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Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

Denmark

Authors and affiliation:

Ida Karlsson

Jacob Kidmose

Geological Survey of Denmark and Greenland

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LIST OF ABBREVIATIONS & ACRONYMS

DK-model	The National Water Resources Model for Denmark
DMI	Danish Metrological Institute
GEUS	Geological Survey of Denmark and Greenland
MSL	Main Stationary Line
GCM	Global Circulation Model
RCP	Representative Concentration Pathway
RCM	Regional Climate Model

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1 EXECUTIVE SUMMARY

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The pilot of Denmark include many different aquifer-types with the most important one being glacial melt-water sand aquifers, Miocene sand aquifers, and chalk aquifers. These aquifers constitutes by far the most impotant, qualitively as well as quantitatively, water-ressource in Demmark. 100 % og the Danish water suply for drinking water is groundwater based.

In the context of TACTIC, a climate change impact asssesment on both shallow and deeper groundwater conditions have been performed by the use of the National water-resources model, the DK-model. The DK-model is an integrated hydrological model based on MIKE SHE and MIKE HYDRO. To assess future groundwater conditions in Denmark, two independant groups of climate change scenarios, climate for the future, have been used to force the hydrological models.

Predictions of the future groundwater conditions are not clear in terms of the direction change. Both groups of scenarios, the TACTIC standard scenarios, developed within TACTIC but based on the international ISIMIP consortium, and Euro-CORDEX based scenarios, show scenarios with lower shallow and deeper groundwater levels and scenarios with higher groundwater conditions. From the larger ensemple (n=21) of the Euro-CORDEX climate change scenarios, the ensemple mean, indicate a genereal increase of groundwater levels between the reference period (1981-2010) and a future period (2071-2100).

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and have the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project "Tools for Assessment of ClimaTe change ImpacT on Groundwater and Adaptation Strategies – TACTIC". By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (http://www.europe-geology.eu).

The Denmark pilot represents one of the country scale pilots in TACTIC where the impacts from climate change on groundwater will be adressed. The general challenge of the pilot is to define if and where future groundwater levels will increase or descrease, respectively.

3 PILOT AREA

The Denmark pilot covers the entire country of Denmark. The area is divided into 7 sub-catchments; three covering western Denmark (Northern Jutland, Central Jutland, Southern Jutland), one covering the island of Funen, two covering the island of Zealand, one covering the island of Bornholm. Previous climate change studies, with focus on groundwater, indicates a potential increase in both flooding and drought occurrence, depending on the geographical location. Most data applied in the pilot originate from the development of the National Water Resources Model for Denmark (DK-Model, Højberg et al. (2015)).

3.1 Site description and data

Denmark covers a total land area of 43000 km^2. Figure 3.1 shows the seven different subcatchments/subareas of the country with areal sizes from 588 km^2, the island of Bornholm, to 11514 km^2, the central Jutland model, Table 3.1.

Table 3.1 Subcatchments of Denmark

No.	Name	Areal Size, km^2
1	Zealand (Sjælland)	7163
2	Lolland, Falster, Møn	2042
3	Funen (Fyn)	4023
4	Southern Jutland (Sønderjylland)	7832
5	Central Jutland (Midtjylland)	11514
6	Northern Jutland (Nordjylland)	9896
7	Bornholm	588

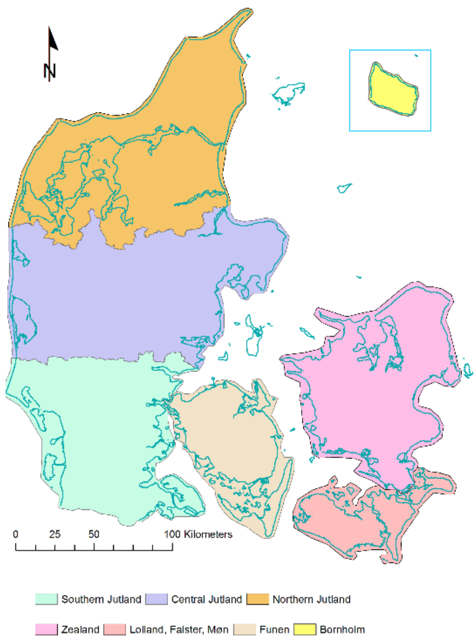

Figure 3.1 Denmark and the seven subareas. The Island of Bornholm is located east of Zealand in the Baltic Sea.

3.1.1 Climate

The climate in Denmark is humid and dominated by precipitation generated in the North Atlantic area. Yearly mean temperature are 8-9 °C with summer mean temperatures of 15.3 °C and winter mean temperatures of 0.5 °C, DMI 2018.

Precipitation in Denmark varies from 700 mm/yr. to 1100 mm/yr., Figure 3.2, with highest rates in the central parts of Jutland and above Zealand and the southern islands. Precipitation, is available from the Danish Metrological Institute, DMI, with daily mean values in a 10x10 km grid system with corrected data, e.g. catch-corrected, and based on an automated climate station system across the country. Uncorrected data are available only a few days after measurement, whereas, corrected and quality assured data are accessible after some months.

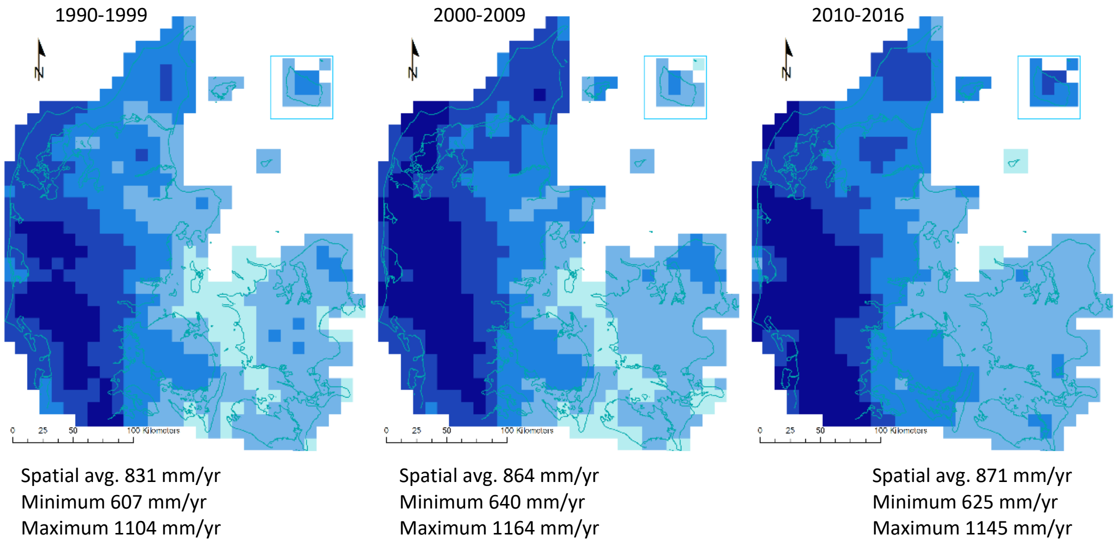

Figure 3.2 Mean yearly precipitation 1990-1999, 2000-2009, and 2010-2016 (lower left is the same as the upper figure

Temperature and calculated potential evaporation, based on a modified Makkink equation, are available from DMI in a 20x20 km grid system, Figure 3.3.

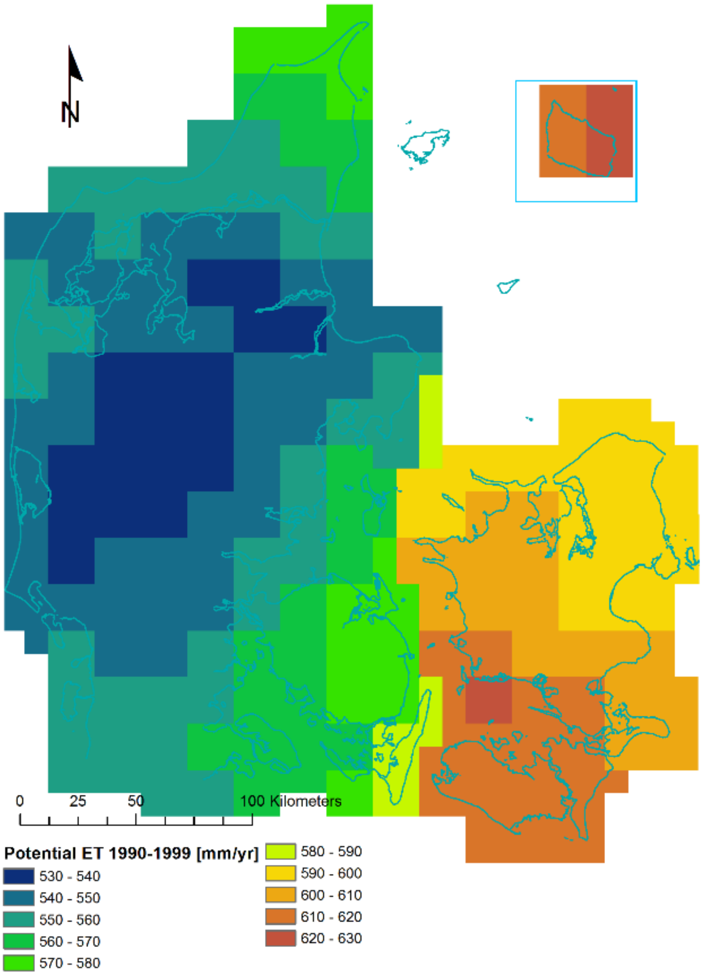

Figure 3.3 Potential evapotranspiration, mean value from 1990-1999 (min=528, max=624, spatial mean=568 mm/yr).

3.1.2 Topography

The topography of Denmark is mapped by The Danish Agency for Data Supply and Efficiency, SDFE in a 40x40 cm raster based digital elevation model. This dataset forms the Danish elevation model, which can be transformed into relevant grids sizes used by spatial distributed models. The Danish elevation model is freely available from SDFE. Elevation of Denmark ranges from 0 to 172 meters above sea level (central Jutland), Figure 3.4.

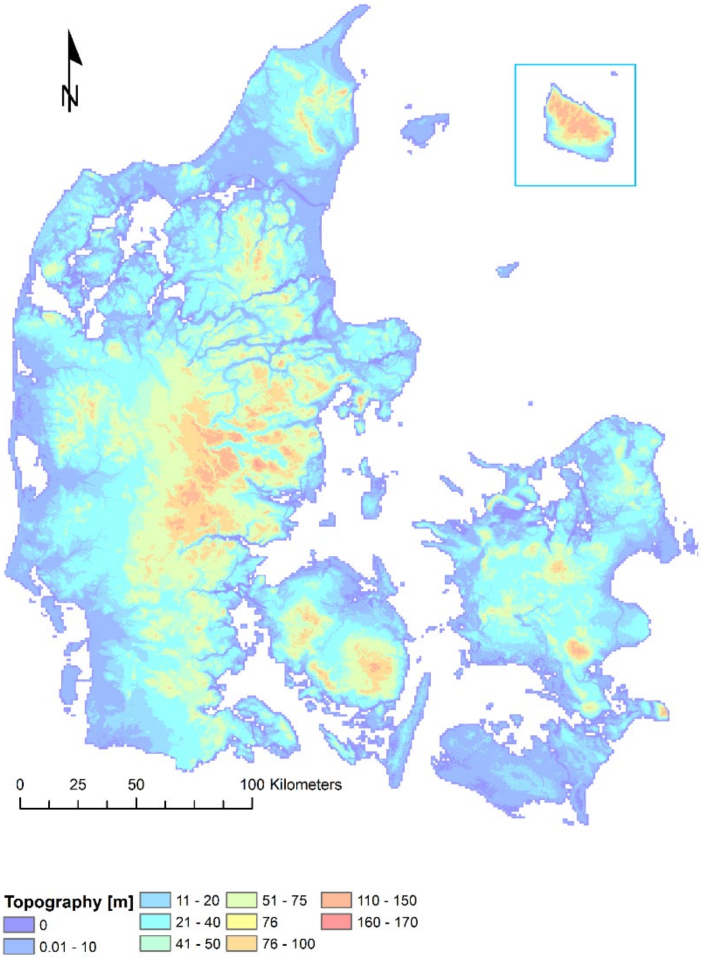

Figure 3.4 Topography of Denmark. Elevation is shown according to meters above mean Danish sea level (DNN).

3.1.3 *Soil types*

The main dataset for soil types in the Danish area is the national dataset on soil physical properties of the unsaturated zone from Børgesen and Schaap (2005) and Greve et al. (2007). The dataset covers all of Denmark in a 250 m x 250 m grid resolution, and consist of 11 soil classes from the most common soil type combinations of three horizons, A, B and C (Figure 3.5). The classes cover different types of soils spanning coarse sand, organic soils and compact clay; they are named JB1 to JB10.

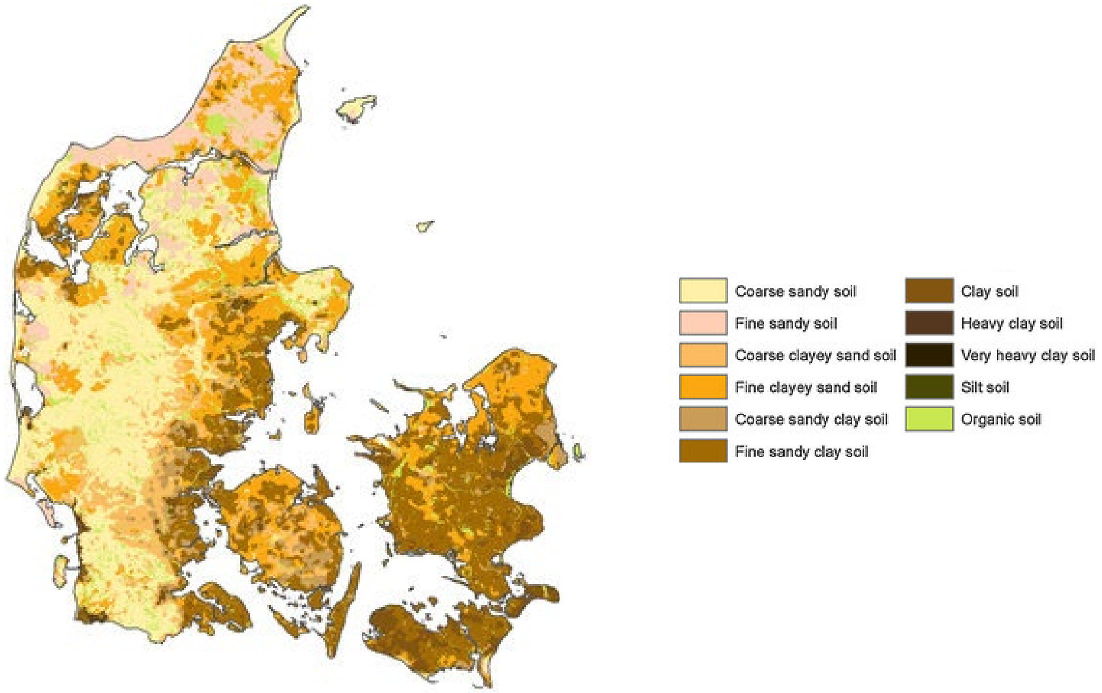

Figure 3.5 Map of the Danish soil types from Odgaard et al. (2017) and Greve et al. (2007)

Later the soil types were further distinguished based on their setting in five georegions (= regions with similar geology, Børgesen et al. (2013)). In the DK-model information on soil physics from the B-horizon are used (Højberg et al., 2015) and as several soil types have similar soil parameter resulting in a total of 19 unique soil parameter types for Denmark (Figure 3.6).

Figure 3.6 Soil types used in the DK-model for parameterization of the unsaturated zone

3.1.4 Land use

Land use in Denmark for the purpose of groundwater assessments is described in primarily in two datasets. One, described by Levin et al. 2012, and available at miljøportalen.dk, covers the entire country of Denmark in a 10x10 raster dataset with 35 different area uses, Figure 3.5. This can be used, for instance, to differentiate urbanized areas from rural areas, and it is possible to calculate needed paved area coefficients within the urban area.

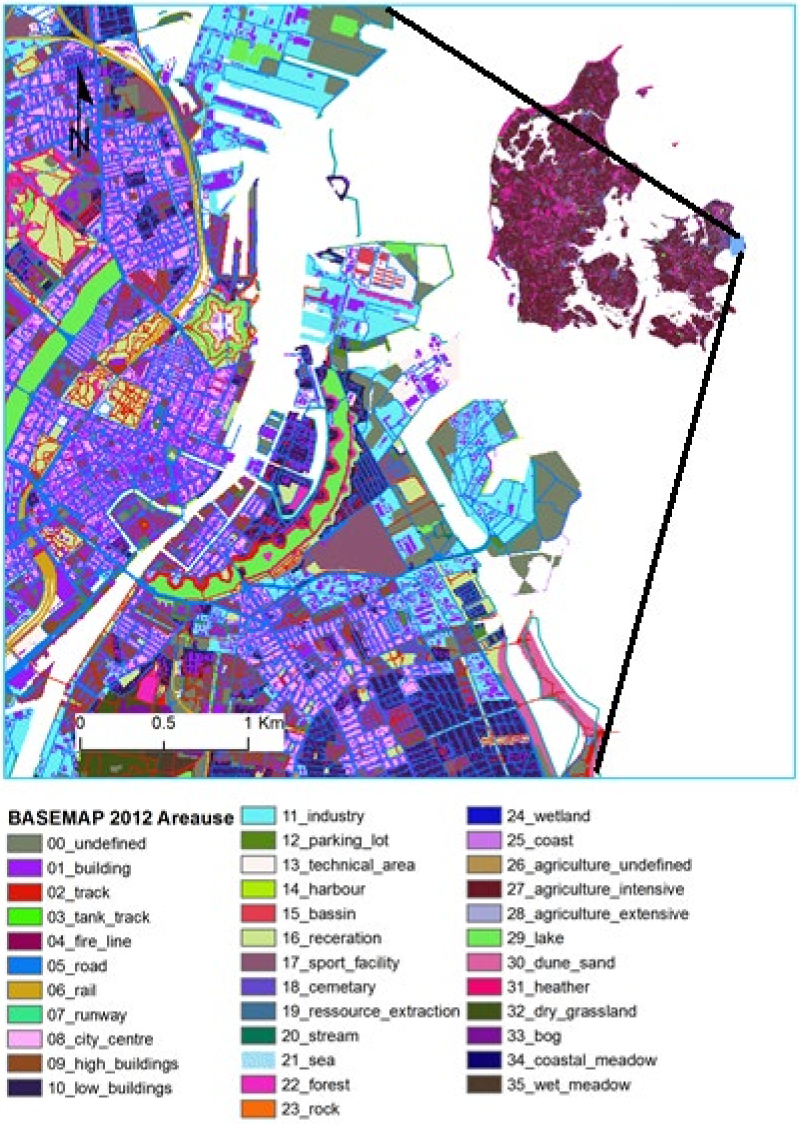

Figure 3.7 Area use in Denmark based on the 10x10 m raster dataset by Levin et al. 2012.

Another important dataset for applied hydrological modelling of Denmark are developed by GEUS (Højberg et al., 2015; Stisen et al., 2012). It is a combination of datasets from the Corine vegetation dataset (www.DMU.dk), crop statistics from Statistics Denmark (www.dst.dk/en) and the Danish soil type classification system (Børgesen and Schaap, 2005; Greve et al., 2007). Six main vegetation types are applied: Permanent grass, (deciduous and coniferous) forest, lakes/sea, heath/sparse vegetation, urbanised and farmland. Farmland is further divided according to soil type (4 categories) and crop type (winter wheat, maize, grass and spring barley); yielding a total of 23 land use combinations. This classification system is incorporated into the DK-model to parameterize leaf area index, root depth and a crop coefficient. The percentage distribution can be seen in Figure 3.7, while a map of the distribution for the whole of Denmark can be seen in Figure 3.6.

Figure 3.8 Map of area/soil codes used in the DK-model (modified from Højberg et al. (2015))

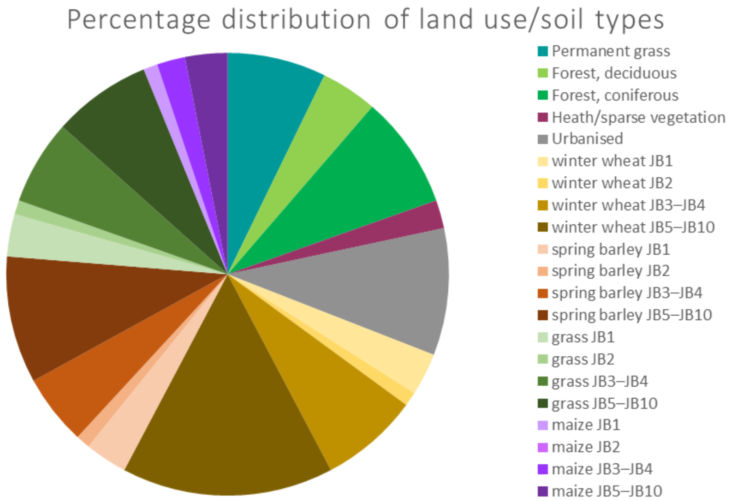

Figure 3.9 Distribution of land use types with soil type classification in farmlands (surface water bodies not included) data from Stisen et al. (2012)

3.1.5 Geology/Aquifer type

The surface geology in Denmark is a result of the last glacial advances in the area (Figure 3.9). To the east, it consists mainly of clayey moraine deposits left by the Weichselian ice advance that reached its widest range in the centre of Jutland at what is referred to as the Main Stationary Line (MSL) (Houmark-Nielsen and Kjaer, 2003). The surface geology at the western side of the MSL is a result of earlier Ice advances (e.g. Saale) and flood plain material, and is therefore a mixed of old moraine hills, glacio-lacustrine clay/sand and sandy outwash.

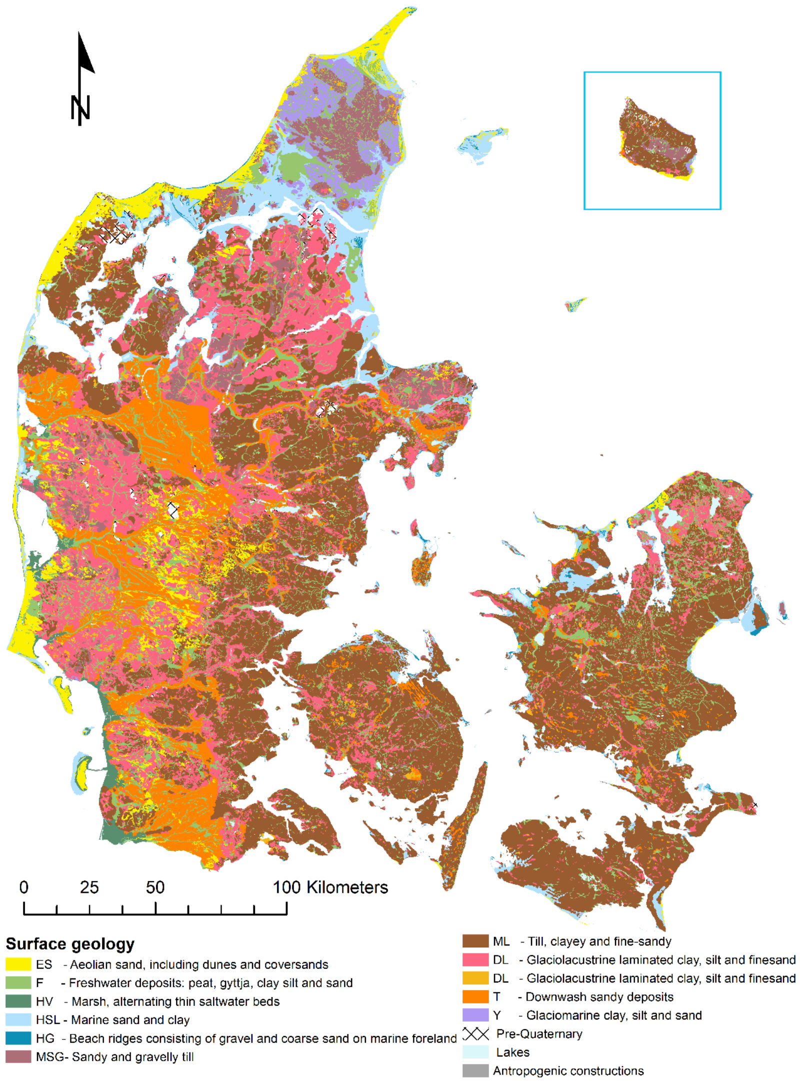

Figure 3.10 Surface geology of Denmark.

The pre-quaternary geology of Denmark mainly consists of large sedimentary basins. Due to fault movement, the basin is sloping so that youngest sediments are found in the southwest and older sediments to the north and east (Barfod et al., 2016) (Figure 3.8). For most of Denmark, the pre-quaternary is 25-75 meters below ocean level, only in the eastern Jutland and Zealand the surface is above sea level.

On the island of Bornholm, the quaternary layers are generally very thin, with underlying the base rock and the geology on the island is therefore very different from the rest of Denmark. In the northern Jutland, large salt diapirs have resulted in the circular shapes of chalk rising with the salt towards the surface (Houmark-Nielsen et al., 2012).

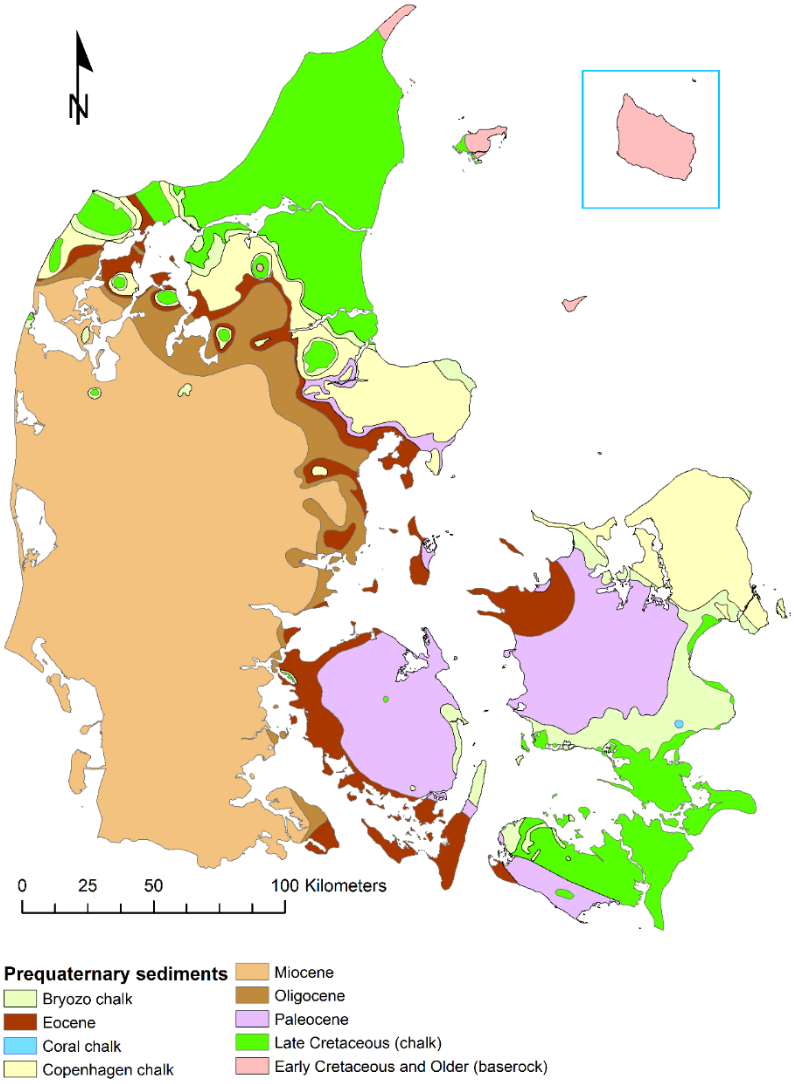

Figure 3.11 Prequaternary surface in Denmark.

Danish aquifers are Cenozoic, mostly unconsolidated, and consolidated Mesozoic sediments. On Zealand and Funen, they are quaternary sand/gravel aquifers and marine chalk aquifers from Cretaceous, Danien and Paleocene. In Jutland the main aquifers area are chalk from the upper Cretaceous and Danien (north), and quarts sand delta deposits from the Tertiary (south and central). On Bornholm, the aquifers are either unconsolidated Cretaceous sediments (West), colsolidated but fractured Cambrian or Silurian sandstone and slates (Southeast), or fractured granites and schists from the Precambrian (Northeast) (Højberg et al., 2015).

The geological model is the backbone of the hydrogeological interpretation in the Dk-model, where geological units with similar hydrological characteristics are merged into larger hydro-stratigraphical units. An example of a hydro-stratigraphical model for Jutland is shown in Figure 3.12; similar interpretations exist for the entire country.

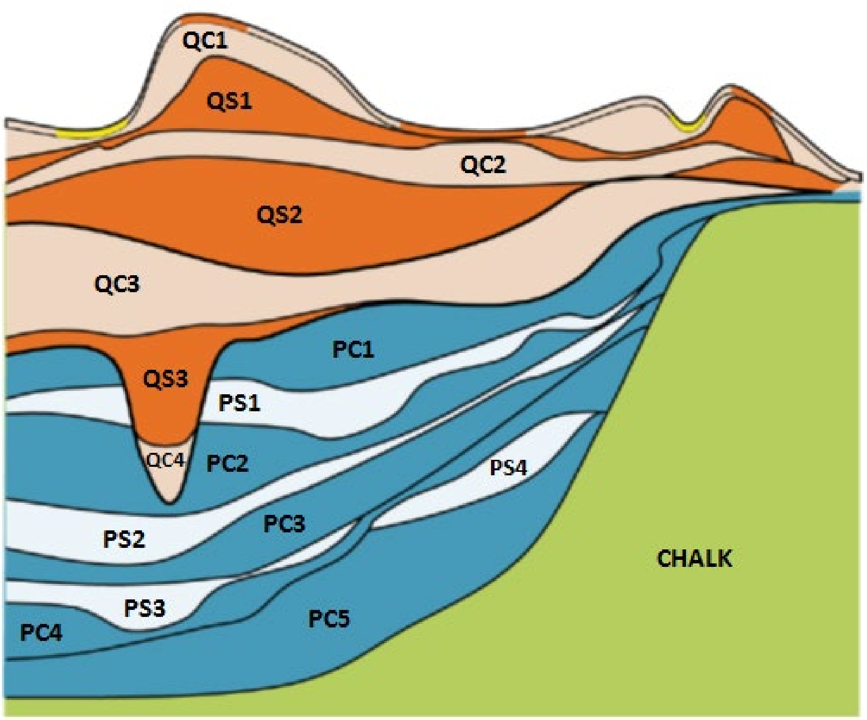

Figure 3.12 Sketch of the principal behind the hydro-stratigraphical model for Jutland. Layers are number from ground surface. QS: Quaternary sand, QC: Quaternary clay, PC: Prequaternary clay, PS: Prequaternary sand.

3.1.6 *Groundwater level*

Figure 3.13: Intakes with groundwater head measurement used in the calibration period for the Dk-model (2000-2006). Left: Intakes in the Quaternary (14.000). Right: Intakes in the Pre-Quaternary (11.000).

The national borehole database, Jupiter (www.geus.dk), is the archive for groundwater, drinking water and environmental data. More than 280.000 boreholes are registered with varying record length and information. All are free available for download. In the Dk-model around 25.000 quality checked boreholes are included, an example of the borehole intakes included in the calibration period from 2000-2006 is shown in Figure 3.13.

3.1.7 *Surface water*

The Danish area has roughly 64.000 km of river network (Larsen et al., 2003). The first discharge stations monitoring the network, were established in 1917 and 14 of these are still active. In all more than 400 stations measures continuous discharge records, their catchments covering 55% of the Danish area (Ovesen et al., 2000). The Danish area has more than 120.000 lakes larger than 100m^2. Information on lakes and river network can be downloaded freely from the Danish environmental portal at www.danskmiljøportal.dk (Dansk Miljøportal 2018).

In the Dk-model 185 stations are included in the calibration and 136 in the validation period (predominantly stations with catchments larger than 25m^2, due to model resolution), the location of these can be seen on Figure 3.14. The river network in Denmark from the Dk-model can be seen on Figure 3.14b, a little less than 16.000 km of the river network is included (Højberg et al., 2015).

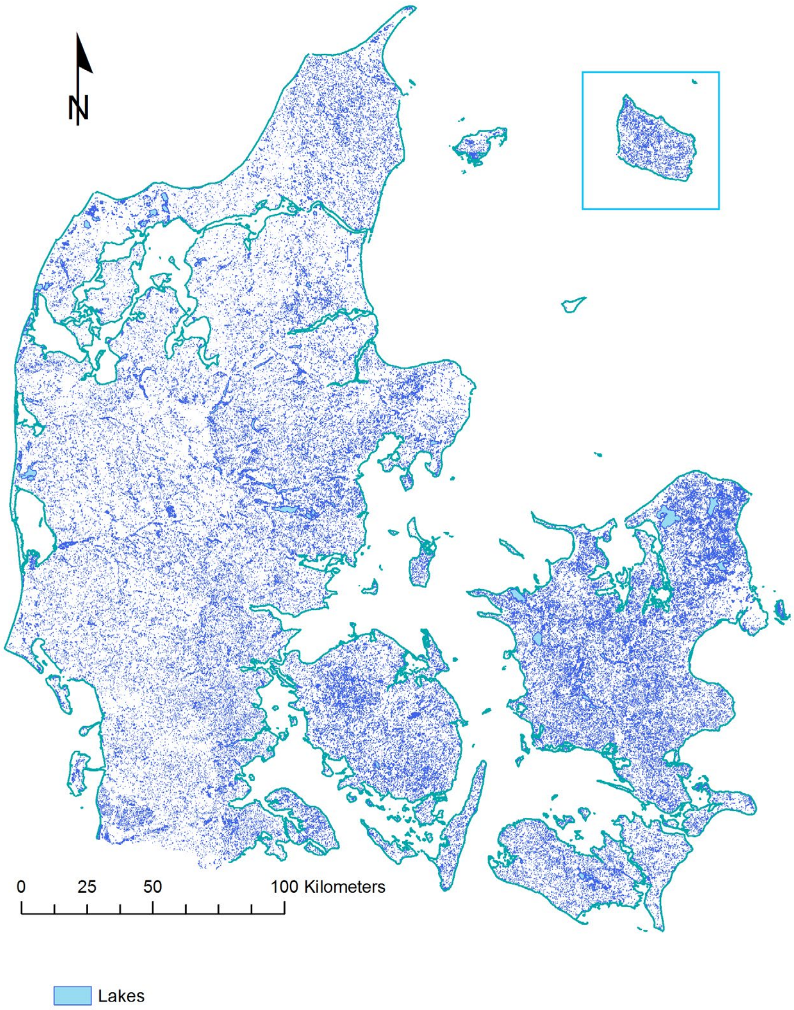

Figure 3.14a Lakes in Denmark

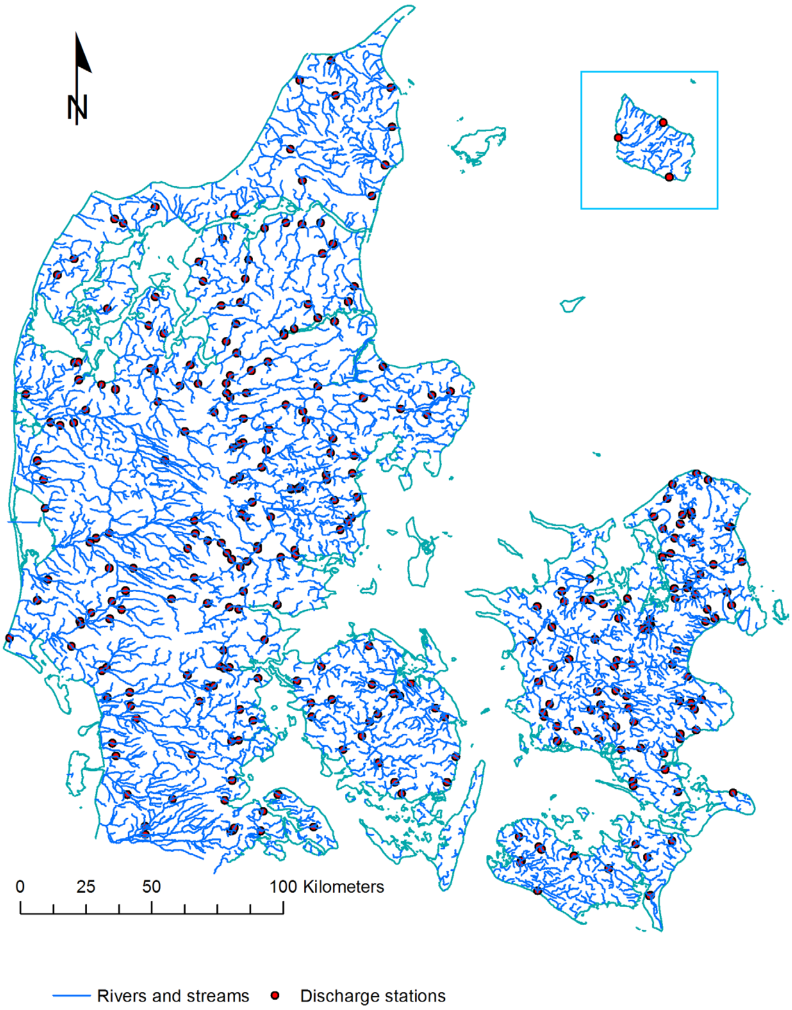

Figure 3.144b River network in DK model and locations of river discharge measurements.

3.1.8 Abstractions/irrigation

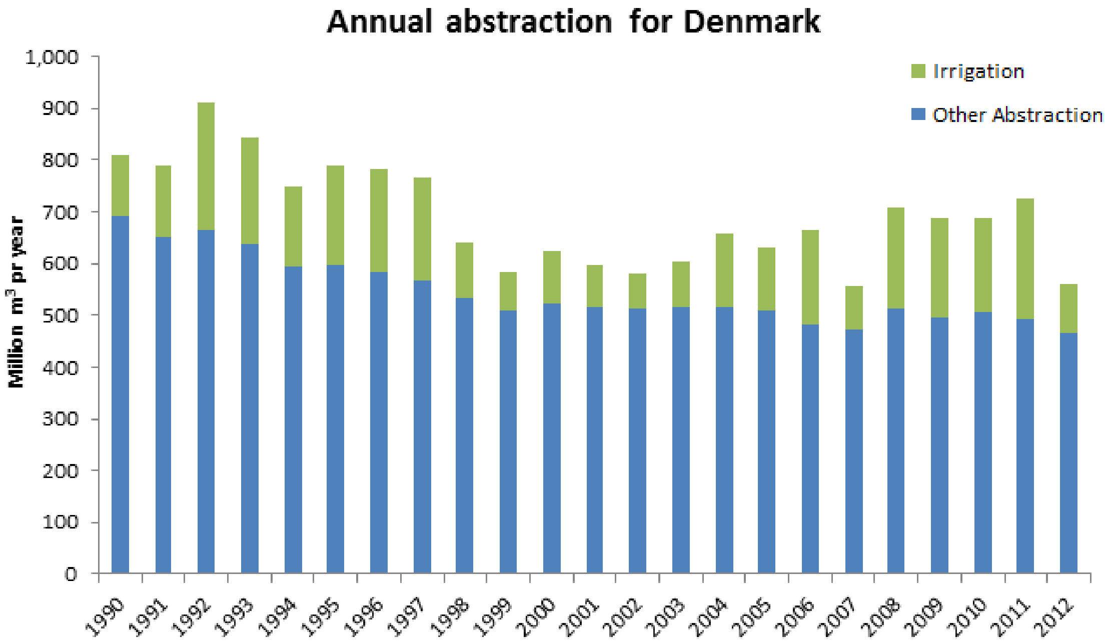

Figure 3.15: Abstraction rate in Denmark from 1990-2012, two abstraction types are differentiated; abstraction for irrigation purposes (green) and abstraction for all other water uses (blue).

In Denmark, general abstraction (defined as abstraction for consumers and industry excluding water abstracted for irrigation purposes) are conducted by municipal and private water works, as well as smaller rural supply wells. From 1990 to 2012, the general abstraction rate in the Danish area (Figure 1) has decreased with a little less than 30%. The special distribution of the abstraction can been seen on Figure 2 (left). The abstraction wells are predominately concentrated around the larger cities, around Copenhagen on eastern Zealand.

The irrigation abstraction shows no general trends (Figure 1), but has a large variation from year to year, reflecting the variation between dryer and wetter years and the coherent demand for watering. On Figure 2 (right) the distribution of the abstraction for irrigation clearly shows a spatial variation, where the highest concentration of field crop abstraction wells are located in west and southwest Jutland, where the top soils are sand dominated (Figure 3.5). Abstraction rate are also available through the Jupiter portal (www.geus.dk).

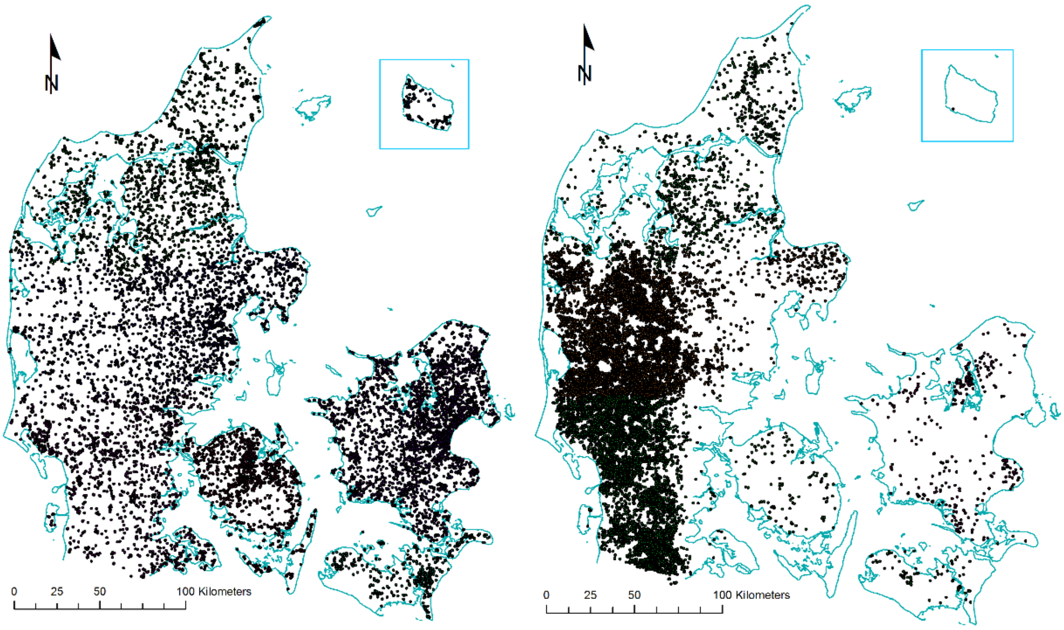

Figure 3.16: Groundwater abstraction for the seven model domains for general abstraction (left) and for field crop irrigation (right).

3.2 Climate change challenge

The Denmark pilot is located in the zones of North-western and central/eastern Europe (Figure 3.12), according to the EEA map. Changes in climate conditions for West Denmark are expected to move towards increasing winter precipitation leading to increasing river flow and risk of flooding, and for the eastern side of the country increasing warm temperature extremes and decreasing summer precipitation causing warmer waters and risk of forest fires.

Nationally, several studies and projects have explored projected climate change in Denmark. Olesen et al., 2014 collected information about the expected climate change projections done for the Danish area, they based the analysis on larger projects from, among others, IPCC (Collins et al., 2013), BACC (BACC Author Team, 2008), European studies and CRES (Centre for Regional Change in the Earth System). In their review, they found that climate change over the Danish area is expected to lead to higher temperatures, increasing winter precipitation and increasing extreme weather events both in numbers and in magnitude. Seaby et al. (2013) found large differentiations in the resulting precipitation change during the other seasons when applying 11 different climate models over the Danish area.

Hydrological impact studies have shown increases in annual stream flow in the magnitudes of 8-28% spanning different catchments, climate models, emission scenarios and downscaling methods (Hansen et al., 2006; Karlsson et al., 2016; Rasmussen et al., 2012; van Roosmalen et al., 2007).

With larger winter precipitation also follows the risk of rising shallow groundwater table potentially leading to groundwater flooding. Climate change adaptation with forced infiltration is already ongoing but effects have yet to be quantified in a systematic way. It is unknown how this climate change adaptation strategy effects the water balances on larger scale, e.g. on regional and national scales.

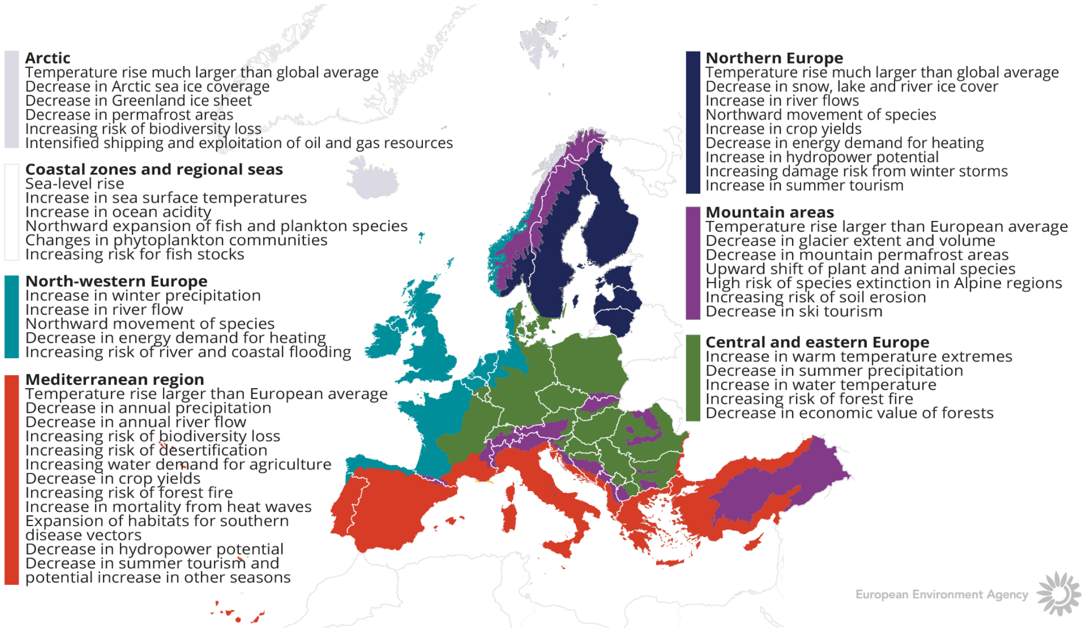

Figure 3.17 European Environment Agency map of projected climate change for Europe

4 METHODOLOGY

The assessment of climate change impacts on groundwater conditions in Denmark are performed using the TACTIC standard climate change scenarios, climate change scenarios from Euro-Cordex and the integrated hydrological model, the DK-model. The DK-model is based on the MIKE SHE code, coupled with MIKE HYDRO code (TACTIC toolbox reference).

4.1 Climate data

The present study relies on the TACTIC standard climate change dataset to reflect future climate conditions, which include a "wet" and a "dry" climate for a +1 and +3 degree global warming scenario. The study has further used an ensemble of climate change scenarios based on the Euro-CORDEX dataset.

4.1.1 TACTIC standard Climate Change scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5°C global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (a.o. bias correction). Data selection and preparation included the following steps:

1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set where selected. RCPs are the Representative Concentration Pathways determining the development in greenhouse gas concentrations, while GCMs are the Global Circulation Models used to simulate the future climate at the global scale. Three RCPs (RCP4.5, RCP6.0, RCP8.5) were combined with five GCMs (noresm1-m, miroc-esm-chem, ipsl-cm5a-lr, hadgem2-es, gfdl-esm2m).
2. A reference period was selected as 1981 – 2010 and an annual mean temperature was calculated for the reference period.
3. For each combination of RCP-GCM, 30-years moving average of the annual mean temperature where calculated and two time slices identified in which the global annual mean temperature had increased by +1 and +3 degree compared to the reference period, respectively. Hence, the selection of the future periods was made to honour a specific temperature increase instead of using a fixed time-slice. This means that the temperature changes are the same for all scenarios, while the period in which this occur varies between the scenarios.
4. To represent conditions of low/high precipitation, the RCP-GCM combinations with the second lowest and second highest precipitation were selected among the 15 combinations for the +1 and +3 degree scenario. This selection was made on a pilot-by-pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.
5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates,

either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).

6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

For the analysis in the present pilot the following RCP-GCM combinations were employed:

Table 4.2. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	4.5	noresm1-m
	"Wet"	6.0	miroc-esm-chem
3-degree	"Dry"	6.0	hadgem2-es
	"Wet"	8.5	miroc-esm-chem

4.1.2 Euro-CORDEX

An ensemble of 21 climate change scenarios, 5 with RCP 4.5 and 19 with RCP 8.5 emission scenarioes were also used to assess future groundwater conditions for the Denmark pilot area. Data for precipitation and temperature were bias-corrected using a distribution-based scaling method, whereby daily simulations from a regional circulation model were fitted to daily observations. Potential evapotranspiration was subsequently calculated from the bias-corrected temperature using the Oudin formula for potential evapotranspiration.Table 4.2 shows the 21 ensemble members and combinations of RCPs, GCMs and RCMs. RCM is the Regional Climate Model.

Table 4.2 The Euro-CORDEX climate change ensemble

RCP	GCM	RCM
8.5	CanESM2	REMO2015
8.5	EC-EARTH	RACMO 2.2
8.5	EC-EARTH	HIRHAM5
8.5	EC-EARTH	RACMO 2.2
8.5	IPSL-CM5A-MR	RCA4
8.5	MIROC5	REMO2015
8.5	MPI-ESM-LR	REMO2009
8.5	MPI-ESM-LR	RCA4
8.5	MPI-ESM-LR	REMO2009v2
8.5	NorESM1-M	HIRHAM5
8.5	HadGEM2-ES	CCLM 4.8.17
8.5	HadGEM2-ES	HIRHAM5
8.5	HadGEM2-ES	REMO2015
8.5	HadGEM2-ES	RACMO 2.2
8.5	HadGEM2-ES	RCA4
8.5	CERFACS	CCLM 4.8.17
4.5	EC-EARTH	HIRHAM5
4.5	IPSL-CM5A-MR	RCA4
4.5	MPI-ESM-LR	REMO2009

4.5	MPI-ESM-LR	REMO2009v2
4.5	HadGEM2-ES	RACMO 2.2

The ensemble is further described and documented in Pasten-Zapata et al. 2019 using the methodology of bias-correction and distribution-based scaling by Seaby et al. 2013.

4.1.3 Differences between the climate change scenarios

The methodology of the assessment of climate change impacts on groundwater conditions are slightly different between the TACTIC standard scenarios and the Euro-CORDEX ensemble. Whereas the TACTIC scenarios apply four selected scenarios representing a 1 and 3 degree temperature change in the 2nd most dry and 2nd most wet scenario, the Euro-CORDEX uses a larger ensemble with no specific attention to most wet or dry scenario. Furthermore, the TACTIC scenarios are not targeted to a specific future time-period but to a specific temperature rise relative to the reference period, of 1 and 3 degrees, respectively. The Euro-CORDEX scenarios targets the specific time-period of 2071-2100, or the changes between this future period and the reference period. The reference period for both applications is 1981-2010.

There are also additional differences in the application of climate model scenario data in forcing of the hydrological models. The TACTIC scenarios apply local datasets of precipitation, temperature and reference evapotranspiration to which the delta change factors are multiplied (or added) to generate the dataset representing the future conditions. Therefore, the dynamics between different events (e.g. numbers of rainy days) in the historical dataset are transferred to the dataset representing the future. With the approach for applying the Euro-CORDEX ensemble, the output from the climate models, is used for both the reference and future periods, and thus dynamics of the input may be projected differently.

4.2 Integrated hydrological modelling of climate change

The DK-model was developed in its first version during 1996-2003 (Henriksen et al., 2003) and have been continuously refined, updated and recalibrated ever since. The MIKE SHE/ MIKE HYDRO model framework, that the Dk-model is based on, simulates overland flow, evapotranspiration, flow in the unsaturated zone, the saturated zone with drainage routing, and river flow, Figure 4.1.

The methodology of the assessment of climate change impacts on groundwater conditions are slightly different between the TACTIC standard scenarios and the Euro-CORDEX ensemble. Whereas the TACTIC scenarios apply four selected scenarios representing a 1 and 3 degree temperature change by the 2nd most dry and 2nd most wet scenario, the Euro-CORDEX uses an larger ensemble with no specific attention to most wet and dry scenario. Furthermore, the TACTIC scenarios are not targeted to a specific future time-period but to a specific temperature rise, relative to the reference period, of 1 and 3 degrees, respectively. The Euro-CORDEX scenarios targets the specific time-period of 2071-2100, or the changes between this future period and the reference period. The reference period for both applications is 1981-2010. There are also some differences in the actual application of scenario data in forcing of the hydrological models. The TACTIC scenarios apply a local dataset of precipitation, temperature and reference evapotranspiration to which the delta change factors are multiplied (or added) to generate the dataset representing the future conditions. In this regard, the dynamics between different events through the historical dataset are transferred to the dataset representing the future. With the approach applying the Euro-CORDEX ensemble, the output from the climate models, is used for both the reference and future periods.

4.2.1 Model description

The Dk-model version applied in this study is based on an update and recalibration documented in Stisen et al. 2019, the DK-model2019. Input data to the hydrological model are thoroughly described in section 3.1 as well as calibration and validation data, primarily, in terms of different aspects of river or stream discharge and hydraulic head measurements. The model is run in a 500 x 500 m model grid discretization in 7 sub-models for the entire Denmark, Figure 3.1.

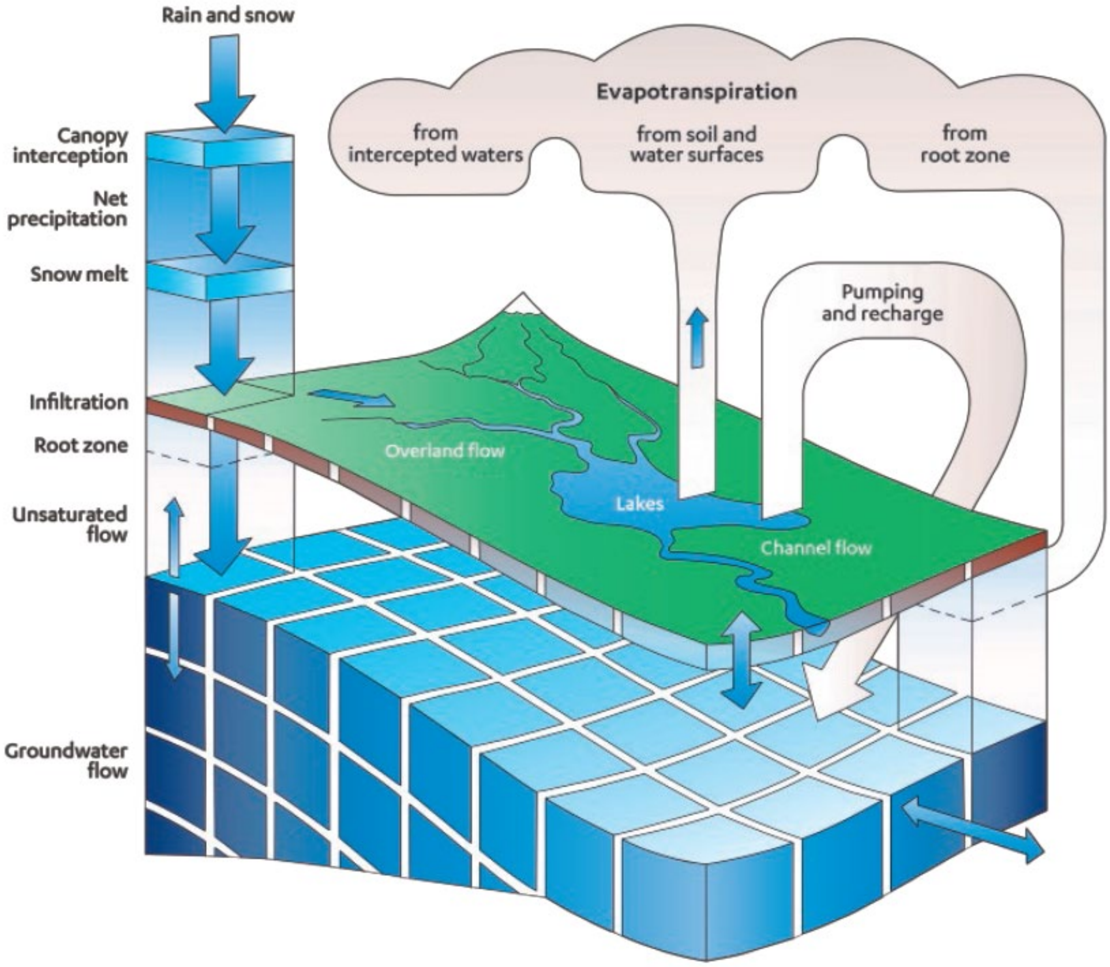

Figure 4.1 MIKE SHE model: Simulated hydrological water fluxes.

The hydro-stratigraphy of the adapted geology of the model is sketched in figure 3.12 and numerical layers follows the principal layer of the hydrostratigraphy. From the surface, the geology is glacial and post-glacial with important aquifers of glacial meltwater deposits and aquitards of clayey till and other glacial clays. In the western part of the country, Miocene sandy layers are important deeper aquifers, whereas, the important deeper aquifers in the eastern part of the county are chalk and other carbonate rocks. Figure 4.2 and 4.3 exemplifies the distribution and thickness of Quaternary (red) and Pre-Quaternary (purple) aquifers in Jutland, covering 3 of the 7 subdomains.

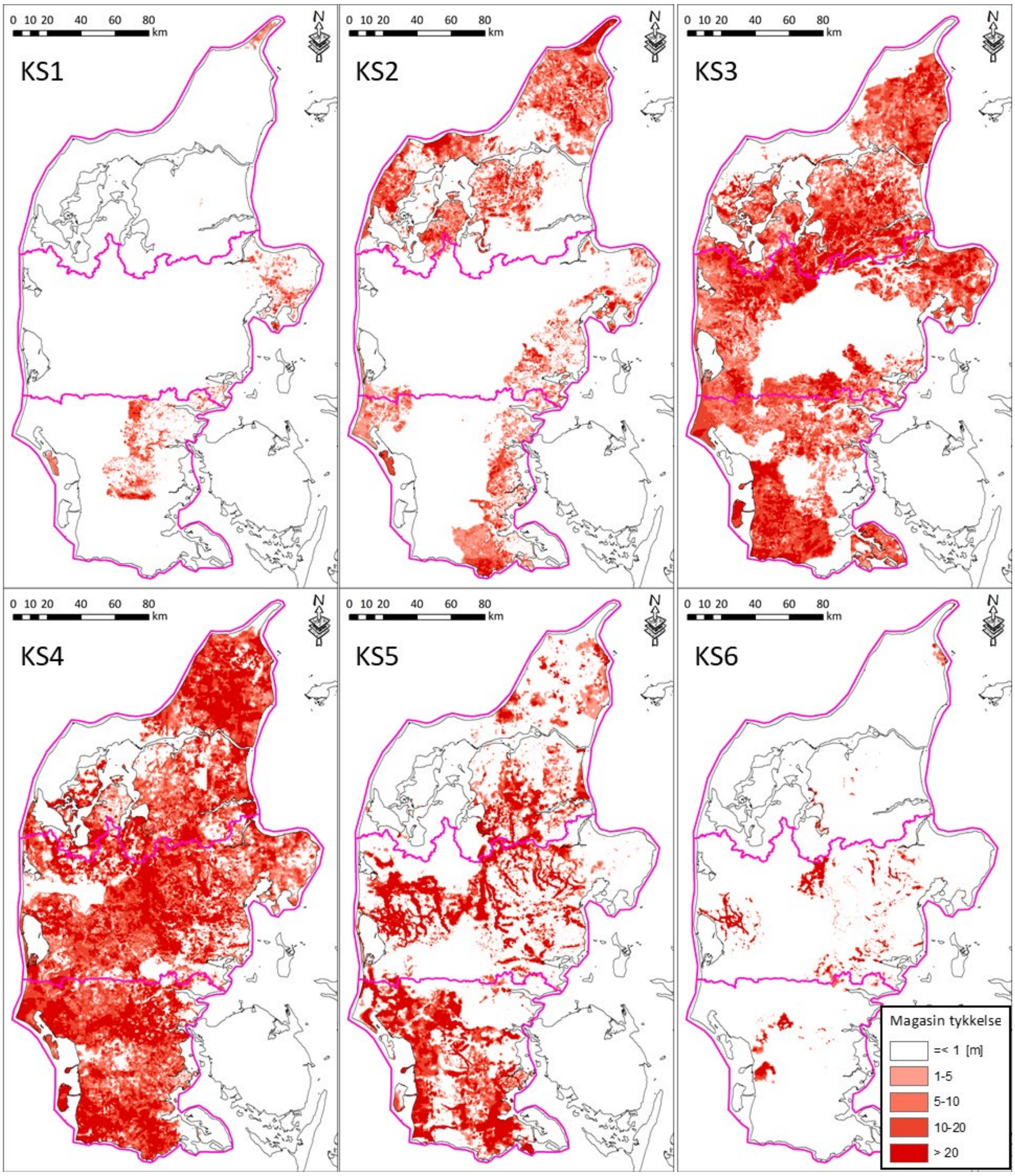

Figure 4.2 Quaternary sand aquifers KS1-6 and their thickness across Jutland. Figure is from Stisen et al. 2019.

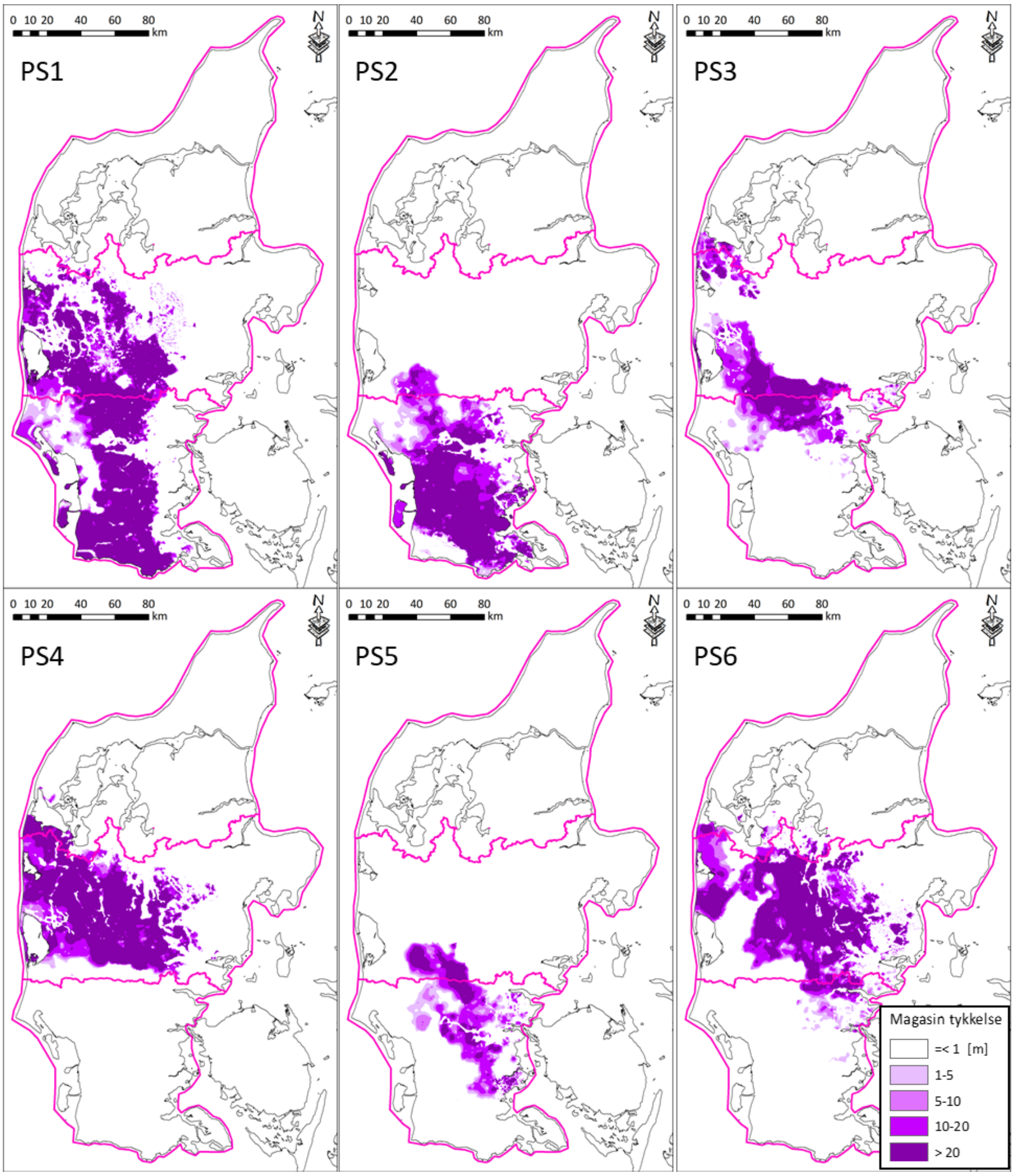

Figure 4.3 Miocene sand aquifers PS1-6 and their thickness across Jutland. Figure is from Stisen et al. 2019.

The DK-model have between 9 (Funen) and 22 (Jutland) numerical calculation-layers depending on the sub-model. Of the roughly 64.000 km of rivers and streams in Denmark, 16.628 km are included in the DK-model2019.

In the assessment of climate change for the future periods or levels of temperature change, the model structure and parametrization are not changed for simulating the future period. The only model differences are the forcing climate states, precipitation, temperature and reference evapotranspiration. Besides these, nothing is changed within the model setup for simulation the future conditions. In reality, it is expected that most of the physical descriptions represented in the model will actually change; this could be inputs such as land use, field crops, morphology of surface waters and others. This means that the model runs only simulates the effect from the change of climate.

4.2.2 Model Calibration

The model is calibrated against hydraulic head data from JUPITER, the Danish borehole archive hosted by GEUS and discharge data from the Freshwater Topic Centre, Bioscience, University of Aarhus. The model is setup and run for the period 1990-2018, with the period 1990-1999 as model warm up (spin up) period, 2000-2010 as calibration period, and the two period 1995-1999 and 2011-2015 as validation periods. In the multiple objective function used for the automated model-optimization (performed with the PEST calibration tool), a number of discharge and hydraulic head statistics were used such as: mean error, root mean squared error, min and max observations for hydraulic head and for discharge, yearly water balance, summer water balance and Kling-Gupta Q-values for discharge dynamics. Qualitative assessments were also a part of the calibration criteria through e.g. realistic parameter values and spatial distribution of model errors. Figure 4.4 illustrates and exemplifies model-precision in terms of mean error for thehydraulic head of the Pre-quaternary layers, and in figure 4.5 results are shown for all layers.

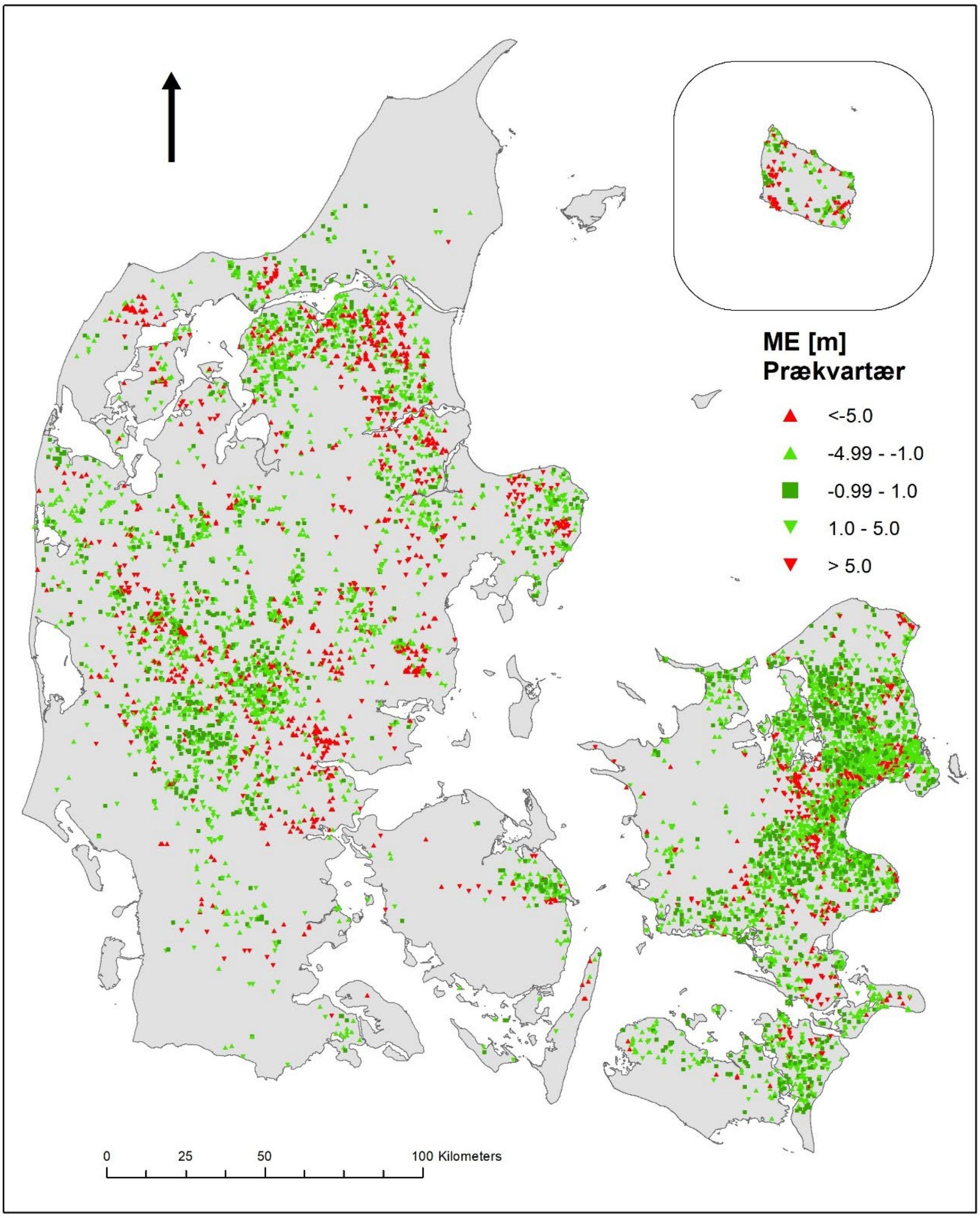

Figure 4.4 Spatial distribution of mean error, pre-Quaternary layers, in the calibration period. Figure is from Stisen et al. (2019).

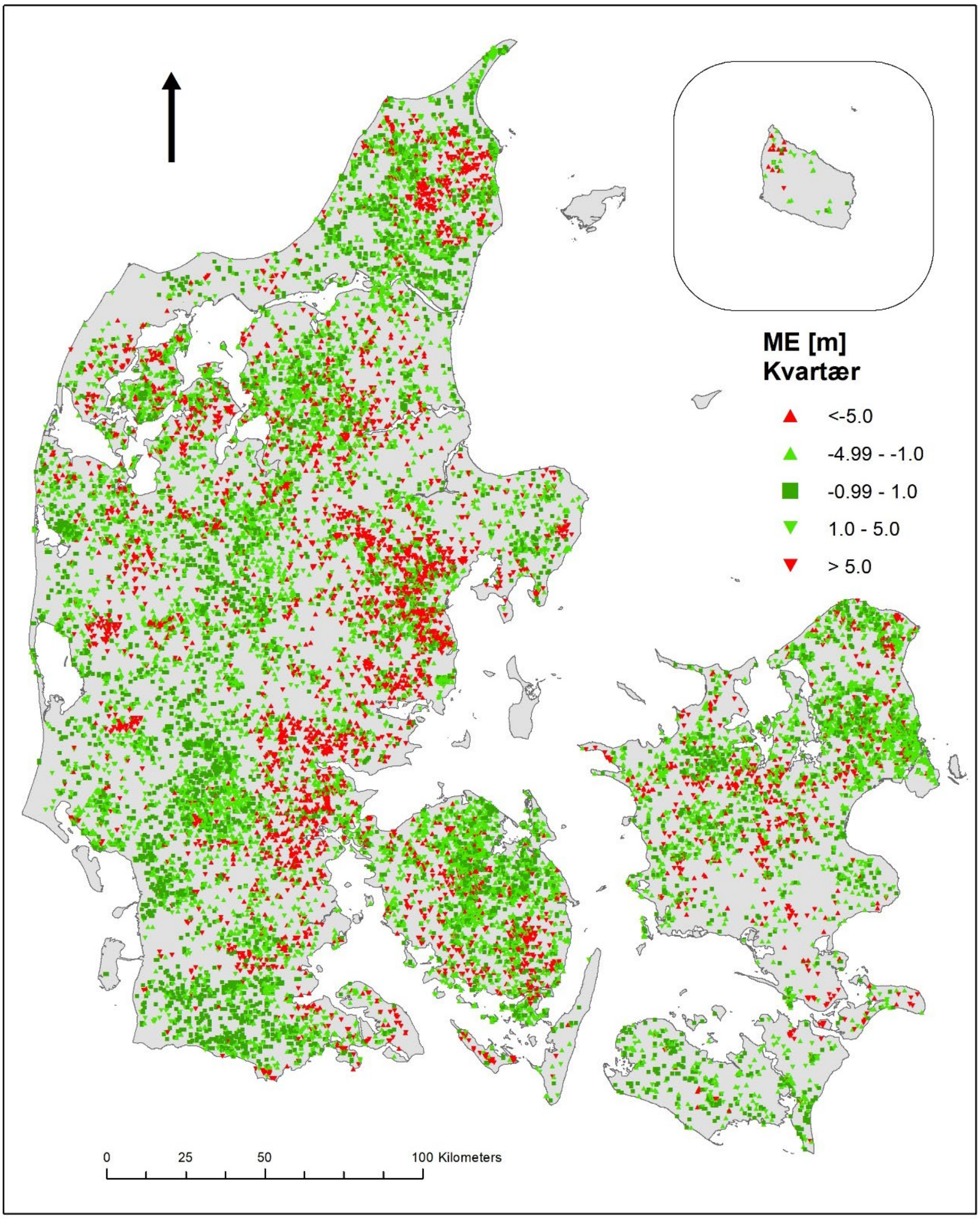

Figure 4.5 Spatial distribution of mean error, pre-Quaternary layers, in the calibration period. Figure is from Stisen et al. (2019).

5 RESULTS AND CONCLUSIONS

5.1 Integrated hydrological modelling

Results from the work in the Denmark pilot will focus on changes of shallow groundwater conditions and on deeper groundwater conditions. The shallow groundwater is represented as the simulated phreatic surface. The phreatic surface is the uppermost (first) saturated zone (seen from the surface) and is often located close to the surface. The most important groundwater resource for water abstraction is represented at the deeper groundwater condition. These aquifers are also termed primary aquifers. In some areas, the shallow groundwater (phreatic surface) and the primary aquifers (deeper aquifers) can be the same, for instance, if a thick sandy aquifer continues from the surface and 100 m below. Whereas the deeper aquifers, in the pilot of Denmark, constitutes the groundwater resource used for abstraction, the shallow groundwater, is often the most important for the interaction to surface waters, groundwater dependant ecosystems and groundwater in contact with infrastructure and buildings.

5.1.1 TACTIC scenarios: Shallow groundwater

Applying the dynamic (non-steady) MIKE SHE - model enables simulated outputs in the format of grid/raster for pre-defined time-intervals. These gridded outputs were printed with a 30 days interval. Therefore, it was possible to analyse, not only the mean changes as the difference between the simulated reference period and the simulated future period, but also to analyse the changes for relatively dry and wet periods throughout the years, respectively. Figure 5.1 shows maps of changes between the future (defined as period of a given relative temperature change) and the reference period (1981-2010). Representing the time of the year with lowest groundwater levels, a change of the 5 % quantile of the simulated 30 periods is shown (Future Q5 – Past Q5). This typically occurs during the summer and fall period. In the same way, the 95 % quantile is used to illustrate the changes of the period with highest groundwater levels, typically, during the winter or early spring.

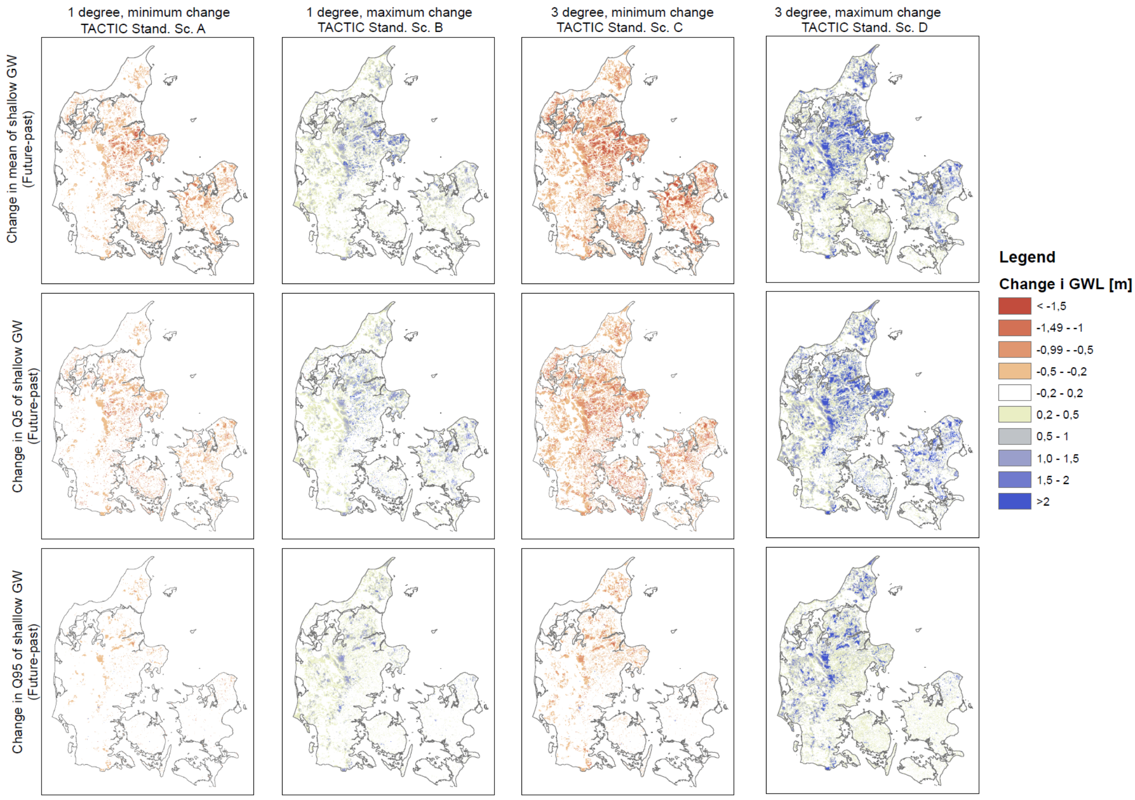

Figure 5.1 Changes in mean, high and low shallow groundwater levels simulated with the 4 TACTIC standard scenarios.

The results generated by the TACTIC standard scenarios are very consistent for the minimum and maximum changes between the 1 and 3 degree scenarios. The minimum change shows “drier” conditions (lower groundwater levels) in the future, and the maximum changes show “wetter” conditions (higher groundwater levels) in the future. As expected, the 3 degree scenarios are more extreme for both the minimum and maximum change than the 1 degree scenarios. For the minimum scenarios, shallow groundwater levels decrease, mostly between 0 and 1.5 m and with a few areas with more than a 1.5 m decrease. For the maximum changes, groundwater levels increase for most areas up to 2 m. The change of groundwater levels for Q95 are clearly less than for the mean (Q50) and Q5. An explanation could be that the groundwater drains, located 2 m below surface in the entire model-domain, control the upper groundwater levels, or acts as an upper boundary condition for the phreatic surface. Because the higher groundwater levels, represented by the Q95, more often is in contact with the drains, the change between future and past is less.

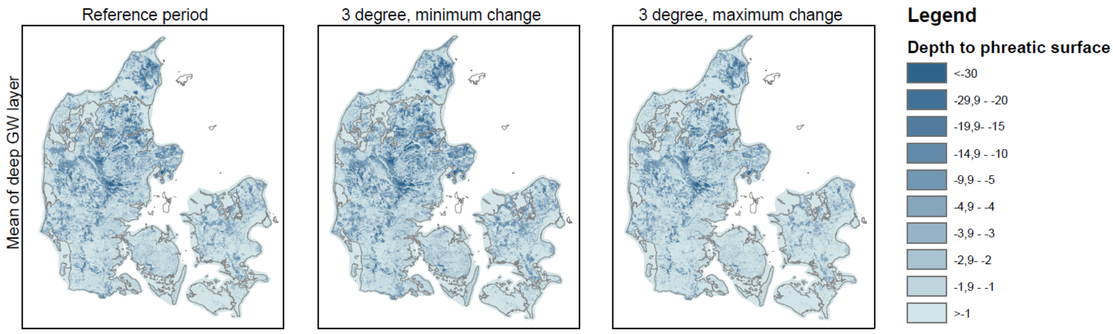

Figure 5.2 Shallow groundwater levels for the reference period (left) and the future period for the 3 degree change scenarios. 3 degree minimum in the middle and 3 maximum to the right.

The changes shown in figure 5.1. are based on simulation of the reference period (past period), 1981-2010, figure 5.2 left, and the future period, figure 5.2 middle and right.

5.1.2 TACTIC scenarios: Deep groundwater

The impact of climate change on deeper groundwater resources is illustrated in figure 5.3. Again, and as expected, changes are amplified in the 3 degree, maximum and minimum scenarios, compared to the 1 degree scenarios. Furthermore, the maximum scenario of both the 1 and 3 degree scenarios show higher future groundwater levels (hydraulic heads), and the minimum scenarios both show lower groundwater levels in the future.

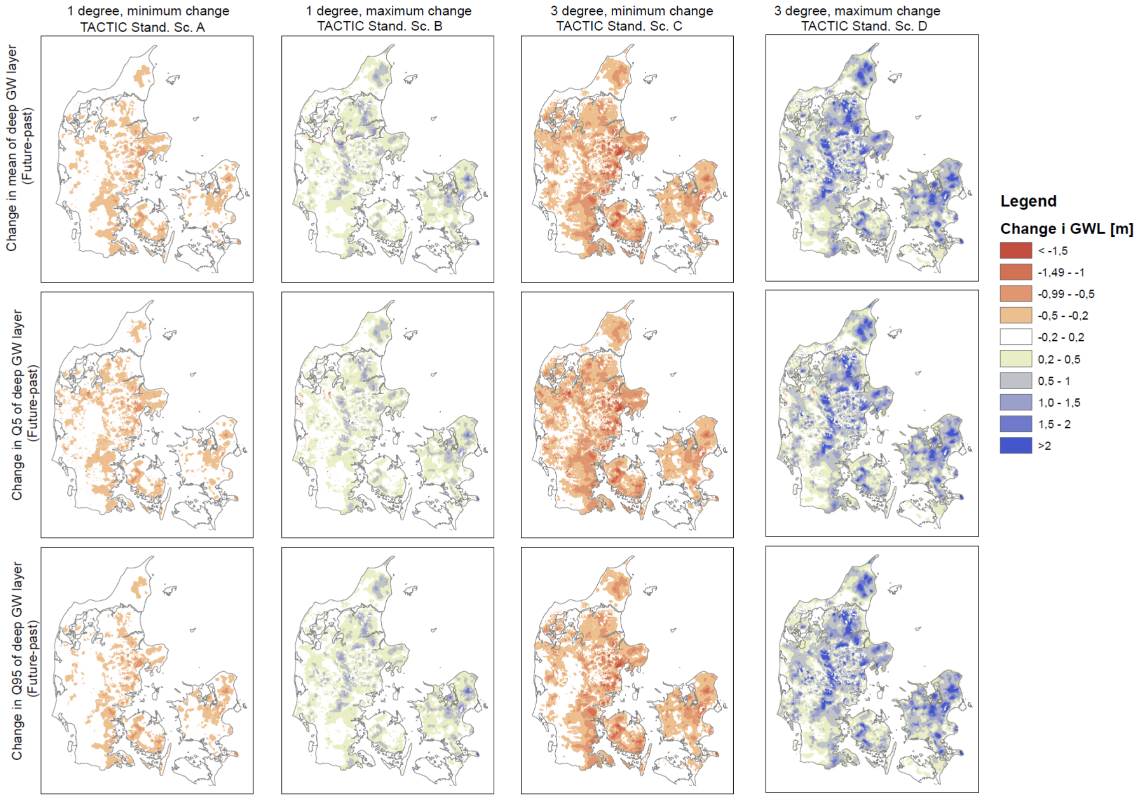

Figure 5.3 Changes in mean, high and low shallow groundwater levels simulated with the 4 TACTIC standard scenarios for the deeper aquifers.

The size of the change for the different hydrological regimes, mean, Q5 and Q95, are more alike for each of the four scenarios than for the shallow groundwater regimes seen in figure 5.1. This could confirm that the reason for the very different changes between the shallow groundwater regimes are affected by the surficial groundwater drainage.

Overall, the shallow groundwater tables, in terms of changes, could appear to be less affected by the climate change than the deeper groundwater. At least, the areas with higher or lower future groundwater levels are less fragmented for the deeper groundwater. This is also the same pattern that can be observed by merely comparing the spatial distribution of the simulated hydraulic heads of the upper numerical model layers versus the deeper model layers caused by the topographical effect on the upper numerical layers.

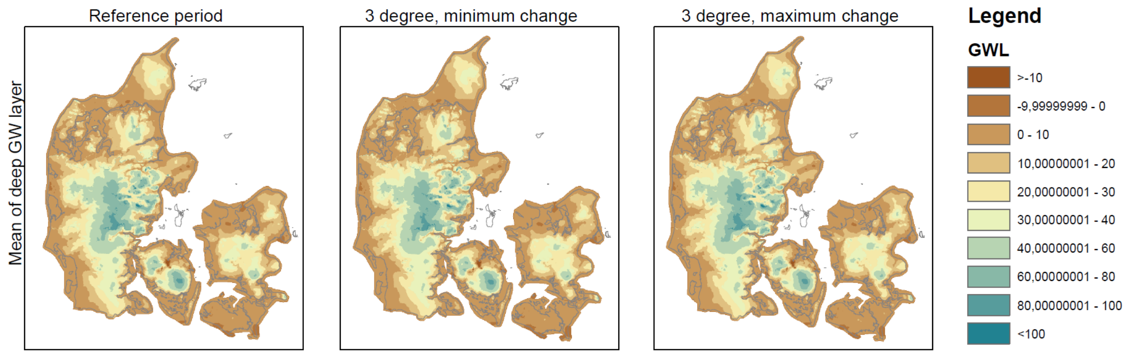

Figure 5.4 Deep groundwater levels for the reference period (left) and the future period for the 3 degree change scenarios. 3 degree minimum in the middle and 3 maximum to the right.

5.1.3 *Euro-CORDEX*

The simulation of future groundwater conditions with the Euro-CORDEX scenarios show less changes between past and future than the TACTIC standard scenarios, when investigating the mean response. Figure 5.5 illustrates the impact on the shallow groundwater and figure 5.6 on the deeper groundwater conditions.

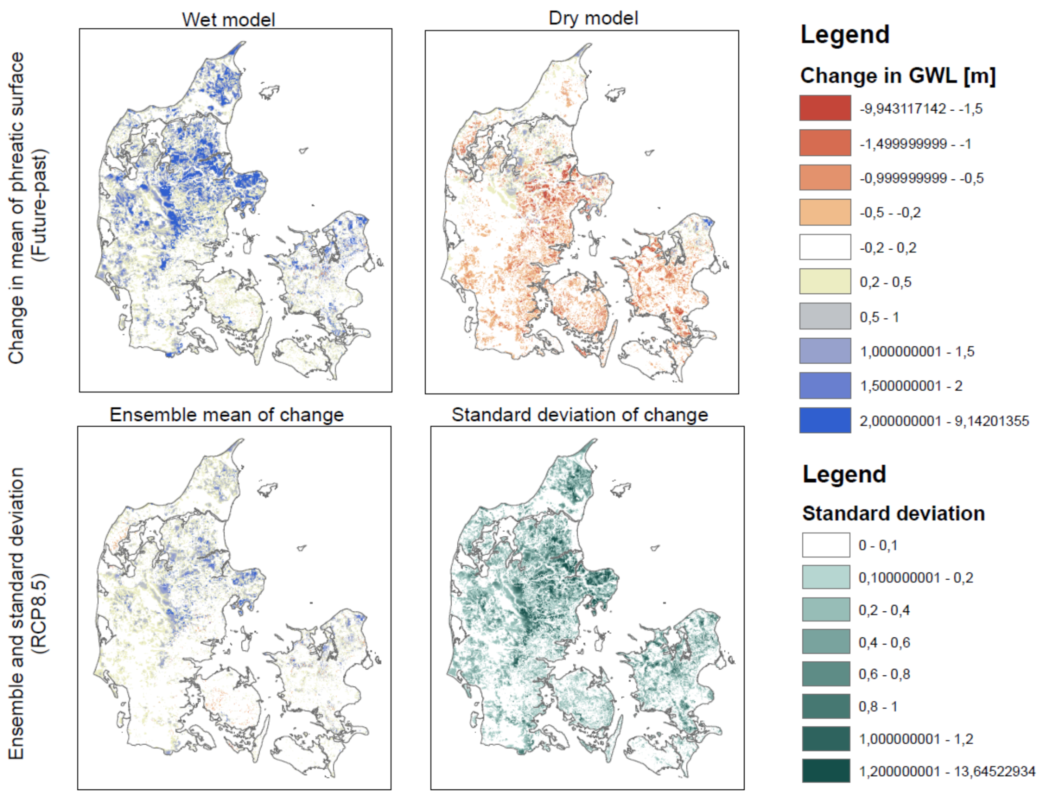

Figure 5.5 Changes of shallow groundwater levels for a wet and a dry ensemble member (upper left and right), and the ensemble mean of the change between past and future

(lower left). The standard deviation of change (lower right) show where the members of the ensemble differs most. Based on the Euro-CORDEX ensemble.

The Euro-CORDEX scenarios show less impact, changes between past and present, on shallow and deeper groundwater resources than the TACTIC standard scenarios. Figure 5.5 and 5.6 illustrate scenarios with some of the highest and lowest change of the Euro-CORDEX ensemble. All of these shows less change than the 3 degree TACTIC scenarios. Especially, the Euro-CORDEX scenarios with a decrease in groundwater levels, top left figure 5.5 and 5.6, are less dry the TACTIC 3 degree minimum scenario. The scenarios with highest increase of groundwater levels, TACTIC 3 degree maximum and Euro-CORDEX seems more comparable. Another difference between the TACTIC and Euro-CORDEX scenarios is that the Euro-CORDEX scenarios show more countrywide variation in changes. For instance, the dry Euro-CORDEX scenario, figure 5.6 upper left, include areas with more than 1.5 m decrease and areas with 1.5 – 2.0 m increase in groundwater levels. This reveals a significant difference by applying scenarios generated by a "distribution based (down)scaling" and a "delta change approach".

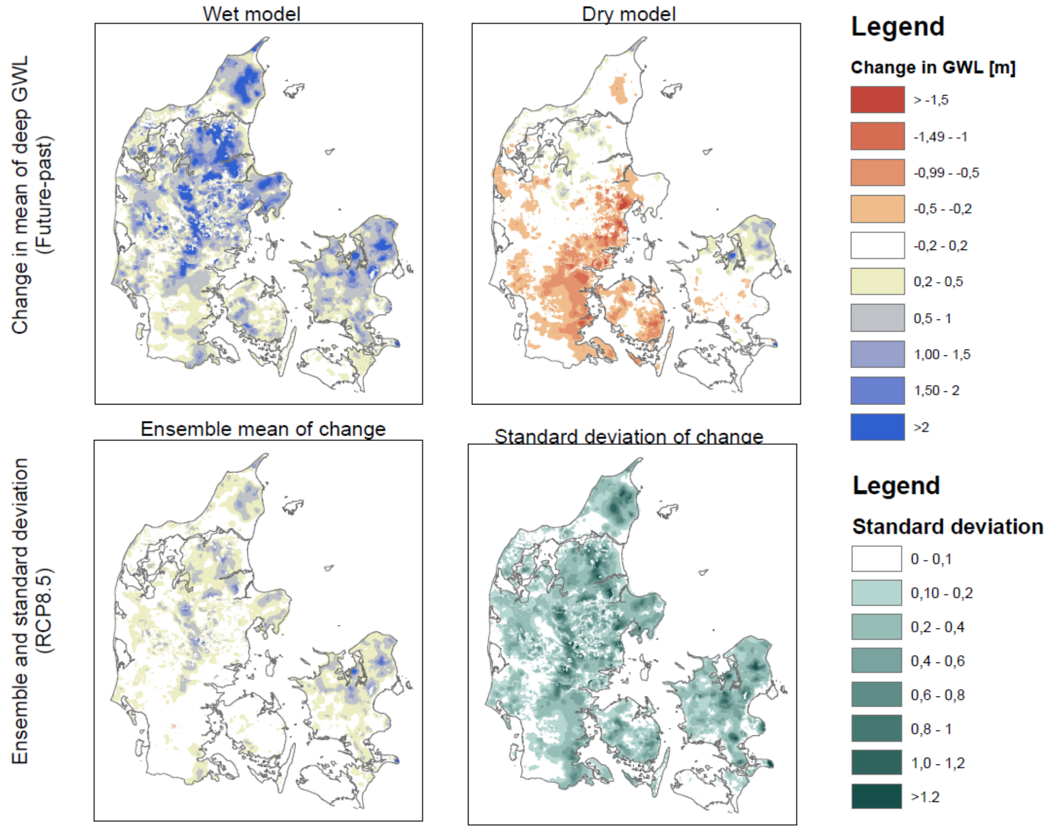

Figure 5.6 Changes of deeper groundwater levels for a wet and a dry ensemble member (upper left and right), and the ensemble mean of the change between past and future (lower left). The standard deviation of change (lower right) show where the members of the ensemble differs most. Based on the Euro-CORDEX ensemble.

Based on the Euro-CORDEX scenarios with 21 ensemble members, a map of ensemble-mean can be generated. These maps indicate a general increase in groundwater levels but with many areas experience low impact or are unaffected by climate change at least for mean conditions.

5.1.4 Conclusions of the assessment based on integrated hydrological modelling

Predictions of the future groundwater conditions are not clear in terms of the direction change. Both groups of scenarios, the TACTIC standard scenarios, developed within TACTIC but based on the international ISIMIP consortium, and Euro-CORDEX based scenarios, show scenarios with lower shallow and deeper groundwater levels and scenarios with higher groundwater conditions. From the larger ensemble (n=21) of the Euro-CORDEX climate change scenarios, the ensemple mean, indicate a genereal increase of groundwater levels between the reference period (1981-2010) and a future period (2071-2100).

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