Kapitel 2. Summary

The exploitable groundwater resource in Denmark is estimated to be 1,0 billion m^3/year based upon simulations using the National Water Resource Model (DK-model). This represents a 45% reduction in the estimated exploitable resource compared to the last national assessment of 1,8 billion m^3/year made in 1992 (based on a much more simplistic approach assuming in general a 15 % exploitable resource of the net-precipitation).

The main reason for this near 50% reduction in the estimate of the exploitable groundwater resource is that the new assessment was made using the results of an integrated groundwater / surface water model for the entire country (43,000 km^2) that is based upon detailed methodology and describes the entire freshwater cycle of the land-phase. Furthermore, the model quantifies the adverse impacts of groundwater abstraction on stream flow depletion and wetlands, thus defining a more critical limitation on the exploitable resource than was previously assumed. Another reason for the reduction in the estimate of the exploitable resource is related to significant problems with the quality of shallow groundwater, which makes this resource unfit for drinking water purposes for many years to come.

The increased detection of contaminants in shallow aquifers over the past several decades has forced a change in groundwater abstraction patterns from the shallow to deep aquifer systems. The new assessment provides a more reliable quantification of the exploitable resources due to a direct and thorough incorporation of restrictions on streamflow depletion, corresponding to the defined objectives for the aquatic environment for the single stream and river reaches.

The new model-based analysis of the hydrologic cycle identified areas around the greater Copenhagen area, Odense and Århus where groundwater resources are overexploited. In addition, areas with coarse sandy soils in western Jutland and areas with a high irrigation demand in central and western Jutland are also threatened by over-exploitation during drought conditions. Groundwater resources are over-exploited by nearly 80 million m^3/year in northeastern Sjælland and around the greater Copenhagen area, 10 million m^3/year on the isle of Funen, and 30 million m^3/year in eastern Jutland. Delineated drinking water areas, which comprise 35% of the entire country and are vital for the protection of the future groundwater supply, also show signs of over-exploitation. In contrast, there is an excess quantity of groundwater in large areas of southern and northern Jutland.

In most of these areas the problem of overexploitation is related to excessive streamflow depletion caused by intense pumping from groundwater abstraction wells. In other areas the limits for how much water can be abstracted is defined by the risk of increased percolation of nitrates and pesticides to depth from the contaminated shallow groundwater and/or release of toxic solutes from soil matrix (e.g. Nickel) caused by lowering the groundwater table. In both cases the unbalanced condition is caused by a groundwater abstraction which is too high, compared to the “natural” groundwater recharge, for the selected reference scenario, defined by 1991-2000 climate conditions and groundwater abstractions “switched off”.

An important reason for the serious situation is the deterioration of the shallow groundwater system due to both nitrates and pesticides. These contaminants are detected in one out of five monitoring screens in the shallow groundwater system showing a content of both nitrates and pesticides above the maximum allowance limit value for drinking water.

Significant abstraction from deep aquifers and the associated enhanced downward transport of contaminants from shallow aquifers presents a threat to not only the future quality of deep groundwater resources, but it may also adversely impact the possible fulfilment of current action plans for the aquatic environment as the deep groundwater ultimately discharges to surface water bodies.

The new assessment is far more detailed and accurate compared to the last national assessment made in 1992. The new numbers for the exploitable freshwater resources are based upon a seven-year modelling effort. The project has shown, that there is a strong need for more knowledge about the various elements of the water balance and their coherence.

The uncertainty related to the new assessment has been estimated to +- 10 % for the total exploitable resources. For the 11 regional model areas the model has been subdivided into, the uncertainty has been estimated to +- 20 % (in size corresponding to Danish WFD areas). For 50 subareas the uncertainty has been estimated to +- 40 %.

The National water resource model (DK-model) use daily precipitation, temperature and reference evapotranspiration as input. The model is calibrated and validated by comparing simulated values of daily stream discharge and groundwater levels with observed values. The model provides a detailed description of the freshwater cycle based upon a 1 x 1 km grid. The geology has been interpreted for 10 to 30 geological layers based upon several thousands of borehole logs. Groundwater flow in the upper soil layers, drainage systems and rivers is described fairly detailed.

Needs for knowledge about hydrological cycle and exploitable groundwater resources

There has been identified the need for improved knowledge about the single elements of the water balance and their interaction in order to provide more accurate water balance evaluations.

A more qualified and precise analysis of the dynamics of flow system development and the possible spreading of the shallow contamination towards deeper aquifers is required. The development of water quality in the various water cycle elements, eg. root zone, unsaturated zone, shallow and deep groundwater, drainage systems, rivers and lakes, and also in transition zones between the elements of the cycle, is important for a better understanding. Will the situation in the deeper groundwater aquifers deteriorate further, or is it stable? What happens in the zone from the shallow groundwater to the deeper groundwater?

Intensive abstraction impacts groundwater vulnerability, both in terms of increase risks of pollution from land surface, but also due to increased risks for the release of solutes from the subsurface when lowering the groundwater table. It has been estimated based on groundwater monitoring data that abstraction of a critical proportion of max. 35 % of the groundwater recharge to the deep groundwater aquifers is sustainable (at depths of 30 to 50 meter below surface). These assumptions, based on rough best estimates for Sjælland, are important for the calculation of the exploitable resources, and should be tested for other areas (Funen and Jutland). Furthermore, there is a need for additional detailed studies.

The analysis of critical streamflow depletion limit values was based on figures from Danish guidelines for water supply planning from 1979. There is a strong need for new and better estimates of limiting values for critical streamflow depletion for both average flow and low flow conditions, linked to ecological parameters, eg. using habitat-models. Another issue which needs further consideration is the choice of reference scenarios in urban areas (like the capital area of Copenhagen). For example, does it make sense to base the reference situation on conditions where the current groundwater abstractions are “turned off” (natural conditions), in an area where creeks and headwaters long ago have been drained?

A better evaluation of climate impacts, especially in areas where the sustainability indicators show significant dependency of net-precipitation (North Sjælland and western Jylland but also the shallow groundwater system) is important. This includes a more detailed analysis of hydrological impacts from irrigation. Coupling of advanced regional climate models with advanced hydrological models is a promising opportunity. Another opportunity could be an evaluation of climate conditions in the period from around 1800 to 1900. In the 19^{th} century several periods with limited winter precipitation occurred. Simulation of this period could be used to define a critical 200-year event assessment of exploitable groundwater under extreme winter drought which is critical for groundwater recharge and subsequent low flow conditions.

The exploitation of groundwater resources in Denmark is not balanced geographically. Today, a number of areas are severely overexploited when considering streamflow depletion above the critical levels corresponding to the objectives for aquatic environment (max. 5, 10, 15, 25 and 50 %). The most common criteria which restricts impacts on streams in Denmark is the 10 % value corresponding to salmon spawning and nursery reaches. The lack of water, which is need to balance the situation has to be imported from great distance. This raises a need for cross WFD co-operation between authorities, water works and stakeholders. A national coordination of water supply across WFD’s is required.

Water quality and quantity are mutually connected

Results of the groundwater monitoring program show that 20 % of the shallow groundwater is polluted with nitrates and pesticides above the drinking water limit value and that half of the screens show detectable impacts from pollution. Contaminants were detected in less than 5% of the wells sampled with screens at depths greater than 30 to 50 meter below land surface. The groundwater recharge at a depth of 30 to 50 m is selected as an indicator of the quantity of clean groundwater that is available for exploitation. It is estimated that 1/3 of the groundwater recharge to this depth can be abstracted on a scale corresponding to the subareas and regional catchments used for the assessment with the DK-model, without increased risk of pollution from upper layers or release of substitutes caused by lowering of the groundwater table.

The pollution of the shallow groundwater threatens both the quality of future drinking water, for a major part based on groundwater from the deeper system, and also water discharging from shallow groundwater back to rivers and lakes. It has been assessed that a 10 % reduction of the average flow in river systems is acceptable. Baseflow depletion is acceptable if it is below a 5, 10, 15, 25 and 50 % reduction, depending on specified goals for the quality of the aquatic environment for the river reaches.

Climate variations interfere with groundwater recharge and flow conditions in rivers.

Water resource management has to assess the exploitable resources at different scales (national, WFD, drinking water protection areas, action plan scale and field scale). The national water resource model can provide information about the hydrological cycle and exploitable resources for the national and the WFD level, and assist as a reference (conceptual model, boundary conditions, parameters, groundwater recharge etc.) for analysis at a smaller scale. In general, the model is not detailed enough to describe solute transport.

Temporal variations of the freshwater cycle

The water balance for a catchment can be described by an equation where precipitation is balanced by the sum of the other components of the water balance (evapotranspiration, river runoff, subsurface discharge, groundwater abstraction and storage in unsaturated and saturated zones).

Due to measurement errors on precipitation, correction factors for each month are used in water balance studies. Especially, correction of precipitation falling as snow affects the total correction values for winter months. Even though point measurements, including the above mentioned uncertainties, may be regarded as fairly accurate, there is also a significant uncertainty related to interpolated areal numbers. For a Danish catchment, the Suså riverbasin, there has been calculated uncertainties on areal-precipitation in the range of 60 % on daily values, 10 % on monthly values and 6 % on yearly values.

Studies have shown that the evapotranspiration for most crops may exceed the potential evapotranspiration by 10-20 %. This implies the need to use surface coefficients that vary with crop and season. The knowledge base for understanding evapotranspiration from different crop types still has some major gaps. There is significant uncertainty related to evaluation of those coefficients. In addition, the evapotranspiration for certain surface types, especially forest and wetland, is poorly investigated. Furthermore, crops production over the past several decades has increased by about 30%. The effect of this increase in crop production on evapotranspiration is not known. The uncertainty on annual evapotranspiration is estimated as 10 %.

Stream discharge measurments possess uncertainties of up to 5% for annual values and 5-10% for daily values for large catchments which are considerably less than the uncertainty associated with precipitation and evapotranspiration measurements.

Signficant short-term variations in climate, namely precipitation, occured during the period from 1991-2000, and include a very dry year (1996) and three wet years (1994, 1998 and 1999). The dry year of 1996 was of a magnitude that has a likelihood of occurrence once every 50 years. The three wet years are the wettest in the entire historical record.

The average precipitation and stream discharge during the period 1991-2000 is comparable to those of the 1980s, a 10-year period with the highest recorded precipitation and stream discharge. For comparison, the precipitation measured during a longer period in the late 19th century was 15 % less. Winter precipitation during the period 1991-2000 was higher than winter precipitation for the period 1961-90. Winter precipitation since 1961 has been greater than decades before this year.

Regional variations of the freshwater cycle

The average annual precipitation during the period from 1991 to 2000 was approximately 1100 mm/year in southwest Jutland and 650-700 mm/yr along coastal areas in eastern Denmark. In the central part of Sjælland the average annual precipitation is 750 mm/year. For a dry year, such as 1996, the precipitation in southwest Jutland was only 750 mm/year and 450-500 mm/year for the coastal areas of Sjælland.

Winter precipitation (1/10-1/4) is a relevant indicator for groundwater recharge, since evapotranspiration for this period of the year is limited. For Sjælland the winter precipitation for 1991-2000 amounted to 400 mm/year, giving a excess precipitation of approximately 300 mm/year.

Mean stream discharge in Denmark is 320 mm/year, and varies from 200 mm/yr in the eastern part of the country to 400 mm/yr in western Jutland. Baseflow to rivers amounts to 125 mm/year in western parts of Jutland, but only 30 mm/year on Sjælland.

In order to prepare a more detailed assessment of the magnitude of the exploitable groundwater resources a further validation of the new recommendations for correction of precipitation and evapotranspiration is needed, including significance of climate data from 10x10 or 20x20 km national grid, compared to the utilised 40x40 km grid.

Construction, calibration and validation of DK-model

An integrated groundwater / surface water hydrological model with a 1 km^2 grid has been constructed for Denmark covering 43,000 km^2. The model is composed of a relatively simple root zone component for estimating the net precipitation, a comprehensive three-dimensional groundwater component for estimating recharge to and hydraulic heads in different geological layers, and a river component for streamflow routing and calculating stream-aquifer interaction. The model was constructed using of the MIKE SHE / MIKE 11 code, and comprehensive national databases on geology, soil, topography, river systems, climate, and hydrology.

The construction of a national hydrological model of the present complexity is a major task. In particular, the task of processing all the data on geology, soil type, land use, topography, river network geometry, water abstraction and climate to fit into the numerical model is comprehensive and challenging. Comprehensive because it involves a vast amount of data originating from different databases, and data processing entails a considerable amount of work. Challenging because all these data have never been used together before and inevitably will contain some mutual inconsistencies. The objective of such modelling study is typically to develop a tool for subsequent use in practical water resources management. This was also the primary objective of our study. However, a very rewarding additional output from the modelling process was that it provided a framework for quality assurance of data and hydrogeological process understanding. Quality assurance can only be fully ensured if data are used, and modelling in this respect may be considered as the ultimate data usage, because it enables consistent checks of one data type against another. The discovery of water balance errors associated with the new climate data products that was a result of the modelling validation test procedure is just one example. Numerous other examples, were experienced, resulting in feedback from the numerical modelling to the geological interpretation.

The final results of the DK-model for Sjælland show that it is possible to construct a combined groundwater/surface water model with a horizontal grid size of 1x1 km^2 that yields reliable results with respect to simulation of hydraulic heads and discharges. The model is now ready for operational applications such as assessing groundwater recharge to different geological layers and assessing impacts of alternative groundwater development scenarios at the regional scale. Furthermore, the model may be a very useful tool for investigating the impacts of climate change on water resources availability. Finally, it will be a useful hydrological basis for assessing the nitrogen fluxes at the catchment and national scale. It must, however, be emphasised that the model has documented predictive capabilities at only the regional and catchment scales. Due to scale problems, the limitations in predicting the behaviour at a local scale with a coarse scale model such as the DK-model are well known.

The model for the isle of Bornholm has not been completed. However, the model set-up has been finalised and it is ready for calibration and validation.

In general, the model for Sjælland meets the predefined performance criteria for river flows and groundwater levels according to the validation tests (RMS, R^2 and F_{Bal}), with only the model for Sydsjælland not meeting the criteria for groundwater levels. Models of eastern and northern Jutland have minor problems in meeting criteria for river flows. However, the models are considered to be valid tools for assessment of groundwater resources as overall, they accurately simulate baseflow. The models of the other seven regions all fulfill the performance criteria.

It has been determined that the hydrogeological conceptual models of the three need to be revised in order to fulfill accuracy criteria. Model accuracy may also be improved by using climate input data based on 20 x 20 km grid, instead of the 40 x 40 km grid used today.

Better monitoring of the freshwater cycle in NOVANA and in relation to the EU Water Framework Directive

The EU Water Framework Directive provides new requirements for the monitoring of the freshwater cycle. Erros in estimation of the water balance affect the quality of mass loading calculations. Estimates of the overall water balance, and in particular groundwater recharge, can be strengthened by a combined use of monitoring and modelling. One way to go is to utilise the DK-model as a reference framework.

In the Danish monitoring programme, NOVA 2003, single elements of the water balance are monitored such as groundwater in GRUMO areas, and small catchments in LOOP areas. However, these sub-programs are only integrated to a limited degree. Water supply wells and some of the monitoring wells in GRUMO areas have focused on deep groundwater systems. These waters are often too old to register changes in the contaminant loads for the land surface within the last 15 years. The GRUMO and LOOP areas have to be redesigned in the upcoming NOVANA monitoring program with more emphasis on young and shallow groundwaters. This data will provide knowledge about possible improvements in water quality resulting from the implementation over the past 15 years of national action plans to reduce groundwater pollution.

NOVANA consists of a number of sub-programmes for monitoring of atmosphere, point sources, land, groundwater, rivers, lakes, marine water bodies, species and terrestrial types. The objective of the program is to document the overall affects of national action plans directed at the environment- and nature.

A number of data is used across the programme: for example data for climate, land use, animal husbandry in different areas. These data has to be purchased across the program.

Monitoring of the water balance and groundwater recharge will be carried out through the combined use of monitoring and modelling. By integrating monitoring and modelling on national as well as on a regional scale (WFD), a coherent and coordinated monitoring and assessment of the exploitable resource can be provided.