Deliverable 3.2 and 6.2

PILOT DESCRIPTION AND ASSESSMENT

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Geological Survey of Denmark and Greenland

Storåen-Sunds, Denmark

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LIST OF ABBREVIATIONS & ACRONYMS

MSL	Main Stationary Line
GCM	Global Circulation Model
RCP	Representative Concentration Pathway
RCM	Regional Climate Model
DMI	Danish Meteorological Institute
GEUS	Geological Survey of Denmark and Greenland
Jupiter	Danish borehole archieve, hosted by GEUS at www.geus.dk

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1 EXECUTIVE SUMMARY

Pilot name	Storåen-Sunds
Country	Denmark
EU-region	NW
Area (km^2)	1052
Aquifer geology and type classification	Sand and gravel
Primary water usage	Drinking
Main climate change issues	Rising shallow groundwater table causing groundwater-introduced flooding
Models and methods used	Hydrological integrated model
Key stakeholders	Herning municipallity, Central Region of Denmark
Contact person	Jacob Kidmose (GEUS)

The pilot of storåen and Sunds include Miocene and glacial sand aquifers. These aquifers constitutes by far the most impotant, qualitively as well as quantitatively. In the Sunds pilot study, focus are on the shallow groundwater conditions and how the shallow aquifer – surface water interaction are affected by climate change and possible climate change adaptation.

In the context of TACTIC, a climate change impact asssesment on the shallow groundwater have been performed by the use of a local scale hydrological model with 25 m simulation cells. The model is an integrated hydrological model based on MIKE SHE and MIKE HYDRO. To assess future groundwater conditions in Denmark, the TACTIC standard scenarios representing a future one and a three degree temperature change have been used to force the hydrological models. Furthermore, a number of adaptation strategies to soften the impacts of climate change has been investigated with the hydrological model.

Predictions of the future groundwater conditions are not clear in terms of the direction of change looking at the most dry and wet of the one and three degree scenarios, respectively. Depending on the scenarios choosen, e.g. 1 degree wet or dry, 3 degree wet or dry, groundwater levels of the shallow groundwater aquifer either increases or decreases. The adaptation scenarios illustrates that unwanted climate change effects can be counteracted by adaptation measures. Based on the different scenarios tested, the most effective measure is to lower the groundwater table in the urban part of the City of Sund is by implementation of a

“3rd pipe”, an urban drainage system installed along the existing sewer system. The scenarios also show that especially renovation of an old sewer system and increasing the rainwater infiltration will increase the upper groundwater table and potentially introduce groundwater flooding.

The combination of deferent scenarios illustrated that different interventions can either work for or against the goal of preventing future groundwater flooding. Comparing the unclear signal of climate change on groundwater conditions with the possible interventions of climate change adaptation measures, it is obvious that special care should be taken in designing the future hydrological conditions within the urban area.

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 Storåen and Sunds pilot represents one of the small 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 most upper groundwater levels will increase or descrease in the future as a result of climate change and adaption measures.

3 PILOT AREA

Storåen and Sunds pilot is located in the western part of Jutland, Denmark. In this area several events with high groundwater table have caused flooding in both rural as well as urban areas. Especially, around the area at the city of Sunds, groundwater conditions have been under investigation because of a believed connection between high shallow groundwater and surface water flooding. The groundwater table in focus is the shallow groundwater table, which is here defined as the upper and most horizontally hydraulic connected groundwater table. In addition, the high groundwater table is believed to interact with the urban sewer system. This has significant economic consequences for the local sewer cleaning facilities.

With high groundwater tables, areas with inflow of groundwater into sewer systems are widespread because the saturated soil zone is above sewer level. In this situation, leaky sewers will not discharge sewerage to the adjacent soils, but groundwater will enter the sewer and increase the cost of cleaning sewer water. In general, the Storåen river catchment, Figure 3.1, are often flooded by a high groundwater table or indirectly by increased groundwater discharge to surface waters. An example of this is the flooding of the city of Holstebro in 1970, 2007, 2011 and 2015. Storåen flows through Holstebro.

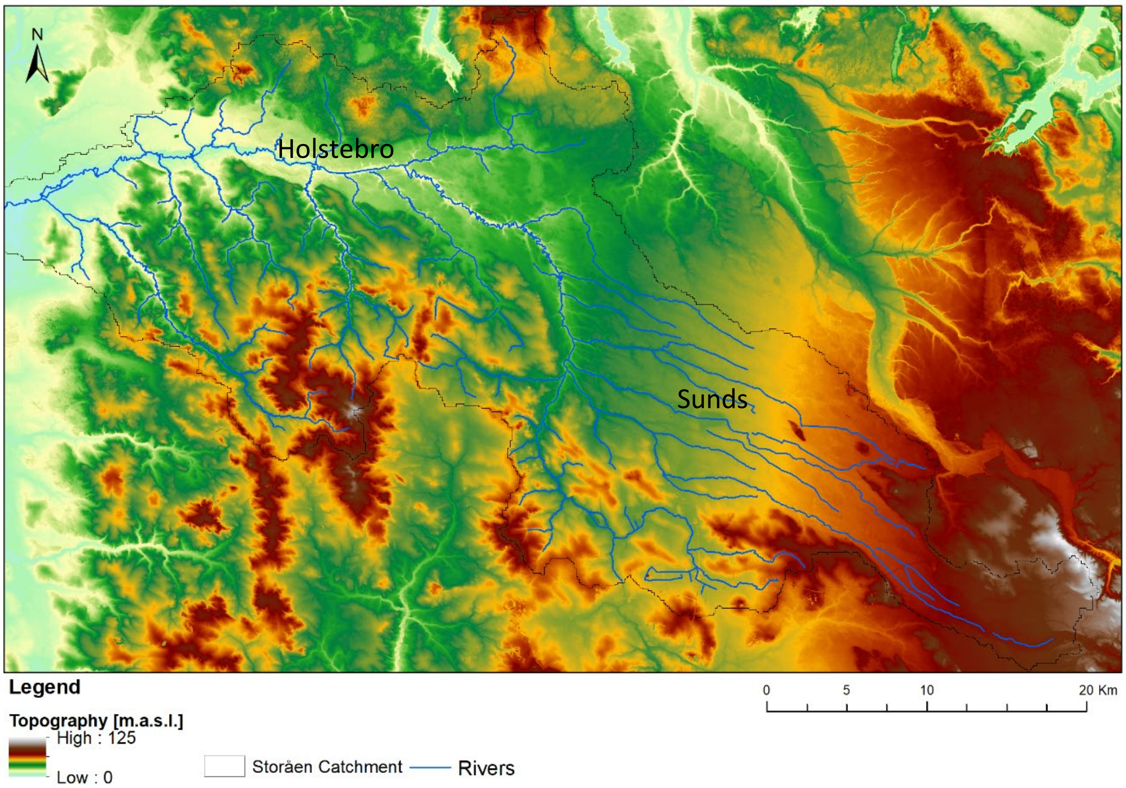

Figure 3.1 Storåen catchment. Sunds city is located in the upper part of the Storåen catchment. Topography in the Storåen catchment varies from 110 m a.s.l. (meters above sea level) to 0 m a.s.l. at Nissum Fjord, where Storåen discharges to, which is connected to the sea.

The Storåen-Sunds pilot will focus on the challenges at the city of Sunds and the Sunds Lake. The lake is an important surface water for the pilot because of its vicinity to Sunds and because it has a hydraulic connection to the aquifer below the city.

3.1 Site description and data

3.1.1 Climate

Denmark and the studied pilot lies in the temperate climate zone. At Sunds, the yearly precipitation is 900 mm and varied in the years 2011 to 2018 between 693 and 1056 mm/yr. The yearly average temperature is just below 9 ^{0}C, and peaks in July with daily average of 16.5 ^{0}C and coldest in February of 1.1 ^{0}C. Potential evapotranspiration is 591 mm/yr. Precipitation is available from 1989 to present with daily values in 10 by 10 km grids. Temperature and potential evapotranspiration calculated by a modified Makkink equation are available in 20 by 20 km grids, also with daily values. Both datasets are from DMI (Danish Meteorological Institute).

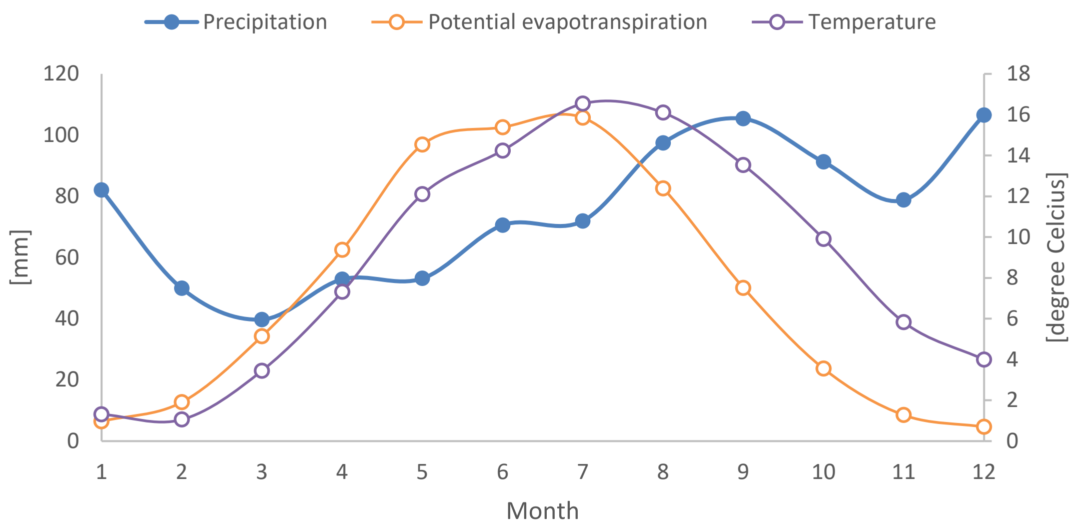

Figure 3.2 Monthly variation in precipitation, potential evapotranspiration and temperature. Average monthly values are derived from the grid-based dataset for the period of 2011-2018.

3.1.2 Area use

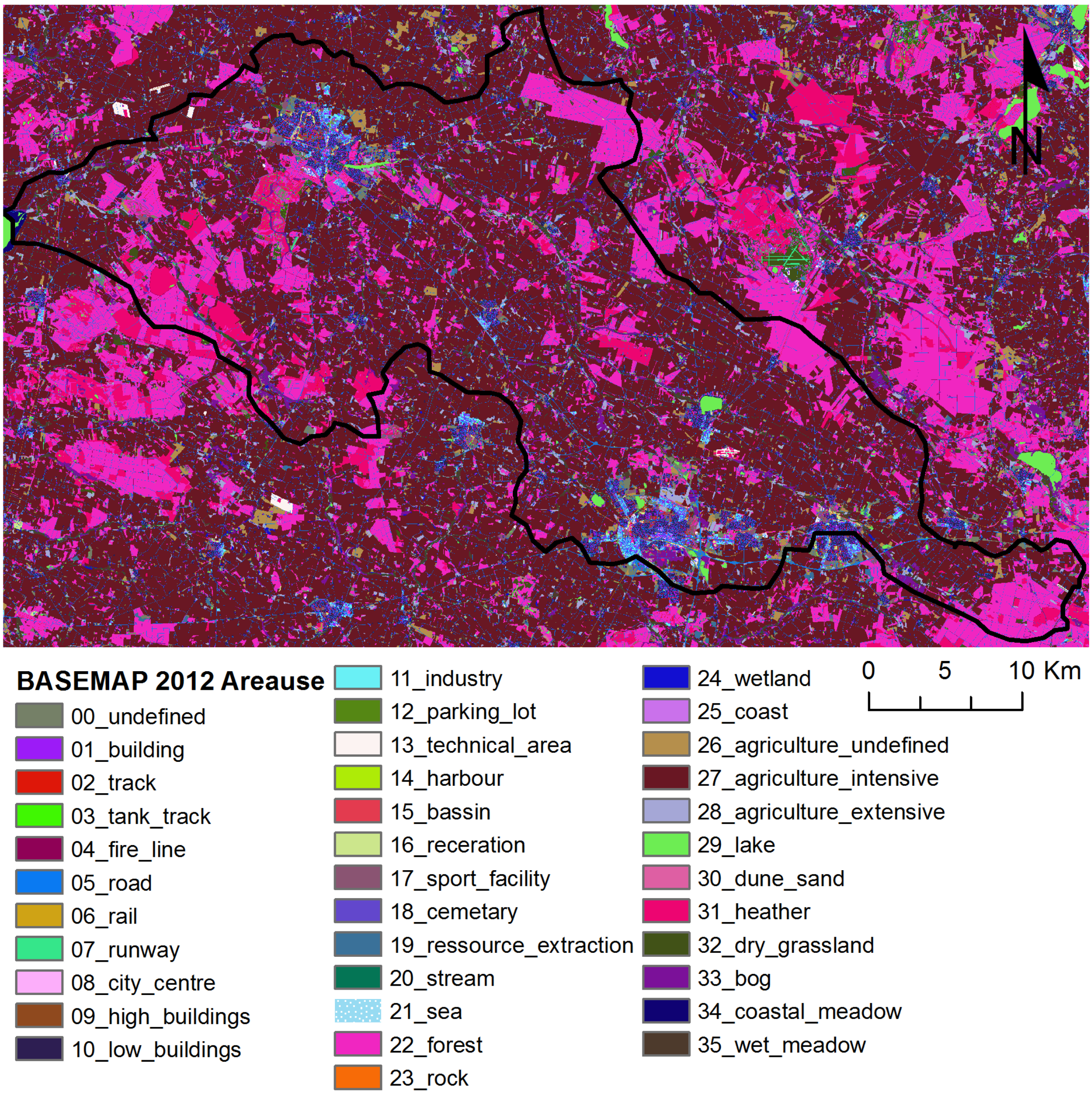

Figure 1.3 Area use in Storåen-Sunds (datasource: Danske Miljøportal 2018).

Area use in Storåen-Sunds is defined by the Basemap 2012 for Denmark by Levin et al. 2012. Basemap 2012 are a 10 by 10 m raster dataset with 35 different area classes, figure 3.3. The dominating area uses in the pilot are agriculture and forest. Other area uses as building, road, industry, heather, wetlands and surface water are also widespread in the Storåen catchment. The 10 m resolution makes even spatial small features as roads and buildings visible in the dataset. The Basemap 2012 are freely available in GIS formats. Hence, the dataset can be manipulated to a reasonable number of classes for hydrological modelling purposes. For instance, the classes building, road, city center, high building, low building, industry and technical area could be merged to describe paved areas.

3.1.3 Geology

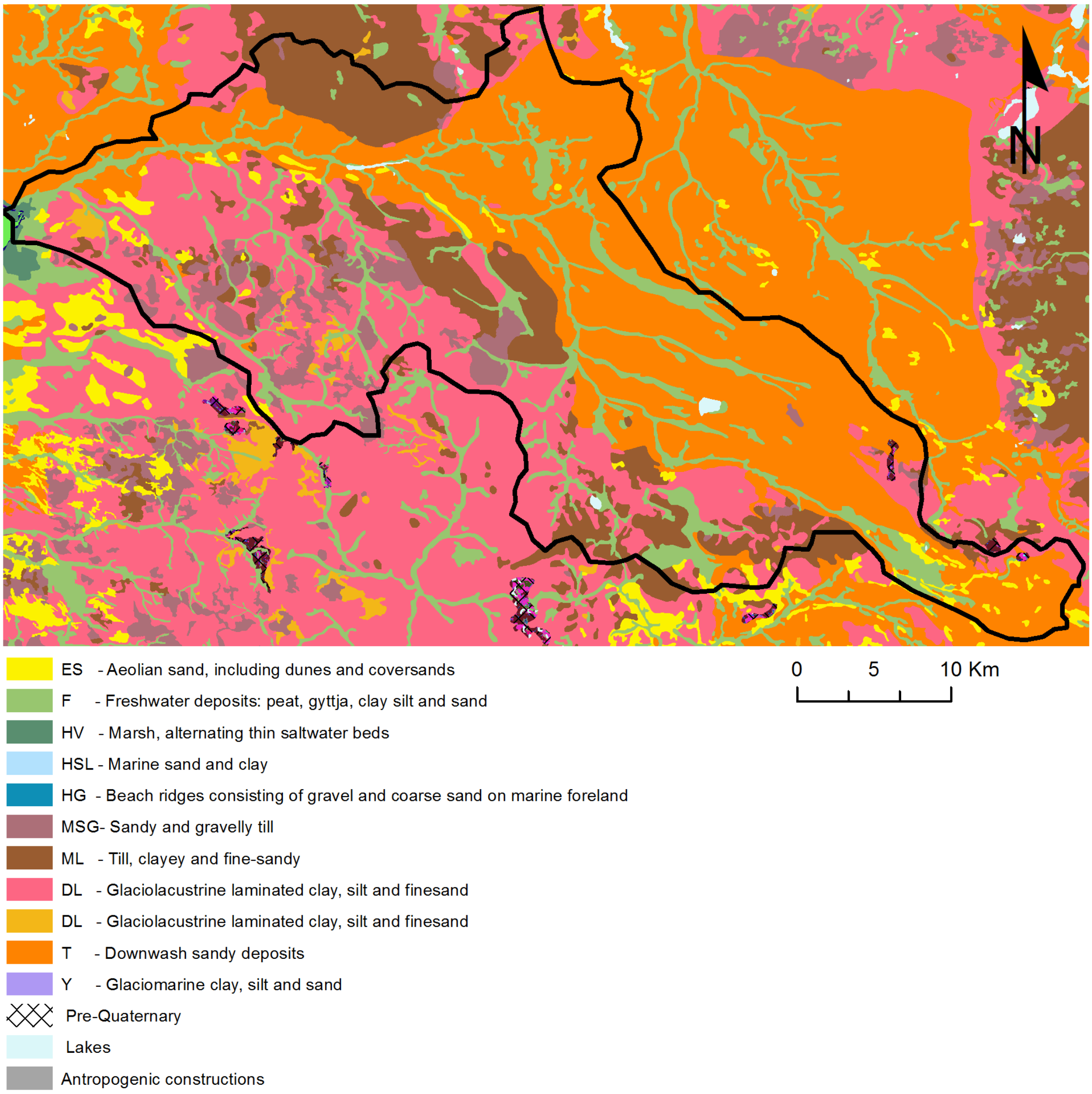

Figure 3.2 Geology at the surface (datasource: GEUS).

At the surface, geology primarily consists of glacial, e.g. sand and clay, and post-glacial sediments, e.g. freshwater sediments as peat, gyttja, sand and clay. Only a few small areas have pre-quaternary sediment outcropping at the surface. The pre-quaternary surface consists of Oligocene un-cemented sediments. The pre-quaternary aquifers are of Oligocene and Tertiary age and unconsolidated in general. The aquifers in the Storåen-Sunds pilot can therefore be characterized as porous and consisting of sand and gravel. Figure 3.4 shows the surface geology and figure 3.5 is a profile of the geology from Nissum Fjord to the most eastern part of the Storåen catchment.

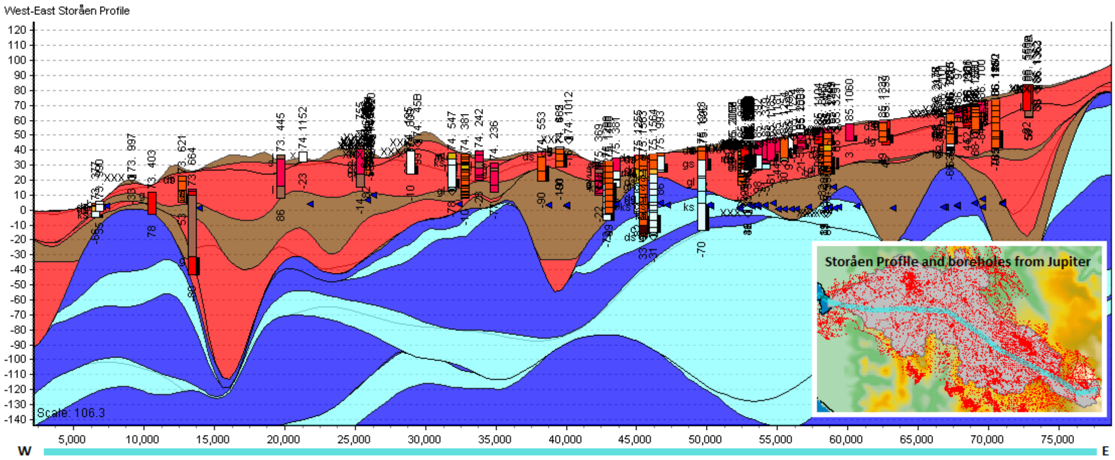

Figure 3.3 Geological profile of the Storåen catchment. Upper quaternary clays (brown), sands (red), and pre-quaternary sands (light blue) and clays (blue).

The geological layers shown in figure 3.5 are shown as hydrogeological units ready to use in a hydrological model. A 3D geological model of the full Storåen catchment are hosted by GEUS on the Danish model database (GEUS model database 2018).

3.1.4 Surface water bodies

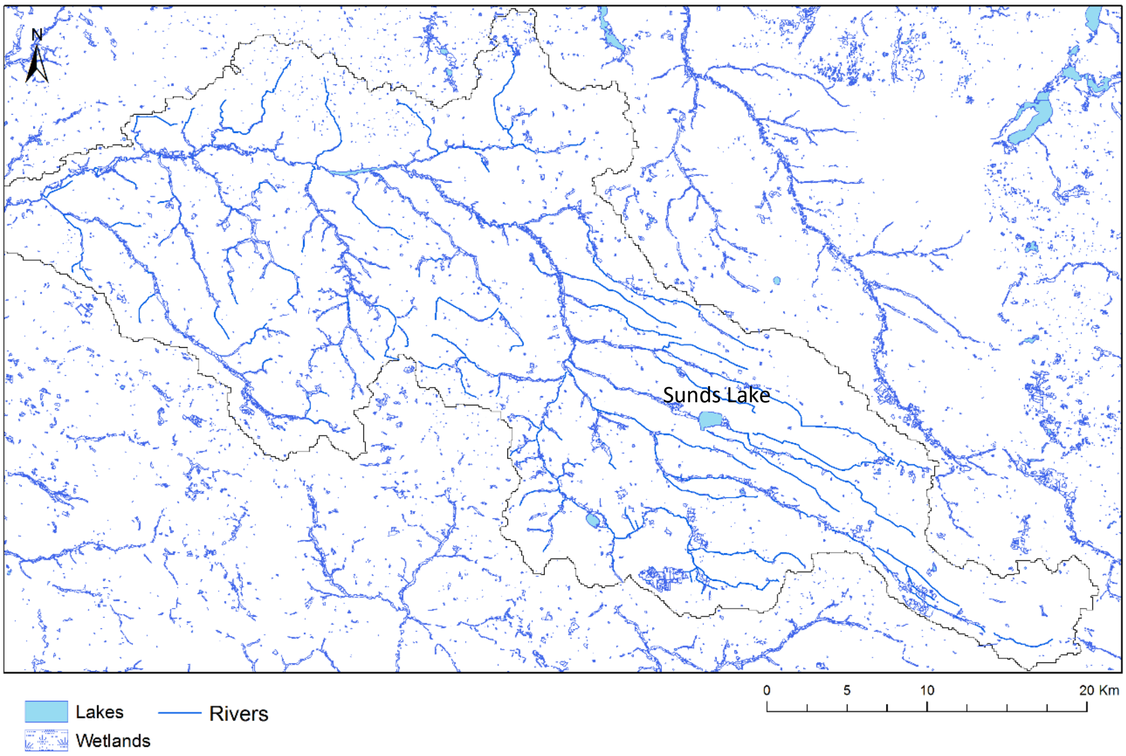

Figure 3.4 Surface waters at Storåen catchment (datasource: Dansk Miljøportal 2018).

The position of shallow groundwater close the surface results in many lake, wetlands and streams. In addition to these water bodies interacting with local groundwater, hanging or purged water tables forming wetland and smaller lakes are also widespread in the catchment. Data are freely available at www.danskmiljøportal.dk (Dansk Miljøportal 2018).

3.1.5 Groundwater table observations and pumping

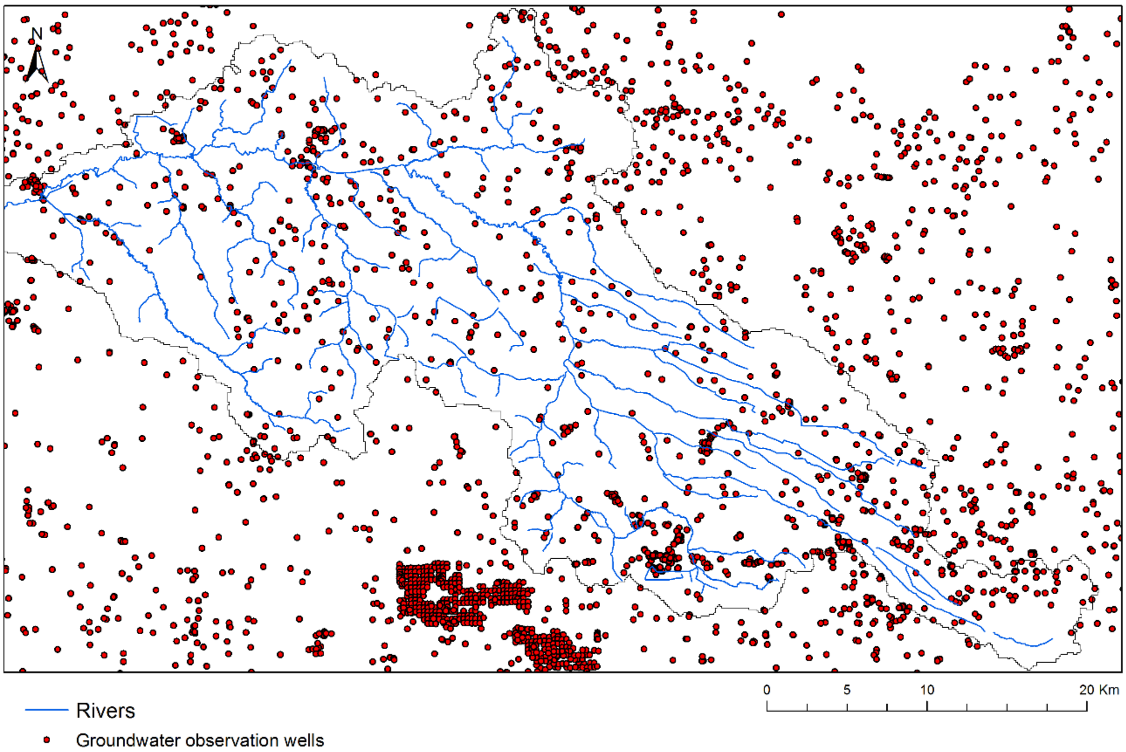

Figure 3.7 Wells with groundwater-level observations at Storåen Catchment.

Well data, observations of groundwater level, permissions for groundwater abstraction, monitored water chemistry and basic borehole data are in Denmark stored in Jupiter, the Danish Borehole archive. Data from Jupiter are freely available and can be downloaded from www.geus.dk. Jupiter are hosted and maintained by GEUS. Figure 3.7 shows the boreholes with groundwater head data between the years 2000-2010. Temporal resolution of observations at the different wells differs significantly (between single observations and one every minute during the analysed period).

Groundwater abstraction data are also reported to Jupiter but often records are incomplete.

3.2 Climate change challenge

The climate change challenge at the Storåen-Sunds pilot is the increasing risk of groundwater-introduced flooding because of future changing climate conditions. At the pilot, relevant climate change aspects for the North-Western Europe are: Increase of winter precipitation, increase in river runoff and, because of increased winter precipitation potentially higher groundwater levels. If true, these conditional changes will strengthen and enhance the already occurring threat of flooding. The pilot will investigate these issues at a local urban scale where anthropogenic effects (man made) on hydrology and groundwater conditions are strong.

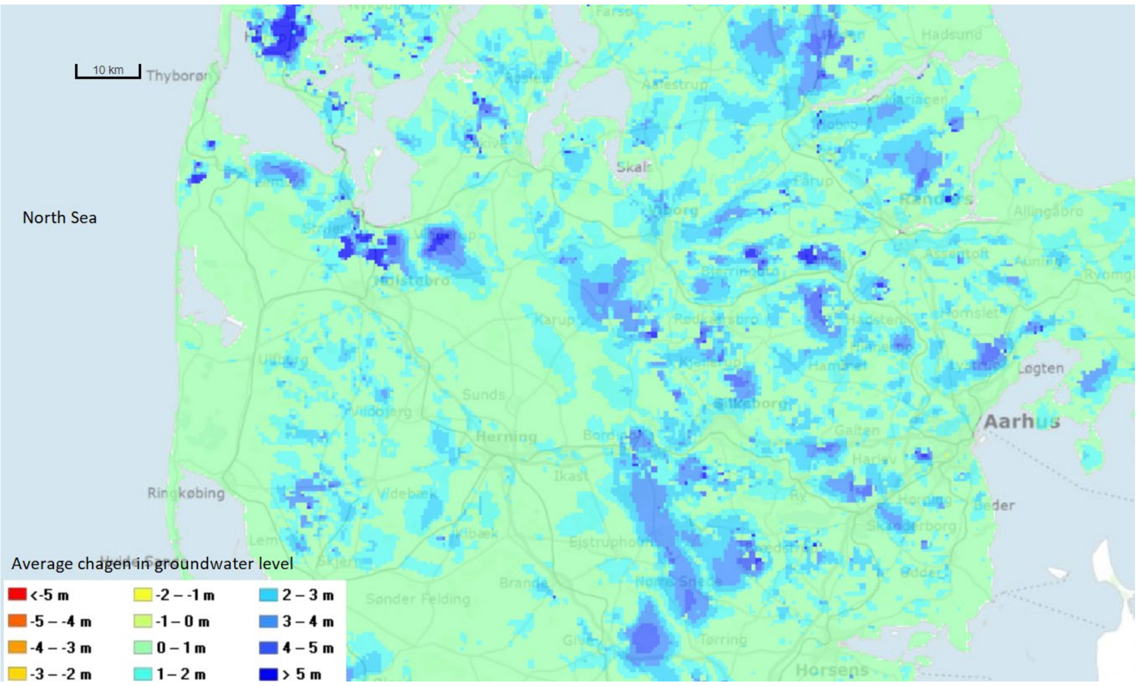

Figure 3.5 Climate change impact on groundwater. Groundwater changes between the historic period of 1961-1990 and the future period of 2021-2050. Results are shown from Central Jutland in meter of change between present and future mean groundwater table (Source: Klimatilpasning.dk 2011).

4 METHODOLOGY

The assessment of climate change and adaptation measures on groundwater conditions at Storåen and Sunds are performed using the TACTIC standard climate change scenarios and an local scale integrated hydrological model around the City of Sunds in the larger Storåen catchment, Western Denmark. The model is based on the MIKE SHE code, coupled with MIKE HYDRO code (TACTIC toolbox). Figure 4.1 illustrate the location of the Sunds model in Denmark (left), the model boundary, the City of Sunds within the model, and Lake Sunds.

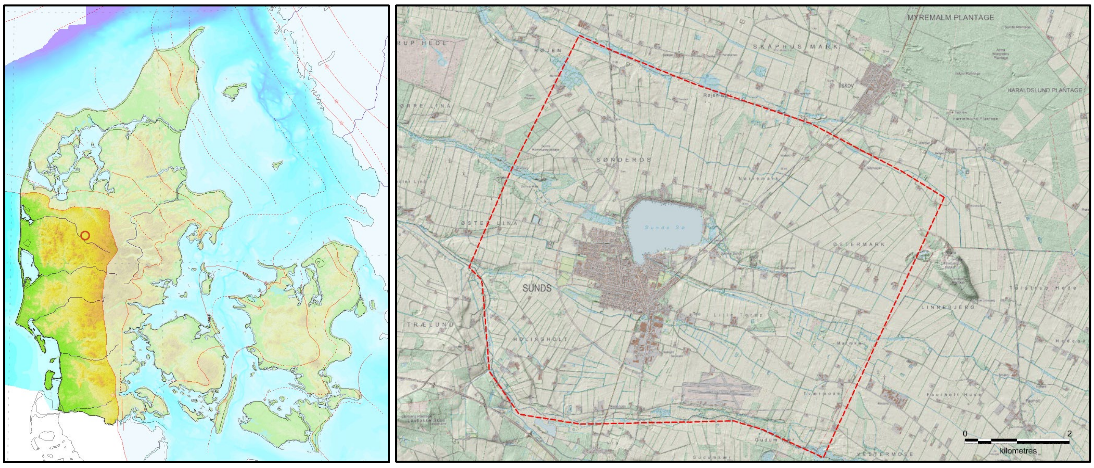

Figure 4.1 Location of Sunds in Denmark (left), and model boundary (red polygon to the right)

4.1 Methodology and 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.

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 4.1. 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

4.2 Integrated hydrological modelling of climate change

The MIKE SHE/ MIKE HYDRO model framework that the Sunds-model is based on, simulates overland flow, evapotranspiration, flow in the unsaturated zone, the saturated zone with drainage routing, and river flow, Figure 4.2, for the area around the city and lake of Sunds, Figure 4.3.

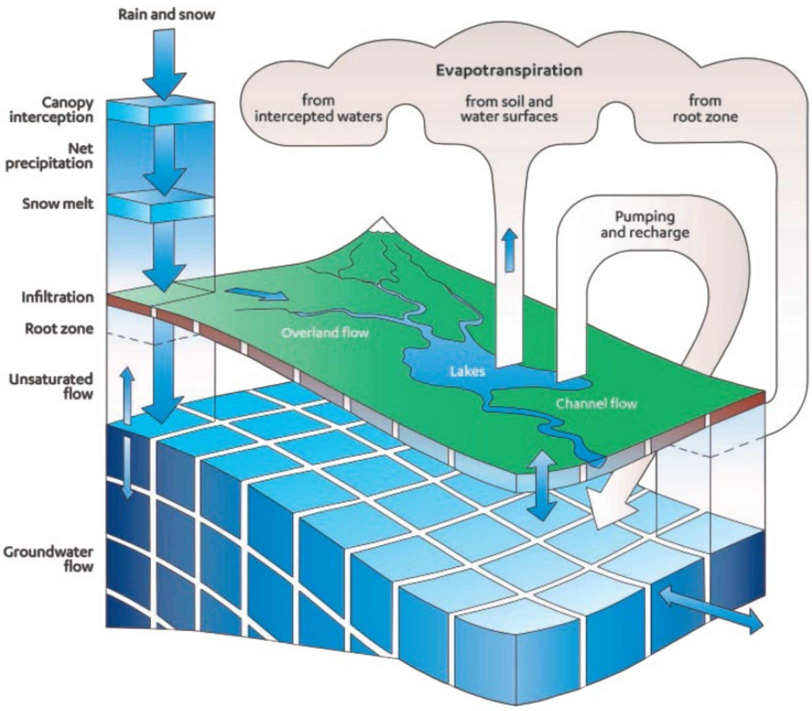

Figure 4.2 MIKE SHE model: Simulated hydrological water fluxes.

The geology of the Sunds model is sketched in figure 4.3 and is based on geophysical measurements. Numerical layers follow the principal layers of the geology, besides near the surface, where additional numerical layers are inserted. From the surface, the geology is glacial and post-glacial with important aquifers of glacial meltwater. Deeper, a Miocene sandy aquifer is separated from the upper glacial meltwater aquifer by a Miocene clay layer. The deepest horizon of the model consists of relatively impermeable clay from the Arnum Formation, also of Miocene origin, Figure 4.3.

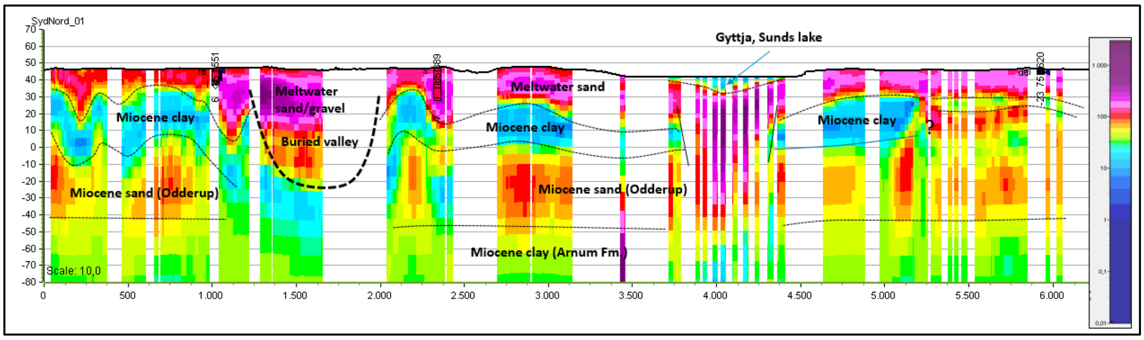

Figure 4.3 The geology of the Sunds model is based on geophysical measurements, Rasmussen et al. 2020.

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.

In the assessment of adaptation measures, other model elements different the climatic states are also changed and can be summed up in the following adaptation scenarios:

1. Groundwater drainage, a dedicated groundwater drainage pipe installed together with the existing sewer system (the 3rd pipe) in urban areas, Sunds City.
2. Plantation of coniferous forest on 395 ha west, south, and east of the City of Sunds.
3. Changed groundwater abstraction close to the City of Sunds.
4. Application of local area recharge, forced infiltration of surface water into the shallow aquifer from 25% (today) to 50% (possible future) of the stormwater.
5. Renovation of sewers. The sewer do not act as groundwater drainage because the leakage are reduced.
6. Keeping the Lake water stage fixed to the summer water stage (lowering the water table in Sunds Lake to a constant elevation of 41.6 m).

The adaptation measures are tested under historic climatic conditions and compared with business as usual run for the same historic period with change maps.

4.3 Model calibration

The hydrological model for Storaa was calibrated against groundwater heads and river runoff using the parameter estimation software PEST. The hydrological observations used include observations of groundwater levels, water level in Sunds Lake and discharge from rivers.

Data from a synchronous groundwater measuring campaign ultimo October 2012 included 68 shallow boreholes with a maximum depth of 5 m. The campaign also included measurements of water levels at 33 locations in the river systems, and water levels measured at 107 locations around the rim of Sunds Lake.

Time series of groundwater level from eight boreholes have been available for the hydrological model. The time series are from seven shallow boreholes and from one deeper borehole. The longest time series was started in 2012. At the western outlet of Sunds Lake the water level of the lake is measured continuously. In the creek, Møllebæk, east of Sunds Lake the river discharge is measured continuously.

Figure 4.4 shows an overall good match between observed and computed groundwater heads with a difference of less than 0.5 m. At a few locations towards the west of the area, a difference of more than 1 m between observed and computed groundwater heads is seen.

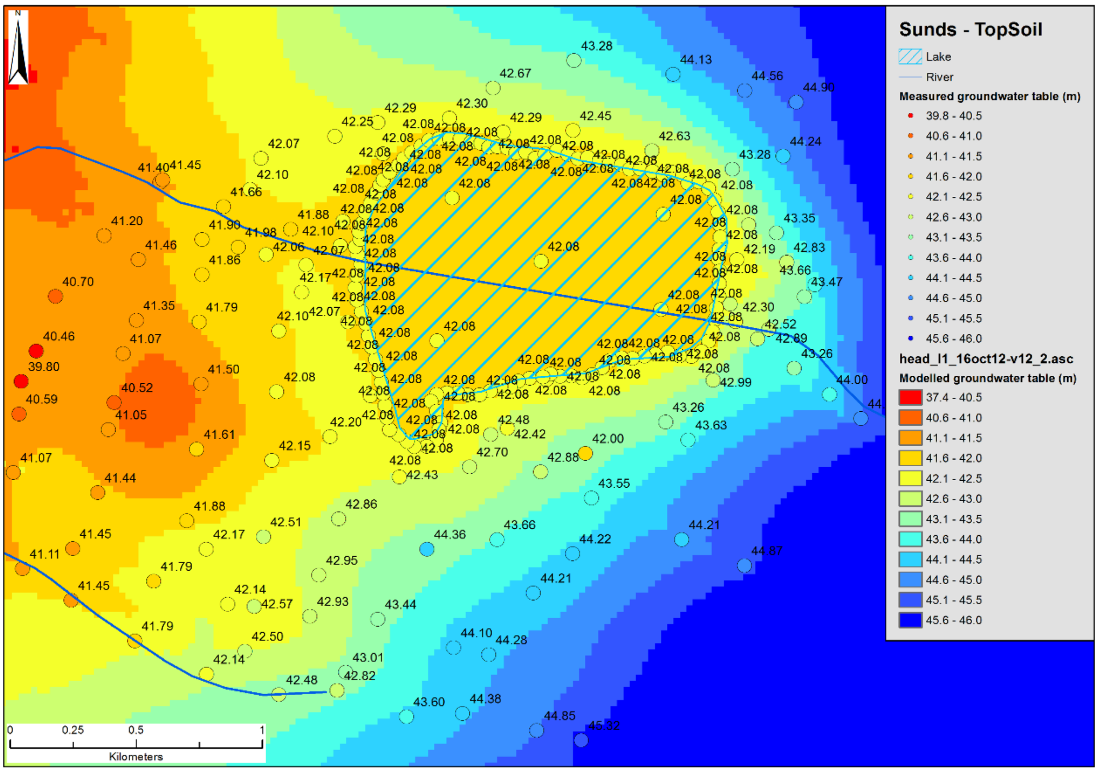

Figure 4.4 Groundwater head elevations from the calibrated hydrological model (colour contours) and the observed groundwater heads and water levels of Sunds Lake (coloured circles and numbers). Rasmussen et al. 2020.

Figure 4.5 Show simulated and observed times-series for som groundwater well within the model.

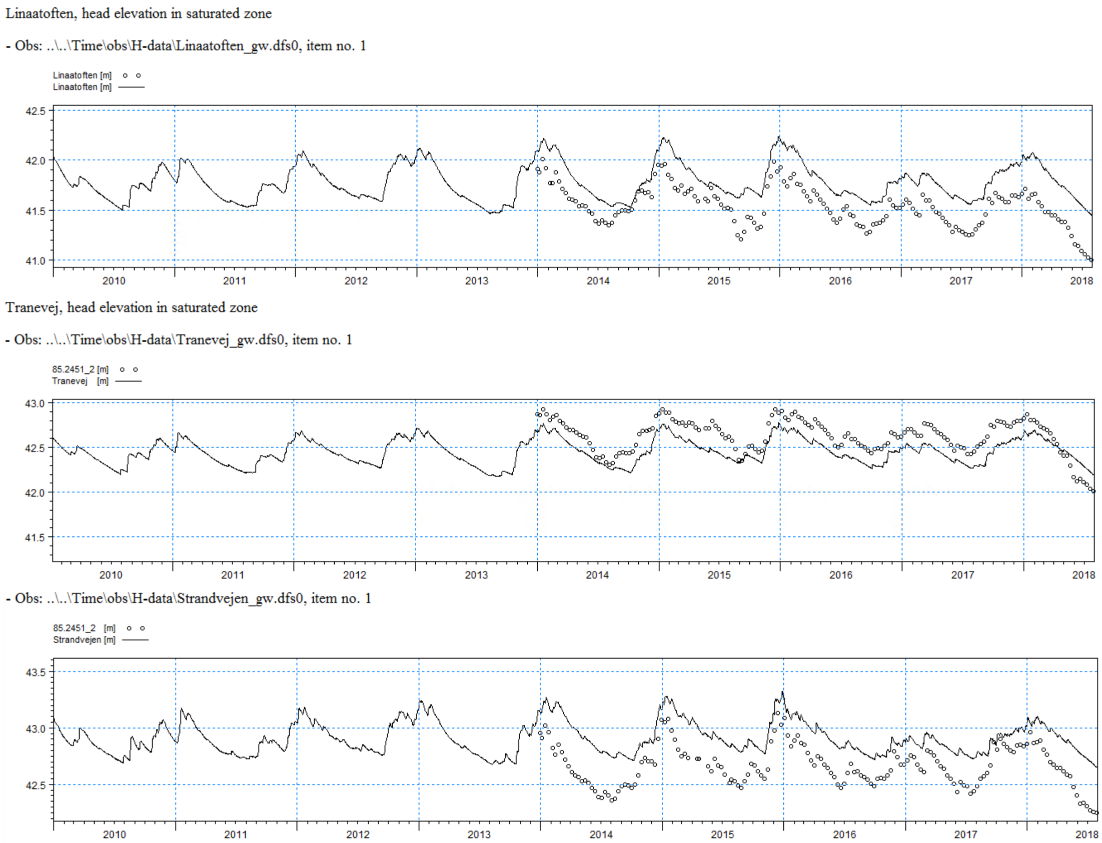

Figure 4.5. Modelled (solid lines) and observed groundwater head (circles) at station Linaatoften, Tranevej, and Strandvejen. Rasmussion et al. 2020.

Based on the calibration results, the model is qualified to be used for the climate change assessment and assessment of adaptation strategies.

5 RESULTS AND CONCLUSIONS

5.1 Integrated hydrological modelling of climate change

The TACTIC standard climate change scenarios simulated in the sunds model show changes in average groundwater levels for a 30 year historic, reference period, and future 30 year periods representing a 1 and 3 degree increase in temperature of the future. Figure 4.6 illustrate changes in groundwater levels between the reference and future periods. Areas with changes below zero (negative numbers), figure 4.6, have rising groundwater levels (blue colours) and areas with values above zero have a decreasing groundwater table (yellow-red colours).

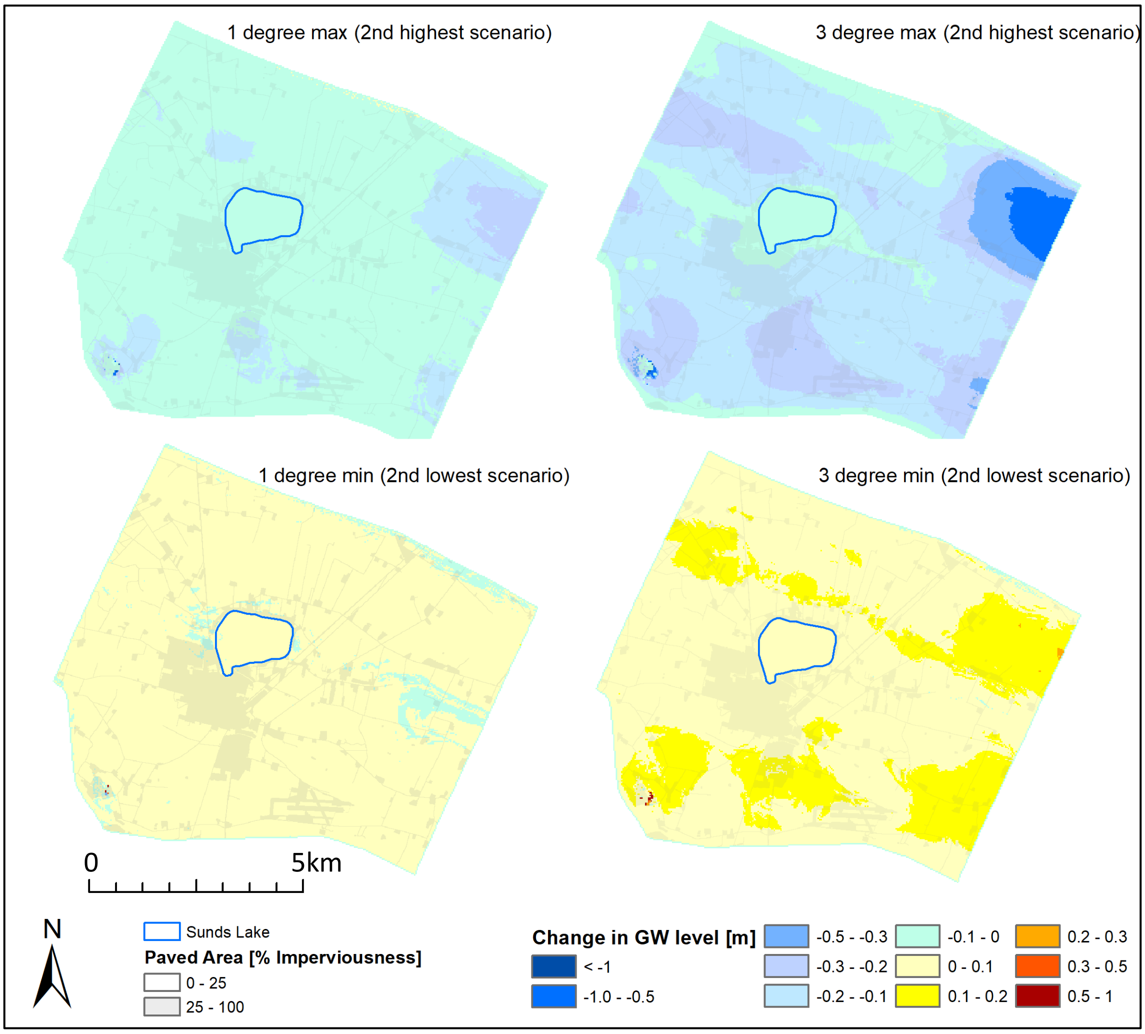

Figure 4.6 Change in groundwater levels for the four TACTIC climate change standard scenarios. The lower ones are the dry scenarios where groundwater levels mostly decrease (yellow-red colour) and the upper ones are the wet where groundwater levels increase (blue colour). Negative numbers (-) indicate an increase groundwater levels. Positive numbers indicate a decrease of the groundwater levels.

Average change for the entire model domain are for the 1 and 3 degree wet scenarios -6 cm and -17 cm, respectively. This shows a phreatic surface in 6 and 17 cm closer to the surface for the scenarios. The 1 and 3 degree dry scenarios show a increasing depths to the upper most groundwater table of 2 and 7 cm. Average of the four scenarios is a 4 cm decrease, a 4 cm lower groundwater surface in the future.

5.1.1 Conclusions of the assessment based on integrated hydrological modelling

Based on the 4 investigated scenarios of a possible 1 or 3 degree temperature change, groundwater levels can either increase or decrease. Average change of all the 4 models show a small increase of the upper most unconfined groundwater of 4 cm.

5.2 Assessment of climate change adaptation strategies

The following section shows selected results for the simulated 5 adaptation scenarios, Figure 4.7-12. The effects in the shallow groundwater table can be divided into measures lowering the groundwater table. The measures lowering the groundwater table and thereby reducing risk of groundwater flooding of infrastructure and building are: Installing the 3rd pipe, (the groundwater drain) along the sewer system, plantation of coniferous forest in the vicinity of the City, and maintaining the lake water stage at the summer level the whole year around. From these interventions, installing the 3rd pipe (groundwater drain) are clearly the most efficient one to decrease the groundwater levels. The measures increasing the groundwater levels include: renovation of the leaky sewer system, increasing the rainwater infiltration to the groundwater aquifer (local area recharge, forced infiltration), and stopping drinking water abstraction close to the city.

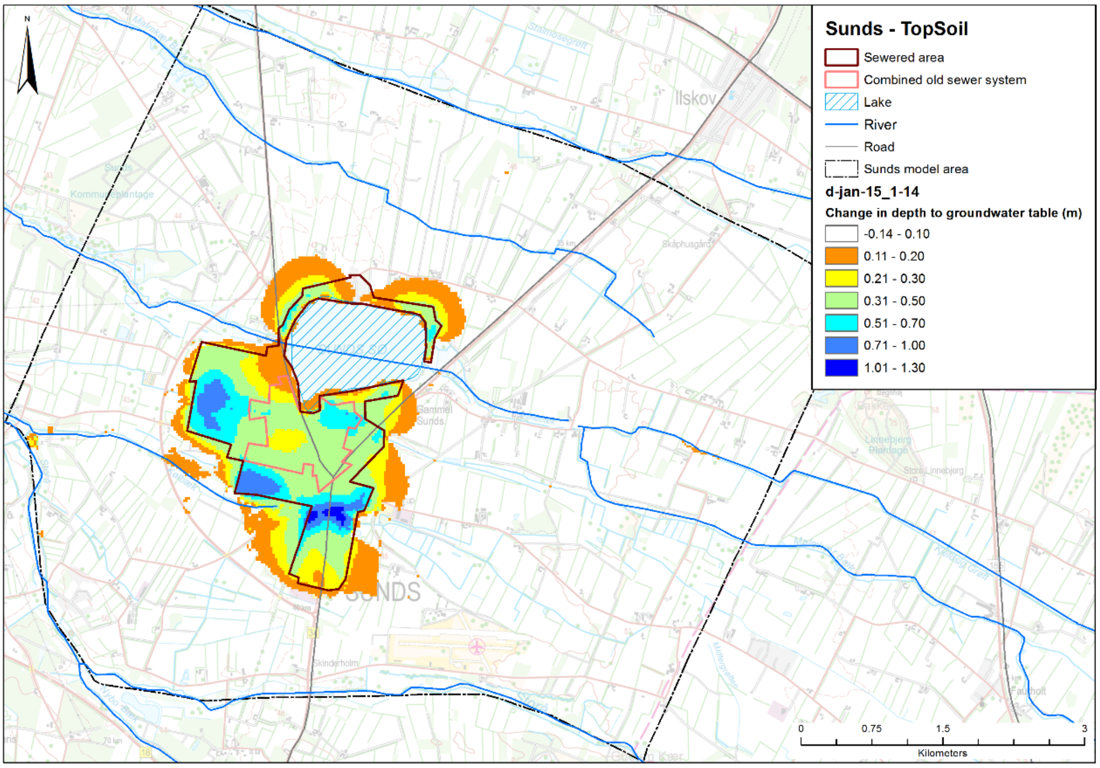

Figure 4.7 Effect on depth to groundwater table if establishing drains (3rd pipe) in the whole town. The figure shows the situation for a January situation with high groundwater table. Rasmussen et al 2020.

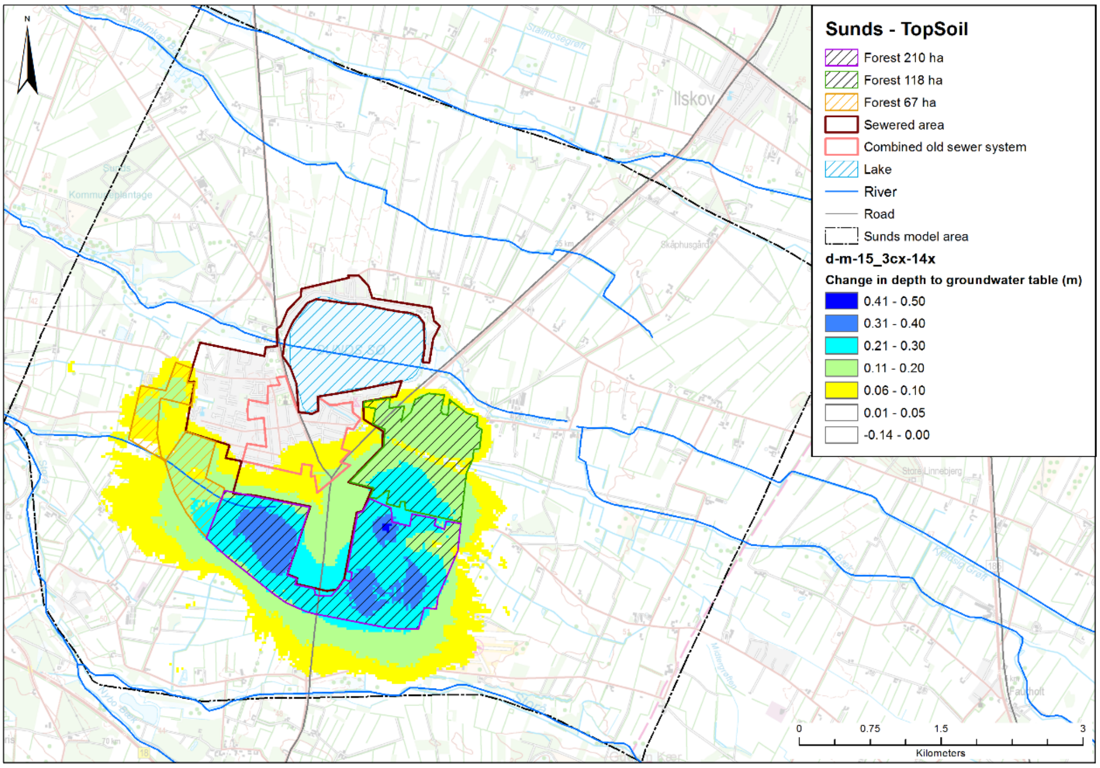

Figure 4.8 Effect on groundwater table with plantation of coniferous forest on 395 ha west, south, and east of town. Rasmussen et al 2020.

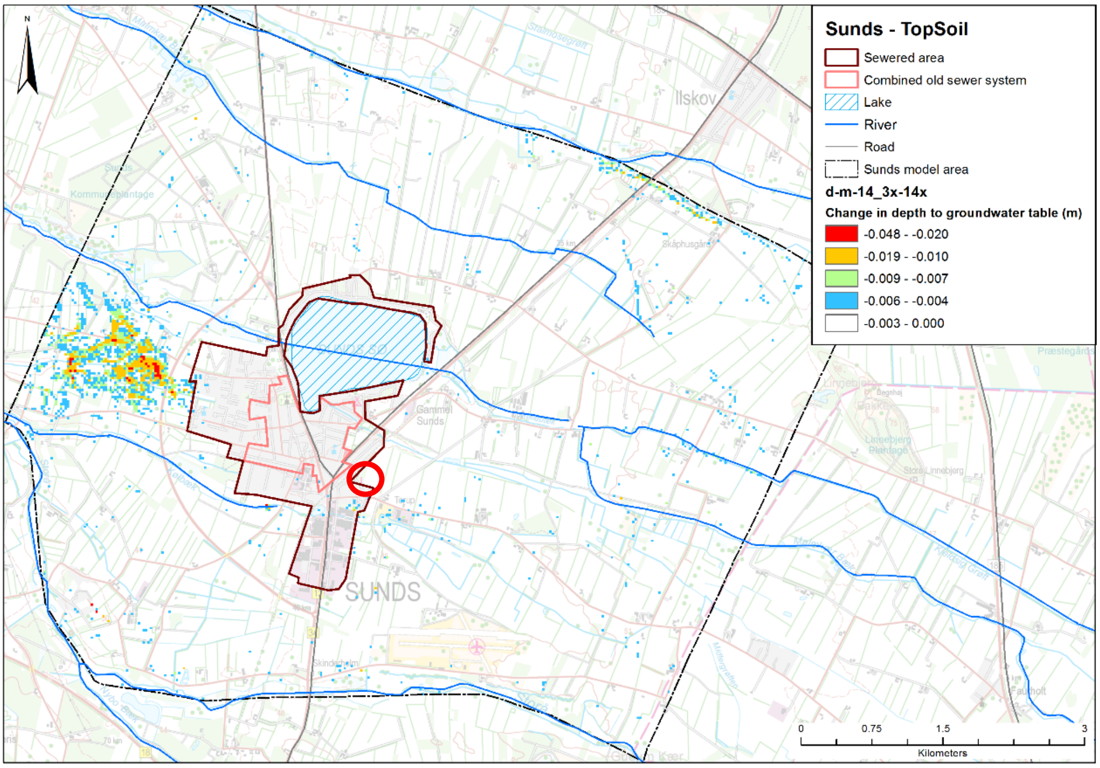

Figure 4.1 Effect on depth to groundwater table if groundwater abstraction for Sunds Waterworks stops. Minus in the numeric scale indicates a rise in groundwater table. Red circle shows the location of the waterworks wellfield. Rasmussen et al 2020.

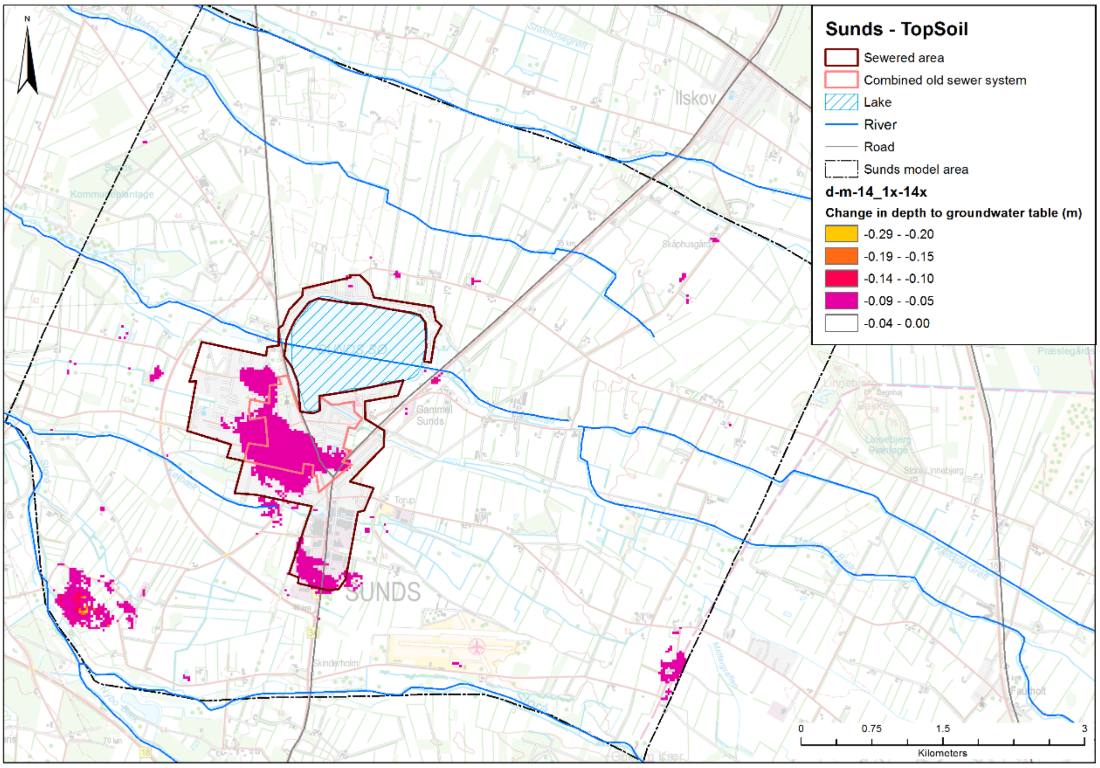

Figure 4.10 Change in depth to groundwater for the scenario with an increase of local rainwater infiltration in the whole town from 25% to 50%. Rasmussen et al 2020.

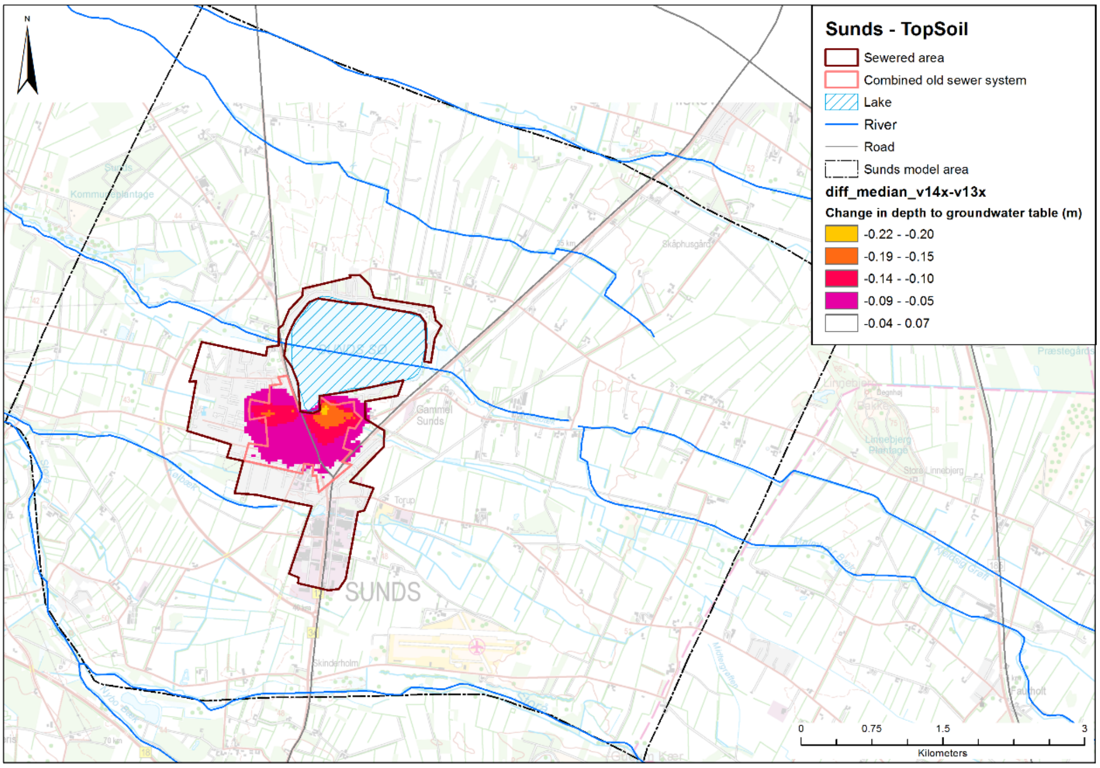

Figure 4.11 Change in depth to groundwater table after renovation of sewers in the centre of town (area inside light red lines). Rasmussen et al 2020.

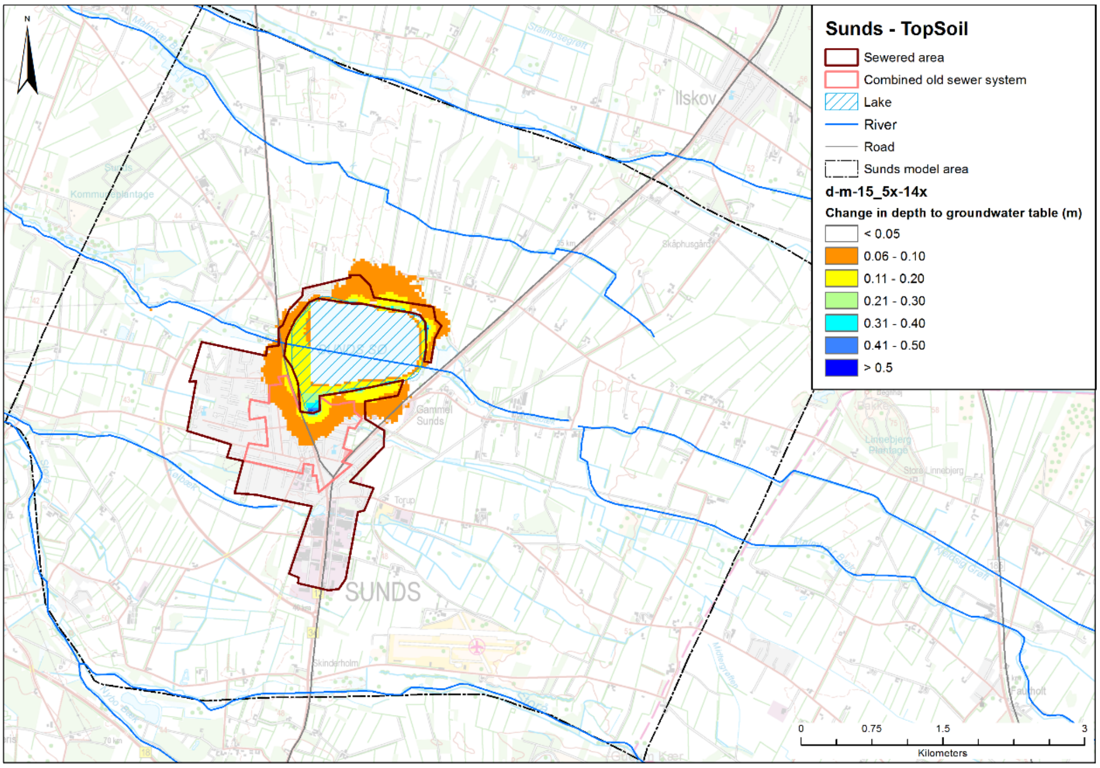

Figure 4.12 Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, "the summer level". The figure shows the situation for a median groundwater table. Rasmussen et al 2020.

5.2.1 Conclusions of the assessment of climate change adaptation strategies

Based on the different scenarios tested, the most effective measure is to lower the groundwater table in the urban part of the City of Sund is by implementation of a "3rd pipe", an urban drainage system installed along the existing sewer system. The scenarios also show that especially renovation of an old sewer system and increasing the rainwater infiltration will increase the upper groundwater table and potentially introduce groundwater flooding.

The combination of deferent scenarios illustrated that different interventions can either work for or against the goal of preventing future groundwater flooding.

6 REFERENCES

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Dansk Miljøportal 2018. Data obtained 1. December at http://www.miljoeportal.dk/-myndighed/Arealinformation/Sider/default.aspx

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