ASSESSMENT OF SUSTAINABLE GROUNDWATER RESOURCE BY USE OF NATIONAL HYDROLOGICAL MODEL

H.J. Henriksen, L. Troldborg, A.L. Højberg and J.C. Refsgaaard

Geological Survey of Denmark and Greenland, GEUS, Hydrological Department.
Øster Voldgade 10, DK 1350 Copenhagen K. Denmark (hjh@geus.dk)

ABSTRACT

To manage water resources effectively, we must first understand how much water is available and where it is located. This knowledge is acquired by undertaking a resource assessment based on the measurement and modelling of the various elements of the water cycle. To achieve a sustainable water management regime, the needs of abstractors and environment has to be balanced. This resource balance may be approached in a number of different ways, with evaluation of 'non-hazard' influences on groundwater levels and low flows in rivers when abstracting groundwater aquifer systems. In the paper four sustainable yield indicators were applied in order to estimate the influences on the freshwater cycle from groundwater abstraction and in this way assess the exploitable groundwater resources for the whole country of Denmark. The result showed that the exploitable resource matches the current abstraction quite well at about 1 x 10^9 m^3/year ~ 23 mm/year for the whole country. However, due to large regional variation in availability of resources and of abstraction, there are areas where the current abstraction constitutes a very significant overexploitation.

INTRODUCTION

In the past, the volume of recharge to an aquifer was accepted as the quantity of water that could be removed from the aquifer on a sustainable basis, the so-called *safe yield*. Today we understand that the sustainable yield of an aquifer must be *considerably less* than the recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and groundwater dependent ecosystems (Sophocleous, 2000). In addition, there is an increased need to understand the fragile relationships between groundwater quality in shallow and deep aquifers, and possible negative effects of excessive groundwater abstraction on future groundwater quality of deep aquifer systems and surface water systems relying on a supply of adequate and good quality groundwater in summer drought periods.

The complexity of the above problems has elucidated the need for more advanced, and exact tools to be used for water resources assessments of exploitable groundwater resources compared to previous simpler and rougher calculations based on estimates of exploitable fraction of net precipitation. In order to address these problems an integrated groundwater-surface water model (the DK model) was set up for the whole of Denmark covering 43,000 km^2. During a seven year study, this model was used to assess the exploitable groundwater resources in Denmark (Henriksen and Sonnenborg; 2003). This study provided new insight in the quantitative status of the available water resources and resulted in an 'alarming' almost 50% reduction in the estimate of the exploitable groundwater resources.

The objective of the present paper is to describe and present the results of the use of the DK model to assess the sustainable exploitable groundwater resources in Denmark.

THE DK MODEL

The DK-model consists of 11 regional sub-models with a delineation based on natural hydrological boundaries (Henriksen et al., 2003; Sonnenborg et al., 2003). 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 on the basis of the MIKE SHE code and by utilising comprehensive national databases on geology, soil, topography, river systems, climate and hydrology.

The modelling for the islands Fyn and Sjælland was applied to a heterogenous glaciomorphological topography, with a near surface geology consisting of Quaternary deposits overlying Tertiary limestone and marls. The Quaternary deposits consist of terrestrial glacial sediments with a thickness ranging from a few meters to 150 meters whereas the pre-Quaternary deposits underneath consist in general of Danien limestone in the eastern and northern parts of Sjælland and Paleocene marl and clay in the western part of Sjælland and Fyn. Much emphasis was put on a proper description of the geological model in three dimensions (Henriksen et al., 2003).

For Jylland, the model to the west, are bounded by the North Sea, and with the Baltic Sea and Kattegat confining the model to the east. The eastern part of Jylland is relatively hilly, with maximum elevations of approximately 100 m above sea level. The western part is gently sloping to the west. A topographical water divide is located at the boundary between the two areas, referred to as the "Jutland Ridge". In a large part of Jylland, Miocene sediments are found directly below the Quaternary deposits.

The average annual precipitation was decreasing from 1100 mm/year in southwest Jylland to only 650-700 mm/year along coastal areas in eastern Jylland, Fyn and Sjælland. Potential evapotranspiration is in the range of 550-650 mm/year, highest for forest and wetland vegetations.

In order to achieve a proper simulation of groundwater flow processes at large scale, it was decided to include the following hydrological processes in the model:

- Snow accumulation and melt.
- Overland flow (2D).
- Unsaturated zone processes including evapotranspiration and irrigation.
- Groundwater flow processes including hydraulic heads, flow between layers and exchange flow between aquifers and rivers and flow from aquifers to drains.
- River flows and water levels.

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The construction of a national hydrological model of the present complexity was a major task. In particular, the processing of all the data on geology, soil type, land use, topography, river network geometry, water abstraction and climate to fit into the numerical model was comprehensive and challenging. Comprehensive, because it involved a vast amount of data originating from different databases. Challenging, because all these data never has been used together, for the purpose of providing an integrated and dynamical water balance covering the freshwater cycle.

As input data, the DK-model use daily precipitation, temperature and reference evapotranspiration. The model was calibrated and validated by comparing simulated and observed values of daily stream discharges for more than fifty river gauging stations, and averaged simulated and observed groundwater head for approximately 20.000 wells for 1991-2000 using inverse and manual calibration (Sonnenborg et al., 2003; Henriksen et al., 2003). The final results of the DK-model for Sjælland, Fyn, Jylland and Bornholm (Henriksen and Sonnenborg, 2003; Troldborg et al. 2006) showed that it was possible to construct a combined groundwater/surface water model with a horizontal grid size of 1x1 km^2 (Bornholm 0,25x0,25 km^2) that yielded reliable results with respect to simulation of hydraulic heads and discharges. The final DK-model honoured the pre-established performance criteria for river flows and groundwater levels in the validation tests and is as therefore ready for operational use e.g. for assessing groundwater recharge to different geological layers and assessing impacts of alternative groundwater development scenarios on river flow on a regional scale. More details on the construction and calibration and validation of the model can be found in Højberg et al. (2006).

Subsequent validation tests of e.g. simulated fluctuations in groundwater head compared to piezometric head observations has further documented the reliability of the DK-model for Sjælland (Christensen and Sonnenborg, 2006). The model has recently been used for different simulation scenarios (Henriksen and Sonnenborg, 2003; Sonnenborg et al., 2006; Troldborg and Henriksen, 2006). Here we shall narrow the presentation to the assessment of sustainable groundwater resources (Henriksen and Sonnenborg, 2003).

The assessment of sustainable groundwater resource availability - the purpose of the present paper - was completed by the following three requirements: (1) the validated DK-model, (2) an established set of criterias (a suite of indicators) for quantifying a maximum allowable change in groundwater table, deep recharge, streamflow and baseflow, corresponding to a given groundwater abstraction strategy (distribution of wells and abstraction rates in space and time). The latter was assumed to follow (3) the current groundwater abstraction strategy for year 2000.

In the next session the set of criteria used for the assessment is described.

CONCEPTUAL UNDERSTANDING OF SUSTAINABLE YIELD

The factors that have to be taken into account when assessing how much groundwater can be abstracted in a sustainable manner are illustrated in Fig. 1.

The limits to groundwater abstraction for most Danish hydrogeological settings are defined by excessive streamflow depletion (*reduced baseflow)* caused by pumping from groundwater abstraction wells. In some of these areas the balance between abstraction and recharge may be more or less critical, but never providing the limit for availability.

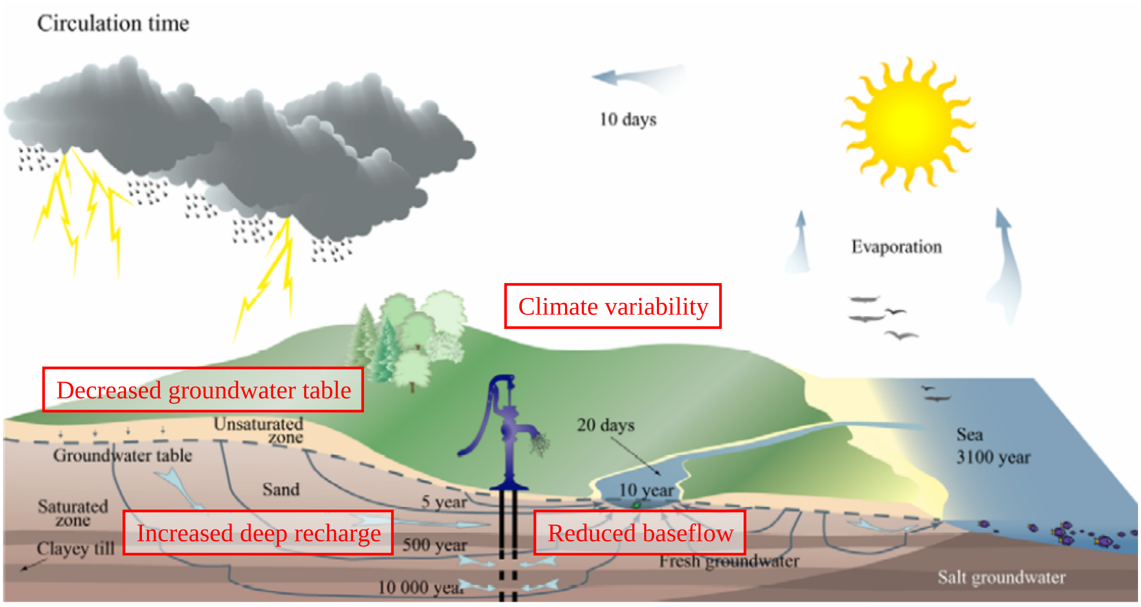

Figure 1 Reduced baseflow, increased deep recharge, decreased groundwater table and climate variability are the factors limiting the sustainable yield when abstracting water from an aquifer system (Henriksen and Sonnenborg, 2003)

The qualitative imbalance regarding abstraction and recharge represents a concern for an increased release of toxic solutes such as nickel from aquifer sediments caused by lowering the groundwater table ands associated transformation from anaerobic to aerobic conditions (*decreased groundwater table).* For confined aquifers increased groundwater abstraction will lead to an increase in groundwater recharge, implying that pollutants, such as nitrate and pesticides, located in the upper soil layers (Stockmarr, 2004) moves faster towards the deeper aquifers where most of the groundwater is abstracted from (*increased deep recharge).*

Groundwater resources are known to be vulnerable to variability or change in climate input (Thomsen, 1990; Sonnenborg et al., 2006) (*climate variability).*

These concerns on sustainability were in Henriksen and Sonnenborg (2003) translated into the four indicators shown in Table 1.

Table 1 The four indicators used to characterise sustainable groundwater exploitation.

Indicator No	**Indicator**	**Factor considered**
1	Max abstraction = 35% of natural recharge	Decreased groundwater table (groundwater quality)
2	Max increase of recharge = 30% of natural recharge	Increased deep recharge (groundwater quality)
3	Max reduction of annual streamflow = 10%	Streamflow depletion
4	Max reduction of low flows = {5, 10, 15, 25, 50%} depending on ecological objective of river reach	Reduced baseflow

The indicators chosen to reflect concerns over groundwater quality were flow indicators, i.e. indirect measures as compared to more sophisticated indicators based on ground water level and/or solute transport. The 35% and 30% limits were derived as an empirical rule of thumb based on an analysis of the actual groundwater quality and abstraction rates for Sjælland, where it had been observed that areas with intense groundwater abstraction and significant lowering of the groundwater table often have extended problems with inorganic trace elements. The present modelling approach based on 1 x 1 km^2 grids and model calibration and validation on sub-catchment scales of 300-2000 km^2 does not allow a direct simulation of groundwater level drawdown near abstraction wells or detailed solute transport modelling.

Overall the exploitable groundwater resources were assessed from aquifers at 30 to 50 m depths from where all the major groundwater abstraction today takes place.

In the translation of the abstraction-runoff balancing principle it has been assessed that a 10 % reduction of the average flow in river systems is acceptable. (*Indicator 3*) In the literature there are 'rule of thumb' values for the balance between surface water abstraction/effluent return by reservoir compensation and surface runoff. Acreman (2000) suggests a hydrological severity indicator composed of two indicators: a) annual groundwater licensed abstraction compared to annual recharge and daily max surface water abstraction compared to the Q_{95} runoff value, and describe the sum of the two as low severity if this sum is in the range of 0-40 %. For the groundwater part an average value of 10 % thus (severity 0-20 %) which supports the selection of a 10 % limit value.

The indicator on depletion of low flows (*Indicator 4*) is based on guidelines from the Danish EPA from 1979 prescribing a maximum reduction of low flows depending on the ecological objectives of the river reach, which is categorised in A (waters for scientific reference areas), B1 (salmonid spawning and nursery waters), B2 (salmonid waters - nursery and living areas for trout), B3 (cyprinid waters) and C-F (watercourses solely used for drainage purposes, waters where authorized waste water discharges cause the quality to be worse, watercourses where the effects of water abstraction render it impossible to maintain fish water objective or watercourses markedly affected by ochre discharge). According to these old guidelines, baseflow depletion is acceptable if it is below a 5 (A), 10 (B1), 15 (B2), 25 (B3) and 50 % (C-F) reduction. These guidelines are based on more than 25 years old knowledge. However, the most important limit value of 10 % for B1 is supported from similar requirements for trout waters e.g. in UK (Acreman, 2003).

RESULTS

For each of the 50 sub-catchments the four indicators were calculated. To include the climate change aspects in a simple way different net precipitation (1991-2000) inputs for average climate, dry and wet year was analysed for indicators 1-3. In this way the temporal variability in sustainable yield indicators was assessed for different regions and settings. Finally, the indicator with the lowest value of sustainable yield was chosen for mapping the national available resources.

The summary results are shown in Table 2.

Table 2 Assessment of available resources for Fyn, Sjælland and Jylland (the results for Bornholm is not yet available). Results for indicator 1-3 (groundwater quality, streamflow decrease and climate variability), compared to indicator 4 (baseblow reduction).

	Region	*Abstraction 2000 mm/year* [1)]	*Area km²*	*Indicator 4 mm/year*	*Indicator 1 mm/year* [2)]	*Indicator 2 mm/year* [2)]	*Indicator 3 mm/year* [2)]	*Available resource mm/year*	*Available resource mill m³/y*	*Total Abstract mill m³/y* [1)]
1	Fyn	12,8	2945	10	15-17	15-16	17-29	10	30	38
2	W-Sjælland	7,9	3281	10	9-10	9-10	17-28	9	28	26
3	S-Sjælland	6,0	3207	8	8- 8	8- 8	21-27	8	26	19
4	N-Sjælland	39,1	2831	14	25-30	23-27	12-23	12	33	111
5	S-Jylland	26,0	4500	47	47-52	40-45	> 52	40	180	117
6	SW-Jylland	66,4	5263	60	57-71	49-61	40-68	40	211	349
7	SE-Jylland	30,8	4705	26	28-31	25-27	41-64	25	118	145
8	W-Jylland	36,0	5291	39	67-86	58-75	> 50	39	207	190
9	E-Jylland	13,1	4418	23	34-41	30-37	26-38	23	102	58
10	N-Jylland	14,6	5478	22	33-42	29-37	31-41	22	121	80
	Total								1054	1133

1) Abstraction for year 2000 for water supply wells, industry etc. Assumed full irrigation according to irrigation permissions (the actual abstracted volume for irrigation only amounted 1/3 of the permision for 2000).

2) The range signifies an estimate of the indicator value given a netprecipitation input of 80 % and 120 % of the average value for 1991-2000. This corresponds approximately to 'critical' dry and wet 5-year periods estimated to occur approximately once every century, based on precipitation variations for the period 1974-2000 (Henriksen and Sonnenborg, 2003:43-45).

If we take Fyn as an example, the actual abstraction for year 2000 was 12,8 mm/year. For this area indicator 4 (*baseflow reduction*) is the most critical of the four indicators (available sustainable resource ~ 10 mm/year), with B1 (salmonid spawning and nursery waters) as the reaches defining the sustainable abstraction. The current abstraction of 12,8 mm/year gave a reduction for Fyn of 11 % in the minimum flow situation, which is slightly above the limit value of 10 %. Indicator 1 and 2 (*groundwater quality)* result in a less critical available resource estimate (15-17 mm/year), based on a calculation of deep recharge of 46 mm/year without pumping, and 51 mm/year for current year 2000 abstraction. Based on these simulations and simulations of deep recharge for Fyn for 50 %, 80 %, 120 % and 150 % of the 2000 abstraction? for dry and wet conditions, indicator 1 and 2 was estimated to the ranges shown in table 1. The reduction in average streamflow (indicator 3) is less critical, compared to other indicators, showing an available resource range of 17-29 mm/year. Based on the indicator results 1-4, the 'worst case scenario' indicator is picked, which for Fyn is indicator 4, and the last two columns in the table show the result of the assessment in mill. m³/year, allowing an easy comparison of the balance between available groundwater resource and total abstraction for each region and in total for the country.

In addition to the estimates for regions shown in Table 1 estimates for subareas e.g. vital drinking water areas (in Danish: Områder med særlige drikkevandsinteresser) and for sub-areas in each region was estimated. For Fyn there are six sub-areas, and the available resource for the country based on sub-areas is slightly reduced compared to the total estimate based on regions shown in table 1. Based on the "sub-area scale" of the 50 sub-areas the total available resource comprise 1024 mill. m³/year, which is 30 mill. m³ /year or 3 % less than the "region scale" result. This finding also indicates that the total resource estimate is ‘scale dependent’, e.g. that indicator criteria has to be reconsidered if using the methodology and the indicators for different scales. In Fig. 2 the resource estimates for sub-areas and regions are shown.

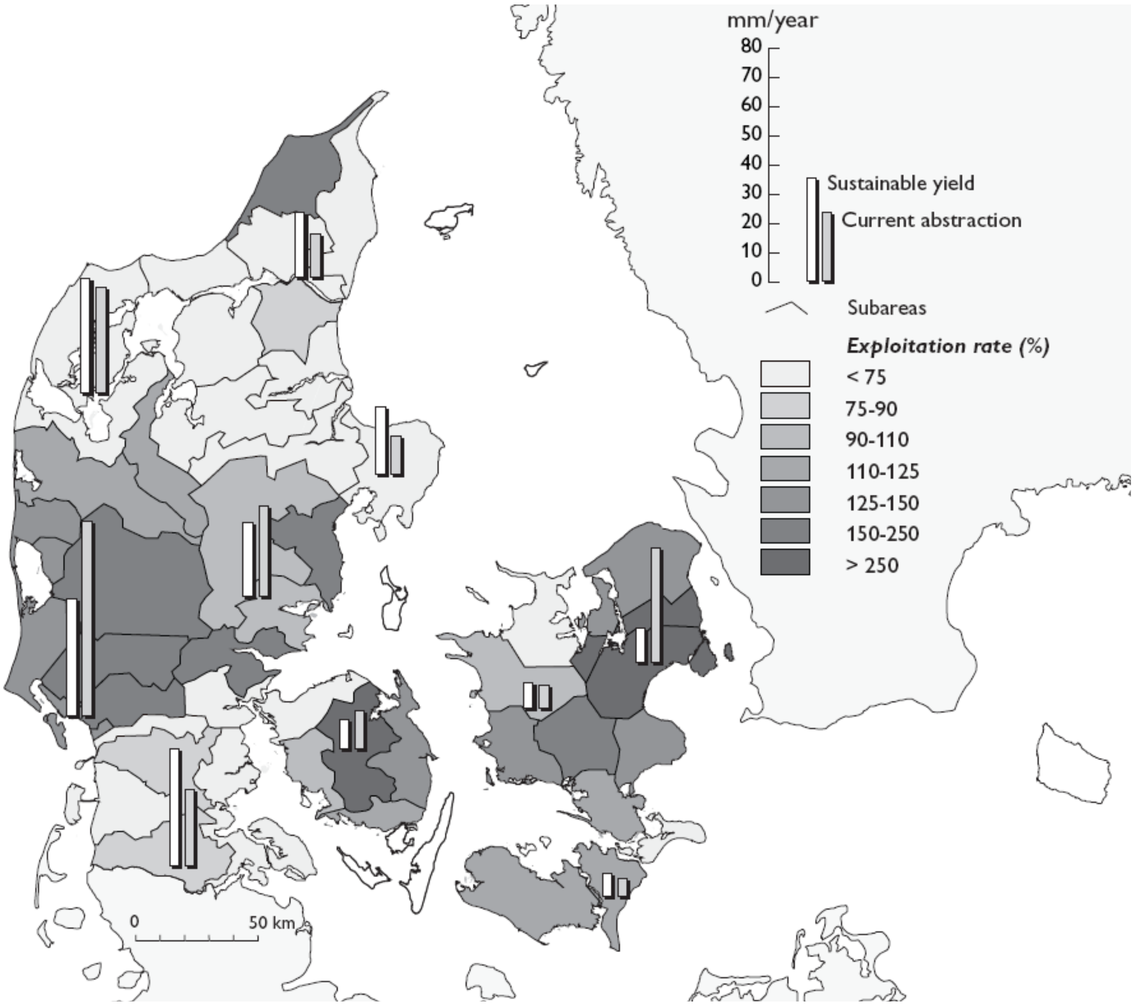

Figure 2 Resource availability status. Areas with lightgray: water available (sustainable yield above current exploitation); gray areas: no water available (current abstraction and sustainable yield is in balance) and darkgray: over-exploitated areas. White bars show sustainable yield and dark bar current abstraction for regions.

For the whole country exploitable groundwater resources is estimated to be 1.0 x 10^9 m^3/year. The assessment shown in Fig. 2 depict areas around Copenhagen, Odense and Århus as overexploited areas due to abstraction for water supply. In addition, areas with coarse sandy soils in western Jutland are also threatened by overexploitation due to irrigation demands. The vital drinking water areas, comprising 35 % of the entire country, 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 over-exploitation is related to excessive streamflow depletion caused by abstraction above the limit value according to reduced low flow in rivers (indicator 4). In other areas the limits for how much water that 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.

The uncertainty related to the new assessment was estimated to ± 10 % for available resource for the country, ± 20 % for the regions, and ± 40 % for the sub-areas (Henriksen and Sonnenborg, 2003).

DISCUSSION AND CONCLUSIONS

The result of this new assessment of sustainable groundwater abstraction represents a 45 % reduction in the estimated exploitable resource compared to the previous assessment of 1.8 x 10^9 m^3/year (Vandrådet, 1992), which was based on a simplistic approach assuming in general the exploitable resource to amount to 15 % of net precipitation. The new assessment is based on a thorough seven years modelling study with extensive use of national data on geology, topography, river geometry and soils and comprehensive monitoring data on climate, discharge, groundwater heads and groundwater abstraction. This gives a detailed and reliable assessment of the groundwater and surface water hydrology at national scale. Together with the explicitly formulated indicators for sustainable abstraction this provides a transparent quantification of the exploitable resources, where the implications of the various restrictions related to streamflow depletion and deep groundwater recharge pattern can easily be analysed.

The analysis of baseflow reduction criterias for indicator 4 was based on figures from Danish guidelines for water supply planning from 1979. There is a strong need for new and improved indicators taking baselflow reduction and aquatic environment into further consideration eventually by application of habitatmodels. In a report for Sjælland some of these problems and perspectives have been further elaborated (Troldborg and Henriksen, 2006).

A better evaluation of impacts of climate change, than applied in the assessment of sustainable resource is also needed. This has to some extent been accomplished in recent additional simulations using inputs from climate models (Sonnenborg et al., 2006).

ACKNOWLEDGEMENT

The project was financed by the Danish Ministry of Environment and Energy during the period 1996-2001 and by GEUS 2002-2003.

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