DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/12**

Geological and hydrological model for Sunds - preventive measures for lowering the groundwater table now and in a future climate

A TOPSOIL project - supported by the Interreg VB North Sea Region programme

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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G E U S

TOPSOIL is an EU cooperation supported by the Interreg VB North Sea Region programme in line with priority 3 of the programme: 'Sustainable North Sea Region, protecting against climate change and preserving the environment'.

Partners in pilot DK1 Sunds:

Content

1. Introduction

The town of Sunds is located in the central part of Jutland in a flat sandy agricultural area, see Figure 1.1. Sunds is one of five Danish pilots in the Interreg Topsoil project (https://northsearegion.eu/topsoil/).
During recent years, Sunds has been facing climate change related challenges with rising groundwater levels due to increasing precipitation in especially the winter period. The consequences are groundwater flooding of basements and low-lying areas. The local water utility company (Herning Vand) is currently renovating the old sewer system to decrease unintentionally inflow of water into the old leaky sewers. One of the consequences of this renovation work is that it speeds up the problem of rising groundwater. Thus, future measures have to be considered in order to ensure a better resilience towards groundwater flooding.

To engage the problems new geophysical data has been collected to better understand the hydrogeological system and essentially to setup and run relevant model and climate scenarios.
Based on the geophysical data acquired in the Topsoil project and existing geological data, a detailed geological 3D voxel model has been set up with the purpose to develop a robust geological framework for the hydrological model.

A hydrological model has been constructed in order to: (1) describe the variations in groundwater levels in space and time under the present conditions in Sunds, (2) quantify the effect of the ongoing renovation of the sewer system and local infiltration solutions on the depth to the shallow groundwater, (3) evaluate the effects of different solutions for lowering the shallow groundwater level in the city, and (4) to analyse the possible effect of projected climate change on the depth to the shallow groundwater.

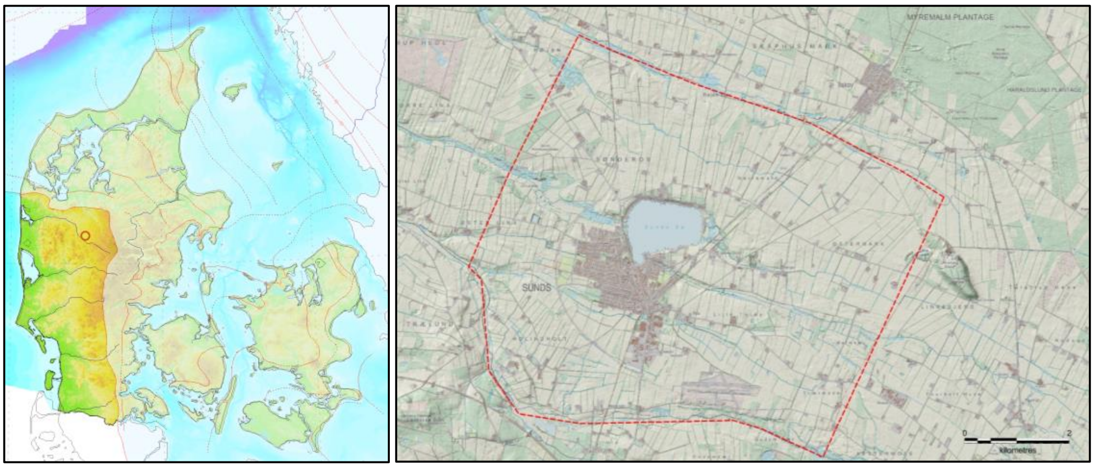


Figure 1.1 Left: Location of Sunds with red circle. The Main Stationary Line in Weichsel is illustrated by the transition from semi-transparent white in east and north to the non-transparent map. Right: Zoom view at Sunds pilot area (red polygon).

2. Model area and data

2.1 Model area

The Sunds pilot area is 47 km^2 (Figure 1.1). It covers the town of Sunds and the surrounding area. Several rivers are present in the area, which are all part of the Storaa catchment. The Storaa flows from central Jutland towards the west coast, where it discharges into Nissum Fjord and the North Sea. Sunds Lake is part of the river system and located to the north-east of the town. Build-up areas are found along most of the lakeshore. The surface elevation in the area reaches from 65m in the east to 35m in the west.

2.2 Geological and geophysical data

2.2.1 Boreholes

The area around Sunds is characterised by many short lignite investigation boreholes drilled in the 1940's. Ten lignite boreholes are drilled on Sunds lake and gives valuable information for the geological interpretation. The distribution of boreholes is shown as black dots on Figure 2.1.

Only a few boreholes give geological information on the deeper parts such as the stratigraphic borehole DGU no. 85.2452 (Sunds) and boreholes at the public water supply (e.g. DGU No. 85.1427), see dark blue circle at Figure 2.1.

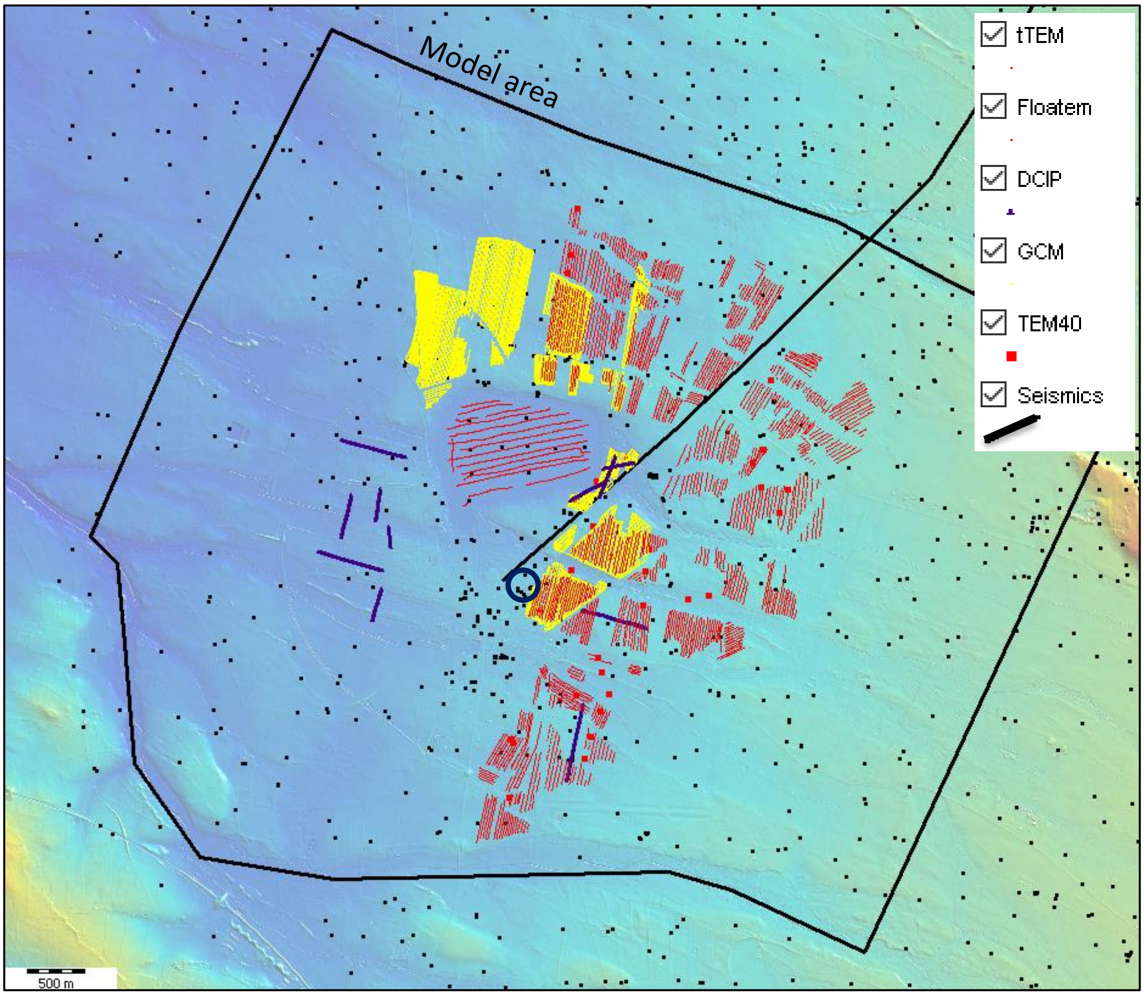


Figure 2.1 Overview on geological and geophysical data in the pilot. The stratigraphic borehole 85.2452 and water supply well 85.1427: dark blue circle. The FloaTEM data are located at the lake in the centre of the map.

2.2.2 Geophysics

As part of a student course at Geoscience, Aarhus University (autumn 2017), traditional geophysical measurements were collected to give a first insight into the geology in the pilot area. The geophysical methods applied were WalkTEM (TEM40), GCM (Ground Conductivity Meter) and DCIP data. Figure 2.1 shows the location of the different collected datasets. The DCIP data was collected along walk paths in the town of Sunds, WalkTEM soundings were measured south, north and east of the lake, and GCM measurements south and north of the lake.

A pilot study with the tTEM method (Auken et al., 2019) covering approximately 600 ha of fields around Sunds town was completed in the beginning of 2018, see Figure 2.1. In the autumn of 2018 additional tTEM data on Sunds Lake were acquired giving valuable input on the geology beneath the lake. The tTEM survey is described in more detail in the report “tTEM Mapping Sunds” (Aarhus University, 2019).

A vibro-seismic line (COWI, 2007) also located in the area has been included in the geological interpretations, see location at Figure 2.1.

2.3 Hydrological observations

Several sources of hydrological observations are used for setting up and calibrating the hydrological model. 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 (Figure 2.2).

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 (Figure 2.3). 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 2.2).

The hydrological data was provided by Central Denmark Region, Herning Water (utility company), and the Municipality of Herning.

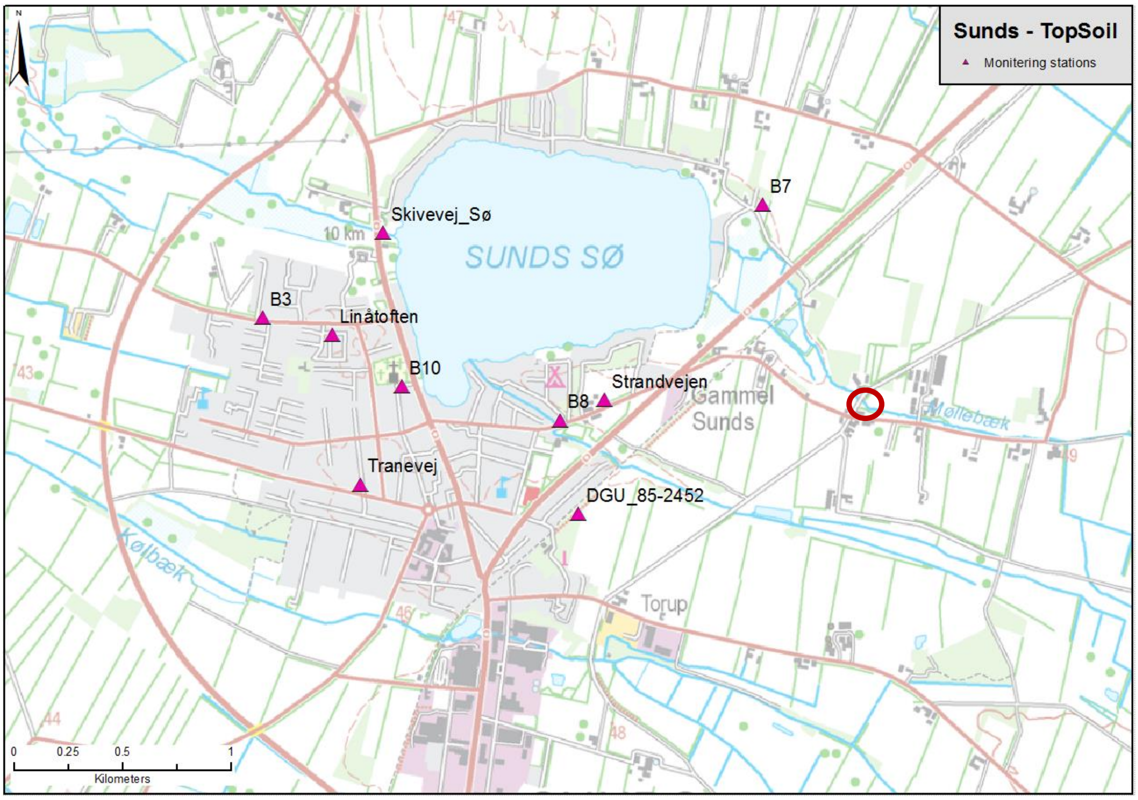


Figure 2.2 Location of boreholes and surface water monitoring stations. Red circle shows the river discharge station Møllebæk.

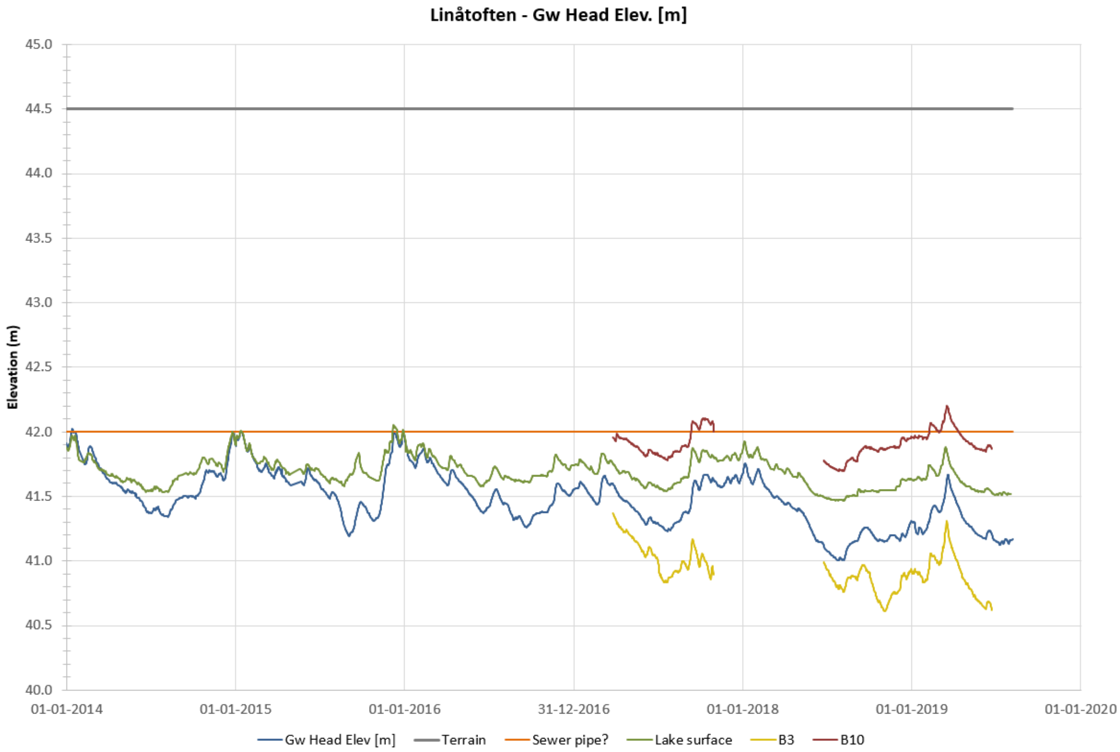


Figure 2.3 Example of groundwater level and lake water level elevation time series.

2.4 Groundwater abstraction

In the Sunds area, there is one waterworks supplying water for domestic use in the town of Sunds. The average annual groundwater abstraction at the Sunds Waterworks for the 20-year period 1999-2018 is 303.000 m^3/year. Outside the town, there are minor private groundwater abstractions for domestic use. In the rural area, the main purpose of groundwater abstraction is for irrigation.

The amount and location of groundwater abstractions included in the model are based on data from the Storaa model (Stisen et al., 2018).

3. Methods

3.1 Geological model

Sunds is located on the Weichselian outwash plain and around Sunds Lake. The location of the lake on the outwash plain is unusual, and its existence is important in understanding the local hydrogeological system. The terrain has a slope towards WNW and the streams are draining the area in the same overall direction. The elevations are close to 55 m in the eastern part of the pilot area and 40 m in the western part. South of the outwash plain, the landscape changes into a hill island consisting of erosional relicts of Miocene deposits and glacial deposits from the Saale glaciation, see Figure 3.1.

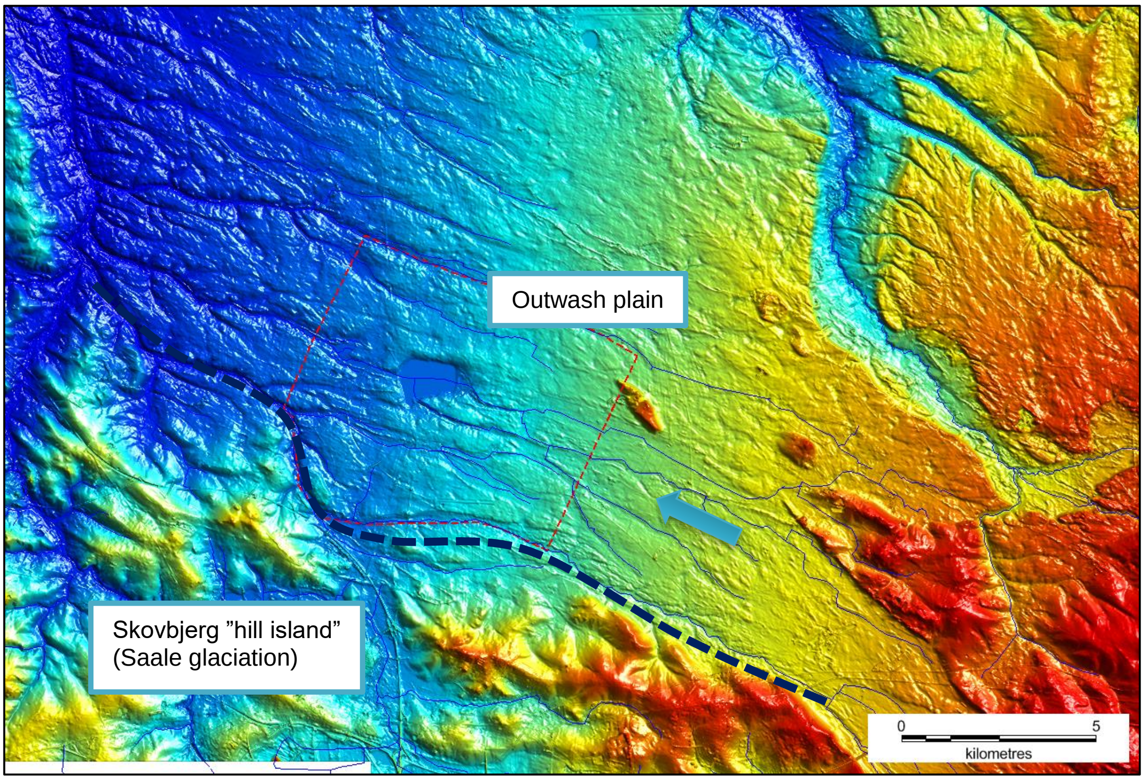


Figure 3.1 Digital elevation model of the region (red represents high elevations and blue represents lower elevations). The dashed line indicates the boundary between the outwash plain and the hill island. Red polygon is the Sunds pilot area.

An important element in the geological understanding of the pilot area is the formation of Sunds Lake. This is a complex challenge, but based on a new data compilation and interpretation, a plausible formation of the lake is discussed in section 3.1.1.

3.1.1 Geological setting

The regional geology consists of sequences of Miocene deposits with varying thicknesses of Quaternary deposits on top. The Quaternary sequence varies in thickness from only a few meters to more than 100 meters in areas where incised buried valleys are present. A stratigraphic table is shown in Figure 3.2.

The Lower Miocene deposits are characterized by layers of mica sand and quartz sand (Bastrup Fm. and Odderup Fm.) separated by thick marine clayey and silty formations (Klintinghoved Fm. and Arnum Fm.). Groundwater for drinking water purposes in Sunds is extracted from quartz sand deposits in the Bastrup Formation. The Middle to Upper Miocene marine clays is commonly described as the 'Måde Group'. The distribution of the Måde Group clays defines in large parts of the area the top of the Pre-Quaternary deposits. As mentioned above, many short investigation boreholes targeted at lignite/brown coal (a sequence of the Odderup Fm.) have been drilled in the area and on Sunds Lake. Most of the lignite borehole samples are poorly described, but they still give valuable information to the geological understanding of the pilot area. For instance, the drillings performed on the lake show an up to 24 m thick sequence of organic sediments (described as gyttja) in the central part of the lake. Also plant roots and pieces of wood are found in grey sand deposits underneath the lake sediments.

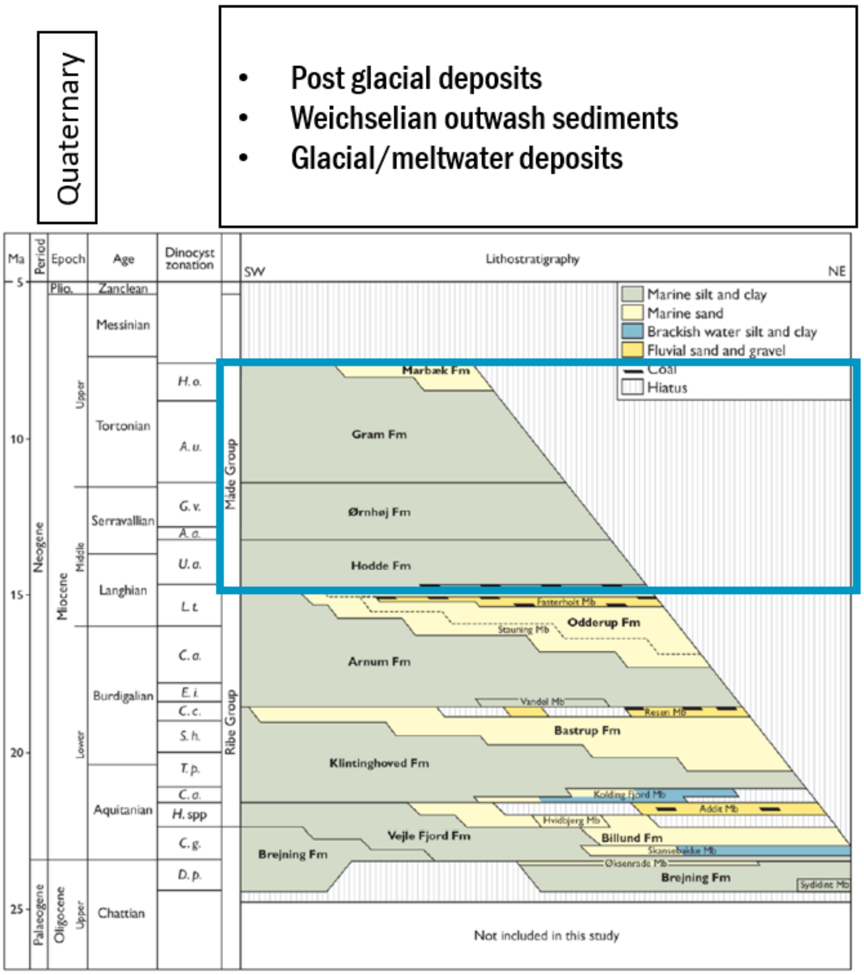


Figure 3.2 Miocene stratigraphy and described Quaternary sediments in the study area. Blue square highlights the Maade Group clays. From Rasmussen, 2010.

Based on the stratigraphic correlations of the Miocene deposits in the region (Rasmussen, 2010) and a study of the influence of tectonics in West Jutland, it is found that the Miocene deposits has been disturbed by several tectonic events - most likely also during the postglacial period after the Weichselian Glaciation. (Lykke-Andersen et al. 1996; Madirazza, 2002).

Figure 3.3 indicate large-scale tectonic trends in West Jutland as proposed by Madirazza (2002). Movement along faults in the area has caused displacements of both Miocene and Quaternary sediments (Lykke-Andersen et al. 1996).

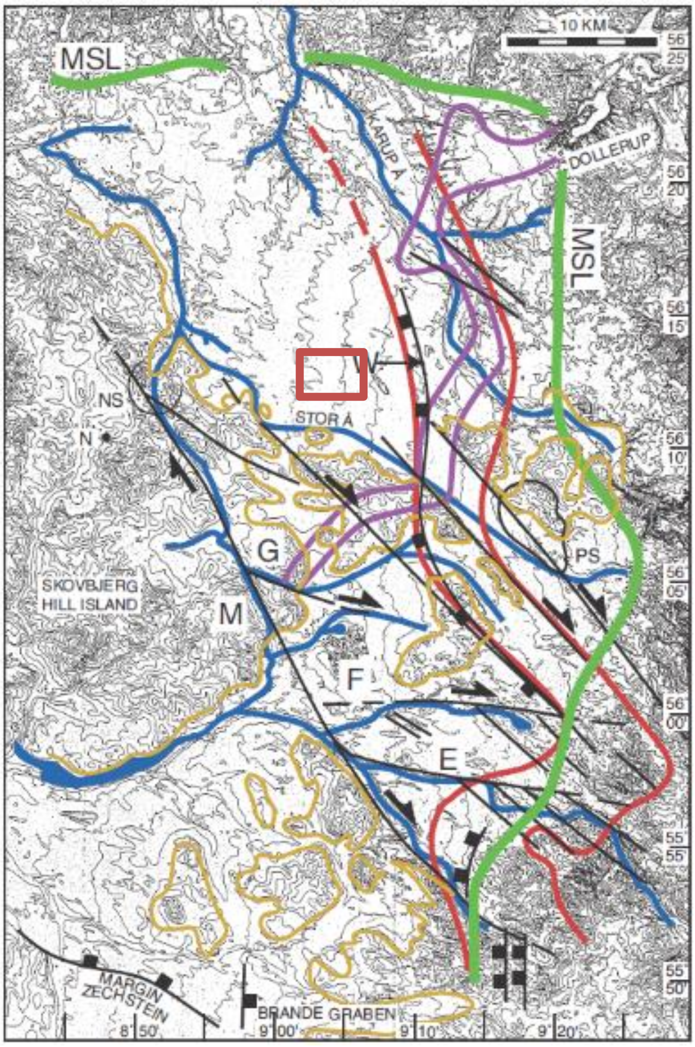


Figure 3.3 Red box: Sunds study area, Green: Weichsel Main Stationary line (MSL), two red parallel lines: limits of the residual positive gravity anomaly, PS and NS: salt diapirs, W: normal fault, Blue: present drainage system. From (Madirazza, 2002).

The Måde Group clay is likely to have been preserved in the areas of subsidence, which is verified in boreholes. Areas of depression in the Top Chalk surface are shown on Figure 3.4, which also correlates to areas of preserved Måde Group clay.

Thorough field investigations in lignite pits at Søby, 15 km south of Sunds, have documented complex strike-slip fault systems with a northwest-southeast orientation (Koch, 1989). The Miocene sediments show wavy sequences with amplitudes of 5-20 m and wavelengths in the interval of 100-3000 m. The presence of the Måde Group clay above the brown coal bearing sequences in this area are up to approx. 15 m in thickness (Gram and Hodde clay) (Koch, 1989).

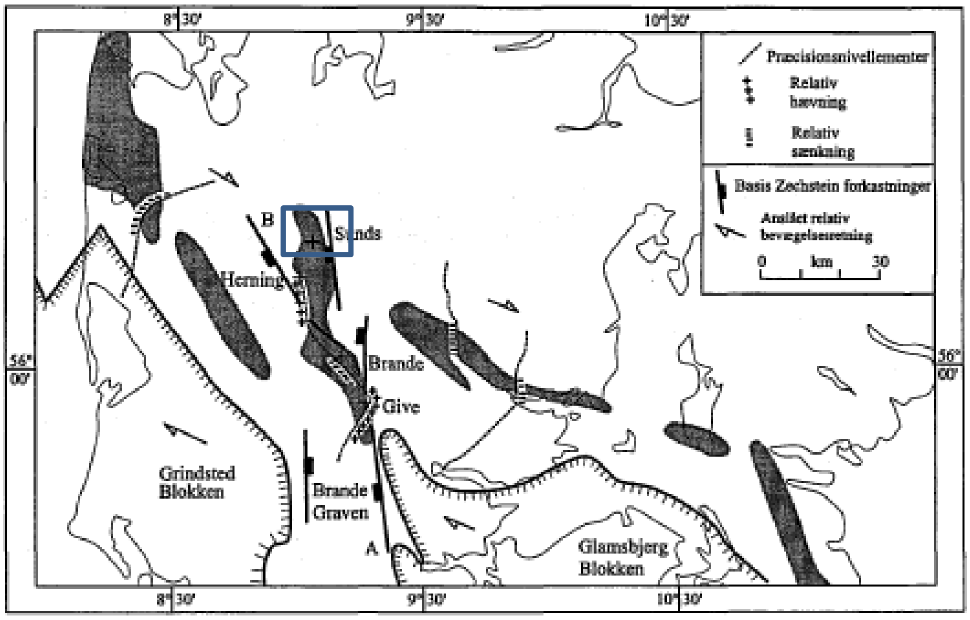


Fig. 32. Depressioner (gråtone) i kalkoverfladen som i Fig. 10. Forkastninger ved Basis Zechstein som i Fig. 2. Stiplede linier angiver tracéer med gentagne præcisionsnivellementer. Med + og – angives strækninger med lokal hævning og sænkning. Med pile angives de formodede relative hovedbevægelsesretninger for Ringkøbing-Fyn Ryggens blokke og området nord herfor.

Figure 3.4 Black areas represent depressions in the Top Chalk surface (From Lykke-Andersen et al. 1996). The pilot area is highlighted with a blue square.

3.1.2 Conceptual geological model

With the new geophysical datasets (especially tTEM) the geological understanding and interpretation between the boreholes has improved significantly. The distribution of the Måde Group clay (low resistivity in TEM data, blue colours) reveals a complex upper Pre-Quaternary landscape beneath 5-20 m of predominantly Weichselian meltwater sand and gravel.

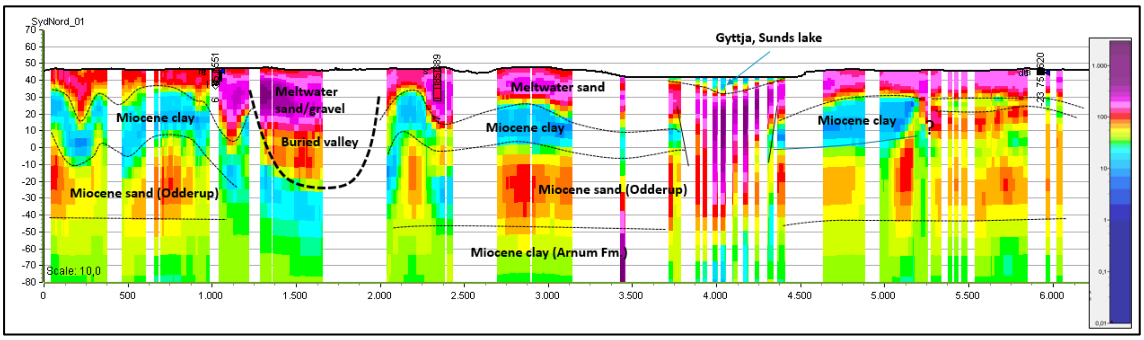


Figure 3.5 Geological interpretation of tTEM data in the pilot area. South-north oriented cross section. Vertical exaggeration: 10.

From Figure 3.5 it can be seen that the Måde Group clay varies in both elevation and thickness. The Måde Group clay is interpreted to have thicknesses up to 30 m in some areas. Below Sunds Lake (see 3700-4300 m on the cross section), the Måde Group clay seems to be absent. The approx. level of the top of the undisturbed Måde clays is expected to be at 25 to 30 m above sea level.

A north-south oriented buried valley system from underneath Sunds Lake to south of the model area has been interpreted from TEM data and borehole data (see cross section in Figure 3.5 at 1200-1600 m). The valley infill mainly consists of meltwater sand and gravel, and the valley shoulders are interpreted to reside at about 20 m below surface.

Based on tTEM data from the lake (referred to as FloaTEM) two areas with rather thick post-glacial sediments in the lake have been interpreted. These areas of gyttja are shown on Figure 3.6, which is a 2D resistivity grid at elevation +30 m. There is a good correlation between the boreholes in the lake and the geophysical data.

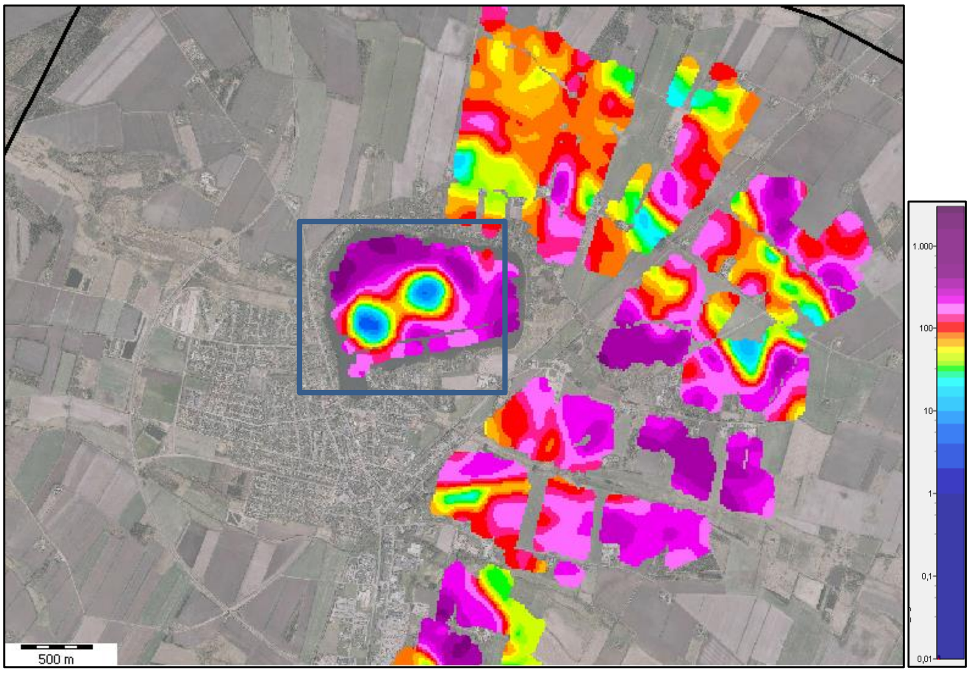


Figure 3.6 2D resistivity grid for tTEM at elevation +30 m. The FloaTEM data on the lake resolves two areas of late-postglacial gyttja deposits with thicknesses up to 20 m (blue/green colours).

Figure 3.7 shows a south-north oriented cross section illustrating glacial deformation of the Måde Group clay (blue colours) in the northern part of the section. A plausible hypothesis is that subsidence due to tectonic activity combined with erosion has removed most of the marine Måde Group clay here, see cross section at 1600-2000 m.

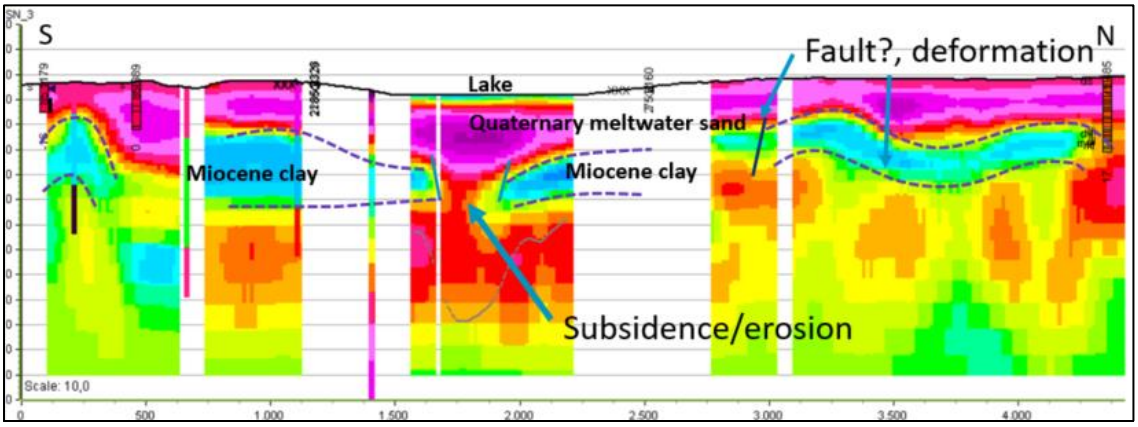


Figure 3.7 South-north oriented cross section illustrating deformation of the Måde Group deposits.

The geological interpretation points towards two important elements that presumably have caused the deformation of the upper part of the Miocene deposits and initiated the formation of Sunds Lake:

1) Neotectonic strike-slip fault activity due to isostatic rebound has affected the area resulting in compression and depression structures (Lykke-Andersen et al. 1996; Koch, 1989). The formation of the Sunds Lake is likely initiated by local subsidence due to movement along faults.

2) Glacial deformation (likely ductile of the Måde Group clay found in the area) possibly took place during the Saale glaciation or earlier.

The coverage of tTEM has made it possible to add high detail in the upper parts of the conceptual geological model (both Quaternary and Tertiary) and afterwards to implement this in a 3D voxel model.

The vibro-seismic line (COWI, 2007) indicates subsidence beneath the lake, see Figure 3.8. The interpreted bottom of the Odderup Fm. seems to be displaced 20 meters deeper beneath Sunds Lake than the surroundings. However, no clear indicators on strike-slip fault with roots deep in the Neogene deposits seems visible in the seismics. Towards the Northeast the seismics shows indications of glacial deformation, which supports the tTEM interpretations.

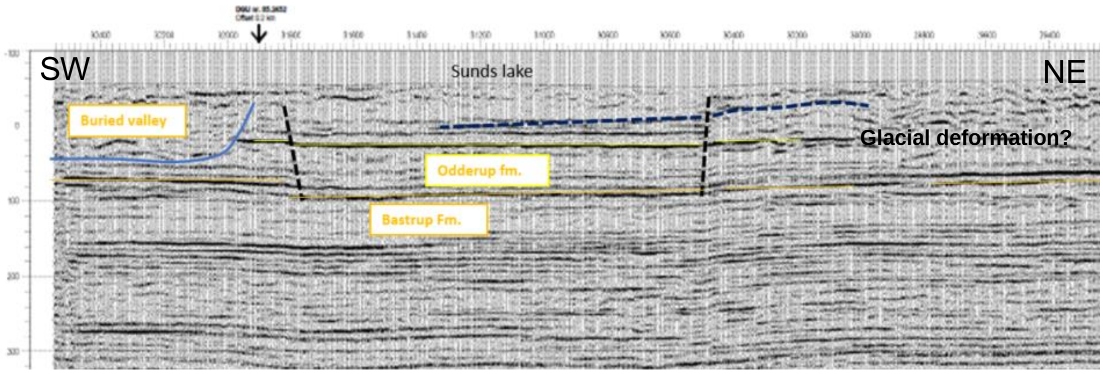


Figure 3.8 Seismic profile and interpretations. Scale: 7.5. See Figure 2.1 for line position.

3.1.3 3D geological voxel model

A 3D voxel model with a discretization of 25 m x 25 m x 2 m has been constructed. The selected voxel dimensions are determined based on the size of the geological features that can be resolved from the datasets. The focus of the 3D modelling has been on the near surface geology, but interpretation of the Miocene deposits at larger depths is also included, see Table 3.1.

Table 3.1 Information on lithological voxel grid

Voxelgrid		
Cell size (XYZ)	25 m x 25 m x 2 m	
No. of layers	154	
No. of lithologies	16	
Min X - Max X	497.110	507.550
Min Y - Max Y	6.225.000	6.234.200
Min Z - Max Z (elevation)	-230	+76
Number of cells		23.753.268

The voxel model is populated with 16 different lithologies (10 Miocene lithologies, 5 Quaternary lithologies and postglacial lake deposits, see Table 3.2.

Table 3.2 Lithologies and corresponding legend for the geological model

Lithologies in model	Legend in model
1. Late-postglacial deposit (Gyttja)	GYT_Gyttja_postgl
2. Weichsel sandur (ds)	DSW_Weichsel_sandur_ds
3. Till (ml)	DS_Meltwater sand, Quaternary
4. Meltwater clay (dl)	ML_Clay till, Quaternary
5. Meltwater sand (ds)	DL_Meltwater clay, Quaternary
6. Buried valley infill (ds/dg) (Saale or older)	VSG_Q. sand/gravel, Buried valley 1
7. Måde Group clay	MAA_Maade_Gr_clay
8. Mica sand (Odderup Fm.)	OQS_Odderup_QS
9. Quartz sand (Odderup Fm.)	ARN_Arnum_Clay (gl,gi)
10. Mica silt/clay (Arnum Fm.)	OGS_Odderup_GS
11. Mica sand (Bastrup Fm.)	BAQS_Bastrup_QS
12. Quartz sand (Bastrup Fm.)	BAGS_Bastrup_GS
13. Klintinghoved Fm (Mica clay)	KLC_Klindtinghoved_Clay
14. Billund sand (Addit Mb.)	BDS_Billund_Sand (addit)
15. Top Vejle Fj. Fm.	VFJ_Vejle_Fj
16. Rearranged/disturbed Miocene sand	MIOS_rearranged miocene sand (marbaek?)

In the modelling approach, geological and stratigraphical 2D surfaces have been interpreted as a framework for the subsequent voxel infill. In the software Geoscene3D, it is not possible to include line elements such as fault lines. Instead, areas with interpreted subsidence along faults has been modelled as changes in elevations in the 2D grid point interpretations. A 3D view of the final model is shown in Figure 3.9.

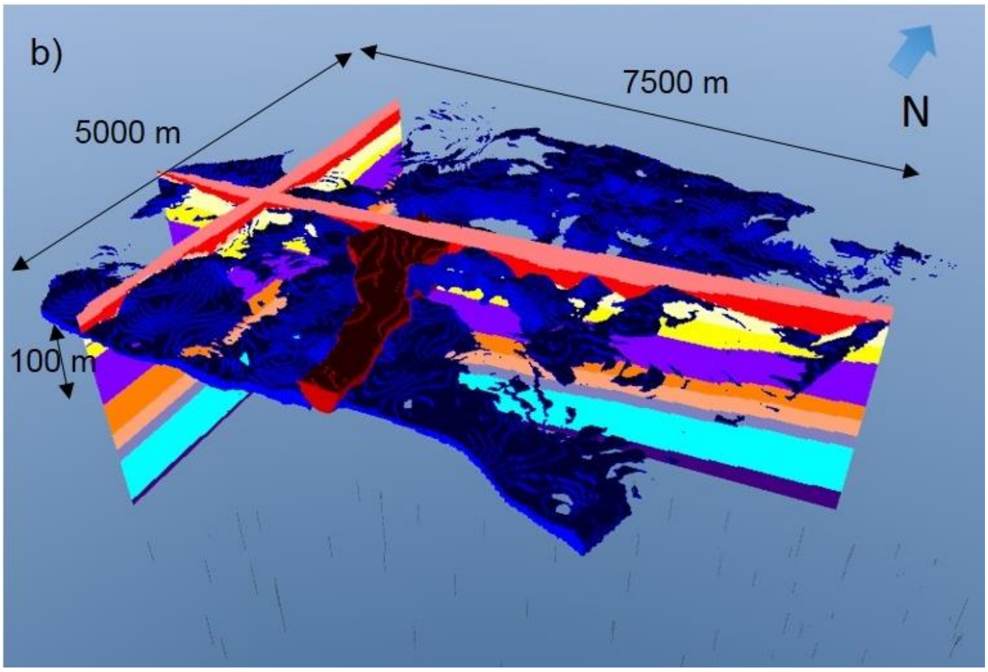


Figure 3.9 3D view of the geological model. Blue voxels represent the distribution of the Måde Group Clay. Red voxels represent the interpretation of N-S oriented buried valley. Legend is shown in Table 3.2.

The two cross sections in Figure 3.10 illustrates how the Måde Group clay (blue) varies in elevation and thicknesses beneath the Weichselian sandur as a result of deformation and erosion.

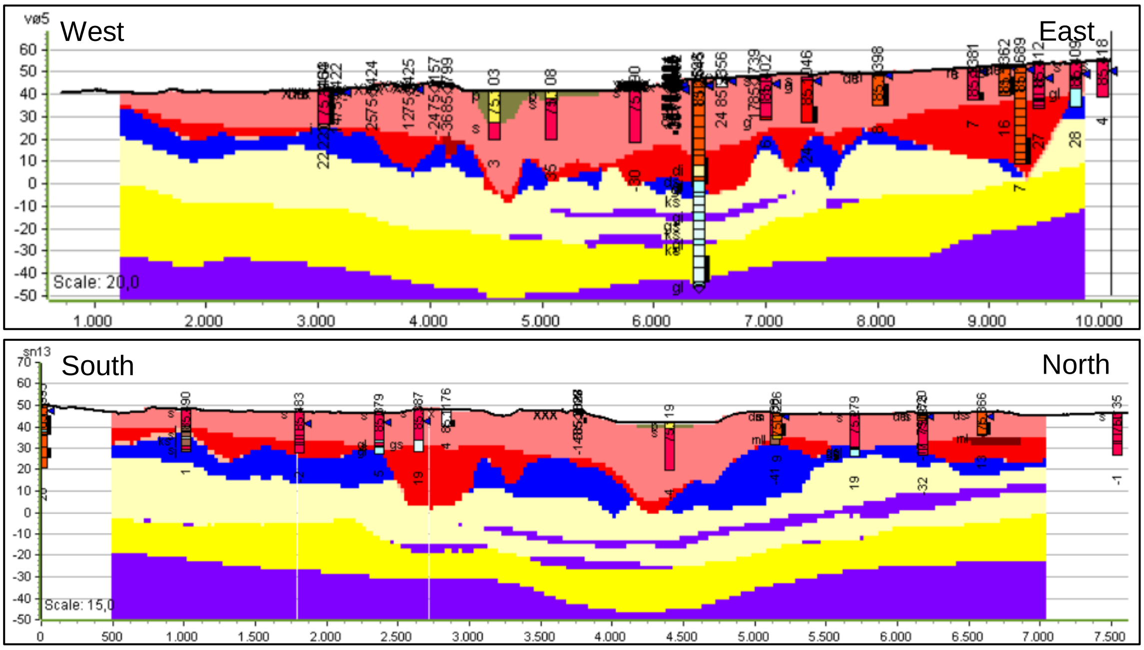


Figure 3.10 Upper: W-E cross section. Lower: S-N cross section. See Figure 3.9 for location of cross sections. Legend is listed in Table 3.2.

3.1.4 Geological model uncertainty

As a part of the geological model, an overall uncertainty assessment of the model has been made. The simple uncertainty assessment (low, moderate and high) is visualised on Figure 3.11 and is based on considerations of data density, geological understanding, and geological complexity. The uncertainty of geological modelling is difficult to quantify, as it is partly subjective. The uncertainty is assessed by the modeller and it reflects - in a qualitative way - where the model is considered to be more reliable compared to other parts. The uncertainty assessment is a GIS theme to be included in the further use of the 3D model.

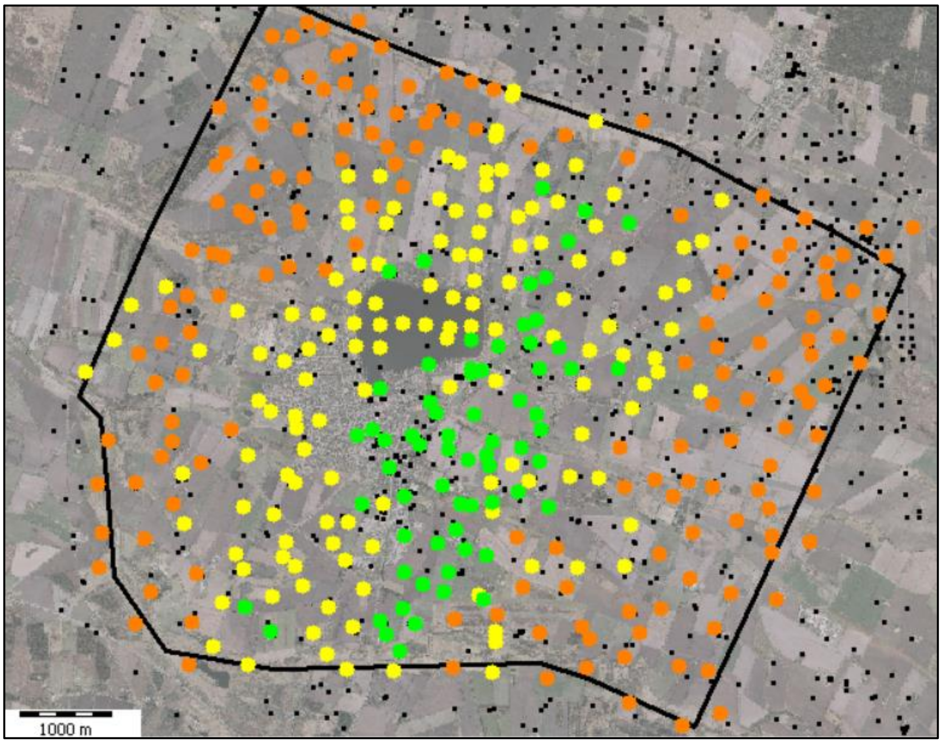


Figure 3.11 Green: low uncertainty, Yellow: moderate uncertainty, Orange: high uncertainty.

3.2 Hydrological model

The hydrological model of Sunds is based on the larger model of the whole Storaa catchment (Figure 3.12).

The advantages of developing the Sunds hydrological model as a sub model of the Storaa model are several. As the general groundwater flow in the Storaa catchment is from southeast towards northwest, it is assumed that there is an inflow of groundwater from southeast through the southeast boundary of the Sunds model and an outflow of groundwater through the northwest boundary of the Sunds model. The groundwater flow gradients for inflow and outflow are obtained from the Storaa model. The groundwater boundary conditions for the Sunds model towards the northeast and the southwest are considered as no-flow boundaries.

From the southeast, the rivers Røjen Bæk, Kjeldsig Grøft, Sunds Nørre Å, Kvalsholm Bæk, and Storaa are running into the Sunds model area adding water to the hydrological model. Time series for this inflow of river discharge are provided from the Storaa model.

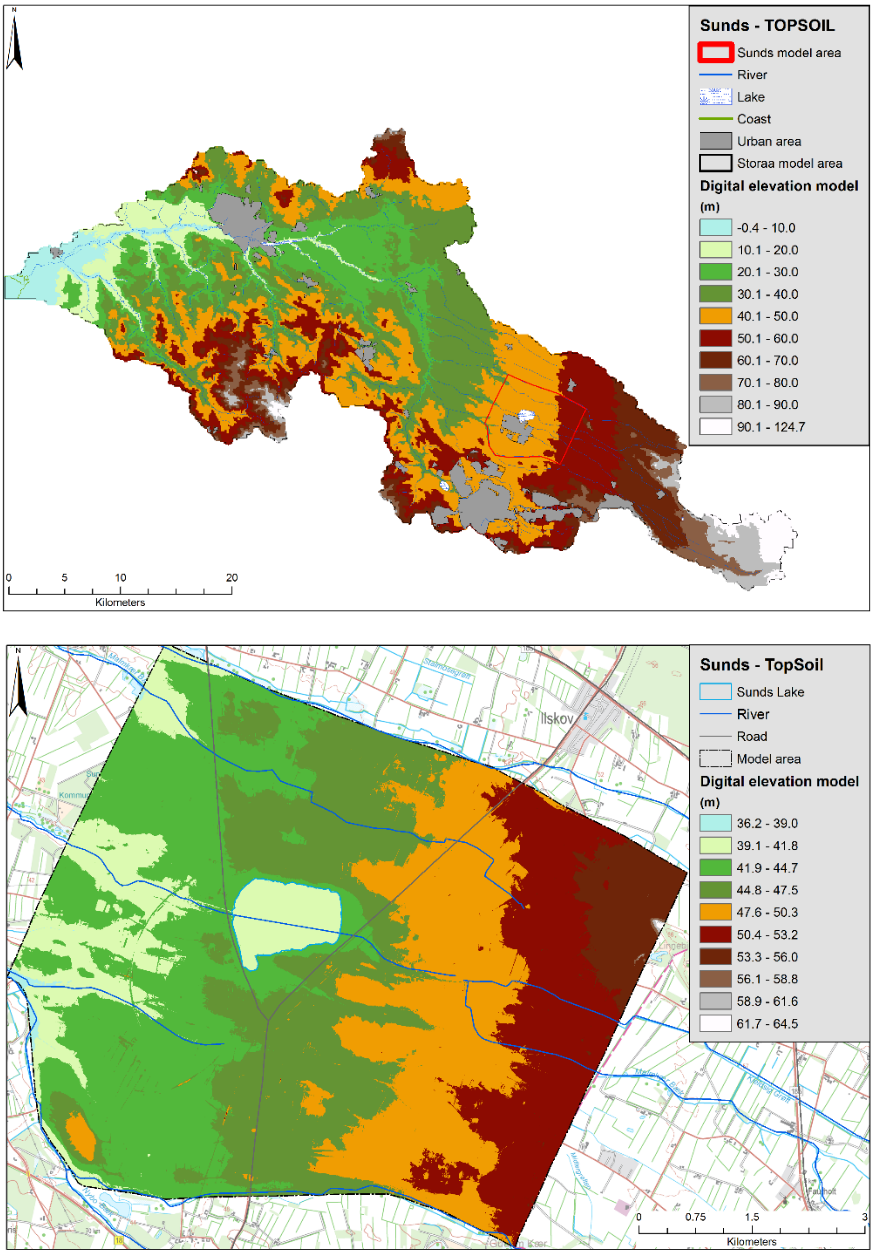
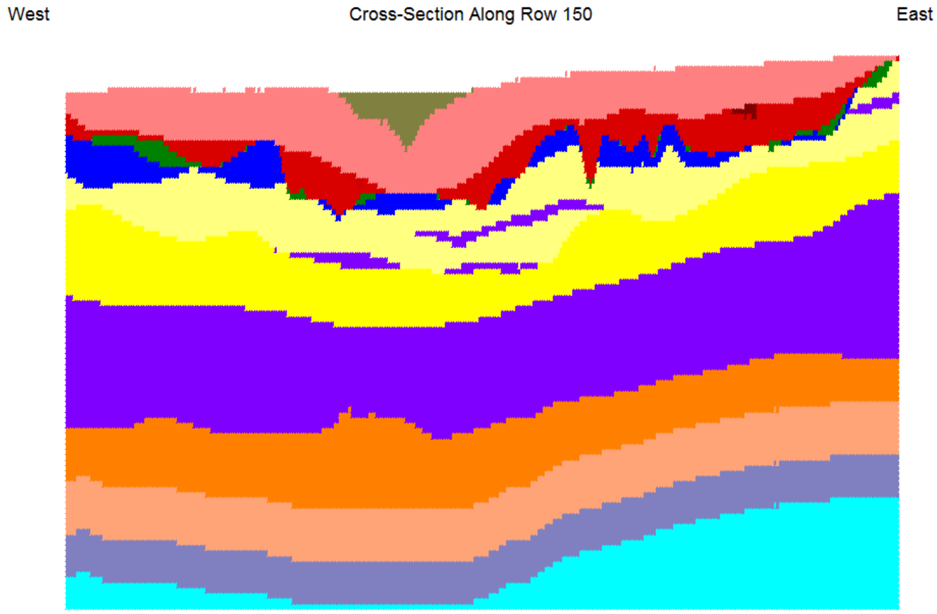


Figure 3.12 Model areas for the Storaa Model (upper figure) and the sub model for the Sunds area (lower figure).

Climate data time series for precipitation, temperature, and evapotranspiration are transferred from the Storaa model. The groundwater used for irrigation is based on the irrigation demand for each crop type specified in the model setup and depending on the available water in the root zone and the actual climate.

The area of the hydrological model of Sunds is 47 km^2 with a model grid resolution of 25 m times 25 m. The maximum surface elevation is 64 m and the model extends to a maximum depth of -140 m below mean seawater level. The model consists of 103 geological layers of each two meters thickness corresponding to the voxel geological model. The geological layers are integrated in nine calculations layers based on the overall geological structure and layers in the area (Figure 3.13).



Geol. layer bottom	Layer boundary	Calculation layer	Lithology	
	Terrain			
		1	Weichel sandur	
1	5 meter below terrain: Bottom			
		2	Weichel sandur	
2	Sandur: Bottom			
		3	Meltwater sand	
3	Maade clay: Top			
		4	Maade group clay	
4	Maade clay: Bottom			
		5	Mica sand (Odderup)	
5	Odderup quartz sand: Top			
		6	Quartz sand (Odderup)	
6	Odderup quartz sand: Bottom			
		7	Mica clay/silt (Arnum)	
7	Bastrup quartz sand: Top			
		8	Quarts sand (Bastrup)	
8	Bastrup mica sand: Top			
		9	Mica sand (Bastrup)	
9	Klintinghoved clay: Top			
			Mica clay (Klindtinghoved)	

Figure 3.13 Upper figure showing the voxel geology in a west-east cross section The calculation layers in the hydrological model are following the overall geological layers.

Around the buried valley in the centre of the model the calculation layers are not following the overall geological layers but the geological layers have been connected laterally through the buried valley. The hydrological properties of the aquifer/aquitard system are linked to the voxels in the geological layers meaning that the hydraulic properties of each grid of the computational layers are found as weighted averages of the individual values of each voxel (Figure 3.14).

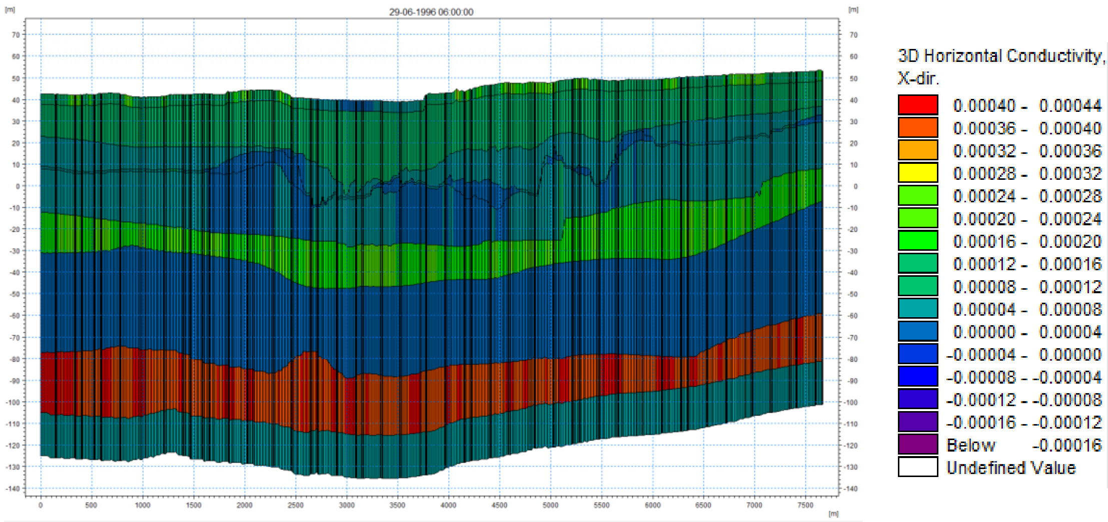


Figure 3.14 The figure shows the calculated average hydraulic conductivities of the nine computational layers (unit: m/s).

The upper layer is set to a constant thickness of five meters in order to include the whole depth of Sunds Lake, the shallow boreholes used for the synchronous groundwater measuring campaign, and to avoid the upper computational layer to dry out during periods of low groundwater levels.

The simulation period for the present groundwater situation is 1996 – 2016. The climate data, the river discharges, and the groundwater abstraction for irrigation are all based on daily values. The groundwater abstractions for domestic use are specified as annual values. The hydrological model is setup to run in daily time steps.

3.3 Rivers and lake

For the river and lake setup, the detailed river network setup from the Storaa model have been used as a starting point. COWI and GEUS developed a very detailed surface water setup for the Storaa model based on a detailed terrain model and including a large number of river cross sections. The Storaa model has a horizontal 100m discretization (Stisen et al, 2018).

Seven rivers and Sunds Lake are included in the surface water model setup for the Sunds model (Figure 3.15).

The surface water system is more detailed with many small creeks and drainage canals (Figure 3.15). To compensate for this simplification drainage systems are included in the model (see next section).

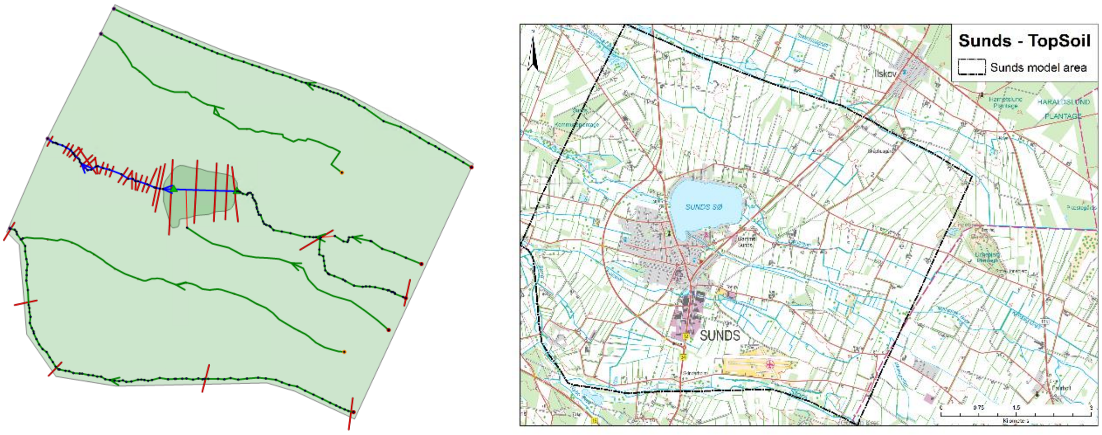


Figure 3.15 Left map showing the rivers and Sunds Lake included in the hydrological model, right topographic map showing the more detailed surface water systems with many small creeks and drainage canals.

3.4 Drainage and sewers

As mentioned in the introduction the sewer system in Sunds, as well as in many other towns and cities, act as a drainage system for shallow groundwater. In the hydrological model for Sunds, three categories of drainage systems have been implemented. In the rural areas drains have be implemented at a constant depth of one meter below ground surface and with a constant leakage factor.

In the urban area the sewer and drainage area has been divided in two zones. One is characterised by the newer and less leaky sewers, and the other drainage zone is the centre of the town where an older and more leaky sewer system is found. The latter is subject to an ongoing renovation with the purpose of reducing the inflow of shallow groundwater into the sewer system (Figure 3.16).

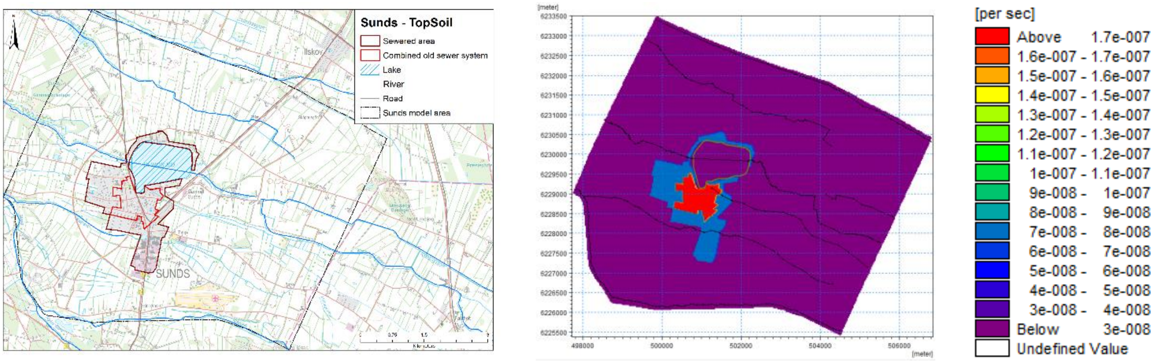


Figure 3.16 The three drainage zones. In the middle figure red area shows location of older sewer pipes; blue area shows location of newer sewer pipes, and purle is the area with rural area drianage (the scale shows the drainage time constant).

3.4.1 Distribution of drain depth

In the urban area drain depths are distributed based on the actual depth of the sewers. An average depth has been calculated for each model grid cell of 25 m x 25 m based on information of the depth of the sewers within the actual grid cell (Figure 3.17).

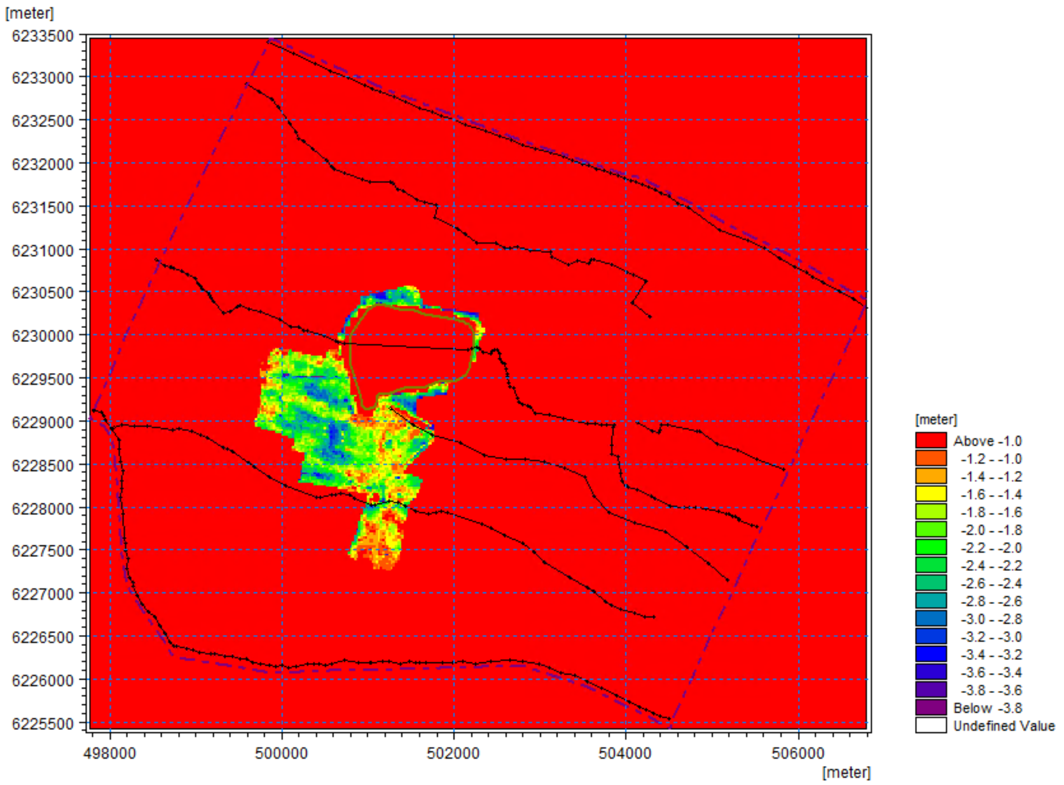


Figure 3.17 Depth of drainage system.

3.5 Pavement, impervious areas and local infiltration

In the town of Sunds large areas are paved or have impervious cover, e.g. roofs. The precipitation that fells on the impervious areas will in the hydrological model be directed to the nearest river. The paved area fraction (PAF) shows the fraction of the surface of a given area (grid) that is covered by impervious material (Figure 3.18).

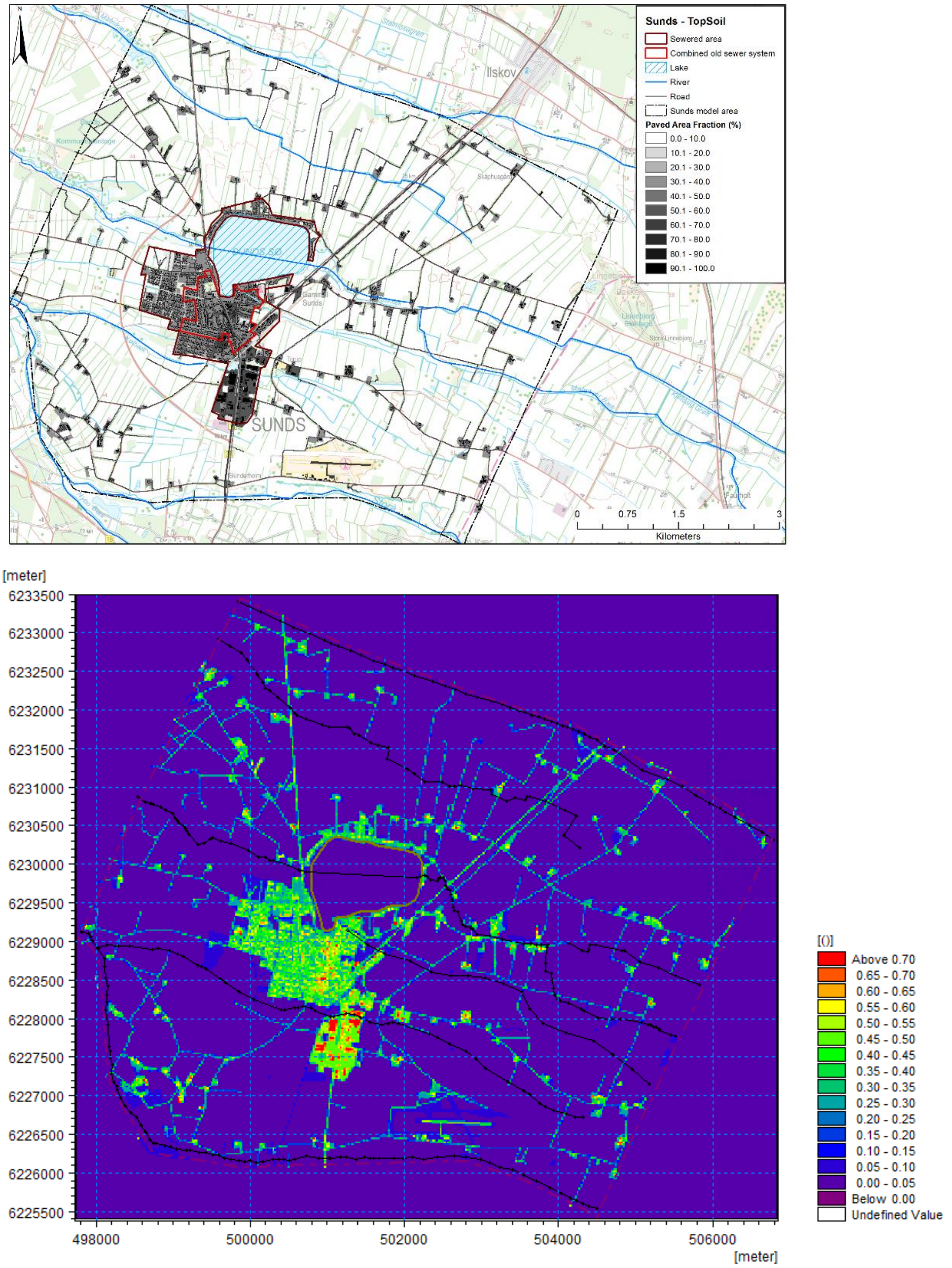


Figure 3.18 Upper figure: The paved area fraction (PAF) in a 10 m grid. Lower figure: The PAF interpolated to the 25 m model grid.

It is assumed that 25% of the precipitation that falls on the paved and impervious areas in the town of Sunds is infiltrated locally and thereby contributing to the groundwater recharge.

The land use distribution in the hydrological model is based on the 500 m resolution from the DK-Model (Højberg et al. 2015 and Stisen et al. 2018). The land use in the urban area of Sunds is adjusted to the 25 m grid to ensure that paved and impervious areas is distributed in accordance with the extent of the urban areas (Figure 3.19).

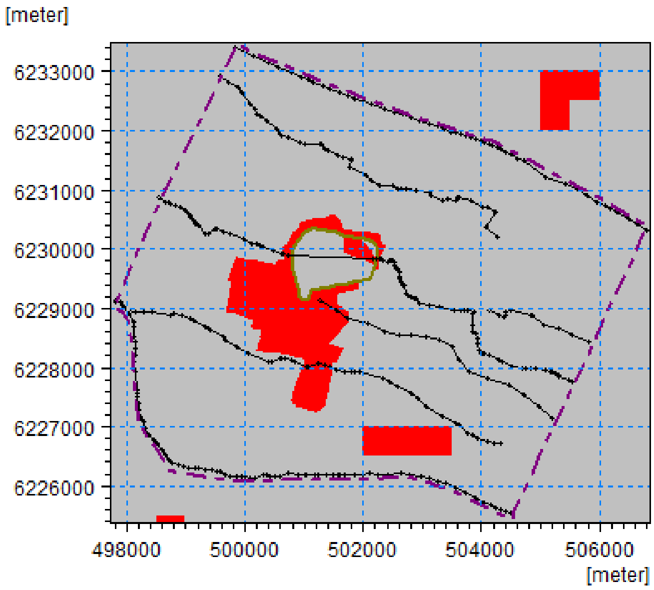


Figure 3.19 Adjustment of paved and impervious areas to the extent of the urban areas in Sunds, from the original 500 m grid to the 25 m grid of the Sunds model.

3.6 Calibration of hydrological model

The hydrological model for Storaa was calibrated against groundwater heads and river runoff using the parameter estimation software PEST. Estimated parameter values for hydraulic conductivity, storage, and porosity for the different soils, leakage factors for rivers and drains were transferred from the Storaa model to the Sunds model.

A manual adjustment of the Sunds model parameters was carried out to match the groundwater head data from the synchronous groundwater measuring campaign and the time series of groundwater head available. Time series of the river discharge measured at the Møllebæk gauging station upstream Sunds Lake and the water level of Sunds lake measure at the western outlet of the lake were also used in the manual calibration of the hydrological model.

3.7 Projected change of climate

For the climate change scenarios, the focus is on the effect on the depth to the shallow groundwater for the two periods, near future 2041-2060, and far future 2081-2100. A projected medium wet climate scenario has been selected (NorESM1-M_rcp85_r1i1p1_DMI-HIRHAM5). Time series for precipitation, temperature, and evaporation in a medium wet future climate for central Jutland have been provided by the AquaClew project (http://aqua-clew.eu) (Figure 3.20).

A subset of the accumulated annual precipitation data for the Sunds model area shows large variations in the year-to-year precipitation for the projected medium wet climate scenario (Figure 3.21). The linear trend of the annual precipitation data shows an increase of around 150 mm for the 80-year period from 2020 to 2100, from 1050 mm/year to 1200 mm/year.

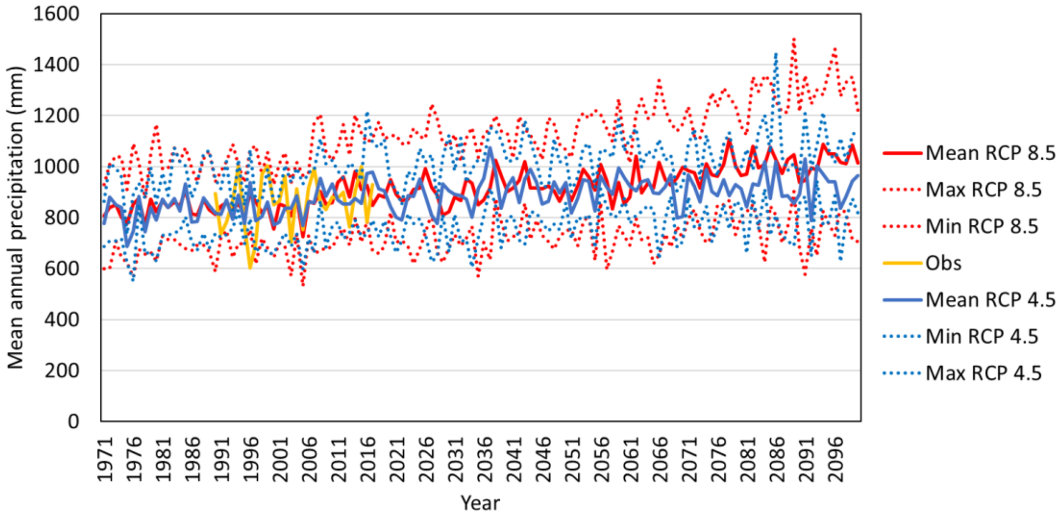


Figure 3.20 Projected mean annual precipitation for two climate model scenarios for central Jutland (Source: AquaClew (http://aquaclew.eu).

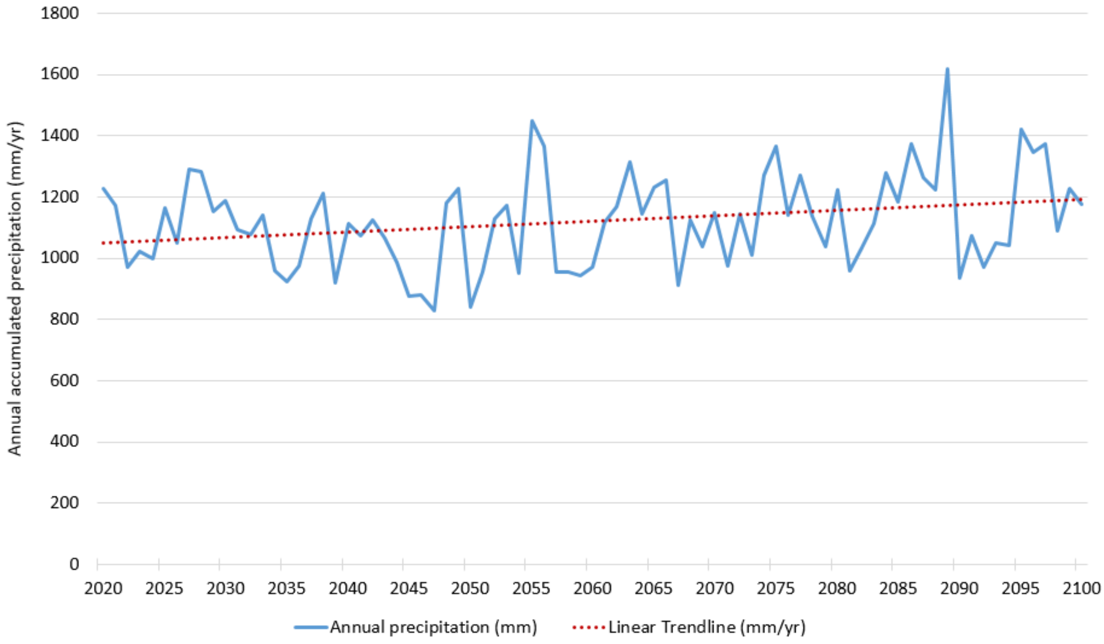


Figure 3.21 Projected annual precipitation for the Sunds model area based on a medium wet climate scenario.

3.8 Calibration results

The hydrological model was calibrated against groundwater head observations from the synchronous groundwater measuring campaign ultimo October 2012. Figure 3.22 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.

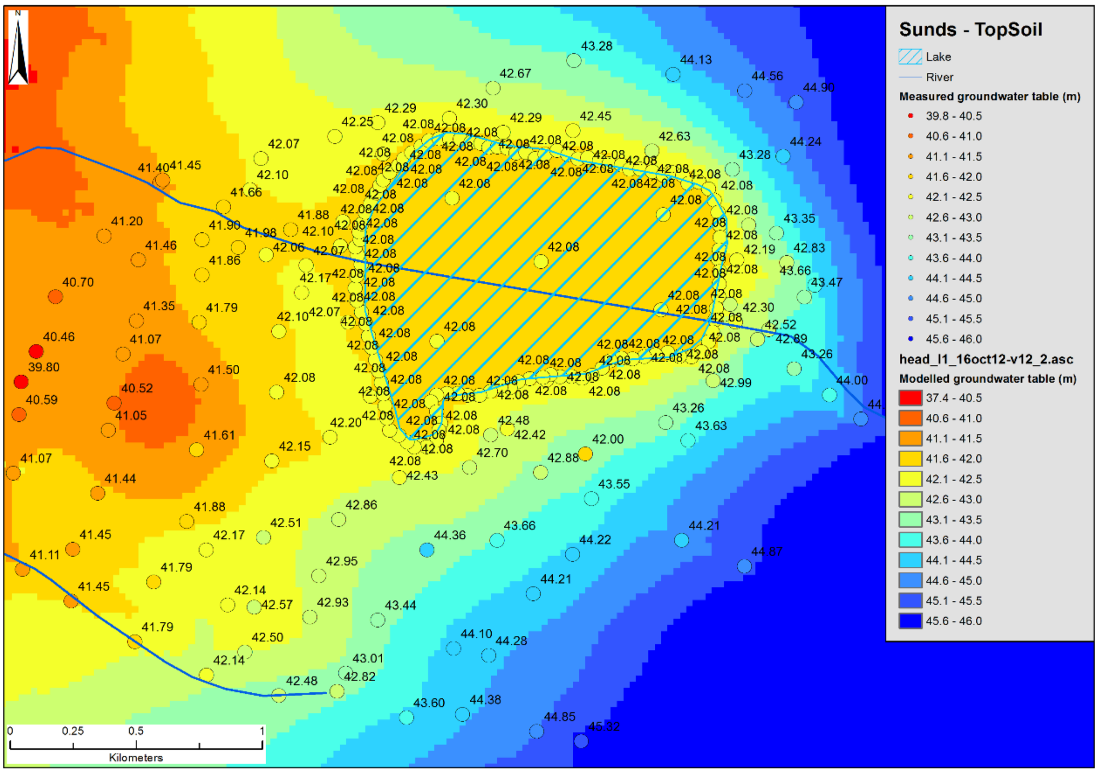


Figure 3.22 Groundwater head elevations from the calibrated hydrological model (colour contours) and the observed groundwater heads and water levels of Sunds Lake (coloured circles and numbers).

Time series of groundwater heads, lake water level, and river discharge have also been used for the calibration of the hydrological model. The location of the monitoring sites is shown in Figure 3.23.

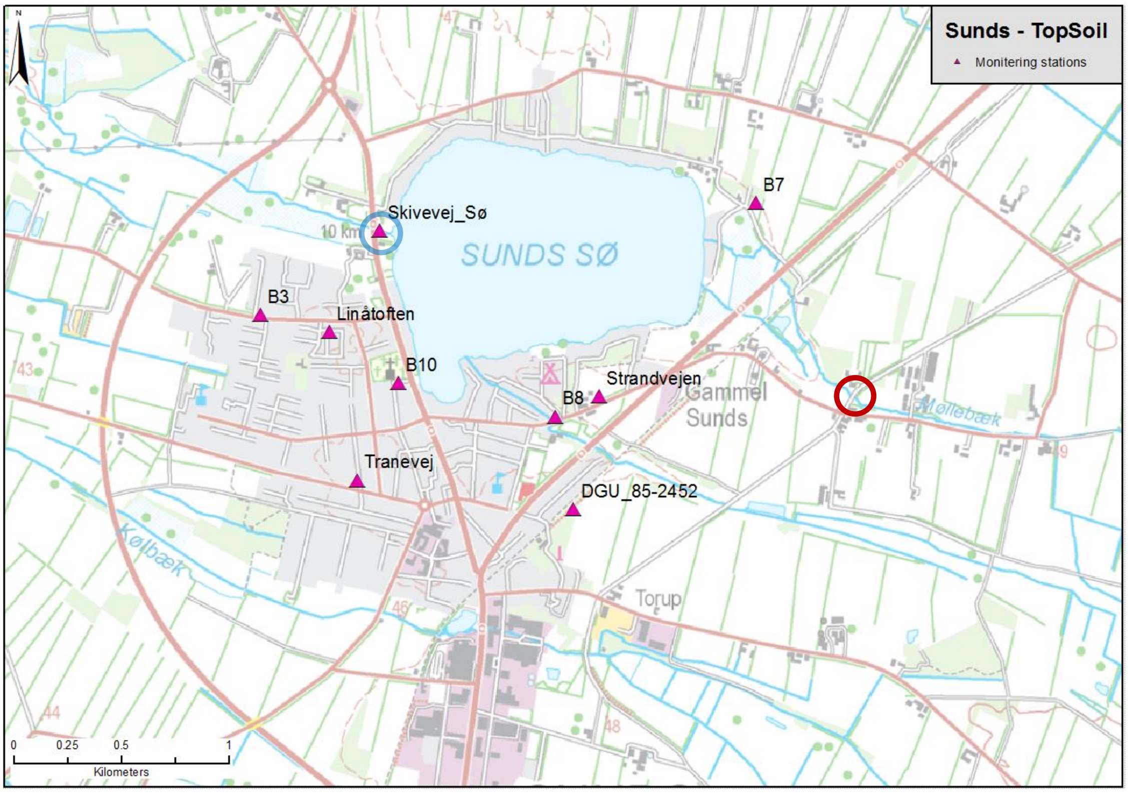


Figure 3.23 Location of monitoring stations for time series of groundwater head, lake water level (blue circle), and river discharge (red circle) used in the model calibration.

There is a good match in both the fluctuations and the elevations in groundwater heads between observations and modelled results (Figure 3.24). For the Linåtoften and Strandvejen stations, the hydrological model overestimates the groundwater levels by 20 to 40 cm, and at the Tranevej station the model underestimates the groundwater levels by 10 to 20 cm.

The hydrological model fit well the annual fluctuations in water level and the high water levels during the winter months. For the summer and autumn months the hydrological model simulates the water level 20 to 30 cm deeper than the observed water levels in Sunds Lake (Figure 3.25, upper panel)

The river discharge observed in Møllebæk is overestimated by the hydrological model when it comes to the low-flow situations. The modelled fluctuations and flow peaks match very well the observed data (Figure 3.25, lower panel).

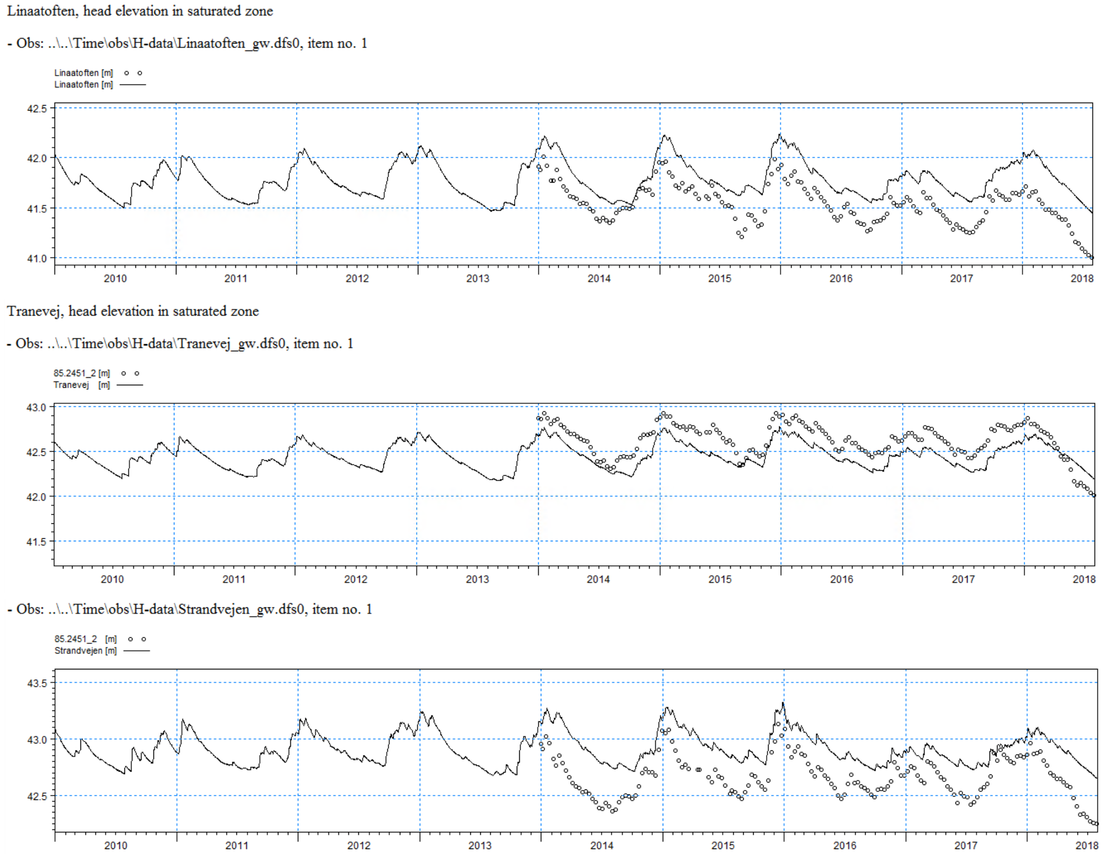


Figure 3.24 Modelled (solid lines) and observed groundwater head (circles) at station Linaatoften, Tranevej, and Strandvejen (see Figure 3.23 for locations).

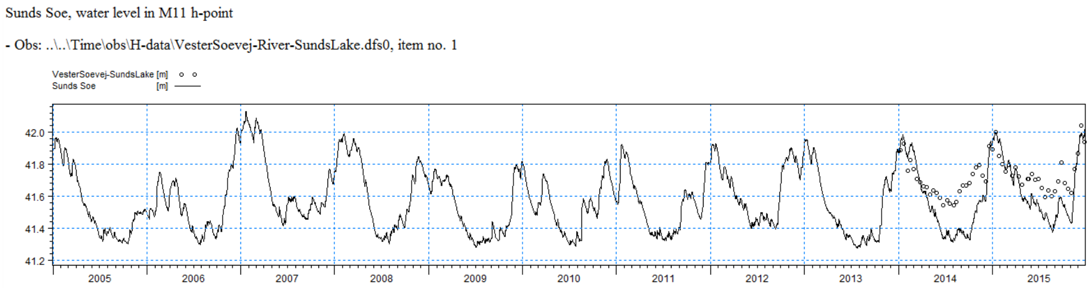


Figure 3.25 Modelled (solid lines) and observed lake water level and river discharge (circles) for two monitoring stations. Upper figure shows water level data from Sunds Lake. Lower figure shows discharge data from Møllebæk.

3.9 Model parameters

The model parameter values found during the calibration process are listed in Table 3.3. The hydraulic parameters are the hydraulic conductivities, the specific yield, and the specific storage. Parameter values for specific yield and specific storage are the same values used for the Storaa model (Stisen et al. 2018).

Table 3.3 Hydraulic conductivities, specific yield, and specific storage values for the different soil types.

Soil type	Soil code	Kx = Ky (m/s)	Kz (m/s)	Sy	Ss (/m)
Late-postglacial deposit (Gyttja)	1	5.18E-06	5.18E-07	0.20	0.0001
Weichsel sandur (ds)	2	1.00E-04	1.00E-05	0.30	0.0001
Weichsel sandur (dg)	3	1.00E-04	1.00E-05	0.30	0.0001
Meltwater sand (ds)	4	5.00E-05	5.00E-06	0.30	0.0001
Till (ml)	5	6.22E-06	6.22E-07	0.05	0.0001
Meltwater clay (dl)	6	6.22E-07	6.22E-08	0.05	0.0001
Meltwater gravel (dg)	7	1.00E-04	1.00E-05	0.30	0.0001
Buried valley 1 infill (ds/dg) (Saale or older)	8	1.00E-04	1.00E-05	0.30	0.0001
Buried valley 2 infill (ds/dg) (Saale or older)	9	1.00E-04	1.00E-05	0.30	0.0001
Måde Group clay	10	2.80E-07	2.80E-08	0.05	0.0001
Mica sand (Odderup Fm.)	11	2.02E-04	2.02E-05	0.30	0.0001
Mica silt/clay (Arnum Fm.)	12	2.80E-07	2.80E-08	0.05	0.0001
Quartz sand (Odderup Fm.)	13	4.62E-05	4.62E-06	0.30	0.0001
Mica sand (Bastrup Fm.)	14	4.04E-04	4.04E-05	0.30	0.0001
Quartz sand (Bastrup Fm.)	15	4.64E-05	4.62E-05	0.30	0.0001
Klintinghoved Fm (Mica clay)	16	1.00E-10	1.00E-10	0.05	0.0001
Billund sand (Addit Mb.)	17	1.00E-04	1.00E-05	0.30	0.0001

The drain leakage factors (the time constant) used for sewer pipes in the urban area and the drains in rural area are shown in Table 3.4. Higher values are used for the old sewer pipes to represent the low resistance at inflow to the pipes.

Table 3.4 Drain leakage factors (time constant).

Drain zone	Leakage factor (/s)
Rural	1.38E-08
New sewer pipes	7.20E-08
Old sewer pipes	1.72E-07

4. Modelled effects of preventive measures

4.1 Groundwater infiltration scenarios

First, the effect of replacing older and leaky sewer pipes with new and more impermeable pipes on the shallow groundwater level is analysed. Subsequently, the combined effect of renewing the sewer pipes and changing the amount of local rainwater infiltrated from paved areas on the depth to the shallow groundwater is analysed next. Several preventive measures for lowering the water table are analysed with the hydrological model. All these scenarios are completed with the version of the hydrological model where the new and more impermeable sewer pipes are included. Table 4.1 lists the different scenarios completed with the hydrological model.

Table 4.1 Hydrological model scenarios.

No.	Description	Changes made
1	Basic hydrological model **before** renovation of sewer pipes	…
2	Basic model **after** renovation sewer pipes	Effect of drainage reduced in renovated area
3	Effect of sewage renovation and 50% rainwater infiltration	Increase local rainwater infiltration from 25% to 50%
4	Effect of sewage renovation and 0% rainwater infiltration	Decrease local rainwater infiltration from 25% to 0%
5	Reducing groundwater abstraction from waterworks	No groundwater abstraction from Sunds Vandværk
6	Horizontal drains, the 3rd tube	Effect of increasing drainage throughout the urban area
7	Increase pavement (impervious cover) by 10%	The current degree impervious cover is multiplied by 1.1
8	Forest planted west of town	Forest area: 67 ha
9	Forest planted west and east of town	Forest area: 67 + 118 ha = 185 ha
10	Forest planted west, east and south of town	Forest area: 67 +118 210 ha = 395 ha
11	Lowering / constant water level in Sunds Sø	Constant water level in Sunds Lake: 41.6 m (summer water level)
12	Combined effect of five preventive measuers	Combination of scenario no. 4, 6, 7, 10, and 11
13	Wet climate model	New climate data, periods: 2041-2060 and 2081-2100

4.2 Data analysis and presentation

4.2.1 Risk map definition

Groundwater levels are grouped in three risk classes for high groundwater levels: very high, high, and low risk for high groundwater table. The risk classes are defined as the depth of the groundwater table below ground surface (Table 4.2).

Table 4.2 Risk classes for high groundwater levels – the depth to the groundwater table.

Colour	Risk class	Depth groundwater table (m b.g.s.)
(red)	Very high	< 0.5 m
(yellow)	High	0.5 - 2.0 m
(green)	Low	> 2.0 m

4.2.2 Extreme value analysis

Extreme value analysis (EVA) is dealing with the extreme deviations from the median of probability distributions. Here the probability of high groundwater levels is estimated for a 2-

year event, a 10-year event, and a 25-year event for the future climate scenarios. Groundwater levels are defined in the same three classes as for the risk maps: very high, high, and low (Table 4.2).

4.2.3 Presentation of results of scenarios

The result of the different scenarios are presented in mainly two types of maps, (1) risk maps using the classification and colours from Table 4.2, (2) 'difference maps' or 'effect maps' showing the effect of a given scenario compared to the starting situation. For the effect maps, the difference in groundwater depth between the scenario and the present situation (the scenario groundwater depth minus the present groundwater depth), is calculated. It means that a negative difference map is showing that the groundwater level is rising for the given scenario, and that a positive difference in groundwater depth map is showing that the groundwater level is lower for the given scenario for the present situation.

4.3 Model results under the present conditions

In this section of the report, results are presented from the hydrological model for the present conditions before renovation of the old combined sewer system in the central area of Sunds was initiated.

Comments to each individual figure in this section is given below, before the actual figures are presented on the following pages. This approach has been chosen in order to give a better overview when comparing the results from the different scenarios. This procedure is also used in the following two sections.

The changes in depth to the groundwater table are in most scenarios relatively small when fitted into the scale used for the risk maps (Table 4.2). Therefore, most risk maps are found in the Annex 1 (figures A-1 to A-9).

Figure 4.1 shows the modelled groundwater head elevation, the phreatic surface, before the renovation of the sewers. The map shows the median (50% fractile) for the simulation period 1996 – 2016. The groundwater flow direction is from southeast towards the northwest. The drainage effect of the surface water bodies, the rivers and the lake, is clearly seen as depressions in the overall groundwater flow map.

In Figure 4.2 areas where the model simulate water on, or above terrain are shown. There is a good consistence between the model results and location of wetlands and areas with minor drain canals.

Figure 4.3 shows areas where the hydrological model simulates groundwater level to be less than 0.5 m below ground surface. The map shows a median situation for the simulation period. The SCALGO software (www.scalgo.com/live) has also been used to calculate areas where depth to groundwater table is less than 0.5 m, but for a typical winter situation occurring once a year (Figure 4.4). When comparing Figure 4.3 and Figure 4.4, the same areas with high groundwater table are found. As expected, the areas with high groundwater table have a larger extent in the SCALGO map (Figure 4.4) as this map shows a winter situation at the time of high groundwater table.

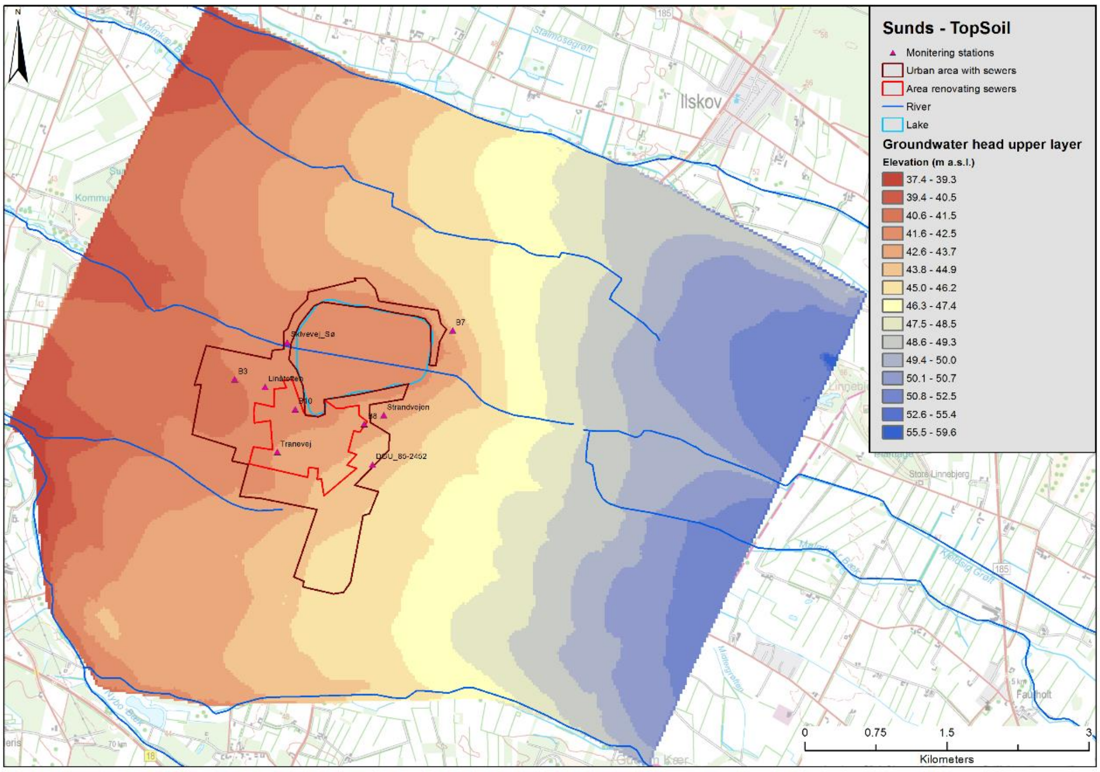


Figure 4.1 Groundwater head elevation of the upper model layer before the start of the renovation of the sewer pipes in the central part of Sunds.

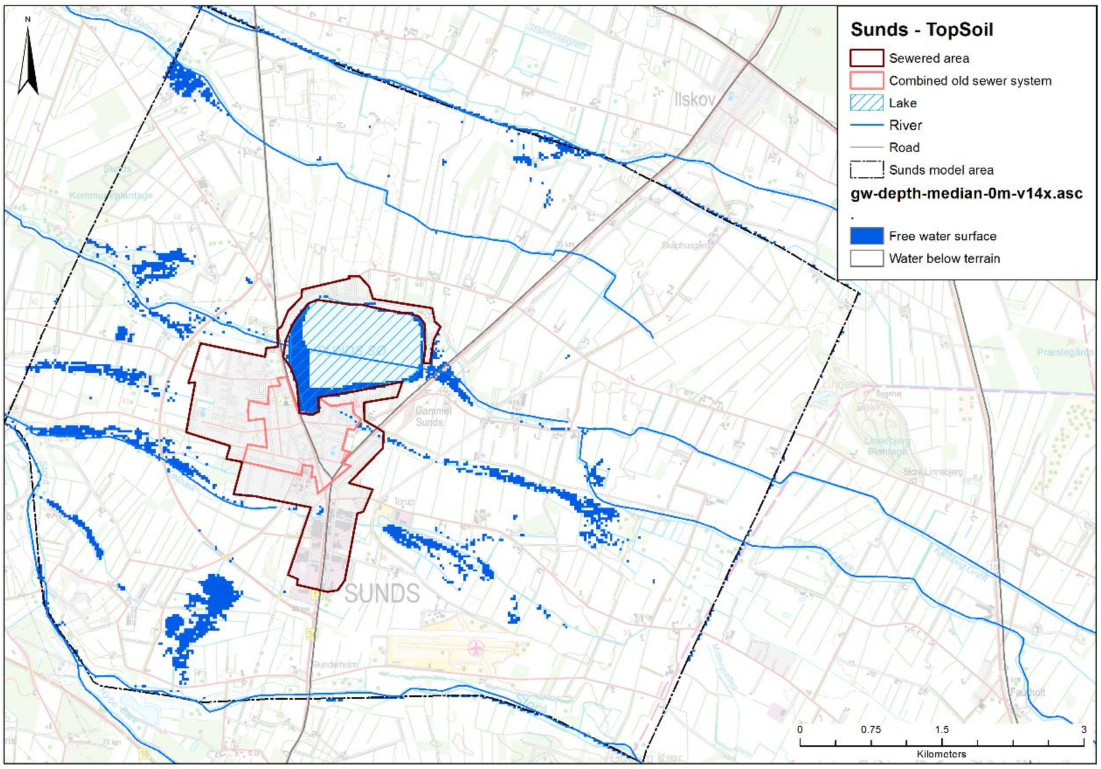


Figure 4.2 Areas where the model simulate water on or above terrain in a median situation (50% fractile).

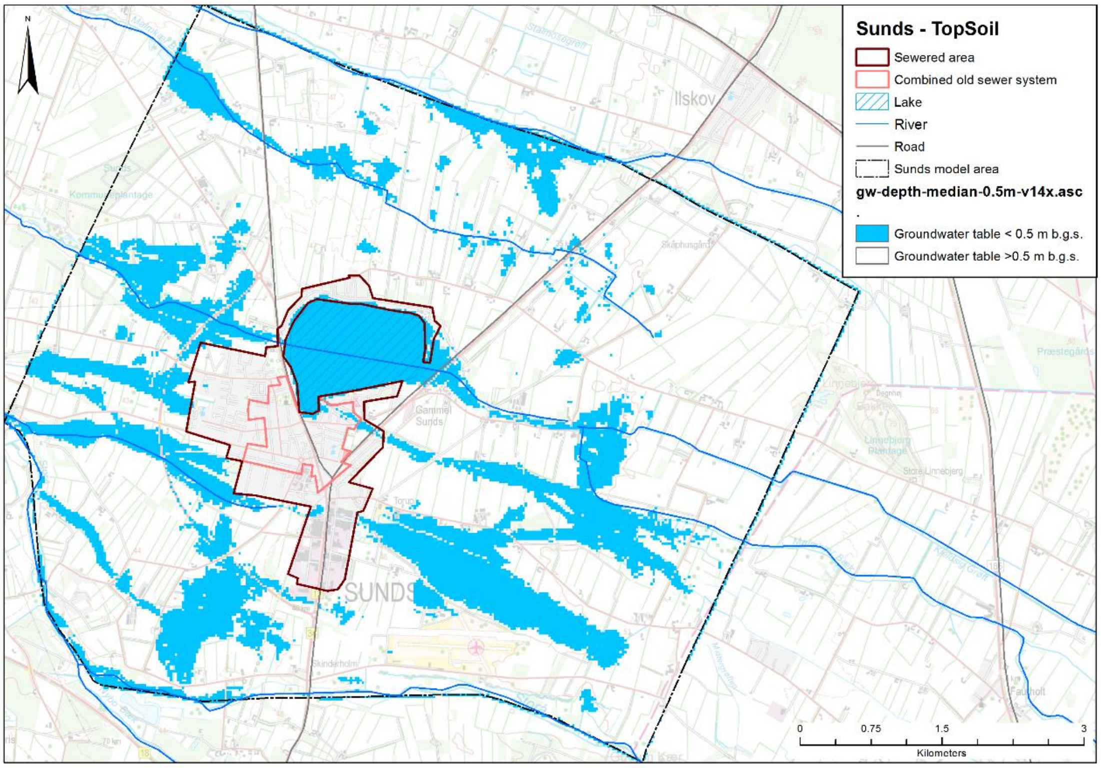


Figure 4.3 Areas where hydrological model simulates groundwater level less than 0.5 m below ground surface in a median situation (50% fractile).

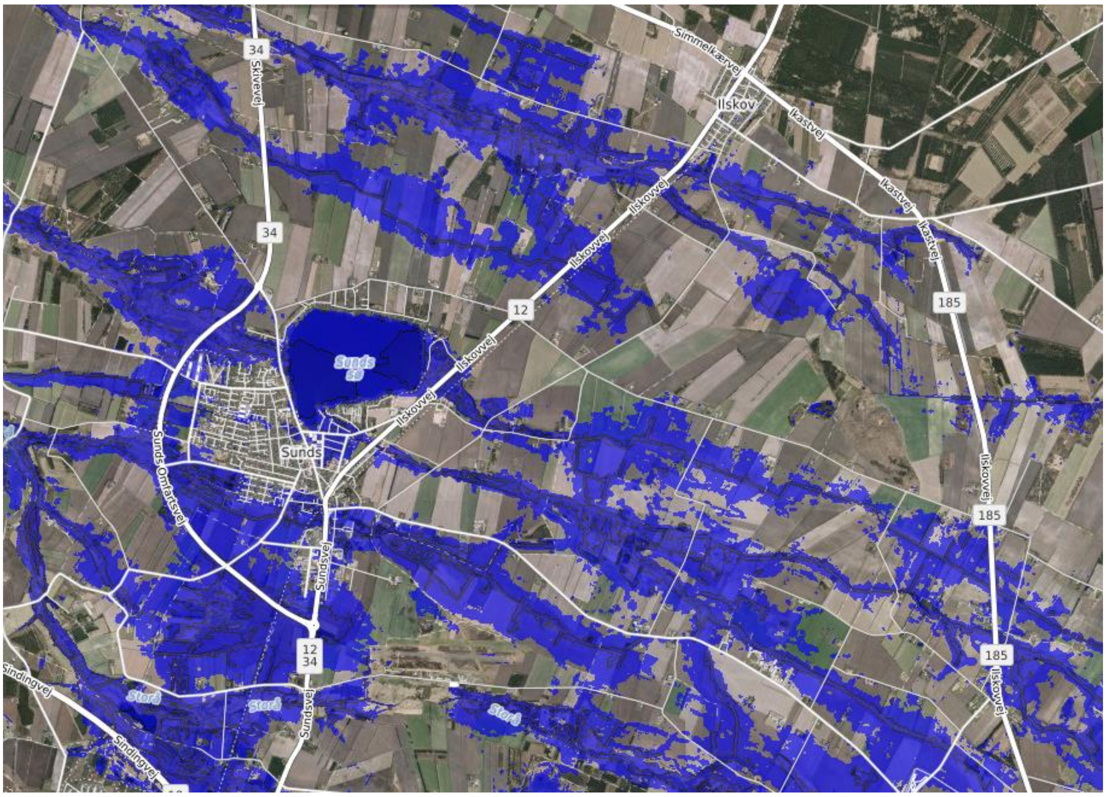


Figure 4.4 Map showing areas where depth to groundwater table is less than 0.5 m in a typical winter situation occurring once a year, calculated by www.scalgo.com/live.

4.4 Model results after the renovation of sewer pipes

In this section, the results of modelling the groundwater and drainage situation after renovation of the sewer pipes in the central part of Sunds are presented. The renovated area with new drains was implemented in the hydrological model by using the same leakage factor for all sewer pipes / drains in town of Sunds, the drain zone 'New sewer pipes' (Table 3.4).

The estimated water balance for the central part of Sunds, where the old sewer pipes have been replaced with new ones, shows that the amount of groundwater drained away by sewers was around 518,000 m^3/year before renovation. After the renovation it is estimated that around 323,000 m^3/year of groundwater will be drained away by the sewer system. It corresponds to a reduction of 40% of groundwater inflow to the sewer system.

Figure 4.5 and Figure 4.6 show the depth to the groundwater table before and after the renovation of the combined sewer system. Only very minor changes are seen between the two maps, partly because a numeric scale of 1 m for the depth to groundwater have been used. In Figure 4.7, the difference in depth to the groundwater table between the situation after and before renovation is shown. It indicates a decrease in average depth to the groundwater table of 5 to 22 cm in the affected areas.

In Figure 4.8 the results from the scenario where local rainwater infiltration from impervious areas is increased from 25% to 50% are shown. It will cause an average decrease in depth to the groundwater table of 5 to 10 cm in parts of Sunds. To some extent, there is a correspondence between the affected areas and areas with higher topographic elevation (Figure 3.12).

Sunds Waterworks is abstracting groundwater from the Bastrup sand formation at a depth of 135 to 150 m below terrain. The annual groundwater abstraction is around 300,000 m^3. The effect of a stop of groundwater abstraction on the average depth to the groundwater table is less than 5 cm. The increase in groundwater table is seen only west of Sunds outside the town (Figure 4.9).

Figure 4.10 shows the effect of increasing the impervious cover by 10% on the groundwater table. The largest effects are seen in the central part of Sunds where the average groundwater table is reduced by 2 to 6 cm due to the lower groundwater recharge.

The effect on the depth to the groundwater table if new drains were established in the whole town, "the 3rd pipe", is seen in Figure 4.11. For this scenario, a leakage factor (time constant) of 3.44 10^{-7} s^{-1} is used. This value is two times larger than the value used for the old sewer pipes. In the urban area, the average groundwater table is lowered by more than 20 cm, and in large areas with 30 to 50 cm. In a winter situation with high groundwater levels, the depth to the groundwater table is lowered with more than 30 cm in the urban area as a whole, and in some areas with more than 50 cm (Figure 4.12).

The amount of additional water that will be drained from the area with the old sewer pipes after implementation of a 3rd pipe is estimated to be around 190,000 m^3/year. For the whole sewered town area the additional drainage water, water from a 3rd pipe, is estimated to be around 1.7 mio. m^3/year. The area of the old combined sewer system covers roughly 25% of the total sewered area.

Figure 4.13 shows the test areas around Sunds laid out for plantation of coniferous forest in three scenarios. Figure 4.14 shows the effect on the depth to the groundwater table for the plantation of 67 ha forest west of Sunds. In Figure 4.15 an additional area east of the town is included for forest plantation giving a total of 185 ha forest. Figure 4.16 shows the effect on the depth to the groundwater table of planting 395 ha forest west, south, and east of Sunds.

The effect of forest plantation west and east of the town has a little effect as a measure to lower the groundwater table inside the town. In the areas where forest are planted, a decrease in the average depth to the groundwater table of 10 to 20 cm is seen (Figure 4.15 and Figure 4.16). If an area of 395 ha forest is planted west, south and east of the town an increase in the average groundwater depth of 10 to 30 cm is seen in town areas enclosed by forest on three sides.

Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, "the summer level" will result in a decrease in the average groundwater table of 5 to 20 cm in the areas located up to 200 m from the lake shore (Figure 4.17). The change in water table in a winter situation with higher groundwater levels, a constant water level in the lake will result in a decrease in the average groundwater table of 5 to 40 cm in the areas up to 300 m from the lake shore (Figure 4.18).

Figure 4.19 shows the combined effect of implementing all measures for lowering the groundwater table at the same time. The measures implemented are forest plantation, reduction of local rainwater infiltration, increased area of impervious cover, drainage in the town ("the 3rd pipe"), and lowering the water level in Sunds Lake. The change in the average depth to the groundwater table is in all areas more than 20 cm. In large areas of the town, the depth to the groundwater table is more than 40 cm and up to 90 cm deeper after implementation of all the measures.

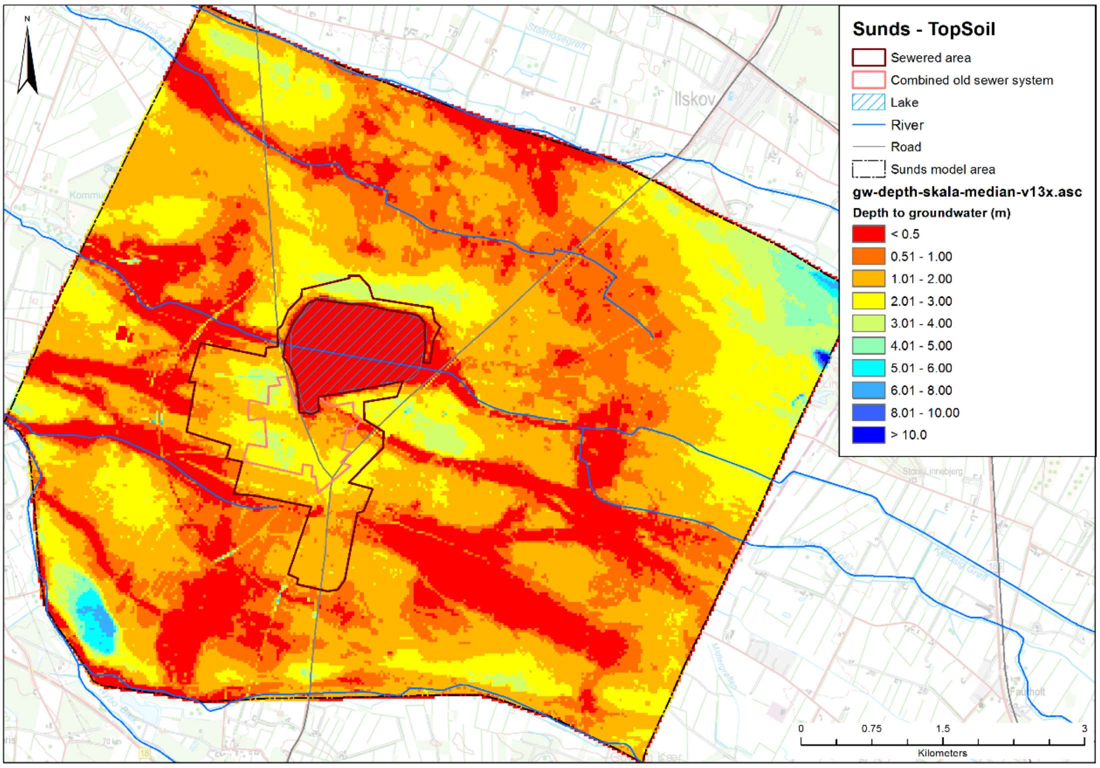


Figure 4.5 Depth to groundwater table before renovation of sewers in the centre of town (area inside light red lines).

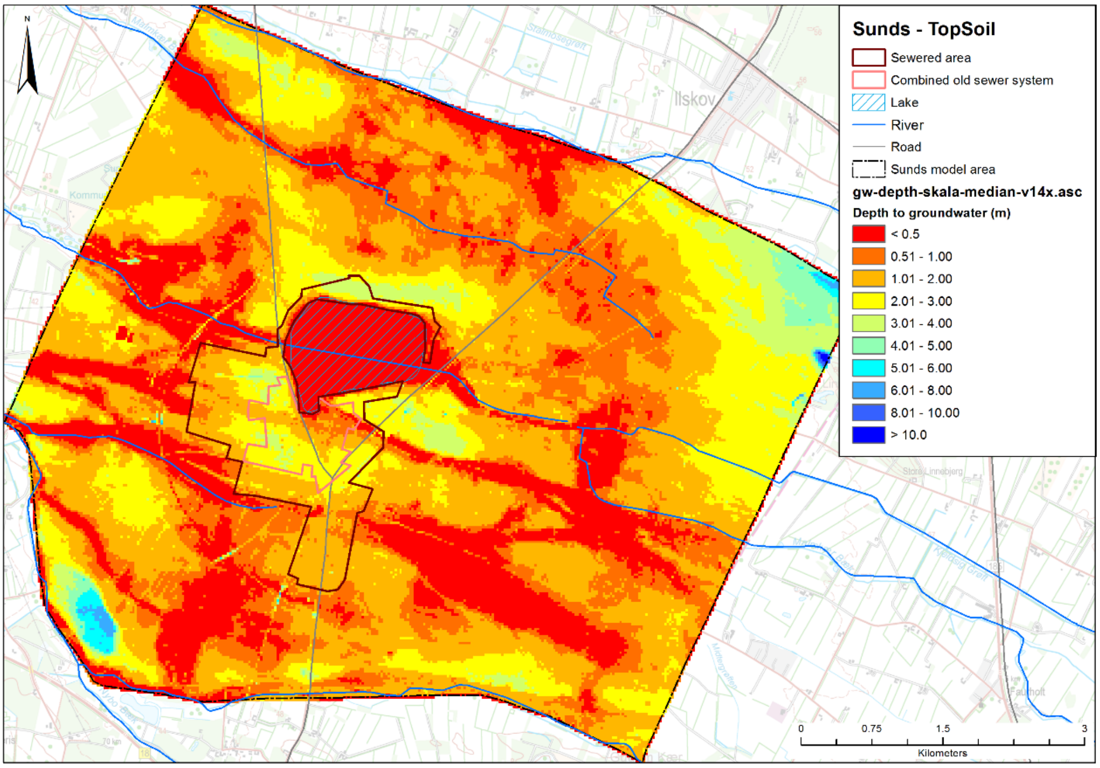


Figure 4.6 Depth to groundwater table after renovation of sewers in the centre of town (area inside light red lines).

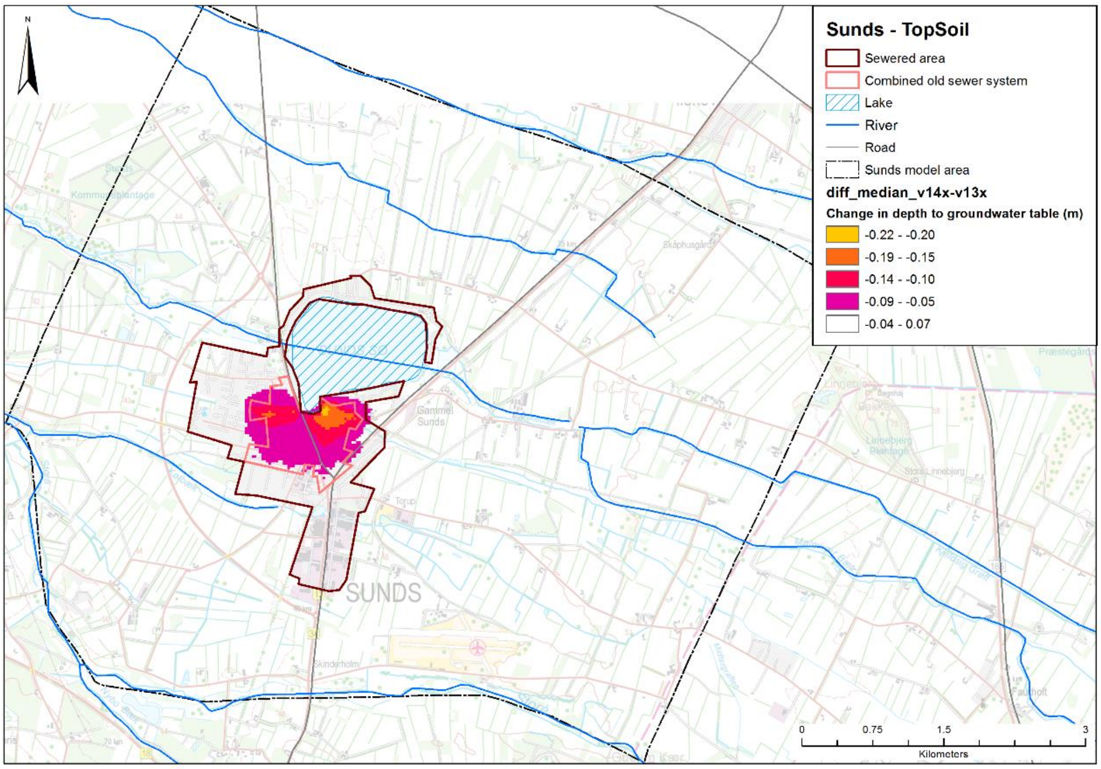


Figure 4.7 Change in depth to groundwater table after renovation of sewers in the centre of town (area inside light red lines), 'minus' in the numeric scale indicates a rise in groundwater table.

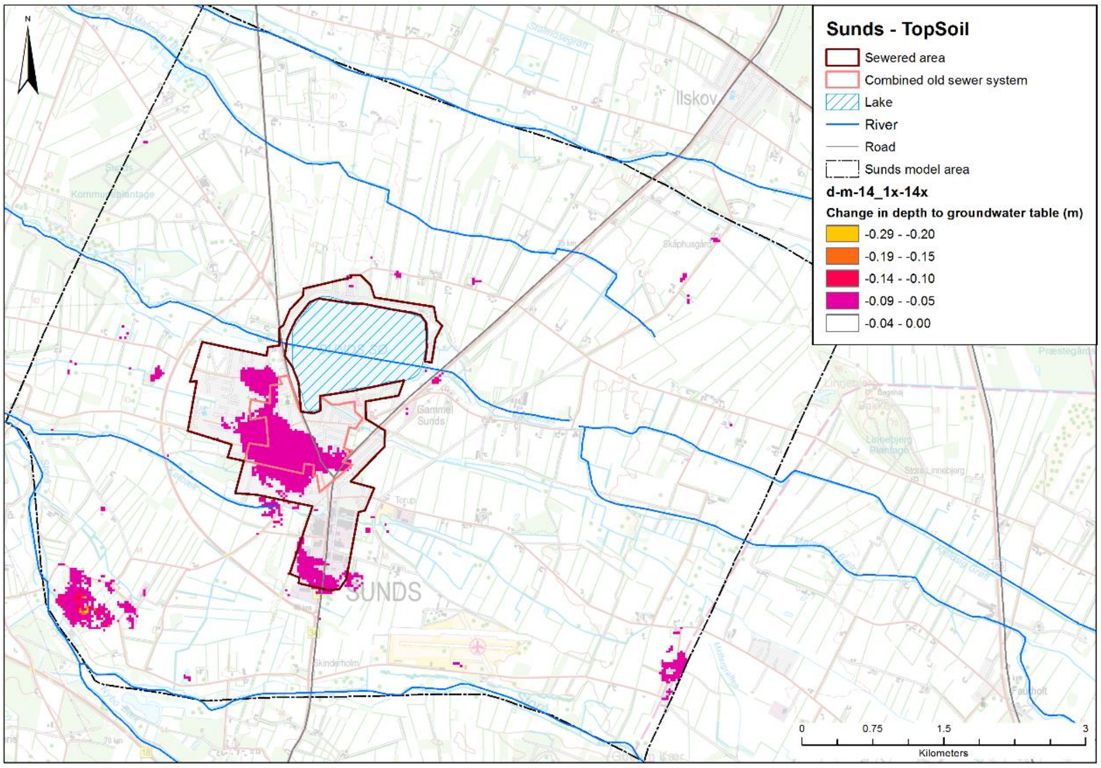


Figure 4.8 Change in depth to groundwater for the scenario with an increase of local rainwater infiltration in the whole town from 25% to 50%, 'minus' indicates a rise in groundwater table.

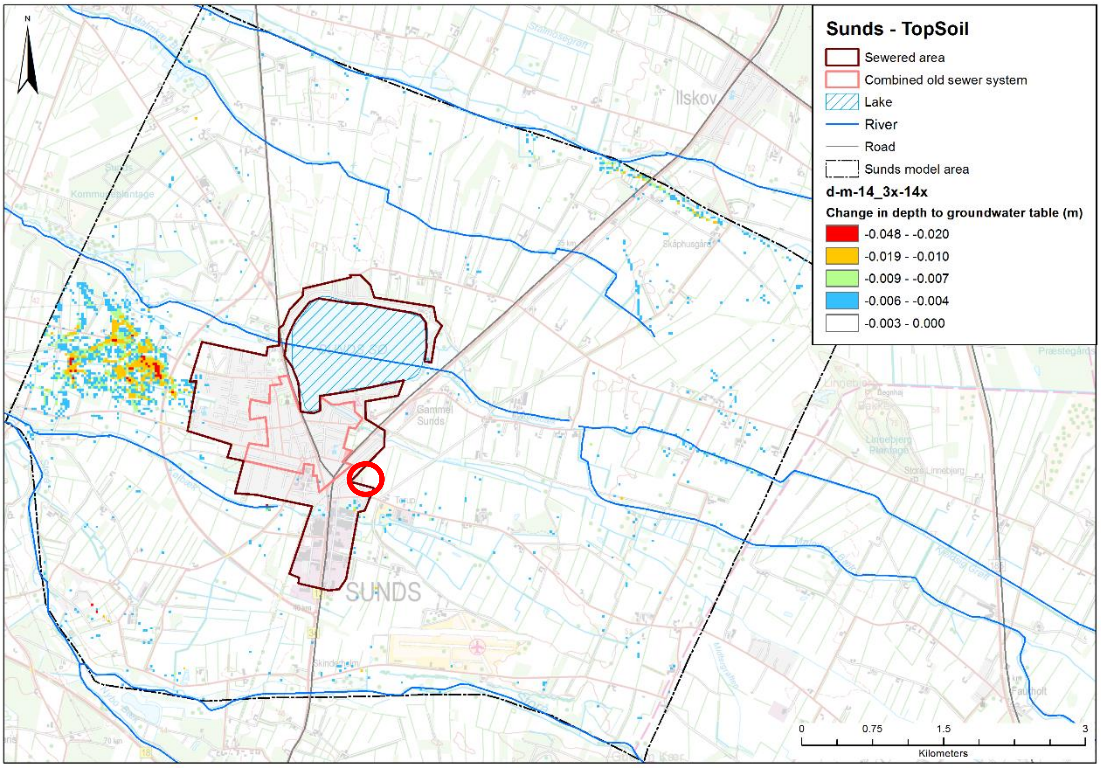


Figure 4.9 Effect on depth to groundwater table if groundwater abstraction for Sunds Waterworks stops. The 'minus' in the numeric scale indicates a rise in groundwater table. Red circle shows the location of the waterworks wellfield.

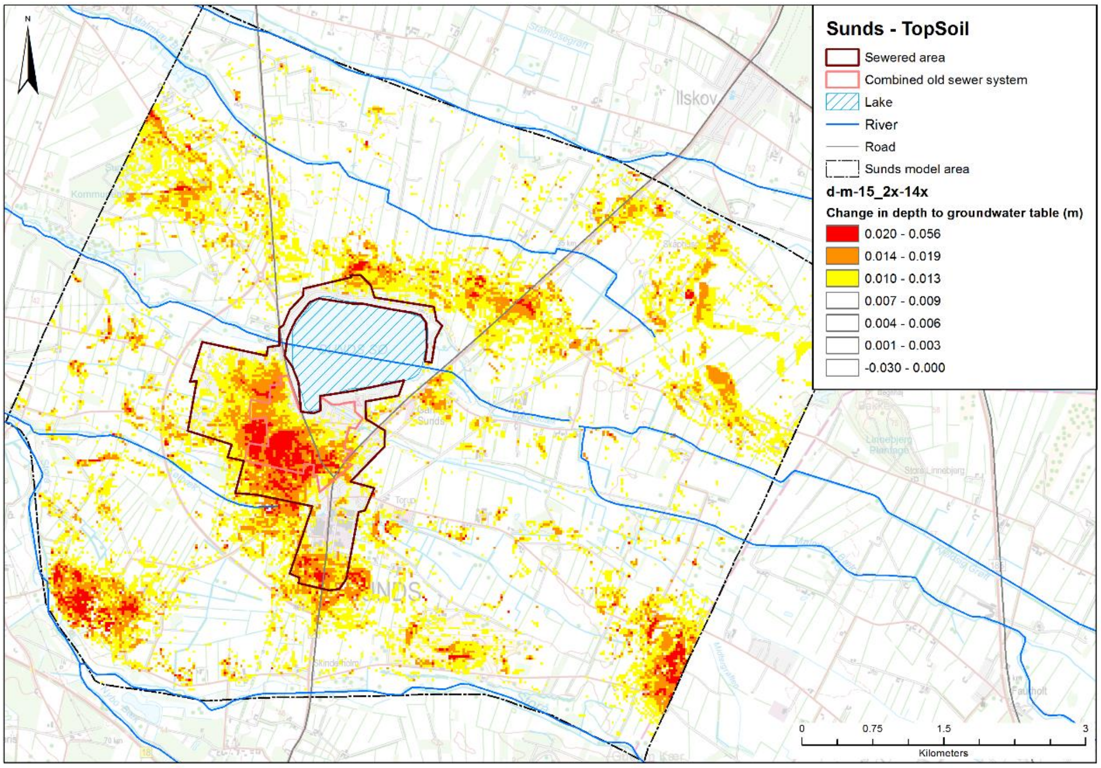


Figure 4.10 Effect on depth to groundwater table if the impervious cover in the town of Sunds is increased by 10%, numeric scale indicates a lowering of the groundwater table.

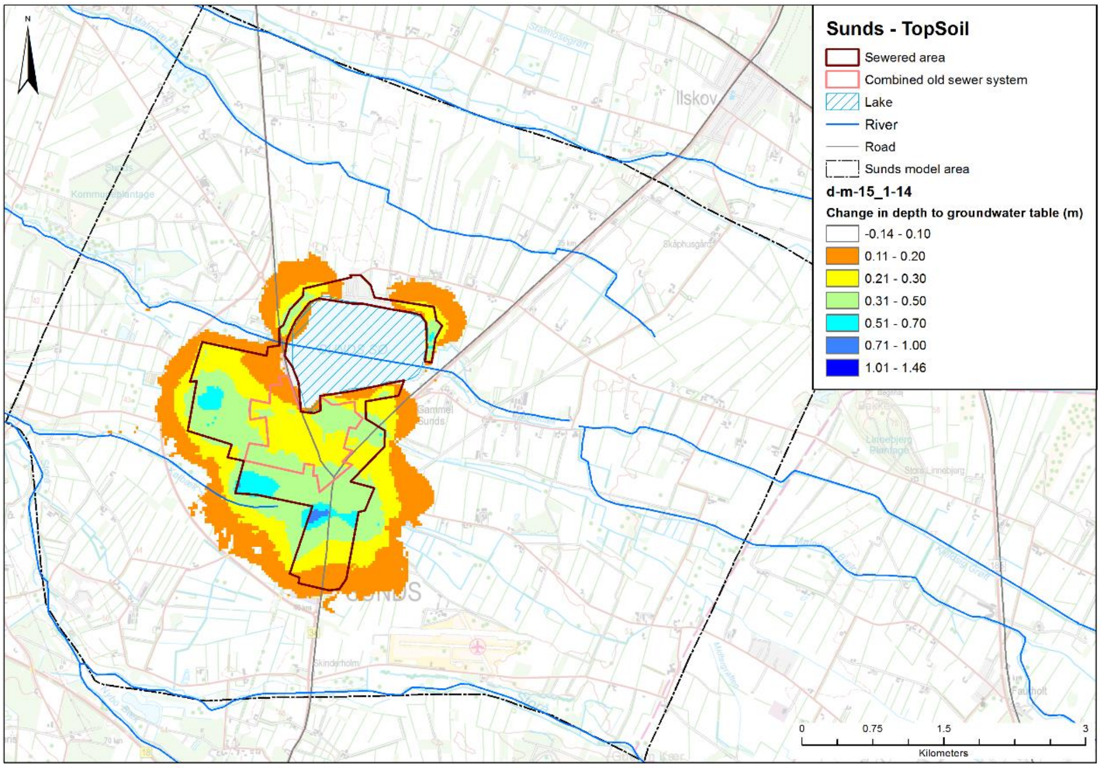


Figure 4.11 Effect on depth to groundwater table if establishing drains in the whole town, "the 3rd pipe". The figure shows the situation for a median groundwater table, the numeric scale indicates a lowering of the groundwater table.

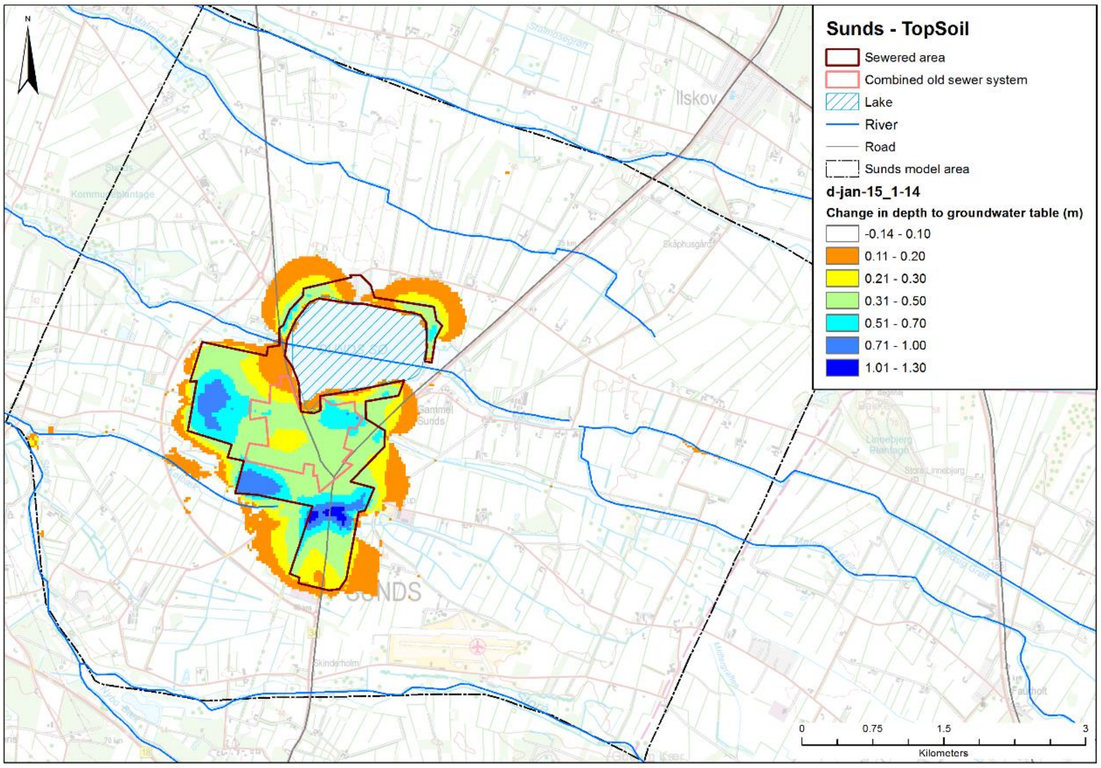


Figure 4.12 Effect on depth to groundwater table if establishing drains in the whole town, "the 3rd pipe". The figure shows the situation for a January situation with high groundwater table.

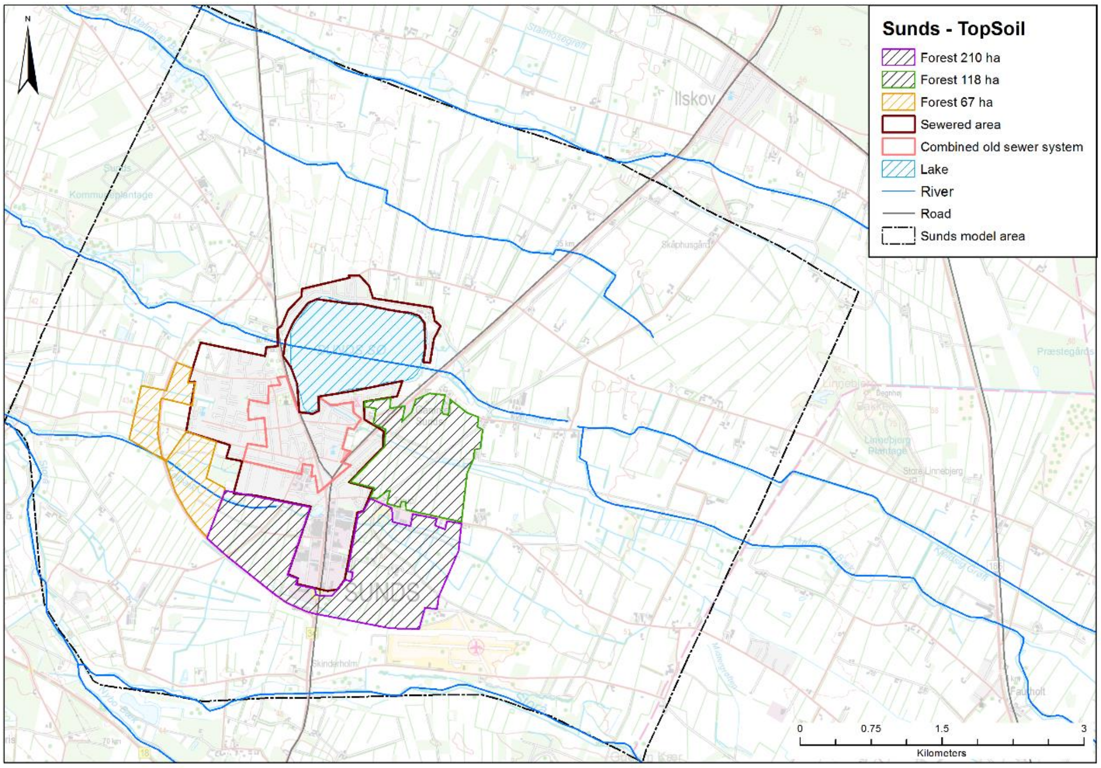


Figure 4.13 The three areas around the town included in the scenarios for plantation of coniferous forest.

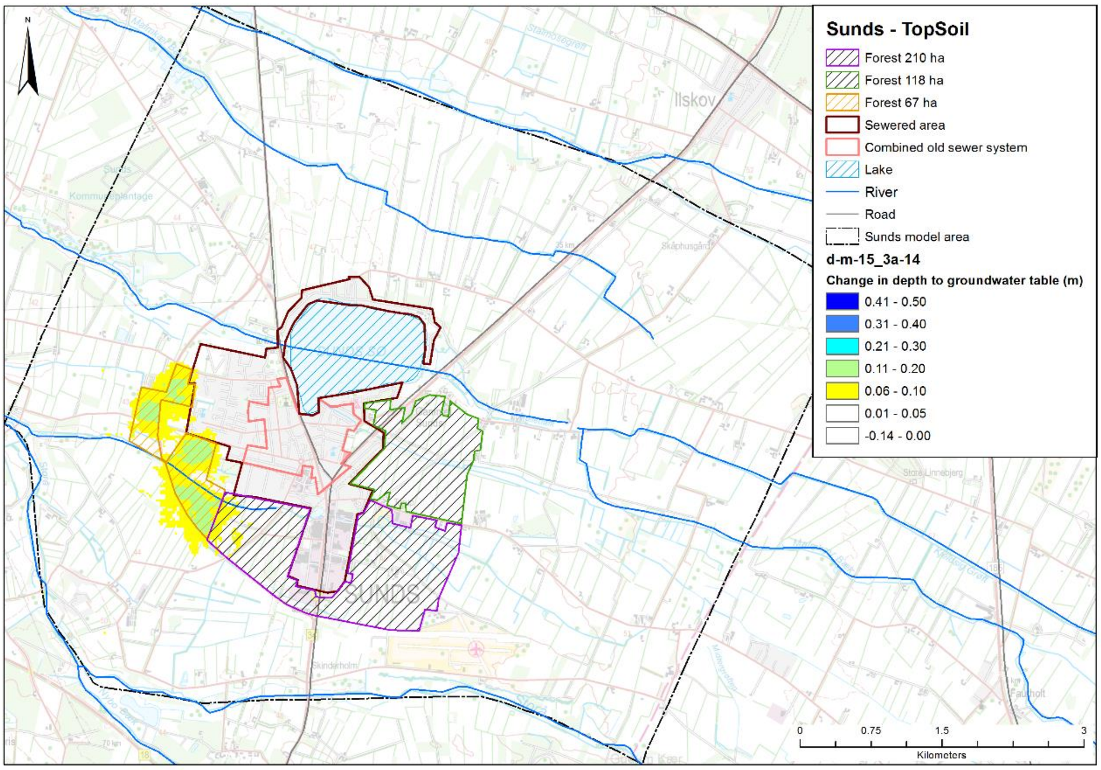


Figure 4.14 Effect on groundwater table for plantation of coniferous forest on a 67 ha large area west of town. The numeric scale indicates a lowering of the groundwater table.

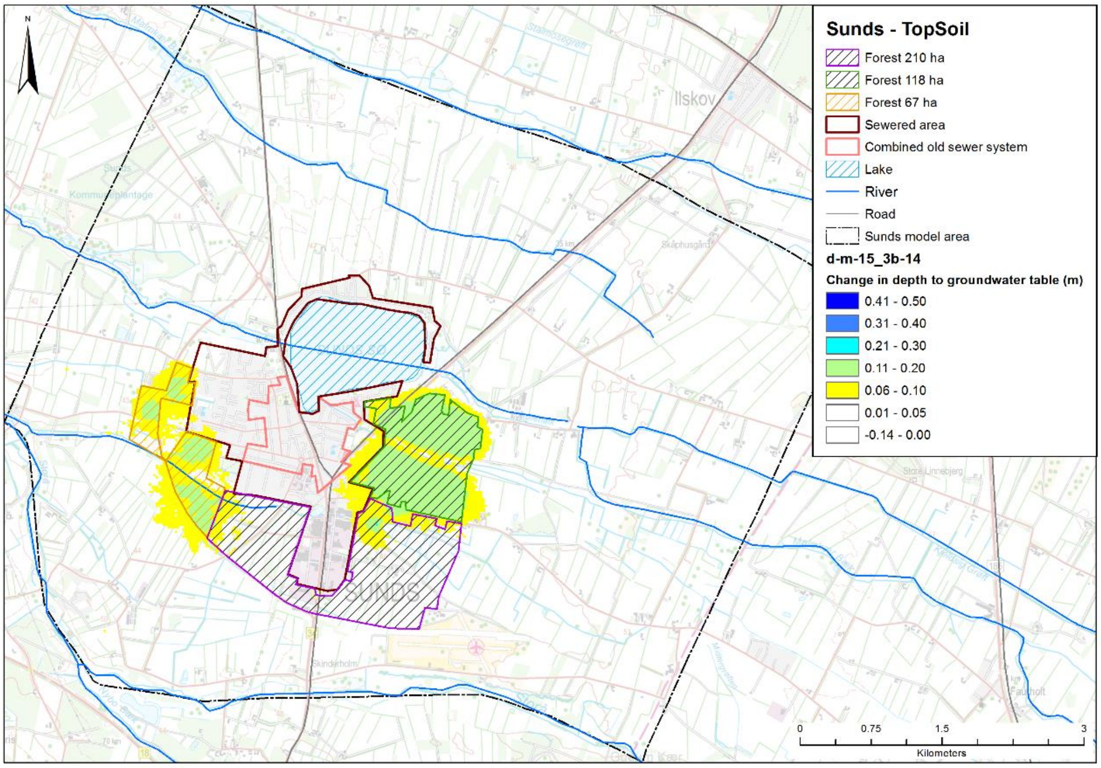


Figure 4.15 Effect on groundwater table for plantation of coniferous forest on two areas of a total of 185 ha west and east of town.

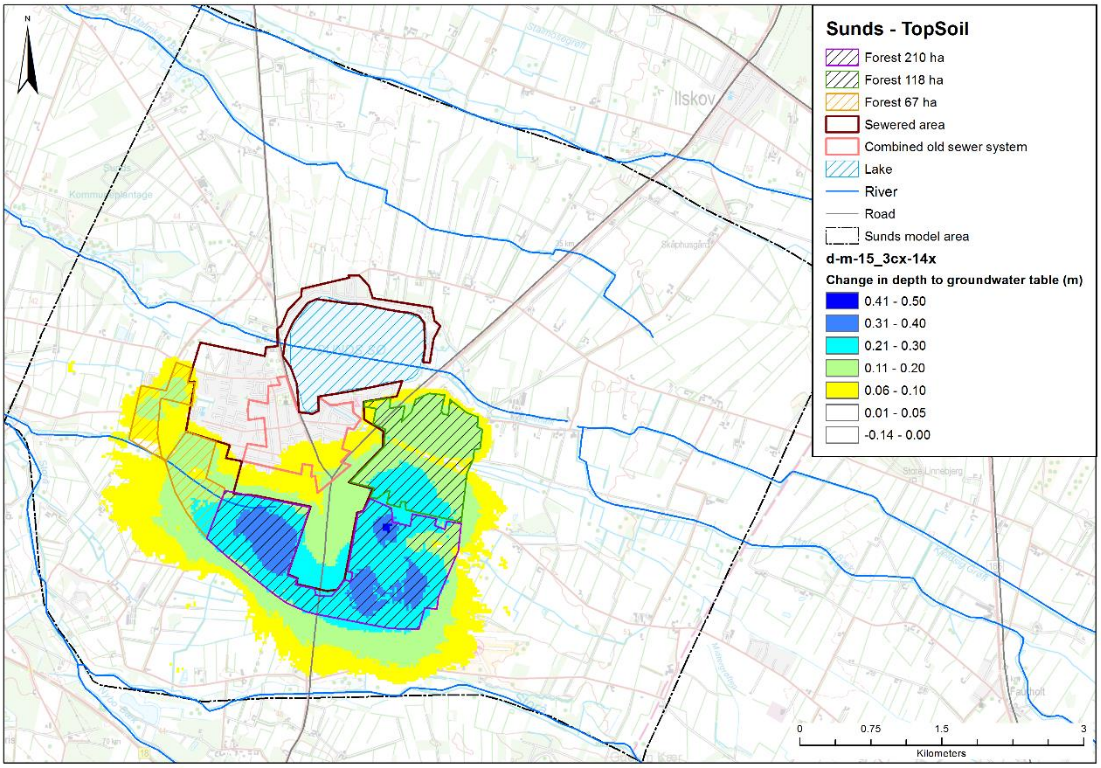


Figure 4.16 Effect on groundwater table for plantation of coniferous forest on 395 ha west, south, and east of town.

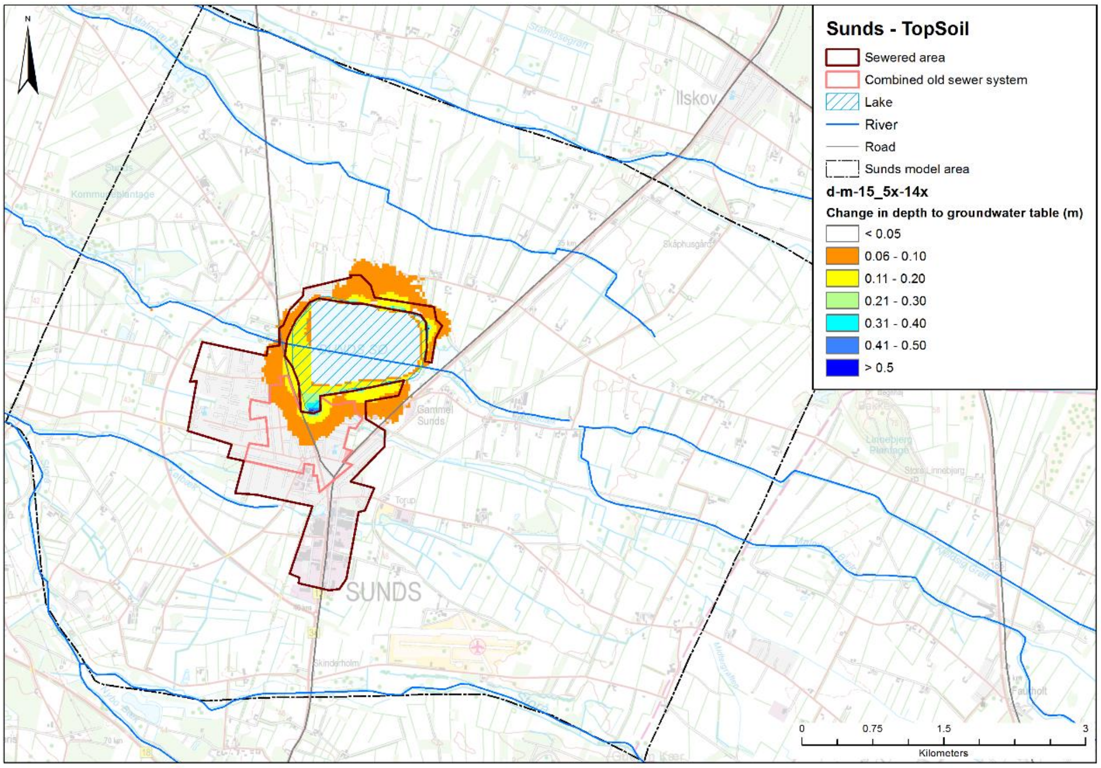


Figure 4.17 Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, “the summer level”. The figure shows the situation for a median groundwater table.

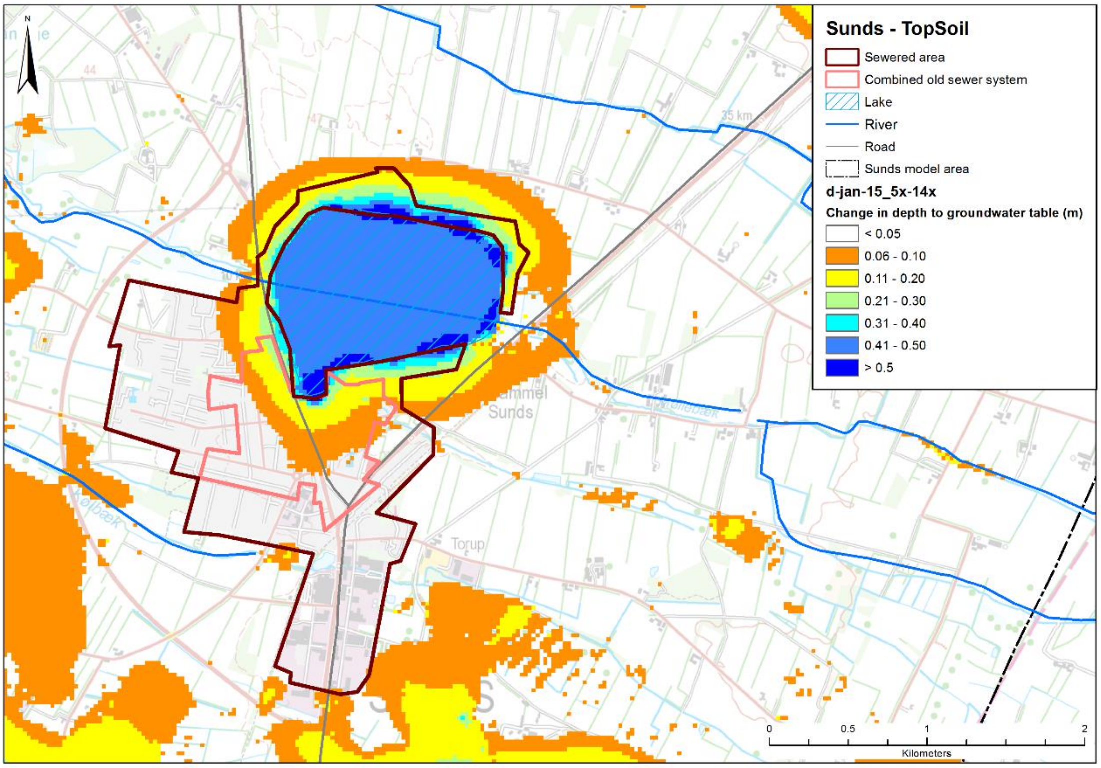


Figure 4.18 Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, “the summer level”. The figure shows the situation for a January situation with high groundwater table.

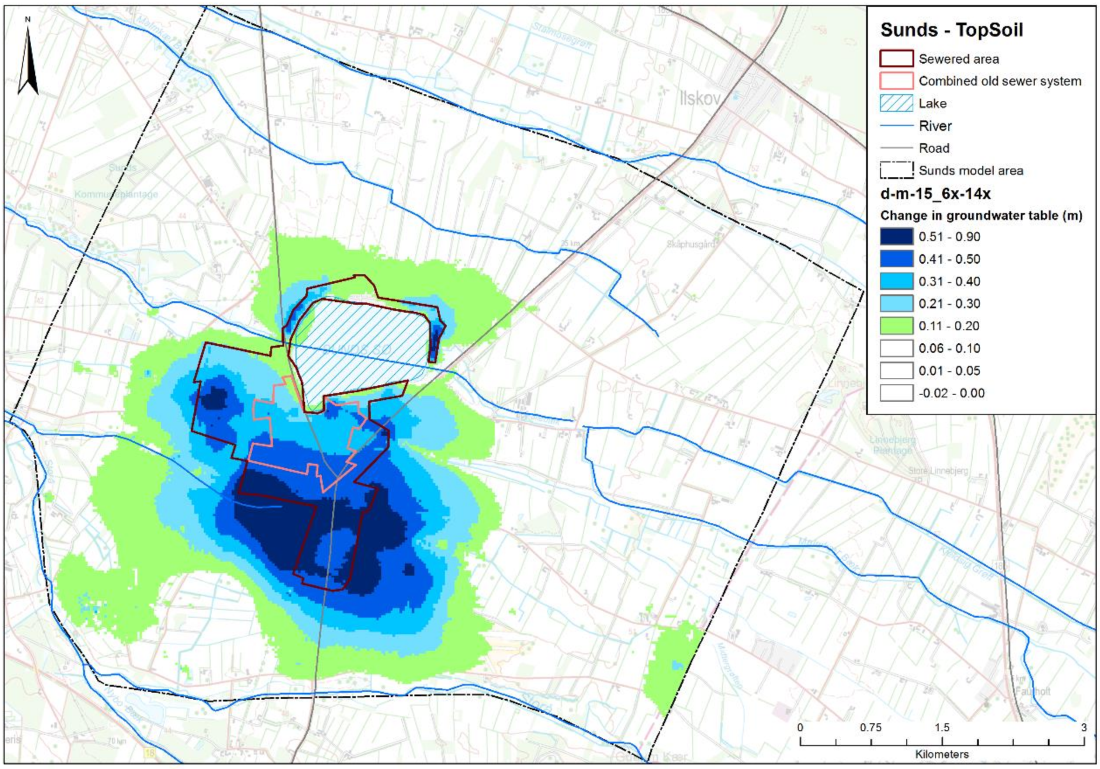


Figure 4.19 The combined effect of implementing all measures at the same time for lowering the groundwater table. The numeric scale indicates a lowering of the groundwater table.

5. Climate scenarios

5.1 Groundwater levels in a future climate

A projected medium wet climate scenario has been selected for the climate change scenarios. Two periods, the near future 2041-2060, and the far future 2081-2100, were selected for analysing the effect on the depth to the shallow groundwater.

Figure 5.1 shows the change in depth to groundwater table for a medium wet climate scenario in near future (2041-2060) compared to the situation today (1996-2016). Only minor areas in the town is affected by an average rise in groundwater table of 5 to 10 cm in the near future.

In the far future scenario (2081-2100) a rise in groundwater table of 10 to 20 cm is seen in south-eastern part of Sunds. In more than half of the urban area of Sunds an increase of 5 to 10 cm rise in groundwater table is seen on the far future scenario (Figure 5.2).

Figure 5.3 to Figure 5.5 show risk maps for the depth to groundwater table for a 10-year event for the present situation (1996-2016), for the near future (2041-2060), and for the far future (2081-2100). See Table 4.2 for the definition of the risk classes. From the present situation to the near future only very small areas change to a higher risk class, from low risk (green) to high risk (yellow), or from high risk to very high risk (red). Comparing the far future with the near future shows that larger areas are seen to change from low risk to high risk in the central part of Sunds, and in the southern part of town to change from high risk to very high risk of high groundwater levels.

Figure 5.6 shows the changes in depth to groundwater table for a 10-year event for the near future (2041-2060) compared to a 10-year event for the present situation. Only in the south-easter part of Sunds high groundwater levels could rise between 5 to 10 cm.

In Figure 5.7 changes in depth to groundwater table for a 10-year event for the far future (2081-2100) are compared to the present situation. In the central and south-eastern part of Sunds high groundwater levels are expected to rise between 10 to more than 50 cm for a medium wet climate scenario.

In the Annex 1 risk maps are presented for high groundwater table for three periods, the present climate for the period 1996-2016, and the medium wet climate scenario for the near future, 2041-2060, and for the far future, 2081-2100. Risk maps are shown for a 2-year event, a 10-year event, and for a 25-year event.

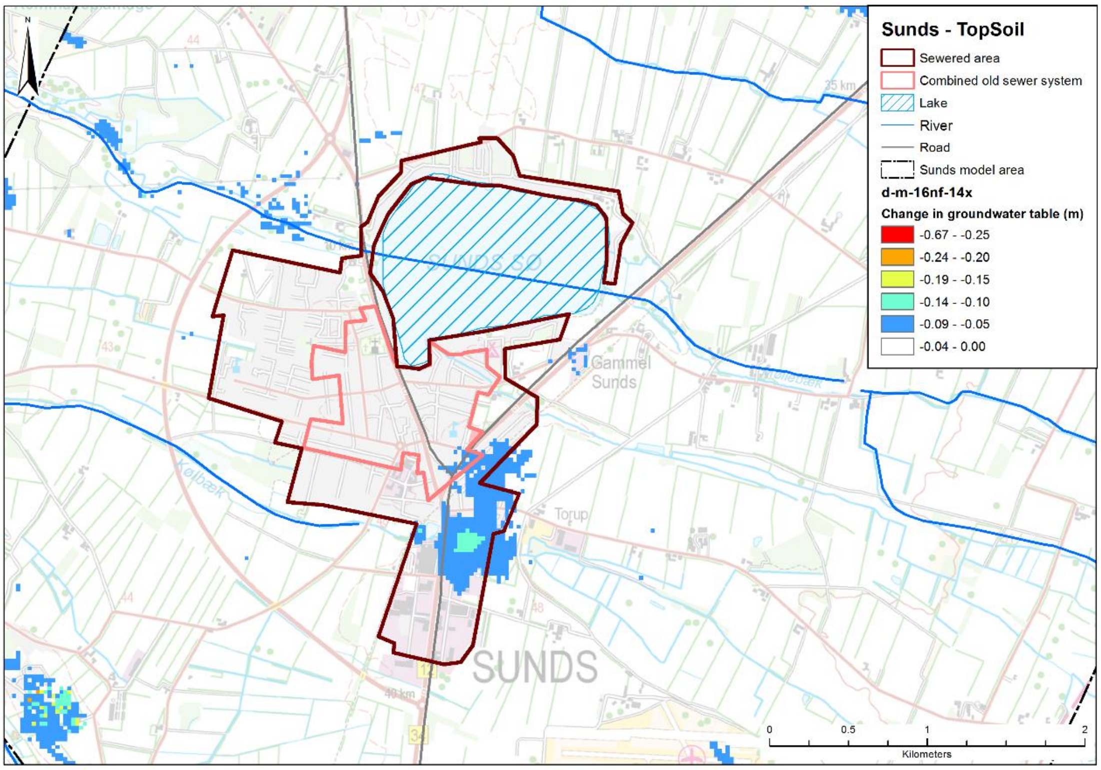


Figure 5.1 Estimated change in depth to groundwater table for a medium wet climate scenario in near future (2041-2060) compared to the situation today (1996-2016). The 'minus' on the numeric scale indicates a rise in groundwater table.

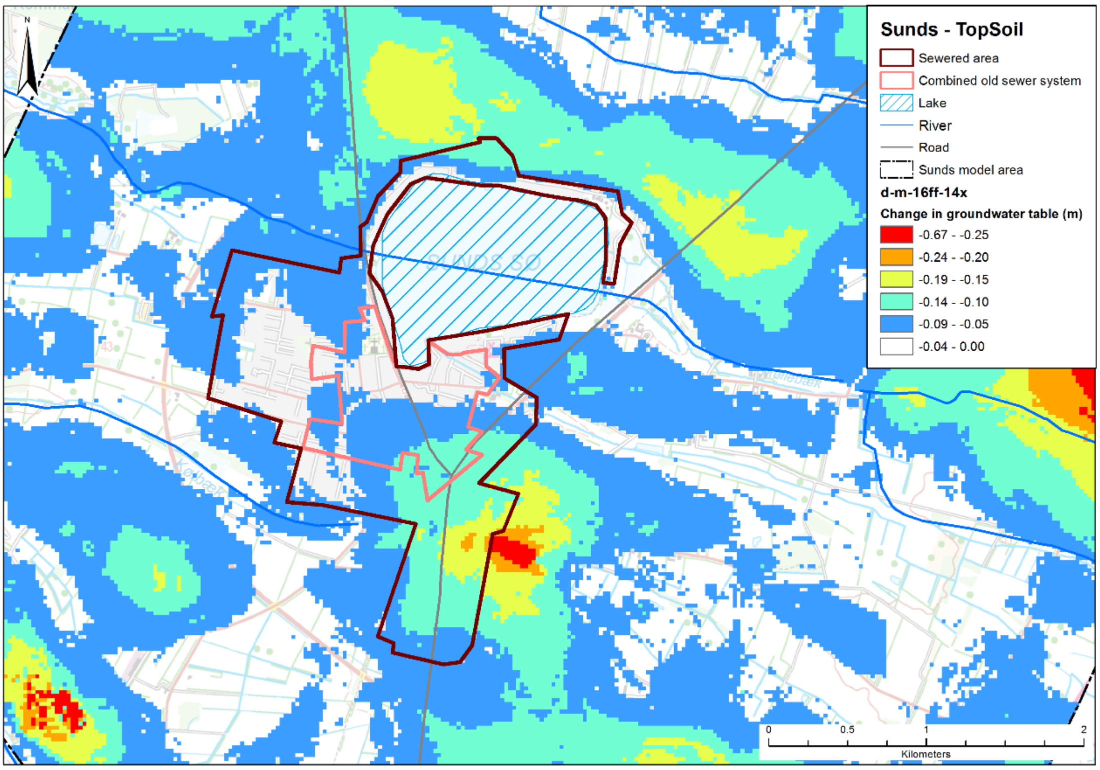


Figure 5.2 Estimated change in depth to groundwater table for a medium wet climate scenario in far future (2081-2100) compared to the situation today (1996-2016).

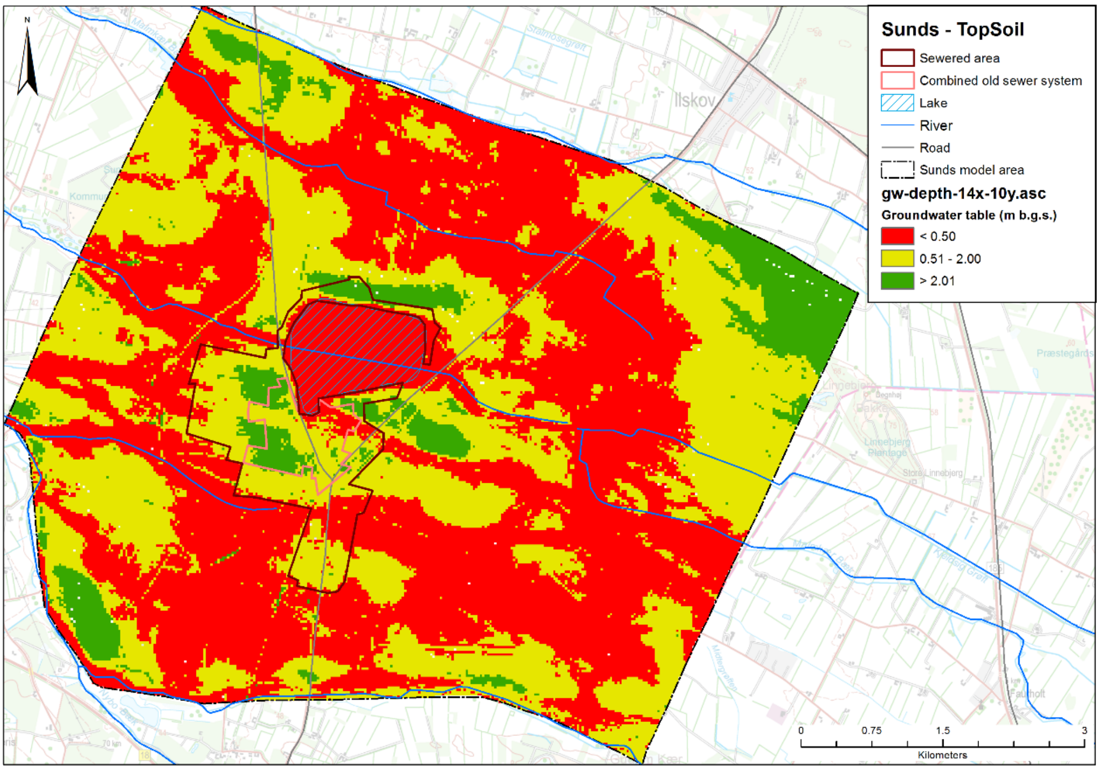


Figure 5.3 Depth to groundwater table for a 10-year event for the present situation (1996-2016).

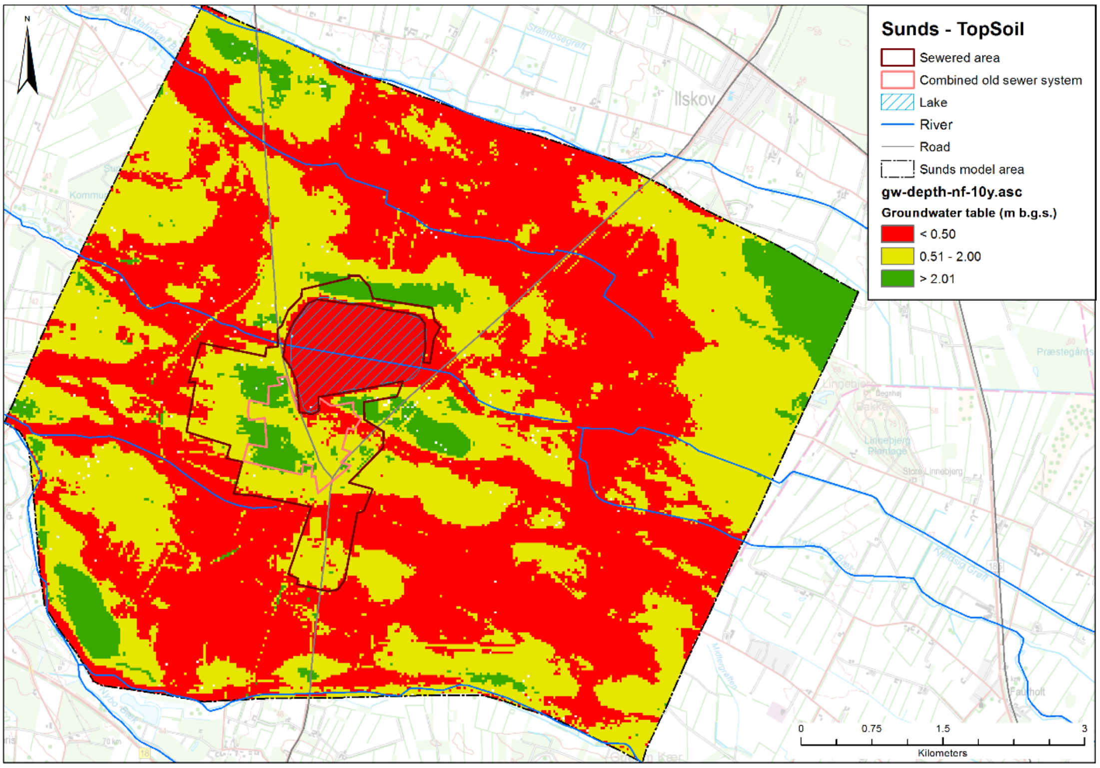


Figure 5.4 Depth to groundwater table for a 10-year event for the near future (2041-2060).

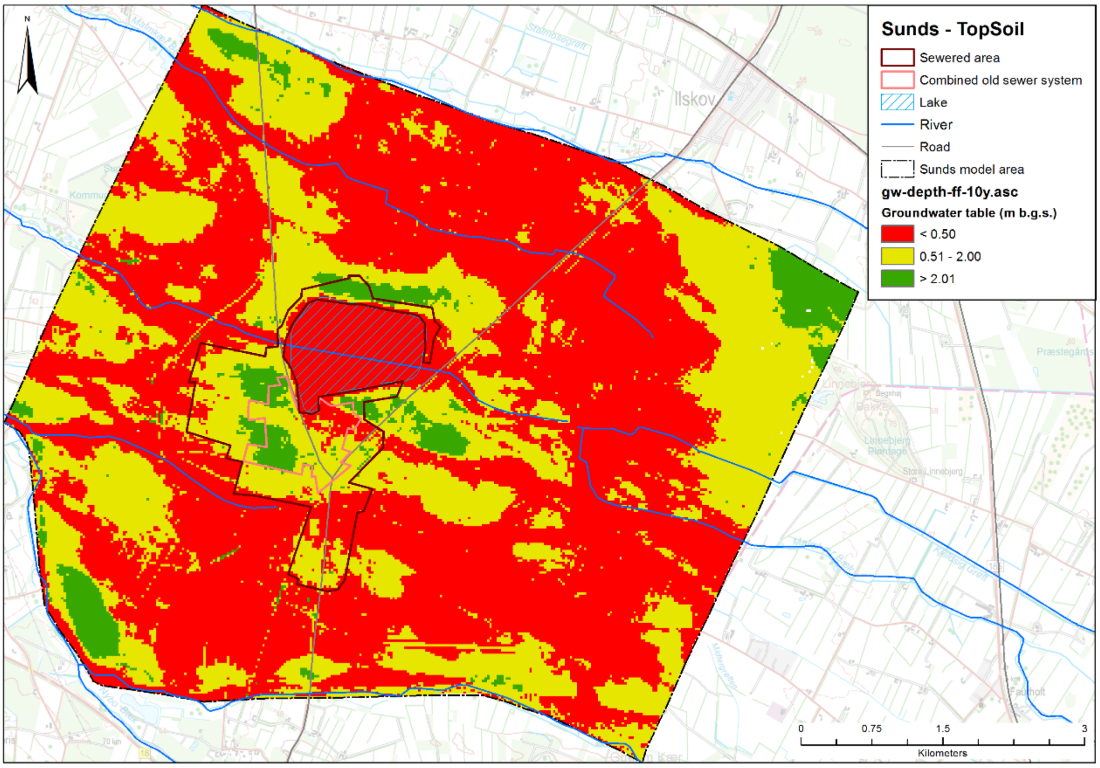


Figure 5.5 Depth to groundwater table for a 10-year event for the far future (2018-2100).

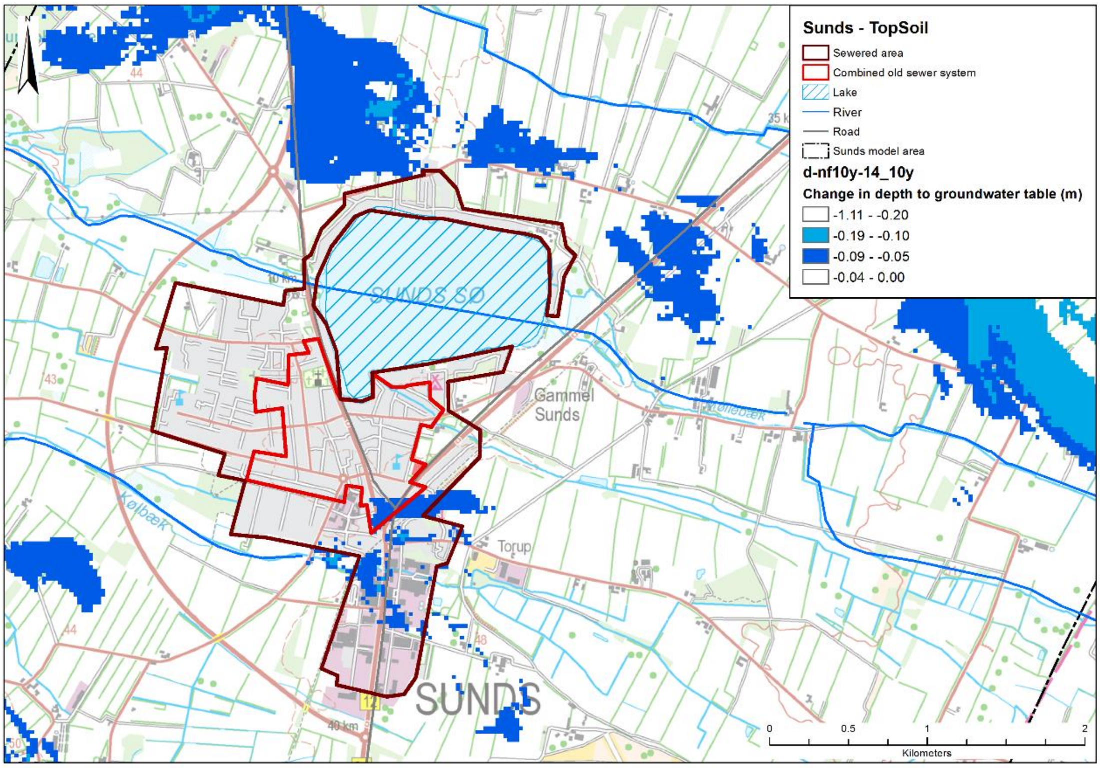


Figure 5.6 Change in depth to groundwater table for a 10-year event for the near future (2041-2060) compared to a 10-year event for the present situation. The 'minus' on the numeric scale indicates a rise in groundwater table.

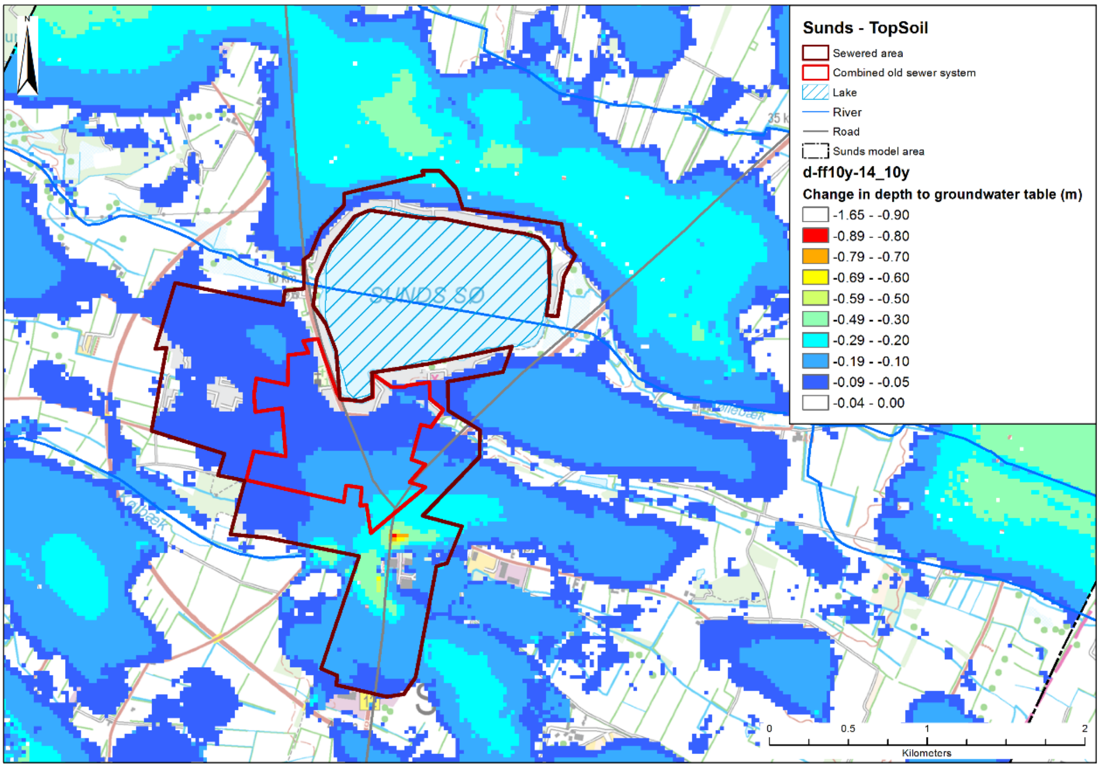


Figure 5.7 Change in depth to groundwater table for a 10-year event for the far future (2081-2100) compared to a 10-year event for the present situation (1996-2016).

5.2 Effect on river discharge

Figure 5.8 shows river discharges downstream Sunds Lake at a location in Sunds Nørreå close to the western boundary of the hydrological model. In the four figures river discharge for the situation after renovation of the sewer pipes (green lines) is compared to a) plantation of 395 ha of forest around Sunds, b) keeping the water level in Sunds Lake constant at the summer level, c) drainage of shallow groundwater in the town by a 3rd pipe, and d) river discharge in medium wet climate scenario in far future (2080-2096). Note that in Figure 5.8 d) the 16-year time series for the far future is copied into the time scale of the present time series, the two simulations cannot be compared directly!

The plantation of coniferous forest around the town of Sunds will not affect the river discharge in Sunds Nørreå downstream Sunds Lake (Figure 5.8 a). It is more likely that the discharge in will be reduced in the Kølbæk river.

Keeping the water level in Sunds Lake constant at the summer level will after a period result in a decrease in river discharge both in summer and winter periods (Figure 5.8 b).

Introducing drainage of shallow groundwater in the town by a 3rd pipe will increase the river discharge in Sunds Nørreå, most significantly in the winter periods (Figure 5.8 c).

River discharge in medium wet climate scenario in far future (2080-2096) shows large variations from year to year comparable to the variations seen today, though the simulations of the present-day situation and the far future climate cannot be compared directly! The drier years and more wet years shown in Figure 3.21 are also seen in discharge time series, see Figure 5.8 d.

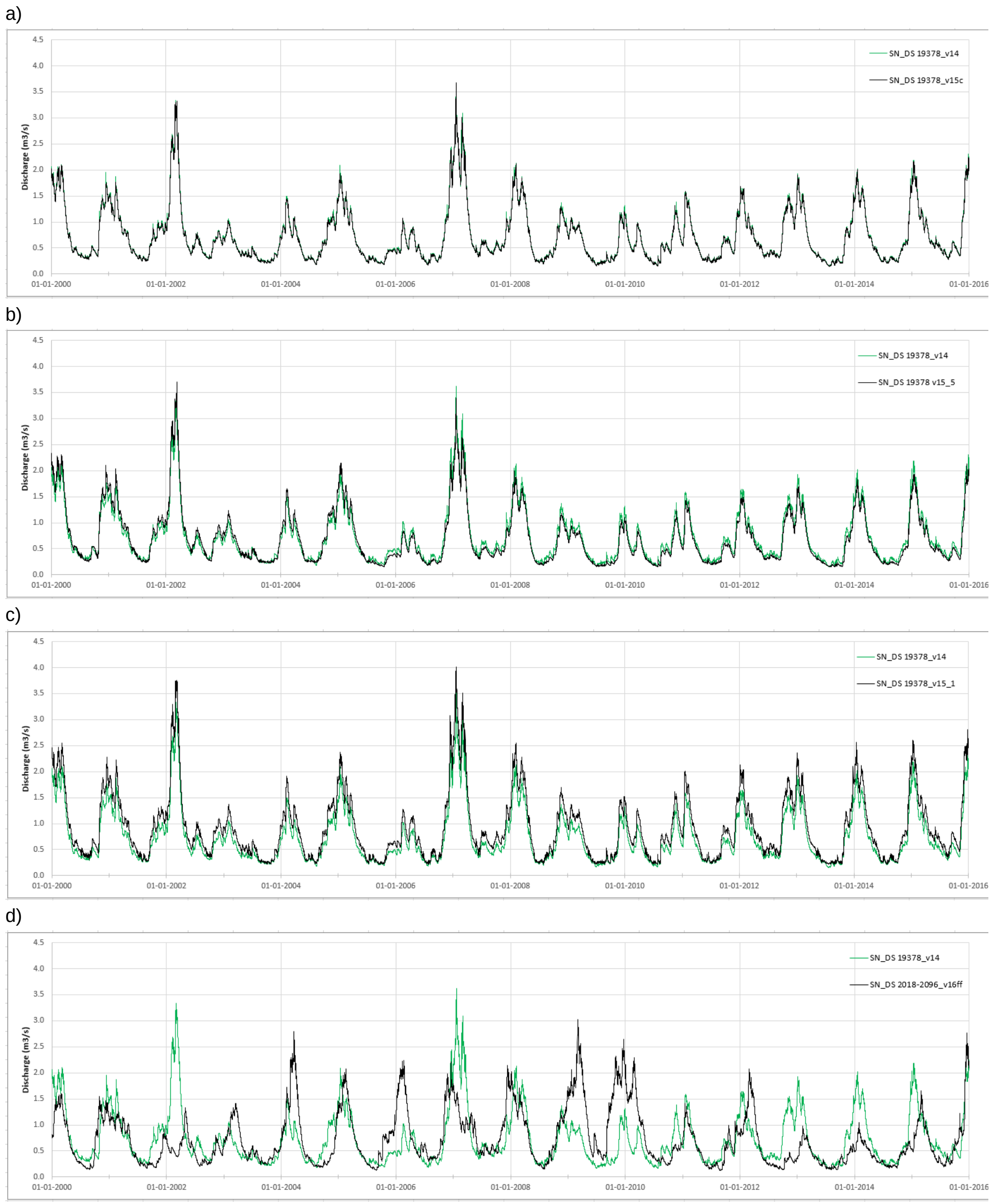


Figure 5.8 River discharge downstream Sunds Lake. Comparison of discharges between the situation after renovation of the sewer pipes (green lines) and a) plantation of 395 ha of forest, b) keeping the water level in Sunds Lake constant, c) drainage in the town by a 3rd pipe, and d) river discharge in medium wet climate scenario in far future (2080-2096), the 16-year time series for the far future is copied into the time scale of the present time series!

5.3 Change in groundwater flow pattern

Figure 5.9 shows the groundwater elevation contours for the situation after implementation of a 3rd pipe compared with the situation after renovation of the old sewer pipes (the base line). The groundwater elevation is lowered in the town area after an implementation of a 3rd drainage pipe. In the western and southwestern part of the town minor changes in groundwater flow directions are seen. However, the overall groundwater flow pattern is not changed.

In Figure 5.10 groundwater elevation contours for the situation after plantation of 395 ha of coniferous forest around Sunds are compared with the situation after renovation of the old sewer pipes. For this scenario minor changes in groundwater elevations is seen in the southern part of the town and outside the town in the areas with plantation of new forest.

In the scenario where the water level in Sunds Lake is kept at the lower summer level (Figure 5.11) only very minor changes in the groundwater elevation contours are seen just south and southwest of the lake.

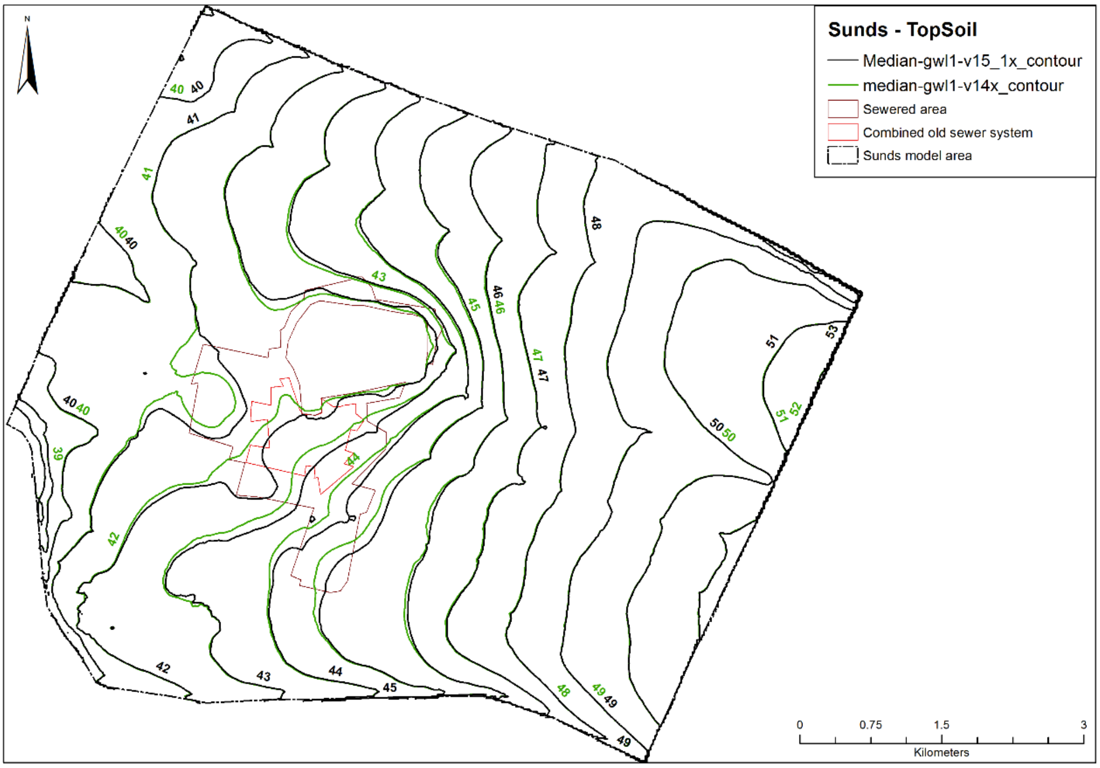


Figure 5.9 Groundwater elevation contours for the situation after implementation of a 3rd pipe (black lines) and the situation after renovation of old sewer pipes (green lines).

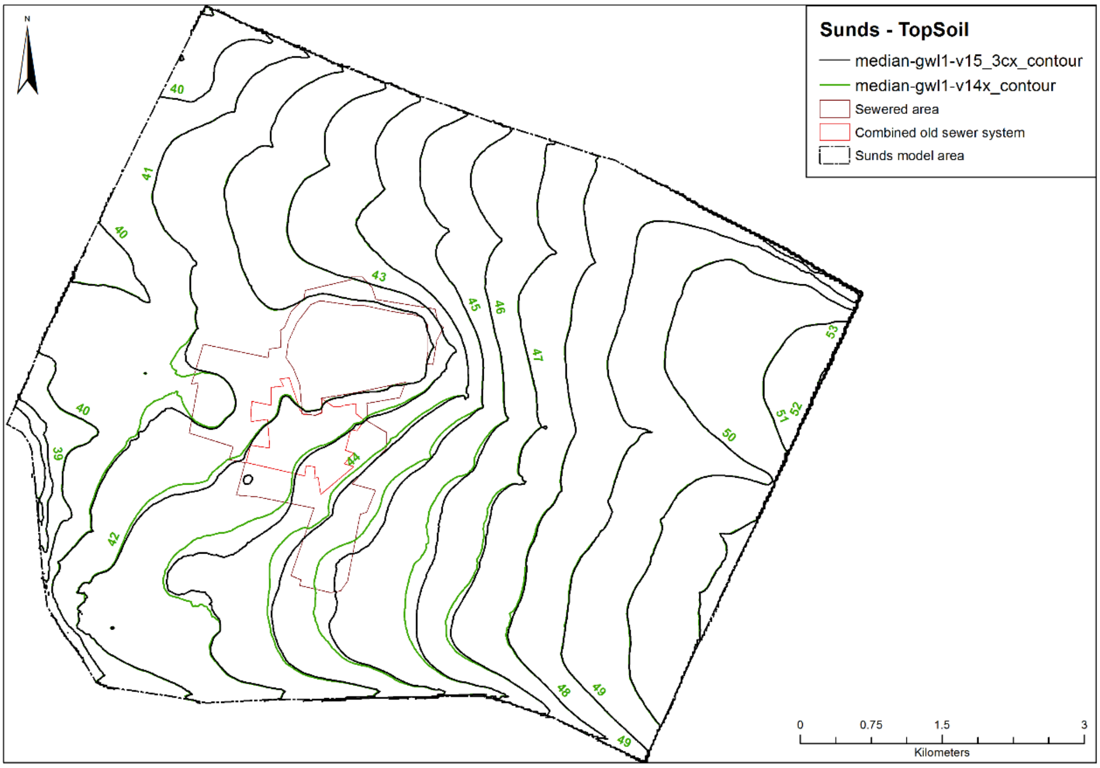


Figure 5.10 Groundwater elevation contours for the situation after plantation of 395 ha of coniferous forest around Sunds (black lines) and the situation after renovation of old sewer pipes (green lines).

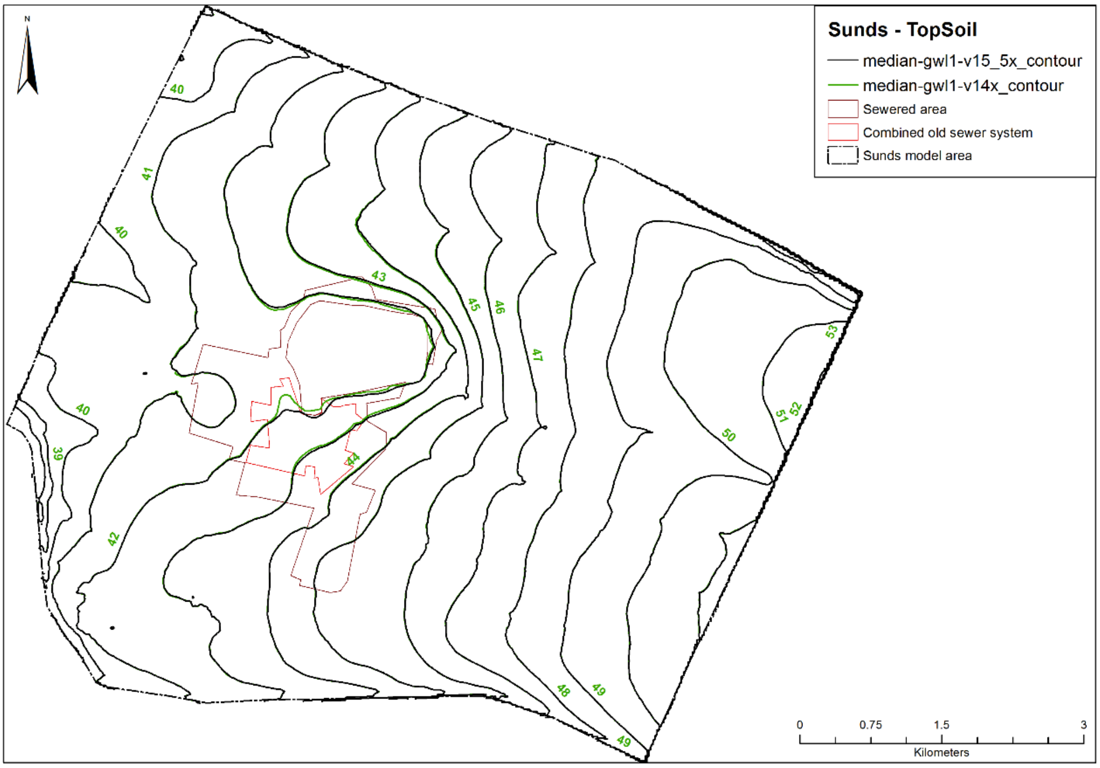


Figure 5.11 Groundwater elevation contours for the situation keeping the water level in Sunds Lake at the lower summer level (black lines) and the situation after renovation of old sewer pipes (green lines).

6. Conclusion

6.1 Geological model

- A 3D geological voxel model with a voxel size of 25 x 25 x 2 m has been established. The model is based on 16 lithology classes (Software used: GeoScene3D).

- TTEM data has revealed a complex “landscape” of deformed and tectonically disturbed Miocene clays (Måde Group clay) beneath the Weichselian outwash sands. The deformed Måde Group Clay is interpreted to have thicknesses from 0 to 25 m.

- A north-south oriented buried valley has been mapped. The valley infill is primarily meltwater sand and gravel. The buried valley is expected to have hydraulic contact to Sunds Lake and is eroded to depths of 80-90 m (elevation -45 m).

- Modelling of FloaTEM data has given important insight in how Sunds Lake may have been formed. It is likely that neotectonic activity resulted in subsidence in the area, which initiated the formation of the lake and affected the overall drainage system.

- The geological model has contributed to an important understanding of the lake-groundwater interaction.

6.2 Hydrological model

- The calibrated hydrological model shows a good agreement between observed and modelled groundwater heads, lake water level and river discharge.

- The hydrological model shows a decrease in drained groundwater of 40% by the sewer system after renovation of sewer pipes.

- The hydrological model shows an increase in the mean groundwater table in the central part of Sunds town of 5 to 20 cm after the renovation of sewer pipes.

- Based on the different scenarios tested, the most effective measure is to lower the groundwater table in the urban part of Sunds by implementation of a “3rd pipe”, an urban drainage system installed along the existing sewer system.

- Plantation of coniferous forest around the town centre have minor effect on the groundwater table in the town. The effects are more local and limited to areas near the forest, e.g. areas enclosed by forest on three sides where an increase in the average groundwater depth of 10 to 30 cm is seen.

- Lowering the water level in the Sunds Lake to the summer level also have the effect of lowering the groundwater table. The effects are local and limited to areas near the lake.

- The preventive measures with less effect on the depth to the groundwater table are the reduction of local rainwater infiltration and the increase of the impervious cover. This is probably explained by the relatively small areas where the measures are implemented.

- The medium wet climate scenario shows only minor effect on the groundwater table for the near future, 2041-2060, whereas for the far future scenario, 2081-2100, the average groundwater levels are estimated to rise more than 40-50 cm in some parts of the town.

7. References

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Annex 1. Risk maps

Annex 1 includes risk maps for high groundwater table for three periods, the present climate for the period 1996-2016, and medium wet climate scenario for the near future, 2041-2060, and for the far future, 2081-2100. Risk maps are shown for a 2-year event, a 10-year event, and for a 25-year event.

The annex includes the following nine figures:
Figure A-1 Depth to groundwater table for a 2-year event for the present situation (1996-2016).
Figure A-2 Depth to groundwater table for a 2-year event for the near future (2041-2060).
Figure A-3 Depth to groundwater table for a 2-year event for the far future (2081-2100).

Figure A-4 Depth to groundwater table for a 10-year event for the present situation (1996-2016).
Figure A-5 Depth to groundwater table for a 10-year event for the near future (2041-2060).
Figure A-6 Depth to groundwater table for a 10-year event for the far future (2081-2100).

Figure A-7 Depth to groundwater table for a 25-year event for the present situation (1996-2016).
Figure A-8 Depth to groundwater table for a 25-year event for the near future (2041-2060).
Figure A-9 Depth to groundwater table for a 25-year event for the far future (2081-2100).

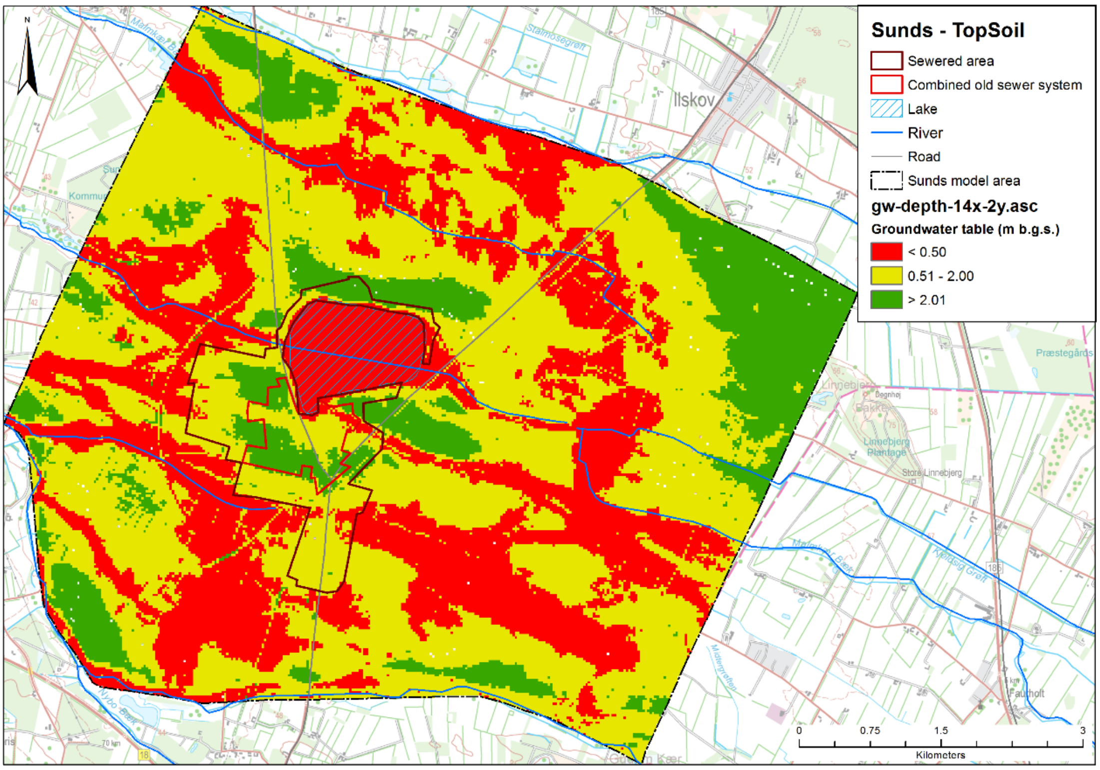

Figure A-1 Depth to groundwater table for a 2-year event for the present situation (1996-2016).

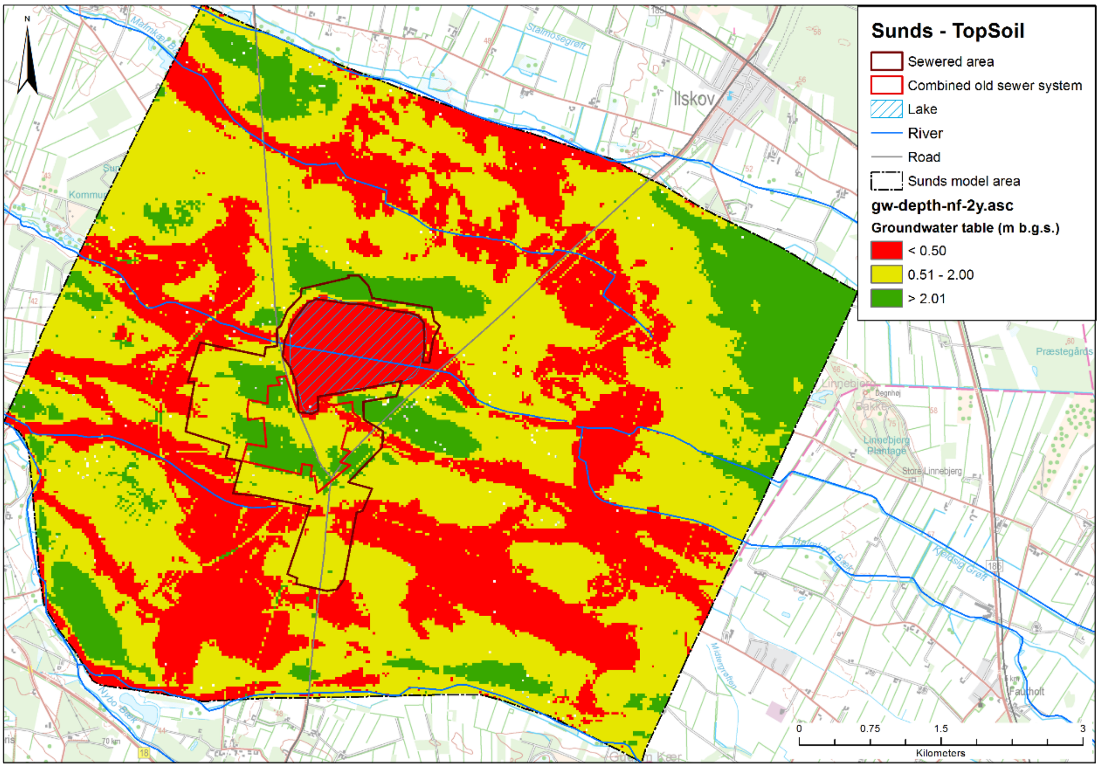

Figure A-2 Depth to groundwater table for a 2-year event for the near future (2041-2060).

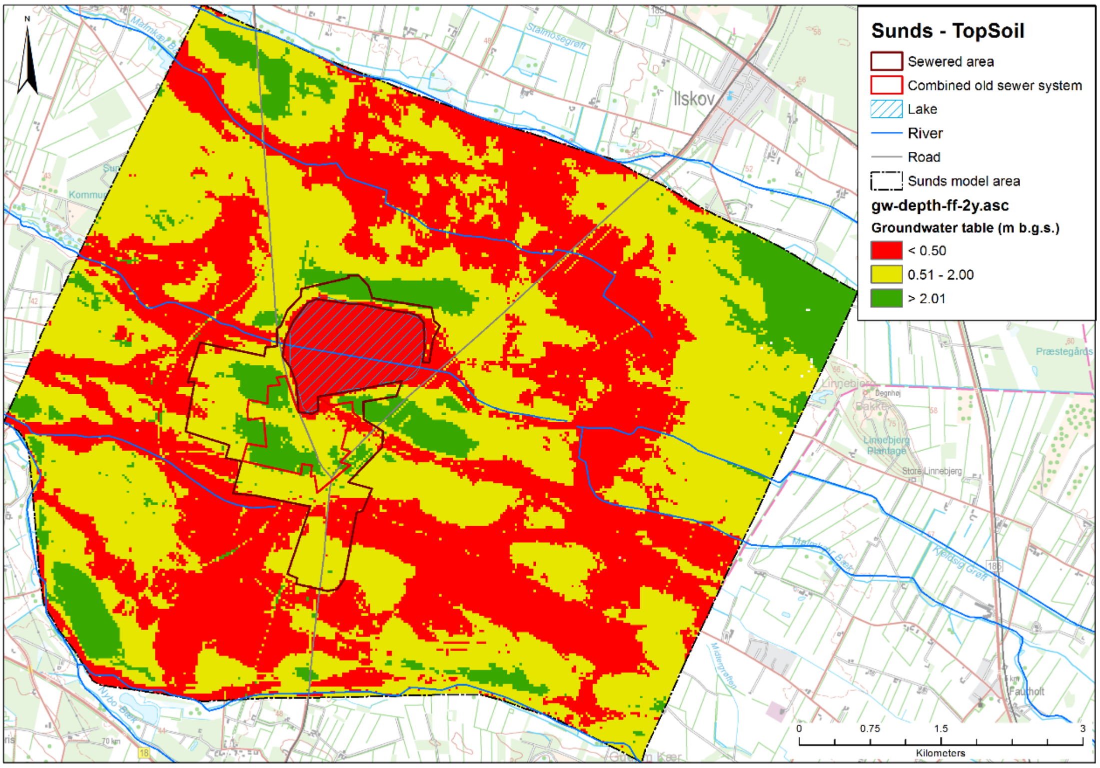

Figure A-3 Depth to groundwater table for a 2-year event for the far future (2081-2100).

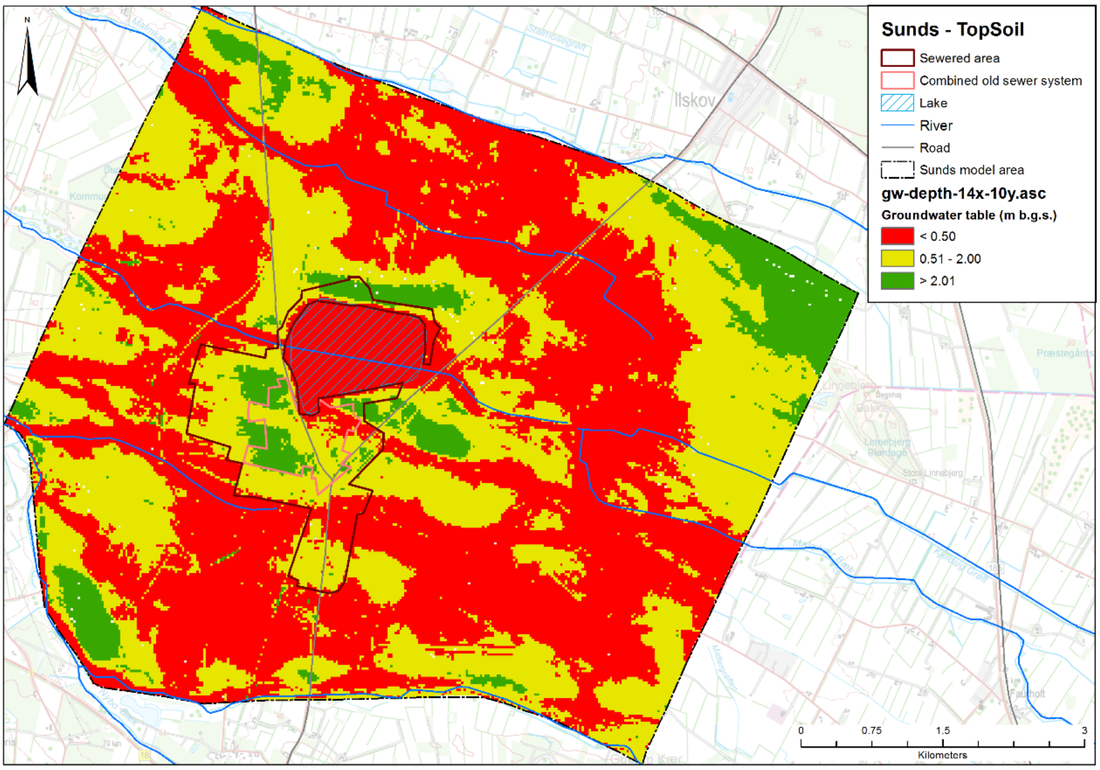

Figure A-4 Depth to groundwater table for a 10-year event for the present situation (1996-2016).

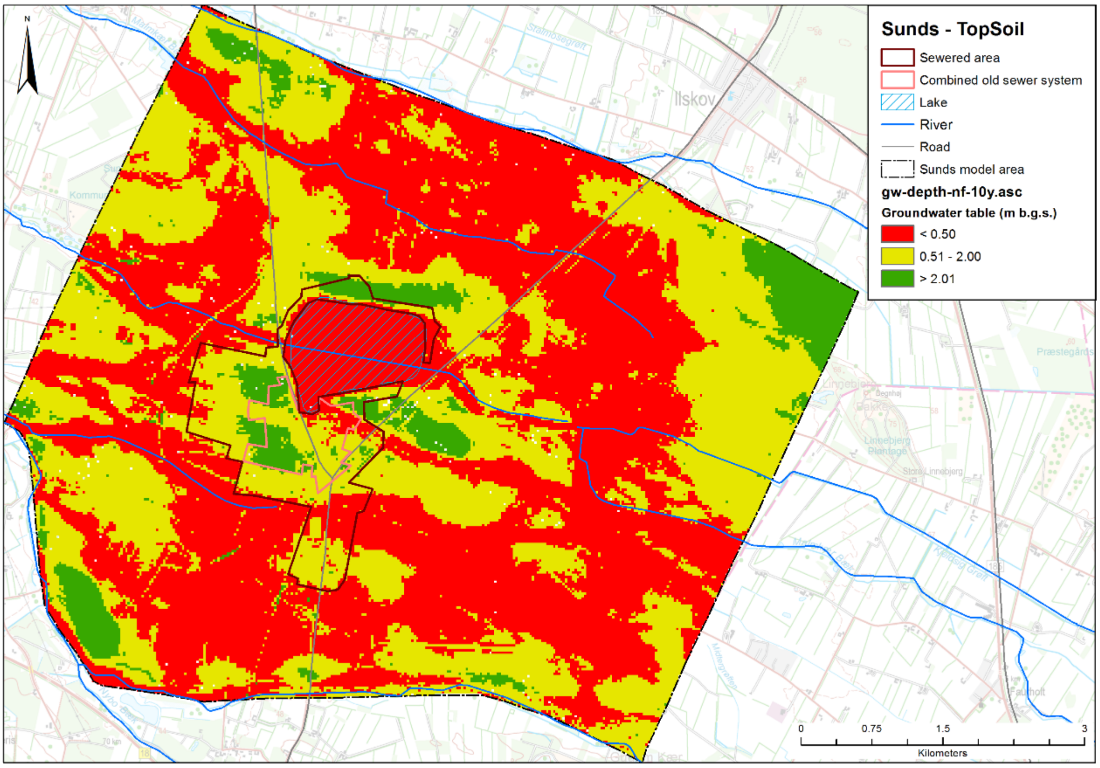

Figure A-5 Depth to groundwater table for a 10-year event for the near future (2041-2060).

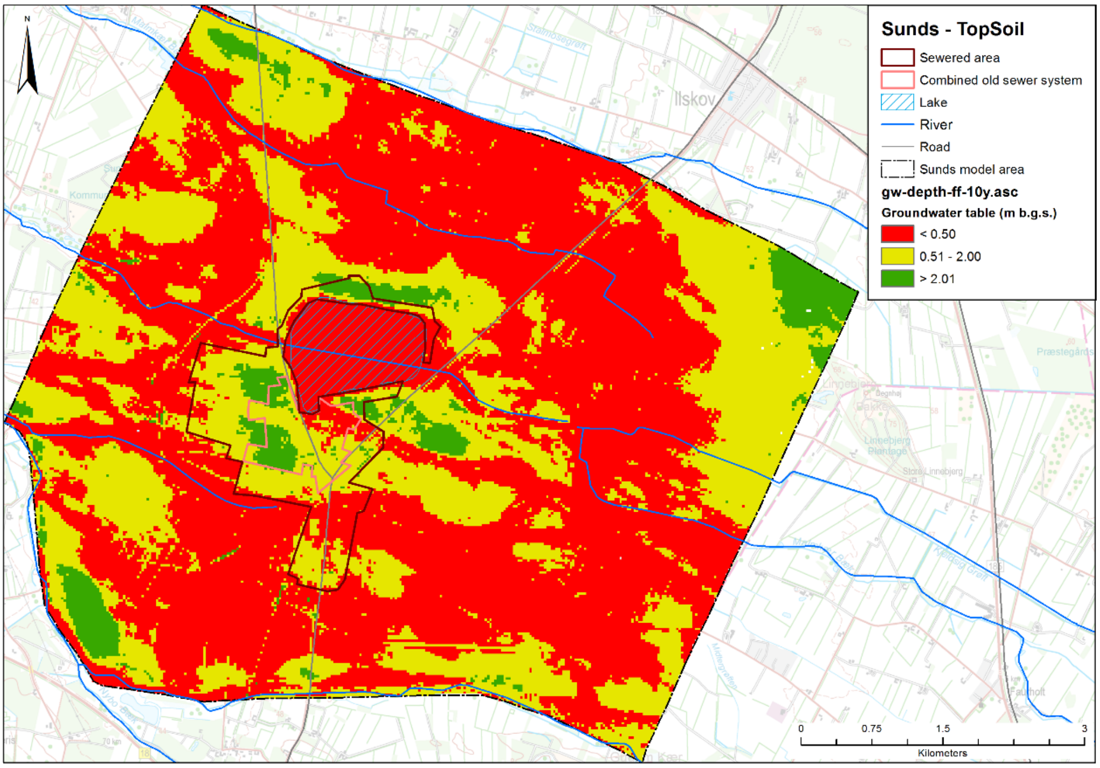

Figure A-6 Depth to groundwater table for a 10-year event for the far future (2081-2100).

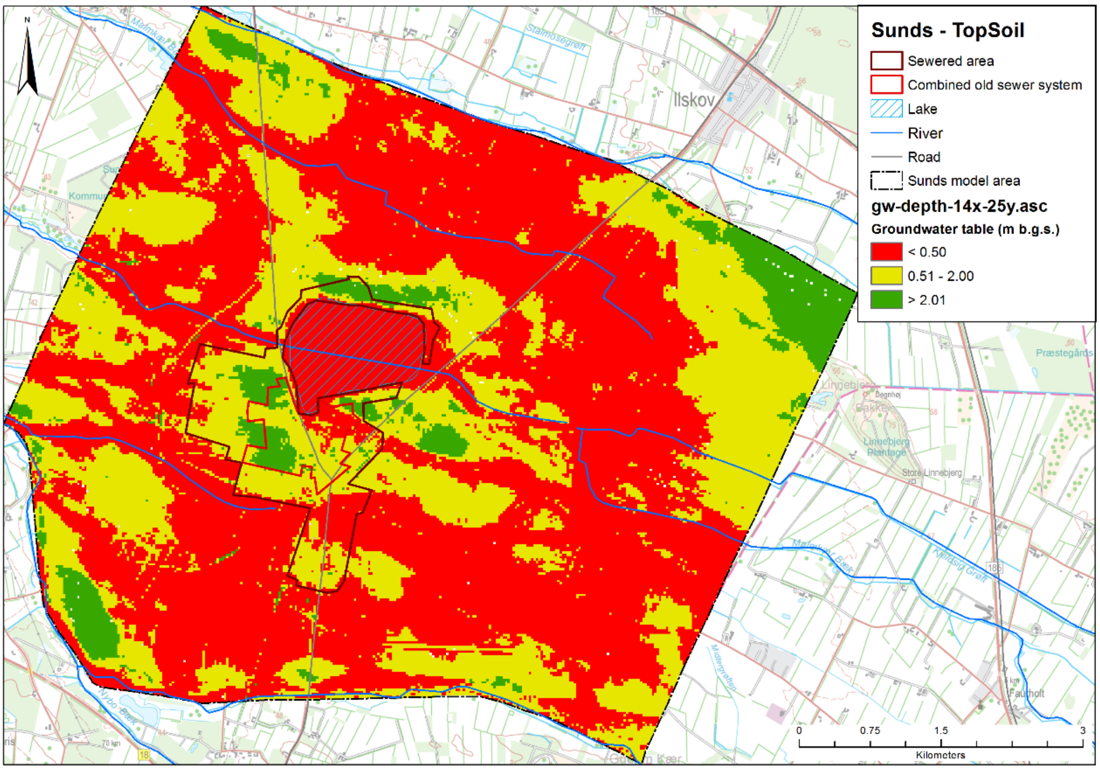

Figure A-7 Depth to groundwater table for a 25-year event for the present situation (1996-2016).

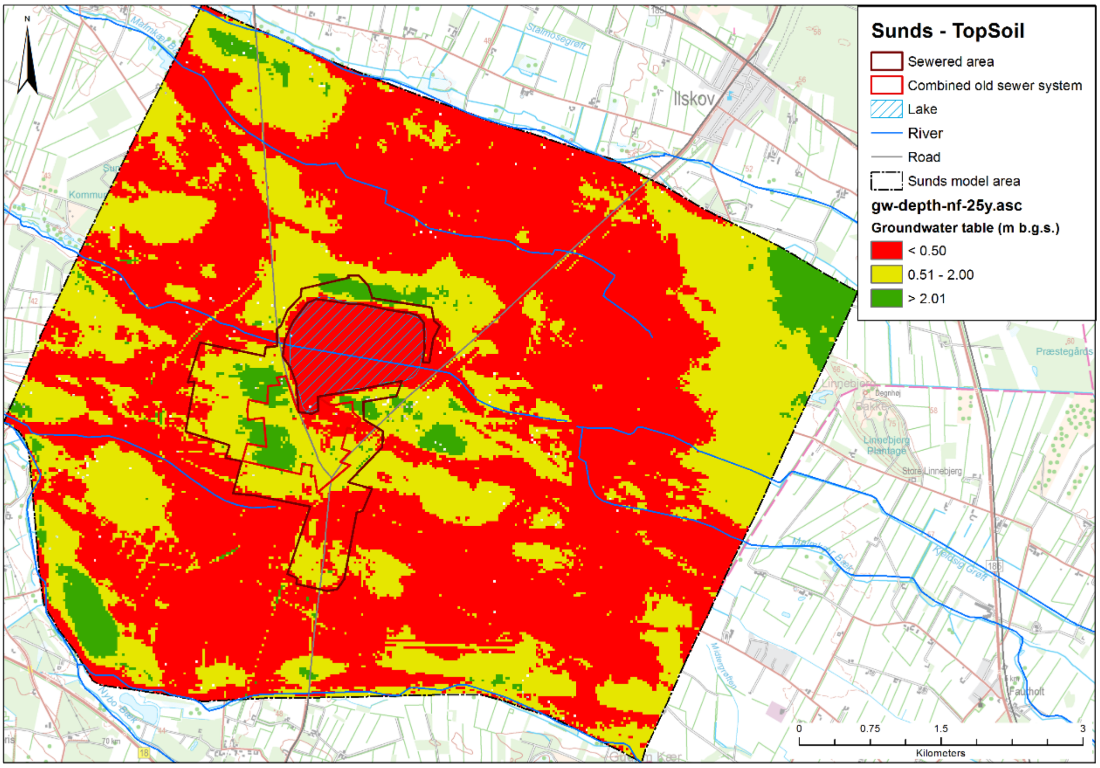

Figure A-8 Depth to groundwater table for a 25-year event for the near future (2041-2060).

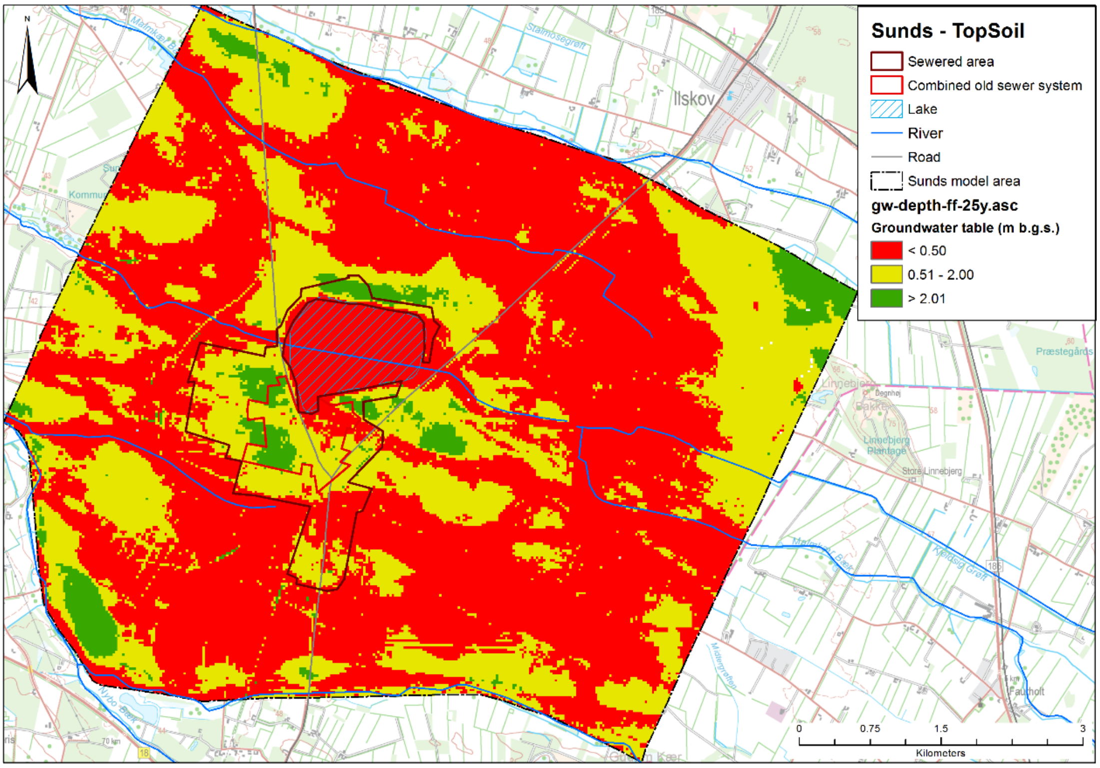

Figure A-9 Depth to groundwater table for a 25-year event for the far future (2081-2100).

Annex 2. Note - Risk of basement flooding in Sunds

Note: Risk of basement floodings in Sunds

Different measures to reduce high groundwater levels have been analysed with the hydrological model. Here we look at how the four most effective measures to lower the groundwater level could change the risk of basements getting flooded by high groundwater levels in different parts of the town of Sunds.

The four measures are:
a) Installation of a third pipe, a drain along the sewer pipes
b) Plantation of coniferous forest around the town
c) Lowering the water level in Sunds Lake
d) Groundwater abstaction during winter from five wells located in the central part of Sunds

The analyses are based on the assumption that the basement floor of each building polygon is 1.5 meter below the terrain surface. Each building polygon was assigned one value for the terrain elevation - the value at the center point.

The risk of groundwater flooding of the individual basement is calculated as the difference between the elevation of the basement floor and the estimated groundwater level of the actual measure. The following definitions of high and low risk are:

- The difference is < 0: **High risk** of groundwater in basements
- The difference is > 0: **Low risk** of groundwater in basements

The median groundwater levels and the 95% fractile of groundwater levels (high groundwater levels) estimated by the hydrological model are used for the calculations of the effect of the different measures.

Table 1, Figure 1 and 2 show the reduction in the number of houses at high risk of groundwater flooding of basements for the four different measures compared to the groundwater level situation after renovation of the old sewer pipes. For comparison, the groundwater levels estimated for a future wet climate scenario are shown for the period 2080-2100.

Table 1. Relative reduction in number of houses at high risk of groundwater flooding of basements for four different measures

Measure	Average groundwater level (%)	High groundwater level, 95% fractile (%)
a) The third pipe (drain)	39	19
b) Plantation of forest	3	0
c) Lowering water level in Lake	2	3
d) Groundwater abstraction	5	1
Wet climate prediction 2080-2100	-3	-15

Table 1, Figure 1 and 2 show that the most effective measure is the installation of the third pipe.

The overall limited effect of groundwater abstraction from shallow wells is most likely due to a relatively low pumping rate (10,000 m^3/year/well) and the small of pumping wells covering only a minor area of the town.

The groundwater levels estimated for a future wet climate scenario show, for the situation of high groundwater levels, a 15% increase in the number of houses a high risk of groundwater flooding of basements.

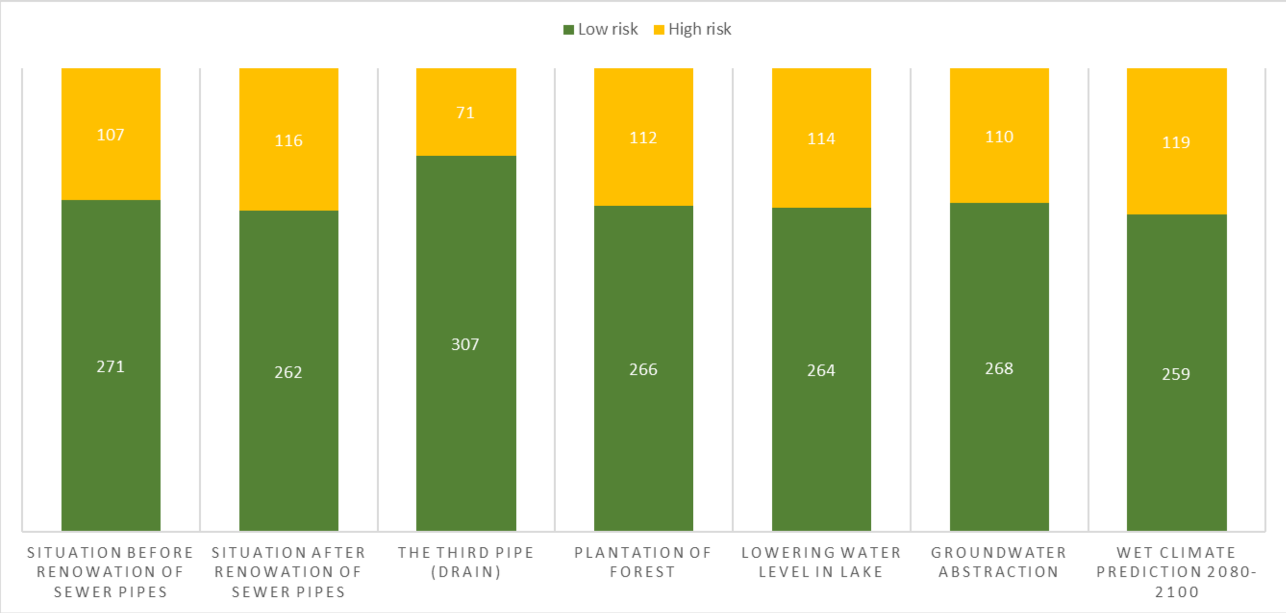

Figure 1 Number of houses at low risk (green) and high risk (yellow) of groundwater flooding of basements for the situation after renovation of sewer pipes and for the four different measures, ***for average groundwater level***

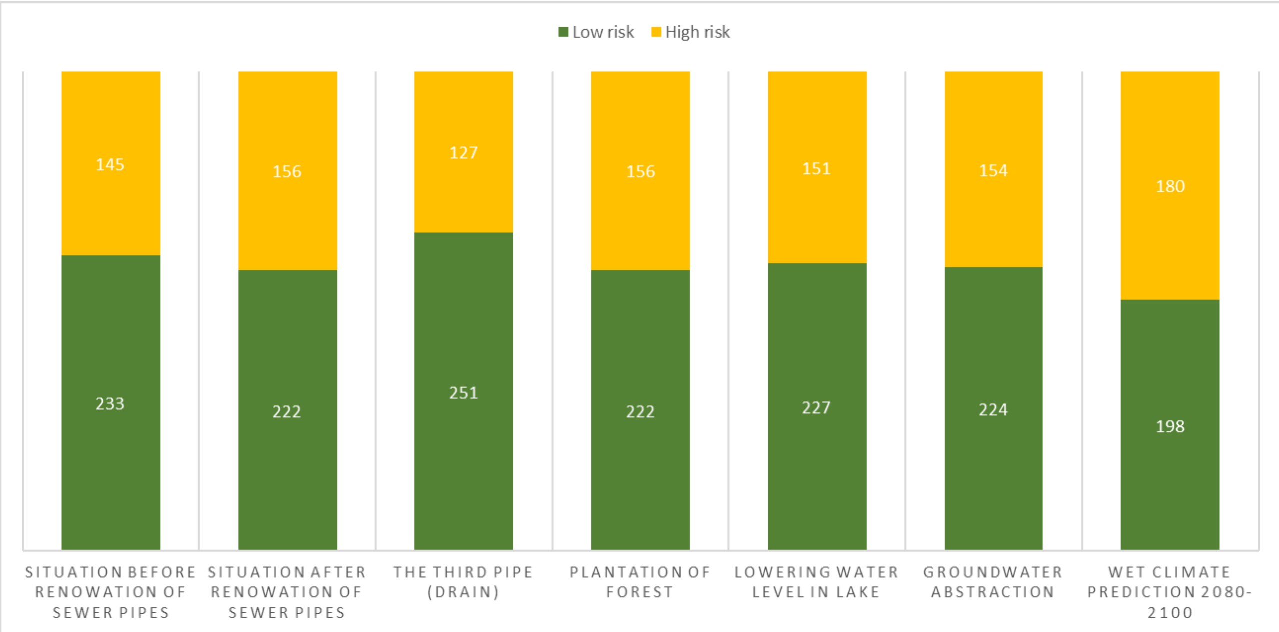

Figure 2 Number of houses at low risk (green) and high risk (yellow) of groundwater flooding of basements for the situation after renovation of sewer pipes and for the for different measures, ***for the situation of high groundwater level*** *(95% fractile)*

Figures 3 and 4 show buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) before renovation of old sewer pipes. Compared with Figures 5 and 6 an increase in the number of buildings at risk of groundwater flooding of basements is seen in the southwest of the town center for the situation after renovation of sewer pipes.

Lowering the water table in Sunds Lake to a constant summer level is seen to have very limited effect on the number of houses that will experience a lower risk of basement flooding. Only at the north shore of the lake a few houses can expect a change from high to low risk of basement flooding (Figures 5 and 6).

The effect of drainage pipes, the third pipe, installed along the existing sewer pipes have a much larger effect on reducing the risk of basement flooding in the central part of Sunds (Figures 7 and 8).

The effect of planting coniferous forest around the town of Sunds is mainly seen in the south eastern part of Sunds (Figures 9 and 10).

Lowering the water level in Sunds Lake to the mean summer water level is effecting a few houses located near the lake shore (Figures 11 and 12).

The effect of pumping groundwater from five wells in the winter period have some effect on reducing the risk of basement flooding in the central area of Sunds, where the wells have been placed in the hydrological model (Figures 13 and 14). Figure 25 shows time series of groundwater levels from a monitoring point located between two abstraction wells. With the applied total abstraction rate of 10,000 m^3/year/well a maximum lowering of the groundwater table of 10 - 20 cm is seen while the effect at the end of summer is almost negligible.

Figure 15 and 16 show groundwater levels estimated for a future wet climate scenario for the period 2080-2100. Areas in the southern central part of Sunds seems to be new areas with high risk of basement flooding.

Figures 17 to 24 show the groundwater depth below basement floor for average and high groundwater level conditions for the four scenarios:

- after renovation of old sewer pipes
- installation of a third pipe
- pumping groundwater from five wells in the winter period
- wet climate prediction 2080-2100

Red and orange colors indicate areas with groundwater levels above basement floor, and green and blue colores indicate groundwater levels below basement floor.

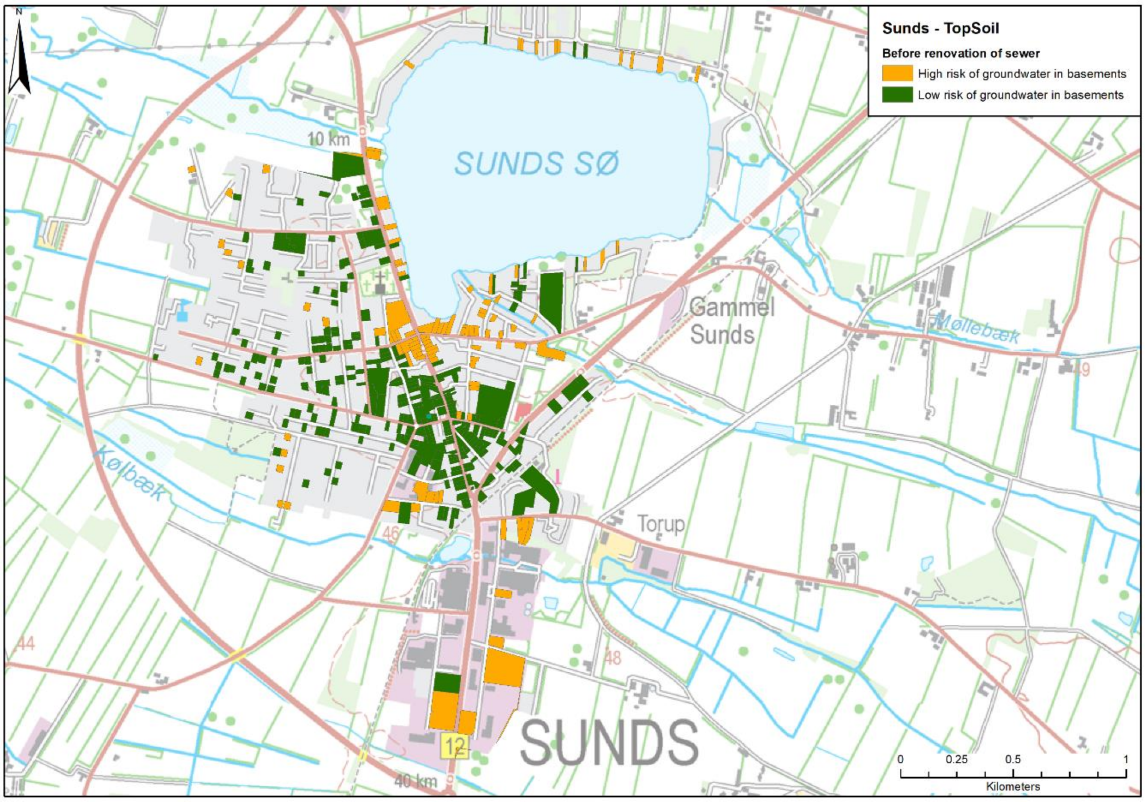

Figure 3 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) ***before renovation*** *of old sewer pipes,* ***average situation***

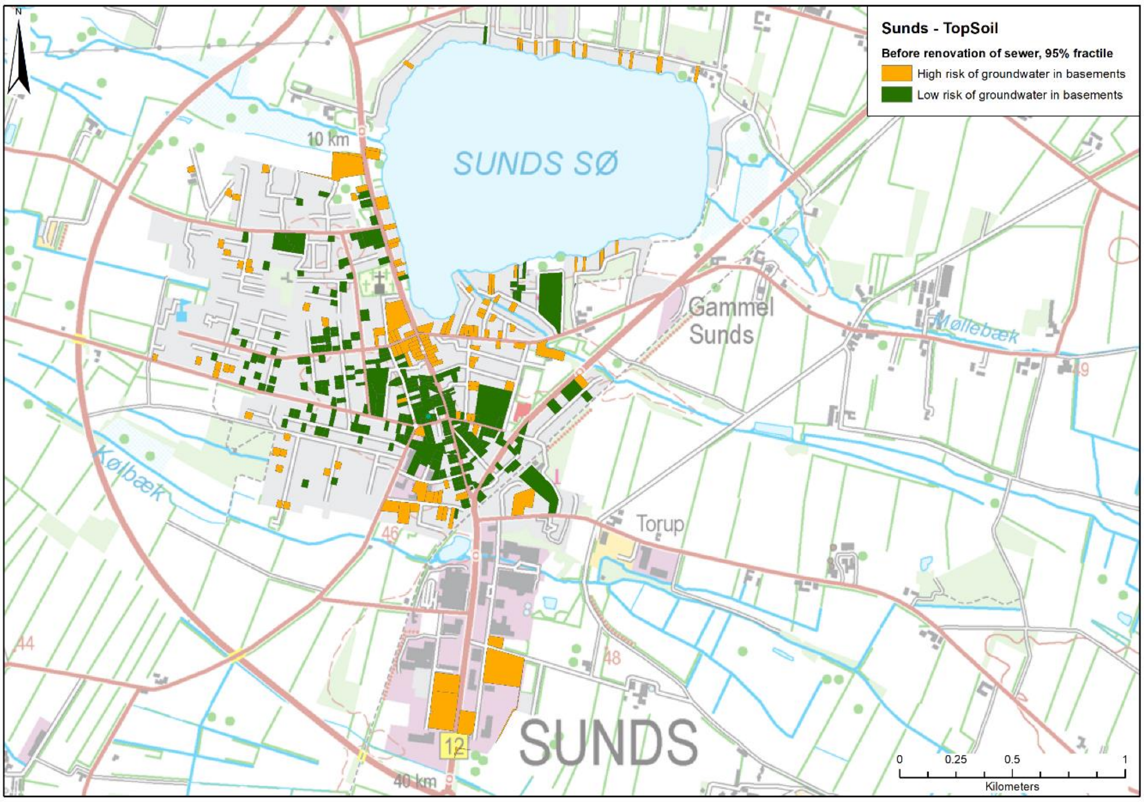

Figure 4 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) ***before renovation*** *of old sewer pipes,* ***situation with high groundwater level***

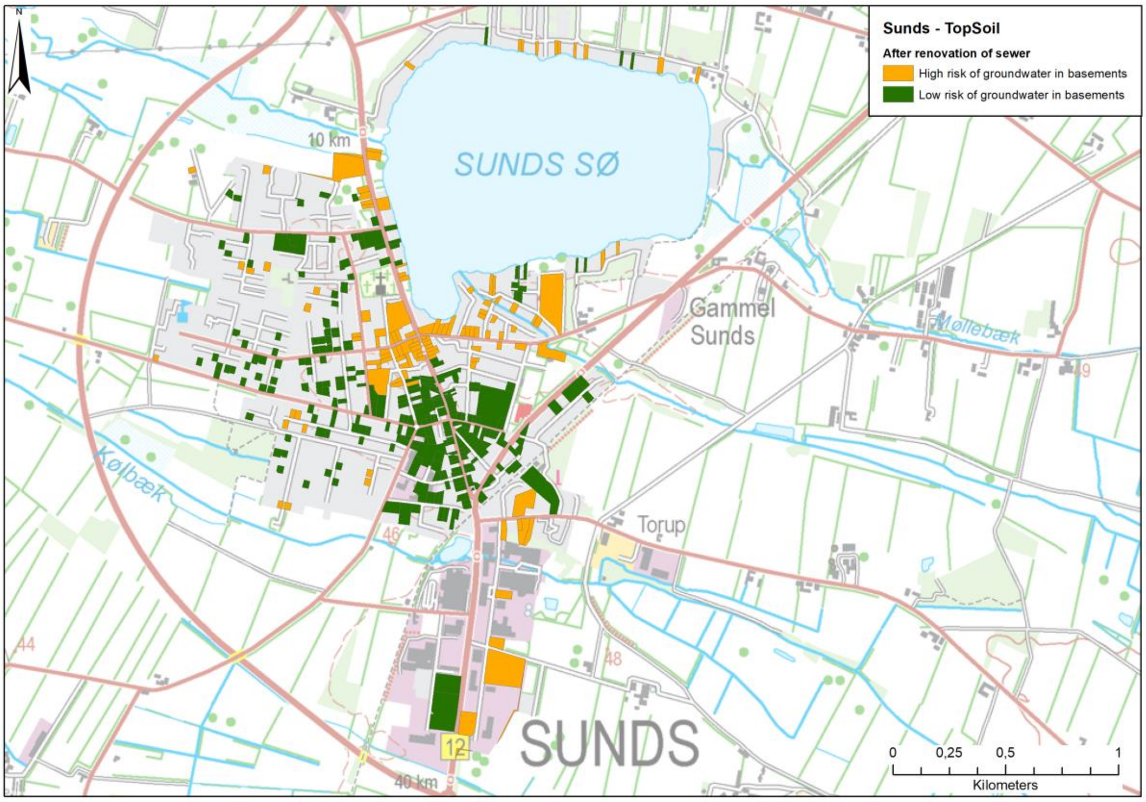

Figure 5 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) ***after renovation*** *of old sewer pipes,* ***average situation***

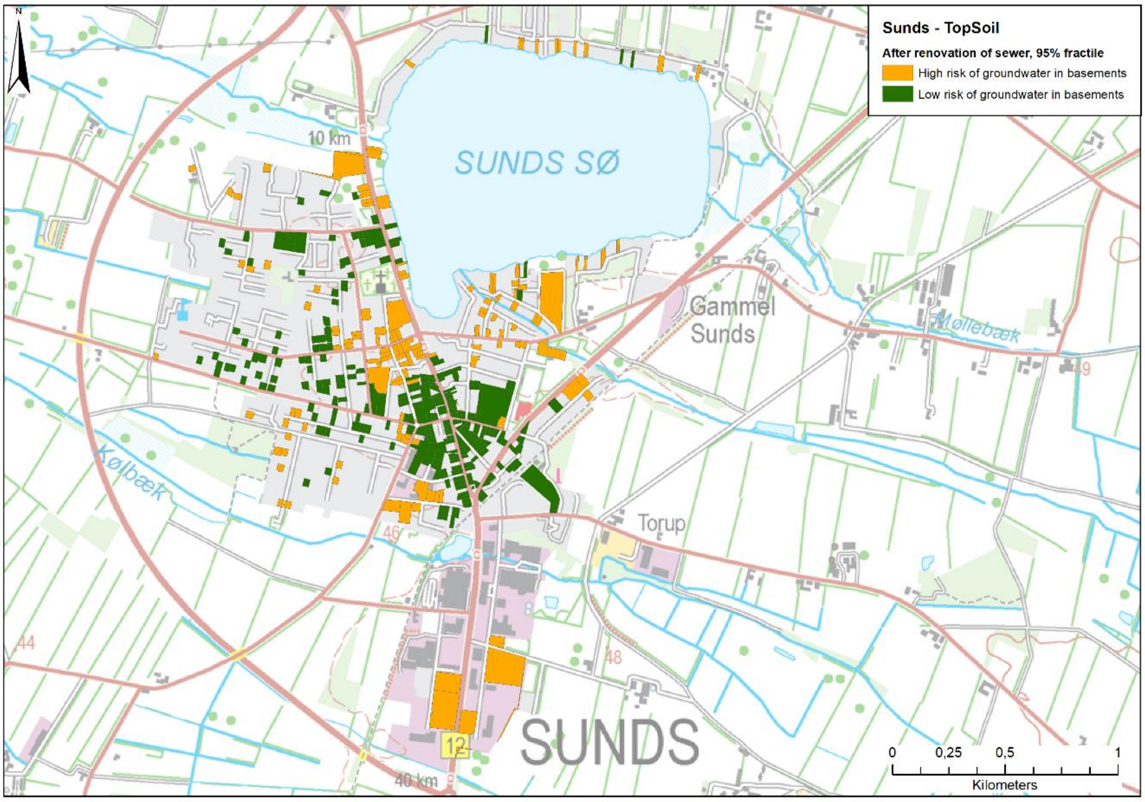

Figure 6 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) ***after renovation*** *of old sewer pipes,* ***situation with high groundwater level***

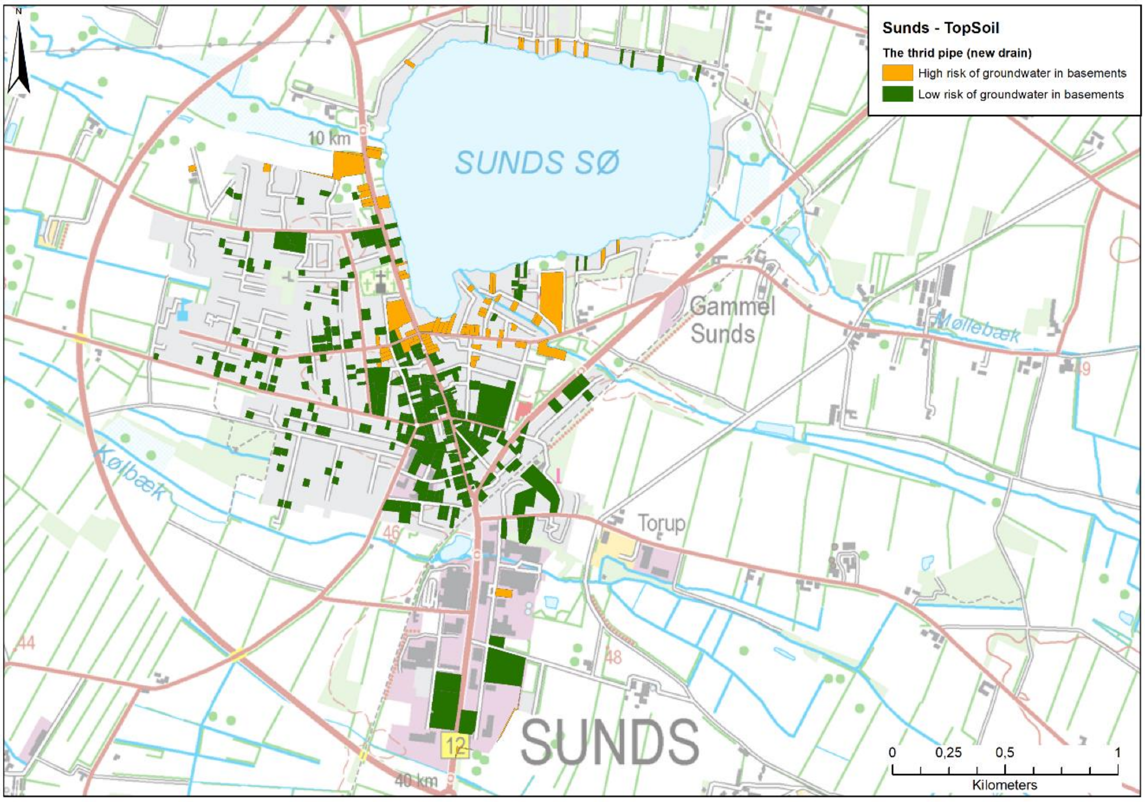

*Figure 7 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if a drainage pipe, **the third pipe**, is installed along the existing sewer pipes, **average situation***

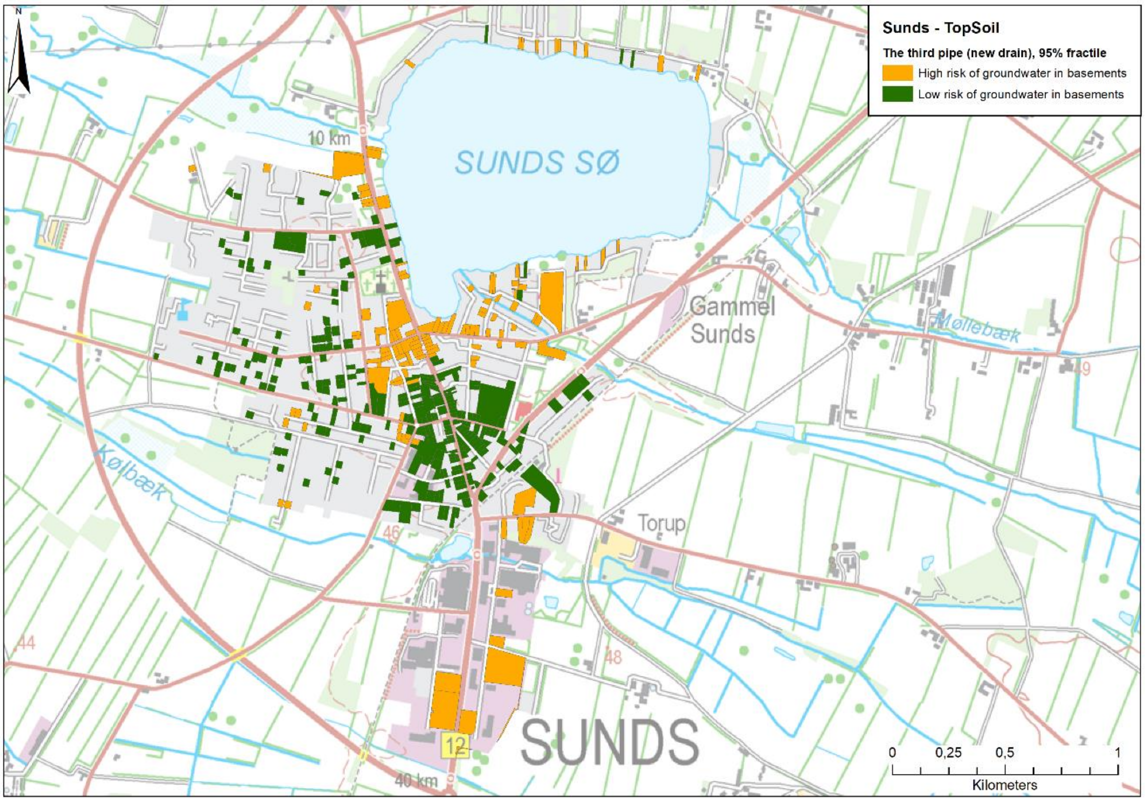

*Figure 8 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if a drainage pipe, **the third pipe**, is installed along the existing sewer pipes, **situation with high groundwater level***

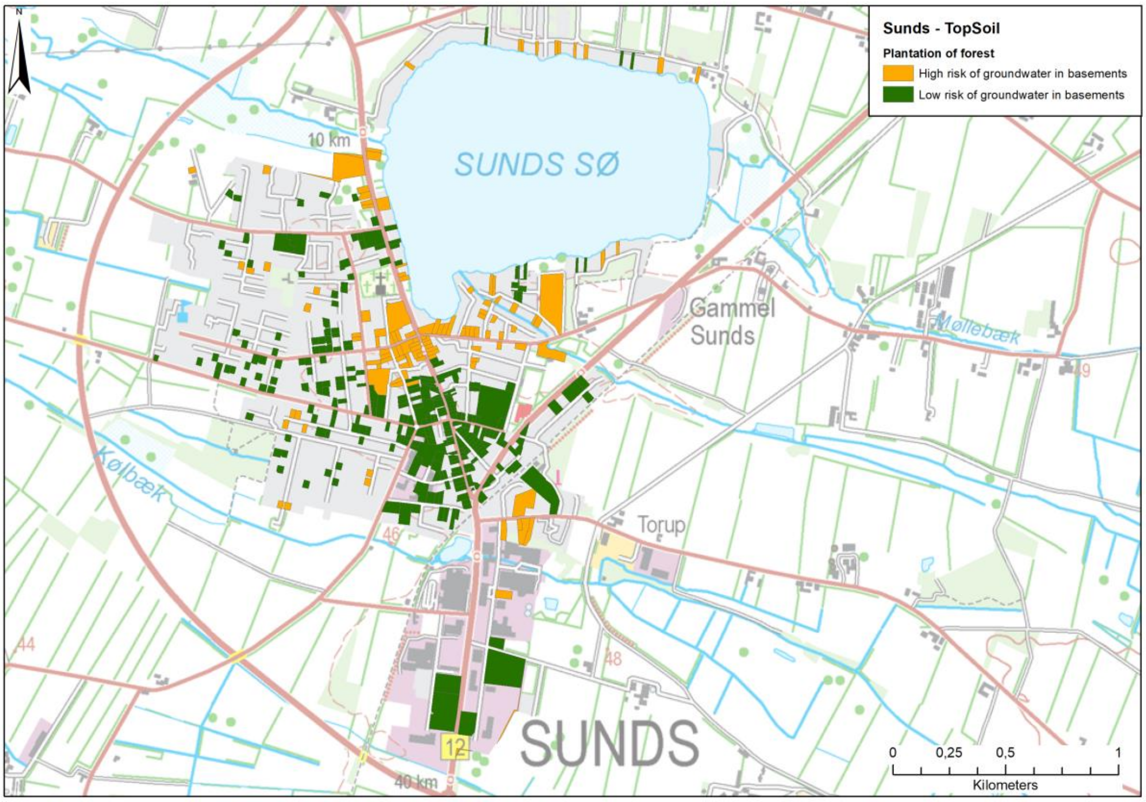

*Figure 9 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if **planting coniferous forest** around the town of Sunds, **average situation***

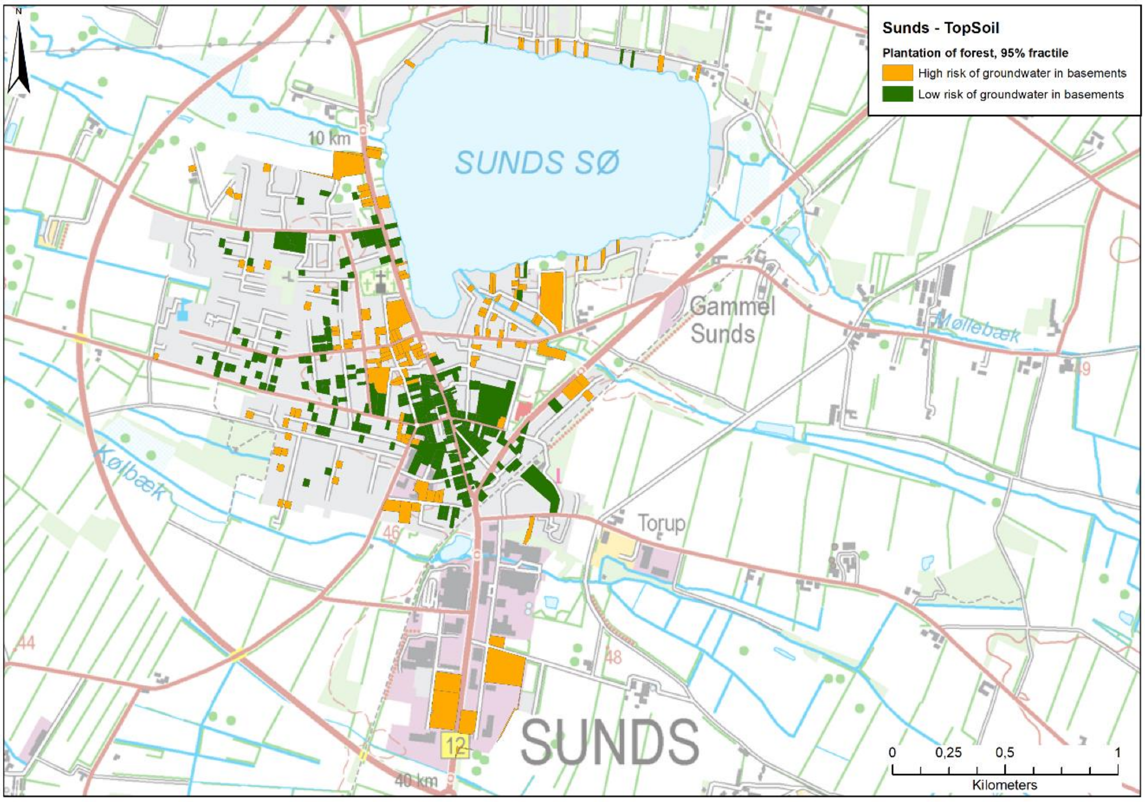

*Figure 10 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if **planting coniferous forest** around the town of Sunds, **situation with high groundwater level***

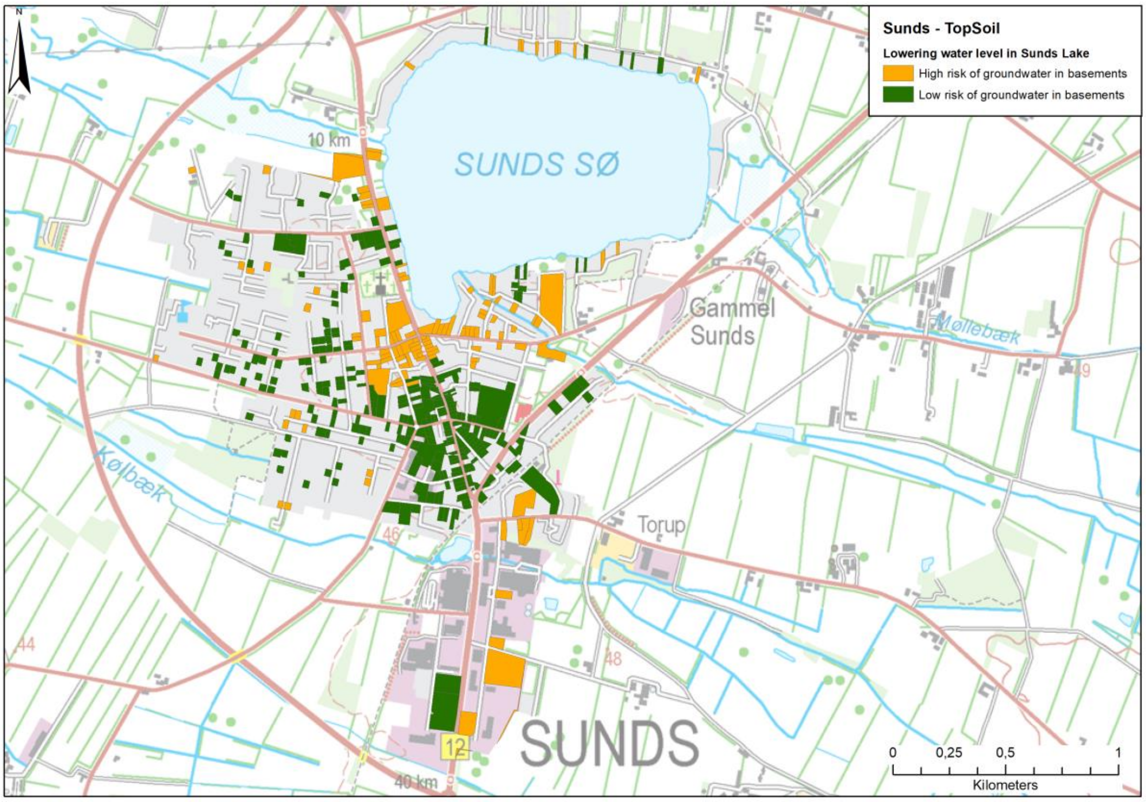

Figure 11 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if ***lowering the water level in Sunds Lake*** *to the mean summer water level,* ***average situation***

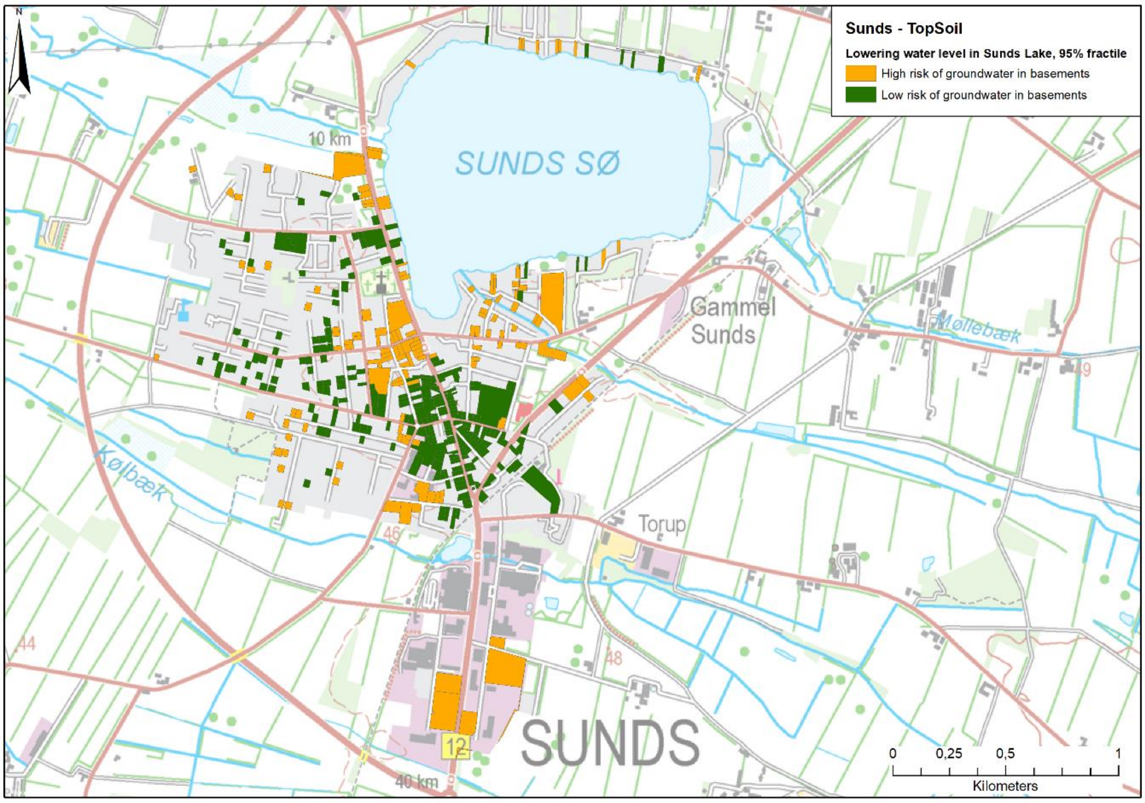

Figure 12 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if ***lowering the water level in Sunds Lake*** *to the mean summer water level,* ***situation with high groundwater level***

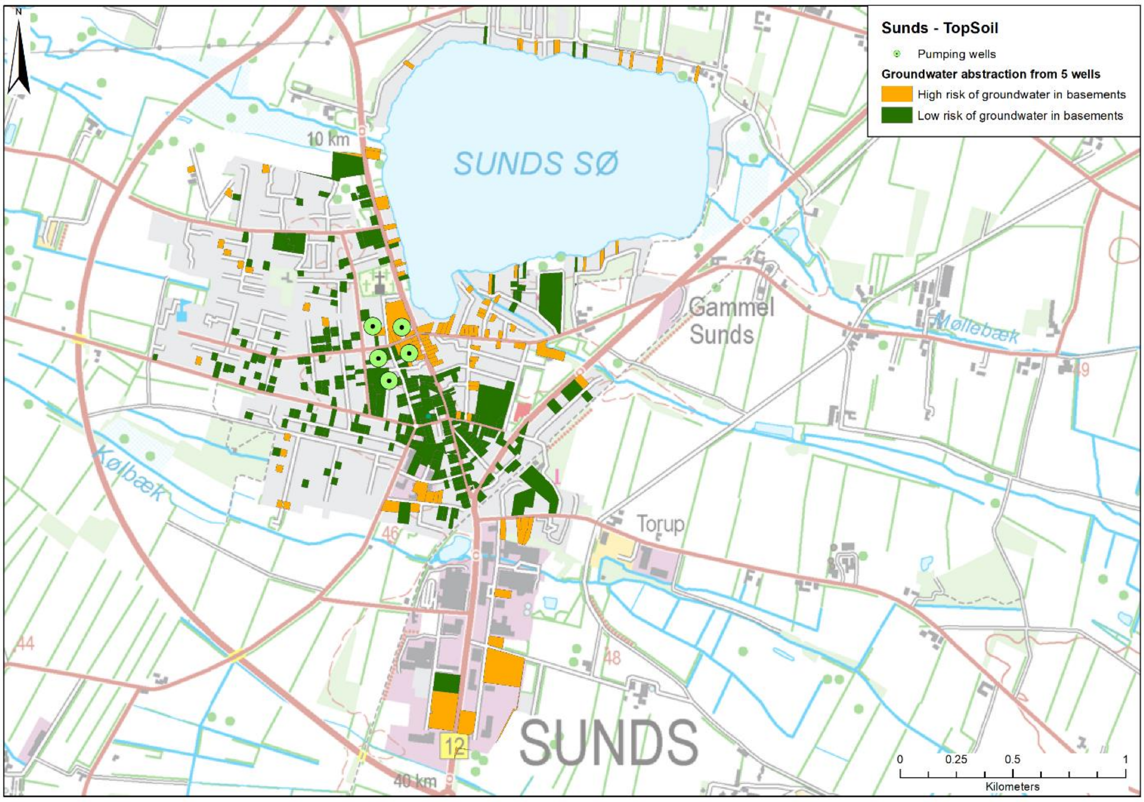

Figure 13 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if ***pumping groundwater from five wells*** *in the winter period,* ***average situation***

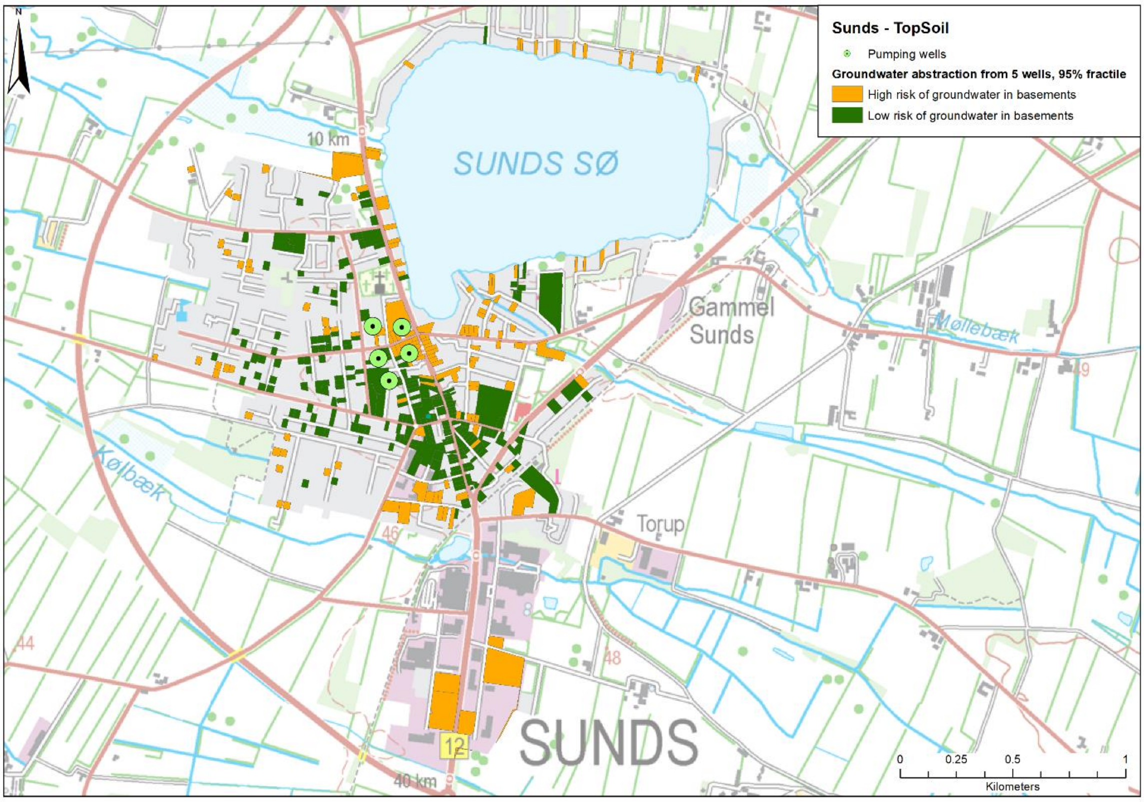

Figure 14 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if ***pumping groundwater from five wells*** *in the winter period,* ***situation with high groundwater level***

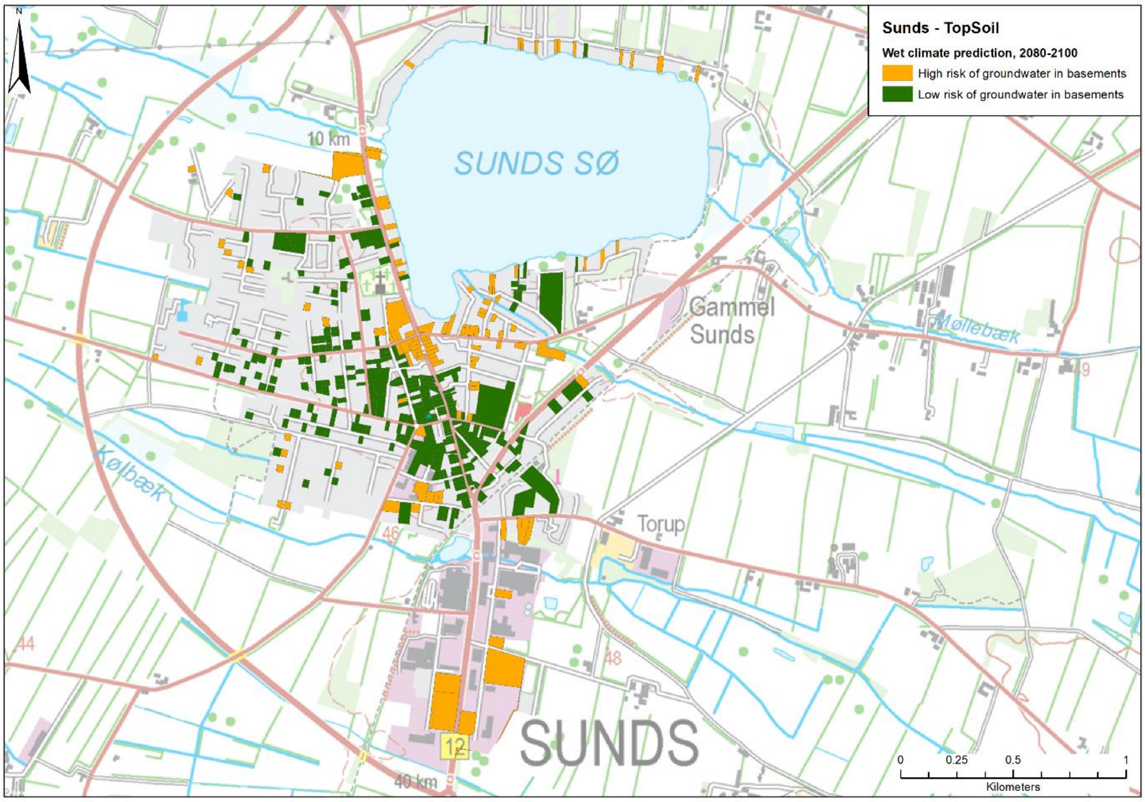

Figure 15 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if for a ***wet climate prediction 2080-2100, average situation***

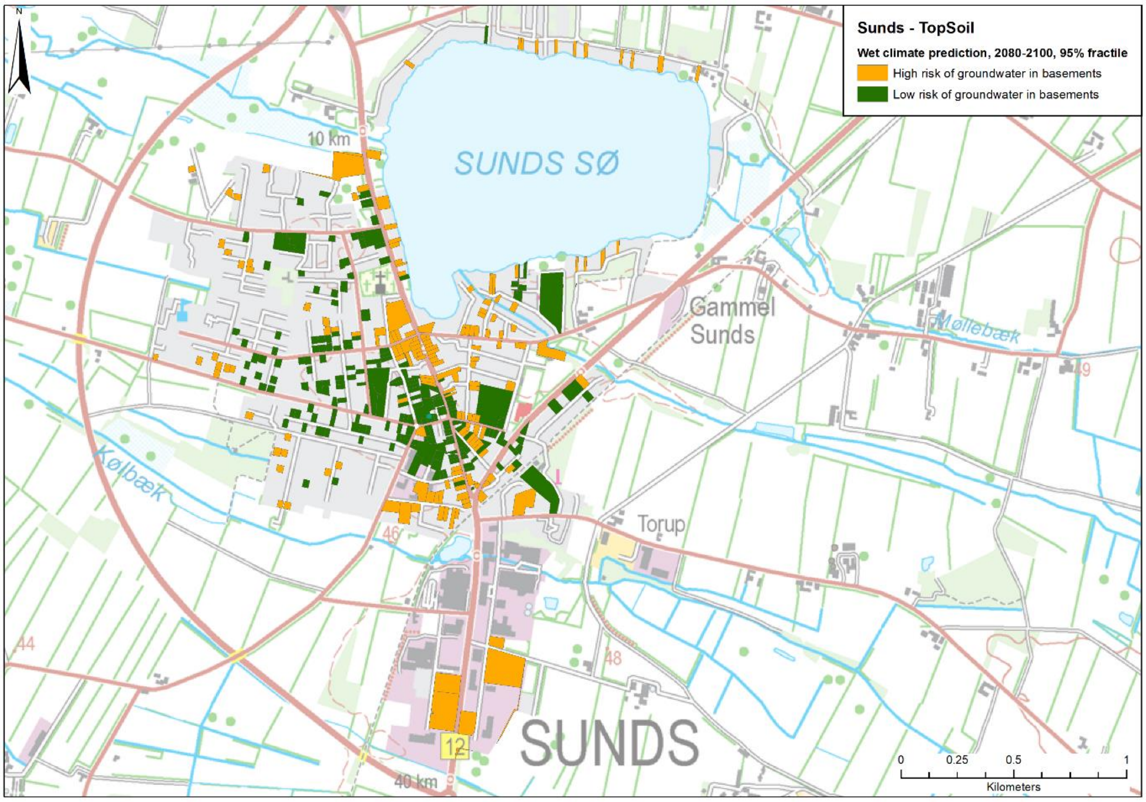

Figure 16 Buildings with high risk of groundwater flooding of basements (yellow) and buildings with low risk of groundwater flooding of basements (green) if for a ***wet climate prediction 2080-2100, situation with high groundwater level***

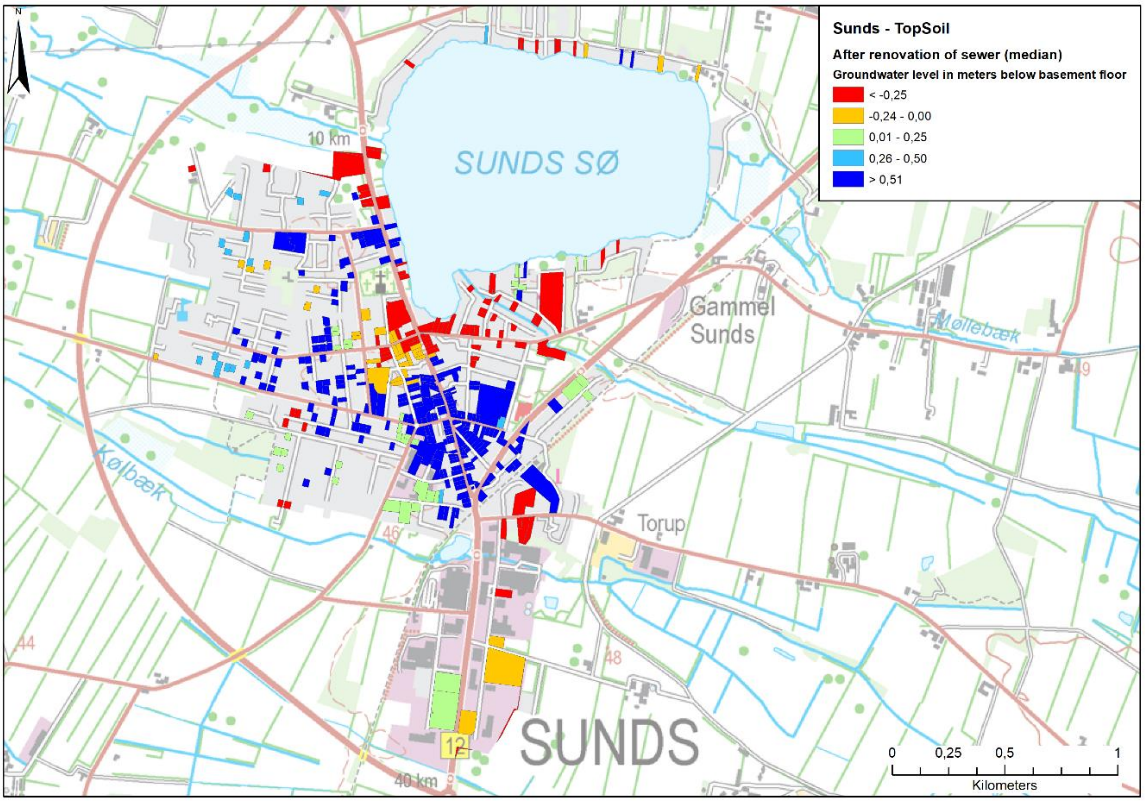

*Figure 17 Average groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding **after renovation of old sewer pipes**. Minus '-' indicates average groundwater level above basement floor, **average situation***

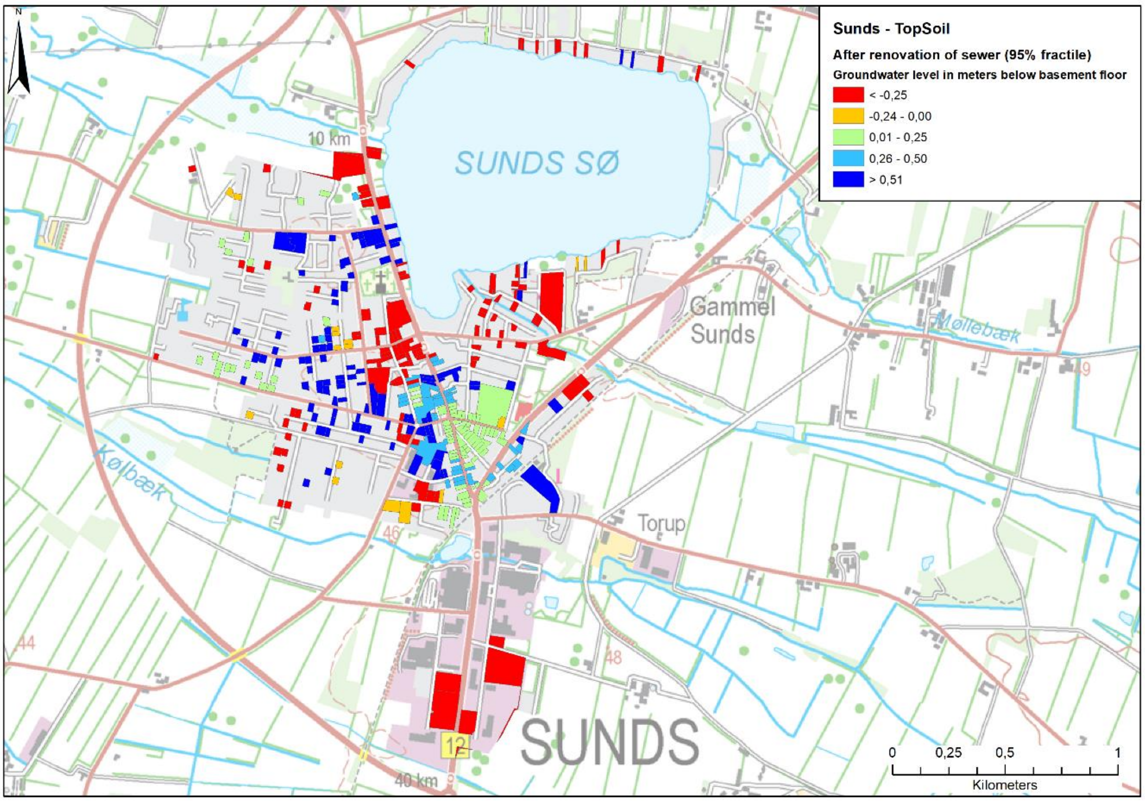

*Figure 18 Groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding **after renovation of old sewer pipes**. Minus '-' indicates average groundwater level above basement floor, **situation with high groundwater level***

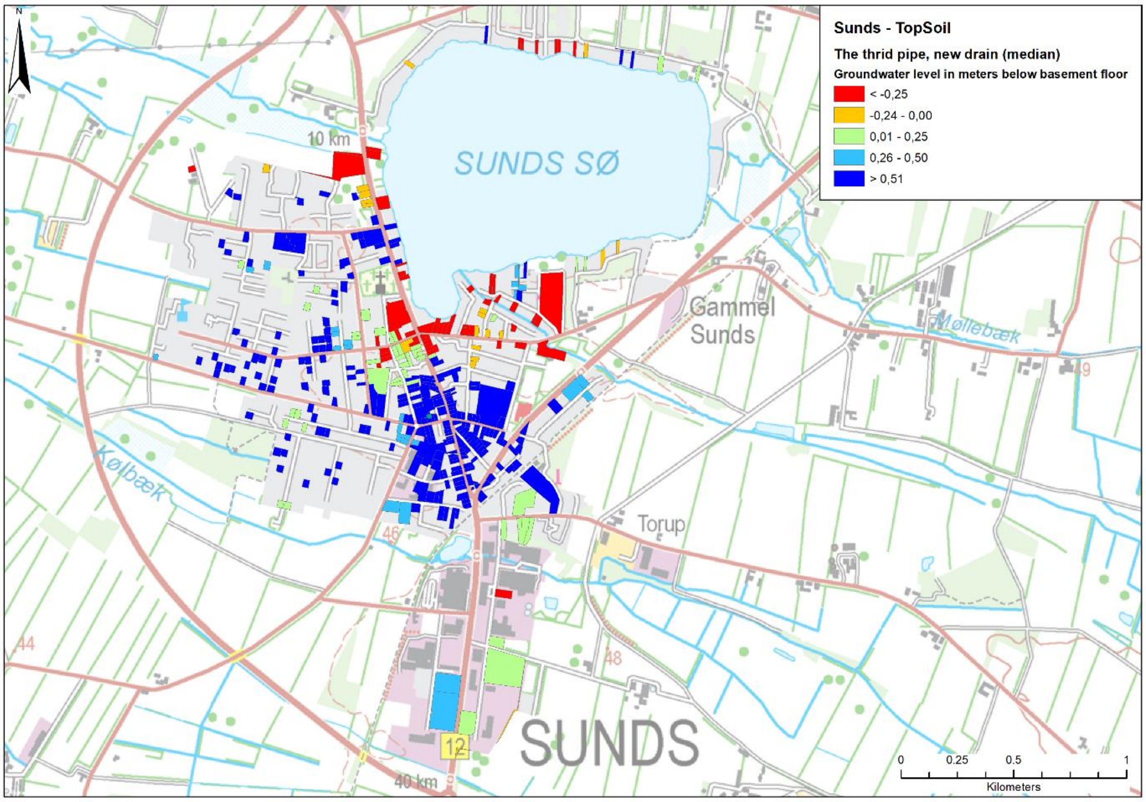

*Figure 19 Average groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding after **installation of a third pipe**. Minus '-' indicates average groundwater level above basement floor, **average situation***

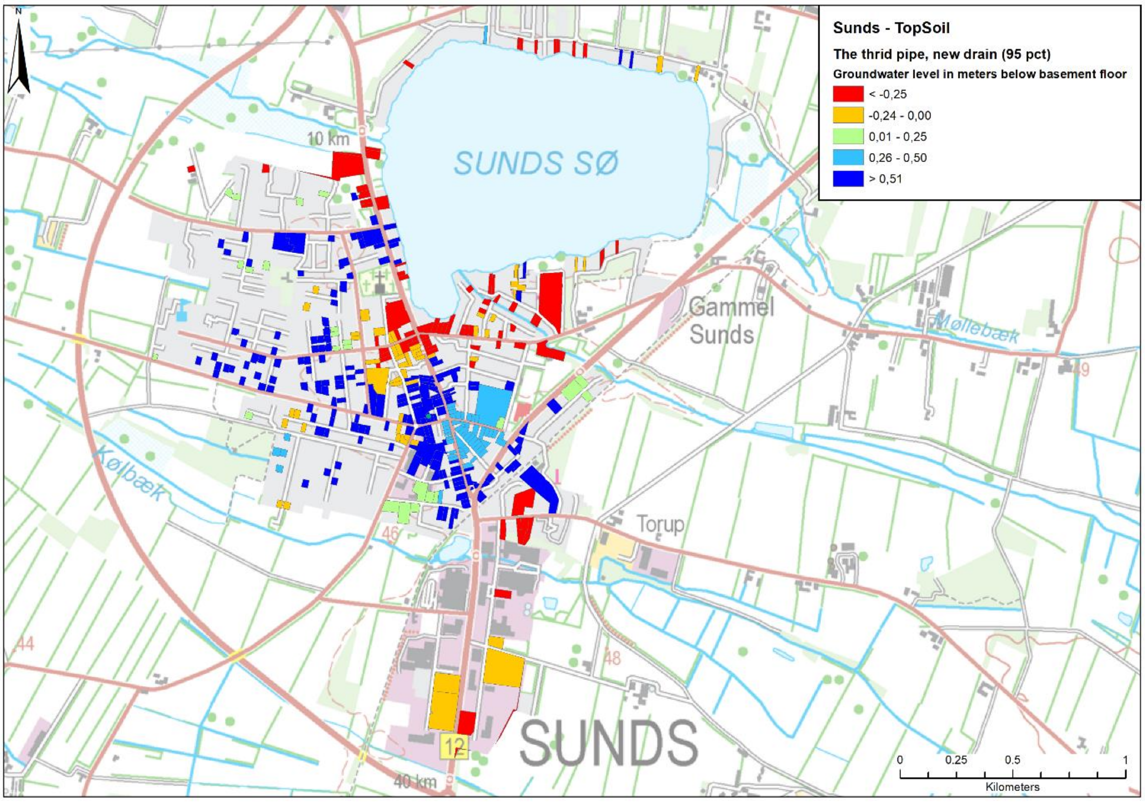

*Figure 20 Groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding after **installation of a third pipe**. Minus '-' indicates average groundwater level above basement floor, **situation with high groundwater level***

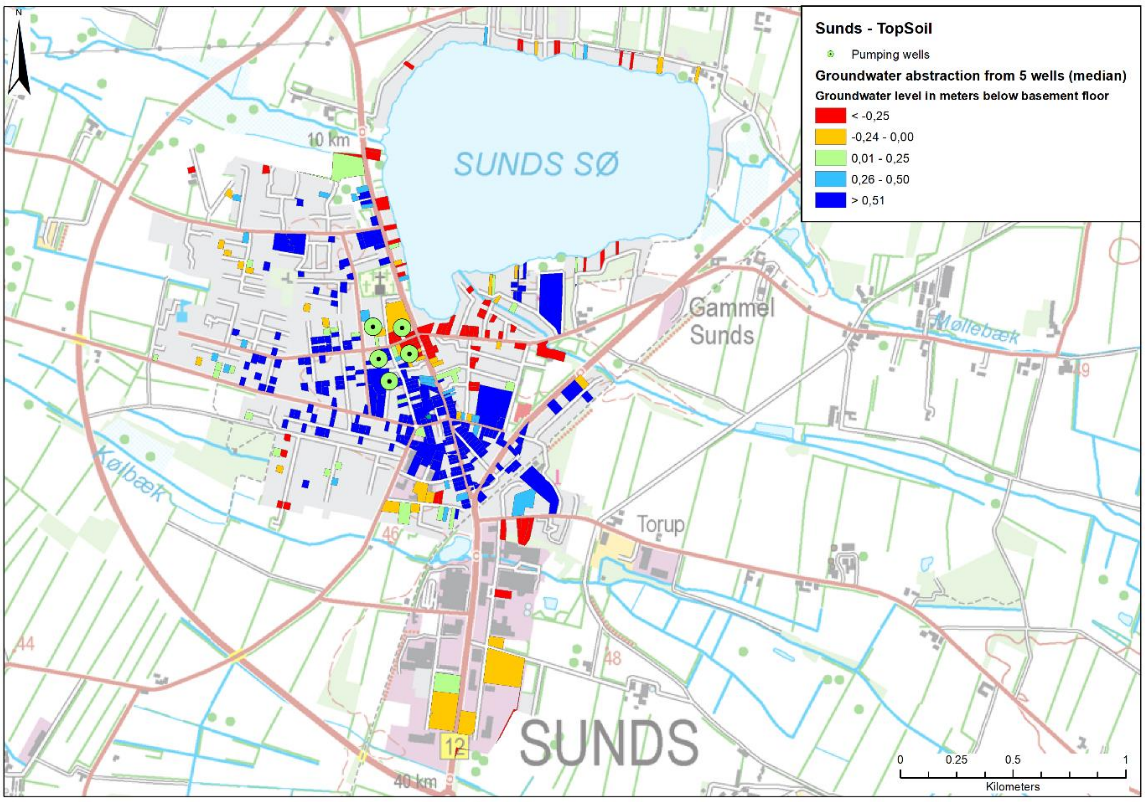

Figure 21 Average groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding after ***installation of five pumping wells****. Minus '-' indicates average groundwater level above basement floor,* ***average situation***

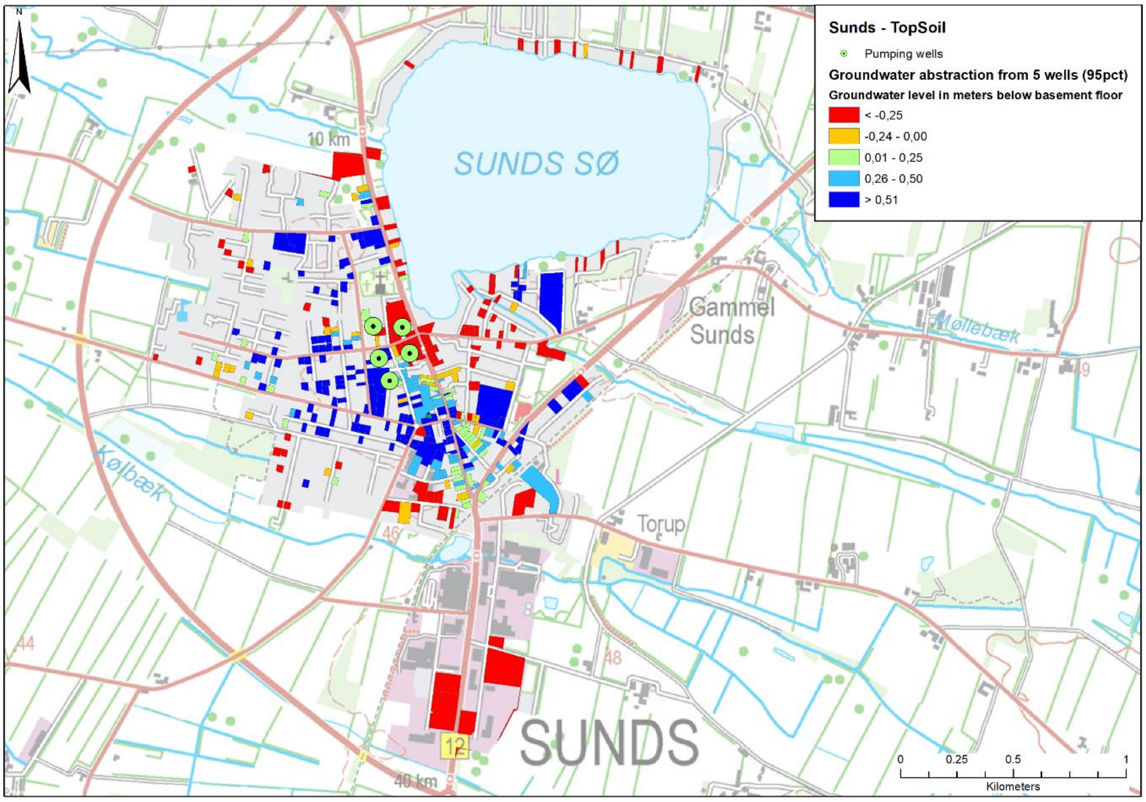

Figure 22 Groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding after ***installation of five pumping wells****. Minus '-' indicates average groundwater level above basement floor,* ***situation with high groundwater level***

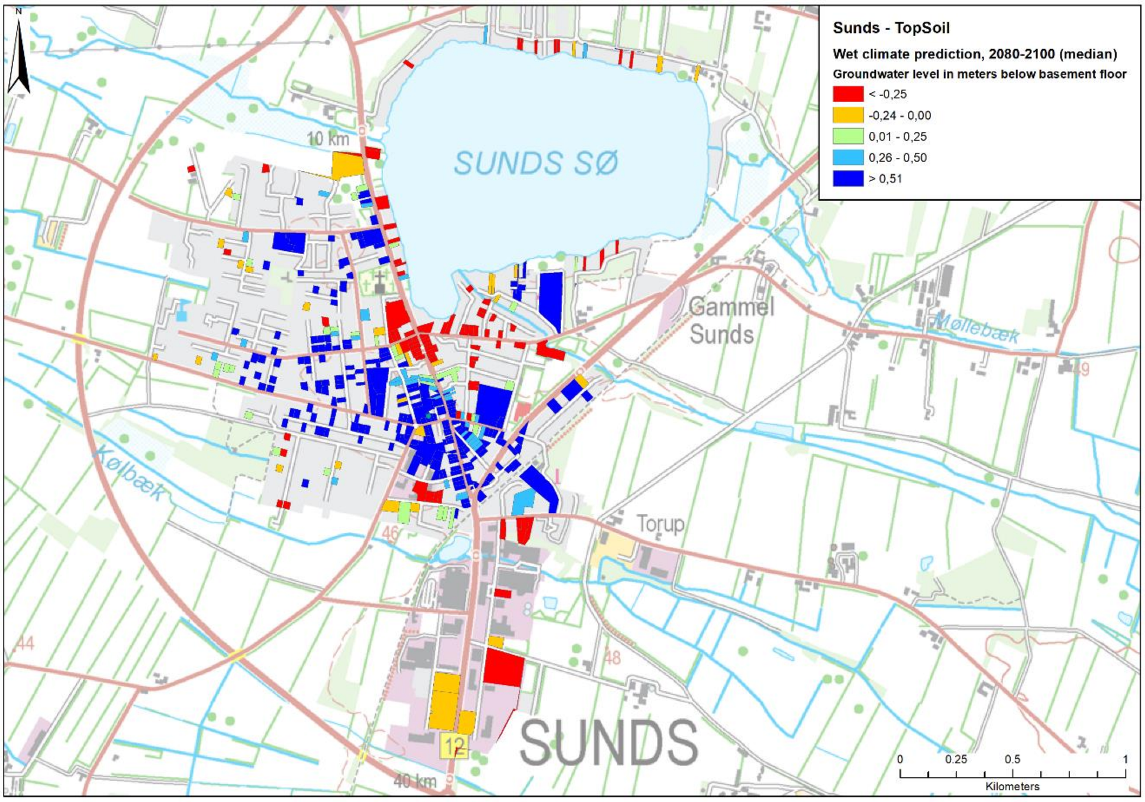

Figure 23 Average groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding for a ***wet climate prediction 2080-2100****. Minus '-' indicates average groundwater level above basement floor,* ***average situation***

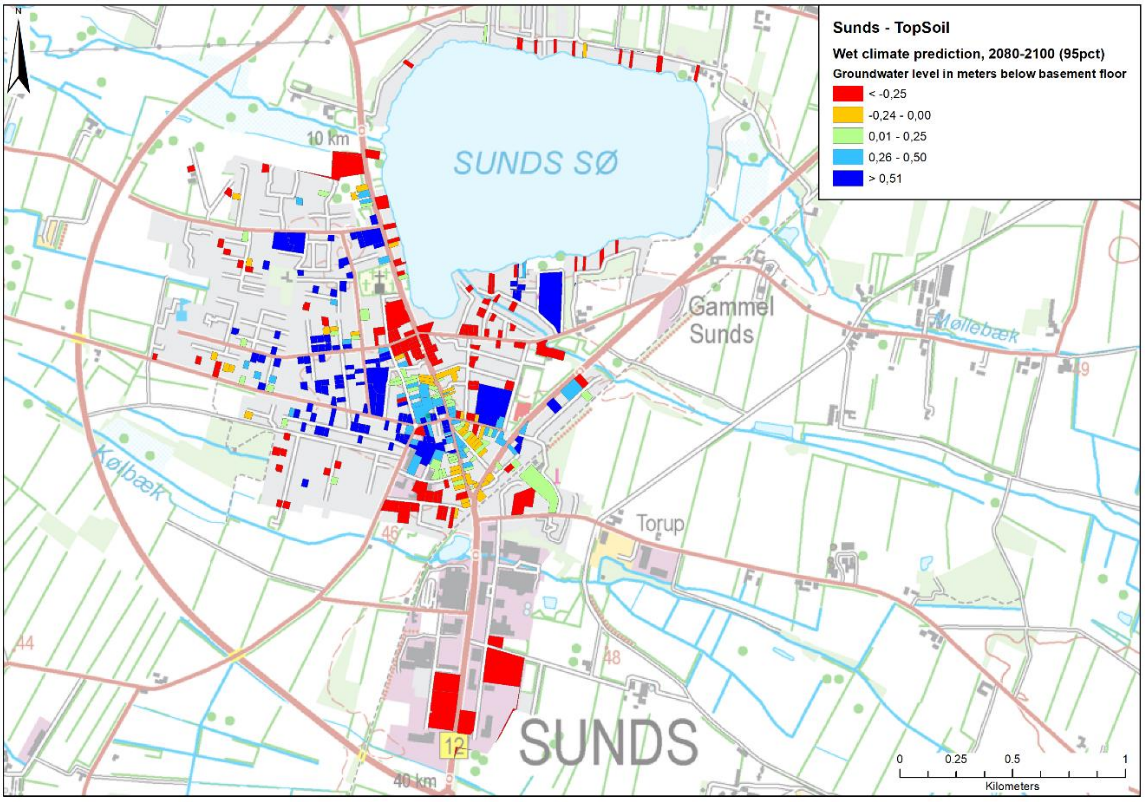

Figure 24 Groundwater depth below basement floor, areas with red and orange colors are at risk of basement flooding for a ***wet climate prediction 2080-2100****. Minus '-' indicates average groundwater level above basement floor,* ***situation with high groundwater level***

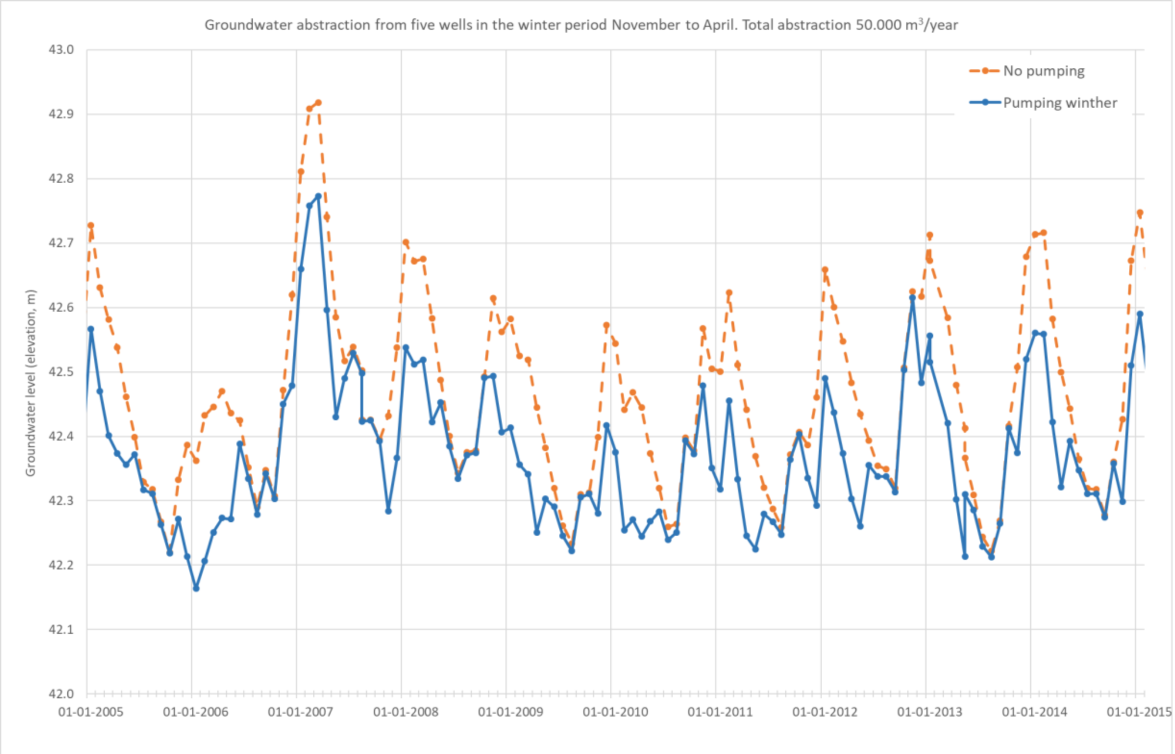

Figure 25 Groundwater levels at observation point M5 (Figure 26). Groundwater abstraction from five wells in the winter period from November to April compared to no abstraction. The total annual abstraction is 50,000 m^3

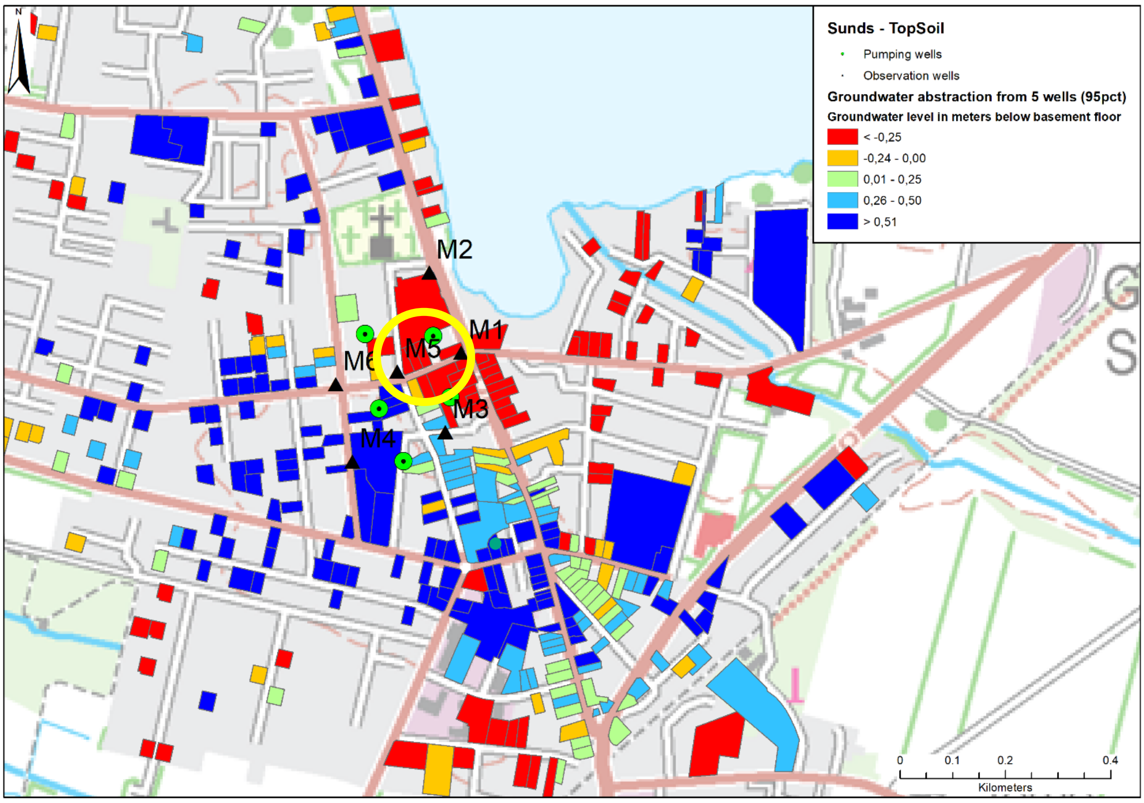

Figure 26 Location of monitoring point M5, see Figure 25

Danish Ministry of Climate,
Energy and Utilities

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/12**

Geological and hydrological model for Sunds - preventive measures for lowering the groundwater table now and in a future climate

A TOPSOIL project - supported by the Interreg VB North Sea Region programme

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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