CHAPTER 9.3

Evaluation of the Quantitative Status of Groundwater—Surface Water Interaction at a National Scale

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9.3.1 Introduction

With the European Union (EU) Water Framework Directive (WFD) the achievement of a good ecological status of surface waters and a good quantitative and qualitative status of groundwater has become obligatory. The ecological status of surface water is here defined by biological, chemical, morphological and hydrological criteria. The WFD calls for combined management of surface water and groundwater, with proper assessment of the influence of groundwater quantity and quality on surface water ecology. Most rivers and other natural surface water systems (lakes, wetlands, etc.) derive their flow from surface runoff and groundwater discharges. The adverse impacts of groundwater abstraction on stream flow depletion define a limit to the exploitable groundwater resources. In addition, it is important to understand better the relationships between groundwater quality in shallow aquifers and deep aquifers, and possible negative effects of excessive groundwater abstraction on future groundwater quality in aquifers that are the backbone for drinking water and the aquatic environment.

The trend in recent years has been to base water management decisions to a larger extent on modelling studies, and to use more sophisticated models. Models have become an essential tool for analyzing complexly managed...
In Europe this trend is likely to be reinforced by the WFD due to its demand for integrating groundwater, surface water, ecological and economic aspects of water management at the river basin scale and due to the explicit requirement to study impacts of alternative measures (human interventions) intended to improve the ecological status in river basins. Large-scale surface water hydrological modelling with dynamic simulation of streamflow hydrographs for catchments of more than 50,000 km² has been carried out in several studies (see Ref. 14 for a review). However, these models did not include simulation of the groundwater system except for the routing of baseflow in large linear reservoirs. Groundwater modelling of hydraulic heads and flow patterns for areas larger than 50,000 km² has been carried out by several researchers. However, these models were all based on steady-state approaches and did not explicitly include surface water processes. Several examples of dynamic and integrated groundwater/surface water models exist for smaller areas. To our knowledge only a limited number of scientifically reported examples cover large-scale modelling of dynamic groundwater-surface modelling with areas of several thousand square kilometres. Examples of such models are the Danubian Lowland in Slovakia and catchments in Kansas.

The adverse impacts of groundwater abstraction on streamflow depletion and wetlands define a limit to the exploitable groundwater resource. 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. Groundwater discharges to streams constitute the major source of streamflow during dry periods, thus the minimum flow can be violated if baseflows are reduced due to groundwater abstraction. The abstraction will influence the flow regime in a way that depends on the characteristics of the aquifer system, the depth and distance of the abstraction from the river and the seasonal/temporal variation in pumping and river runoff. The flow regime is vital for the temporal variability of water depth and velocity, river morphology, sediment transport and bed sediments, and consequently for the water quality and ecosystem that develops.

Freshwater ecosystems are an integral part of the environment and human culture. Even though the WFD clearly states that the utilisation of water, including groundwater, must not negatively impact surface water ecology, an evaluation of how much the regime can be changed for a given catchment or river reach is rather difficult. Traditionally, some of the methods have been used to define a minimum flow, below which no direct influences should take place. However, the current trend is towards methods that consider the flow regime, with some degree of flow variability, to maintain the natural morphology and ecosystem, instead of methods that set one “minimum flow”, e.g. historic flow, or “rule of thumb” methods. The most advanced methods to assess the link between physical/chemical variables and ecosystem state are habitat models.

The literature and the scientific research that focus on the impacts of groundwater abstraction on groundwater quality in shallow and deeper aquifers are rather limited. Todd defined the safe yield of a groundwater basin in a
broad formulation as "the amount of water which can be withdrawn from it annually without producing an undesired result." A review of different methods for determining sustainable yield in groundwater systems can be found in Ref. 30. Sustainable yield is best determined in the context of the basin or groundwater entity water balance. Estimation of basin or groundwater entity pre-development recharge is a relevant activity in the determination of sustainable yield. However, variation in climate and land-use changes will produce uncertainty.

Recently there has been a debate in the literature about the concepts of sustainable development of groundwater resources (sustainability) vs. sustainable pumping.\textsuperscript{31}\textsuperscript{33} The debate was caused by a perceived communication gap between two groups in the hydrogeological community: those concerned with sustainable pumping and those concerned with sustainability. The former group has held that sustainable pumping rates can be determined without measuring recharge (to the aquifer). The latter group holds that recharge measurements are necessary because sustainability is broader than just sustainable pumping. Due to the effects recharge is likely to have on water quality, ecology and socioeconomic factors, it remains important in the assessment of sustainability. For example, recharge could affect the quality of the water in the aquifer and its nutrient content, thus also impacting associated ecological communities.\textsuperscript{31} Sustainability is a goal for the long-term welfare of both humans and the environment. As a result, effort should be made to estimate recharge rates as accurately as possible, when an assessment of sustainability is the objective.

Especially in confined aquifers groundwater recharge may be increased significantly as an effect of abstraction and decrease of groundwater heads. As it is difficult to provide general numbers on the acceptable change in flow regime due to groundwater abstraction, it is also very difficult to give general numbers on how much recharge can be increased before the groundwater quality is significantly affected. Degradation of groundwater quality can become a severe problem due to many different and complex processes. Returned irrigation water or downward leakage from saline aquifers can lead to poor water quality over a period of time. Saltwater intrusion may also limit abstraction. In some areas small changes in water level and release of substances when redox conditions are altered may make a proper assessment delicate and extremely difficult. Prediction of these effects could be achieved using numerical models where necessary, but for basin sustainable yield assessment experience values about the groundwater system resilience would be appropriate. Comprehensive water quality groundwater monitoring datasets could be used for assessment of, for example, a sustainable fraction of the pre-development (virgin) groundwater recharge rate.

The objectives of this chapter are to:

- describe an approach for surface water-groundwater modelling that enables assessment of the effects of groundwater abstraction on surface water quantity at river basin/national scale;
• describe possible criteria for assessing the effect of the quantitative groundwater status on surface water ecology and for groundwater quality also; and
• present results of assessment of sustainable groundwater abstraction at regional and national scale.

9.3.2 The National Water Resource Model
(DK Model)

9.3.2.1 Conceptual Model

The DK model consists of 11 regional sub-models with a delineation based on natural hydrological boundaries.\textsuperscript{34-36} 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 (see Figure 9.3.1) 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.

Four regional sub-models covering the islands of Fyn and Sjælland were applied to a heterogeneous 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 metres to 150 m 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.\textsuperscript{34}

Jylland is split up into six regional sub-models. 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 last sub-model covers the Baltic Sea island of Bornholm. The topography is hilly and most aquifers are found in granite or sandstone and Pre-Quaternary sand. The Quaternary sequence is relatively limited on Bornholm. In terms of both geology and discretisation the Bornholm sub-model differs from the rest of the sub-models.

9.3.2.2 Processes and Data

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.\textsuperscript{34}
Figure 9.3.1 The groundwater model for Sjælland comprises 10 Quaternary layers of alternating sand and clayey till above the chalk and limestone aquifer: south–north cross-section (above) and topographical variation with location of cross-section (below).

- 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 tile 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. Typical cross-sections were applied 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.

The national water resource model (DK model) uses daily precipitation, temperature and reference evapotranspiration as input. The geology has been interpreted for 10 to 50 geological layers based upon several thousands of borehole logs. Groundwater flow in the upper soil layers, drainage systems and rivers is described in a fairly detailed manner.

### 9.3.2.3 Model Code

To simulate the groundwater flow system with emphasis on groundwater-surface water interaction, the MIKE SHE code\textsuperscript{37-40} was chosen. MIKE SHE is a deterministic, fully distributed and integrated hydrological modelling system, which can describe the most important flow processes in the land phase of the hydrological cycle.

In order to save computational time and reduce the data requirements, it was decided to disregard the complex unsaturated zone component in MIKE SHE that is based on Richards’ equation. Instead a simple root zone module was developed for calculation of daily snowmelt and net precipitation.

### 9.3.2.4 Model Parameterisation and Calibration

A grid size of 1 km was chosen as a reasonable compromise. The use of 1 km grids is a rough approximation with simplification of a number of conditions important to the groundwater recharge and streamflow generation, but can be considered reasonable in relation to the modelling purposes.\textsuperscript{34} The guiding principle in the parameterisation was to construct a model with as few free parameters as possible.\textsuperscript{31} 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.

Initial best estimates of hydraulic parameter values and expected ranges have been assessed based on data from field work, previous modelling results and the literature.\textsuperscript{34,35} For the chalk aquifer underlying the Quaternary deposits measured values of transmissivity (extracted from GEUS’s national database) were \textit{a priori} used to interpolate the spatial distribution of the hydraulic conductivity.
Recorded groundwater heads from GEUS's well log archive from 1970 to 1996 were used for calibration. Thus, head data from more than 20,000 wells with screens distributed over different geological layers were used as the measure of observed steady-state hydraulic heads. Daily streamflow data from more than 50 river gauging stations for the period 1990–2000 were used for calibration and validation purposes.

A critique often expressed against distributed models concerns the many parameter values which can be modified during the calibration process. Hence, according to Beven,32 the problem of over-parameterisation is a key characteristic of the distributed model type. In our case we have designed the basic conceptual model with the aim of making maximum use of any structural information, especially geological data, and other existing data sources. For the parameters that had to be assessed through calibration, the general policy was to maintain global parameter values, wherever possible. This implies for instance that all geological layers consisting of sand across one of the 11 model areas are given the same parameter value. Thus in spite of a potential number of different parameter values of the order of $10^6$ for the combined model, all parameter values, except about 10 “free” parameters, were assessed directly from field data. Given the large amount of calibration and validation data, this number of adjustable parameters is small and comparable to a simple lumped conceptual-type rainfall runoff model. We estimated 10 parameter values on the basis of more than 2000 hydraulic heads and daily discharge data from 50 river gauging stations. The parameter values showed robust results when the model was subject to powerful validation tests such as using model parameters assessed in one sub-model to data from other sub-models. This indicates that the present model is not over-parameterised.

The performance criteria were selected in order to reflect the objectives of the modelling, namely to be able to simulate aquifer hydraulic heads and river flows at multiple sites. The four selected criteria, RMS for head simulation, $R^2$ for runoff simulation, $F_{bal}$ for water balance and F-low for low flow simulation, are described in detail elsewhere.34,43

RMS values are basically calculated for each of the nine geological layers, while $R^2$ and $F_{bal}$ are calculated for each of the gauging stations used for calibration. This results in a confusingly large number of performance criteria. Therefore, global values based on averages over the nine layers (weighted by the number of observations per layer) and the 4–20 stations in each of the 11 model areas (simple arithmetic mean) were to a large extent used in the calibration and validation process. While a global value has the advantage of providing a very easy overview, considerable information is lost as compared to the distributed information contained in the individual values. Therefore, two different ways of aggregating the performance while maintaining the distributed information from the different layers/stations have been attempted.

Inverse modelling for steady-state conditions was carried out against groundwater heads and mean river discharges as calibration targets.34,35 This was done by linking MIKE SHE and the universal inversion code UCODE.44 Selected hydraulic conductivity parameters based on sensitivity analysis from each of the 11 model areas were optimised through inverse modelling. Subsequently, the
parameter values for specific yield, surface detention storage and drainage time constant were assessed through trial-and-error using dynamic simulation and discharge as calibration targets. In selected areas (e.g., Sjælland and Jylland) the optimised parameter values were then transferred and applied also to other areas.

9.3.2.5 Model Validation

The following model validation scheme was adopted:

- an ordinary split-sample test using one subset of the period 1990–2000 for calibration and the other part for validation (different selections in different areas dependent on the model construction process which lasted from 1996 to 2003 for the 10 models for the islands and Jylland; for Bornholm the model calibration and validation has recently been finalised); and
- a proxy-basin test with the same parameters as obtained from calibration of a neighbouring model.

Subsequent validation tests of, for example, simulated fluctuations in groundwater head compared to piezometric head observations have further documented the reliability of the DK model for Sjælland.

9.3.2.6 A Few Examples of Model Results

The final results of the DK model for Sjælland, Fyn and Jylland showed that it was possible to construct a combined groundwater/surface water model with a horizontal grid size of $1 \times 1 \text{km}^2$ 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 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. Figure 9.3.2 shows the simulated 1 km $\times$ 1 km net precipitation. Figure 9.3.3 shows the water balance as simulated for Sjælland.

With the DK model well validated, it could be used for scenario calculation for assessing sustainable groundwater abstraction. This was done on the basis of the following.

- The DK model which was used to simulate the groundwater–surface water situation both for pre-development conditions and various scenarios of groundwater abstraction. The model was also able to simulate the effects of different climatic conditions using data from the period 1990–2000.
- A set of criteria or indicators established to quantify the maximum allowable impacts of groundwater abstraction in terms of change in groundwater table, recharge to deep aquifers and baseflow.
- The actual groundwater abstraction in 2000.
The most difficult and controversial of these was the establishment of the set of criteria characterising sustainability. This is described in the following section.

### 9.3.3 Criteria for Sustainable Groundwater Abstraction

Denmark has a rather unique situation. The water supply for drinking water, industrial usages and field irrigation is almost exclusively based on groundwater. The question we have asked ourselves is if we have sufficient amounts of this resource and if the present utilisation of the groundwater resource is sustainable.

For the country as a whole, water abstraction may be less than the exploit-able water resource, which is the amount of water we can pump up, while at the same time maintaining a “good” status of ecosystems and ensuring that
groundwater quality does not deteriorate due to the pumping. A concern here is the uneven distribution of the resource across the country, with the highest net precipitation rates in the western part of the country where the population density is relatively low, and the much smaller net precipitation in the eastern parts of the country where the major cities (Copenhagen, Århus, Ålborg and Odense) are located. This regional pattern is to some extent “compensated” by large irrigation requirement in the western part of the country where soils are more sandy and agriculture is more intense.

The significant utilisation of groundwater, especially in the capital area, has resulted in decreased baseflows and in many situations dried up reaches and wetlands. Furthermore, a decline in groundwater levels of 5–10 m compared to the pre-development (virgin) situation has been seen in some areas. At the same time pesticides, nitrate and other contaminants are transported downwards though the soil layers degrading groundwater quality of shallow groundwater aquifers.

Nitrate and pesticides primarily infiltrate the soil from agricultural land, whereas organic or metallic pollutants come from contaminated land and are released from the soil when groundwater levels decline. Within the last 5 years, pesticides have been found in 26% of waterworks wells, and in 6% of wells the limit values for drinking water have been exceeded. In around 25% of drinking
water wells nitrate is found and the limit value is exceeded in 1%. A new study of the population’s attitude towards treatment of polluted groundwater vs. groundwater protection has shown that Danes are willing to pay extra to protect groundwater and that they prefer to protect groundwater rather than clean it.47

As groundwater movement is very slow this situation is critical when viewed within the WFD framework prescribing future goals for the environment and the groundwater bodies to be achieved within fixed time schedules. Therefore, an assessment of the long-term sustainable exploitable groundwater that can be abstracted is important for water management and policy-making in Denmark.

The factors that have to be taken into account when assessing how much groundwater can be abstracted in a sustainable manner are illustrated in Figure 9.3.4. 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.

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 and 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 layers48 move faster towards the deeper aquifers where most of the groundwater is abstracted (increased deep recharge).

Finally, groundwater resources are known to be vulnerable to variability or change in climate input49,50 (climate variability). These concerns on sustainability

![Diagram of groundwater circulation and related processes.](image)

**Figure 9.3.4** 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.43
Table 9.3.1 The four indicators used to characterise sustainable groundwater abstraction.

<table>
<thead>
<tr>
<th>Indicator no.</th>
<th>Indicator</th>
<th>Factor considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Max. abstraction = 35% of natural recharge</td>
<td>Decreased groundwater table (groundwater quality)</td>
</tr>
<tr>
<td>2</td>
<td>Max. increase of recharge = 30% of natural recharge</td>
<td>Increased deep recharge (groundwater quality)</td>
</tr>
<tr>
<td>3</td>
<td>Max. reduction of annual streamflow = 10%</td>
<td>Streamflow depletion</td>
</tr>
<tr>
<td>4</td>
<td>Max. reduction of low flows = 5, 10, 15, 25 or 50% depending on ecological objective of river reach</td>
<td>Reduced baseflow</td>
</tr>
</tbody>
</table>

were translated by Henriksen and Sonnenborg\(^{43}\) into the four indicators shown in Table 9.3.1.

The indicators chosen to reflect concerns over groundwater quality were flow indicators, *i.e.* indirect measures as compared to more sophisticated indicators based on groundwater 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 × 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.

It should be remembered that the selected 35% and 30% limits were derived for the specific sub-catchment scale and settings for Danish aquifer systems viewed “as an entity” and not as a measure for evaluating the sustainable pumping rate from a single specific well field. This also means that if we zoom in on a single well field and a scale of say 30–200 km\(^2\) then the limit values would probably increase to say 70% and 60% or even higher in some areas, while it would decrease in other areas. This means that the sustainability is bounded to the scale used for the modelling purposes and the assessments.

Overall the exploitable groundwater resources were assessed for aquifers at 30 to 50 m depths from where the majority of groundwater abstractions 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.

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 as
A (waters for scientific reference areas), B1 (salmonidae spawning and nursery waters), B2 (salmonidae waters; nursery and living areas for trout), B3 (cyprinid waters) and C-F (watercourses solely used for drainage purposes, waters where authorised 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 knowledge more than 25 years old. However, the most important limit value of 10% for B1 is supported from similar requirements for trout waters, e.g. in the UK where a maximum 10% reduction in habitat area is used as a requirement for salmonidae spawning and nursery areas (B1) and when assuming a "linear relationship" between habitat area reduction and flow reduction which is a fair assumption for the minimum flow regime.

9.3.4 Model Results

In the assessment of the national resource of Denmark, 50 sub-catchments (2–7 in each of the 11 areas) were delineated in order to provide a detailed enough picture for the whole country without being compromised by too large a model uncertainty.

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 were 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 sustainable abstraction. The summary results for the four indicators are shown in Table 9.3.2.

If we take Fyn as an example, the actual abstraction for 2000 was 12.8 mm yr\(^{-1}\) (Table 9.3.2). For this area, indicator 4 (baseflow reduction) is the most critical of the four indicators (available sustainable resource \(\sim 10 \text{ mm yr}^{-1}\)), with B1 (salmonidae spawning and nursery waters) as the river reaches defining the sustainable abstraction. The current abstraction of 12.8 mm yr\(^{-1}\) gave a reduction for Fyn of 11% in the minimum flow situation, which is slightly above the limit value of 10%. Indicators 1 and 2 (groundwater quality) result in a less critical available resource estimate (15–17 mm yr\(^{-1}\)), based on a calculation of deep recharge of 46 mm yr\(^{-1}\) without pumping, and 51 mm yr\(^{-1}\) 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, indicators 1 and 2 were estimated to the ranges shown in Table 9.3.2. The reduction in average streamflow (indicator 3) is less critical, compared to other indicators, showing an available resource range of 17–29 mm yr\(^{-1}\). Based on the indicator results 1–4, the "worst case scenario" indicator is picked, which for Fyn is indicator 4, and the last two
Table 9.3.2  Assessment of available resources for Fyn, Sjælland and Jylland (the results for Bornholm are not yet available). Results for indicator 1–3 (groundwater quality, streamflow decrease and climate variability), compared to indicator 4 (baseflow reduction).

<table>
<thead>
<tr>
<th>Region</th>
<th>Abstraction 2000 mm/ year(^a)</th>
<th>Area km(^2)</th>
<th>Ind.1 mm/ year(^b)</th>
<th>Ind.2 mm/ year(^b)</th>
<th>Ind.3 mm/ year(^b)</th>
<th>Available resource mm/ year</th>
<th>Available resource mill m(^3)/y</th>
<th>Total Abstract mill m(^3)/y(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fyn</td>
<td>12.8</td>
<td>2945</td>
<td>10</td>
<td>15–17</td>
<td>15–16</td>
<td>17–29</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>2 W-Sjælland</td>
<td>7.9</td>
<td>3281</td>
<td>10</td>
<td>9–10</td>
<td>9–10</td>
<td>17–28</td>
<td>9</td>
<td>28</td>
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<tr>
<td>3 S-Sjælland</td>
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<td>3207</td>
<td>8</td>
<td>8–8</td>
<td>8–8</td>
<td>21–27</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>4 N-Sjælland</td>
<td>39.1</td>
<td>2831</td>
<td>14</td>
<td>25–30</td>
<td>23–27</td>
<td>12–23</td>
<td>12</td>
<td>33</td>
</tr>
<tr>
<td>5 S-Jylland</td>
<td>26.0</td>
<td>4500</td>
<td>47</td>
<td>47–52</td>
<td>40–45</td>
<td>&gt;52</td>
<td>40</td>
<td>180</td>
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<tr>
<td>6 SW-Jylland</td>
<td>66.4</td>
<td>5263</td>
<td>60</td>
<td>57–71</td>
<td>49–61</td>
<td>40–68</td>
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<tr>
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<td>4705</td>
<td>26</td>
<td>28–31</td>
<td>25–27</td>
<td>41–64</td>
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<tr>
<td>8 W-Jylland</td>
<td>36.0</td>
<td>5291</td>
<td>39</td>
<td>67–86</td>
<td>58–75</td>
<td>&gt;50</td>
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<tr>
<td>9 E-Jylland</td>
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<td>4418</td>
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<td>34–41</td>
<td>30–37</td>
<td>26–38</td>
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<tr>
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<td>33–42</td>
<td>29–37</td>
<td>31–41</td>
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<tr>
<td>Total</td>
<td></td>
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</tbody>
</table>

\(^a\) 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 to 1/3 of the permission for 2000).

\(^b\) The range signifies an estimate of the indicator value given a net precipitation 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).
columns in the table show the result of the assessment in million m$^3$ yr$^{-1}$, 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 9.3.2 estimates for sub-areas e.g. vital drinking water areas (in Danish, Områder med særlige drikkevandsinteresser) and for sub-areas in each region were determined. 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 9.3.2. Based on the “sub-area scale” of the 50 sub-areas the total available resource comprises $1024 \times 10^6$ m$^3$ yr$^{-1}$, which is $30 \times 10^6$ m$^3$ yr$^{-1}$ 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 have to be reconsidered if using the methodology and the indicators for different scales. In Figure 9.3.5 the resource estimates for sub-areas and regions are shown.

For the whole country exploitable groundwater resources is estimated to be $1.0 \times 10^9$ m$^3$ yr$^{-1}$. The assessment in Figure 9.3.5 depicts areas around Copenhagen, Odense and Arhus as overexploited areas due to abstraction for water supply. In addition, areas with coarse sandy soils in western Jylland are also threatened by overexploitation due to irrigation demands.

In most of these areas the problem of overexploitation 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 are 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 increased detection of contaminants in shallow aquifers over the past several decades has forced a change in groundwater abstraction patterns from 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 uncertainty related to the new assessment has been estimated to ±10% for the total exploitable resources. For the 11 regional model areas into which the model has been subdivided, the uncertainty has been estimated to ±20% (in size corresponding to Danish WFD areas). For 50 sub-areas the uncertainty has been estimated to ±40%. To reduce these uncertainties a more detailed model with a finer grid and a more explicit analysis of the spreading of the shallow contamination towards deeper aquifers are required.

Intensive abstraction impacts groundwater vulnerability, both in terms of increased risks of pollution from land surface, and also in terms of increased risks for 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 maximum 35% of the groundwater recharge to the deep groundwater aquifers is sustainable (at depths of 30 to
Figure 9.3.5 Resource availability status. Light grey areas: water available (sustainable yield above current exploitation); gray areas: no water available (current abstraction and sustainable yield is in balance); dark grey: overexploited areas. White bars show sustainable yield and dark bar current abstraction for regions.

50 m 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 (Fyn and Jylland). 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, e.g. 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 were long ago drained?
9.3.5 Discussion and Conclusions

9.3.5.1 Appropriateness of Approach for the WFD

The approach is considered appropriate for the WFD. It offers an integration of groundwater and surface water by the use of groundwater and surface water models that can be used to analyse the interaction between these two domains. The sustainability criteria focusing on avoiding significantly negative impacts of groundwater abstraction on both surface water ecology (criteria 3 and 4) and groundwater quality (criteria 1 and 2) are well in line with the underlying WFD principles. Furthermore, the approach provides a transparent, practical and scientifically based methodology for assessment of sustainable groundwater abstraction.

As phrased by Sophocles, sustainability depends on the entire system, "not just the trees, but the whole forest; not just the fish, but the marine food chain; not just the groundwater, but the running streams and wetlands, and all the plants and animals that depend on them." Sustainability is a goal for the long-term welfare of both humans and the environment. Additionally, any scientifically based evaluation of sustainability requires model support to assess the behaviour of all the important flow processes within the hydrological cycle and to assess the behaviour of the aquifer, including the interaction with surface water systems, and its sustainable exploitation. Devlin and Sophocles support this choice of recharge to the aquifer as an important part of such an assessment of sustainability arguing that it is evident that sustainability is a function of recharge, and that recharge rates cannot be ignored.

But sustainable use of groundwater in the WFD must ensure not only that the future resource is not threatened by overuse, but also that natural environments that depend on the resource, such as baseflows, riparian vegetation, aquatic ecosystems and wetlands, are protected. By applying two indicators, one for evaluation of influence on mean river flow and the other for evaluation of reduction of river low flow when pumping under present groundwater development conditions compared to the pre-developmental (virgin) situation, a sound and intuitive methodology ensures that both groundwater recharge and runoff are included. Thereby, the groundwater body as an entity is encapsulated by the suite of four selected indicators.

By using four indicators it is possible to view the resource either as a question of ecological sustainability or as a groundwater quality sustainable abstraction problem or even, as presented for the Danish case, by assuming that both conditions should be supported simultaneously, by selecting the most critical of the four indicators when assessing a sustainable resource. However, although the general methodology is sound and balanced with the four indicators, the argumentation for their specific limit values, e.g. a maximum abstraction of 35% of the groundwater recharge to an aquifer entity in a depth of 30–50 m below the surface in the virgin, pre-development situation or a maximum reduction of baseflow by, say, 10%, have to be based on proper monitoring data. Without any relation to monitoring these assessments are not valuable for
marking the boundary between sustainable yield and overexploitation of an aquifer.\textsuperscript{11} Of course they may be used for overall mapping purposes, but as something that guides the WFD and the management of groundwater in reality. The challenge is to link the modelling approach with monitoring.

\textbf{9.3.5.2 Linking the Modelling Approach with Monitoring}

Even though the main cause of groundwater pollution is related to poor land use, intensive agriculture and insufficient industrial and domestic waste treatment and disposal, there is a growing recognition that changes in groundwater flow and groundwater level (and abstraction) can significantly change the chemical composition of groundwater with detrimental effects on the sustainable yield for an aquifer.\textsuperscript{10,53} Examples include sea water intrusion as a result of intensive pumping of near-coastal aquifers, the release of toxic constituents (manganese, iron, selenium, sulfide, nickel) as a consequence of lowering groundwater levels and subsequent entry of oxygen into the previously anaerobic environments. Furthermore, certain chemicals intentionally or unintentionally released to groundwater environments, like pesticides and petrol products, may undergo transformation and degradation processes in the subsurface rendering them more harmful to the environment and health than their original counterparts.\textsuperscript{10,53} These interrelated factors and processes are complex and difficult to predict which means that site-specific and chemical-specific knowledge and data are necessary with requirements for proper and focused groundwater monitoring.

Limitations in data and analyses can result in misinterpretation of groundwater conditions, primarily due to the use of an inadequate conceptual model. There is a great need for improved data collection to better estimate groundwater conditions, including long-term changes in storage by aquifers and for an appropriate hydrological study period, and for understanding future water availabilities. Long-term, systematic monitoring and assessment programmes are integral to sustainable, adaptive groundwater management.\textsuperscript{12}

The EU WFD provides new requirements for the monitoring of the freshwater cycle. Errors in estimation of the water balance will affect the accuracy of mass loading calculations. Estimates of the various water balance elements can be strengthened by a combined use of monitoring and modelling. This is particularly the case for groundwater recharge, which cannot be measured directly. Use of a catchment-scale integrated surface water/groundwater model like the DK model is an obvious opportunity in this respect. In the Danish monitoring programme single elements of the water balance (quality and quantity) are monitored in supply wells, monitoring wells from 70 small monitoring areas (GRUMO) and in five small catchments (LOOP). However, these sub-programmes are only integrated to a limited degree and each of them only provides windows instead of the complete picture of the state of the water environment. Therefore, a combination of the monitoring and the national model provides an opportunity to get a more complete picture of the water
status. On the one hand, the model can be used to make knowledge-based (e.g. using geological data) interpolation between the various monitoring sites and provide information on variables such as groundwater recharge that are impossible to measure in practice. Furthermore, the model can help in separating variability (noise) generated by climate from anthropogenic effects. On the other hand, the model is based on data from the monitoring programme both for conceptualisation of aquifer systems and for selecting suitable indicators such as 35% of the pre-development recharge being considered as a sustainable fraction of groundwater abstraction.

9.3.5.3 Strengths and Weaknesses of Approach

The sustainability criteria represent both the major strength and the major weakness of the approach. The fact that the approach is based on transparent criteria is a major advantage. Many sustainability studies in practice rely on qualitative criteria such as the definition of safe yield by Todd\(^{29}\) as an amount of water abstraction that does not produce undesirable results. Such qualitative (“undesirable”) criteria enlarge the room for non-specific politically oriented statements and ambiguity among stakeholders and water resources managers. We believe that it is much sounder to define quantitative criteria and then use models to assess the consequences. This will not remove the differences of interests among stakeholders, but it will make the dialogue more knowledge based and more transparent.

The major weakness then lies in the establishment of the specific criteria. All of the criteria we have selected can be subject to a dispute and the knowledge bases behind some of them are arguable. The criteria aimed at ensuring groundwater quality (indicators 1 and 2) are based on large-scale monitoring data from only a part of the country (Sjælland) and it is not documented that the specific figures also apply to hydrogeological conditions in other parts of the country. It may also be argued that the indicators instead ideally should be based on a more qualified and precise analysis of the dynamics of flow system development and the possible spreading of shallow contamination towards deeper aquifers, including the influence of abstraction. This was, however, not possible within the scope of the present study and would, among other things, require a lot of detailed data that were not available.

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, e.g. using habitat models. Another issue which needs further consideration is the choice of reference scenarios in urban areas (e.g. in Copenhagen). For example, does it make sense to base the reference situation on conditions where the current groundwater abstractions are “turned off” (virgin, pre-development conditions), in an area where creeks and headwaters were long ago drained?
A better evaluation of climate impacts, especially in areas where the sustainability indicators show significant dependency of net precipitation, 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.

A weakness in the approach is that water level is not part of any of the proposed four indicators; however, this may also be seen as a strength because the approach is entirely flow based, and therefore much more robust and useful for assessment of groundwater aquifers as an entity. However, for optimisation of situations at well fields more detailed studies and analysis are required.

In general the strength of the approach is the robust flow-based methodology where the sustainability factors (in percentage of flow, e.g. 35% of deep recharge for indicator 1 and 10% reduction of baseflow discharges from groundwater to surface water for salmon spawning for indicator 4) are assessed based on groundwater quality monitoring data, and/or “rule of thumb” assessments of how much baseflow can be reduced without impacting ecological goals.

An important weakness is that the approach is designed for a specific scale (300–2000 km²) of sub-areas and that use on other scales requires reassessment of “sustainable fractions” for the four indicators. Furthermore, for management of licences and optimisation of abstractions in an area, more specific and physical-based indicators are necessary, e.g. those that focus on groundwater levels and/or water levels and water moisture contents in wetlands and surface water systems. The DK model is primarily set up for simulating flow and not water levels, which require a much more detailed approach for defining the variations in water level (grid refinement, more detailed representation of rivers, drains and abstractions and a more detailed geological model, especially for the shallow flow system).

The scenario approach makes it flexible for exploring the effects of the alternative approaches and linking groundwater and surface water, groundwater quantity modelling and quality monitoring, rural and urban areas and groundwater resources and socioeconomic factors. These links govern the human decisions on how to develop and benefit from natural resources and ultimately adapt to potential negative consequences of overexploited and degraded resources. This interrelatedness of the DK model and the four indicators is perhaps the greatest strength of the approach. Thus it will be very easy to carry out new scenario calculations if stakeholders and water managers want to study the effects of using other sustainability criteria.

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. During the modelling process we experienced a large number of errors in data and conceptualisation that were corrected after feedback from the numerical model. One example is that we discovered significant water balance errors
(groundwater recharge and streamflow discharge overestimated by around 20%) that might have affected the estimates of nitrate leaching.

9.3.5.4 Novelty of This Work

The construction of a national hydrological model of the present complexity is a major task and a novelty. 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 they inevitably will contain some mutual inconsistencies.

Development of criteria for sustainable developments enabling scenario simulations based on four different sustainability indicators applied for examining the influence on river runoff (mean and minimum flow) and groundwater recharge (drawdown and water quality issues) using a practical model-based approach to predict the present quantitative exploitation is another novelty. In the approach emphasis is directed toward the documentation of the predictive capability of models in order to avoid the often and sometimes with good reason questioned credibility of model-based sustainable resource assessments for groundwater aquifers and/or river catchments.

The major novelty and perspective of this work are probably the combination of a comprehensive integrated groundwater/surface water model and the sustainability criteria for a tool used for scenario simulations on issues that are directly relevant for the WFD implementation.

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