IMPACT ASSESSMENT OF FUTURE CLIMATE CHANGE ON GROUNDWATER IN DENMARK

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ABSTRACT

The effects of future climate change on groundwater in Denmark are studied using the national water resource model. One model area in the west of Denmark is selected (south-west Jutland) and one area in the east (Zealand). The meteorological input for the hydrological simulation of the future conditions consists of a perturbed database of observed variables representing the present climate (precipitation, temperature and reference evapotranspiration). The database is perturbed using climate change signals derived from output from a regional climate model (delta change method) for two climate scenarios (A2 and B2). The change in the output from the root zone module shows the effect of changes in meteorological input on recharge to the groundwater system. For the Jutland area an increase in hydraulic head is predicted for both climate scenarios, though large variations within the area occur and the largest increase occurs during the winter months. For Zealand the A2 scenario results in no change in hydraulic head whereas the B2 scenario shows an increase.

1. INTRODUCTION

The water supply in Denmark is largely based on groundwater. For this reason it is important to determine the effects of future climate change on groundwater as soon as possible and as realistically as possible. In this study meteorological output from a regional climate model is used to generate scenario simulations with a groundwater model. The effects of future changes in precipitation, temperature and evapotranspiration on the output from the root zone model are presented in this article. The effect of climate changes on groundwater in Denmark are assessed by simulating the change in hydraulic head in a number of layers of the goundwater model.

2. NATIONAL WATER RESOURCE MODEL

The national water resource model for Denmark is used to study the effects of future climate change on water resources in Denmark. As described in Henriksen et al. (2003) this is an integrated groundwater/surface water hydrological model with a 1 km^2 grid resolution covering Denmark (43,000 km^2 in all). The model is constructed on the basis of the MIKE SHE code and is composed of a comprehensive three-dimensional groundwater component for estimating recharge to and hydraulic heads in different geological layers, a river component for stream flow routing and calculating stream-aquifer interaction. A relatively simple, stand-alone root zone component (Sonnenborg et al., 2003) is used to calculate the recharge (precipitation minus actual evapotranspiration and storage in the root zone) to the uppermost layer of the groundwater/surface water model.

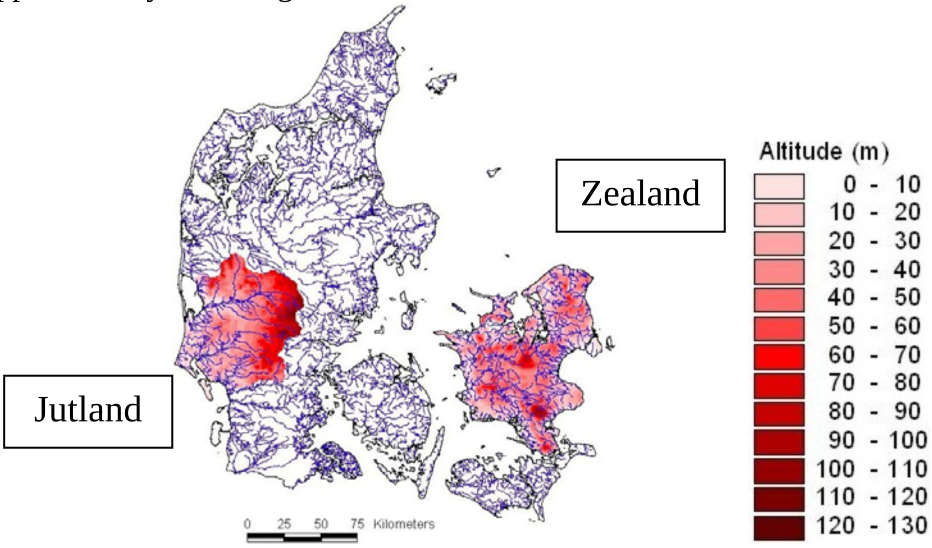

FIGURE 1. Map of Denmark showing the two model areas, south-west Jutland in the west and Zealand in the east of Denmark.

The national water resource model is divided into a number of sub-models of which two have been selected for this analysis. Figure 1 shows one model area on the west coast of Jutland (5263 km^2) and another covering the whole island of Zealand (7031 km^2). These areas have been selected because they differ from each other geologically, with the Jutland area being characterized by relatively highly permeable formations, whilst the Zealand area has a lot of low permeable moraine deposits in the upper layers. These areas also differ climatologically, with significantly more precipitation in the Jutland area than in the Zealand area, while the potential evapotranspiration is slightly higher on Zealand. Due to the higher precipitation and permeability of the geological layers the groundwater recharge is much larger for Jutland than for Zealand.

3. PRESENT AND FUTURE METEOROLOGICAL INPUT

In this study three meteorological variables are used to study the effects of future climate change on water resources in Denmark, namely precipitation, temperature and reference evapotranspiration. The meteorological database with observed values, used in the hydrological model for the present climate simulation, consists of daily values for the three variables for the period 1971-2004. The first 20 years are considered as a warm-up period in which the initial conditions influence the hydrological output, so only the last 15 years, 1990-

2004, are used for the analysis of changes in the hydrological system. In this article this period will from now on be indicated as the present period.

The regional climate data used in this study has been dynamically downscaled using the regional climate model (RCM) HIRHAM (Christensen et al., 1996) from the Danish Meteorological Institute. In this experiment HIRHAM is nested in the global circulation model HadAM3H (from the Hadley Centre) and the Intergovernmental Panel on Climate Change A2 and B2 scenarios are used. HIRHAM gives output for two time-slices: the control period 1961-1990 representing the present climate and the scenario period from 2071-2100 representing the future climate. The climate output for the A2 scenario is available at 12 km horizontal grid resolution whilst the output for the B2 scenario has a resolution of 50 km.

3.1 Delta change method

It is not straightforward to use output from regional climate models directly in hydrological studies, due to the fact that systematic biases occur between the meteorological output from regional climate models for the control climate and observed data. In this study the so-called delta change method (Graham et al., 2004; Lenderink et al., 2004) is applied to by-pass these biases. This method consists of perturbing an observed database with monthly delta change factors, so as to obtain the “future” database. These delta change factors have been calculated using the relative change (for precipitation and evapotranspiration) or absolute change (for temperature) between the RCM output for the control and future run. The future input series are given by:

$$P_{fut}(t) = P_{obs}(t) \times (\overline{P}_{scen} / \overline{P}_{cont}), t = 1,...,15\, years$$

$$T_{fut}(t) = T_{obs}(t) + (\overline{T}_{scen} - \overline{T}_{cont}), t = 1,...,15\, years$$

where P_{fut} is the precipitation input (in mm/day) for the hydrological simulation of the future situation. P_{obs} is the average precipitation rate (mm/day) in the observed database, which is used as input for the hydrological simulation of the present climate. $\overline{P}_{scen}$ and $\overline{P}_{cont}$ represent the average precipitation rate (mm/day) as predicted by the RCM for the scenario period and the control period, respectively. The input database for reference evapotranspiration is perturbed in the same way as for precipitation, where the ET_{ref} for the climate model control and scenario is calculated using the FAO Penman-Monteith method (Allen et al., 1998). T is temperature and the same subscripts are used as for precipitation.

The climate model output used in this study are monthly averages of daily values, where these monthly averages have been averaged over the 30 years of the control or scenario run. This results in sets of 12 values (one for every month) for the control and 12 for the scenario for precipitation, temperature and reference evapotranspiration. Spatial averages for Denmark are used, representing 256 climate model grid cells for the A2 scenario and 16 cells for the B2 scenario.

3.2 Precipitation

The following analysis of precipitation, temperature and potential evapotranspiration is based on one grid cell (40 x 40 km) from the observed meteorological database covering the central part of the model area on Jutland and on another cell covering the central and south-western part of Zealand. Table 1 gives the average annual precipitation for Jutland and Zealand for the present period and for the two scenarios. For the A2 scenario the average annual precipitation increases with 129 mm (12%) for Jutland and 71 mm (9%) for Zealand.

Even though the same monthly delta change factors are used for Zealand and Jutland to generate the scenario precipitation input, the relative change in annual precipitation is different for the two areas due to slight differences in the monthly distribution of precipitation. The B2 scenario shows a larger increase in precipitation than the A2 scenario. For Jutland the increase in annual precipitation is 171 mm (16%) and for Zealand the increase is 110 mm (14%).

TABLE 1. Average annual precipitation (mm), temperature (°C) and reference evapotranspiration (mm) for the model areas Jutland and Zealand for the present period and for the A2 and B2 scenario. Relative changes are shown in brackets for precipitation and evapotranspiration and absolute changes are given for temperature.

	Jutland			Zealand		
	Present period	A2 scenario	B2 scenario	Present period	A2 scenario	B2 scenario
Precipitation (mm)	1073	1202 (11.9%)	1244 (16.0%)	762	833 (9.1%)	872 (14.4%)
Temperature (°C)	8.2	11.4 (3.2)	10.5 (2.3)	8.6	11.7 (3.1)	10.8 (2.2)
Reference evapotranspiration (mm)	570	677 (19.2%)	649 (14.1%)	611	725 (19.2%)	695 (13.8%)

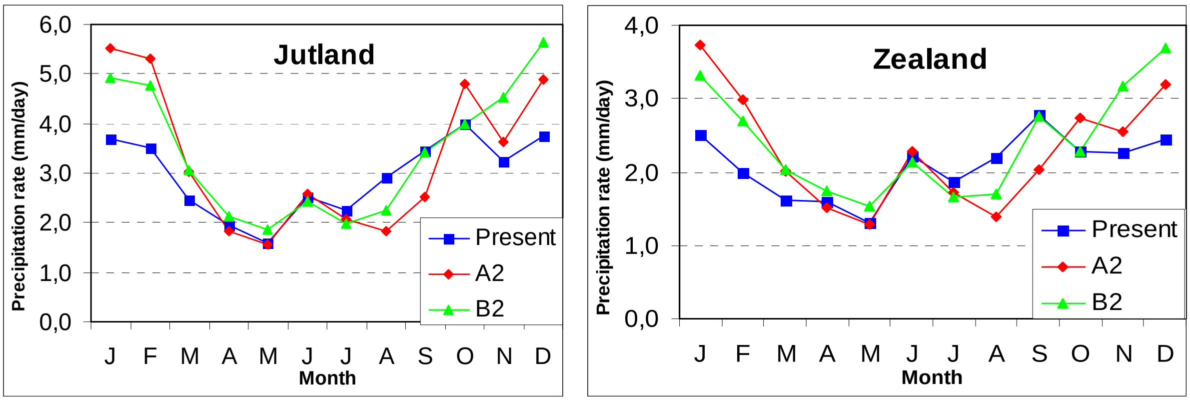

FIGURE 2. Average monthly precipitation rate (mm/day) for the present period and for the A2 and B2 scenario for Jutland and Zealand.

Figure 2 shows the seasonal distribution of the average monthly precipitation rate (mm/day) for Jutland and Zealand for the present and future. The largest absolute difference compared to the present period occurs in the winter months (December to February), whilst there are smaller changes throughout the rest of the year. Only August shows a clear reduction in precipitation for both scenarios, but the A2 scenario also predicts a large reduction in September.

3.3 Temperature

In the hydrological simulations temperature controls whether precipitation is fluid or solid and whether the snow storage increases or decreases. Furthermore the temperature is incorporated in the calculation of reference evapotranspiration. Table 1 shows the average annual temperature for the model areas on Jutland and Zealand for the present period and the two future scenarios. The temperature is predicted to increase around 3 and 2 degrees, for the A2 and B2 scenario respectively. No large variations occur in the temperature increase for the various months or seasons, but a slightly larger increase can be seen from August to November, whilst the increase is smallest from February till June (van Roosmalen, 2006). The increase in average temperature during the winter months will have a large influence on the number of days with snow in the future.

3.4 Reference evapotranspiration

Table 1 gives the annual ET_{ref} values for Jutland and Zealand for the present period and the two scenarios. The A2 scenario results in an increase of 107 mm for Jutland and 114 mm for Zealand, which for both areas is an increase of 19%. For the B2 scenario the increase is not as large as for the A2 scenario with an increase of 79 mm and 84 mm for Jutland and Zealand, respectively, which is around 14% for both areas. The average monthly ET_{ref} rates are predicted to be higher in the future period than for the present period for all months and for both the A2 and B2 scenarios. Relatively, the largest change occurs during the winter months (60-80%), but due to the low ET_{ref} during winter, the largest absolute changes occur during summer, where the relative change is around 30%.

4. RESULTS

4.1 Root zone module output

The meteorological input data is used in the root zone module to calculate the recharge to the uppermost computational layer of the surface water/groundwater model. The recharge results presented here are averaged over the whole model area of either Jutland or Zealand and the analysis is based on the observed data from the period 1990-2004. Table 2 gives the average annual recharge and Figure 3 shows the average monthly recharge rate for the present period and for the A2 and B2 scenario for the two model areas.

For both scenarios and both areas the annual average recharge calculated by the root zone module is larger compared to the present period. Especially the B2 scenario predicts a large increase, with absolute values of 128 mm/year and 79 mm/year for Jutland and Zealand, respectively, corresponding to increases over 20%. The absolute values for the increase when using the A2 scenario are 77 mm/year and 42 mm/year for Jutland and Zealand, respectively. The seasonal distribution of recharge (see Fig. 3) shows similar trends for both areas and both scenarios. A large increase in recharge is predicted for the period December to March. From April till June the changes are relatively small, whilst a decrease in recharge is predicted for the period July till October. In November the B2 scenario predicts a large increase in recharge whilst the A2 scenario results in a value close to the recharge in the present period.

TABLE 2. Average annual recharge (mm) for Jutland and Zealand for the present period and for the A2 and B2 scenario with the relative change in brackets.

Area	Present period	A2 scenario	B2 scenario
Jutland	580	657 (13.2%)	708 (22.0%)
Zealand	287	329 (13.9%)	366 (26.6%)

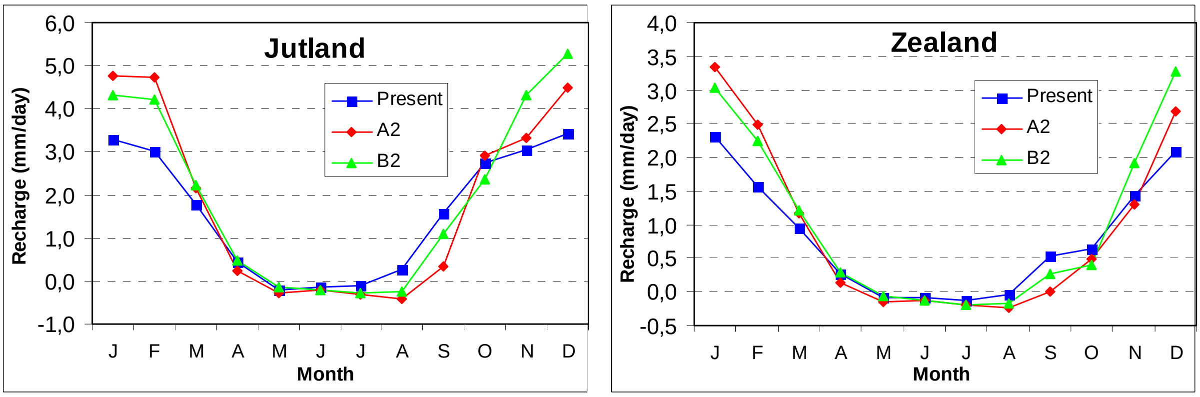

FIGURE 3. Average monthly recharge rate (mm/day) for the present period and for the A2 and B2 scenario for Jutland and Zealand.

4.2 Change in hydraulic head – Jutland

The changes in hydraulic head presented here are based on simulations with the hydrological model without irrigation and groundwater abstraction, so that only the change in meteorological inputs influences the change in groundwater level and that a change in irrigation demand does not. Table 3 shows the average increase in hydraulic head for computational layers 1, 3 and 5 of the model for Jutland for the A2 and B2 scenario, averaged over the model area. Layer 1 represents the upper groundwater reservoirs and has a free water table. Layer 5 represents the primary reservoir in this area. The B2 scenario results in nearly double as large an increase (30 cm in layer 1 and 43 cm in layer 3 and 5) as for the A2 scenario (16 cm in layer 1 and 25 and 26 cm in layer 3 and 5 respectively). It should be noted that the drains in layer 1 are located at half a meter under the surface, which means that the increase in hydraulic head is limited above this level. For this reason the increase in hydraulic head in layer 1 might well be underestimated.

Figure 4 shows the change in hydraulic head when comparing the B2 scenario to the present period for computational layer 1 and 5 of the Jutland model area. The average increases in hydraulic head cover a large geographical variation. The largest increases occur at the watershed boundary in the north-east with increases of around 1-2 metres. Layer 1 shows smaller increases alongside water bodies. Larger increases occur in the northern part of the model area than in the south. The groundwater level (layer 1) drops during the period May to October in many places due to the reduced recharge during the summer months for both scenarios. During the winter months the groundwater level increases significantly, especially for the B2 scenario with increases over 25 cm for most of the model area.

TABLE 3. Average change in hydraulic head (m) for layer 1, 3 and 5 of the Jutland model when comparing the A2 and B2 scenario to the present period.

Model layer	A2 scenario	B2 scenario
1	0.16	0.30
3	0.25	0.43
5	0.26	0.43

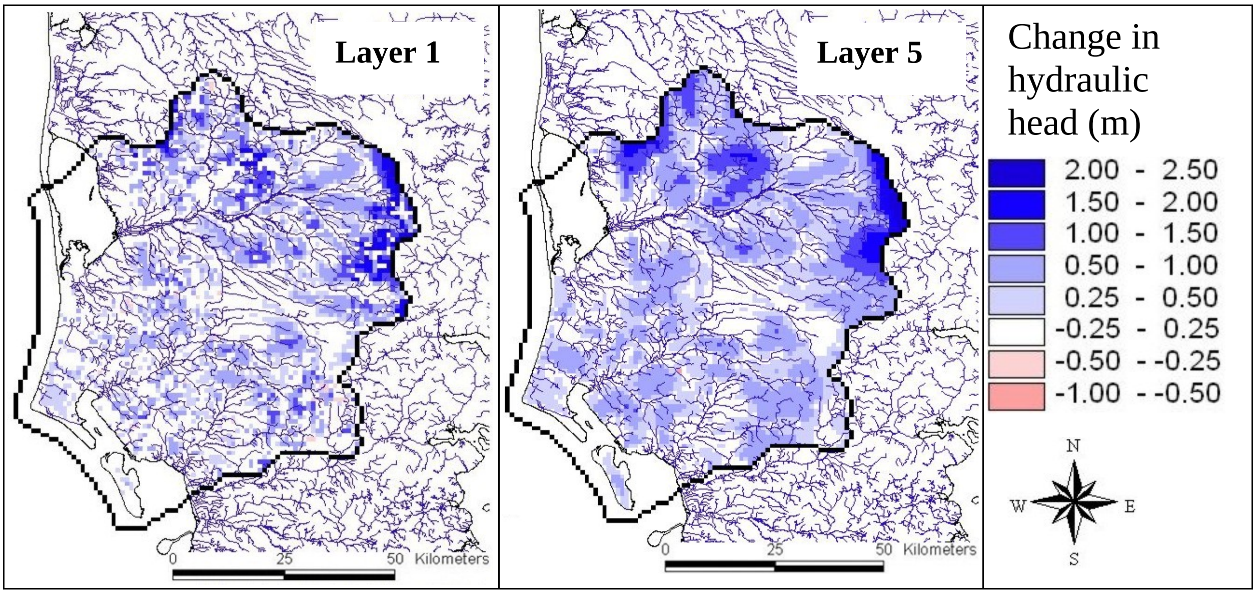

FIGURE 4. Average change in hydraulic head (m) in Jutland for model layer 1 and 5 when comparing the B2 scenario to the present period.

4.3 Change in hydraulic head – Zealand

The results presented for Zealand are also for the hydrologic simulation without irrigation and groundwater abstraction. Table 4 shows the average increase in hydraulic head for computational layers 3 and 9 of the model for Zealand for the A2 and B2 scenario, averaged over the model area. Layer 3 represents the upper groundwater reservoirs and layer 9 represents the primary reservoir of the area. For the A2 scenario it can be seen that the hydraulic head hardly changes, whilst for the B2 scenario an increase of around 15 cm is predicted.

Figure 5 shows the change in hydraulic head when comparing the A2 scenario to the present period for computational layer 1 and 5 of the Zealand model area. A considerable regional variation occurs with an increase in the north-eastern part for both scenarios whereas in the south-western part the A2 scenario results show decreases in many places and the B2 scenario predicts hardly any change for this part of Zealand. This geographical difference can partly be explained by looking at the geographical distribution of the change in recharge (output from the root zone module), which shows that most places where the hydraulic head drops correspond with locations where the change in recharge is negative. In the north-eastern part the soil layers above the primary aquifer are more permeable than in the rest of Zealand resulting in higher recharge during winter and increasing hydraulic head (similar to the results found for Jutland). For more details and results see Sonnenborg et al. (2006).

TABLE 4. Average change in hydraulic head (m) for layer 3 and 9 of the Zealand model when comparing the A2 and B2 scenario to the present period.

Model layer	A2 scenario	B2 scenario
3	-0.02	0.15
9	0.01	0.15

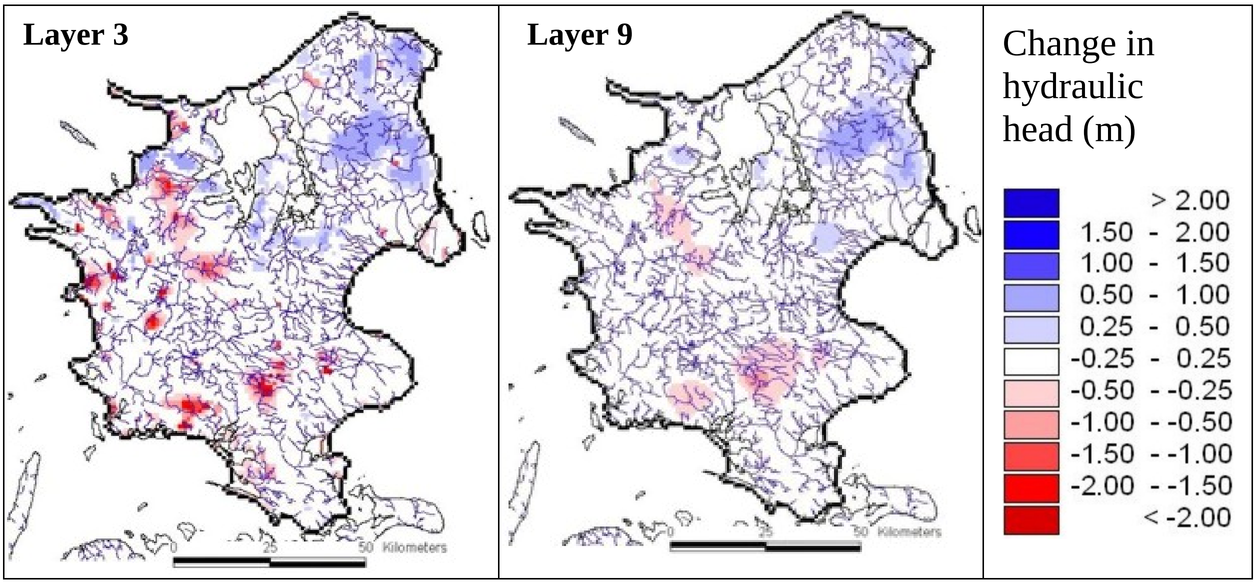

FIGURE 5. Average change in hydraulic head (m) in Zealand for model layer 3 and 9 when comparing the A2 scenario to the present period.

5. CONCLUSIONS

The results of this study show that future climate changes most likely will have an effect on groundwater in Denmark. For both scenarios and both model areas the annual recharge calculated by the root zone module is larger compared to present. The increase is especially large for the B2 scenario with increases in average annual recharge over 20%, as compared to around 14% for the A2 scenario. During the period December to March the largest increases occur, whilst from July till October the largest decreases occur.

In Jutland the hydraulic head is shown to increase for both scenarios, though the B2 scenario results in nearly double as large an increase in head as the A2 scenario does. The average increase in hydraulic head for the whole area is in the order of 20 till 40 cm, though in some places increases of 1-2 m occur. For Zealand the A2 scenario gives no change in average hydraulic head, but in the south-western region large decreases occur locally. The north-eastern region shows an increase in hydraulic head. For the B2 scenario an average increase of around 15 cm is predicted.

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