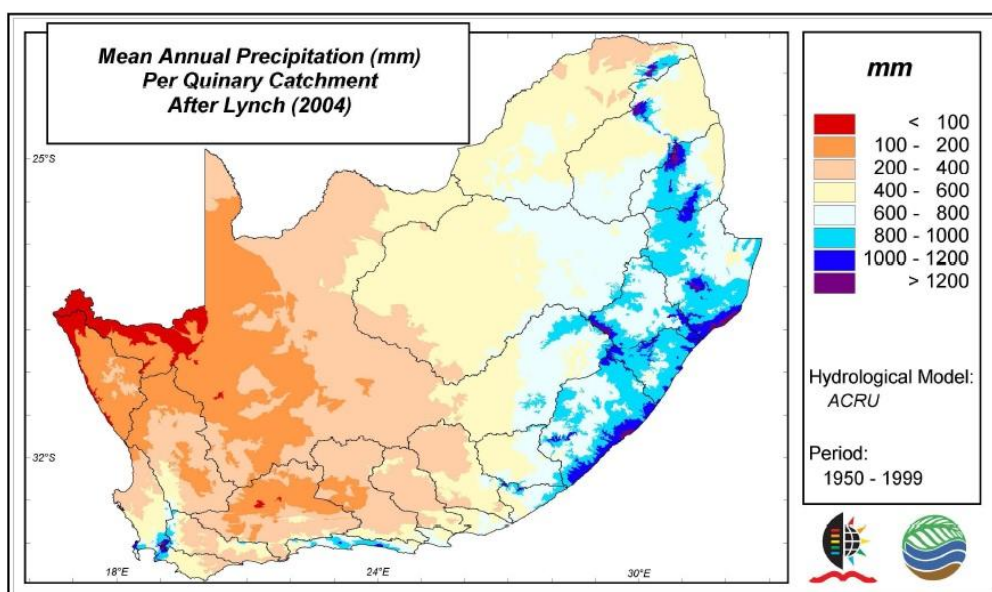


Figure 18: South Africa's Mean Annual Precipitation (MAP) (Schulze 2011).

The evaporation rate in South Africa is high (Figure 19), varying from more than 3000mm/year in the northern parts of the Kalahari to less than 1400 mm/year on the east coast, south coast and the high mountains in the Western Cape. The evaporation rate exceeds the mean annual precipitation, with implications for water management.

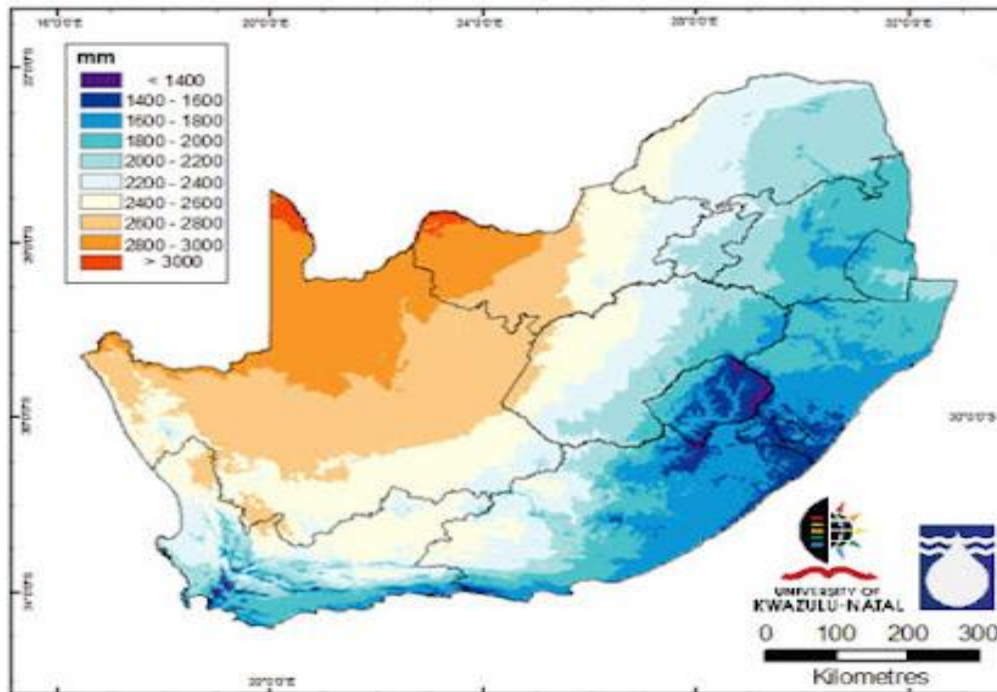


Figure 19: Map of evaporation from open-water surfaces across South Africa (mm/a) (Schulze, et al., 2008).

Recharge follows the same general pattern as the precipitation and evaporation maps, Figure 20, with higher recharge expected in the east and south of the country, and low recharge to the west and north.

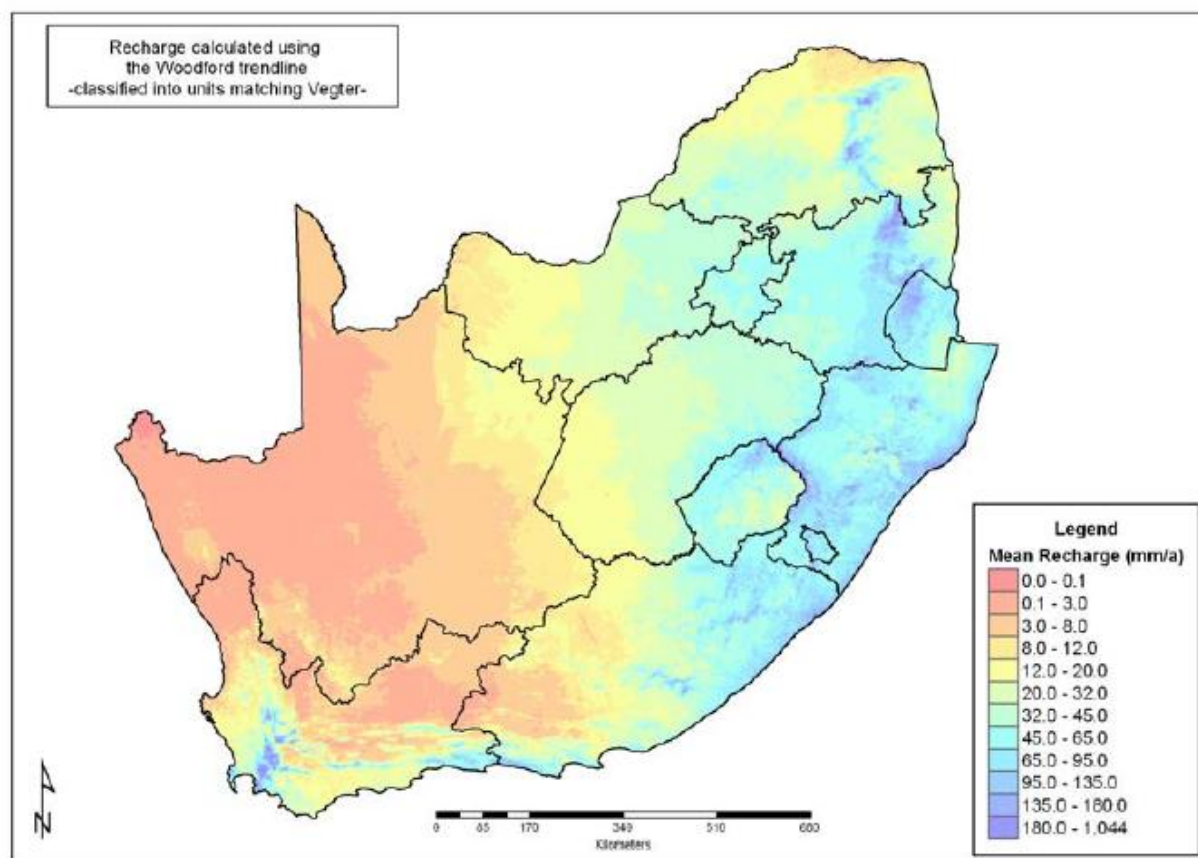


Figure 20: Groundwater recharge map of South Africa - derived from the Woodford rainfall /recharge relationship (DWA, 2005)

2.4 Challenges and threats

Threats to groundwater encompass both quantitative and qualitative aspects. Quality threats include diffuse and point-source pollution.

The most general diffuse source of pollution comes from agriculture, where potential pollutants are nitrates, pesticides and herbicides. Feedlots are also a potential source of nitrates and phosphates.

Point-sources that are most often associated with urban settings includes filling stations (volatile organic compounds, i.e., hydrocarbons, BTEX; also heavy metals and chlorinated solvents), cemeteries (bacteria such as *Escherichia coli* and *Clostridium perfringens*; nitrates), landfill sites (leachate containing soluble and insoluble organic and inorganic products from physical, chemical, hydrolytic and fermentative processes), and wastewater treatment works (nitrogen and phosphates), while French drains and soak-away sanitation systems are usually a problem in rural settings.

Mining also has the potential to pollute groundwater, with contaminants linked to geology, ore bodies, and ore processing. One important example is acid mine drainage, which is a major problem in karst aquifers, especially in the Witwatersrand.

In addition to anthropogenic threats, groundwater may not meet potable standards due to geologically linked contamination, which can cause high levels of arsenic, fluoride, iron, manganese, and nitrates. The naturally occurring pollutants include the high salt content of

shale, high iron and manganese concentrations associated with the Table Mountain Group aquifers, and other sources. High fluoride and arsenic have also been measured. Groundwater abstraction can also induce seawater intrusion into the groundwater aquifer, degrading water quality.

The extent of pollution from natural (geogenic) sources and human activities is often unknown, as groundwater monitoring is limited.

Groundwater quantity is under threat both due to limited recharge and the complexity of groundwater systems, where approximately 90% of South African groundwater occurs in secondary openings in hard rock. Yields from the different aquifer systems are often low. High yields are mostly associated with the coastal aquifers, highly fractured aquifers (such as the Table Mountain Group) and karst aquifers. Poor management practices can lead to over-abstraction and over-allocation of the resource, with significant impacts, such as reduced baseflow in rivers, aquifer collapse, and subsidence. This is exacerbated by highly variable recharge.

Figure 21 provides an overview of registered groundwater use across South Africa, based on the WARMS database. It tends to follow the same pattern as the precipitation, evaporation, and recharge maps, except in the most eastern parts, where high precipitation made groundwater use unnecessary. Agriculture is a major water consumer, with irrigation accounting for about 60% of water use in South Africa.

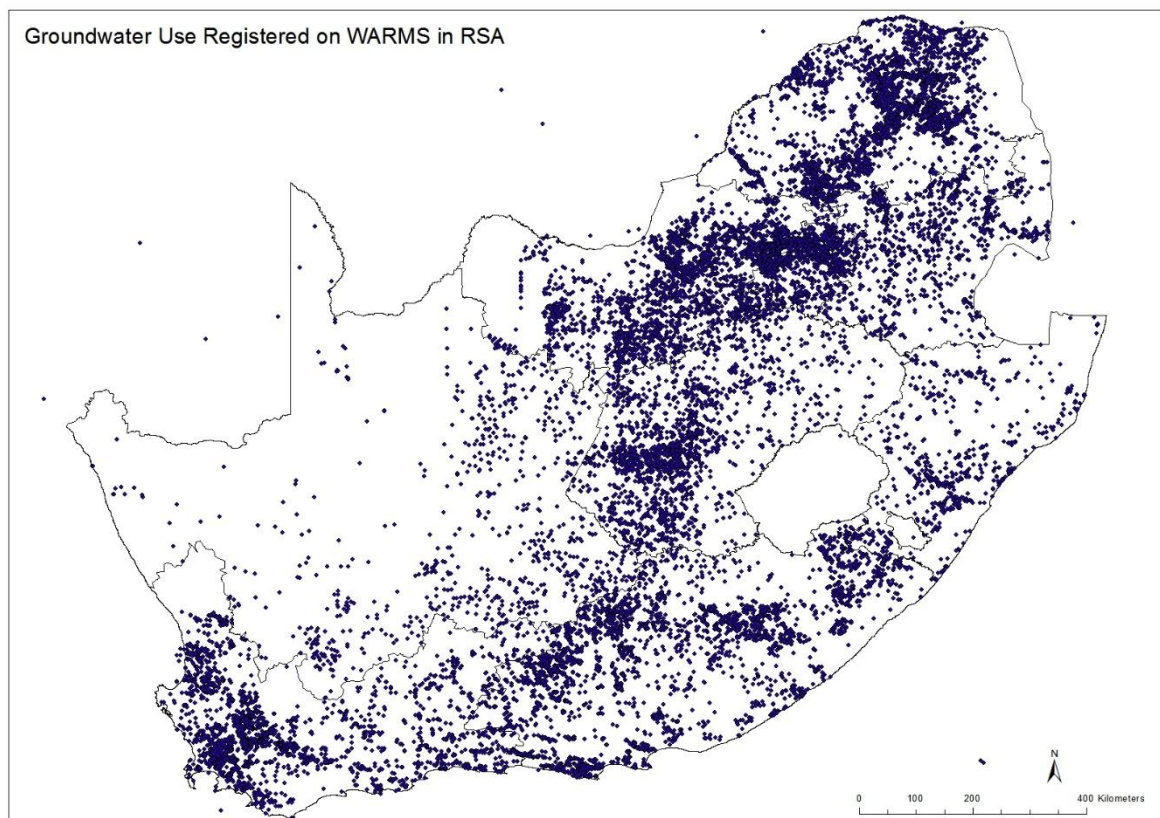


Figure 21: Indication of groundwater use based on water use registrations on the WARMS database.

Figure 22 and Figure 23 compare groundwater availability with registered groundwater use. In Figure 22, the comparison is based on the Water Management Area (or river catchment). Groundwater in the Berg-Olifants WMA is over-allocated relative to current groundwater availability, while the Pongola-Mtamvuna WMA has almost no groundwater abstraction.

Figure 23 provides the same analysis for each province, with Gauteng over-allocated and KwaZulu-Natal with almost no groundwater abstraction. This correlates with the trend seen in Figure 21.

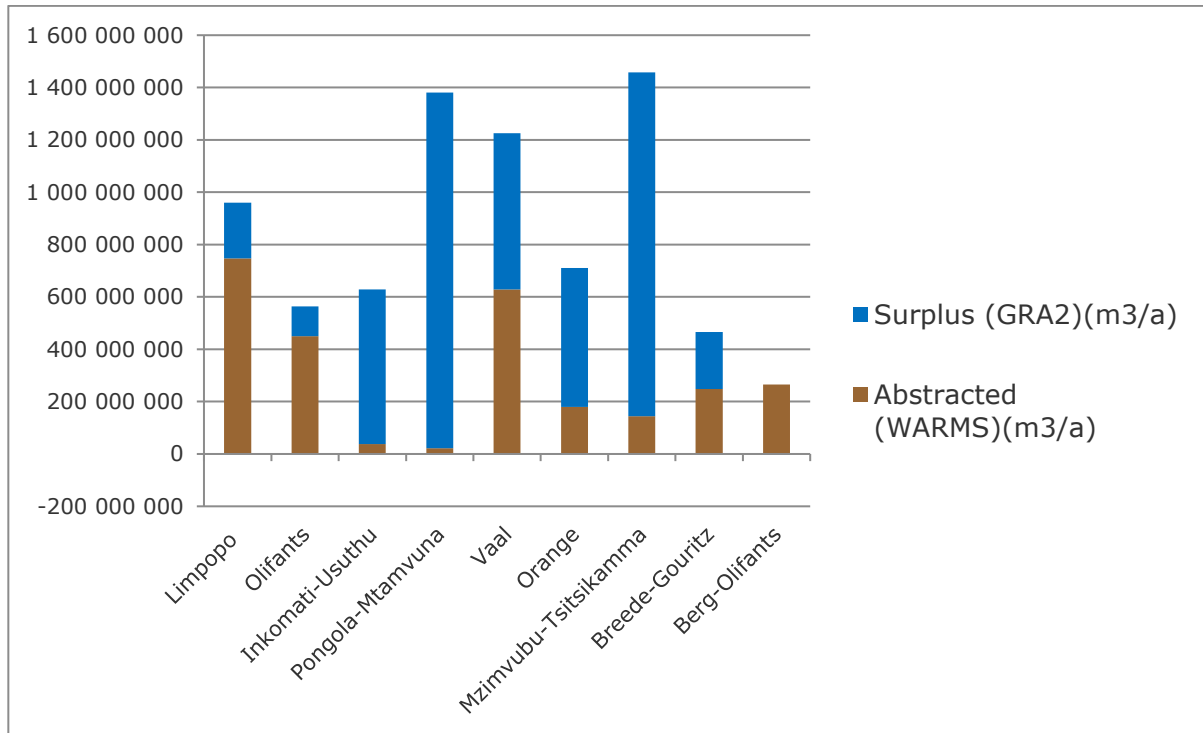


Figure 22: Groundwater availability compared to water use registered on WARMS according to Water Management Areas.

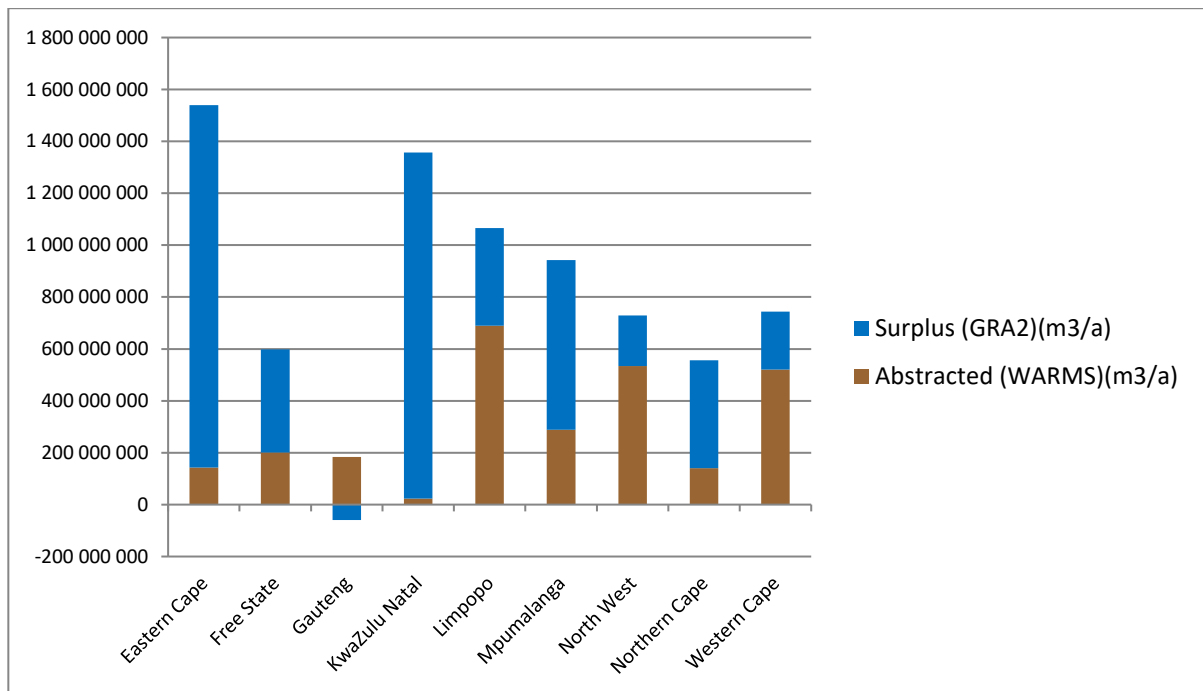


Figure 23: Groundwater availability compared to water use registered on WARMS according to provincial boundaries.

3. CONCEPT AND STRUCTURE OF GROUNDWATER MAPPING AND ASSESSMENT

3.1 Groundwater mapping and assessment

Groundwater mapping and assessment are done at different levels in South Africa (See Figure 24 for a brief summary), depending on the purpose of the study, e.g. site-specific explorations required to establish wells/wellfields or national assessments required to attain an overall overview of the groundwater resource, its availability and quality. Additional factors controlling the studies include their size and complexity.

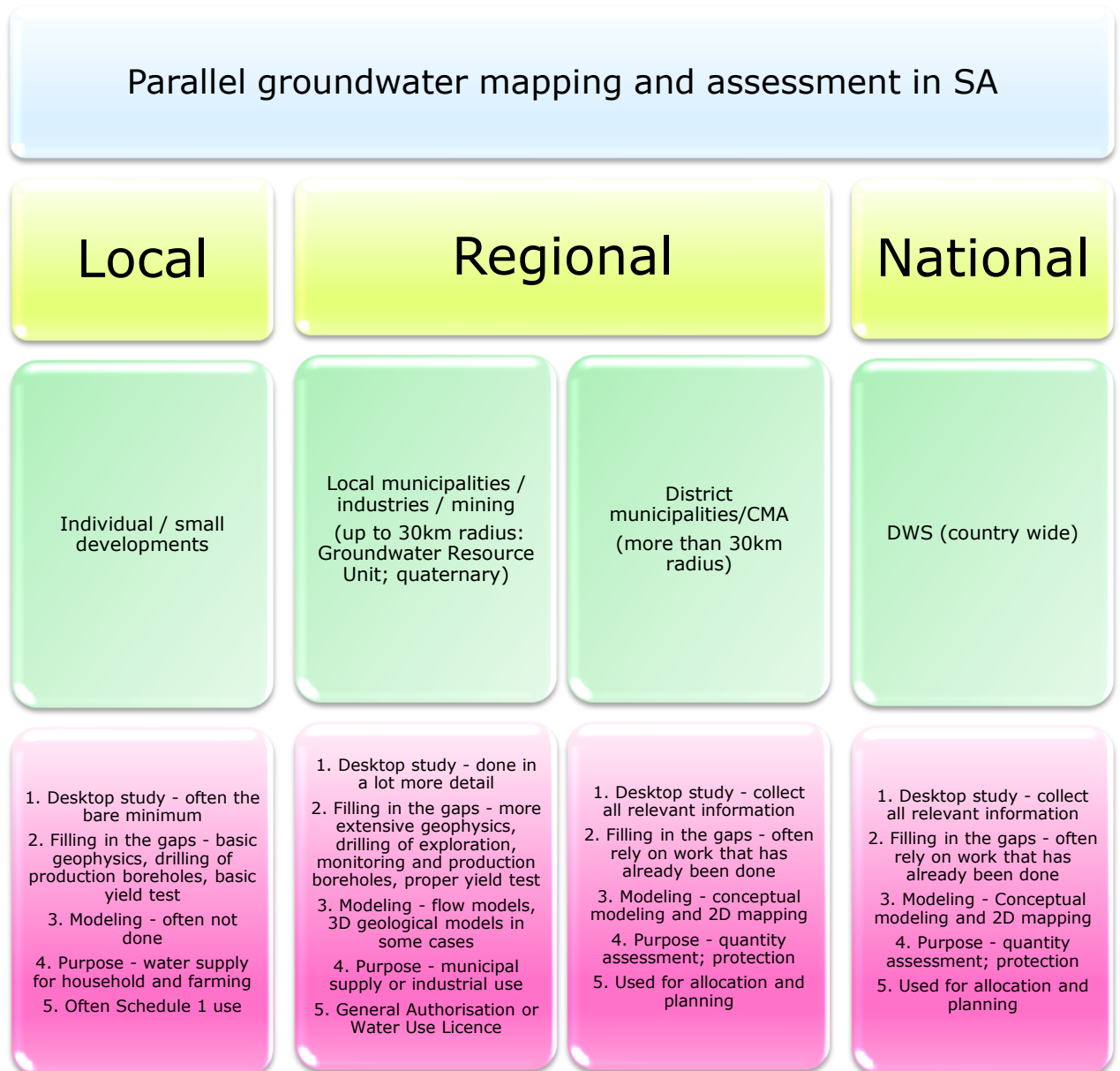


Figure 24: Parallel processes for groundwater mapping and assessment in South Africa at different levels.

3.1.1 Site-specific assessments

Site-specific groundwater assessment is done on different scales, depending on the client and the level/volume of groundwater use. Basic water supply will entail the least assessment, with the least amount of data collected, and no monitoring or management afterwards. An industrial client or municipality will lead to a more detailed assessment with greater data collection, monitoring and management afterwards. The level of the investigation is usually dependent on the requirements for a license versus a GA and the client's willingness to spend additional money.

Data collection for many small-scale assessments is often limited. Clients may call in a consultant (hydrogeologist) to assist with exploration, geophysics, etc., but this is mostly reserved for larger clients who can afford to hire one. When data are collected, it is not made available for a groundwater mapping phase. This means that a large amount of potentially valuable information is lost with smaller clients.

The flow diagram in Figure 25 gives an indication of the basic approach followed for a groundwater assessment in the development of a bulk supply to a municipality. Smaller scale groundwater developments do not follow these steps, and data that could inform national scale groundwater assessment and mapping are not always collected.

Early groundwater exploration work (1960s to 1990s) went through the whole process of desktop survey – geological maps, etc., hydrocensus work (collecting groundwater related data), geophysics, exploration drilling, pumping tests, developing maps – sometimes very basic, but in some cases very detailed, and in some cases a numerical groundwater model.

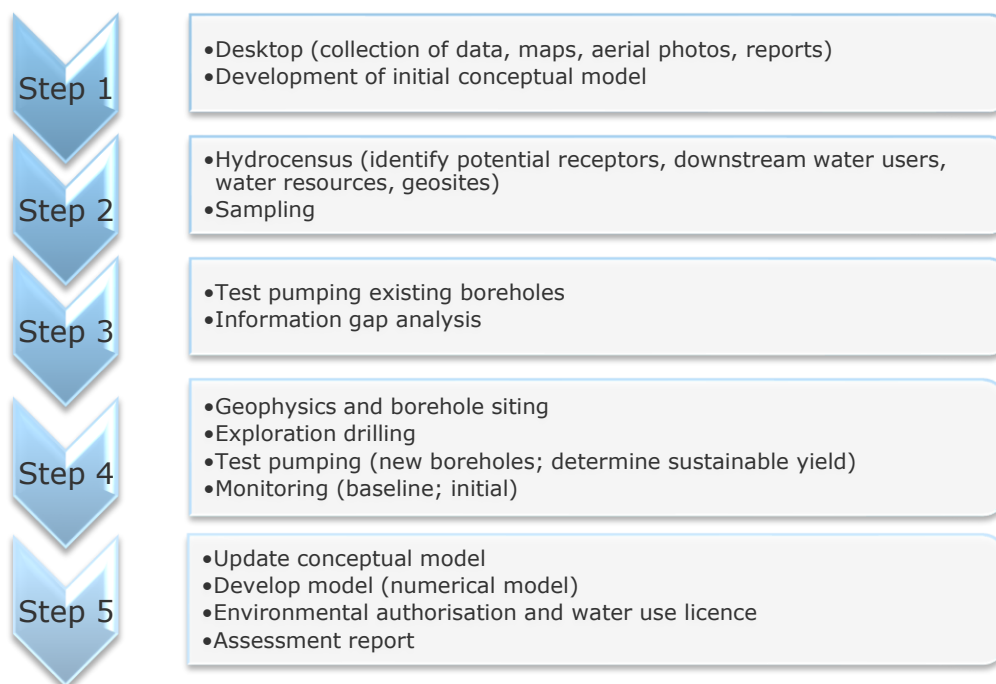


Figure 25: Flow diagram providing the steps for a groundwater assessment.

Below are the steps followed in two case studies, illustrating that the steps may vary from one case to the next.

Case study: Groundwater Potential at Free State towns:

- Collection of existing geohydrological data;
- Perform a hydrocensus, which is typically for groundwater potential and development schemes done within a 30 kilometres radius per project within the Free State;
- Interpret aerial photographs;
- Interpret aerial magnetics;
- Perform a geophysical field survey;
- Compilation of GIS maps;
- Determination of high groundwater abstraction areas;
- Recharge volume estimation; and
- Compilation of a Geohydrological Potential Report.

Case study: Vaal Gamagara Groundwater Potential and Development Scheme within the Northern Cape province:

- Detailed desktop study: Collection and updating of existing geohydrological data;
- Landowner Engagement process;
- Perform a hydrocensus: Identification and verification of water use and sampling;
- Perform high resolution airborne geophysical surveys: electromagnetic and time-domain electromagnetic surveys;
- Detail remote sensing and assessment of airborne geophysical data;
- Ground geophysical field survey: electromagnetic and gravity
- Test pumping existing boreholes;
- Drilling of exploration/test boreholes;
- Groundwater sampling on newly drilled boreholes;
- Aquifer test pumping of exploration boreholes:
- Short term test: Sustainable discharge test and 24h Constant discharge test – borehole yield capacity + aquifer sustainability
- Long term test: 72h – aquifer sustainability + aquifer hydraulic parameters for modelling
- Conceptualising of a hydrogeological model;
- Numerical 3D modelling: simulate aquifers + predict long term pumping performance + test feasibility of implementing development;
- Management recommendations: production design + buffer effect; and
- Compilation of investigation report.

3.1.2 National assessments/compilations

The assessment of groundwater at the national scale is seen as the responsibility of the national Department of Water and Sanitation. Various efforts have been made to map groundwater and its characteristics in South Africa. This has relied heavily on the early work done by the Geological Survey (40's to 70's) and later by the Geohydrology Directorate of the Department of Water Affairs (Vegter maps (1995) and GRAI (1995-2003). Work done later (GRAII) by consultants was incorporated into later mapping and quantification, but most of the data used to develop the Hydrogeological map series came from the NGDB (now NGA).

Groundwater Quality Map (Bond, 1949)

The first map was compiled in 1949 (See Figure 26) and provides an indication of the groundwater quality of South Africa.

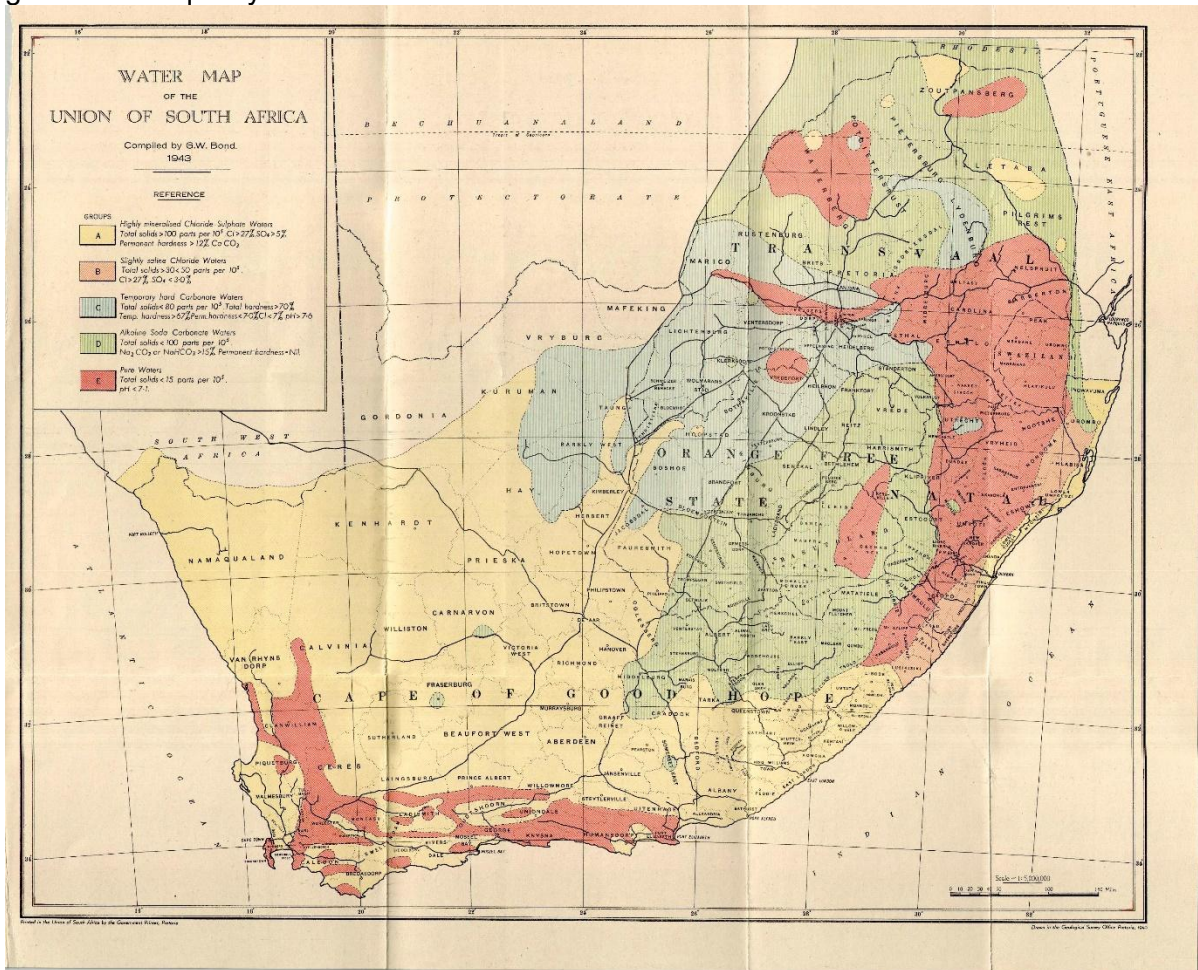


Figure 26: The first groundwater quality map was produced for South Africa (Bond, 1949).



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Vegter, 1995

Early national scale maps were produced as a set of two maps, containing information such as recharge (Figure 27), borehole yields, water strikes, possibility of drilling a successful borehole and other hydrogeological characteristics. It was one of the first attempts to quantify groundwater availability for South Africa. The maps are explained in two reports published by the WRC (Vegter, 1995).

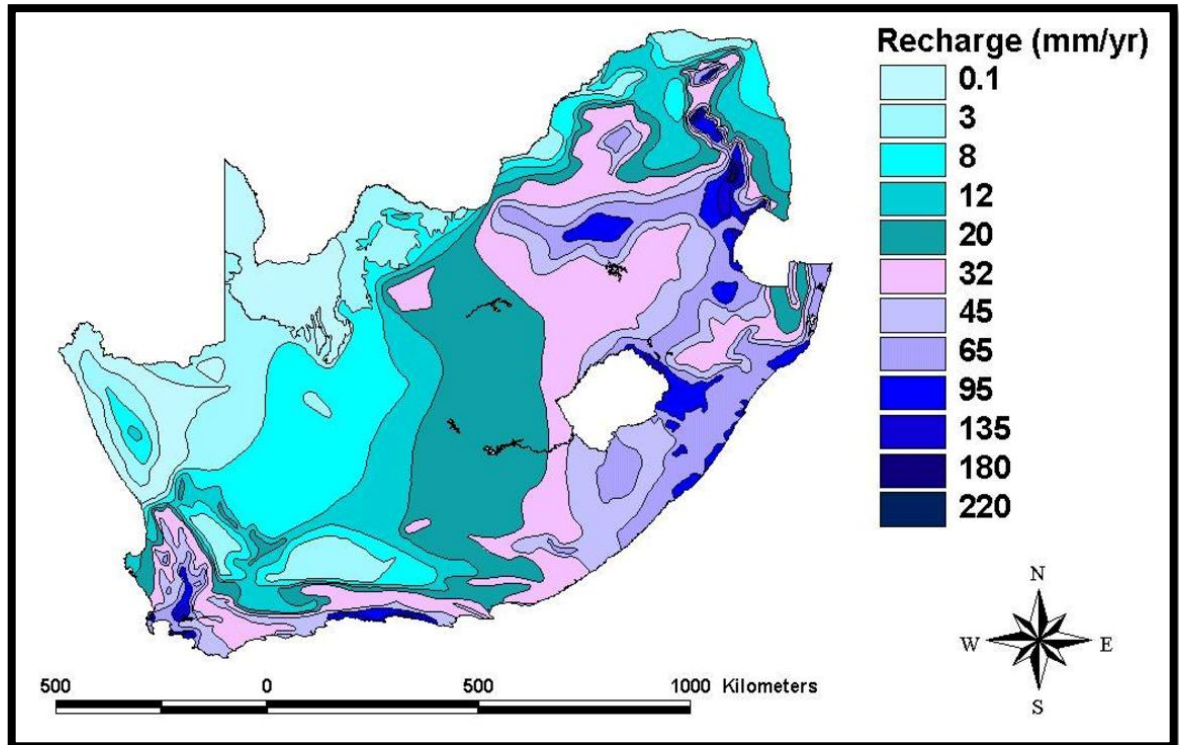


Figure 27: Groundwater recharge map (Vegter, 1995).

Harvest potential map (Baron et al., 1996)

The Harvest Potential maps were the second attempt at quantifying the available groundwater resource. It built on the work of Vegter (1995) and used recharge, storage, and the time between recharge events to estimate a national sustainable groundwater resource value. A number of maps were produced as part of the project.

GRA I (Hydrogeological Map Series and Brochures)

The Department of Water and Sanitation provided, during 1995-2003, a classification of aquifers into four classes during the development of the 1:500,000 Hydrogeological Maps (GRA I). These maps covering the whole of South Africa were published as a set of 21 hydrogeological maps. Explanatory brochures for most of the maps were developed.

The aquifers are classified as follows:

- Intergranular (Class A) are aquifers associated either with loose and unconsolidated formations such as sands and gravels (primary aquifer), or with rock that has weathered to the extent where its primary structure is that of loose or only partly consolidated material (secondary aquifer). Under these circumstances, water is stored in and transmitted through the intergranular voids that render the material porous and permeable.
- Fractured (Class B) describes an aquifer associated with generally hard and compact rock formations in which fractures or joints occur that are capable of both storing and transmitting water in useful quantities.

- Karst (Class C) Karst describes aquifers associated with carbonate rocks (dolomite or limestone) in which groundwater is predominantly stored in and transmitted through cavities and/or fractures.
- Intergranular and Fractured (Class D) are aquifers in which the intergranular interstices serve primarily as a storage, and water is transmitted mainly through the fracture-type interstices. This is a common feature for many South African aquifers.

More than 90 % of South Africa's aquifers are classified as secondary aquifer systems (intergranular & fractured). Thus, groundwater occurrence is mainly controlled by secondary fracture systems. Therefore, understanding the geology and geological processes (faulting, folding, intrusive dyke/sills, weathering) responsible for the development of these fracture systems and how they relate to the geohydrology becomes an important tool in locating groundwater resources.

The development of GRAI coincided with that of the National Groundwater Database (NGDB), which served as the predecessor to the National Groundwater Archive (NGA). This formed the basis of the 21 hydrogeological maps. Figure 27 is a typical example of the maps produced for South Africa.

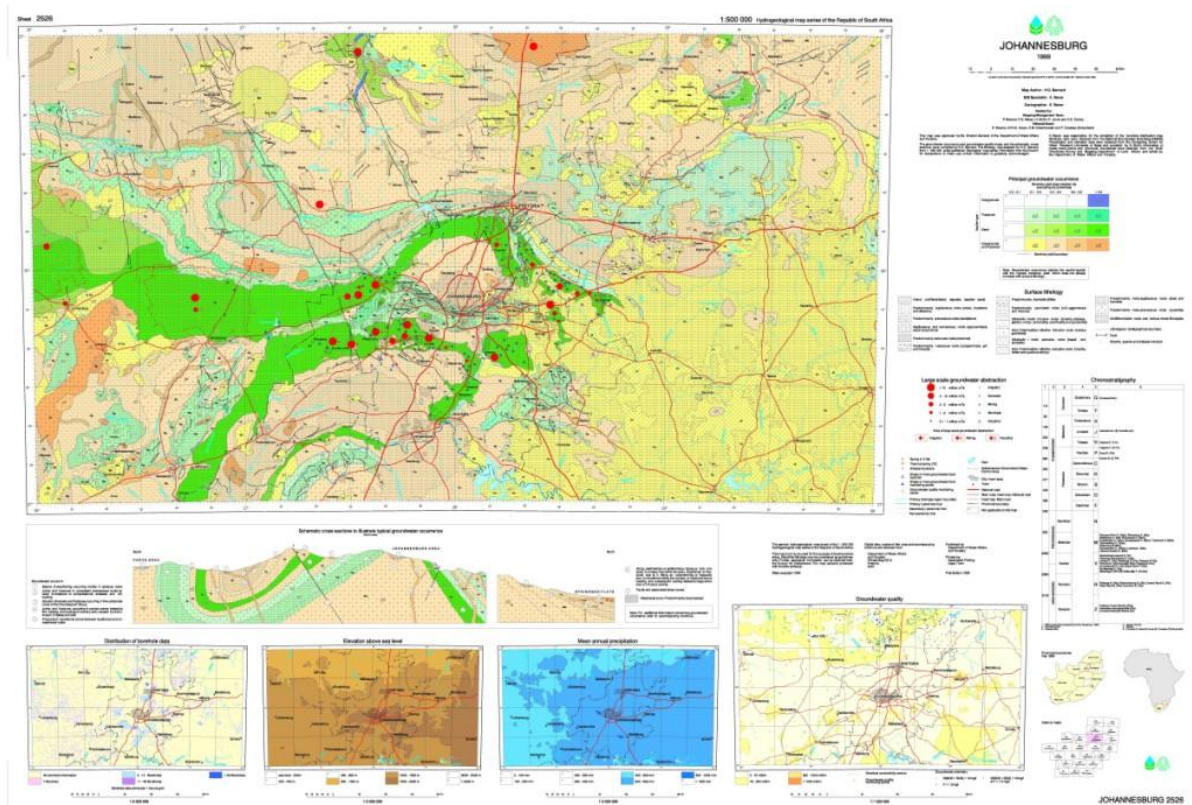


Figure 28: A typical example of the hydrogeological maps produced as part of GRA 1.

Figure 29 provides a compilation of the 1:500 000 scale hydrogeological map series. The primary purpose of groundwater mapping to date has been to provide an overview of aquifer characteristics.

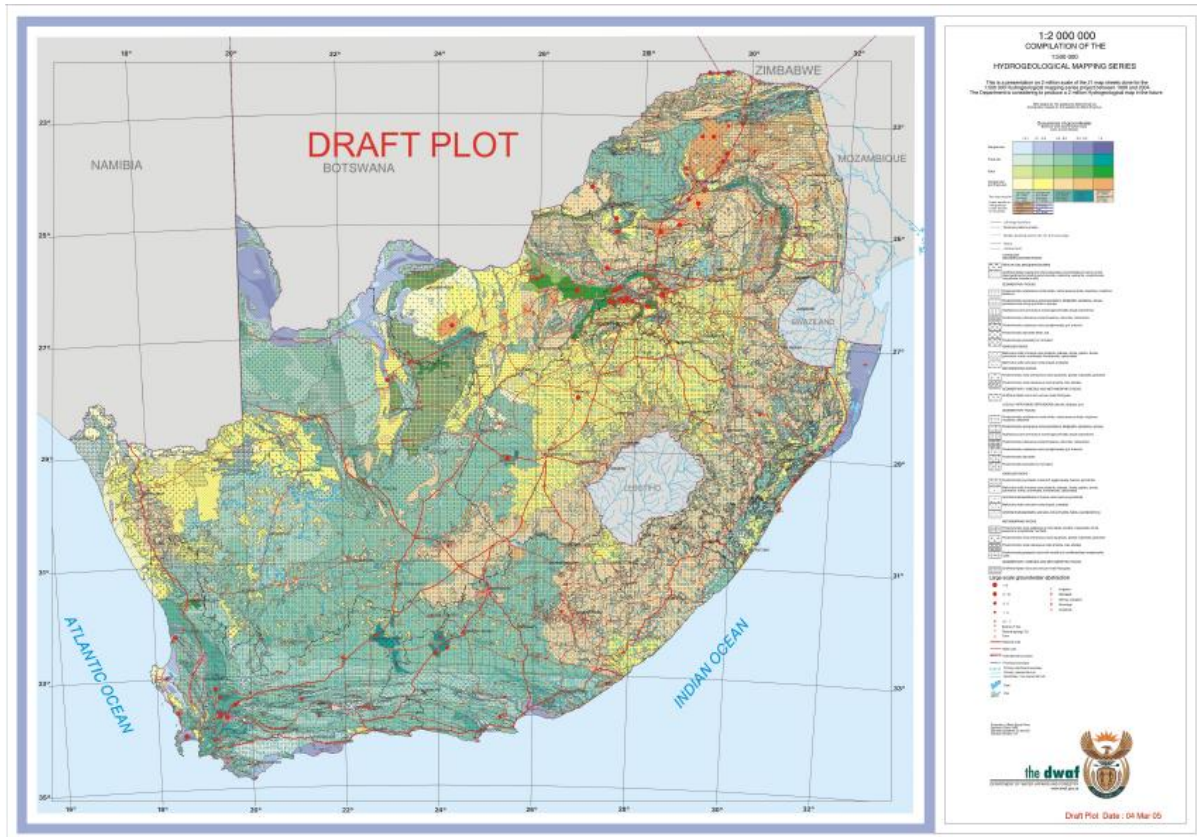


Figure 29: A 1:2 000 000 scale compilation of the 1:500 000 scale hydrogeological map series of South Africa, from GRA 1.

The following maps are an amalgamation of the 21 hydrogeological maps, portraying one parameter, with Figure 30 showing the expected borehole yield, Figure 31 the aquifer type and Figure 32 the electrical conductivity.

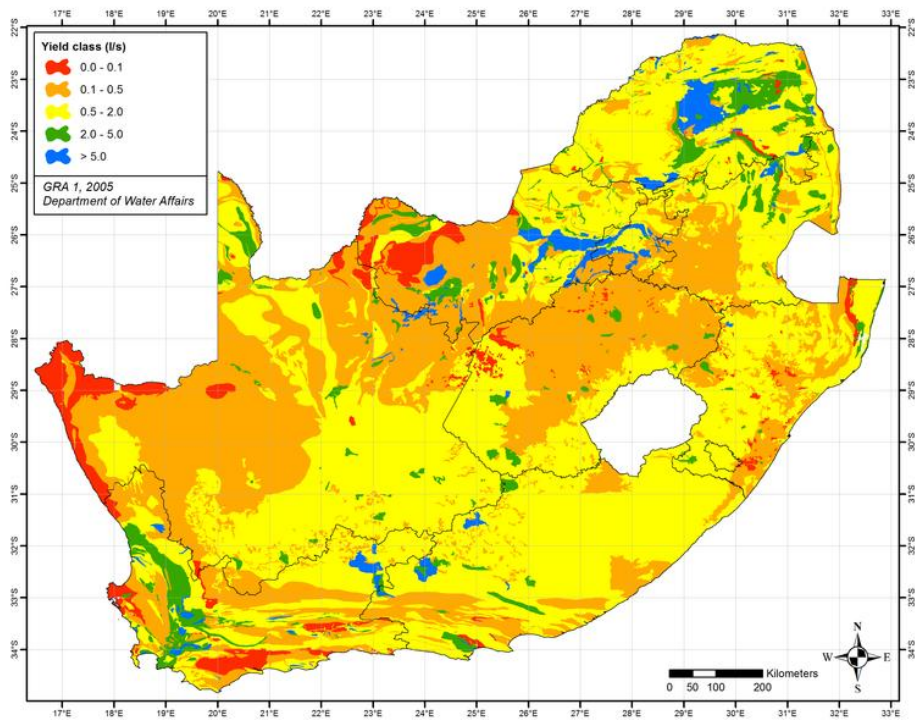


Figure 30: An amalgamation of the 1:500 000 hydrogeological map series, giving a country-wide extent of the expected borehole yield, from GRA 1.

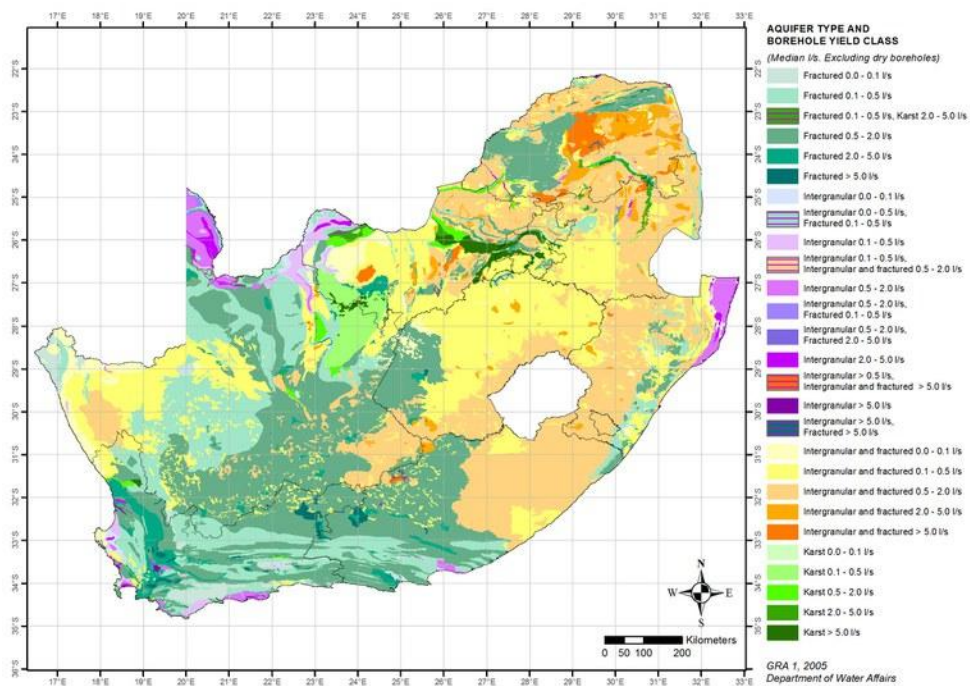


Figure 31: An amalgamation of 1:500 000 Hydrogeological Map series, giving a country-wide extent of aquifer type (groundwater classification) and expected borehole yield, from GRA 1.

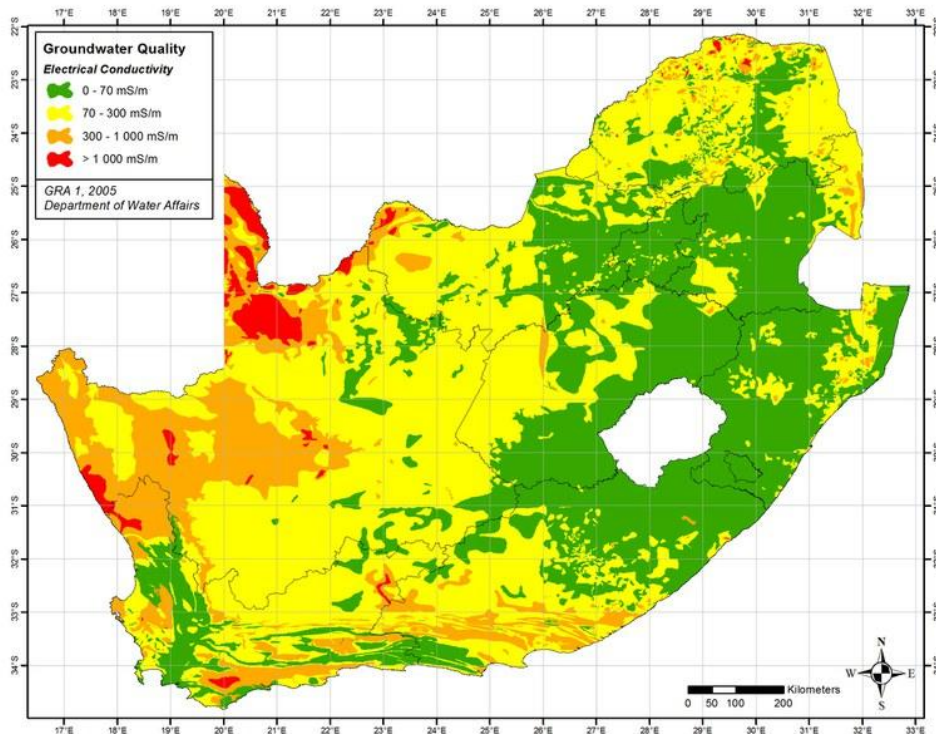


Figure 32: Amalgamation of Hydrogeological Map series, giving an interpolated country-wide extent of the Electrical Conductivity of groundwater, from GRA 1.

GRA II

In late 2003, the Department of Water and Sanitation initiated the Groundwater Phase 2 Project (GRA II), aimed at quantifying South Africa's groundwater resources on a national scale, and completed in June 2005. The project developed algorithms for estimating storage, recharge, baseflow, and the impact of the reserve and the present groundwater used. The main purpose of the was to aid in allocating groundwater use.

The primary aim of GRA II was not the production of maps, but the quantification of groundwater resources. It was built on the work of Vegter, Baron and GRA I, with improvements to the methodology. It determines a Utilisable Groundwater Exploitation Potential that is conservative and can help allocate groundwater through the various water use authorisations, while ensuring a Reserve to supply basic human needs (25 litres per person per day) and environmental needs. Maps were plotted with the data, as can be seen in Figure 33. It is still used extensively and serves as the basis for some software programs, such as the Firm Yield Model.

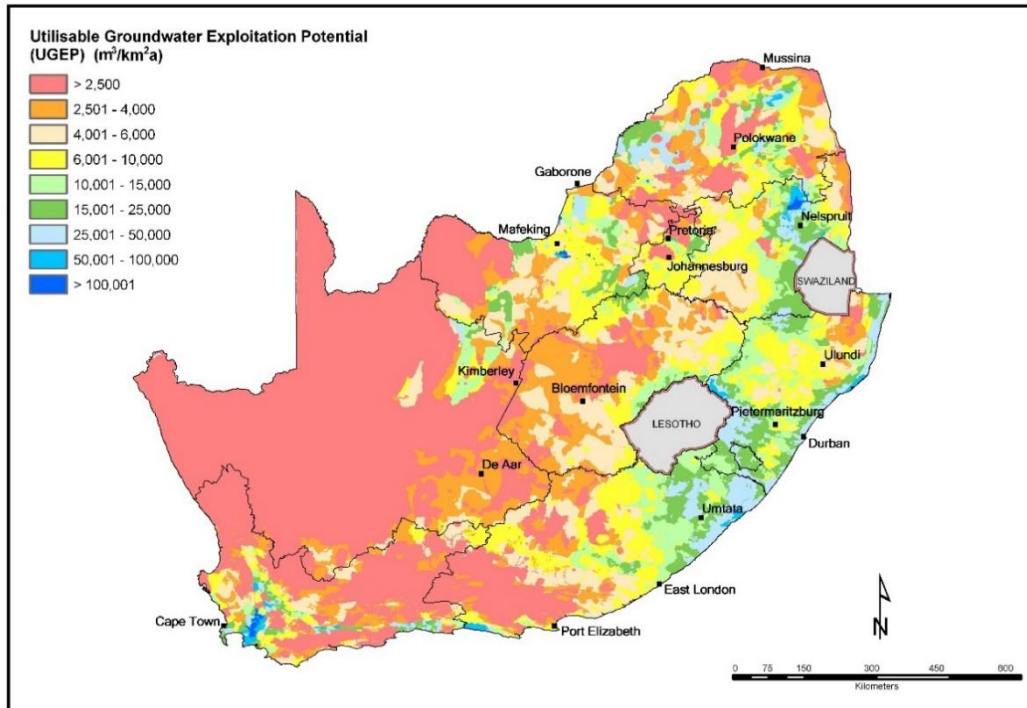


Figure 33: Map showing the Utilisable Groundwater Exploitation Potential for South Africa.

GRIP

The Groundwater Resource Information Project (GRIP) was developed to assist in the collection of groundwater data and to improve the assessment and management of groundwater resources in rural South Africa. It was initiated in Limpopo Province in 2002/2003 by a continuous process of capturing and conducting field verification and investigations of the groundwater data, to confirm information where available and to obtain essential information in areas where it is not available.

GRA III

The proposed methodology continues to build on the previous work, with improved quantification of the groundwater contribution to baseflow (Allwright, 2013), and other improvements. GRA III is still in development and is therefore not complete.

Groundwater Protection

A number of maps were plotted with groundwater protection in mind. This includes the Aquifer vulnerability map (Figure 34), and the Aquifer susceptibility map (Figure 35). The Strategic Water Source Areas project by the WRC was conducted to map recharge areas, important aquifers, and aquifers that are the sole water supply to communities.

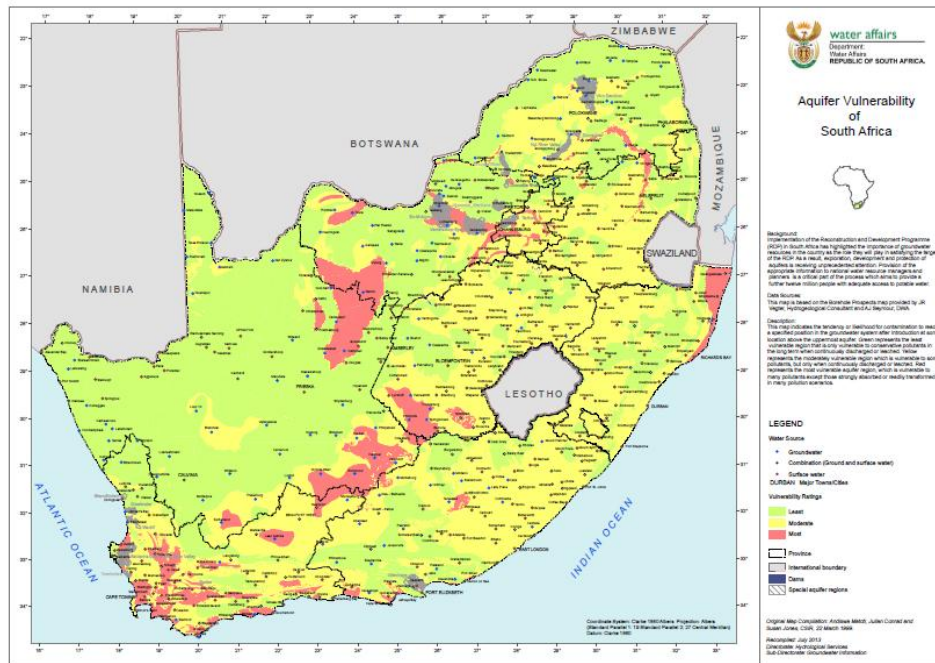


Figure 34: Aquifer vulnerability map of South Africa.

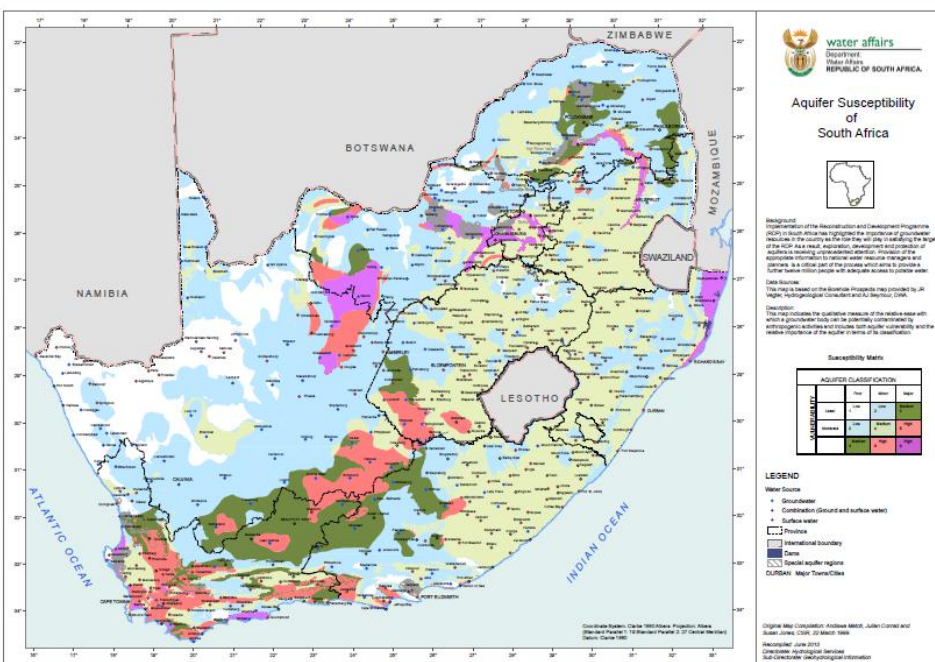


Figure 35: Aquifer Susceptibility map for South Africa.

The Strategic Water Source Areas project was completed in 2018 (See Figure 36). This project included both surface water and groundwater. It identified where water sources should receive better protection.

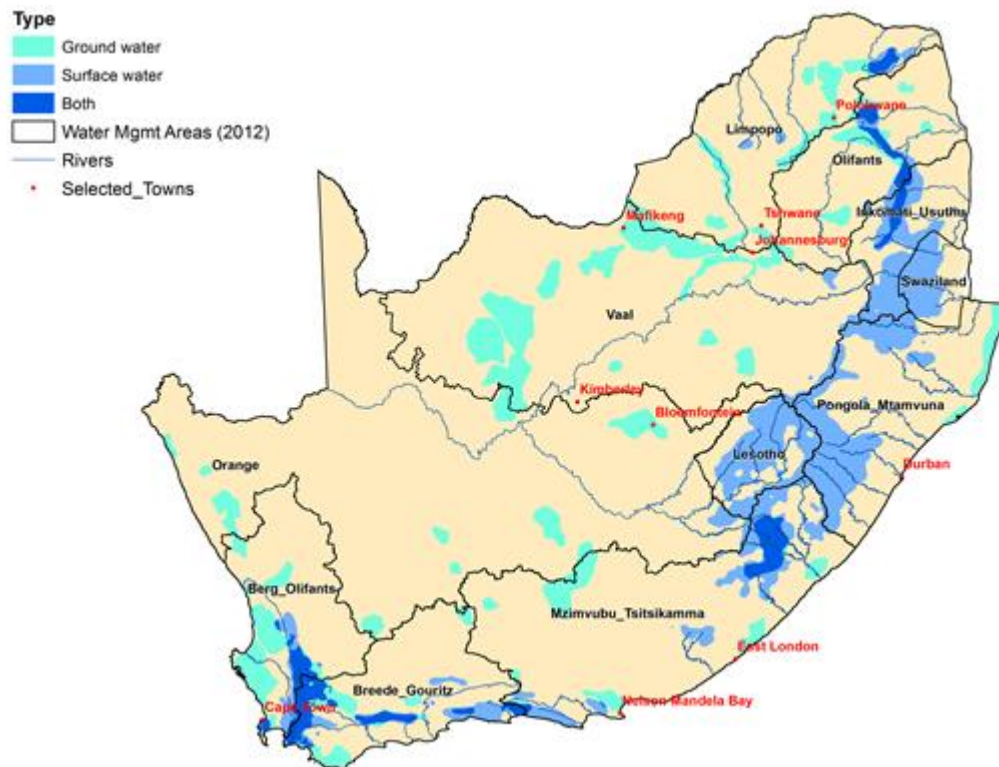


Figure 36: Strategic water source areas in South Africa (Le Maitre, et al, 2018).

3.2 Pollution sources

Pollution incidents are handled by the National Department of Environmental Forestry and Fisheries (DEFF) and its provincial counterparts, i.e. the Department of Environmental Affairs and Development Planning (DEA & DP) in the Western Cape. DWS only provides guidance and comments on the management of pollution sites. Groundwater pollution due to long-term releases of pollutants is often handled by DWS, in conjunction with the department's responsibility for environmental matters.

Groundwater protection against potential pollution is carried out jointly by DWS and DEFF, i.e., through the EIA process for potentially harmful developments and water-use licenses for the storage or release of hazardous material.

3.3 Data flow

Data can be uploaded to the national databases run by DWS, but this is not mandatory. Access to data from various projects is, therefore, often difficult, thereby limiting data flow between institutions and activities related to the use and protection of groundwater. The ideal is that the data flow should be from municipalities to CMA or DWS, from the user to DWS, from consultants to municipalities and clients, and ultimately to DWS.

3.4 Funding

The supply of water to all people at an acceptable level of assurance, quality, and accessibility costs money – both in capital investment in infrastructure and in the operation and maintenance costs associated with water treatment, bulk water distribution, and reticulation

within human settlements. The criteria for setting the tariffs and the procedures are described in various legislation and regulations, notably the two water acts: i) the Pricing Strategy for Raw Water Use Charges (National Water Act) and ii) the Water Services Tariff Regulations (Water Services Act).

Water tariffs under the NWA are collected at two levels. The first is the Raw water tariff, which covers the bulk supply of raw water from DWS to water users, such as municipalities, water boards, and agriculture. The legal mandate for this is in Section 56 of the NWA. It is divided into three categories (DWS, 23 August 2019):

1. Raw water Use Charges, which include charges for water resources management such as the protection, allocation, conservation, management and control of water resources and the management of water quality within a WMA;
2. Water Resource Development and Use of Water Works Charges, which covers the costs of planning, design, construction, operation, maintenance, refurbishment, and improvement of Government schemes, including operation and maintenance;
3. Water Research Levy is the tariff set in respect of water research charges, levied on quantities of water supplied, or made available for use for various purposes. The charges are paid into the national Water Research Fund and used by the Water Research Commission (WRC) to fund water-centred Research and Development.

The second level of tariffs under the WSA is paid to the municipality, water service provider or Water board for water provided to water users within the municipal boundaries.

The various charges in the pricing chain accumulate to the end user/consumer tariff. It is thus important to examine the pricing chain in its entirety and to consider all sub-cost elements when evaluating the consumer tariff.

- DWS sets its raw water price in terms of the NWA and National Pricing Strategy for Raw Water Use Charges
- Water Boards set bulk water prices in terms of the Water Services Act, and prices are (in effect) approved by the national government.
- Municipal tariffs in terms of a local tariff policy which must comply with nationally defined norms and standards.

Part of the tariffs collected for water in South Africa is earmarked for water research. However, research funding covers all waters, and as surface water is the main resource, the largest share of funding has also been directed towards surface water topics. Lesser money is thus earmarked for groundwater research or for the general assessment and development of groundwater through national projects.

DWS administers two (2) conditional grants, viz., the Regional Bulk Infrastructure Grant (RBIG) and the Water Services Infrastructure Grant (WSIG). These grants support the predominantly indigent areas. The goal of the Regional Bulk Infrastructure Grant (RBIG) is to facilitate the achievement of targets for access to bulk water and sanitation by successfully executing and implementing regional-scale bulk projects. The purpose is:

- to develop new, refurbish, upgrade, and replace ageing bulk water and sanitation infrastructure of regional significance that connects water resources to infrastructure serving extensive areas across municipal boundaries or large regional bulk infrastructure serving numerous communities over a large area within a municipality.
- to implement bulk infrastructure with a potential of addressing water conservation and water demand management (WC/WDM) projects or facilitate and contribute to the implementation of local WC/WDM projects that will directly impact bulk infrastructure requirements.

The Regional Bulk Infrastructure Grant (RBIG) is intended to fund the social component of regional bulk water and sanitation projects approved by DWS, unless DWS recommends and

National Treasury approves affordability exemptions. All identified projects must be referenced to and included in the municipal Integrated Development Plan (IDP) and Water Services Development Plans (WSDP) and show linkages to projects under the Municipal Infrastructure Grant (MIG) and/or the Water Services Infrastructure Grant (WSIG). Funds may be used only for drought relief interventions approved in a business plan submitted to DWS. The goal of the Water Services Infrastructure Grant (WSIG) is to provide water and sanitation services and reduce backlogs. The purpose is:

- Facilitate the planning and implementation of various water and sanitation projects to accelerate backlog reduction and enhance the sustainability of services, especially in rural municipalities.
- Provide basic and intermittent water and sanitation supply that ensures provision of services to identified and prioritised communities, including spring protection and groundwater development.
- Support municipalities in implementing water conservation and water demand management (WC/WDM) projects.
- Support the close-out of the existing Bucket Eradication Programme intervention in formal residential areas.
- Support drought relief projects in affected municipalities.

All project scopes funded must be aligned to, and not duplicate, any existing or planned projects funded by other conditional grants or municipalities' own funds. Municipalities must demonstrate in their business plans how they plan to manage, operate, and maintain the infrastructure over the long term. The maximum allocation for WSIG projects is R50 million; any project above this threshold is to be funded in the Regional Bulk Infrastructure Grant. Projects should ideally be implemented over 1 year, and the maximum implementation period is 3 years.

3.5 Groundwater protection instruments

It is important to develop clear goals for the quality of relevant water resources, so that criteria are available to manage them. The NWA requires a balance between the need to protect and sustain water resources on the one hand, and the need to develop and use them on the other. The Reserve, Water Resource Classes and Resource Quality Objectives are tools provided for in Chapter 3 of the National Water Act (Act 36 of 1998) to help protect water resources, including groundwater. The Reserve consists of 2 parts: the basic human needs reserve and the ecological reserve. It refers to both the quantity and quality of the water in the resource, which will vary depending on the resource's class. The water resource classes are divided into three classes; i) a water resource which is minimally used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is minimally altered from its pre-development condition; ii) a water resource which is moderately used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is moderately altered from its predevelopment condition; and iii) a water resource which is heavily used and in which the configuration of the ecological categories of the water resources within a catchment result in an overall condition of that water resource that is significantly altered from its pre-development condition. The class of a water resource must describe the extent of use of the water resource, the Reserve, the resource quality objectives and the determination of the allocable portion of the water resource for use.

The resource quality objectives of the resource in question may relate to the Reserve, the instream flow, the water level, the presence and concentration of particular substances in water, the characteristics and quality of the water resources and the instream and riparian habitat, the characteristics and distribution of aquatic biota, the regulation or prohibition of instream or land-based activities which may affect the quantity of water in or quality of the water resource and any other characteristics. It must be noted that these instruments are

designed and implemented based on surface water behaviour, scale and boundaries, and have limited applicability to groundwater.

4. SUPPORTING INFRASTRUCTURE

The DWS has a number of databases, with the National Groundwater Archive (NGA) – successor to the National Groundwater Database (NGDB) containing most of the borehole related data. Data from reports were captured by the DWS on the NGDB. With the transition to NGA, a web-based system, external users can now capture and extract data themselves. Data collected from groundwater assessment projects is seldom captured, as it is neither mandatory to upload it to national databases nor is there legislation to enforce it. This means that the data are not readily available for subsequent groundwater mapping and assessment exercises. Currently, the DWS is sourcing data and reports from relevant stakeholders.

Data, for the most part, is collected by consultants during client projects. These data are stored by consultants and shared with DWS only upon request, with the client's permission. To access data from consultants may be difficult, and some are unwilling to share their data, or sometimes not with their clients. Models tend to remain the property of the consultants or, in some cases, their clients.

Data storage on the national level is done in a number of databases – NGA for borehole data; Hydstra for water levels; Water Authorisation and Registration Management System (WARMS) for water use and revenue collection; and Water Management System (WMS) for water quality data. The same municipalities have their own databases to capture their own data. Data storage can also be done by the consultants.

NGA data is available to the public through a web-based program if they have registered to use the system. The other databases are not open to the public, but a request can be sent to DWS to get the data.

The geophysical data are not yet captured in a national database. DWS is developing the functionality on NGA. Most data reside with the consultants or are hard copy reports. It is thus not readily available for use. Non-disclosure agreements between clients and consultants are signed, meaning that no data or information regarding the specific project may be provided to any third parties without consent. Thus, often a legal process has to be followed to access the data.

There is no set structure or mandate for groundwater mapping and assessment in South Africa. A number of guidelines have been developed and reports written on the best way to conduct groundwater assessments for wellfield developments, but it is not mandatory to follow them. Furthermore, the various guidelines are not centrally stored, which can make it difficult to identify the latest version, and some are paid for.

Research infrastructure includes the various universities and the Water Research Commission which support and fund groundwater related research.

Appendix C



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Comparison of approaches

1. INTRODUCTION

To fully understand and compare groundwater mapping and assessment programs in Denmark and South Africa, a number of key factors have been identified. These key factors are the internal and external forces that drive and shape the mapping and assessment activities, as well as the program's characteristics.

The key factors for this project are divided into four different groups: drivers, institutional factors, supporting infrastructure and key characteristics. The drivers are the circumstances that necessitate groundwater mapping and assessments, grounded in both technical and societal issues. The institutional factors include policies that provide the legal and institutional framework necessary to implement the mapping and assessment. The key factors supporting infrastructure include the developed methods, tools, and resources that enable mapping and assessments to meet political ambitions. The key characteristics are activities and results/outputs from the groundwater mapping and assessment.

The relationship between the key factors is shown in the diagram presented in Figure 37. Understanding this relationship is important when analysing and comparing groundwater mapping and assessment activities in Denmark and South Africa.

The drivers are seen as the factors that create the need for groundwater mapping and assessment; in essence, they are the situation the country is in. This includes, for example, the degree to which a country or region depends on groundwater, the natural and human threats to the quality and quantity of the resource, and the different users of the resource, including municipal, industrial, agricultural, and nature-based uses. The interaction between these creates a need to manage groundwater resources. This need, then, drives the creation of policies towards the management and protection of groundwater resources, as illustrated in Figure 37.

The policies adopted create the institutional framework within which groundwater mapping and assessment take place. Policies generally start with the creation of a strategy for how the needs for groundwater management and protection should be addressed; in essence, what should be done. Under the agreed strategy, legislation is passed to put the strategy into law and, in turn, provides funding for the activities. This, in turn, determines how the activities should be organised and who is responsible for carrying out the mapping and the standards that need to be achieved. These aspects can change over time, particularly as the situation driving the groundwater mapping and assessment changes.

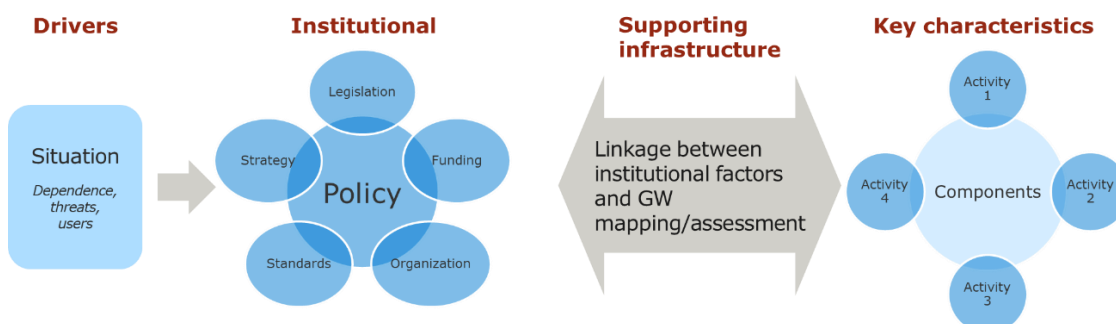


Figure 37 Diagram showing the relationship between the different key factors in the groundwater mapping and assessment activities.

The supporting infrastructure links the policy to the actual mapping and assessment activities. This includes, e.g. the databases, tools and guidelines that are available. These provide guidance on what should be included in the groundwater mapping and assessment activities, as well as tools and software that can be used to support the assessments. The development of the infrastructure, tools and guidelines is determined through the policy decisions taken.

Finally, the key characteristics are the mapping and assessment activities undertaken within groundwater mapping and assessment programs. Included among the key characteristics are what is actually conducted and the types of results obtained from the mapping and assessment. Mapping and assessments can be carried out for various purposes, which will define the relevant activities. However, here we define mapping as: Activities related to the analysis and understanding of the groundwater system. The analyses are based on existing and newly collected data. Although mapping, to some degree, is targeted at a specific challenge related to groundwater quantity and/or quality, it includes generic steps that need to be carried out independent of the final assessments. On the other hand, activities related to the assessment are specifically targeted at the assessment's objective. We define assessment as utilising the mapping results to plan and protect groundwater resources. This includes assessments of the quantity available, where protective measures to secure groundwater quantity and quality need to be implemented, and possible activities such as monitoring and groundwater protection initiatives.

Assessing the links between the key factors, as shown in Figure 37 can help identify gaps or incongruities between the different key factor groups. For example, the policies outlined in the institutional key factors may not be implemented due to insufficient development of supporting infrastructure. Thus, by linking these different groups, weak points in the process can be identified.

2. KEY FACTORS - DENMARK

The following are the key factors that have influenced groundwater mapping and assessment programs in Denmark. The diagram in Figure 38 shows the relationship between the key factors in Denmark. This starts with the drivers: a nearly 100% dependence on groundwater for the water supply, combined with pollution threats. From these threats, a strategy has been developed that Denmark's water supply should be based on simple treatment. From this strategy, legislation has been implemented that outlines the objectives, funding, organisation, and standards. The legislation has also provided the groundwork for the development of supporting infrastructure, including staff dedicated to mapping and assessment activities, mandatory data collection and availability, specialised tools to assist with the activities, and supporting guidelines. This has provided groundwork for the three different groundwater mapping and assessment programs in Denmark, as described in section 2 and illustrated in Figure 38.

A more detailed description of the key factors associated with groundwater mapping and assessment in Denmark is provided in sections 4.1.1-4.1.4 below.

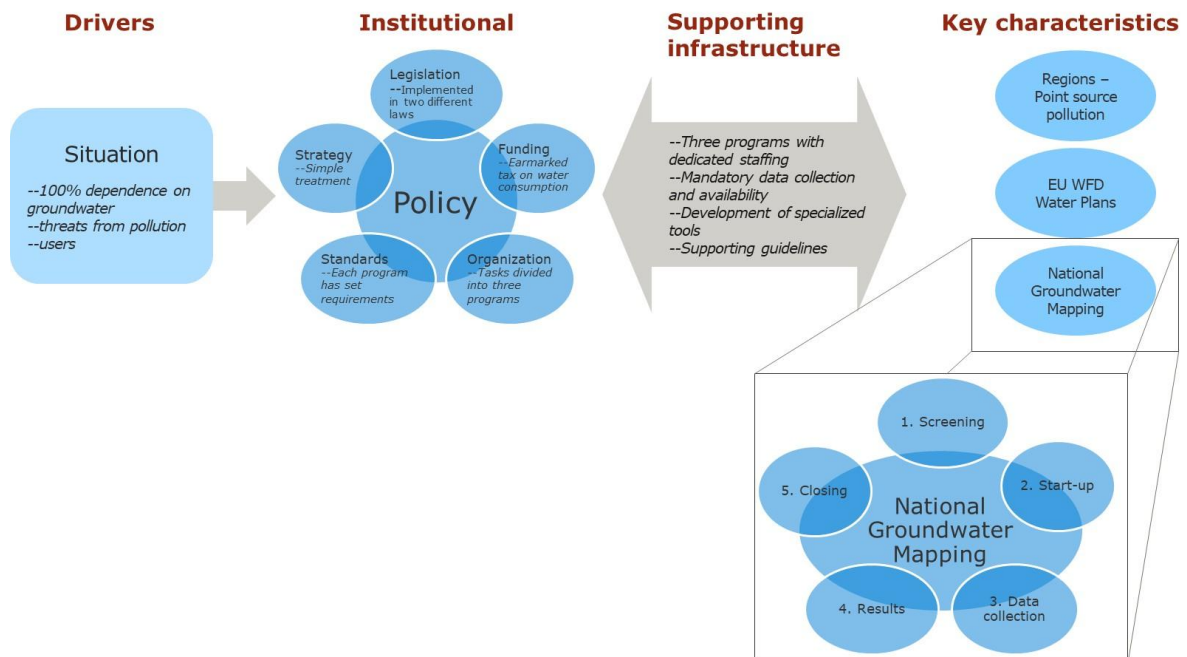


Figure 38 Diagram showing the relationship between the key factors in Denmark.

2.1 Drivers

The following are the key factors driving groundwater mapping and assessment in Denmark.

1. Reliance on groundwater:
Nearly 100% of drinking water in Denmark comes from groundwater, and the largest part of the water is used for industry and agriculture.
2. Threats to the groundwater quality:
The primary driver that started the Danish groundwater mapping and assessment was the observation of increasing pollution of the groundwater resources from particularly agriculture (nitrates and pesticides), but also from point sources including industrial sites and landfills, as well as abstraction induced saltwater intrusion and naturally occurring ions such as fluoride, nickel, strontium and arsenic.
3. Water balance:
Denmark has a relatively high groundwater recharge, where quantity is generally not an issue. There are, however, some local and regional aquifers where abstraction affects baseflow in streams and groundwater dependent ecosystems.
4. Users:
The primary users of groundwater resources in Denmark are private and municipal water supply companies providing drinking water to domestic consumers. These users require a water supply that meets a high water quality standard, one that exceeds EU water quality standards. In addition, industrial consumers require a specific water quality.
5. Ownership:
Groundwater resources are owned by the state and always have been. All users need permission to use the resources, and it is the state's obligation to protect the quantity and quality of the country's groundwater resources.

2.2 The institutional key factors

1. Simple treatment:
Denmark has maintained an overarching policy that drinking water provided to

consumers is based only on a simple water treatment consisting of oxidation and sand filtration. Although advanced water treatment techniques, such as activated carbon filtration and reverse osmosis, have been used in drinking water treatment, they are permitted only when no other alternatives are available. Thus, this policy has been a key driver in the groundwater mapping and assessment program.

2. Legislative framework:

To address these groundwater quality problems, legislation was enacted at the national level, imposing a levy per cubic meter withdrawn by waterworks. The legislation was vital, since it required that the areas to be protected be defined and provided the legal framework for restricting activities that could compromise groundwater quality. In addition, it provided the legal basis for both the studies on groundwater systems that need to be carried out and the subsequent development of the Groundwater Protection Plans. The legislation also established requirements for data gathering, storage, and sharing at all levels. In addition to national legislation, there are also requirements from the EU, particularly under the EU Water Framework Directive, which considers both quantitative and qualitative aspects for human and ecosystem health.

3. Funding:

Critical to the legislative framework was the inclusion of the groundwater levy. This levy on every cubic meter of groundwater pumped by the waterworks is essential to providing the resources needed to carry out groundwater mapping and to support the development of techniques, guidelines, tools, and a data storage platform (including operations and maintenance).

4. Organisation:

The Danish groundwater mapping and assessment is divided into three main program units. This includes groundwater mapping, which assesses the protection of groundwater quality from non-point source pollution; EU Framework Directive Water Plans, which primarily address groundwater quantity and take environmental needs (ecosystem needs) into consideration; and regional mapping, assessment, and remediation of point source pollution.

2.3 Supporting infrastructure key factors

1. Capacity building:

The critical part of this was to build institutional capacity to conduct groundwater mapping in Denmark. As directed by Danish legislation, the counties in Denmark were initially responsible for conducting groundwater mapping and implementing groundwater action plans. During this time, the counties built up the needed personnel and expertise to conduct the mapping and assessment. After the government's structural reform in 2007, this capacity was partly transferred to the state to conduct the mapping and partly to municipalities to develop and execute the action plans.

2. Data collection, storage and access:

All data collected through the groundwater mapping and assessment is assembled and stored in their respective databases. The state operates and maintains these databases, and all public and private institutes and stakeholders have free access to this data. This includes all data required to be delivered by law, including water level measurements, water quality, abstraction amounts, borehole reports, geophysical data, stream measurements, models, model results and reports. Data is well organised, easy to find and available for all users.

3. Development of specialised tools:

A part of the funding was provided to develop specialised tools to assist with the groundwater mapping and assessment process. This development has primarily been



carried out by universities, but consultants have also been funded in this regard. The geophysical methods developed helped fill data gaps, and the software developed assisted in the efficient processing of geophysical data and in the development of a new 3D geological modelling software that can directly incorporate data from national databases.

4. Development of the guidelines:

The development of the guidelines was critical to ensuring that the mapping and assessment were conducted to a uniform, high technical standard. This includes methods and standards for data collection, modelling, and risk assessment. The guidelines are actively used by both the Danish EPA and consultants to ensure that groundwater mapping and assessment are consistent across the country.

2.4 Key Characteristics

1. Three approaches:

Groundwater mapping in Denmark is divided into three approaches, each with its own set of deliverables.

a. Groundwater mapping: provides a detailed assessment of the geology, hydrology, groundwater chemistry and groundwater modelling, resulting in the delineation of the well head protection areas, well field catchment areas and groundwater vulnerability to nitrates and pesticides.

b. EU Water Framework Water Plans: have the aim to protect all waters, i.e., to preserve and enhance the status of aquatic ecosystems related to both quality and quantity. Hence, resource use assessment is carried out to identify areas with sustainable/unsustainable groundwater use

c. Danish Regions point source pollution mapping, assessment and remediation.

2. Data sharing:

Even though groundwater mapping and assessment are divided into three separate programs, data collected and produced in the three different programs are readily available and used in the other programs.

3. Results used in groundwater management:

The municipalities are responsible for developing and implementing groundwater management and protection plans, as well as for permitting and controlling. These plans are based directly on the results of the three mapping and assessment programs, where the collected data informs the actions and decisions taken for groundwater protection.

4. Data coverage:

Denmark has a very high data density, which can be used for groundwater mapping and assessment. This starts with a relatively high density of boreholes in the country. With over 300.000 boreholes registered in the Jupiter database, there is an average of 7 boreholes per square kilometre. In addition, high spatial coverage of geophysical data has been collected in connection with groundwater mapping. As an example, nearly 80% of the area of the island of Funen is covered by the different geophysical surveys, see Figure 39. Particularly, airborne electromagnetic surveys (SkyTEM), developed in conjunction with the Danish Groundwater Mapping Project, have provided significant coverage over large areas.

5. Model development:

At a very early stage, the Danish groundwater mapping projects began developing both digital 3D geological/hydrostratigraphic models and hydrological models. Nearly the entire country is now covered by a 3D hydrostratigraphic model, and efforts over the last two years have coupled these models to ensure continuity of geological layers across them. In addition, nearly all local groundwater mapping areas have



incorporated results from 3D groundwater models, from which recharge and well-field catchment areas are calculated. In addition, there are 7 large-scale 3D regional hydrological models that cover the entire country, except for some of the smaller islands.

6. Co-interpretation of data:

During groundwater mapping, several types of data are collected, and different types of results are used to arrive at a concluding assessment. This includes geological data, hydrological data, groundwater quality, groundwater modelling results, land use, and mapped contamination. These results are combined into a single analysis for the vulnerability assessment, identifying where protective actions should be taken.

7. Scale:

Individual groundwater mapping and assessment projects are generally carried out in smaller mapping areas, often covering only one or two municipalities, totalling 100-500 km², with the largest areas being around 3,000 km². Thus, groundwater models from these mapping areas tend to be local to small regional models. However, the combined results cover at least half of Denmark's total area (43,000 km²), and nearly all of Denmark is covered by the geological model. The mapping and assessment activities conducted in association with the EU Water Framework Directive water plans are, conversely, on a larger regional scale, with four water basins defined and results covering the entire country.

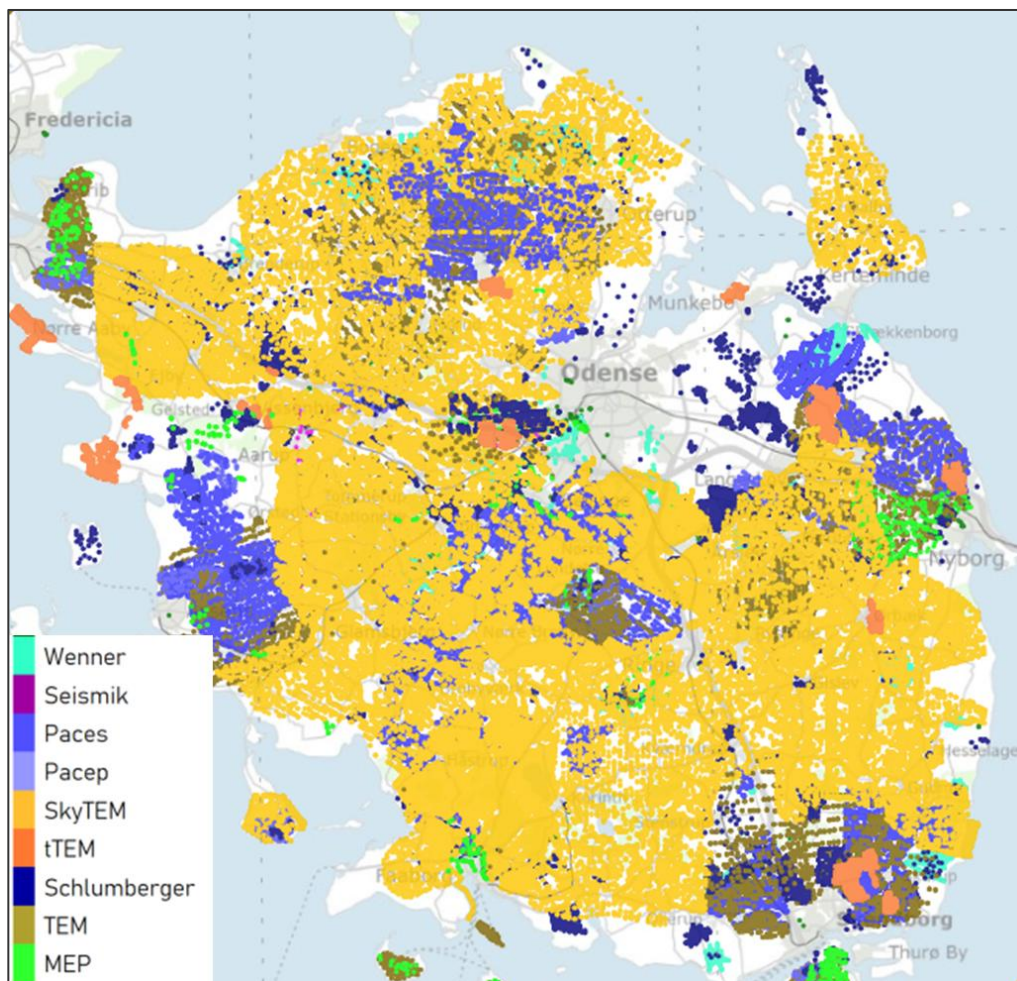


Figure 39 Coverage of geophysical data for the island of Funen.

3. KEY FACTORS – SOUTH AFRICA

The relationship between the key factors and key characteristics for South Africa is illustrated in Figure 40. For the Danish conditions, different studies can be carried out for different purposes, e.g., the construction of new wellfields, the assessment of groundwater quantity, or protection (under Key Characteristics), each of which includes different activities. The key factors within each category: Drivers, Institutional, Supporting infrastructure and Key Characteristics are detailed in the sections below.

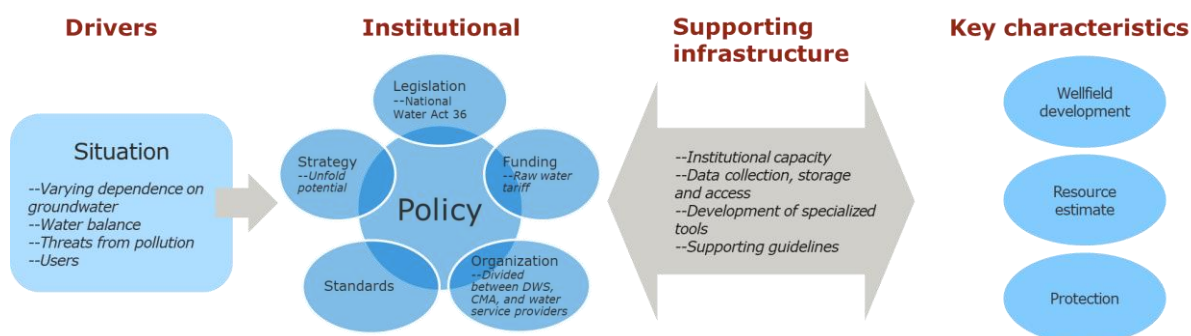


Figure 40 Diagram showing the relationship between the key factors in South Africa

3.1 Drivers

The following are the key factors that are the primary drivers for groundwater mapping and assessment in South Africa.

1. Sources of water:
South Africa is reliant on surface water for most of its water supply. Although the groundwater supplies only 15% of all the water in volume, more than 50% of smaller towns are either solely reliant on groundwater or surface water and groundwater is conjunctively used for water supply.
2. Threats to the groundwater:
The quality of groundwater in South Africa is very variable and linked to the geology and other natural processes. It is thus possible to have naturally occurring pollutants in addition to pollutants from human sources. Pollutants from human activities are mainly in the form of diffuse pollution from agriculture and point source pollution from industries, mining, and filling stations. These have an impact on the water quality and can influence the quality of the resource for future generations. Over-abstraction and its associated consequences are a threat to groundwater quantity (see 'Water balance' below).
3. Water balance:
South Africa has a variable amount of groundwater recharge depending on factors such as precipitation volumes and geology. The western half of the country tends to be semi-arid to arid with rainfall below the world average. High evapotranspiration rates, often higher than precipitation, exacerbated by high temperatures and wind further reduce recharge. Recharge to groundwater tends to be periodic, associated with above average rainfall events in these areas. Rainfall and recharge in the eastern part of the country tends to be seasonal, with lower evaporation.
4. Users:
Groundwater users have different requirements. Irrigation, accounting for nearly 60% of the total groundwater abstracted, often does not set the same requirements for the water quality as potable water, but is more concerned with a sufficient supply,

especially during drought. In rural towns and on private properties with wells where groundwater is used without treatment, a high quality is, on the contrary, a prerequisite, while some treatments are often associated with larger cities where the bulk water resource is from surface water.

5. Ownership:

Prior to the National Water Act of 1998 (Act 36 of 1998) the groundwater was a private entity, where the landowners had water rights, and thus the privileges to utilise the resource without a permit. With the National Water Act of 1998 (Act 36 of 1998) the water resource became a public entity with the national government being a custodian and responsible for the allocation of the resource. However, the authorisation depends on the amount of water used and its potential impact. Small scale use falls under Schedule 1 use, e.g., household and small stock watering, and does not require registration.

3.2 The institutional key factors

1. Strategies:

Several national strategies have been developed that have formulated visions and goals for groundwater use. Three National Groundwater Strategies were developed since 2000 (2003, 2010 and 2017), which were incorporated into the National Water Resources Strategies (NWRS1 – 2004 and NWRS2 – 2013). While the NGS considers both qualitative and quantitative challenges, more emphasis is placed on quantity, as five of seven objectives for the NGS relate to how best to unlock the potential of groundwater to secure the water supply, while one relates to quality. This suggests that the most important factor in utilising groundwater is the presence of a source, while poor quality can be treated, as is already common practice with surface water.

2. Legislative framework

Groundwater quality for various uses is guided mainly by the South African National Standards (SANS) and by the Department of Water and Sanitation guidelines. Groundwater mapping and assessment are supported by the latest Groundwater Strategy from the Department of Water and Sanitation. Groundwater was private property until the National Water Act (Act 36 of 1998) was promulgated. Groundwater became a public entity under the care and protection of the Minister of the Department of Water and Sanitation. The management of the water resources was delegated to the local level.

3. Funding

There is a raw water tariff that includes raw water use charges, water resource development charges, and waterworks use charges. Beyond paying for administrative management, a levy is also allocated to water related research through the Water Research Commission (WRC), but it is not specifically targeted at groundwater mapping.

4. Organisation:

DWS is responsible for providing the legal framework for the governance of water resources and for providing raw water to water services authorities and national mapping programs. The Catchment Management Agencies (CMAs) are responsible for implementing the legal framework and issuing water use authorisations. They also collect tariffs from water users outside the municipal supply system, such as water users' associations and irrigation boards. Water services authorities, such as water boards, District Municipalities, and Local Municipalities, are responsible for treating raw water to potable standards. Water Service Providers – usually local municipalities



– are responsible for reticulation systems, sanitation, wastewater treatment, and the collection of tariffs.

3.3 Structural Key Factors

1. Capacity building:

Institutional capacity is one of the most important challenges in groundwater mapping and assessment. The Department of Water and Sanitation currently has limited capacity, with the bulk of the increased capacity within the private sector or consultancies. Not all municipalities have the capacity to effectively develop, manage, and assess their groundwater resources, nor to perform in-house mapping. The City of Cape Town is one of the few municipalities to have employed dedicated hydrogeologists; the rest contract consultants. The importance of capacity building is stressed in most strategies, but it has not yet been fully developed.

2. Data collection, storage and access:

Data used for groundwater mapping and assessment must be sourced from various sources. This includes geological maps, hydrogeological maps, reports, borehole information from the National Groundwater Archive (NGA) (previously the National Groundwater Database (NGDB)), water levels (Hydstra), water quality from the Water Management System (WMS), geophysics, aquifer yield and borehole yield from pumping test data (NGA & reports), stream measurements (Hydstra) and water use registrations from the Water Use Authorisation and Registration Management System (WARMS). DWS manages the databases (NGA, Hydstra, WMS, and WARMS), including capturing and sharing data on request. The only exception is the NGA, which is web-based and allows registered users to extract and upload data. Municipalities, water users' associations, consultants, etc., tend to maintain their own databases that are not aligned with DWS's and are not available to the general public.

3. Development of specialised tools:

A number of software programs were developed for groundwater related applications, such as the Flow Characteristic program (FC method) for the analysis of pumping test data, the GRDM (Groundwater Resource Directed Measures) software for groundwater management in Karoo aquifers, Aquiworx, and many other software programs for the interpretation of groundwater related data and processes. Most of these have focused on fractured rock environments, while far fewer have been developed with porous aquifers in mind. Different recharge estimation methods were also developed in South Africa, such as the Cumulative Rainfall Departure (CRD) method. Many other analysis tools have been developed as part of WRC projects but have not yet found general application.

4. Development of guidelines:

Guidelines and standards for the assessment, development, and protection of groundwater have been developed by the Department of Water and Sanitation through research projects funded by the WRC or the SABS (South African Bureau of Standards). The guidelines are not centrally stored, making it difficult to identify the most recent version. People are often unaware of the guidelines or unwilling to pay for them. The use of guidelines is generally not enforced, and often they are disregarded. In addition to guidelines, standards have been developed, such as the South African National Standards (SANS) for drilling, pumping tests, and water quality. The SANS for drinking water quality is implemented and enforced.

3.4 Key Characteristics

1. Mapping at different scales:

Mapping consists of assessing subsurface properties, potential groundwater

resources, and associated challenges. The DWS is mainly responsible for national and regional mapping. The DWS relies on data and information sources from DWS databases, hydrocensus work, consultants and other sources. The Water Resource Classes, Resource Quality Objectives, and Reserve are in place to protect the quality and quantity of groundwater, with groundwater protection zones to be implemented in the future. At the regional/local scale, mapping is often carried out as part of an assessment to identify a suitable location for the development of water abstraction wells and to assess the suitability of the water resource. It is done at different scales reflecting the amount of water required and may thus cover a large area. The mapping, however, is targeted at the specific objectives of the assessments and is not part of a groundwater mapping aimed at a general evaluation or protection of groundwater.

2. Data sharing:

Data is available for DWS databases, mostly through requests. The NGA is the only database accessible to the general public, with the option for consultants and others to update it. Hydstra, WMS and WARMS are managed by DWS. Data from these databases is available on request. It is not compulsory to share data with DWS or to capture the data on the NGA. This is also true for geophysical data, models and reports.

3. Results used in groundwater management:

The results of groundwater assessment programmes – mostly from assessments carried out as part of wellfield development, with GRA I and GRA II results playing a minor role – and the monitoring conducted during operations at the wellfields are used to manage the municipal wellfield. Regional and national assessments, large-scale activities with inherently coarser resolutions, have thus far played a very small role, if any, in the management of groundwater resources at the local scale. They do play a role in planning at the national and regional scales and were used in the different Reconciliation Strategies, e.g., the All Towns Reconciliation Strategies.

4. Data coverage:

The NGA holds more than 255 000 borehole records and an additional 11 000 other geosites. A major contribution to the database was during the investigations that led to the production of the national hydrogeological maps between 1992 and 1996. The density of borehole records varies across the country, with high densities around large exploration projects, such as the Cape Flats, Atlantis, and the Lower Berg River area, but almost no data in other areas. The average borehole density is 0.2 boreholes per square kilometre. The NGA data record has not kept up to date with groundwater drilling, due to the sheer number of boreholes drilled annually and the fact that it is not compulsory to provide DWS with the data or to upload it to the NGA. Approximately 100 000 new boreholes are drilled each year by private individuals but are not uploaded to NGA. An average of 720 new sites per year have been uploaded to the NGA (2015-2021).

The coverage of geophysical data is limited and tends to be localised, with transects connected to specific projects and/or used to determine the best site for drilling production boreholes. The geophysical module in the NGA is in process and will be available in 3-4 years. The fractured rock aquifers lend themselves to more localised investigations due to the complexity of the geology. Geological maps/information and structural analysis are used to identify areas for detailed geophysical surveys. Large scale geophysics has only been undertaken recently in connection with wellfield development projects to address the impact of the drought. Examples of this include airborne geophysics conducted by the City of Cape Town over the Cape Flats and Atlantis, and work by SkyTEM for Ramotswa and Saldanha Bay Local Municipality on coastal aquifers around Saldanha. The same reports are logged in a library called the



GH Report system and are freely available for the public to download. The data within the reports is not captured on the NGA. The reports from the water use licence application process are not captured in the GH Report system.

5. Development of 3D models:

When groundwater flow models are developed, they are, in most cases, based on a simplified geology without detailed geological/stratigraphical modelling (no voxel model). The development of 3D geological models is carried out by only a small number of consultants, especially when working with very complex geologies. Models are predominantly used to evaluate the productivity of new wells/wellfields in feasibility studies, based on pump tests from newly developed production wells. Consultants are free to choose their own modelling software. There are no modelling standards or guidelines developed to account for specific South African conditions, which thus rely on international guidelines and best practice.

6. Co-interpretation of data:

Different data types are combined in the assessment and mapping of groundwater, i.e., when developing a hydrocensus. This includes topographical, geological, and hydrogeological maps on different scales. Data sets from different databases and reports of previous studies include geology/lithology of boreholes, geological structures, yields, water strike, recharge, storage, water quality, water level measurements, stream flow measurements, and climate data.

7. Scale:

Assessments for the development of individual abstraction wells or small wellfields generally have a limited areal extent and may not include detailed subsurface mapping/geological interpretations. Explorations for large scale waterworks may cover local to regional areas, i.e., tens to hundreds of square kilometres, and mostly involve more detailed investigations. At the largest scale, national mapping covers the entire country and cannot include all the details found at local scales. Knowledge thus exists at different scales, national, locally/regional and points, and while the national studies per se cover the entire country, the studies at a smaller scale are rarely combined to provide detailed interpretations for larger areas.

4. SIMILARITIES AND DISSIMILARITIES IN APPROACHES

The key factors are compared one-to-one in Table 3, followed by an evaluation of how differences in the approaches have contributed to the differences observed in the two approaches.

Table 3 Comparison of key factors in Denmark and South Africa.

| Drivers - Situation | |
|---|--|
| Denmark | South Africa |
| 100% reliance on groundwater for municipal water supply. | Heavy reliance on surface water, but groundwater constitutes the main or sole supply outside surface water distribution networks, often in urban areas and smaller towns. Groundwater is historically considered a secondary, unreliable resource. |
| Groundwater quality threats – the initial concern has been diffuse agricultural pollution but point source pollution is also considered. Natural pollution sources from geology are generally | Quality issues are related to both diffuse (agricultural) sources and point sources, as well as natural pollution from geology. This phenomenon is widely spread throughout South Africa as dominated by the type of geology. |

| | |
|--|---|
| limited and local, with some introduced by overexploitation. | |
| Generally sufficient recharge and only local groundwater quantity issues, particularly considering freshwater ecosystems. | Groundwater quantity is limited by both low precipitation in some areas and a complex aquifer system, where yields are often low. |
| Primary users are private and public municipal water supply companies (59%), agriculture (32%), with a minor amount for industry (9%). | Users range from private well owners to large municipal water supplies (13%). Agriculture is the largest groundwater user in terms of quantity (65%). |
| The state owns all groundwater rights in the country. | The state is the custodian of all water resources, while water is a public entity. The public can apply for water rights, though the state determines whether they are entitled to exercise or use the water right. |
| Institutional - Policy | |
| Denmark | South Africa |
| The strategy for drinking water should be based on simple treatment and thus a public focus on clean water supply. | National strategies include protecting groundwater but have focused primarily on unlocking its potential as a reliable resource. Given the reliance on surface water, potable water purification is standard. |
| Legislation mandates groundwater protection. | National strategies support national activities, but legislation does not mandate groundwater mapping. |
| Funding for groundwater mapping and assessment set in legislation in the form of a per m ³ levy (tax). | Funding from a water consumption levy is used to pay for the administration of the water distribution network and general water resources research. There is currently no dedicated funding for groundwater mapping; however, DWS initiated a process to secure funding in the near future. |
| Mapping and assessment are divided among different actors: the state, assessing vulnerability to non-point source pollution; regions, dealing with point source pollution, and the state/EU, dealing with groundwater abstraction impacts on aquatic ecosystems. | Only the state is responsible for a general mapping and assessment, which is realised in targeted projects. The authorities below the state may conduct assessments to develop wellfields, but are not responsible for general mapping or protection. |
| Supporting infrastructure | |
| Denmark | South Africa |
| Programs and staffing dedicated to groundwater mapping and assessment programs. | High competencies among consultancies, while capacity among other key actors varies and, at some levels, is limited. |
| All government-collected data, models, and reports are publicly accessible through national databases. | Public access to data in NGA. Other public data is available on request, except for some reports, while no models are stored centrally. Not all data collected in state funded projects are uploaded to national databases. |

| | |
|---|---|
| The national groundwater mapping program has included resources for developing specialised tools and software. | Specialised methods and software have been developed as part of general water research projects. |
| Guidelines developed as part of the mapping program and integrated into the process to assure high and consistent quality. | Several guidelines have been developed but are not fully integrated in the mapping and assessments. |
| Key Characteristics | |
| Denmark | South Africa |
| Three separate approaches for the different areas, rather than one unified groundwater mapping and assessment program. | DWS are responsible for national mapping and assessments, while local/regional activities predominantly focus on developing specific water supply systems rather than mapping for general purposes. |
| Data are shared among the different programs and agencies and are available for municipalities and other stakeholders to use. This data is widely available, free of charge, through the publicly accessible databases operated by the state. | Data stored in national databases is made available by DWS, while data collected by consultants in customer paid projects is often not freely available. |
| Results are used actively in groundwater management and planning. | Results from mapping and assessments are used actively in groundwater management and planning. |
| A high-density data coverage across the country, including borehole and geophysical data. | Data is available across the country, but varies in density. |
| Development of local and regional 3D geological and groundwater models, covering nearly the entire country. | The development of local and regional groundwater models often relies on simplified geologic models. Detailed 3D geological models are primarily used to clarify complex geology. |
| Co-interpretation of hydrology, groundwater chemistry, geological and groundwater modelling data. | Several data types are combined, but the co-interpretation of hydrology, groundwater chemistry, geological and groundwater modelling data is limited. |
| Mapping is generally carried out for smaller areas, but together they cover most of the country, which has been combined into one national interpretation. However, the country is approximately 30 times smaller than South Africa. | Mapping has been carried out nationally. With the size of the country, such mapping cannot cover all details. Mapping is also carried out as part of smaller scale projects, but is integrated into national scale mapping. |

4.1 Drivers

A comparison of the drivers for groundwater mapping and assessment in Denmark and South Africa reveals stark dissimilarities between the two countries. Given its reliance on resources, as a lowland, island, and peninsula country, Denmark lacks sufficient, reliable surface water resources. Thus, groundwater is virtually the country's sole source of water for drinking, agriculture and industry. In contrast, surface water has traditionally been the most important water resource in South Africa, supplying cities and areas with high population density through the surface water distribution network. In less populated areas, such as rural areas and towns, groundwater often comprises the main or sole resource. Nevertheless, in terms of quantity, the surface water is by far the largest resource, and in relation to water suppliers, groundwater has been considered a secondary and unreliable resource.

In Denmark, precipitation is sufficient and stable across the country, and challenges with groundwater quantity are limited to some local areas and have adverse effects on groundwater dependent ecosystems. Therefore, the question in Denmark is not whether there are sufficient resources to abstract, but rather where those resources can be abstracted without adversely affecting water quality and groundwater dependent ecosystems. In contrast, South Africa has widely varying precipitation across the country and is susceptible to extended droughts. This greatly affects the availability of surface water, while groundwater, with its buffering capacity, can provide a more robust water resource. However, groundwater recharge, and thereby groundwater availability, is similarly affected by the large spatial variation in precipitation, resulting in spatial variation in the groundwater resource. This is further amplified by the complex groundwater systems, where groundwater in some places is associated with discrete features, e.g., fractures, dykes, etc., and thus difficult to map and utilise, or the groundwater bearing units are associated with low yields.

Denmark is a very agriculturally intensive country, resulting in many groundwater aquifers across the country becoming polluted with fertilisers (nitrate) and pesticides. Point source pollution from industry and landfills is also a local problem. As the primary use of groundwater in Denmark is drinking water, which must be of high quality, this puts threats to groundwater quality directly into the spotlight. In South Africa, groundwater pollution is primarily local scale, though it is also driven by agriculture and industry. Agriculture primarily uses groundwater resources, but abstraction for clean drinking water is rising. Groundwater aquifers are mainly contaminated with nitrates from agricultural activities. Point sources that are most often associated with urban settings and thus have a more local impact.

It is also important to recognise the historical ownership of the groundwater resource. In Denmark, the resource has always been a public good, and a permit is required for all water usage, which is thus registered.

These drivers have led to distinct purposes for groundwater mapping and assessment. In Denmark, groundwater mapping and assessment have focused primarily on groundwater quality and the need to protect groundwater resources for current and future generations. On the other hand, groundwater mapping and assessment in South Africa have focused on water quantity, with emphasis on groundwater recharge, availability, and well yield.

4.2 Institutional - Policy

In Denmark, the primary political strategy has been that Danish groundwater should be supplied with only simple treatment of oxidation and filtration. This has resulted in legislation that focuses the groundwater mapping and assessment on groundwater protection, including dedicated funding for national groundwater mapping and assessment programs.

In South Africa, the primary strategy has been to increase groundwater use to provide a more resilient water supply, particularly during droughts. Legislation in South Africa has been passed to support the national strategies, but it does not mandate groundwater mapping and assessment at the national scale. Funding is designated for the entire water resource, of which groundwater constitutes a minor part. The funding allocated to groundwater primarily goes towards the development of new well fields and infrastructure, administration for issuing permits and support for general water resources research. Currently, no ongoing funding is earmarked for more general groundwater mapping and assessment to protect a future resource.

The differences in policies between the two countries are clearly driven by their respective drivers. Denmark's policies defining the purpose of groundwater mapping and assessment are clearly defined by the need to protect the groundwater quality. Although groundwater quality is considered, South Africa's policies are primarily focused on increased use of the groundwater resource, driven by pressure on and the unreliability of its surface water resources.

4.3 Structural support

In Denmark, state-run programs with dedicated staffing have been established to run the national groundwater mapping and assessment. Guidelines have been developed to support the efforts and are directly integrated into groundwater mapping and assessment activities. Databases have been established with the requirement that all publicly funded or legislatively mandated data be included, and that all be free of charge. These databases include a wide range of data, including geological information, hydrological data, groundwater abstraction, water quality, geophysical surveys, geological modelling and groundwater modelling. The databases provide free, easy access to data through web portals and are continually being developed to improve accessibility and accommodate new data types and web services.

In South Africa, programs with dedicated staffing are primarily for oversight and administration, while consultancies with high competency work on a local scale. Guidelines supporting groundwater mapping and assessment have been produced but not fully integrated into mapping processes. Like in Denmark, national databases have also been established. However, not all state-collected data is uploaded to these databases, and access to upload and download is only possible for the National Groundwater Archive (NGA), while data from other databases is available upon request. Groundwater related reports are not always centrally located, and no system exists to store models for future reuse. The amount and structure of stored data may limit public access.

As an important part of the Danish groundwater mapping program, substantial funding was dedicated to the development of specialised tools and approaches tailored to Danish conditions, including hydrogeological settings, mapping and assessment purposes, and the administrative setup. Funding is similarly allocated to groundwater research in South Africa, and while this has led to the development of tools specialised for South African conditions, the research also supports broader aspects of water resource management.

4.4 Key characteristics

Even though there are significant differences in the Danish and South African approaches to groundwater mapping and assessment, there are still several key characteristics shared by the countries. These include:

- Both countries have national databases that are accessible to the public.
- Local and regional 3D geological and groundwater models are developed.
- Both countries actively co-interpret the different data types in the different groundwater mapping and assessment processes.

The difference in approaches also leads to differences between the two systems, particularly in the details of the processes. The first difference lies in the expanse of data available in each country's databases. Although both countries have publicly accessible databases, the amount of data and results submitted to the databases varies (DK has 35 times more data points/sites per km² than SA). Data collected in Denmark must be submitted to the various databases, and this mandate is actively enforced. This includes all borehole-related data (geological, hydrological, pumping and water quality), geophysics and models. Data and

results submitted to the databases in South Africa are not as expensive. Often, data and results from groundwater mapping and assessment programs are collected by private consultants, and these results are considered proprietary and not required to be shared. Much of the mapping and assessment in South Africa is also privately funded by the utilities themselves and thus not required to share data in public databases.

In Denmark, 3D geological and hydrological models play a key role in protecting and assessing the sustainable groundwater resource to improve system understanding and assess sustainable groundwater use prior to the development of new wellfields. The widespread use of models has enabled integrating 3D models into a national model that covers nearly the entire country. It, however, needs to be emphasised that this is possible primarily because Denmark is a relatively small country with a fairly simple geological setting. In contrast, the models in South Africa are isolated local or regional models, predominantly used to assess the feasibility of a wellfield after the production wells have been established and pump tested. Furthermore, 3D models are primarily developed to map complex geological systems, and given the highly varied geology throughout South Africa, developing a national 3D geological model is much more ambitious.

Groundwater mapping and assessment in Denmark has been conducted using a standardised process. Even though the mapping and assessments have been conducted at the local and regional scale, the standardisation has allowed the results to be combined into a highly detailed national interpretation. In contrast, groundwater mapping and assessments in South Africa, carried out at the smaller scale, have not been integrated into a national interpretation. Mapping on the national scale is only conducted at a low level of detail, such as the national water resource map. The reason for this difference is, in part, the size of the country and the complexity of the hydrogeology across South Africa. In addition, the mapping activities, with a focus on finding new resources and development of new well fields, are conducted by the individual utilities using their own methods. Thus, without a standardised methodology, it is more difficult to combine the results into a national interpretation.

4.5 Additional issues

The analyses and interviews carried out during the current project revealed additional topics that have influenced the mapping and assessment approaches in the two countries. These are briefly summarised here for a concise overview and organised according to the identified key factors. Recommendations are provided for technical topics based on comparisons with the Danish approach. In addition to the technical aspects, some observations have been made regarding the Institutional Policy setup. However, it is out of scope for the current project to make recommendations on these topics, which have therefore been listed only for completeness.

Institutional – Policy

- The Danish groundwater mapping and assessment approach is deeply rooted in policy, with political ambitions on securing current and future groundwater resources and providing a mandate for protection and the collection of levies earmarked to groundwater mapping. The development and protection of groundwater in Denmark is thus highly prioritised and supported by policy. In South Africa, several national strategies and initiatives have been developed in the past decade, providing political ambitions, but have not received an equivalent support in the political system.

Supporting infrastructure

- Competences and capacity

- o It is recommended that focus be placed on capacity building among all actors involved in groundwater mapping/assessments and management to foster an environment with high technical competencies, thereby ensuring high technical quality.
- o Additionally, capacity building should be broadened to include awareness raising among the public to develop a general understanding of groundwater and the qualitative and quantitative vulnerability of the resource.
 - Guidelines
- o Several guidelines exist, but their use is limited. It is recommended that a structure and mechanism for enhancing the use of guidelines be put in place. This could, e.g., be implemented by making it mandatory for consultants to relate their proposed project solutions to national guidelines.
- o If guidelines are to be better integrated, it is necessary that the clients are similarly aware of these guidelines and know the latest version. For this, a better dissemination to professionals in the field is necessary, as is a central access to guidelines providing the newest version.

Key Characteristics

- Modelling
 - Several local/small scale geological interpretations already exist, but have not been combined for an improved large scale understanding. It is recommended to analyse whether frameworks can be developed that incorporate existing interpretations to provide larger scale interpretations.
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5. FACTORS SUPPORTING OR IMPEDING THE SOUTH AFRICAN APPROACH

This section examines factors that support or impede groundwater mapping and assessment in South Africa. Identification of the impediments can highlight areas where a possible transfer from the Danish approach may be beneficial.

Surface water has historically and continues to be the main water resource in South Africa. Although groundwater is an important or the sole resource in areas where surface water is not available, it is often seen as an unreliable secondary water resource. It has therefore received only minimal recognition, political support, and funding for sustainable development and resource management. However, groundwater gained more attention through the development of various acts and strategies, which may potentially increase future support and enhance groundwater assessments, such as groundwater mapping. Strategic groundwater use has been addressed in more recent water strategies, such as the National Groundwater Strategy, which provides groundwater specific input to the National Water Resources Strategy, and in the inclusion of groundwater in the Strategic Water Resource Areas in 2018. Hence, groundwater is receiving growing political attention, which is likely to increase groundwater research and funding and thereby advance the mapping and assessment.

Numerous good and valuable technical guidelines have been developed; their use is not mandatory, and it is not customary for projects to request that the work be aligned with them. The guidelines are furthermore not centrally accessible, which may limit their accessibility and knowledge about them. Hence, although clients may like the work to follow best practice as described in the guidelines, they may not be aware of them and thus not refer to them in the tenders.

Sufficient capacity among all actors is required to both request and conduct the assessments at a high technical level. Thus, the shortage of capacity and lack of knowledge at authoritative levels is expected to impact the quality of assessments, and a need has been identified to educate professionals in the water resource management discipline. Enhancing knowledge through education will lead to the development and implementation of sustainable water management plans and to an expected increase in groundwater utilisation. Raising awareness of groundwater related issues among communities, interested individuals, and stakeholders may promote participation in discussions without requiring technical know how. Professional continuous development and capacity building for technicians will lead to high quality assessments on request.

Geophysicists with limited hydrological knowledge often conduct geophysical investigations, so geophysical data is often not properly analysed in the mapping of groundwater aquifers. Different geophysical methodologies and instrumentation are better suited for different geological settings. During various projects, the use of unsuitable methods is not uncommon. This is mostly due to financial constraints, unavailability of specific instrumentation and/or limited knowledge of which instrument will be most suitable for a specific geophysical investigation. Geological logs are seldom kept by local drillers. A geologist, trained technician or geohydrologist may do the logging themselves depending on the type of groundwater provision project and the client.

It is not mandatory to report data to a central entity, and relevant data are stored in different databases at various levels, e.g., by national, regional, or municipal entities, or by consultants or customers. Data from the National Groundwater Archive (NGA) is freely available through a web portal, but several other national databases are not accessible to the general public. Data, digital maps and shapefiles can be obtained free of charge from DWS, while hard copy maps can be procured from DWS at a cost. Other data and maps are often not freely available and must be purchased from relevant government departments, the South African Weather Services and the Council of Geosciences. Similarly, access to databases held by other parties may be difficult and involve payments. The lack of compulsory reporting of data to a central entity with free, easy access creates a barrier to data reuse. Where data exists but is unavailable, the result will be either collecting new data in the same area or excluding that data from the mapping and assessment. Hence, the assessment will either be more expensive than necessary or the basis for the assessment will be poorer.

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