THE CONSTRUCTION AND UPDATE OF A NATIONAL WATER RESOURCE MODEL

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ABSTRACT

The Water Framework Directive (EC, 2000) imposes the EU member states to assess the quantitative and qualitative status of all surface- and groundwaters. A key aspect in the assessment of the groundwater bodies is the establishment of a comprehensive and coherent conceptual understanding of the system. Such an assessment has been carried out in Denmark by the construction of a national water resources model from which the exploitable resource was estimated taken into account that the extractable resource is limited by pollution of shallow aquifers and an unacceptable depletion in the stream base-flow. Compared to previous estimates of the groundwater resource based on more simplistic mass balance approaches the exploitable water resource was nearly halved by the use of an integrated hydrological model. This result clearly indicates that the groundwater system is complex and the resource difficult to evaluate without the use of integrated models describing all relevant processes of the freshwater resources. The current paper describes the construction of the national water resources model and the present update hereof.

INTRODUCTION

The overall objective of the Water Framework Directive (WFD) (EC, 2000) is to achieve a good quantitative and qualitative status of all waters by 2015. To obtain this goal the EU member states are obliged to prevent further deterioration, protect and enhance the status of the water resources. The WFD thus prescribes both an improvement for waters already negatively affected by anthropogenic activities, as well as the protection with respect to future activities. For this purpose, a comprehensive and coherent understanding of the hydrological cycle must be established from which the qualitative and quantitative status may be assessed. Well in line with the WFD obligations a national water resources model has been established for Denmark.

The quantitative groundwater resource has long been of major concern in Denmark, where groundwater accounts for approximately 99% of the total drinking water consumption. In 1992 the first attempt to estimate the exploitable resource at the national scale was made based on mass balance computation. Increasing pressure on the groundwater resource resulting in shortage in some areas, and adverse impacts of groundwater abstraction in terms of depletion of streamflows and wetlands in combination with widespread groundwater pollution that makes the water unsuitable for drinking purposes, prompted the need for a national overview of the present state and future trends in the available groundwater resource. Therefore, the Geological Survey of Denmark and Greenland (GEUS) initiated the development of a National Hydrological Model (DK-model) in 1996 (Henriksen et al., 2003).

The overall goal of the construction of a numerical national water resource model was to conduct a more accurate assessment of the exploitable groundwater resources. This was accomplished by making full use of the available geological data, the groundwater-level monitoring network, and river discharge observations in the construction, calibration and validation of the model. Besides a refined estimate of the water balance, the use of an integrated hydrological model made it possible to take into account that the exploitable resource is also limited by factors like pollution of the upper young groundwater that makes it unsuitable for drinking water purposes, and an unacceptable reduction of the baseflow in streams, due to abstraction. The first national water resource model was finalised in 2003. Since then the geological knowledge has been updated significantly by extensive mapping of the hydrogeology and the model is presently being updated to improve the hydrogeological description and otherwise refined to meet the specific requirements of the WFD.

The present paper provides an overview of the construction of the initial national water resources model and the methodology used for handling such large scale modelling with respect to model set-up, calibration and validation. Also, the approach for the present update of the model is briefly described. The methodology applied to assess the exploitable resource may be found in Henriksen et al. (2006).

MODEL CONSTRUCTION

An integrated groundwater/surface water hydrological model was constructed that covered the entire 43.000 km^2 of Denmark. For computational efficiency the country was divided into 11 sub-models, Fig. 1. A grid size of 1x1 km^2 in the horizontal direction was chosen as a reasonable compromise between the required level of detail and computational burden. Although this is a coarse grid resolution, which simplifies the spatial description it was considered sufficient for water balance computations, which where the primary objective of the model. The geology on the island of Bornholm differs markedly from the rest of the country and a grid size of 0.25x0.25 km^2 was chosen here.

Geology

The national geological database, containing geological data for approximately 300.000 boreholes, provided the basis for the hydrogeological interpretation. Due to the large amount of geological borehole information, it was not possibly to interpret the hydrogeology in the classical way by construction of vertical profiles. Instead, two alternative approaches were followed. For the islands (except Bornholm, submodel no. 11) the geological sequence is alternating sand/gravel and clay layers underlain by pre-‘quaternary deposits of clay and/or chalk/limestone. For these areas a conceptual hydrological model was constructed in which the quaternary deposits were divided into aquifers and aquitards. The conceptual model was based on relatively few characteristic profiles and guided by the distribution of groundwater abstraction wells indicating the presence of water bearing units. The upper and lower boundaries for the

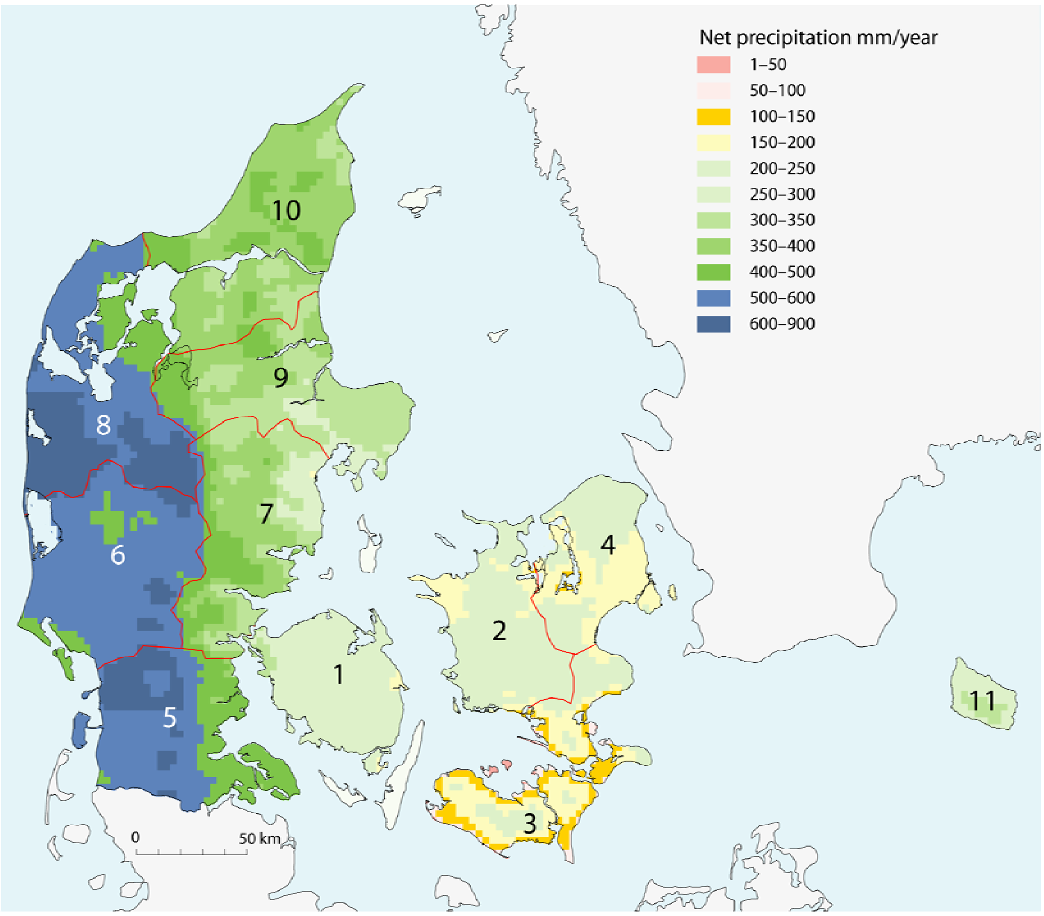

Fig. 1 Extent of the 11 sub-models on top of the net precipitation

identified aquifers were next interpreted from cyclogram data in a 2x2 km^2 grid and the resulting interpretation was continuous hydrological layers of varying thickness.

Due to a highly spatial variation in the geology on the peninsula of Jylland (submodels 5 – 10) and the island Bornholm, the construction of continuous layers was not appropriate in these regions. The hydrogeology in these areas was interpreted by slicing all boreholes into 10 m sequences and assigning the dominant lithology for each sequence. Next, the area was overlaid by a 1x1 km^2 grid and the lithology for each grid interpreted on the basis of the dominant lithology in the grid and the knowledge on the geological setting from previous studies in the area. This approach is illustrated in Fig. 2 and the differences in the two alternative interpretations are shown in Fig. 3. A more thorough description on the model concepts for the islands and Jylland are provided by Henriksen et al. (2003) and Sonnenborg et al. (2003), respectively.

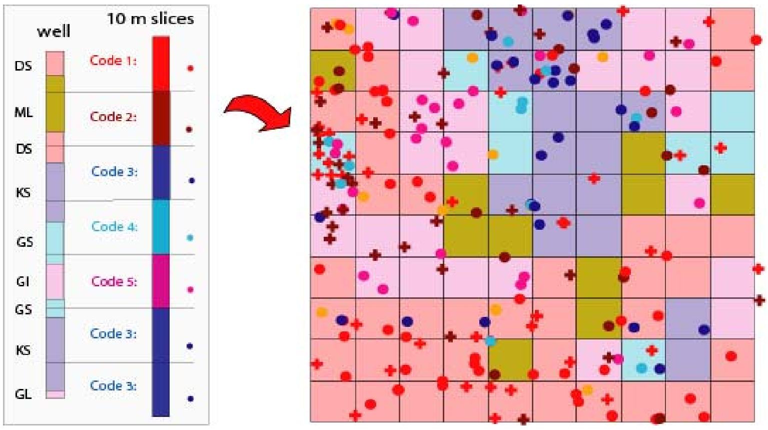

Figure 2 Illustration of the approach used for geological interpretation of Jylland and Bornholm

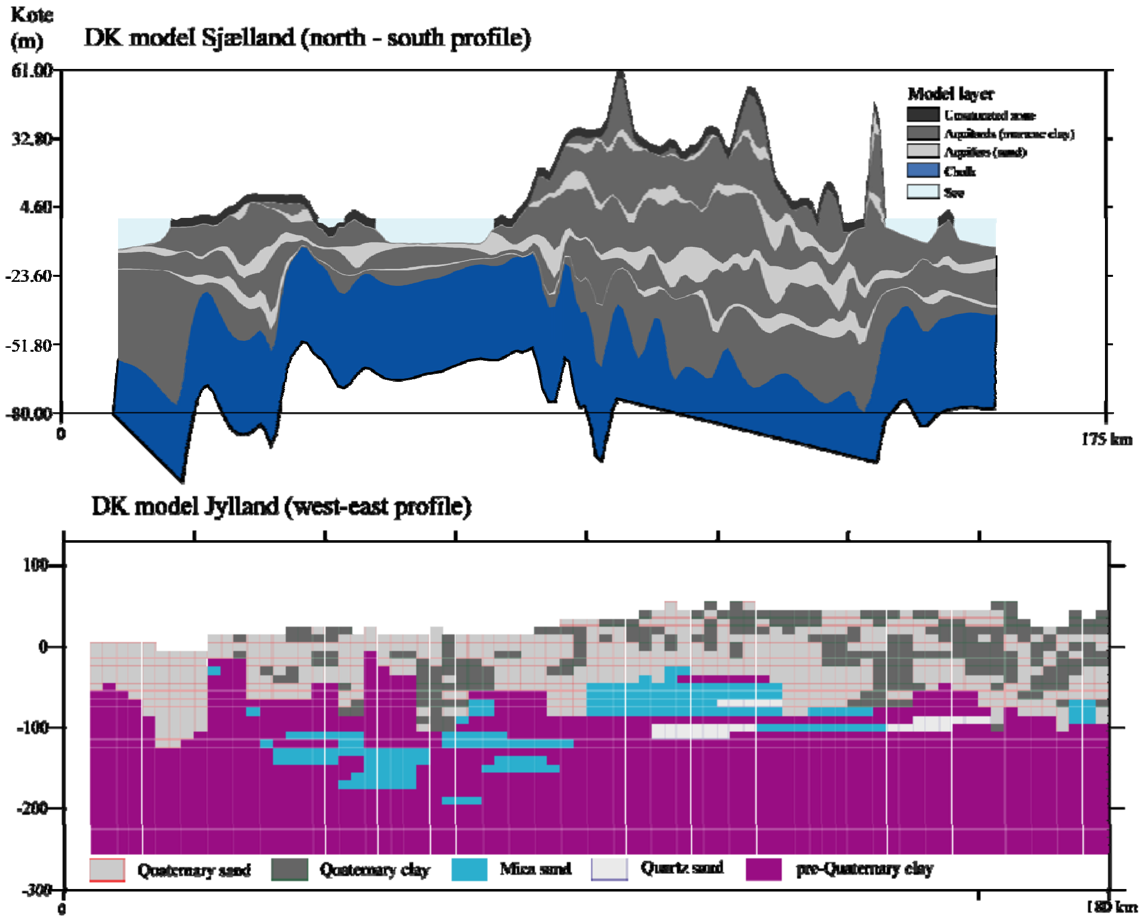

Figure 3 Illustration of the results from the two approaches used in the geological interpretation

Hydrological processes

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 in order to be able to take into account the delay in net precipitation due to snow.
- Overland flow.
- Unsaturated zone processes including evapotranspiration. The main requirement to this description is that the net precipitation (precipitation minus evapotranspiration) is assessed correctly on a seasonal and annual basis.
- Groundwater flow processes including hydraulic heads, flow between layers and exchange flow between aquifers and rivers. Because a significant part of the country is drained with artificial tiled drains, a drainage component is included for the upper phreatic aquifer.
- River flows and water levels. The extension of rivers was determined from digitised river points. Measured cross-sections were implemented in the model, where no measurements were available the cross-sections were estimated based on measured flow magnitudes and catchment areas. Some smaller headwater tributaries could not be incorporated in the river network. Instead these areas are drained by the drainage component of the model.

Model code

The hydrological processes were simulated by the physically distributed model system MIKE SHE (Abbot et al., 1986a,b), which describes the most important hydrological processes at the land phase. Modules included were the 3D saturated flow model, 2D overland flow and stream flow where the latter was modelled by the MIKE 11 model code (Havnø et al., 1995). For computational efficiency it was decided not to use the detailed unsaturated flow description based on Richards equation included in the MIKE SHE system. Instead a simple root zone module was developed for calculation of daily snowmelt and net precipitation. Results from this root zone module have been compared with those of a more advanced physically based model, Daisy (Hansen et al., 1991), for two different soil types. This comparison showed a relatively good agreement in annual and monthly water balances and groundwater recharge figures (Christensen et al., 2000).

Calibration and validation

The guiding principle in the parameterisation was to construct a model with as few free parameters as possible. Thus, uniform parameter values throughout the model area were used for geological layers composed of clayey till and sand as well as for most overland parameters. A split-sample test was used for the calibration and validation of the model, where observation data were divided into two periods, and one period employed for model calibration and the second period reserved for model validation. The model was calibrated by a two-step approach. Hydraulic conductivity was calibrated by inverse optimisation using a steady state version of the model. Hydraulic head observations and mean stream-flow discharge were used as calibration targets, while mean recharge for the period was used as input as recommended by Sonnenborg et al. (2003). Following the steady state simulations the dynamic parameters were estimated by trial-and-error in transient simulations.

1) A deviation between observed and simulated groundwater heads:

$$RMS = \frac{1}{N}\sqrt{\sum_{j}^{N}\left(H_{o,j}-H_{s,j}\right)^2} \quad ;\in [0;\infty[$$

2) A measure of the ability to simulate the average discharge at a gauging station:

$$F_{Bal} = 100\,\frac{\overline{Q_O}-\overline{Q_s}}{\overline{Q_O}} \quad , \quad (\%)$$

3) A measure of the ability to simulate the variation in the discharge hydrograph for a gauging station (Nash and Sutchilffe, 1970)

$$R^2 = \frac{\sum_i (Q_{o,i}-\overline{Q_o})^2 - \sum_i (Q_{s,i}-Q_{o,i})^2}{\sum_i (Q_{o,i}-\overline{Q_o})^2} = 1 - \frac{\sum_i (Q_{s,i}-Q_{o,i})^2}{\sum_i (Q_{o,i}-\overline{Q_o})^2} \quad ; \quad \in \left]-\infty;1\right]$$

where

$H_{s,j}$	simulated groundwater level for well j (m)
$H_{o,j}$	observed groundwater level for observation well j (m)
$Q_{s,i}$	simulated daily discharge at day *i* (l/s)
$Q_{o,i}$	observed daily discharge at day *i* (l/s)
$\overline{Q_o}$	mean observed discharge in test period (l/s)
$\overline{Q_s}$	mean simulated discharge in test period (l/s)

Box 1 Perfomance criteria used in the calibration and validation of the national water resources model

Three numerical performance criteria were used in the calibration and validation strategy, Box 1. Observations on the groundwater level were extracted from the national database at GEUS which contain only a very limited number of time-series of the hydraulic head. Both the steady state and transient calibration therefore focused on the models capability to simulate the mean hydraulic head for the period. Discharge measurements were, in on the contrary, available at a daily basis, which were used in the calibration and validation.

Table 1 Model performance criteria and five performance intervals used to categorise the performance level of a given model

Performance Indicator	Excellent (5 points)	Very good (4 points)	Good (3 points)	Poor (2 points)	Very poor (1 point)
RMS (m)	< 4	4 – 6	6 – 8	8 – 10	> 10
R^2	0.85	0.65 – 0.85	0.50 – 0.65	0.20 – 0.50	< 0.20
F_{bal} (%)	< 5	5 – 10	10 – 20	20 – 40	> 40
Performance category	☆☆☆☆☆	☆☆☆☆	☆☆☆	☆☆	☆

Assessment of the exploitable resource

In the past it has often been assumed that the exploitable resource equalled the recharge to the groundwater. This assumption is, however, not valid as several aspects need to be considered, which may lower the groundwater quantity available for abstraction. In the assessments based on the DK-model study four sustainability yield indicators were defined expressing an acceptable balance between the recharge and the abstraction rate as well as a balance between groundwater abstraction and river discharge. A lowering of the groundwater table due to abstraction is critical as it may cause oxidation of geological layers and an increased release of toxic solutes, such as nickel, from the soil matrix. Similarly a lowering of the groundwater table will increase the percolation of pesticides and nitrate from the shallow contaminated aquifers. Finally, a reduced discharge in the stream may be unacceptable due to the ecological status of these surface waters. The basis for the indicator as well as the methodology used to assess the exploitable resource is described in more detail by Henriksen et al. (2006).

Results

The DK-model study reduced the exploitable drinking water resource to 1.0 x 10^9 m^3/year compared to the previous estimate of 1.8 x 10^9 m^3/year back in 1992, and revealed large regional variations in the degree of overexploitation. Additionally, the work revealed large spatial variations in the exploitable resource, with the areas around the major cities generally being significantly overexploited. For a more detailed description of the exploitable resource and its spatial variability see Henriksen et al. (2006).

Besides an updated estimate on the exploitable resource, the DK-model study served other purposes, such as quality assurance on the fundamental input variables and helped identifying an inconsistency in the climatic data. Precipitation and evaporation were obtained from two national research institutes, Danish Meteorological Institute and Danish Institute of Agricultural Sciences, respectively. Both institutes have extensive quality assurance on data sampling and use a scientific based state-of-the-art approach to correct the precipitation data (accounting for wind effects and wetting) and estimate evaporation (modified Penman equation). From a scientific standpoint the data resembled thus the best and most reliable data set. But when data were applied in the national water resources model and model outputs compared to measured groundwater head and river discharge data, significant water balance errors were observed. This error could only be explained by inconsistency in the climatic input data. While the precipitation and evaporation data were sufficiently accurate when only the precipitation or the evaporation were of interest, the methods used were not adequate when the entire water balance was the target. As such the inconsistency was crucial for the assessment of the quantitative status of the water resource, and certainly crucial for the water management at local and regional scales. These findings resulted in the collaboration of four national institutes involved in the assessment of the water resource. It was concluded that the water balance problem could not be fully solved based on the available knowledge, but a consensus was agreed (Plaugborg et al., 2002) providing recommendations for the correction of precipitation and estimation of the evaporation, which are now used nationwide for estimation of net precipitation.

NATIONAL WATER RESSOURCE MODEL – PHASE TWO

The drastic reduction in the estimated exploitable resource as depicted by the DK-model made it clear that integrated hydrological modelling is essential in the assessment of the groundwater resource. Following the DK-model, the national monitoring programme, NOVANA, dictated the use of hydrological modelling in the assessment of the quantitative status of the groundwater. The DK-model is currently being updated with new information on geology, and the model is refined in order to fulfil the national obligations as well as the requirements set by the Water Framework Directive. A lesson learned from phase one is the importance of the participation of the parties involved in the national water resource management, in order to reach consensus on the quantitative estimate of the national exploitable resource. The model update is therefore carried out as joint project between GEUS and the Danish counties, who acts as the regional authorities.

Model update

Compared to the first version of the DK-model, the model will be refined to provide a more detailed regional description of the freshwater cycles. This refinement includes, e.g., the use of a finer numerical grid (now 500 x 500 m^2 in the horizontal discretisation), a more detailed representation of the abstractions and the inclusion of more rivers in the model. The most important update is, however, the update and refinement of the hydrologeological basis.

Since the first version of the DK-model national legislation on water resource management has prompted an extensive exploration of the geology by the counties. The conceptual understanding of the geology and hydrological system has thus been gained over the last five to ten years. One of the primary objectives of the model update is therefore to adjust the initial geological understanding in accordance with the new knowledge. This task has proven to be very challenging. The counties are obliged to carry out detailed studies in areas designated as having special interest for groundwater abstraction (OSD-områder). Although these areas cover approximately

35% of Denmark they often form non-continuous areas within the individual counties. As the focus of the counties has been to evaluate the groundwater vulnerability within the OSD areas most counties have developed individual models for each area and only few have developed a coherent conceptual model covering the entire county. Due to the geological complexity the conceptual hydrological models often vary greatly for the individual OSD areas. Similarly, each county has been responsible for the hydrological interpretation within their county, and collaboration between neighbouring counties to check consistency in the models across county boundaries has been rare. Finally, the counties have been free to choose the methods used to explore the subsurface, e.g. by geophysics, seismic and traditional boreholes (Thomsen et al., 2004) and the approach for model construction, e.g., geological interpretation by profiles or pixels. The basis for the update of the geological model thus consists of a mixture with respect to data format and type as well as the degree to which hydrological models exist and if so, which model system that has been used.

To assure a coherent geological model the updating process was started by national seminars, in which an overall geological framework was agreed upon. Next a series of seminars have been arranged between GEUS and the counties, where geologists and modellers are represented from both organisations. In these seminars an agreement is reached on how the counties' geological understanding can be included in the overall geological framework. In areas where the counties do not have a geological model the existing geology in the DK-model is used as a basis to develop one coherent geological model.

Another important issue, which will be updated in phase II, is the indicators used to estimate of the exploitable resource. The approach used in the first version of the DK-model proved to be robust, but the experience on how to translate qualitative requirements into quantitative indicators is novel and needs further development. The indicators will therefore be refined and more indicators may possible be added, based on the experiences from the first DK-model phase.

FUTURE PERSPECTIVES

The vision is to provide an ongoing process in which the national water resources reference model (the DK-model) is gradually updated and adapted as more knowledge becomes available from the continuing geological mapping, the national monitoring program and research activities. For a consistent estimate of the water resource the national water resources model will provide the overall hydrogeological framework at all levels for the water resource management, i.e. from a national overview to the definition of actions plans at a local level, where the national water resources model can act as the off-set for more detailed model studies.

The national water resource model for Denmark has become a kind of transitional object in the present moment for water managers and modellers for integrating regional and national scale knowledge. By 2007 the regional political structure is redefined in Denmark, where the counties are replaced by larger regions, and the work related to water management is reorganised between the future municipalities and the Danish state. This structural reformation will result in a break of the technical groups in the counties, where some employees are transferred to the municipality, while others will be employed by the state. A severe risk is that the technical expertise and knowledge on the hydrological system, retained in the counties, are lost when the structural reform is effectuated. The updating of the DK-model is thus also seen as a means by which the present knowledge can be stored centrally in a database (the model) combining both soft knowledge, like the perceptions of the hydrological model, as well as hard information, like abstractions, hydraulic head measurements, river discharges etc.

ACKNOWLEDGEMENTS

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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