TACTIC GROUNDWATER

GeoERA

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2

Pilot description and assessment reports work package 3

Contribution partners:

GEUS, TNO, DLT, IGME, HGI-CGS, BRGM, MBFSZ, GSI.

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INTRODUCTION

The pilot description reports are compiled in this document (as a single D3.2 document) but are separate reports from the individual pilots. Reports can include more than one pilot from the same country and present work performed in other work packages (WPs) together with the work done in work package 3. Hence, there is only one pilot report for each pilot although the pilot appears in several TACTIC work packages.

The hereby presented document include all the pilot assessments reports and results performed in WP3. Assessments in WP3 focuses on assessments of climate change impacts on groundwater and associated surface water conditions at the pilot scale. The pilot scale varies from local and regional scale (Avre, Gort, Boutonne, De Raam, Drava-Mura, Storåen-Sunds, Segura, Upper Guadiana) to large country scale (Hungary, The Netherlands, Denmark). Common for the WP3 pilots are the application of integrated hydrological models as tool to the climate change assessments (with Gort lowlands, Ireland as the only exception). The pilots illustrate a large variety of different models used for the assessment, e.g. pure groundwater models simulating steady state conditions toward full hydrological models simulating all land-based hydrological fluxes from evapotranspiration to stream and groundwater discharge to the ocean. Despite of the large variety of groundwater modelling concepts, all models produce spatially distributed results of the investigated aquifer, or aquifer-systems. Also common for the assessments performed in WP3-pilots is the application of the TACTIC standard climate change scenarios, developed in WP3.

The pilot assessment reports are ordered alphabetically and organized into separate documents within D3.2 because the individual reports are used for documentation toward local stakeholders.

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 & 6.3

PILOT DESCRIPTION AND ASSESSMENT

Avre Basin (France)

Authors and affiliation:

Nadia Amraoui, Jean-Pierre Vergnes and Kenza Minhaji

Geological Survey of France (BRGM)

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

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LIST OF ABBREVIATIONS & ACRONYMS

BDGSF	Base de Données Géographique des Sols de France
CC	Climate Change
DEM	Digital Elevation Model
EEA	European Environment Agency
FAO	Food and Agriculture Organisation of the United Nations
GCM	Global Circulation Model
GSOs	Geological Survey Organisations of Europe
IGN	Institut national de l'information géographique et forestière
ISIMIP	Inter Sectoral Impact Model Intercomparison Project
ME	Mean Error
NSE	Nash Sutcliffe Efficiency
PET	Potential evapotranspiration
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
SPLI	Standardized Piezometric Level Index
TACTIC	Tools for Assessment of Climate change ImpacT on Groundwater

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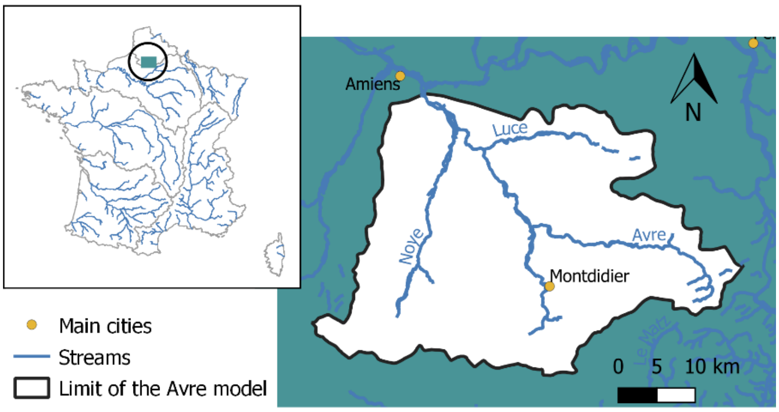
1 EXECUTIVE SUMMARY



Pilot name	Avre
Country	France
EU-region	North Western Europe
Area (km^2)	1 294 km^2
Aquifer geology and type classification	Chalk ; Porous and fissured aquifer
Primary water usage	Irrigation and drinking Water
Main climate change issues	The chalk aquifer is the main water resource used for drinking water supply and irrigation in the Somme river basin. Groundwater in this basin is in strong interaction with rivers, pond and Wetland, which represent outlets of the water table. Although this basin experienced historical groundwater floods in 2001, some of its sub-bassin, particularly the Avre sub-basin (located in the left bank of the Somme river) has known several drought periods in the past, which seem to be renewed with increased frequency in recent years. Extreme events (flood and drought) are predicted to increase under future climate, so it is important to assess the effects of climate change on the hydrological extreme and to design and evaluate adaptation measures in relatioship with water ressources managers and all groundwater users.
Models and methods used	Integrated Hydrological model (Numerical model, time series analysis …)
Key stakeholders	Water Agency; agricultural profession of Somme valley; AMEVA (territorial Public establishment), DDT 80 (water police)
Contact person	Nadia Amraoui, BRGM French Geological survey, n.amraoui@brgm.fr

The Avre pilot is located in the north of France in the Somme department. The Cenomanian-Turonian chalk represents the major geological structure in this basin. Chalk aquifer forms the main water resource for drinking water supply and irrigation uses. The groundwater is in strong interaction with rivers, pond and Wetland, which represent the water table outlets. In the past two decades, the Avre basin has experienced tensions over water resources due to growing water demand and a deficit in groundwater recharge due to several drought episodes. An intensification of extreme events is expected due to global warming, so it is important to assess the effects of climate change on groundwater resources under different warming scenarios, and to assess the relevance of adaptation measures to cope with the climate change effects.

As part of the TACTIC project, a study of climate change impacts on the chalk aquifer recharge, groundwater level and river discharge was performed. Moreover, two adaptation scenarios were tested and their effects on groundwater resources were assessed. The assessment of climate change impacts on water resources is carried out using four selected TACTIC standard climate change scenarios and the regional hydrological model of the Somme River basin developed with the MARTHE computer code from BRGM. MARTHE allows the simulation of flows in aquifers and in river networks, including climatic and human influences, from climatic variables taken as inputs for the model. The selected TACTIC standard climate change scenarios represent an increase of global annual mean temperature by +1 and +3 degrees compared to the reference period (1981-2010), under wet and dry precipitations conditions. The four TACTIC datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. It supposes similar evolutions of climatic variables for the current and the future climate. Moreover, changes in groundwater abstraction in the future climate scenarios are not considered. The impact is quantified by comparing simulated results obtained with the data provided by each TACTIC standard scenario to those simulated on the reference period (1981–2010). Annual changes in mean groundwater recharge and mean groundwater levels are analysed and the seasonal responses of the system are assessed.

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. Their impacts on groundwater levels and river flows were assessed. The first scenario SA1 assumes a 20% reduction in withdrawals for drinking water supply, and the second scenario SA2 assumes a 30% reduction in irrigation withdrawals during irrigation period. The Somme model was used to simulate the groundwater level and river flow over the 1981-2010 period under the two adaptation scenarios. The results were compared to the reference simulation (without abstractions reduction) to assess the effects on the groundwater level and the river flow.

For the Avre basin, dry TACTIC climate change scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such results are due to a global increase of potential evaporation whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios show longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) for the worst scenario (i.e. the 3°C dry scenario). River discharges decreases throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios show increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on

groundwater level over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.
At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.

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 has 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 present document reports the TACTIC activities in the pilot Avre River Basin located in the Northern France, in the Picardie province. Climate change effects groundwater levels, river flow is analysed, and the relevant of two adaptation scenarios is discussed.

3 PILOT AREA

The chalk aquifer forms the main water resource of the Somme administrative county located in the north of France. This unconfined aquifer is directly connected to the Somme River and its associated tributaries. The Avre River basin corresponds to the most impacted sub-basin of the Somme River basin in terms of groundwater abstractions, mainly for supplying irrigation demand and drinking water needs (Amraoui et al., 2014). Since the 90s, the overexploitation of the underlying aquifer has resulted in a decrease of the river discharges over this basin, leading to conflicts between the different usages (Arnaud, 2017). Moreover, the majority of the climate models predict an increase of the severe drought frequency over this sub-basin in the future, which could reinforce this problem. We intend in this project to evaluate the potential impact of climate change scenarios and to assess the effects of some adaptation scenarios on the water resources of this pilot area.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The case study corresponds to the Avre River basin and covers an area of about 1294 km^2 located in the north of France (cf. Figure 1). It corresponds to the main affluent of the Somme River and its sub-basin is located on the left bank. The total length of the river is 60 km. At the upstream, its path crosses tertiary terrains and then go on through the chalky plateau of the Santerre until reaching the Somme River.

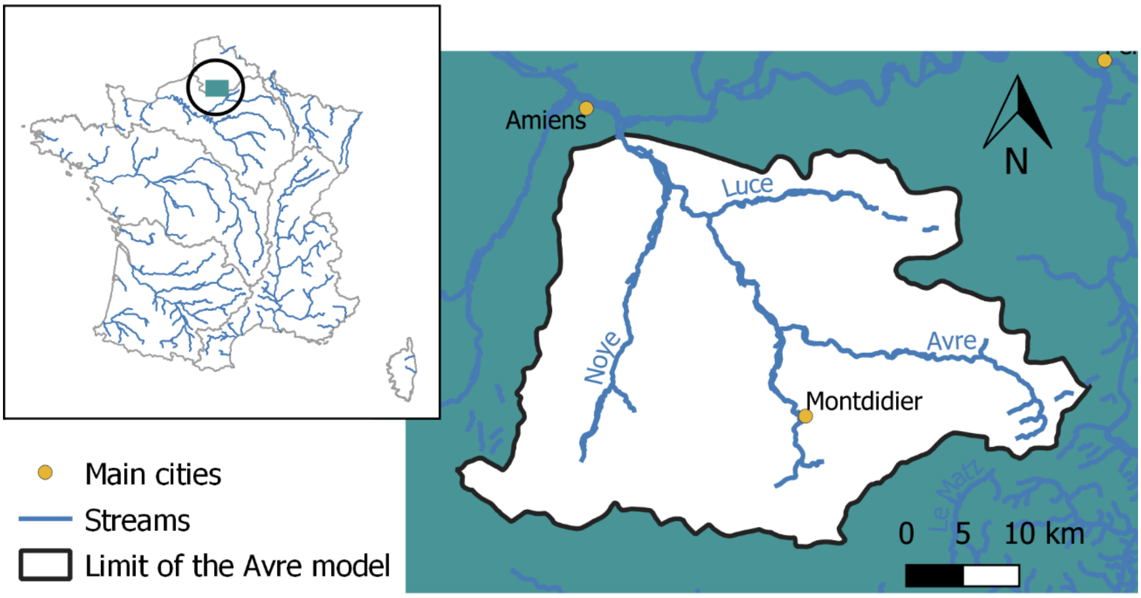


Figure 1: Location of the pilot area

3.1.2 Geology/Aquifer type

According to the BDLISA French hydrogeological reference system (https://bdlisa.eaufrance.fr/), the Cenomanian-Turonian chalk of the Somme River watershed represents the major geological structure of the Avre River sub-basin (green areas in Figure 2). It extends over the whole basin while some tertiary terrains covers the south and the east of the basin. A quaternary upper layer with a 1-m thickness (Ypresian period) is also present in the southeast of the basin. Ancient to recent alluviums characterized the downstream of the Avre riverbed.

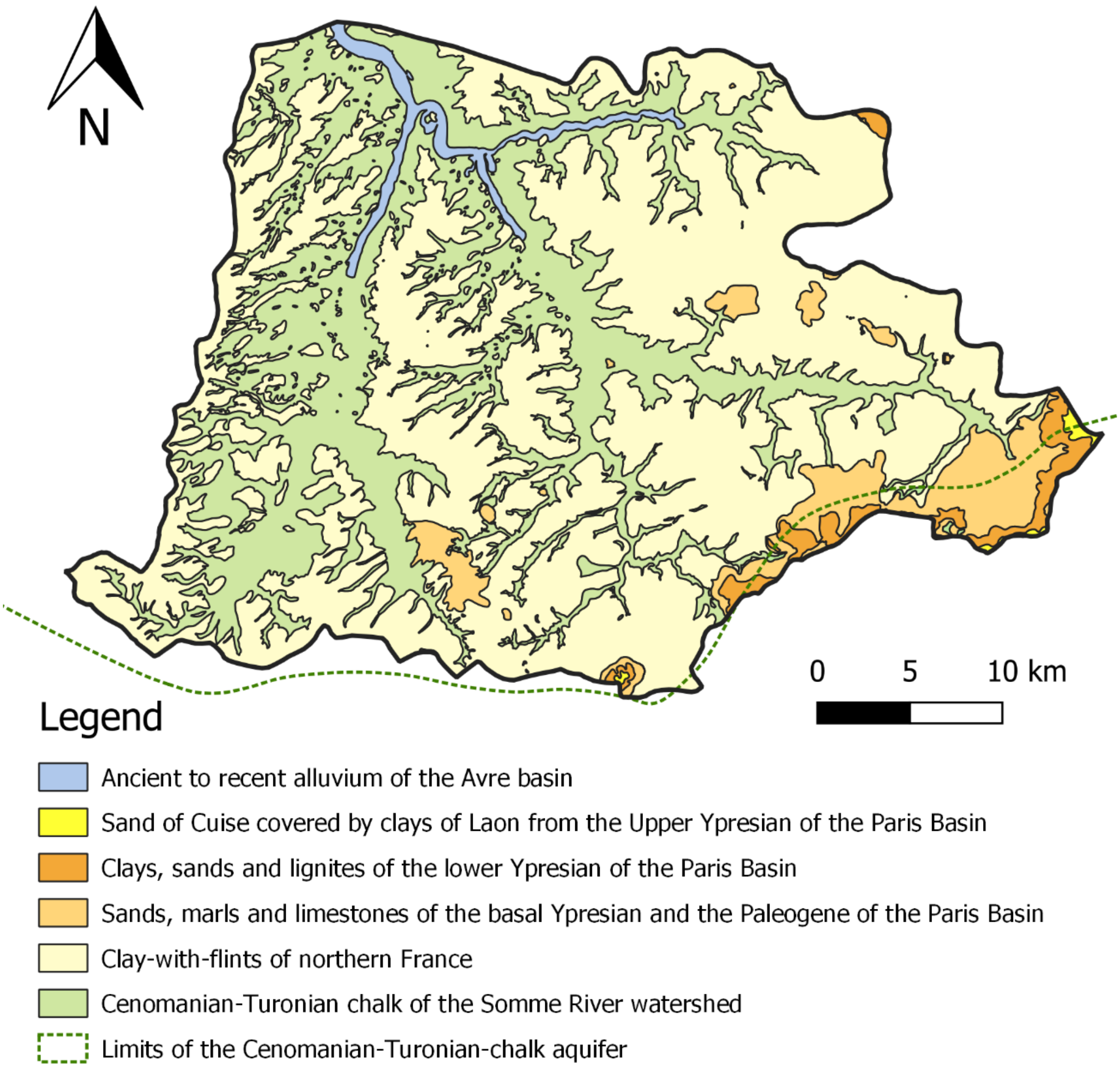


Figure 2: Groundwater bodies of the Avre River basin classified by geological type as defined in the BDLISA (database of aquifer system delineation) French hydrogeological reference system (https://bdlisa.eaufrance.fr/).

The upper chalk cretaceous formation is an extending and powerful reservoir fed by effective rainfall falling over the basin. The water table is unconfined. Groundwater flows toward the valley through fissures generally developed in the upper part of the chalk (in the tertiary terrains) and then feeds the river in the bottom of the valley. An underlying flow occurring in the coarse alluviums of the River characterized the bottom of the valley.

3.1.3 Topography and soil types

The topography varies from 23 m.a.s.L at the downstream of the Avre River to a maximum of 189 m.a.s.l. reached in the southwest of the basin (Figure 3). The area is predominantly flat with shallow valleys. The soils in the basin mainly belong to the Luvisols group according to the FAO classification (Figure 4). Alluvial plains are characterized by Regosols, Histosols and Fluvisols. Others such as Cambisols are also found in the basin.

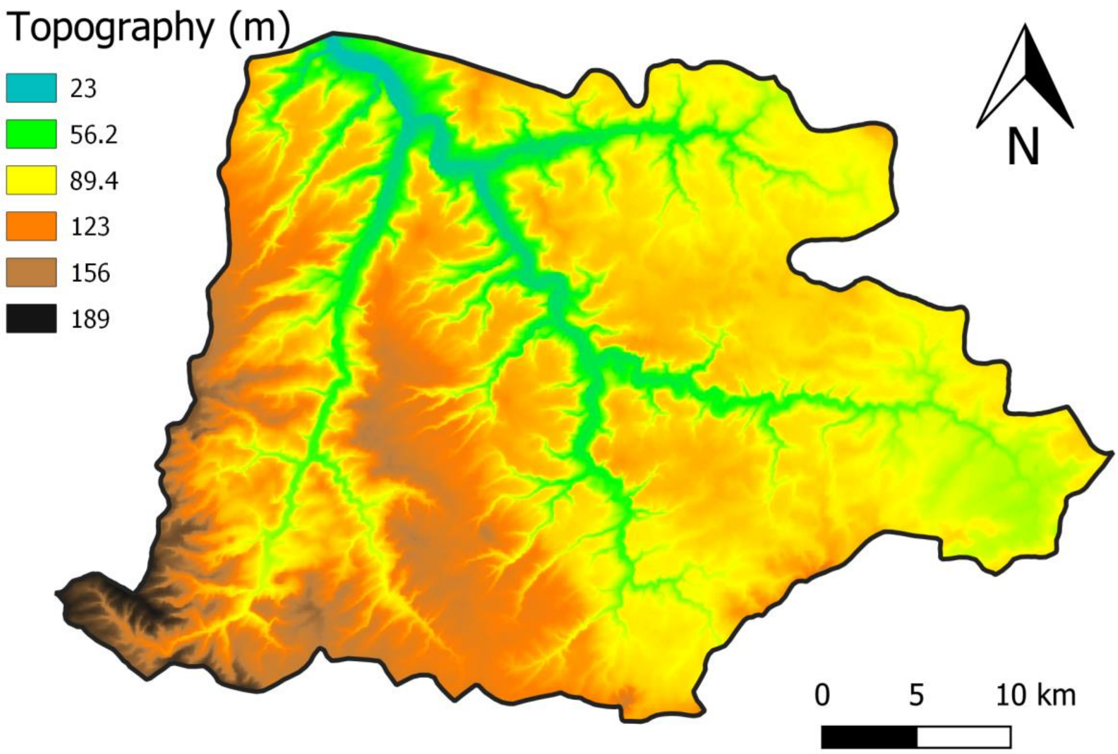


Figure 3: Topography of the Avre River basin from the BDALTI Digital Elevation Model (IGN) (25-m resolution)

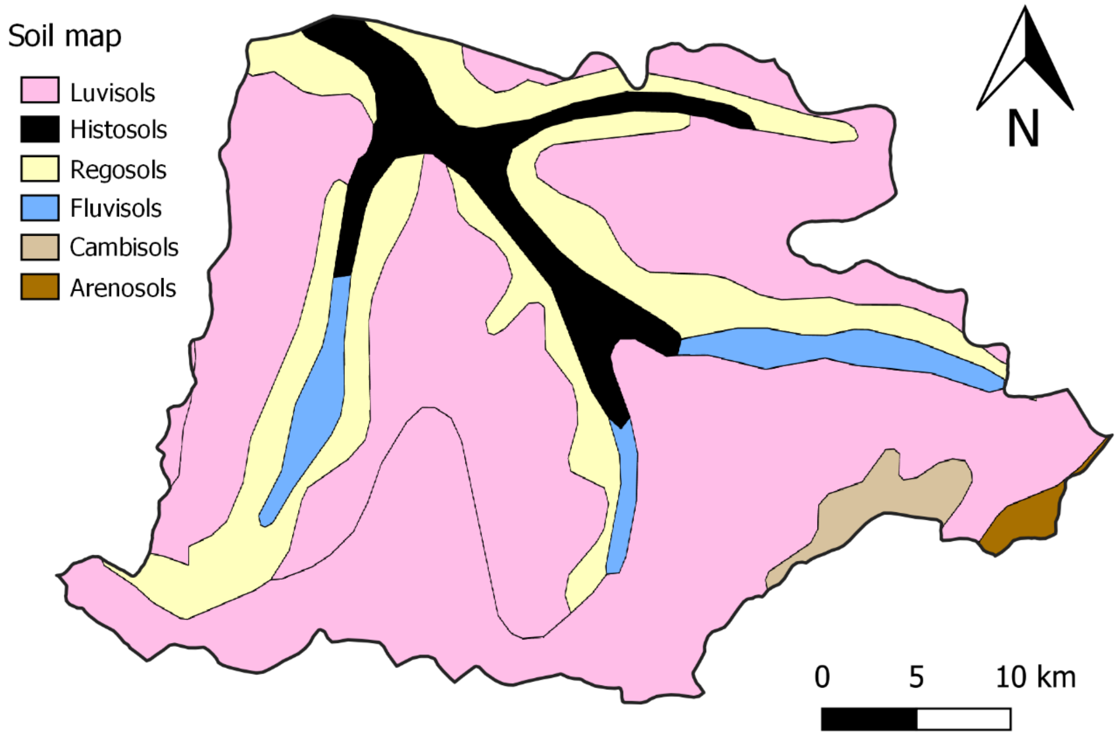


Figure 4: Soil map from BDGSF (Geographical Database of the French Soils)

3.1.4 Surface water bodies

The main affluents of the Avre River are, from upstream to downstream, the Trois-Doms River (18 km), the Noye River (26 km) and the Luce River (16 km). All these rivers drain the chalk aquifer during both dry and humid periods. Three gauging stations are available to monitor the river discharges of the Noye River and the Avre River. They are described in Table 1 and time series are shown in Figure 6.

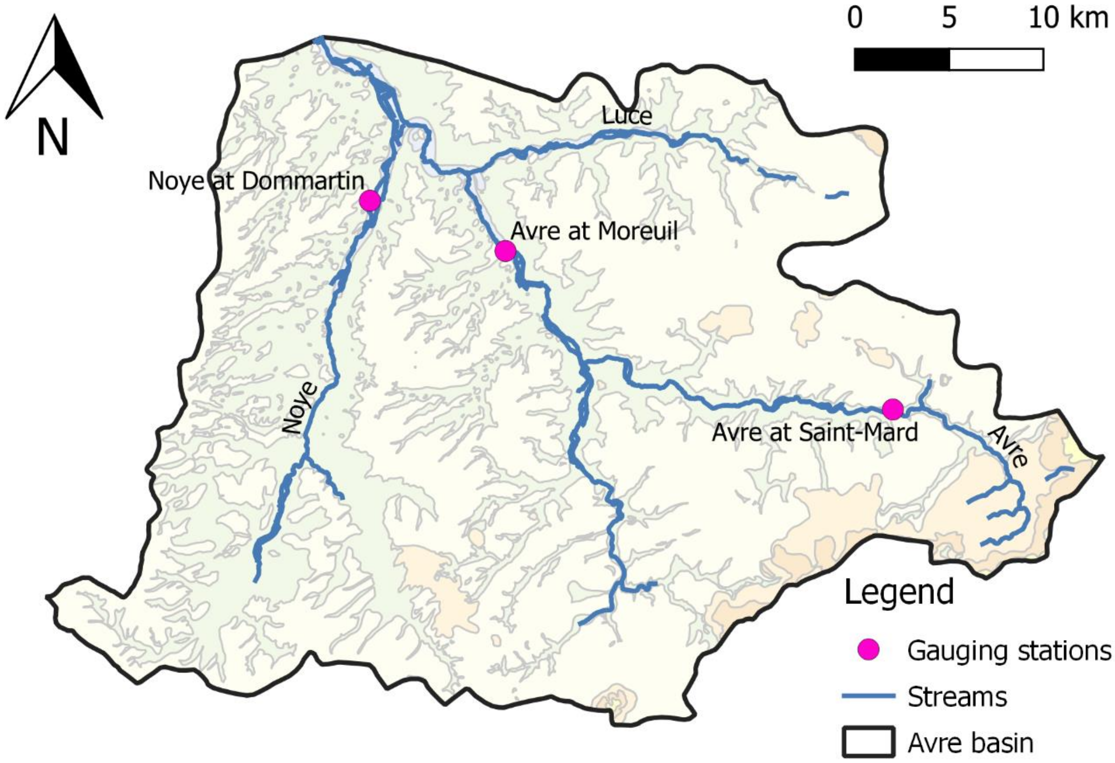


Figure 5: Main rivers and gauging stations of the Avre basin.

Table 1: Statistics of the flow gauges

Flow gauges	Average Q (m3/s)	Period	Surface (km^2)
E6406010	2.2	1968-2018	624
E6406035	0.3	2001-2018	113
E6407540	1.3	2010-2018	311

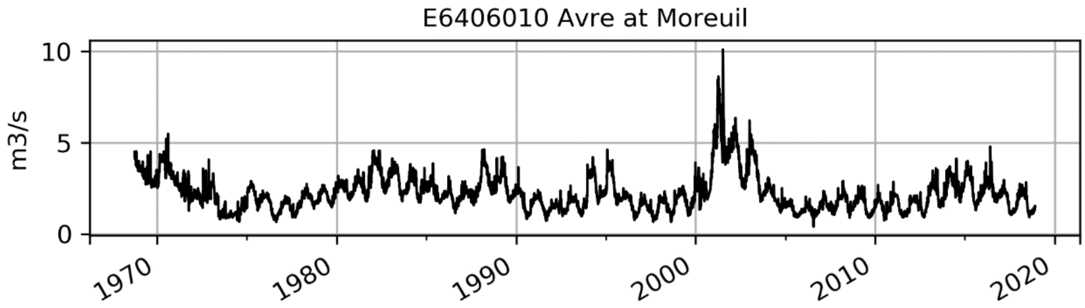


Figure 6: Time series of river discharges for the gauging station located at Moreuil.

3.1.5 *Hydraulic head evolution*

Figure 7 represents the spatial distribution of the hydraulic head observations and Figure 8 shows three examples of hydraulic head evolutions that are representative of the chalk aquifer behaviour. The hydraulic head evolution of the chalk aquifer is characterized by pluri-annual cycles superimposed with inter-annual cycles.

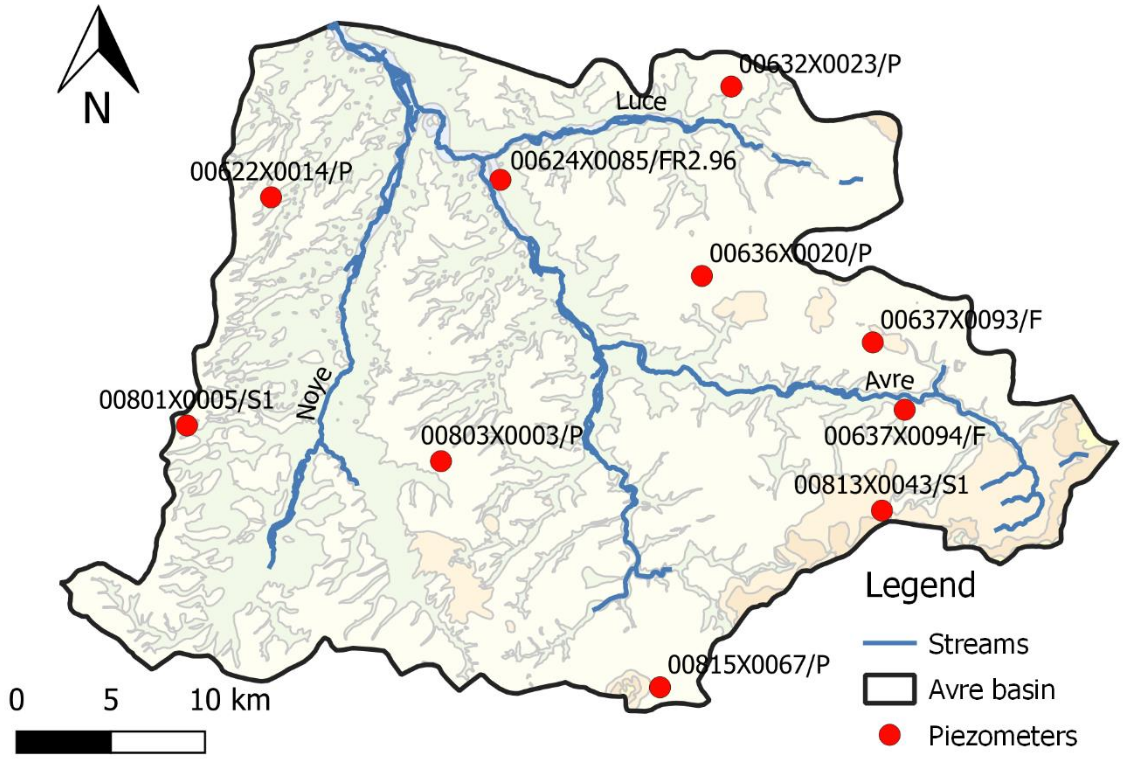


Figure 7: Spatial distribution of the available piezometers

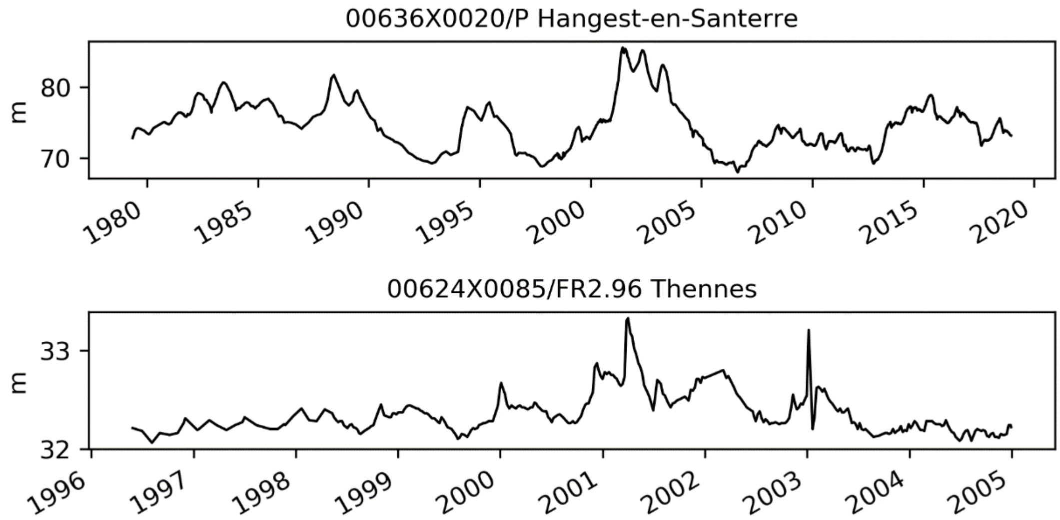


Figure 8: Time series of hydraulic head for two piezometers.

3.1.6 Climate

The climate condition of the Avre basin is semi-oceanic and temperate. Dominant winds come from the coast. According to the SAFRAN meteorological reanalyses (Vidal et al., 2010), the annual mean rainfall is equal to 700 mm/year in the 1958-2018 period. The mean annual temperature is 9°C, oscillating between a maximum daily mean temperature of 18.5 °C in July and a minimum of 1.3 °C in January. The mean potential evapotranspiration is 665 mm/year.

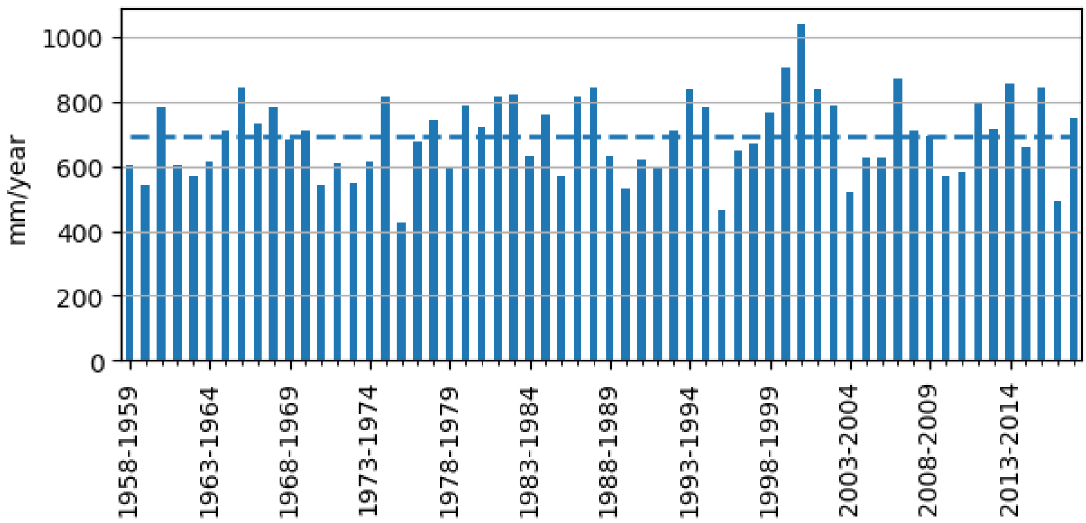


Figure 9: Time series of the precipitation (mm/year). The dashed line corresponds to the mean precipitation.

3.1.7 Land use

According to the Corine Land Cover database (cf. Figure 10), agriculture constitutes the major part of the land use of the Avre River basin. Forests are scattered and essentially constituted of oaks, hornbeam and lime trees. Swamps are also present in some locations.
The Avre basin is classified as a wetland of international importance according to the RAMSAR convention since the beginning of 2018.

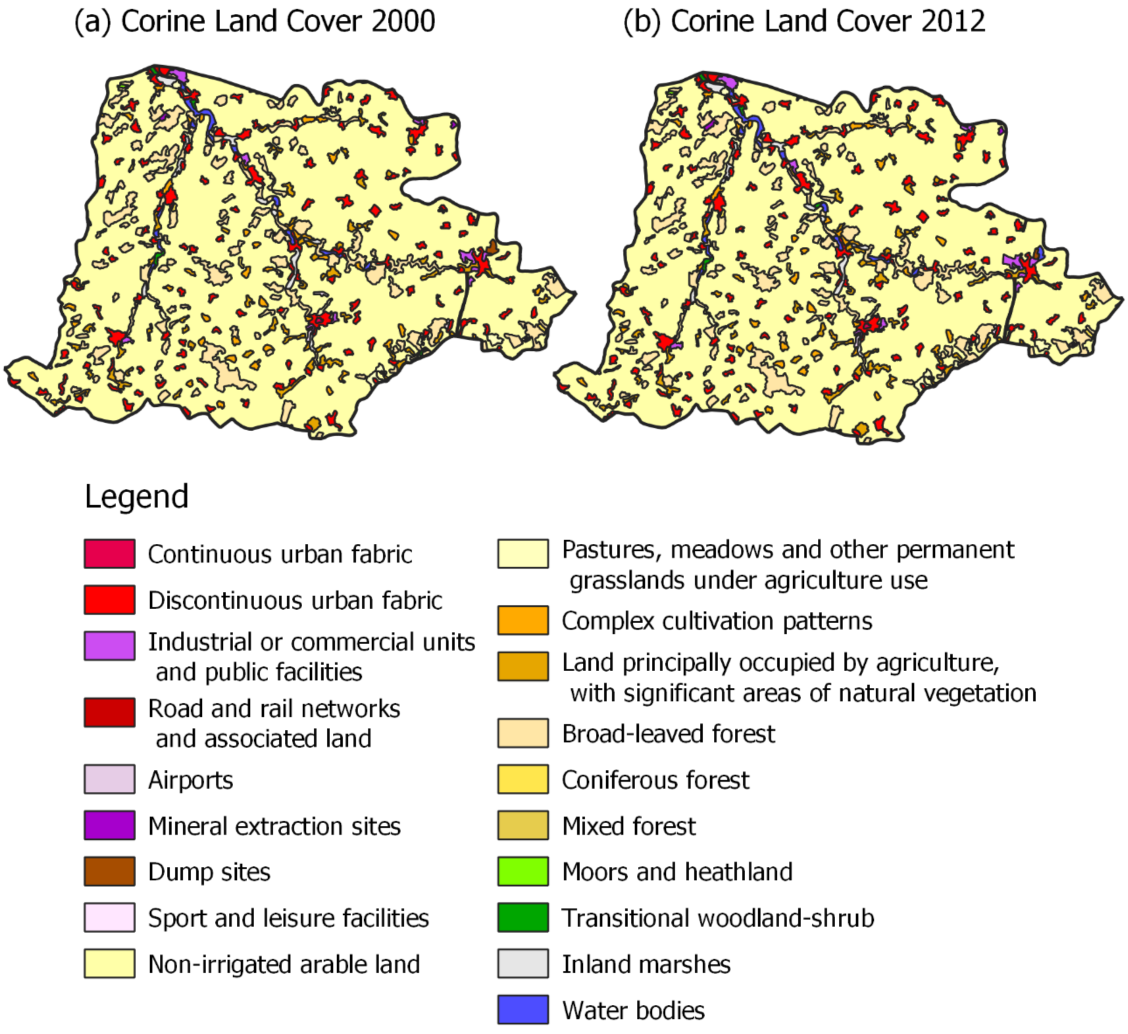


Figure 10: Land use maps from Corine (2000 and 2012)

3.1.8 Abstraction/Irrigation

The chalk aquifer is the only groundwater resource of the Avre basin. Three usages characterize this resource: drinking water with 39 wells located for most of them in the Noye and Trois-Doms river basins, agriculture (irrigation) in 83 well, and in a lesser extent industry with four wells. Agriculture and drinking water are the biggest water consumer. In 2003, 49% of the water use corresponds to agriculture and 43% corresponds to drinking water. During the period of irrigation, these percentages evolve to 73% and 24% respectively.

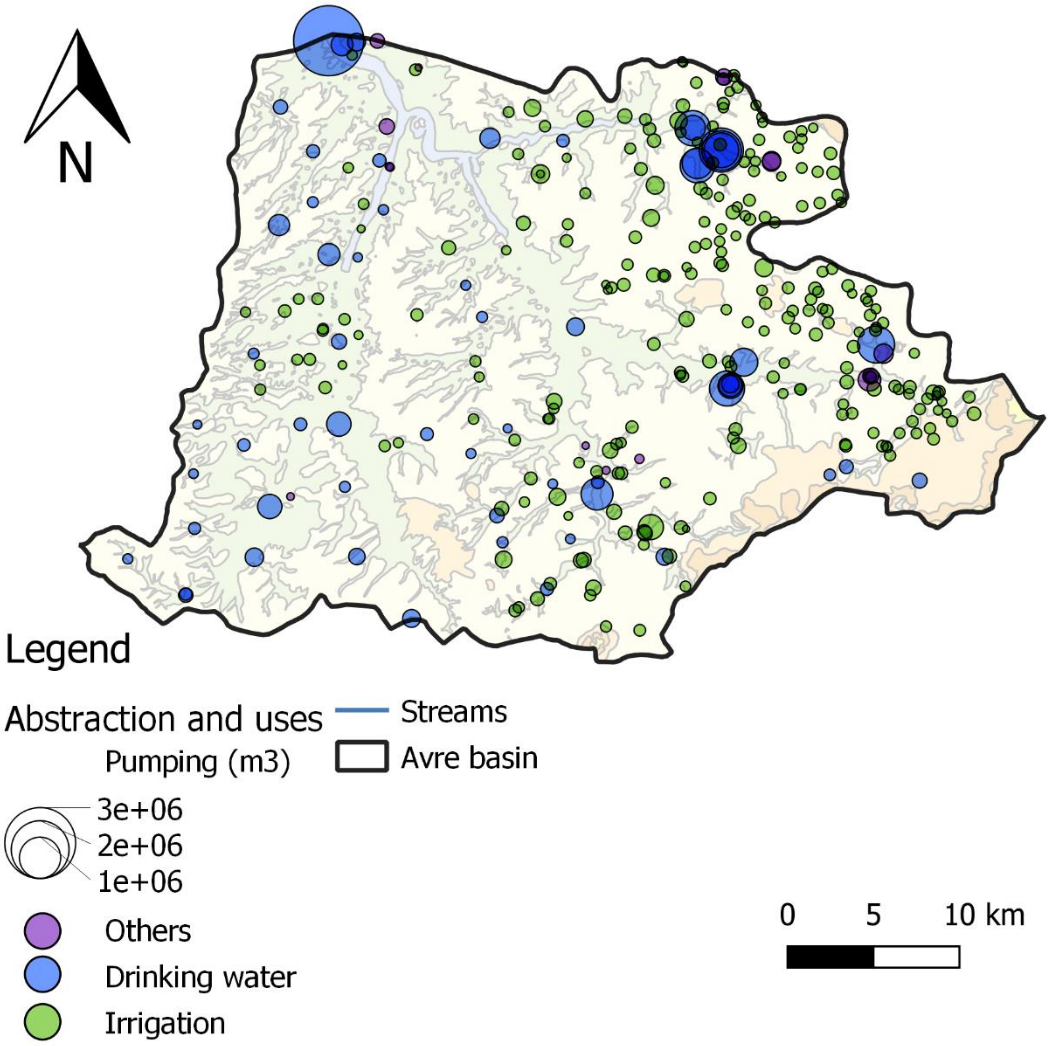


Figure 11: Spatial distribution of the pumpings classified by usages.

3.2 Climate change challenge

The Avre pilot site is located in the North-western Europe region where an increase of precipitation in winter is expected in accordance with the European Environment Agency (EEA) map (Figure 12).

At France scale, recent work based on CMIP5 (Coupled Model Intercomparison Project) models simulations using several climates models, emissions scenarios and different downscaling methods (Dayon 2015; Jouzel et al., 2014) shows an expected increase in precipitation in winter and decrease in summer. General increase in mean annual air temperature is expected that is more pronounced in summer. Results of national Climsec project indicate a continuous increase in soil dryness over the 21-century (Soubeyroux et al. 2011)

Previous study on the hydrological climate change impact in two basins located in the northern France show a marked tendency towards a decrease of the water resource in the rivers and aquifers (on average in 2050 about −14 % and −2.5 m, respectively) (Habets et al. 2013). Hydrological impact study in Somme river basin using projection from 7 GCM and median emission scenario A1B, shows a decrease in groundwater recharge (around -18.7% average of 7 climate models) and decline in river flow expected by 2065 (Amraoui et al 2019). However, two climate models show that high water level are possible confirming the likelihood groundwater flooding risk.

The main challenge in this area is to find adaptation measures to anticipate the future climate conditions in order to better manage available water resources regarding to demands under drought period. In addition, as groundwater Chalk permanently support Rivers and ponds in this area, it is important to ensure a good status in these ecosystems.
In the study area, the main expected issues due to climate change are related to the groundwater droughts.

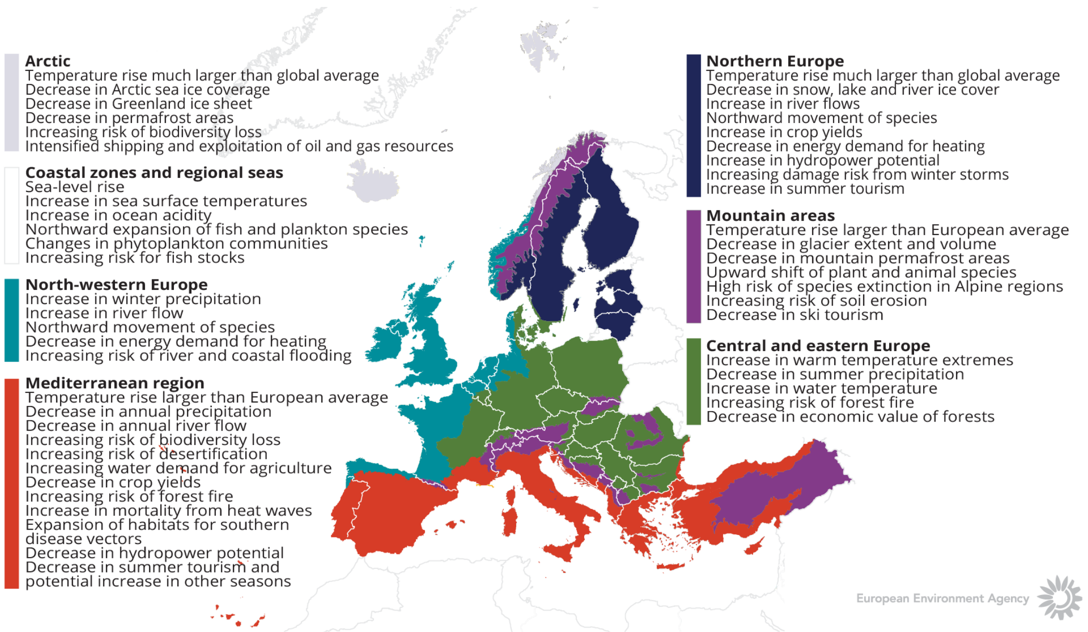


Figure 12 : Key observed and projected impacts from climate change for the main regions in Europe (European Environment Agency)

4 METHODOLOGY

The assessment of climate change effects on the groundwater resource in the Avre River basin uses the TACTIC standard climate change scenarios and the integrated hydrological model developed with the MARTHE computer code (see TACTIC toolbox reference). The ESTHER software allows to analysing droughts from output time series. Moreover, two adaptation scenarios were defined and their effects on both the groundwater levels and the river discharges were assessed by using the Somme hydrological model.

4.1 Climate data

In this study, only TACTIC standard climate change dataset are used to assess climate change impact on groundwater resources for the Avre pilot under +1 and +3 degrees global warming scenarios considering low and high precipitation conditions.

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 include the following steps:

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

delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

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

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

		RCP	GCM
1-degree	"Dry"	6.0	hadgem2-es
	"Wet"	4.5	ipsl-cm5a-lr
3-degree	"Dry"	6.0	hadgem2-es
	"Wet"	8.5	miroc-esm-chem

4.2 Hydrological modelling of climate change

The regional hydrological model of the chalk aquifer of the Somme Basin (Somme model) has been developed in its first version in 2002 (Amraoui et al., 2002) and completed, updated and recalibrated since then (Amraoui, 2004; Amraoui et al., 2014; Amraoui and Seguin, 2012; Arnaud, 2017). The Somme model uses the finite difference groundwater modelling approach implemented in the MARTHE computer code to compute the groundwater evolution of the chalk aquifer (Thiéry, 2020). MARTHE allows the simulation of flows in aquifer systems and river networks, including climatic and human influences. MARTHE implements the GARDENIA lumped parameter hydrological model to compute from surface water balance from climate data (i.e. rainfall and potential evapotranspiration (PET)), which includes surface runoff and groundwater recharge. More details on MARTHE functionalities are available in the Tactic Toolbox.

The assessment of climate change effects on the groundwater resource relies on:
1) The four selected TACTIC climate change scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to reference period (1981-2010) under wet and dry conditions
2) The Somme model simulating groundwater conditions over the current period.

The application of delta change factors to the current local dataset of precipitation, PET and temperature generated the four TACTIC climate change scenarios. This method assumes no changes in the evolution of climatic variables for the current and the future climates.

The groundwater recharge, piezometric head and river discharge evolutions were simulated over the period 1958-2018 using the historical local climate data as well as the four climate projections generated from the delta change factors provided by TACTIC. In total, five simulations are available: four Tactic future simulations corresponding to the four Tactic standard future scenarios, and one historical simulation. Future climate simulations assume no changes in groundwater abstractions. Only the results of the 1981-2010 30-years periods are used to assess climate change impacts on groundwater and surface water resources.

4.2.1 Model description

The Somme model extends over an area of 7,400 km^2 and covers the entire hydrologic catchment of the Somme basin, half of the Southwestern Authie basin in its North, and half Northwestern of the Bresle basin in its Southwest (Amraoui et al., 2019). This model integrates the data described in paragraph 3.1. The borders of the Somme River basin includes the Authie River and the Cambrésis heights to the North, the Vermandois to the East, the Noyonnais hills to the Southeast, the Bresle River to the Southwest, and the English Channel to the West (Figure 13). Figure 14 shows the location of the Avre basin in the Somme model. The Somme model includes the full extent of the Avre basin.

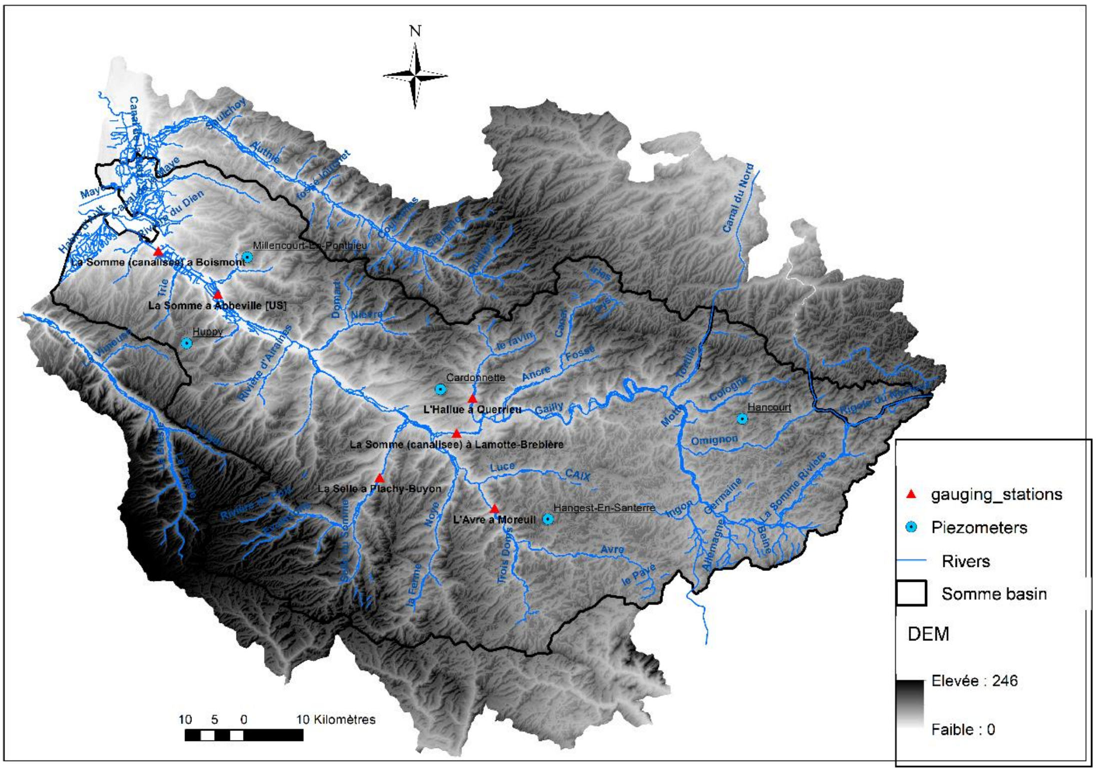


Figure 13 – Geographic map of the Somme River basin (Amraoui et al., 2019)

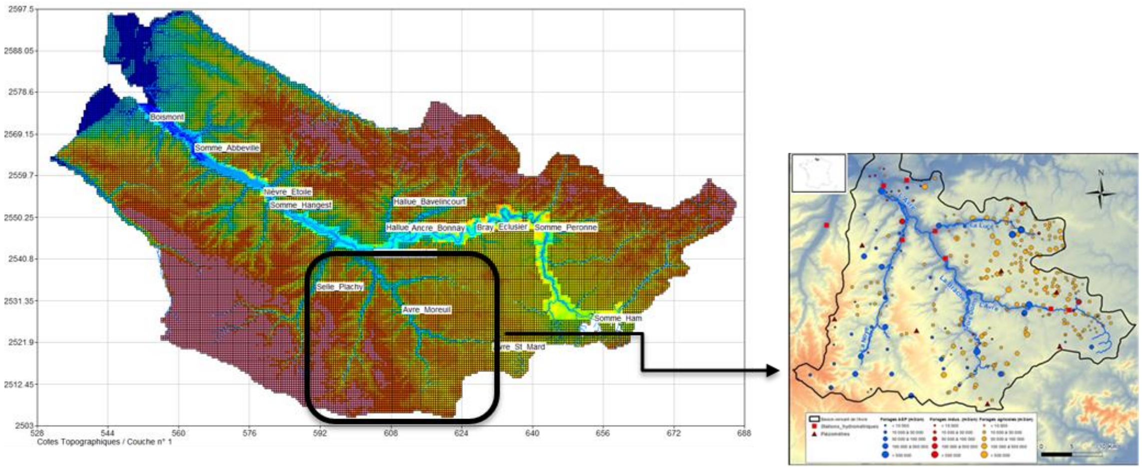


Figure 14 – Location of the Avre watershed in the Somme River basin – the black outline on the right figure represents the limits of the basin on a topographic map background

The chalky aquifer is discretized with a single layer and a computational grid of 500m x 500m resolution except in the humid valley of the Somme where the grid is locally refined down to 100m X 100m for an improved numerical discretization of the aquifer-river interactions close to the Somme river and its tributaries (Amraoui, 2004). In total, the model contains more than 66 000 computational cells. The model takes into account groundwater flow in the chalky layer, flow routing into the associated river system, and the interactions between these two sub-systems. Boundary conditions of the imposed potential type are applied to the west of the regional model and correspond to the see. Elsewhere, no flow limits are applied at the borders of the domain.

The Somme model takes into account all water withdrawals (agriculture, drinking water, industry). The model run in unsteady state conditions. It simulates the evolution of piezometric heads, stream river flows, and interactions between groundwater and surface water. The model runs with a daily time step when computing runoff and recharge and at a weekly time step when computing the groundwater flow in the aquifer system. The calibration period is 1989 - 2012 to include known observations.

The computation of the surface water balance uses spatial distributions of climate data including daily rainfall, PET, and soil parameters, using the lumped hydrological model GARDENIA. This model simulates the evolution of the piezometric heads and streamflows at each point of the river system. More details on this model are reported in Amraoui and Seguin (2012) and Arnaud (2017).

In this study, we used the 2017 version of the Somme model. In this version, the model was updated over the Avre basin with new refinement of the river grid to 100 m x 100 m, an actualisation of the withdrawal dataset over the 1989 – 2012 period, and an updated calibration of the hydrodynamic parameters (river-aquifer parameters and aquifer permeabilities).

In the frame of the TACTIC project, the model was updated over the period 1958-2018 with daily climatic data. Concerning water abstractions in aquifer and river, the acquisition of new datasets during the TACTIC project extends the withdrawal data from 1982 to 2018. Data on surface water withdrawals are available over the period 1992-2018 and over the period 1982-2018 for the groundwater withdrawals. These data, made available by the Artois Picardie Water Agency, were introduced into the Somme river model. Moreover, we assumed that the withdrawals prior to 1982 (from 1958 to 1981) are identical to those of 1982 for all types of uses (irrigation, drinking water supply, industry …). Indeed, analysis of groundwater withdrawals show that they do not vary significantly over the 1982-1992 period. The river water abstractions of the 1993 year were applied to the previous years (1958-1992).

4.2.2 Model calibration

Calibration consists in adjusting the model parameters in order to reduce the difference between the observed and simulated values at the observation points (groundwater time series and the rivers flow rates measured at the gauging stations). The calibration of the Somme model was updated in 2017 over the Avre basin by Arnaud (2017). As part of the TACTIC project, and following the update of the Somme model with recent datasets, a recalibration was undertaken. The calibration was performed over the 1989-2017 period by trial and error approach and concerns only the Avre basin. This calibration concerns the permeability values of the chalk aquifer.

The model evaluation is focused on its capacity to mimic observed groundwater dynamics and river discharges measured at different observation points. The location of the piezometers and the gauging stations used in the evaluation of model calibration is shown in Figure 7 and in Figure 5.

Examples of comparison between the simulated and observed values of groundwater levels and river discharges are shown in Figure 15 and Figure 16. In addition, statistical criteria (Root Mean Square Error: RMSE, Mean Error: ME and the Nash criteria : NSE) were calculated on the basis of monthly values of the groundwater levels and river flow over the calibration period. Chalk groundwater dynamic is well reproduced by the model for the following piezometers: Guillaucourt (ME = -0.58; RMSE = 0.97m; NSE = 0.79); Hangest-en-Santerre (ME = 0.65; RMSE = 0.6.m; NSE = 0.8); Damery (ME = 0.62 and RMSE = 1.m; NSE = 0.84). The Avre River discharge at the Moreuil gauging station is well reproduced by the model with ME = 0.1, RMSE = 0.5 m^3/s and a NSE of 0.76 (NSE criterion is considered to be very good when it is greater than 0.7).

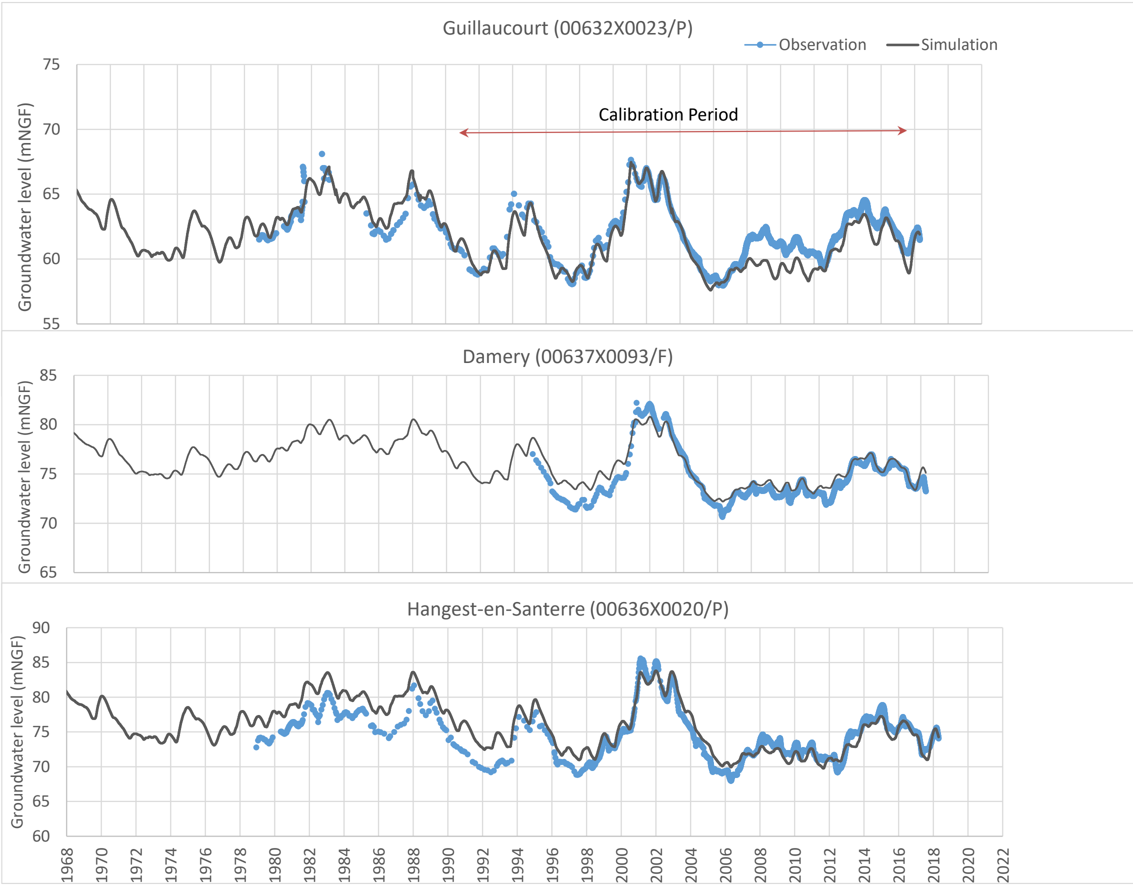


Figure 15 : Examples of observed and simulated groundwater levels in 3 piezometers located in Avre basin.

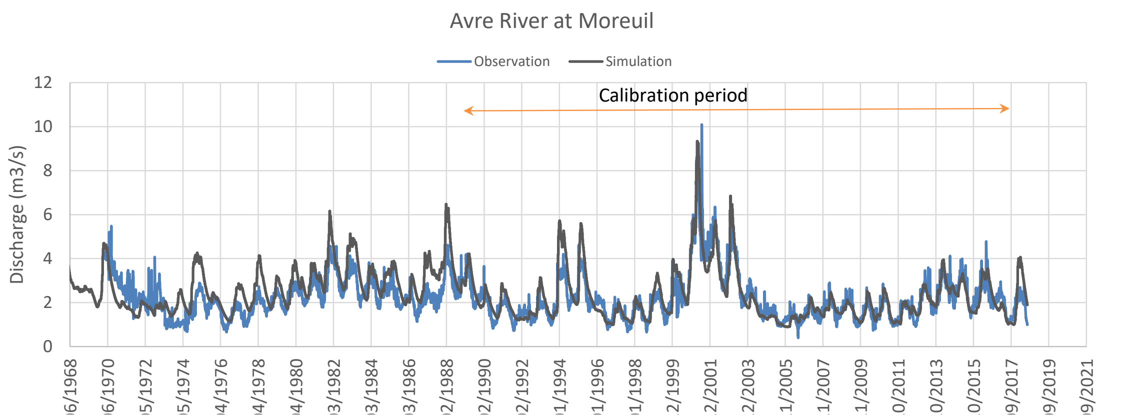


Figure 16 : Daily observed and simulated discharges in the Avre River at the Moreuil gauging station

4.3 Adaptation scenarios simulated with hydrological model

Adaptation measures to cope with the impact of climate change on water resources can relate to: 1) water demand, such as land use change, adaptation of irrigation techniques and economic instruments etc. 2) water offer, which mainly lean towards complementary resources such as active management, natural water retention measures, water transfer, etc. 3) Mixed (improving resilience) such as improving planning, control and allocation of resources, technological innovation etc.. Developing adaptation strategies at the territorial level is generally laborious since it involves climate, land use and socioeconomic scenarios. Two types of approaches exist: the top-down approach, which focuses on the analysis of physical vulnerability and the bottom-up approach, which attempts to assess the social vulnerability. The latter defines plausible scenarios and adaptation measures through participatory processes and workshops with the main actors. The top-down approach aims to identify the optimal measurement programs for the different climate scenarios.
The implementation of a participatory approach involving the main actors of the territory (elected officials, socio-economic actors, institutional users, etc.) and mobilizing foresight tools is laborious and cannot be carried out in this study given the project budget allocated to this task. It was difficult to interact with water stakeholders because of 2020 sanitary conditions (Covid19). Therefore, the method used is to rely on some of proposed actions, in the adaptation plan to climate change of the Artois Picardie basin (developed in 2016), to define two scenarios based on orientation actions already proposed in this plan in connection with water resources, drinking water supply and agriculture.

4.3.1 Adaptation scenarios used

Two adaptation scenarios were defined based on a reduction in water demand for drinking water supply and irrigation. The location of drinking water supply wells and agricultural boreholes is reported in figure 11.

<u>The first scenario called SA1</u> : this scenario assumes a **20% reduction in withdrawals for drinking water supply** that would be expected through induced by the awareness of water savings among citizens, the improvement of water leaks in the water distribution network; rainwater recovery…
<u>The second scenario called SA3</u>: This scenario assumes a **30% reduction in irrigation withdrawals during irrigation period** who could be reached by the optimization of irrigation (practices & innovative devices for irrigation), by using less water-consuming crop; diversification of water resources (rainwater, treated wastewater, etc.).

The Somme hydrological model is used to simulate the groundwater level and river flow over the period 1981-2010 by considering a reduction of 20% of water drinking supply withdrawals distributed in the same way over the whole year and over all the pumping wells. In the same way, a simulation was carried out taking into account a 30% reduction in irrigation withdrawals during irrigation period (May to September), this reduction is applied to all agricultural boreholes. The results were compared to the reference simulation to assess the effects of withdrawals reductions on the groundwater level and the river flows (Avre River and its main tributaries).

In addition, a third simulation was achieved without any abstraction in groundwater and rivers in order to evaluate the effect of abstractions on the river flows. Impact of tested adaptation scenarios on the groundwater level and river flow was assessed

4.4 Uncertainty

The most important sources of uncertainty concern the data on groundwater and river water withdrawals, which were not known before 1982 and 1993 respectively. Therefore, the assumption made on withdrawals before 1982 for groundwater uses and 1993 for rivers constitutes an important source of uncertainties. In addition, the withdrawal variation over time is not known, only annual volumes are known.

5 RESULTS AND CONCLUSIONS

This section assesses the impact of climate change on the evolution of groundwater recharge, groundwater levels, and river stream flows. Results show comparisons between each future periods of the four Tactic scenarios and the reference period (1981–2010) in terms of annual changes of groundwater recharge and mean, low and high groundwater level. Analyses carried out for the Tilloloy piezometer (corresponding to the 00813X0043/S1 piezometer in Figure 7) and river stream gauges propose local and seasonal responses of the system to the future climate change.

5.1 Effects of climate changes on precipitation, evaporation, and groundwater recharge

Figure 17 compares the monthly mean seasonal cycle of precipitation and PET computed for the four future Tactic simulations in relative changes with respect to the reference historical simulation. Dry scenarios correspond to the simulations labelled with minimum changes and wet scenarios to the simulations labelled with maximum changes. Three scenarios (+1°C dry, +3°C dry and +3°C wet) present increases of precipitation during winter. Precipitation rises also occur in summer for 1°C and 3°C wet scenarios. Conversely, precipitation decreases occur in summer for both the 1°C and 3°C dry scenarios. Monthly changes in PET shows an increase for all scenarios, and it is more important in summer under +3°C global warming

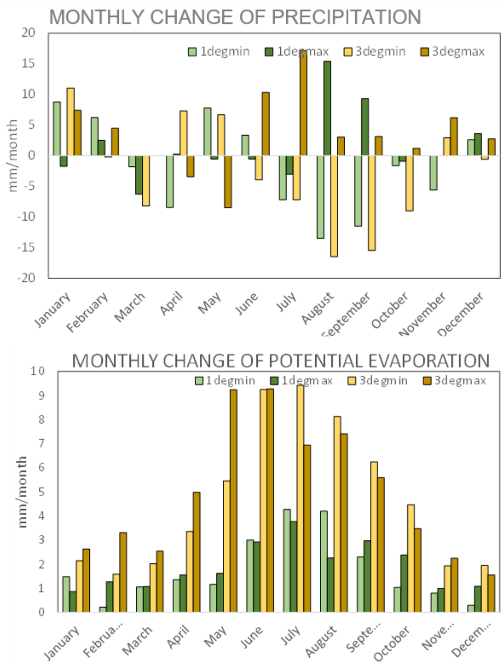


Figure 17: Monthly changes of precipitation and PET under +1° C and +3°C for the 4 Tactic standard scenarios. In the legend, the “min” suffix means dry and “max” means wet.

Regarding groundwater recharge, results shows that the 1°C and 3°C dry scenarios generate a decrease of -5.5% and -13% respectively with respect to the reference period in terms of mean annual changes in average over the Avre basin. The 1°C and 3°C wet scenarios generate an increase of +0.7 % and +3.79% respectively.

5.2 Effects on piezometric heads and river flows

5.2.1 Change in groundwater resources

Applying the Somme model with MARTHE enables simulated outputs in the format of grid/raster for pre-defined time-intervals. These gridded outputs were printed with a 30 days interval. Therefore, it was possible to analyse, not only the mean changes (the difference between the simulated future periods and the simulated reference period), but also to analyse the changes for relatively dry and wet periods throughout the years, respectively. Figure 18 shows the relative changes of simulated piezometric heads between the four future Tactic simulations and the reference period (1981-2010) computed for each grid cell of the Somme model focused on the Avre basin. Representing the time of the year with lowest groundwater levels, a change of the 5 % quantile of the simulated 30 periods is shown (Future Q5 – Past Q5). This typically occurs during the summer and fall period. In the same way, the 95 % quantile is used to illustrate the changes of the period with highest groundwater levels, typically during the winter or early spring.

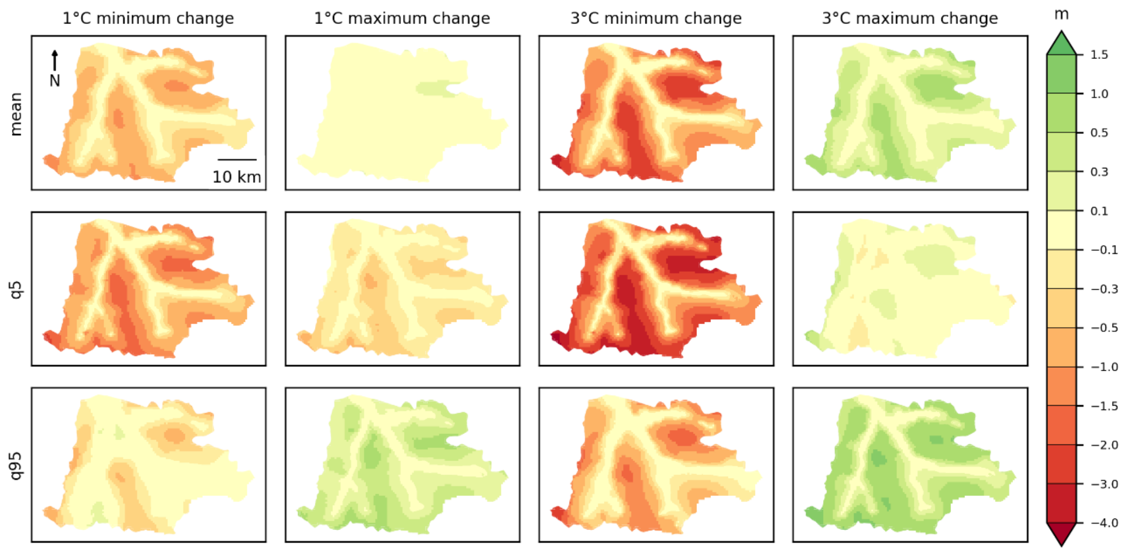


Figure 18 : Changes in mean, high and low shallow groundwater levels simulated with the four TACTIC standard scenarios

Results show an increase of mean groundwater levels for the 3°C wet scenario (maximum change scenario), while no significant changes appear for the 1°C wet scenario. The change of groundwater levels for Q95 shows increases for the two scenarios. The change for Q5 shows decreases for the 1°C wet scenario while no significant pattern appear for the 3°C wet scenario.

Both 1°C and 3°C dry scenarios show decreases of mean groundwater levels. This decrease becomes accentuated for the 3°C dry scenario and can reach locally -3 m. The changes for Q5

and Q95 are in accordance for decreases in the future, which can reach locally about -6 m locally for the 3°C dry scenario for Q5.
Changes occur mainly on plateaus than on wet valleys. Those results concord with the relative changes computed for the groundwater recharge over the Avre domain described previously.

5.2.2 Climate change impact on drought evolutions

One way to evaluate the ability of the simulation to capture extreme events is to use the Standardized Piezometric Level Index (SPLI). The SPLI is an indicator used to compare groundwater level time series and to characterize the severity of extreme events such as long dry period or groundwater overflows (Seguin, 2015). The SPLI indicator is based on the same principles as the Standardised Precipitation Index (SPI) defined by McKee et al. (1993) to characterize meteorological drought at several time scales. First, monthly mean time series are computed from time series of piezometric heads. Then, twelve monthly time series (January to December) are constituted over the N years of the time series period. For each time series of N monthly values, a non-parametric kernel density estimator allows estimating the best probability density function fitting the histogram of monthly values. At last, for each month from January to December, a projection over the standardised normal distribution using a quantile-quantile projection allows deducing the SPLI for each value of the monthly mean time series of piezometric heads. The SPLI values most often range from -3 (extremely low groundwater levels corresponding to a return period of 740 years) to +3 (extremely high groundwater levels). The SPLI allows representing wetter and drier periods in a similar way all over the simulated domain.

Figure 19 shows the SPLI evolution for the Tilloloy piezometer located over the Avre basin (corresponding to the 00813X0043/S1 piezometer in Figure 7), which presents results representative of the behavior of the other piezometers located over the Avre basin. The SPLI was computed from the 1981-2010 reference period for the four future simulation using the Tactic climate changes projections and for the historical simulation. The SPLI indicator computed for the historical simulation shows a 21-months length drought in 2005 (evolution not shown here). The SPLI evolutions of Figure 19 shows the most important increase of the severity and length of droughts for the 3°C dry scenario, especially in 1992, 1997 and 2005. In 2005, the projected length of the 3°C dry simulation drought is 41 months, i.e. twice the length of the historical drought.

The 1°C dry scenario also shows an important increase of the severity of droughts in 1997 and 2005. For this scenario, the 2005 drought lasts 26 months. At last, the 1°C and 3°C wet scenarios show an increase of the severity of droughts in 2005 less significant, with similar durations compared to the 2005 historical drought.

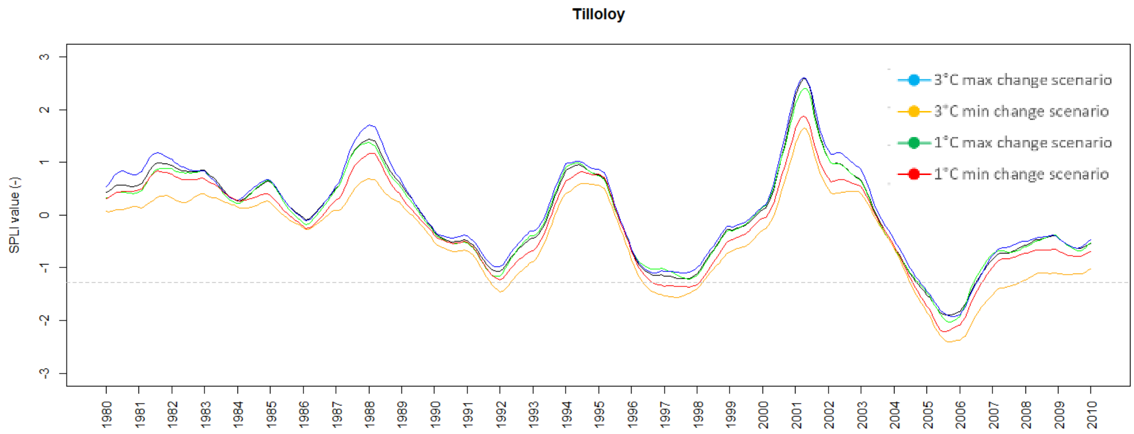


Figure 19: SPLI evolution for the reference period and the four Tactic standard scenarios for the Tilloloy piezometer.

5.2.3 Change in river flow

Figure 20 represent the monthly mean river flows of Avre river at Moreuil gauging station calculated over 30-years for the historical period and under the four Tactic climate change standard scenarios.

Figure 21 shows the monthly mean seasonal cycle of the relative changes of simulated river stream flows for the Avre River at the Moreuil gauging station between the four Tactic future simulations and the historical simulation. The 1°C and 3°C dry scenarios show a decrease of the river discharges for all months. The high flow period from November to March present marked decreases with about -15% and -25% of changes in winter for the 1°C and the 3°C dry scenarios respectively. Changes for the 3°C dry scenario are more severe than for the 1°C dry scenario in all seasons.

Conversely, the 1°C and 3°C wet scenarios depict an increase of the simulated stream river flows for the high flow period, with a bigger impact of the 3°C wet scenario.

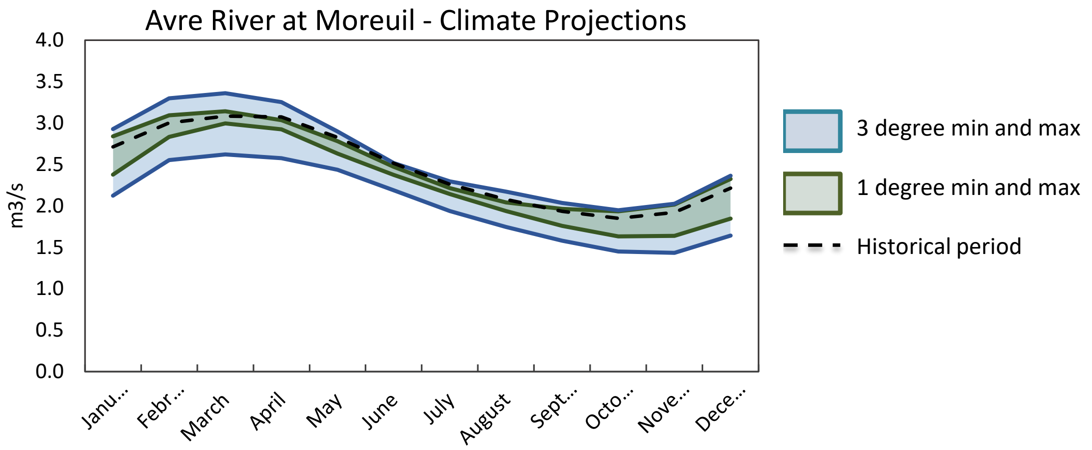


Figure 20 : Monthly mean Avre river discharge at Moreuil station calculated over 30 years for the reference period and for the Tactic standard scenarios

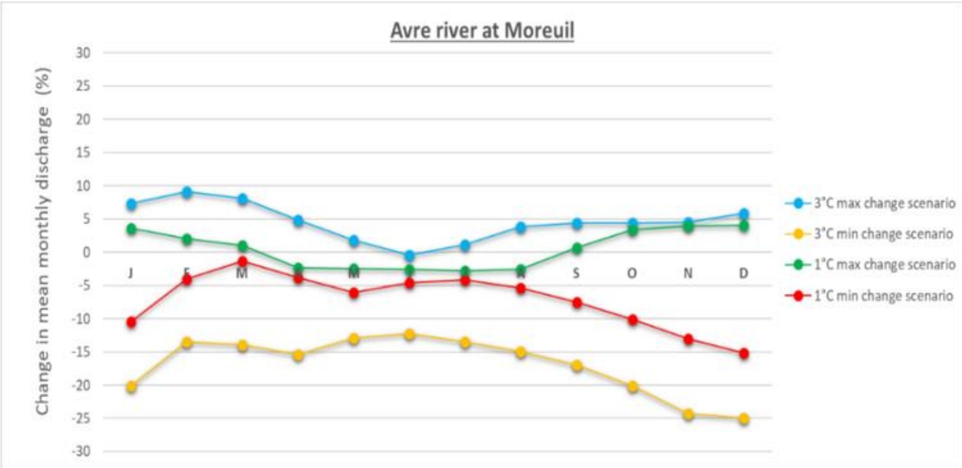


Figure 21 : Monthly mean seasonal cycles of the river discharges for the Avre River at the gauging station located at Moreuil. Results for the four Tactic future simulations are shown relative to the historical simulation.

5.3 Effects of adaptation scenarios on water resources

5.3.1 Effects on groundwater level

Figure 22 shows the change in average groundwater level over the 30-years period (1981-2010) induced by the SA1 adaptation scenario compared to the mean reference groundwater level simulated over the same period with current withdrawals. Reduction in drinking water withdrawals has a local impact at and around wellfield, in particular those located at the upstream of the Luce basin for which the rise in the water table appears significant with a maximum local groundwater level rise of +1.4 metres.

Figure 23 shows the change in mean groundwater level and average groundwater level of July, over 30 years, induced by the SA3 adaptation scenario compared to the mean reference groundwater level. Concerning the impact of SA3 scenario on the mean groundwater level, there is an increase in water table over a large area over the north of the basin. This is due to an important use of the irrigation on this part of the basin.

The impact of the SA3 adaptation scenario is much greater in July and August as shown on the right map in Figure 23. Indeed, as more than half of the annual volume used for irrigation is withdrawn between July and August, the impact on the water level is more important for these two months. The increase in the water table is greater on the plateaus (in particular the Santerre plateau) and at the head of watersheds than in the wet valley. The increase in the water table in July can reach 2.43 m locally for the AS3 scenario.

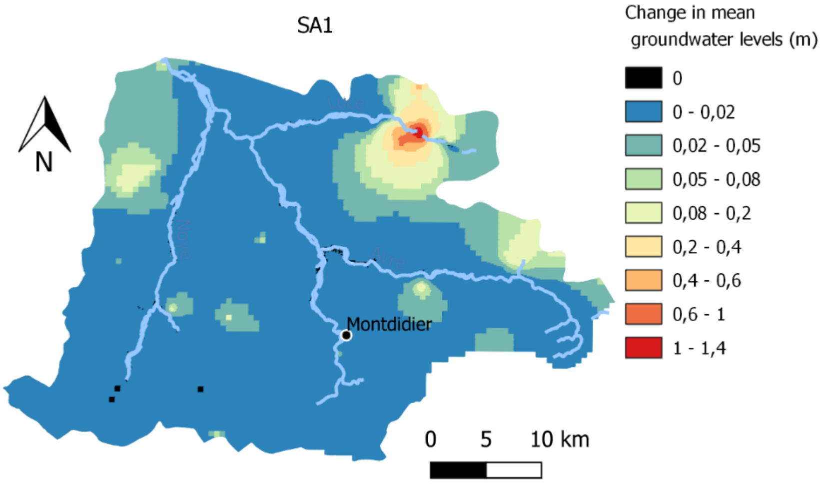


Figure 22 – Change in mean groundwater level for the SA1 adaptation scenario in relative to current situation.

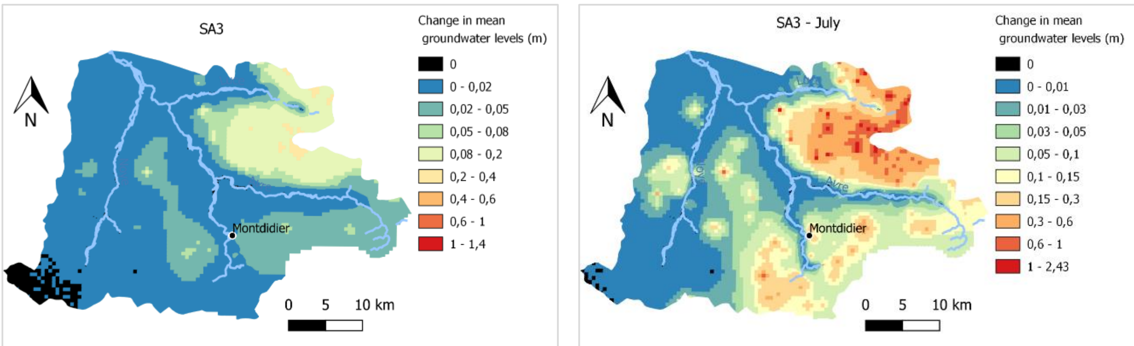


Figure 23 : Change in mean groundwater level over 30 years (map on the left) and in July mean groundwater level (map on the right) for the SA3 adaptation scenario in relative to current situation.

5.3.2 Effects on River flow

The impact of the tested adaptation scenarios on the river flow is quantified by comparing simulation results obtained for each adaptation scenarios to those obtained for the reference period (1981-2010) using current abstraction conditions. Figure 24 shows that the impact of the SA1 adaptation scenario on the mean monthly discharge of the Avre River at Moreuil is very low (less than 1%) and remains stable over the years. The impact of the SA3 adaptation scenario is significant during the irrigation period and reached 3.7% in July. The figure shows also that the impact of the current water abstraction (red curve) ranges between 4% and 10% depending on the considered month.

The impact on the Avre river flow is more visible at the upstream of the basin (i.e. the Saint-Mard gauging station in Figure 25 reaching 8.5% for the SA1 scenario and 7.5% for SA3 scenario.

Effects of current pumping(red curve) at the upstream of the Avre River and the Luce River is important, 10% to 30% and 18% à 40% respectively, as shown in Figure 25.

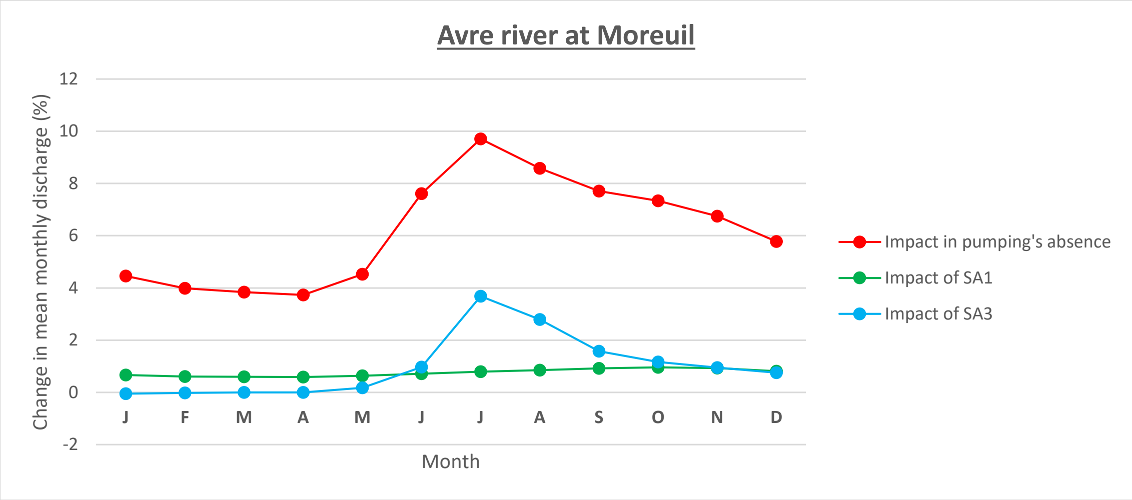


Figure 24 : Change (in %) of monthly mean discharge in Avre River at Moreuil for SA1 and SA3 adaptation scenarios compared to the reference period.

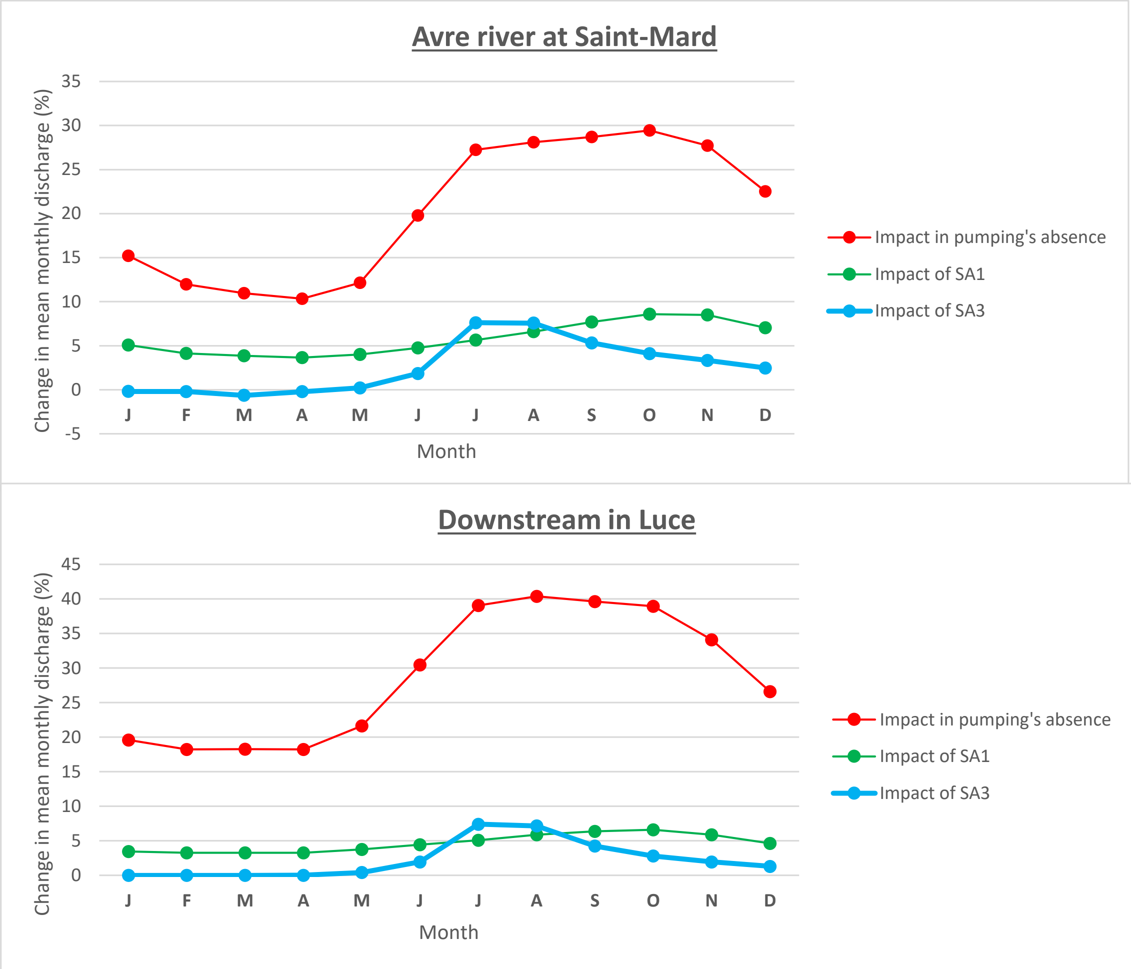


Figure 25 : Change (in %) in monthly mean discharge in Avre River at Saint-Mard and at the outlet of the Luce River for SA1 and SA3 adaptation scenarios compared to the reference period

5.4 Conclusion

For the Avre basin, dry scenarios with lower precipitations show higher impacts on the groundwater conditions than wet scenarios with higher precipitations. Such a result is due to a global increase of PET whatever the considered scenarios, meaning much less effective rainfall available for groundwater recharge for dry scenarios. Dry scenarios shows longer drought periods with decreases of groundwater levels during all the years that can reach about -6 m (on the plateaus) in periods of lower water table (e.g. in summer) in the worst scenario (i.e. the 3°C dry scenario). River discharges diminishes throughout all the year with -20 % of the river base flow expected for the 3°C dry scenario with respect to the 1981-2010 period. The wet scenarios shows increases of groundwater levels (reaching +1.5 m locally) and river discharges (+ 9% maximum) during winter. Absolute changes are nevertheless lower for the wet scenarios than for the dry scenarios.

Concerning the tested adaptation scenarios, the scenario assuming a drinking water withdrawals reduction has a local impact on groundwater level, at and around wellfield. On the other side, the scenario assuming an agricultural abstractions reduction has an impact on groundwater over a large area in Santerre plateau and Avre basin upstream where agricultural boreholes density is greater.
At the territorial level, the development of adaptation scenarios to mitigate climate change need to be done with territory actors. A participative approach involving the main actors of the territory (socio-economic actors, institutional users, etc.) and mobilizing foresight instruments should be privileged.
Finally, raising public awareness of the climate change effects on water resources and the implementation of several actions and adaptation measures will reduce the climate change effects on groundwater resources.

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TACTIC GROUNDWATER

GeoERA

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Deliverable D3.2

PILOT DESCRIPTION AND ASSESSMENT

Gort Lowlands, Ireland

Authors and affiliation:

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Owen Naughton[2,1]
Joan Campanya[2,1]
Taly Hunter Williams[1]

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Deliverable Data	
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Lead WP/Deliverable beneficiary	Geological Survey Ireland
Deliverable status	
Version	*Version 1*
Date	22/04/2021

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LIST OF ABBREVIATIONS & ACRONYMS

SAR	Synthetic Aperture Radar
API	Antecedent Precipitation Index
SMD	Soil Moisture Deficit

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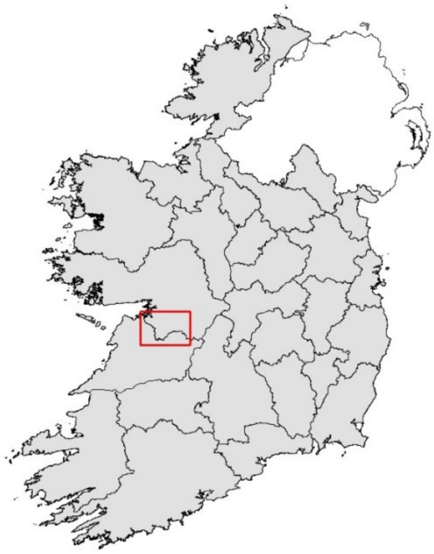
1 EXECUTIVE SUMMARY

Pilot name	Gort Lowlands	
Country	Ireland	
EU-region	Western Ireland	
Area (km^2)	480km^2	
Aquifer geology and type classification	Sedimentary. Porous and karstified Aquifer System	
Primary water usage	Drinking Water	
Main climate change issues	Increased risk of flooding	
Models and methods used	Earth Observation and Hydrological Modelling	
Key stakeholders	Local Authorities, Office of Public Works (Ireland)	
Contact person	Ted McCormack (Ted.McCormack@gsi.ie)	

This pilot describes the novel approach developed to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive. A monitoring network of over 50 sites was established during the winter of 2016/2017 to improve our understanding of groundwater flood regimes and provide baseline model calibration data. A methodology for delineating flood extents and water elevations from multi-temporal Synthetic Aperture Radar (SAR) imagery was developed to provide flood data from the 2015/2016 extreme flood event at gauged and ungauged sites. Maximum flood extents derived from SAR imagery from this event were combined with limited field observations to produce historic groundwater flood maps.

Identifying and mapping areas vulnerable to flooding is a key step in the management of flood risks. However, the nature of groundwater flooding on the lowland karst limestone plains of Ireland pose significant technical challenges in this respect. These areas are susceptible to groundwater flooding due to the combination of low soil and aquifer storage, high diffusivity and limited surface drainage. Unprecedented groundwater flooding in Ireland during winter

2015/2016 reinforced the need for a greater understanding of groundwater flooding as a geohazard and improve our ability to quantify the location and likelihood of flood occurrence.

Hydrological models capable of reproducing groundwater flooding time series from antecedent rainfall and soil moisture conditions were developed. Models for viable groundwater flooding locations were calibrated on a combination of observed and SAR hydrographs. Using long-term observational and stochastic meteorological series as input, the models have been used to construct long-term hydrological series suitable for extreme value analysis and the generation of predictive groundwater flood extents and maps.

Predictions of the future groundwater flood conditions are not clear in terms of the direction change. The impacts to groundwater flooding differ depending on the TACTIC scenario being applied. The dry scenarios indicate minor mean annual change in water levels and minor change in peak flood levels but with an increase in dry conditions during summer. The wet scenarios indicate an increase in mean water levels, an increase in peak levels and a reduction in dry conditions during the summer.

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 Gort Lowlands pilot represents a local scale study where the impacts of Climate Change on groundwater flooding is assessed. The winter of 2015/2016 saw unprecedented levels of rainfall across the Republic of Ireland. Over 600mm of rainfall fell across the island of Ireland between December and February, representing 190% of the long-term average and making it the wettest winter on record in a rainfall time series stretching back to 1850 (McCarthy et al., 2016; Noone et al., 2016). The sustained heavy rainfall caused exceptional and widespread flooding, with rivers across the country bursting their banks and registering some of the highest levels on record. The winter also saw the most extensive groundwater flooding ever witnessed on the karstic limestone plains in the west of Ireland (Naughton et al., 2017b). Here homes were flooded or cut off, roads submerged, and agriculture disrupted, with some affected areas remaining inundated for months after flooding had subsided elsewhere.

Groundwater flooding in Ireland is primarily associated with the lowland limestone areas of western Ireland. The prevalence of groundwater flooding in this region is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between ground and surface waters, which leaves them susceptible to groundwater flooding (Naughton et al., 2017a). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Mott MacDonald, 2010; Naughton et al., 2012). There are over 400 recorded examples of turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare.

Unlike fluvial flooding (or fluvially derived groundwater flooding due to seepage through permeable deposit riverbanks), where the flood is typically caused by high intensity rainfall, groundwater flooding in karst regions is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration.

In response to serious flooding during winter 2015, Geological Survey Ireland, in collaboration with Trinity College Dublin and Institute of Technology Carlow have developed a monitoring, mapping and modelling programme to address the knowledge gap regarding groundwater flooding in karst systems. The study is providing the requisite data to address the gap in groundwater hydrometric data by establishing a permanent telemetric network, as well as developing modelling tools to help address issues surrounding groundwater flood mapping and flood frequency estimation. A key output from this project is to devise and implement a novel approach to produce historic and predictive groundwater flood maps for Ireland in line with the 2nd implementation cycle of the EU Floods Directive.

The EU Floods Directive (Directive 2007/60/EC) requires all Member States including Ireland to reduce and manage the risks that all forms of flooding pose through the mapping of probabilistic flood extents and the establishment of flood risk management plans. For flooding from groundwater sources, the Floods Directive stipulates that Member States may decide that the preparation of flood hazard maps shall be limited to the scenario floods with a low probability, or extreme event scenarios. This was the approach taken for groundwater flood mapping during the first implementation phase of the Floods Directive, where an evidence-based method was used to map areas vulnerable to groundwater flooding (Mott Mc Donald, 2010). After the extensive flooding of the winter of 2015/2016 there was a requirement to incorporate this new information into updated historic groundwater flood maps. Furthermore, considering the increased frequency of groundwater flooding in recent decades, methodologies for the estimation of flood frequency would also provide a valuable tool for groundwater flood management.

It is in this context that Geological Survey Ireland has developed a groundwater flood mapping methodology for gauged and ungauged sites, which includes the first approach to groundwater flood frequency estimation undertaken in the State.

3 PILOT AREA

The Gort Lowlands is an extensively karstified lowland limestone catchment located in Co. Galway, on the western coast of Ireland. The hydrogeomorphological history of the Gort Lowlands is complex; recurrent karstification and glaciation of the Carboniferous limestone formations has created an extensive conduit and cave system that dominates groundwater flow. Variations in the lithology, stratigraphy, fracturing and faulting of the limestone bedrock have all played a role in shaping this subterranean system. So too has the nature of catchment recharge, with just over half of annual recharge supplied by rivers from adjacent non-carbonate mountains. Surface flow in the lowlands is intermittent and drainage is via the karst network which discharges at a series of intertidal and submarine springs along the coast.

3.1 Site description and data

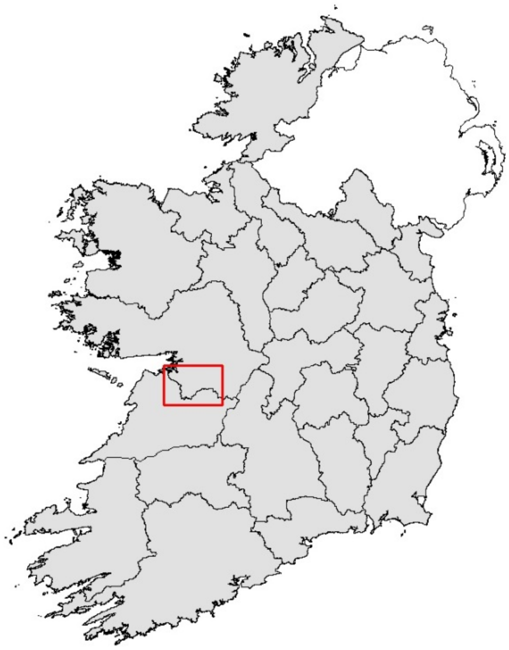


Figure 1: Location of Pilot Area

The Gort Lowlands is a 480 km2 catchment located in County Galway in the west of Ireland. The eastern portion of the catchment is dominated by the mountains underlain by Devonian Old Red Sandstone. The western portion of the catchment is mostly flat and underlain by pure carboniferous limestone. Similar to the majority of karstic regions found within Ireland, the catchment is primarily lowland (rarely rising above 30 m), and, as such, the region is subject to considerable interaction between ground and surface waters.

Average annual rainfall (1981–2010) across the region area ranges from more than 1500mm on the high ground, to approximately 1100mm in low-lying areas (Walsh 2012). The lowest monthly average rainfall generally occurs in April (60 to 80mm), followed by a gradual rise in average rainfall to the highest values between October and January (110 to 150mm). Recharge can be divided into those sources which originate within the karst body (autogenic) and those that originate from outside the karst aquifer (allogenic). Recent studies estimate that the discharge from the catchment is split approximately 55% allogenic to 45% autogenic in origin (McCormack et al. 2014).

The presence of ephemeral lakes known as turloughs is a key characteristic of Irish lowland karst regions. These lakes are described as topographic depressions in karst, which are intermittently flooded on an annual cycle via groundwater sources and have substrate and/or ecological communities characteristic of wetlands (Environmental Protection Agency, 2004). These seasonal lakes provide storage for excess recharge in the Gort Lowlands that cannot be accommodated by the groundwater system.

3.2 Climate change challenge

Regionally downscaled climate models indicate that future climate conditions in the pilot area will consist of reduced summer precipitation and increased winter precipitation (Nolan, 2015). These changes will result in an amplification of the seasonal flooding pattern already occurring within the catchment. This change in seasonal precipitation patterns, as well as the predicted increased frequency of storm events, will likely cause an increased risk of river, coastal and groundwater flooding.

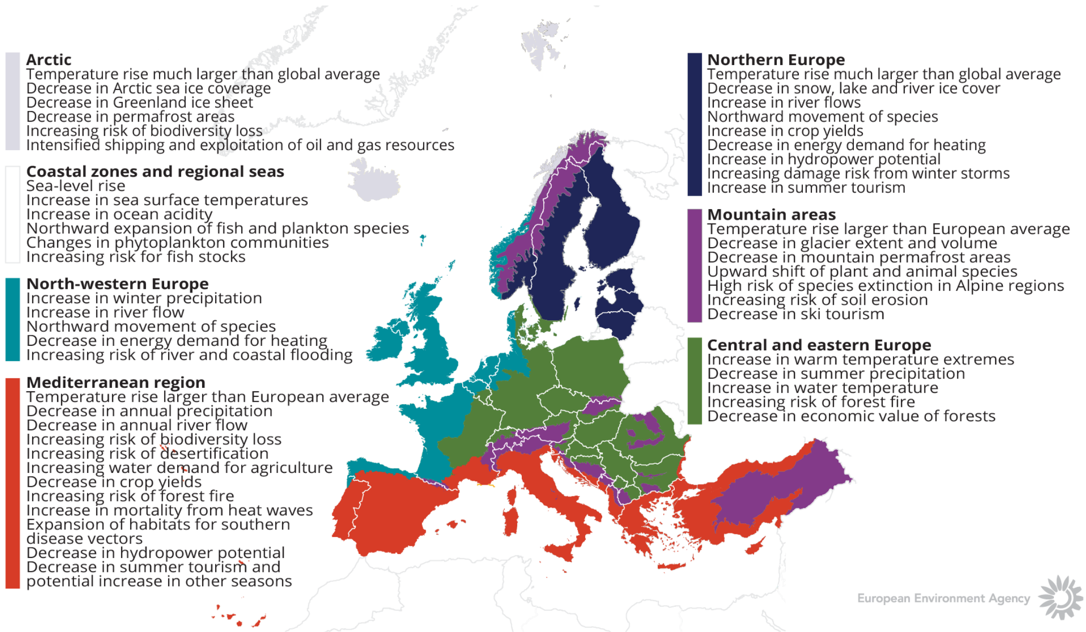


Figure 2: Observed and projected climate change and impacts for the main biogeographical regions in Europe (European Environmental Agency).

4 METHODOLOGY

Hydrological models capable of reproducing groundwater flooding time series from antecedent rainfall and soil moisture conditions were developed. Models for viable groundwater flooding locations were calibrated on a combination of observed and SAR hydrographs. Using long-term observational and stochastic meteorological series as input, the models have been used to construct long-term hydrological series suitable for extreme value analysis and the generation of predictive groundwater flood extents and maps. The modelling technique consists of two broad steps:

- Generation of hydrometric data using earth observation techniques.
- Hydrogeological modelling of flood sites based on

4.1 Climate data

Hydrogeological models require daily rainfall and evapotranspiration data from nearby weather stations. This data is obtained from the Irish National weather agency, Met Eireann.

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

4.1.1 TACTIC standard Climate Change scenarios

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

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

pilot basis to accommodate that the different scenarios have different impact in the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflects outliers.

5. Delta change values were calculated on a monthly basis for the four selected scenarios, based on the climate data from the reference period and the selected future period. The delta change values express the changes between the current and future climates, either as a relative factor (precipitation and evapotranspiration) or by an additive factor (temperature).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

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

Table 4.4.1-1. 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 Hydrological Modelling based on Earth Observation data

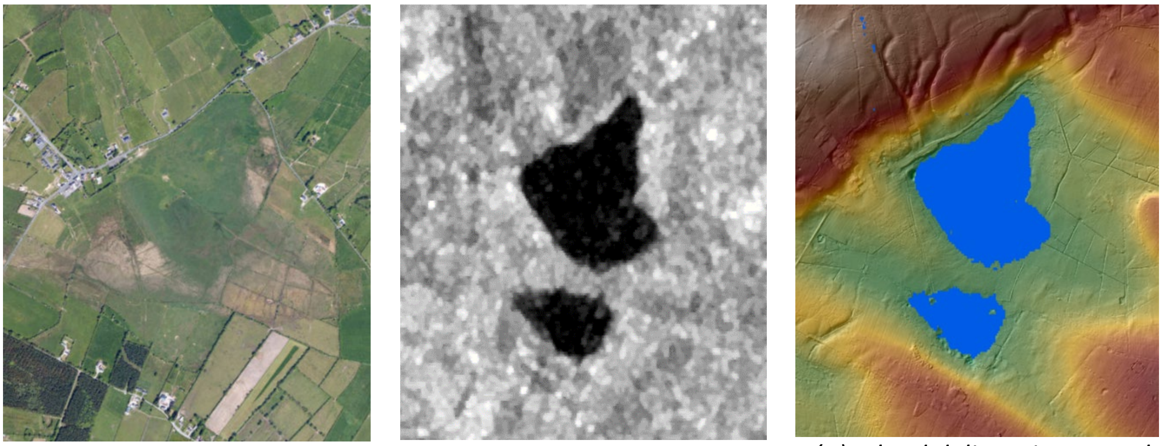
4.2.1 Generation of hydrometric data using earth observation techniques

While traditional monitoring is an effective tool for hydrometric data collection at priority sites, the distributed nature of groundwater flooding in karst lowlands hampers any systematic mapping efforts. Groundwater flooding occurs in isolated basins across the landscape. The large number and wide distribution of these basins makes them impractical to monitor using field instrumentation. Earth Observation and Geographical Information System (GIS) approaches offer significant advantages in this respect. The ability to describe and map how floods develop and recede accurately and at a large spatial scale is a prerequisite for effective flood risk management

Active systems, such as synthetic aperture radar (SAR), are particularly useful for flood mapping as they have a day-and-night capability and are not impacted by cloud cover. SAR systems emit radar pulses and record the return signal at the satellite. Flat surfaces such as water operate as specular reflectors for the radar pulses resulting in minimal backscatter signal returning to the satellite thus providing a contrast between dry and flooded areas. While interpretation of SAR images involves a degree of ambiguity due to factors such as speckle effects and dielectric properties, overall SAR systems offer a powerful tool for water delineation (see Figure 3).

The information gained from SAR imagery can be further enhanced by adding contextual information from high-resolution topographic mapping. The flood boundary can be cross-referenced against the topographic data to calculate the elevation of the land-water interface and thus the depth of water in the turlough. This methodology benefits from the fact that turlough flooding typically occurs in enclosed, isolated basins. As a result, and unlike river flooding scenarios, the water surface can be assumed to have a uniform elevation value.

An additional benefit of Sentinel-1 is the frequency of image capture; the satellites have been collecting imagery over Ireland at a 1 to 3 day revisit time since late 2014. While this revisit time may be inadequate for observing flash floods, which appear and dissipate within hours, it is suitable for monitoring groundwater flooding which occurs at a much slower rate (weeks to months). The considerable catalogue of Sentinel-1 imagery available has allowed us to track groundwater flood development through time. For sites with suitable size and topography characteristics the depth calculation process can be repeated for every satellite orbit enabling the generation of dynamic flood mapping and hydrographs.



(A): Orthophotography *(B): SAR imagery, March 2017* *(B): Flood delineation, March 2017*

Figure 3: Imagery of Castleplunket turlough showing (A) orthophotography of it empty, (B) pre-processed SAR flood image and (C) flood delineation overlaid on LiDAR data

Image processing techniques have been developed by the GSI in-house optimise detection of groundwater flood extents from SAR data. By combining satellite derived flood extents with high resolution topographic mapping, it is possible to extract water level information from each satellite image. This methodology enhances the accuracy of once-off flood extent maps as well as enabling the generation of historic flood hydrographs for previously unmonitored sites. The flood monitoring methodology consists of five broad stages (for more information, see McCormack et al. (2020)):

1. Data acquisition and pre-processing
2. Flood delineation using an automated, repeatable image thresholding algorithm
3. Image filtering & correction
4. Application of topography to establish the most probable land-flood interface elevation value.
5. Map and hydrograph generation

Hydrographs were generated for the 12 sites shown in Figure 4. Once complete, the hydrographs were then used as inputs to the hydrological models.

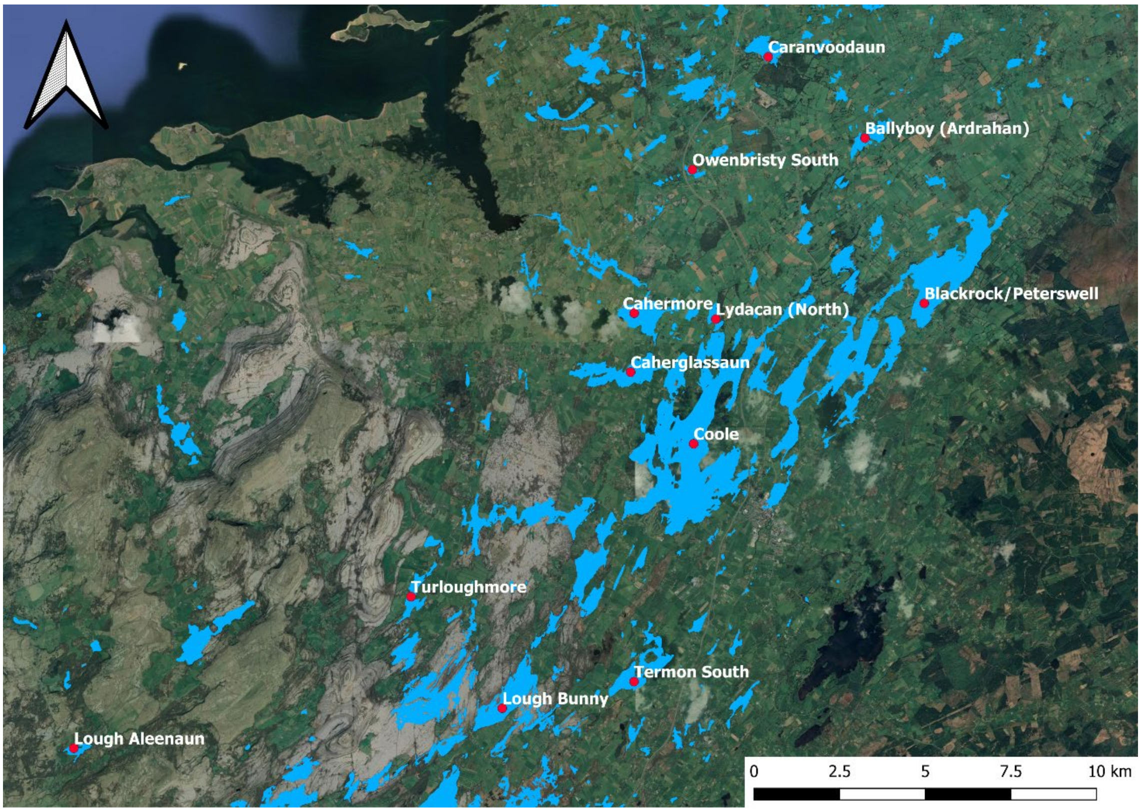


Figure 4: Locations of sites chosen for hydrograph generation and climate change modelling

4.2.2 Hydrological Modelling

Geological Survey Ireland developed a hydrological modelling methodology to quantify the relationship between rainfall and turlough flooding to reconstruct the requisite long-term hydrological series from observed and stochastic rainfall data.

There are two fundamental approaches to the mathematical modelling of karst hydrogeological systems; distributive models and global models. Given the limited data availability in Irish karst groundwater flow systems, and the required broad application of the methodology, a global modelling approach was deemed the most appropriate approach. Global (or lumped parameter) models concentrate on mathematically deriving a relationship between input and output; they consider the karst aquifer as a transfer function, transforming the rainfall input signal into the output hydrograph signal. The transfer function is taken to represent the overall (or global) hydrogeological response of the karst aquifer to recharge events (Kovacs and Sauter, 2007).

The primary objective of the global modelling approach was to develop predictive relationships between antecedent rainfall and flooding within individual turlough basins. Once established, this would allow the reconstruction of hydrological series sufficiently long for flood frequency analysis to be carried out and predictive flood levels to be estimated.

A version of the Antecedent Precipitation Index (API) (Kohler and Linsley, 1951; Smakhtin and Masse, 2000) was used to model flood behavior. The API assumes the effect of antecedent precipitation can be represented by catchment or site-specific recession coefficient (Beschta, 1998). A modified version of the API, the Current Precipitation Index (CPI) (Smakhtin and Masse, 2000), has been used to model turlough flood volumes and is given by:

$$CPI = \sum_{t=-1}^{-i} R_t k^{-t}$$

Where *i* is the number of antecedent days, *k* is a decay constant and R_t is recharge on day *t*. The coefficient *k* represents the percentage water that remains after a specified time interval; a large *k* leads to a slow recession after the cessation of rainfall while a small *k* indicates a quick recession (Lee and Huang, 2013). To ensure convergence and remove the influence of initial conditions on analysis, effective rainfall series beginning at least one year before the corresponding hydrological series were used in the calculation of the CPI. CPI series using a range of *k* values were generated, with the *k* value showing the highest correlation with observed volume selected. The model then took the form of a simple linear regression between the CPI (predictor) and flood volume (response) where:

$$V = S + C * CPI$$

where *S* is the intercept *C* is the slope. Conceptually the intercept *S* represents a groundwater storage term, or the volume of water required to have built up in the karst groundwater flow system before flooding occurs. The slope term *C* represents a notional contributing area, defining the minimum zone of contribution required to supply the recorded water volume.

A soil moisture deficit (SMD) model was used to estimate recharge based on the SMD model developed for Irish grasslands by Schulte et al. (2005). The soil and unsaturated zone were represented as a single reservoir with the flux in the reservoir dependent on the inputs and outputs, namely rainfall (R) as input and actual evapotranspiration (ET_A) and recharge (R_E) as output.

4.2.3 Calibration

Accuracy for both remote sensing data generation and hydrological modelling was calibrated and validated a network of water level monitoring stations installed at flood hazard areas throughout the Gort Lowlands. Goodness of fit for the SAR hydrograph process was assessed using Nash-Sutcliffe Efficiency (NSE) for flood volume (volume is preferred to stage as it prioritises model efficiency at high flood conditions).

Observed water level data were compared to SAR derived hydrographs at a subset of sites and the hydrograph generation variables were tweaked to achieve maximum efficiencies. Nash Sutcliffe efficiency coefficients of between 0.95 and 0.7 were achieved at the test sites. See Figures 5-7 for examples.

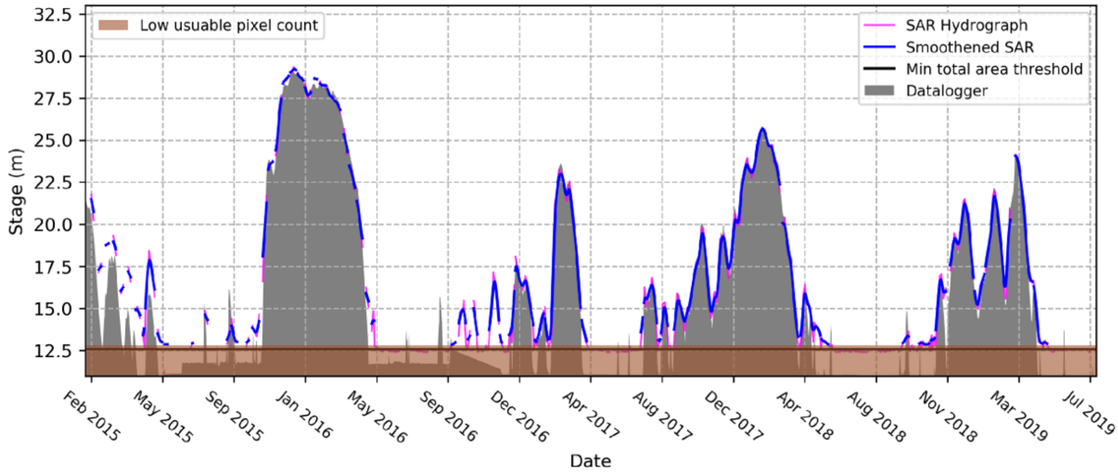


Figure 5: SAR Derived hydrograph for Blackrock Turlough.

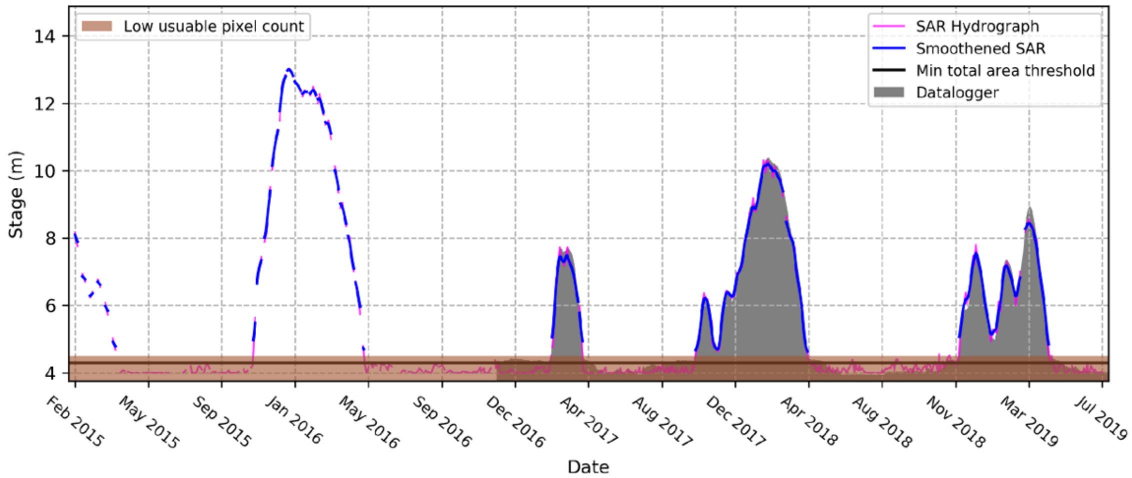


Figure 6: SAR Derived hydrograph for Cahermore Turlough

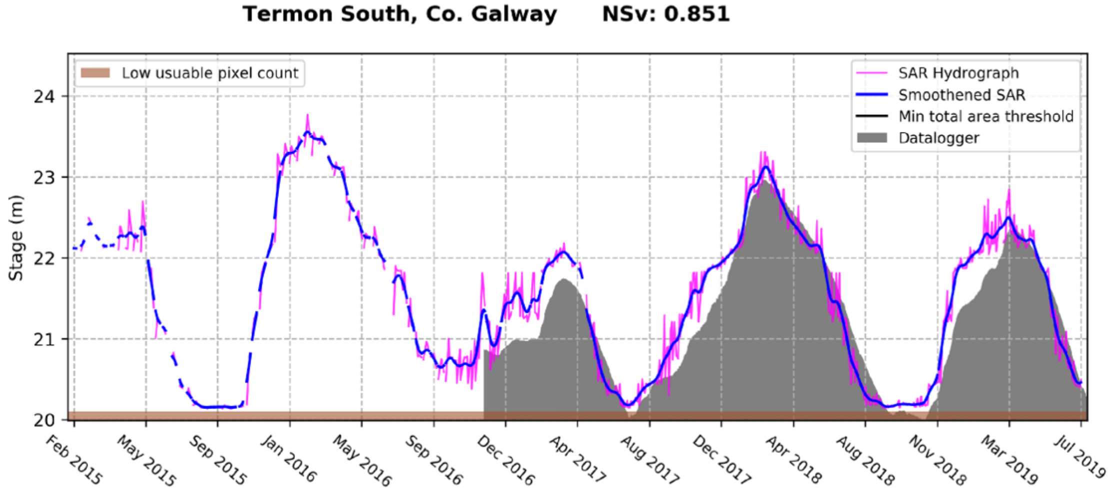


Figure 7: SAR Derived hydrograph for Termon South

Models were calibrated using a combination of observed and SAR hydrographic data see Figure 8 and Figure 9 for examples). Goodness of fit was assessed using the NSE, percentage bias (PBIAS), and annual maxima error (AmaxE) criteria for volume. The average NSE value for all accepted models was 0.80.

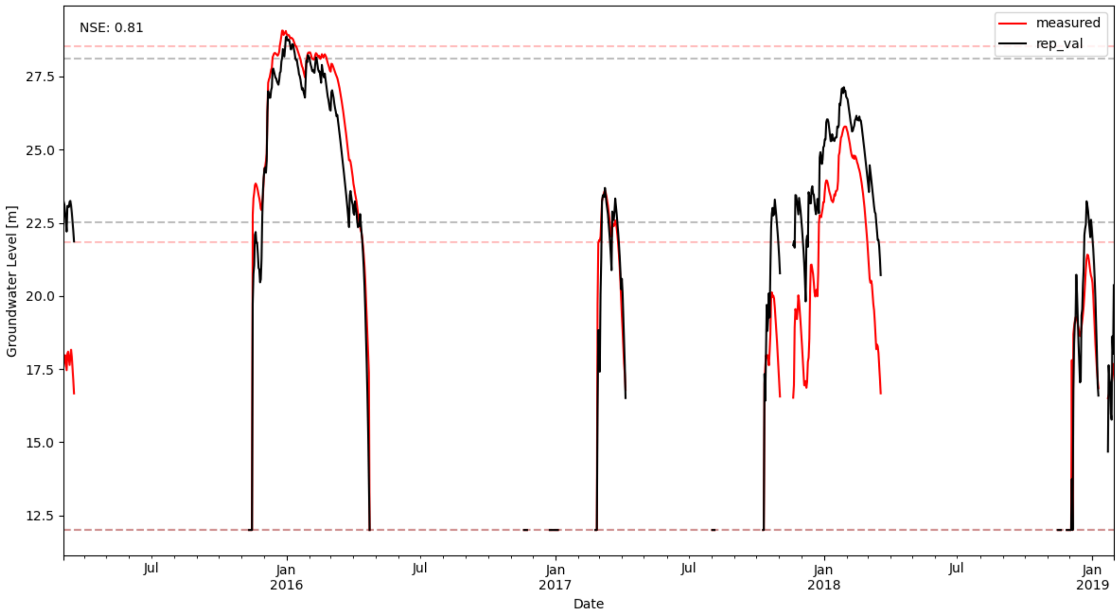


Figure 8: Observed (red) and modelled (black) hydrograph. Blackrock Turlough, Co. Galway.

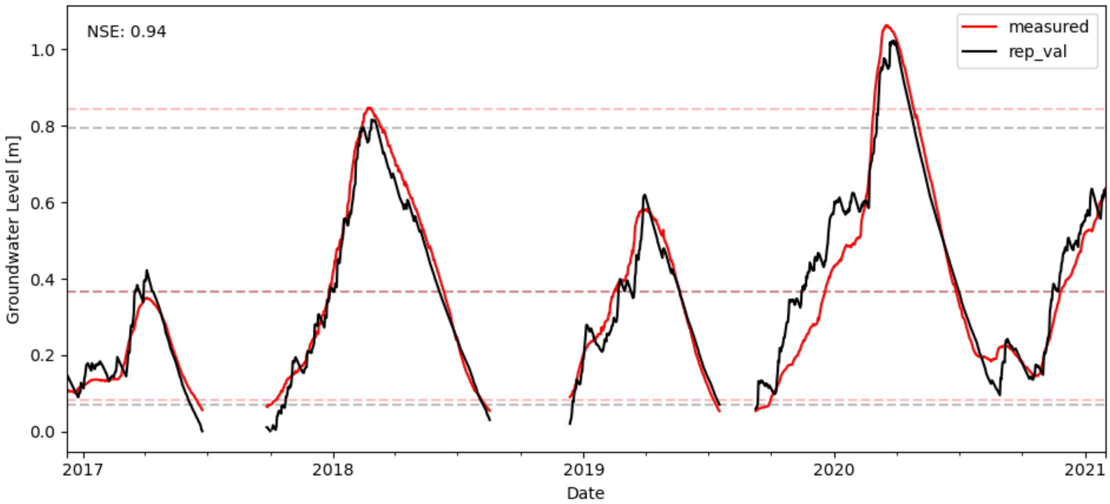


Figure 9: Observed (red) and modelled (black) hydrograph. Termon South, Co. Clare.

5 RESULTS AND CONCLUSIONS

5.1 Hydrological Modelling based on Earth Observation data

Once calibrated, the models were run for the reference period as well as for the TACTIC standard scenarios. Modelling the TACTIC scenarios consisted of applying the delta change factors to precipitation and reference evapotranspiration (the models to not require temperature). In the Gort Lowlands, the delta change factors for precipitation varied between 1.3 and 0.77 (see Figure 10) whilst evapotranspiration only varied between 1.07 and 0.993.

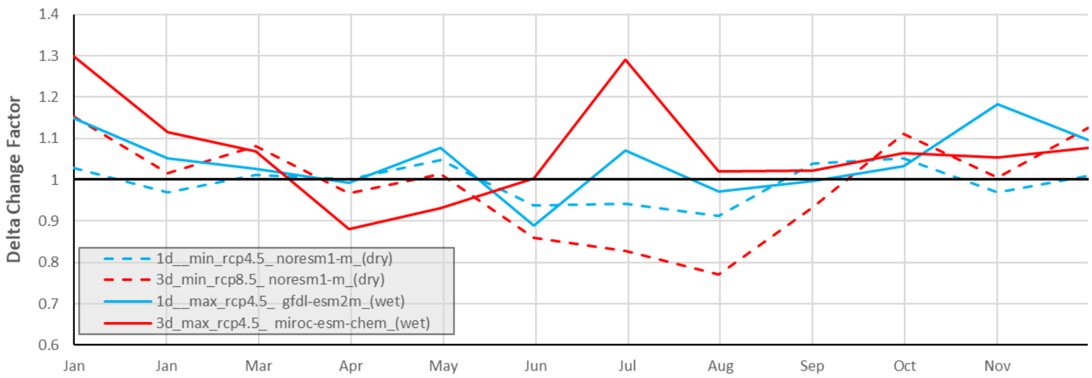


Figure 10: Delta Change Factors for precipitation in the Gort Lowlands. Factors for 1 and 3 degree change are shown in blue and red respectively. "Wet" scenarios are shown as unbroken lines and "Dry" scenarios are shown as solid lines.

Outputs from the 12 models was produced in the format of daily timeseries of water levels over the specified time period. For the purposes of consistency and comparison with other TACTIC pilot studies, the model results are presented here as mean water levels over the analysis period and changes to mean water levels due to climate change. The mean water levels for the reference period and for the TACTIC scenarios are presented in Table 5.1-1 and the relative changes in mean levels are shown in Table 5.1-2.

Table 5.1-1: Mean Water levels for individual sites over the reference period and TACTIC scenarios

Site Name	Reference Period	1d min (dry) rcp4.5 noresm1-m	1d max (wet) rcp4.5 gfdl-esm2m	3d min (dry) rcp8.5 noresm1-m	3d max (wet) rcp4.5 miroc-esm-chem
Termon South	21.15	21.07	21.29	21.12	21.41
Lough Aleenaun	72.70	72.65	72.78	72.66	72.82
Blackrock	14.57	14.53	14.98	14.82	15.43
Coole Lough	5.35	5.19	5.56	5.25	5.80
Caherglassaun	4.74	4.64	4.93	4.72	5.13
Caranavoodaun	23.52	23.48	23.58	23.49	23.63
Turloughmore	27.60	27.57	27.67	27.57	27.69
Lough Bunny	16.91	16.89	16.94	16.89	16.97
Cahermore	5.47	5.47	5.62	5.61	5.83
Ballyboy	29.90	29.89	29.96	29.95	30.04
Owenbristy	18.04	18.03	18.09	18.06	18.14
Lydican	13.92	13.89	13.99	13.92	14.06

Table 5.1-2 Relative changes in mean water levels between the reference period and TACTIC scenarios

Site Name	1d min (dry) rcp4.5 noresm1-m	1d max (wet) rcp4.5 gfdl-esm2m	3d min (dry) rcp8.5 noresm1-m	3d max (wet) rcp4.5 miroc-esm-chem
Termon South	-0.07	0.14	-0.02	0.27
Lough Aleenaun	-0.05	0.08	-0.04	0.12
Blackrock	-0.05	0.41	0.25	0.86
Coole Lough	-0.16	0.22	-0.10	0.45
Caherglassaun	-0.10	0.19	-0.02	0.39
Caranavoodaun	-0.04	0.06	-0.02	0.11
Turloughmore	-0.03	0.07	-0.03	0.09
Lough Bunny	-0.02	0.03	-0.02	0.05
Cahermore	0.00	0.15	0.14	0.36
Ballyboy	-0.01	0.07	0.05	0.14
Owenbristy	-0.01	0.05	0.02	0.10
Lydican	-0.03	0.07	0.00	0.14
Average	-0.05	0.13	0.02	0.26

Further summary statistics are presented in Table 5.1-3 and Table 5.1-4 which show the change in maximum water levels and number of dry days (i.e. the number of days the turlough is empty, typically in summer) respectively.

Table 5.1-3: Relative changes in maximum water levels between the reference period and TACTIC scenarios

Site Name	1d min (dry) rcp4.5 noresm1-m	1d max (wet) rcp4.5 gfdl-esm2m	3d min (dry) rcp8.5 noresm1-m	3d max (wet) rcp4.5 miroc-esm-chem
Termon South	-0.01	0.31	0.27	0.54
Lough Aleenaun	-0.15	-0.01	-0.08	0.31
Blackrock	-0.09	-0.01	-0.22	0.50
Coole Lough	-0.12	0.06	0.17	0.43
Caherglassaun	-0.15	0.02	0.26	0.52
Caranavoodaun	-0.06	0.03	0.08	0.20
Turloughmore	-0.06	-0.03	-0.04	0.11
Lough Bunny	-0.03	0.00	0.05	0.12
Cahermore	-0.01	0.33	0.59	0.99
Ballyboy	-0.03	-0.01	-0.07	0.13
Owenbristy	-0.06	0.01	0.09	0.21
Lydican	-0.09	0.14	0.18	0.33
Average	-0.07	0.07	0.11	0.37

Table 5.1-4: Relative changes in number of annual dry days (i.e. the turlough is empty) between the reference period and TACTIC scenarios

Site Name	1d min (dry) rcp4.5 noresm1-m	1d max (wet) rcp4.5 gfdl-esm2m	3d min (dry) rcp8.5 noresm1-m	3d max (wet) rcp4.5 miroc-esm-chem
Termon South	7.21	-8.28	5.89	-12.80
Lough Aleenaun	6.51	-1.04	8.91	-0.64
Blackrock	1.83	-3.14	0.77	-6.24
Coole Lough	4.66	-2.23	5.74	-4.42
Caherglassaun	3.92	-2.91	5.05	-4.96
Caranavoodaun	6.02	-3.65	7.72	-3.47
Turloughmore	4.58	-5.93	5.67	-3.53
Lough Bunny	5.18	-3.03	8.27	-1.67
Cahermore	0.65	-2.42	-1.22	-5.87
Ballyboy	0.75	-2.60	-0.77	-5.59
Owenbristy	3.31	-3.11	2.79	-6.73
Lydican	0.03	-0.03	0.03	-0.07
Average	3.72	-3.20	4.07	-4.66

From Table 5.1-2 it can be seen that average water levels in the turloughs show consistent reductions under the 1 degree dry scenario and mixed impacts under the 3 degree dry scenario. However, the impacts of these dry scenarios are relatively minor with most sites presenting changes of less than 5cm. For the wet scenarios the impacts are more significant. The average change in the 1 degree wet scenario is a 0.13m increase while the 3 degree wet scenario shows a 0.26m increase (with one site, Blackrock, increasing by 0.86m).

The seasonal effects of the TACTIC delta change factors are presents in Table 5.1-3 and Table 5.1-4. From these tables it can be seen that the dry scenarios show mixed changes in peak water levels (7cm drop for 1 degree and 11cm rise for 3 degree) but a consistent increase in dry days per year (+3.7% and +4.1%). This indicates that the winter levels are not dramatically changed but the summer is significantly dryer resulting in longer periods of without groundwater flooding. These findings broadly follow the dry scenario delta change factors as shows in Figure 10 which show mixed winter impacts but consistent dryer summer months. In contrast, the wet scenarios show consistent impacts from increased rainfall throughout the year. The maximum flood level is increased and the number of dry days is reduced.

5.1.1 Conclusions

Predictions of the future groundwater flood conditions are not clear in terms of the direction change. The impacts to groundwater flooding differ depending on the TACTIC scenario being applied. The dry scenarios indicate minor mean annual change in water levels and minor change in peak flood levels but with an increase in dry conditions during summer. The wet scenarios indicate an increase in mean water levels, an increase in peak levels and a reduction in dry conditions during the summer.

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

Boutonne Basin (France)

Authors and affiliation:

Nadia Amraoui, Jean-Pierre Vergnes

French Geological Survey (BRGM)

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LIST OF ABBREVIATIONS & ACRONYMS

BDGSF	Base de Données Géographique des Sols de France
CC	Climate Change
DEM	Digital Elevation Model
EEA	European Environment Agency
FAO	Food and Agriculture Organisation of the United Nations
GCM	Global Circulation Model
GSOs	Geological Survey Organisations of Europe
IGN	Institut national de l’information géographique et forestière
ISIMIP	Inter Sectoral Impact Model Intercomparison Project
ME	Mean Error
NSE	Nash Sutcliffe Efficiency
PET	Potential evapotranspiration
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
SPLI	Standardized Piezometric Level Index
TACTIC	Tools for Assessment of Climate change ImpacT on Groundwater
SYMBO	Syndicat Mixte du Bassin de l’Or
OUGC	Organismes Uniques de Gestion Collective

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1 EXECUTIVE SUMMARY

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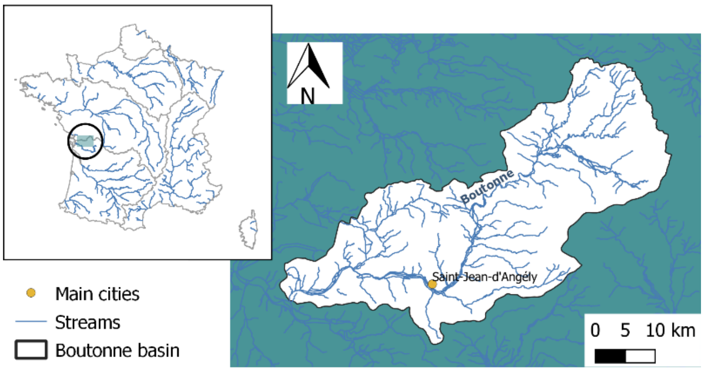
<tr><td>Pilot name</td><td>Boutonne basin</td><td rowspan="6">
</td></tr>
<tr><td>Country</td><td>France</td></tr>
<tr><td>EU-region</td><td>North Western Europe</td></tr>
<tr><td>Area (km^2)</td><td>1320</td></tr>
<tr><td>Aquifer geology and type classification</td><td>Limestones; fissured & karstifed aquifer</td></tr>
<tr><td>Primary water usage</td><td>Irrigation/Drinking water/Industry</td></tr>
<tr><td>Main climate change issues</td><td colspan="2">Climate variability and change influence groundwater systems and associated ecosystems both directly through recharge and indirectly through changes in groundwater use. Projected climate change might exacerbate the current tensions due to water scarcity in some sub-basin of south west of France like Charente basin. Indeed the Boutonne basin is experiencing an imbalance between available water resources and needs with important socio-economic issues for agricultural activities. Several droughts periods have been recorded in the last decades, this situation is likely to worsen under future climate, and would affect the volume of water available for different uses. Assessment of climate change impacts on water reserves and on drought severity is important for future land use planning and water resource management. Futhermore, preventing of winter flooding is also a major issues on certain points, particularly in the vicinity of the town of Saint Jean d'Angély.</td></tr>
<tr><td>Models and methods used</td><td colspan="2">Integrated Hydrological model (Numerical model, time series analysis …)</td></tr>
<tr><td>Key stakeholders</td><td colspan="2">Water Agency; SYMBO (drinking water); OUGC Saintonge (irrigation control); agricultural profession (ASA Boutonne).</td></tr>
<tr><td>Contact person</td><td colspan="2">Nadia Amraoui, BRGM French Geological Survey, n.amraoui@brgm.fr</td></tr>
</table>

The pilot of Boutonne basin is located in the west of France. The Boutonne River is the longest and the closest tributary to the mouth of the Charente River. *Aquifers in this basin correspond to sedimentary carbonate formations locally karstified*. The Jurassic aquifers (upper Jurassic, Dogger and Infra Toarcian) represent the main groundwater resource for irrigation demands and drinking water supply. The main challenge is the sustainable water resources management in connection with aquatic environments. The Boutonne basin is experiencing, in recent decades, an imbalance between available resources and needs with important socio-economic issues for agricultural activities and environmental issues.

In the framework of TACTIC project, a study of climate change impacts on aquifer recharge, groundwater levels and river discharges has been performed using the TACTIC standard climate change scenarios and the regional hydrological model of Jurassic aquifers developed with the BRGM's MARTHE computer code. It allows the simulation of flows in aquifers and river networks, including climatic and human influences. The methodology applied in this assessment is based on selected TACTIC scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to reference period (1981-2010), under wet and dry precipitations conditions, and on the hydrological model of the Jurassic aquifers, which simulates groundwater conditions over the reference period. Four datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. This assumes that the evolution of climatic variables is the same for the current and the future climate. Otherwise, change in groundwater abstraction in the future climate scenarios is not considered. The impact is quantified by comparing simulated results obtained with the data provided by each Tactic standard scenario for future to those simulated on the reference period (1981–2010). Annual changes in average groundwater recharge and mean groundwater levels are analysed and the seasonal responses of the system are examined at local scale in some piezometers and at stream gauges.

Predictions of future groundwater reaction to TACTIC climate change scenarios are contrasted and depend on the evolution of future precipitation (dry scenario or wet scenario). Changes are amplified in the +3 degree wet and dry scenarios compared to the +1 degree scenarios. Results show that, for +3 degree scenarios, future mean groundwater recharge is expected to increase for both dry and wet scenarios (+2% and 19% respectively) compared to recharge for the historical period leading to an increase of mean shallow groundwater level. Increase of shallow groundwater levels would concern all seasons exept spring in the case of the +3 degree wet scenario for upper Jurassic aquifer and all season for Dogger aquifer; however, the drop in the water level is more marked in summer and in autumn for the + 3 degree dry scenario.
River discharge is expected to increase in winter for all Tactic Scenarios ; Increase is more important for the +3 degree scenarios (dry and wet). However, for +1 degree and + 3 degree dry scenarios, low flows would be comparable to the reference period or slightly more severe.

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, 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 present document reports on the work carried out within the TACTIC project on Boutonne pilot located in the northern part of Charente Basin in the west of France. Among the major challenge in this basin is the sustainable water resources management in connection with aquatic environments, in particular the controlled management of low water levels and winter flooding risk. In this study, climate change impacts on groundwater levels and river flow will be addressed. The challenge is to assess its effects on groundwater recharge and river flow in low and high water conditions.

3 PILOT AREA

The Boutonne pilot site is located in the west of France. Jurassic sedimentary aquifers represent the main groundwater resource for irrigation demands and drinking water supply. A natural and complex groundwater - surface water interactions is observed during low water periods. Since 1990, this basin is experiencing an imbalance between available resources and needs with important socio-economic issues for agricultural activities and environmental issues (compliance with low flow rates compatible with the functioning of aquatic environments). Several drought periods have been recorded in the last decades, this situation might be exacerbated in the future due to the climate change effects. In this project, potential future impacts of climate change on the groundwater and surface water will be assessed according to different climate change scenarios.

3.1 Site description and data

3.1.1 Location of pilot area

The pilot site of the Boutonne basin covers an area of approximately 1320 km2. It is located in the west of France (Figure 1), in the department of Deux-Serves (500 km²) for its upstream portion, and in the department of Charente-Maritime (820 km²) for its downstream part. The Boutonne River is the closest tributary to the mouth of the Charente River.

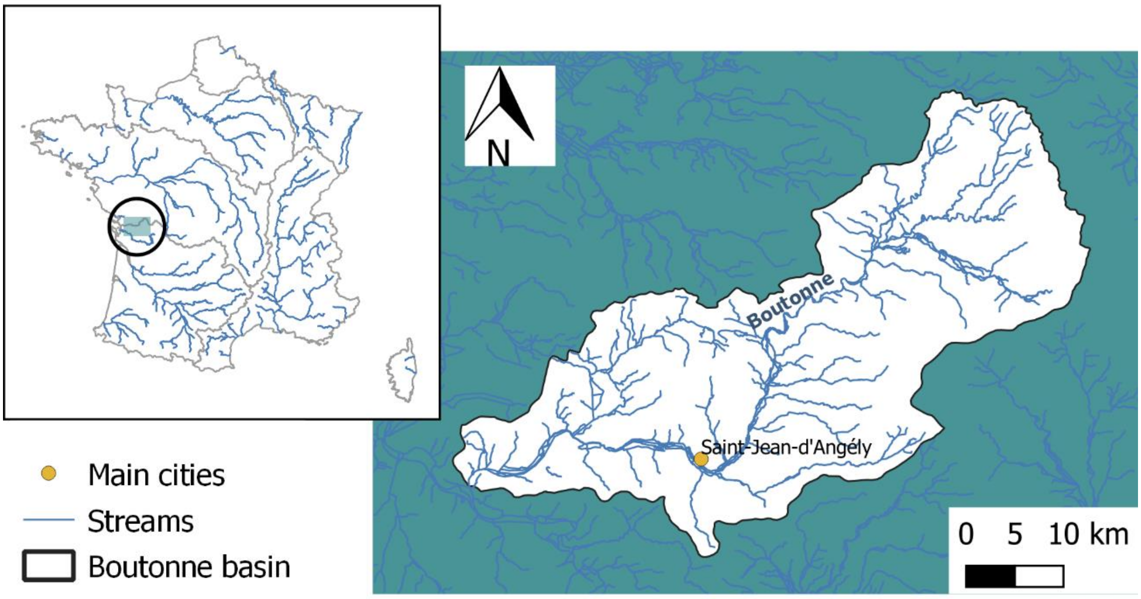


Figure 1: Location of the pilot area

3.1.2 Climate

Located not far from Atlantic Ocean, the Boutonne basin has a temperate oceanic climate with cool and well-watered winters and inter-seasons, and hot and dry summers.

The meteorological data (rainfall, temperature and Potential Evapotranspiration "PET") are available in daily time steps in both meteorological stations located in the Boutonne basin over a regular grid of 8-km resolution given by the meteorological analysis system SAFRAN (Quintana-Segui et al. 2008). The mean annual rainfall ranges between 820 mm in the north (Brioux meteorological station) and 910 mm in the south of the basin (St-Jean- d'Angély meteorological station). At the basin scale, the mean annual rainfall and PET values calculated over period 1958-2018 are 850 mm/year and 822 mm/year respectively (see Figure 2 for rainfall).

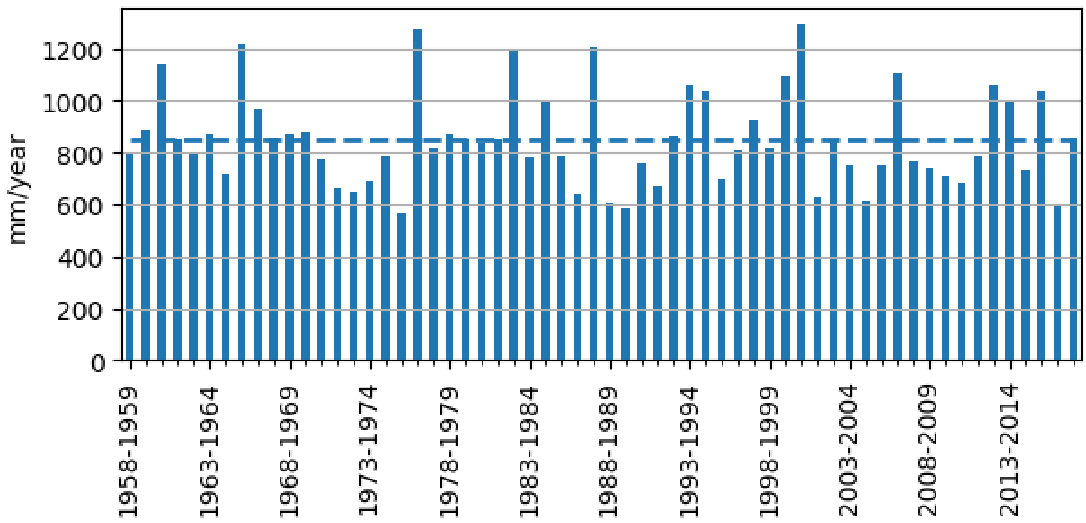


Figure 2 : Time series of the precipitation (mm/year). The dashed line corresponds to the mean value over period.

3.1.3 Topography and soil types

The Boutonne basin is mainly composed of plains. The topography varies from 3 metres (above sea level a.s.l) at the downstream of the Boutonne River at the confluence with the Charente River and can reach 190 metres (a.s.l) at the upstream of the basin (Figure 3). The digital elevation model (DEM) data are available at a 25-m spatial resolution. Four major soils types are present in the basin according to Geographical Database of French Soils: Luvisoil on the Miellois plateau, Cambisols and regosoils in the large part of basin and Fluvisoil in the valley bottoms (Figure 4).

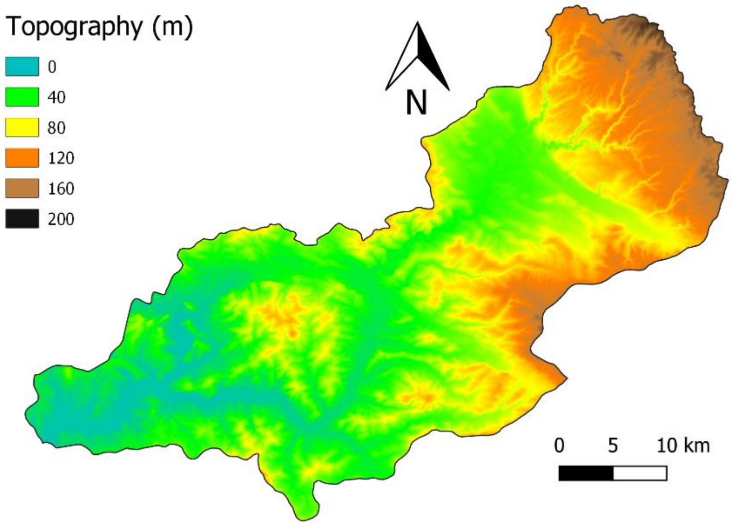


Figure 3 : Topography of Boutonne pilot site (DEM with grid resolution of 25 m, IGN)

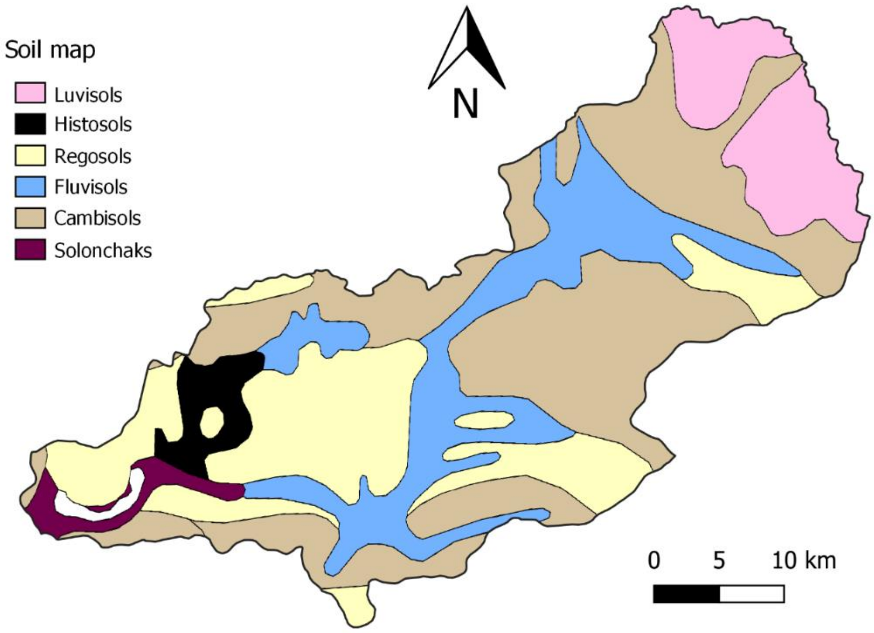


Figure 4 : Soil map of Boutonne basin from BDGSF (Geographical Database of the French Soils)

3.1.4 Geology/Aquifer type

- Geology

The Boutonne basin corresponds geologically to the northern edge of the Aquitaine basin, characterized by the outcrop of Jurassic horizons, covered by transgressive deposits of the Upper Cretaceous (Cenomanian series). The general basin structure and the different geological levels encountered are illustrated in the Figure 5.
Oriented globally northeast / southwest, the basin is mainly located on the Jurassic formations. The northern half of the basin is characterized by the presence of faults aligned along ONO-ESE

direction that structure the landscape. The northern part of the basin corresponds to the southern part of the Melle Dome, which is characterized by the Lias and Dogger formations. This dome is limited by two major faults that surround the Boutonne valley and collapse the basement more than 100 meters (Figure 5). The basement is visible in the Béronne valley and gradually dipping southward under Jurassic and Cretaceous sedimentary formations. Thereby the most recent formations are outcropping to the south of the basin, while the older ones are visible at the outcrop to the north.
In the southern part of this fault system, there is a second compartment limited to the south of Chizé by another fault. Outcrops of the Oxfordian and basal Kimmeridgian (Upper Jurassic) characterize this compartment. South of Dampierre, a major fault aligned along ONO-ESE direction delimits the downstream part of the Boutonne valley characterized by outcrops of the Upper Kimmeridgian (Upper Jurassic), Tithonian and Cretaceous.

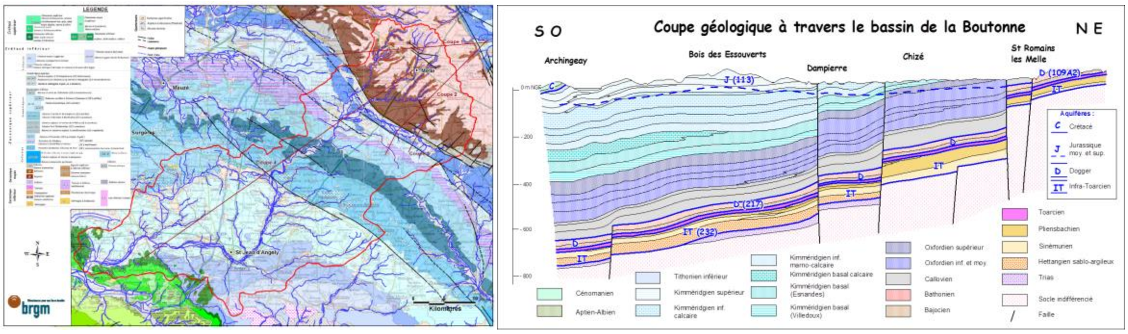


Figure 5 : Geological map and geological cross section through the Boutonne basin *[Lavie J. (2005) after Lemordant Y. (1998)]*

- *Aquifer type*

Aquifers in the study area correspond to sedimentary carbonate formations locally karstified. Four main aquifers are identified in the Boutonne basin in the stratigraphic order:
The Lower Jurassic or Infra-Toarcian aquifer (Lias): this reservoir consists essentially of dolomitic and sandstone limestones of the Pliensbachian, Hettangian and Sinemurian sedimentary formations. This aquifer rests on a bedrock, which constitutes its substratum. Groundwater is mainly confined under Toarcien marl, the thickness of the reservoir can reach 60 meters. This aquifer is recharged by the effective precipitations, by the faults affecting the series and being able to put in contact this aquifer with another more superficial one (Dogger) and probably by losses of rivers (Béronne, Légère) in the areas where the aquifer is outcropping.
The Middle Jurassic or Dogger aquifer: This aquifer is composed of all the Dogger stratigraphic units. The reservoir is mainly constituted by Oolitic limestones. The Bathonian is particularly karstified. This aquifer rests on the Toarcian marls that separate it from the underlying aquifer of the Infra-Toarcien. The total thickness of this aquifer can reach 50 m on the studied area.
Groundwater is mainly unconfined in the whole area north of the Boutonne Faults; the aquifer becomes confined by sinking under the marly formations of the Callovian and the Oxfordian. Groundwater flow directions in this aquifer are comparable to those of the infra-Toarcien aquifer (Figure 6). More locally and on its unconfined part, it follows the flow directions of the hydrographic network.

Upper Jurassic aquifer: Located south of the Secondigné-Chef-Boutonne fault corridor, this aquifer, with heterogeneous characteristics, consists of marl-limestone series that are altered on the surface. The substratum of this aquifer is formed by a characteristic level, locally called "blue bench", which means unmodified gray marly limestones, located at 20 to 30 meters deep. This is an unconfined aquifer drained by streams in some areas or draining streams in others. Interactions between groundwater and surface water are complex and can be reversed according to the seasons.

The Upper Cretaceous (Cenomanian) aquifer: Located in the confluence area between the Boutonne and the Charente, the Cenomanian aquifer corresponds to sand, sandstone and limestone with clay levels, which results in a multiplication of interconnected or independent reservoir levels. Groundwater is unconfined free but can be locally confined under an impermeable level.

Other aquifers, more marginal, are encountered on this basin. North of the Boutonne fault, the tertiary surface formations, sometimes reservoir, are drained by small springs or by the underlying Dogger groundwater. The quaternary alluvium and colluvium, because of their small thickness (a few meters at most), constitute "relay" horizons for the large underlying aquifers that are drained by rivers.

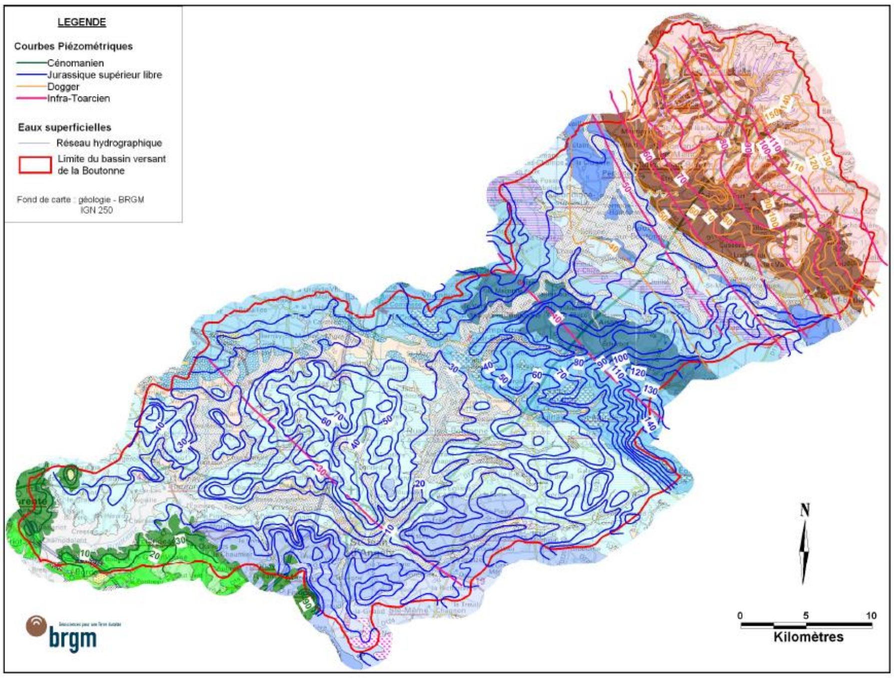


Figure 6 : Piezometric map of Jurassic aquifers showing the main groundwater flow direction in Boutonne basin (Bichot et al., 2005).

3.1.5 Surface water bodies

The Boutonne river spring is located at Chef-Boutonne at an altitude of about +90 meters above sea level (a.s.l) in the Dogger formations. In its upstream part, it flows from east to west between two faults, mainly on the Dogger and Lower and Middle Oxforden formations. It receives on this

section and on the right bank the waters coming from the following rivers: the Sumptuous, the Béronne and the Belle. These tributaries are flowing on Dogger and Lias formations.
In the middle part, between the confluences with the Belle and the Vau, the Boutonne River has a direction northeast / southwest. The hydrographic network is less developed. Thus, on the Oxfordian formations superior to the Upper Kimmeridgian, the Boutonne receives only a few streams on the left bank (Bellesebonne, Bondoire and Vau)
Downstream from the confluence with the Vau, the Boutonne flows on the higher Kimmeridgian formations on which the hydrographic network is well developed. Thus in this downstream sector, the Boutonne receives on the right bank tributaries (La Bredoire, La Saudrenne, Padome, La Nie). On the Left Bank, the Boutonne River receives the following tributaries: Le Pouzat, La Soie, and the Trézence, via the Sainte Julienne canal.
In this sector, between Dampierre and Saint Jean d'Angely, the Boutonne is, at low water period, perched in relation to the unconfined and superficial aquifer of the Upper Jurassic (Lavie J (2005)).
The Boutonne river flow is monitored at the gauging station of Saint-Séverin-sur-Boutonne. The average annual flow at this station is 5.52 m^3/s; Table 1 summarizes some information about this station and the Saint-Jean-d'Angély station located downstream. The monthly (natural) flows calculated over 50 years is reported in Figure 7.

Table 1 : Flow gauge information

Flow gauge ID	*Surface km2*	*Name of station*	*River water level data period*	*River Flow data period*
R6092920	535	La Boutonne à Saint-Séverin-sur-Boutonne [Moulin de Châtre]	*1972 - 2001 - 2020*	*1969 -* 1998 - 2021
R6142927		Boutonne[total] at Saint-Jean-d'Angély	*Not available*	*2011-2021*

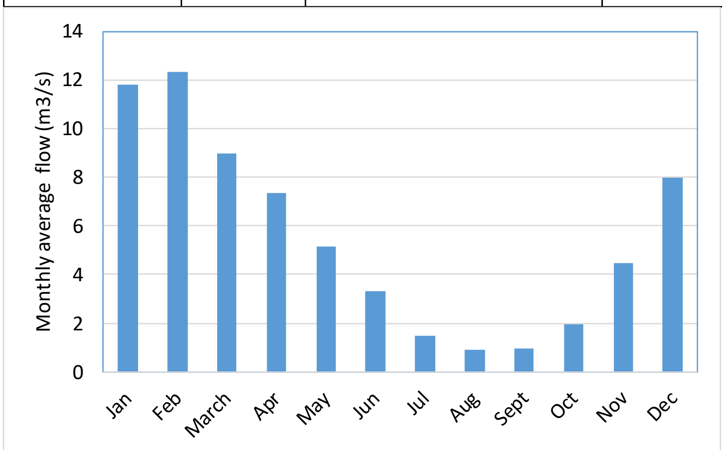


Figure 7 : *Monthly average flow at Saint-Séverin-Sur-Boutonne calculated over 50 years (Banque hydro : http://www.hydro.eaufrance.fr/)*

3.1.6 Hydraulic head evolution

Groundwater table of Jurassic aquifers is monitored at several observation boreholes (piezometers). Piezometers locations are reported in Figure 8. Concerned aquifer and the monitoring period are reported in Table 2.

Table 2 : Groundwater observation points

Piezometer ID	Name	Aquifer	Period
06357X0062/S	Villenou	Lower Kimmerigien	**1992-2018**
06358X0012/S	Fosses	Infra-Toarcien	2006-2009
06364X0001/P	Chail	Dogger	1993-2001
06366X0006/P	Ensigne	upper Jurassic	**1992-2018**
06367X0126/P	Lesvaux	Dogger	**1993-2001**
06367X0138/S	Outre 2	Infra-Toarcien	**1990-2018**
06367X0172/F	Outre 1	Dogger	**1990-2018**
06367X0195/S	Tillou	Infra-Toarcien	2005-2011
06601X0012/S	Poimier	upper Jurassic	**1992-2018**
06603X0093/P	Paizay	upper Jurassic	**1993-2018**

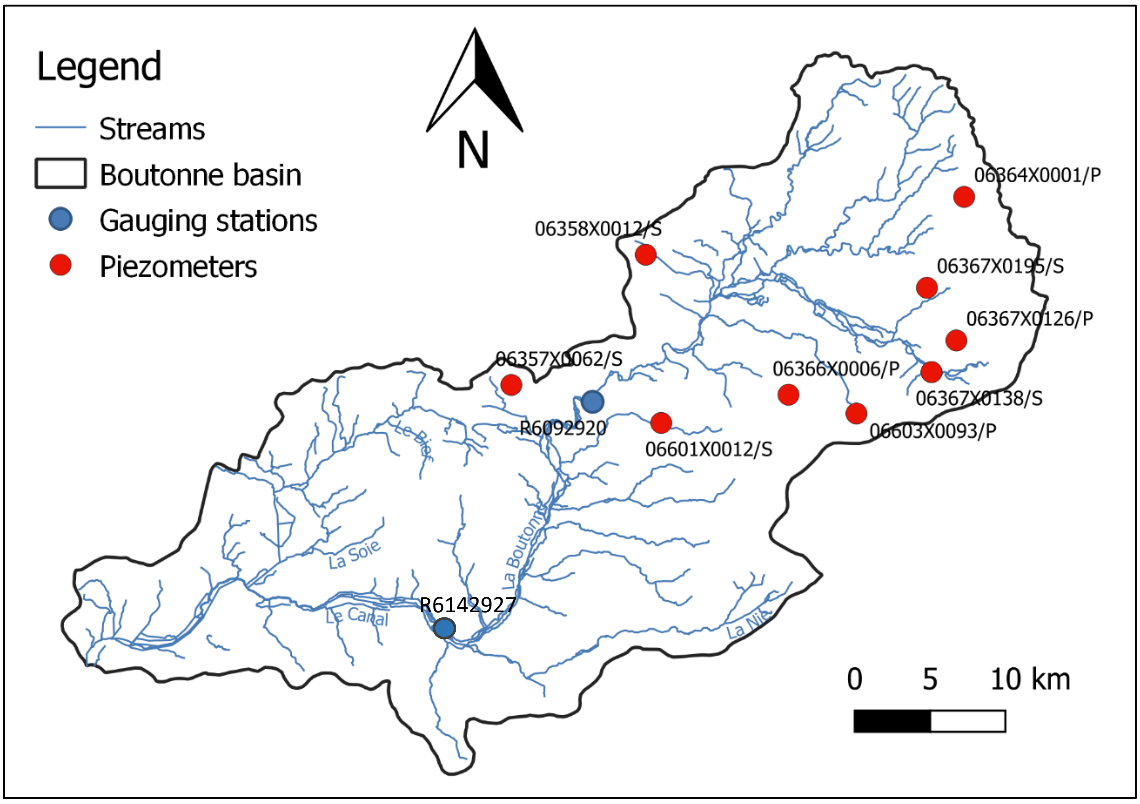


Figure 8: Gauging stations and piezometers over the Boutonne River basin.

3.1.7 Land use

The Boutonne pilot is a rural and weakly urbanized area dominated by agricultural land use (Figure 9). The most important wooded area of the basin is at the limit of the departments of Charente-Maritime and Deux-Sèvres. Alluvial forests are present very intermittently along the rivers.

There are two urban areas on the basin: Saint-Jean-d'Angély and Melle. Elsewhere, the population is distributed sparsely over the territory.

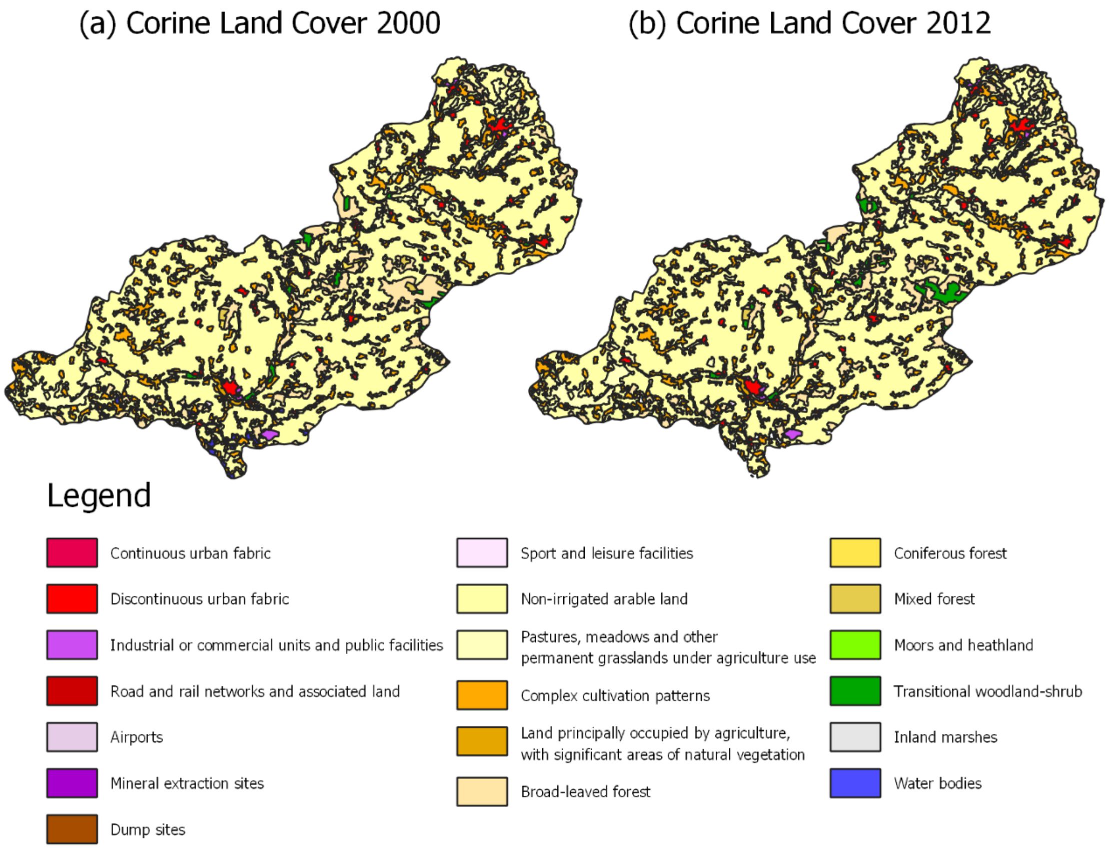


Figure 9: Land use maps from CORINE Land Cover (2000 and 2012)

3.1.8 Abstractions/irrigation

The Boutonne site pilot is under strong anthropic pressure since several years. From a quantitative point of view, abstractions for crop irrigation represent 73% of total water uses (concentrated over 4 to 5 months in summer), followed by the drinking water supply with 17.35% (spread over 12 months and peak consumption in hot season) and finally industrial use with 9.56% spread over 12 months (Sage Boutonne 2016). Water withdrawals are mainly carried out in the upper Jurassic aquifers, with boreholes of some tens of meters deep mainly located in the valleys, and in the Dogger and especially the Infra-Toarcien for the upstream part of the basin (Bichot et al 2005). Figure 10 show the location of boreholes and abstractions according to the type of water use and aquifer.

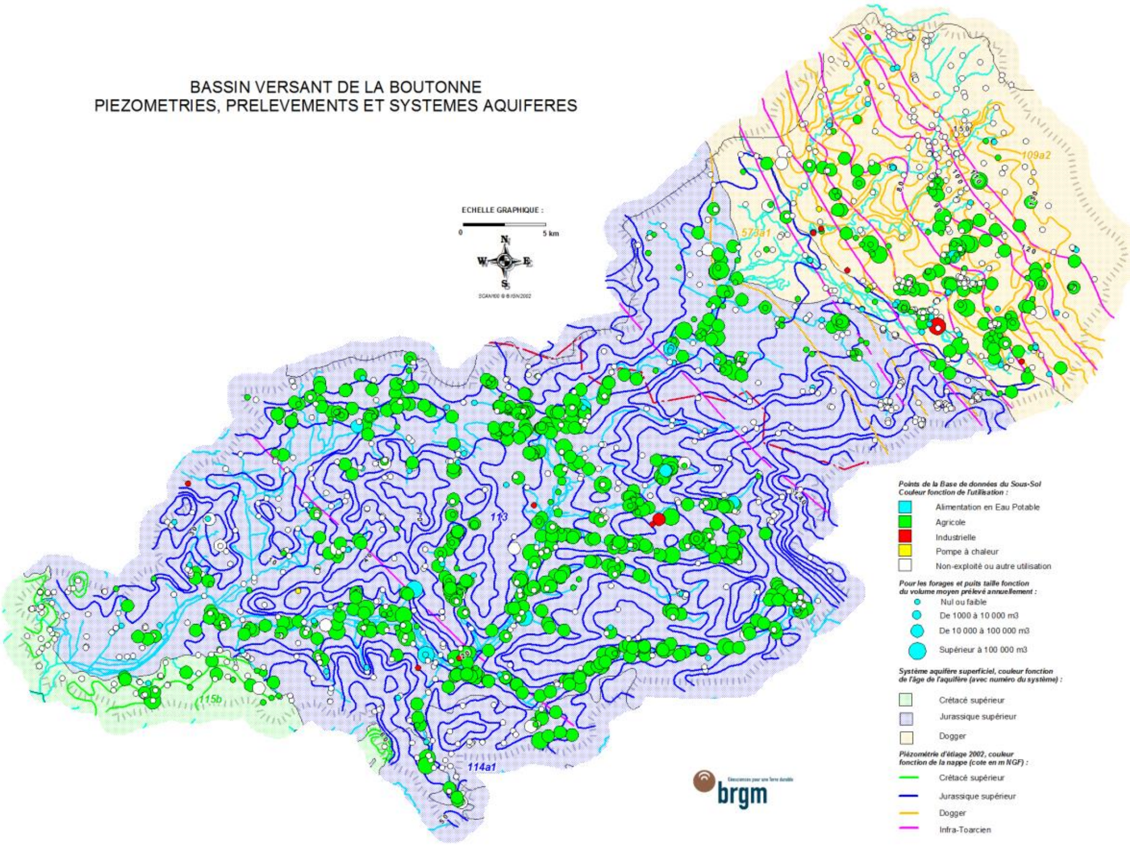


Figure 10 : Location of boreholes and abstractions according to the type of water use and aquifer (Bichot et al. 2005)

3.2 Climate change challenge

The Boutonne pilot site is located in the North-western Europe region where an increase of precipitation in winter is expected in accordance with the EEA map (Figure 11).
Existing hydrological impact studies based on projections ensemble from sept GCMs and median emission scenario A1B (Explore 2070 project) have shown a decrease of the inter-annual average river discharge by 2070 compared to reference period (1960-1990). However, for the most optimistic GCM model (GFDL-CM2.1), river discharge in the winter could be higher (20% to 40%) compared to reference period and could lead to flooding downstream of the basin (Stollsteiner 2012). A drop in average flow is expected in summer for this watershed.

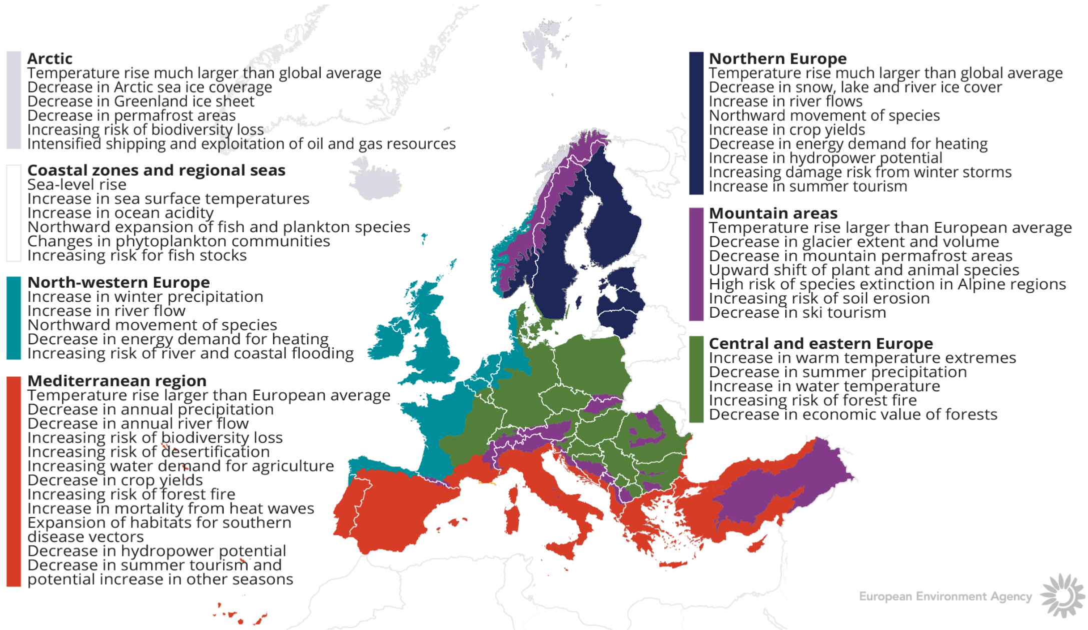


Figure 11 : Key observed and projected impacts from climate change for the main regions in Europe (European Environment Agency)

4 METHODOLOGY

The assessment of climate change effects on groundwater resources in Boutonne basin is performed using the TACTIC standard climate change scenarios and the regional hydrological model of Jurassic aquifers developed with BRGM's MARTHE computed code (see TACTIC toolbox reference).

4.1 Climate data

In this study, TACTIC standard climate change dataset are used to assess climate change impact on groundwater resources in Boutonne pilot under +1 and +3 degrees global warming scenarios considering low and high precipitation conditions.

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"	8.5	hadgem2-es
	"Wet"	6.0	miroc-esm-chem

4.2 Hydrological modelling of climate change

The regional hydrological model of Jurassic aquifers in Poitou Charentes (Jurassic aquifers model) has been developed in its first version in 2007 (Putot et al., 2007) and completed, updated and recalibrated in 2011 (Douez et al 2011). This last version was improved by integrating daily surface water balance computation (Amraoui et al. 2018, Vergnes et al 2020). The Jurassic aquifers model was developed with the MARTHE computer code (Thiéry, 1993, 2015a, 2015b). MARTHE allows the simulation of flows in aquifer systems and river networks, including climatic and human influences. Surface water balance (runoff and aquifer recharge) is calculated from climate data (rainfall, potential evapotranspiration) and soil parameters using the lumped hydrological model GARDENIA (Thiéry, 2015a). More detail on the MARTHE functionalities are available in the Tactic toolbox.

The methodology applied to assess climate change effects on groundwater resources is based on:

i) the four selected TACTIC scenarios representing an increase of global annual mean temperature by +1 and +3 degrees compared to the reference period (1981-2010) under wet and dry conditions
ii) the hydrological model of the Jurassic aquifer which simulates the groundwater conditions over the current period.

Four datasets representing the future climate conditions are generated by applying the delta change factors to current local dataset of precipitation, evapotranspiration and temperature. It assumes that the evolution of climatic variables is the same for the current and the future climates. The groundwater recharge, groundwater level and river discharge evolutions were simulated over the period 1958-2018 using current local climate data and future climate data generated for the four Tactic scenarios. It is assumed that there is no change in groundwater abstraction for the future climate scenarios. Only the results over the 1981-2010 period were used to assess the climate change impacts on groundwater and surface water resources.

4.2.1 Model description

The Jurassic aquifers model covers an area of 19,280 km^2 and entirely includes the Boutonne basin (Figure 12). This model integrates the data described in paragraph 3.1. Built from a geological model, the main Jurassic aquifers and the aquitards that separate them are represented there. The model has 8 layers described from top to bottom: 1- Bri du Marais ; 2 - Cretaceous and alterites ; 3 - Weathered Upper Jurassic (aquifer), 4 - Unaltered Upper Jurassic, 5 - Dogger (aquifer), 6 - Toarcian, 7 - Infra-Toarcian (aquifer) and 8 - the basement. The spatial extension of these layers and the main aquifers present in the Boutonne basin (upper Jurassic aquifer, Dodder aquifer and Infra-Toarcian aquifer) are shown in Figure 13.

The model is discretized in 1 km square meshes. Boundary conditions of the imposed potential type are applied to the northeast, southwest and west of the regional model and correspond either to large deep faults or to the ocean. Elsewhere, no flow limits are applied. The hydrographic network taken into account represents 3050 km of linear streams. The Jurassic aquifers model considers groundwater and river withdrawals (agricultural, drinking water supply and industrial). The model run in unsteady state condition and allows simulating the fluctuations of the groundwater levels and flow in the associated rivers as well as the interactions between groundwater and surface water. The 2011 version of the model runs in transient mode at a monthly time step and is calibrated over the period 2000-2007. More details on this model are reported in Douez et al 2011.

In this study, we used the 2018 version of the Jurassic aquifer model. In this version, surface water balance (runoff and aquifer recharge) is calculated with a daily time step from spatial distributions of climate data, including daily rainfall, potential evapotranspiration and soil parameters, using the lumped hydrological model GARDENIA. In addition, the hydrodynamic calculation is done at a weekly time step (Amraoui et al., 2017).

The model was updated over the period 1958-2018 with daily climatic data. Concerning water abstractions in aquifer and river, as the data are not available outside the calibration period (2000-2007), the assumption of average monthly withdrawals calculated based on data known between 2000 and 2007 was considered for the period prior to 2000 and that subsequent to 2007.

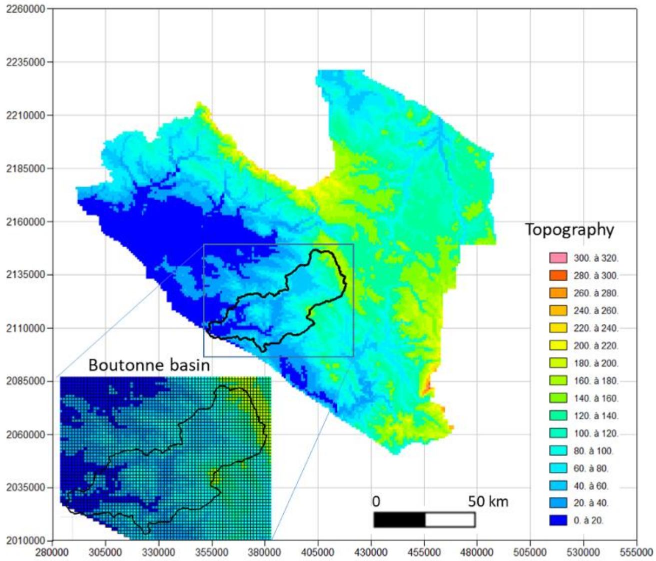


Figure 12 – Location of Boutonne watershed in the Jurassic Aquifers Model – the black outline represents the limits of the basin on a topographic map background

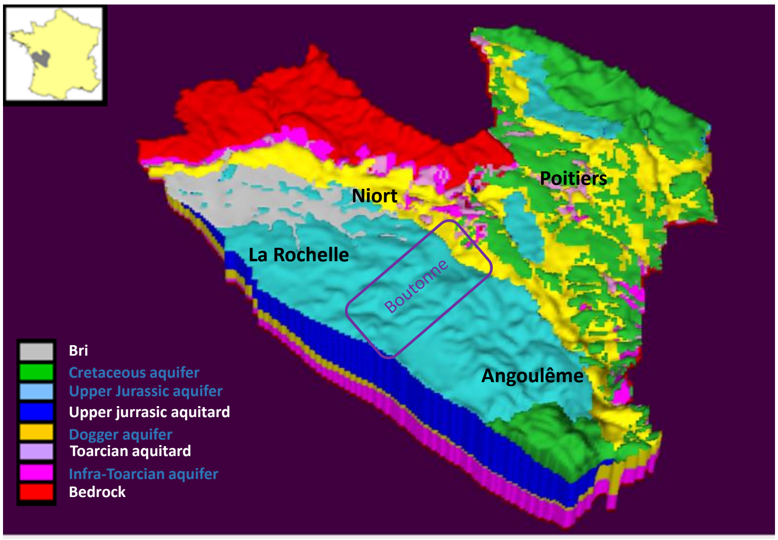


Figure 13 : Extension of the Jurassic Model layers and the main aquifer present in Boutonne basin.

4.2.2 Model calibration

Calibration consists in adjusting the model parameters in order to reduce the difference between the observed and simulated values at the observation points (groundwater time series and river flow rates measured at the gauging stations).

The Aquifers Jurrasic model was already calibrated in 2011 based on aquifers regional knowledge, groundwater levels and river flows observations. Calibrated parameters are: the hydraulic conductivities and the storage coefficient maps (for the 8 layers of the model), recharge and river bed conductance.

Calibration carried out within the framework of TACTIC concerns only the Boutonne basin. The GARDENIA parameters was calibrated according to the daily climatic data and soil parameters. Calibrated parameters are the soil capacity, partition coefficient between surface runoff and infiltration and percolation delay. The calibration was achieved over the 2000-2007 period by trial and error approach. The periods before and after the calibration period were used to initialize the simulation and to validate the model. The location of the piezometers and gauging stations used in the evaluation of model calibration is shown in Figure 8.

The Villenou, Poimier, Ensigne and Paisay piezometers are considered for the Upper Jurassic aquifer, the Outres 1 and Chail piezometers for the Dogger aquifer and the Outres 2 piezometer for the infra-Toarcian aquifer. In addition, the river discharges measured at the Saint-Severin-sur-Boutonne and Saint-Jean-d´Angély gauging stations allow assessing the restitution by the model of the river flow. Examples of comparison between the simulated and observed values of groundwater level and river discharge are shown in Figure 14 and Figure 15. In addition, statistical criteria (Root Mean Square Error: RMSE, Mean Error: ME and the Nash criteria) were calculated on the basis of the monthly values of the hydraulic head and the flow rate over the observation period (Figure 16).

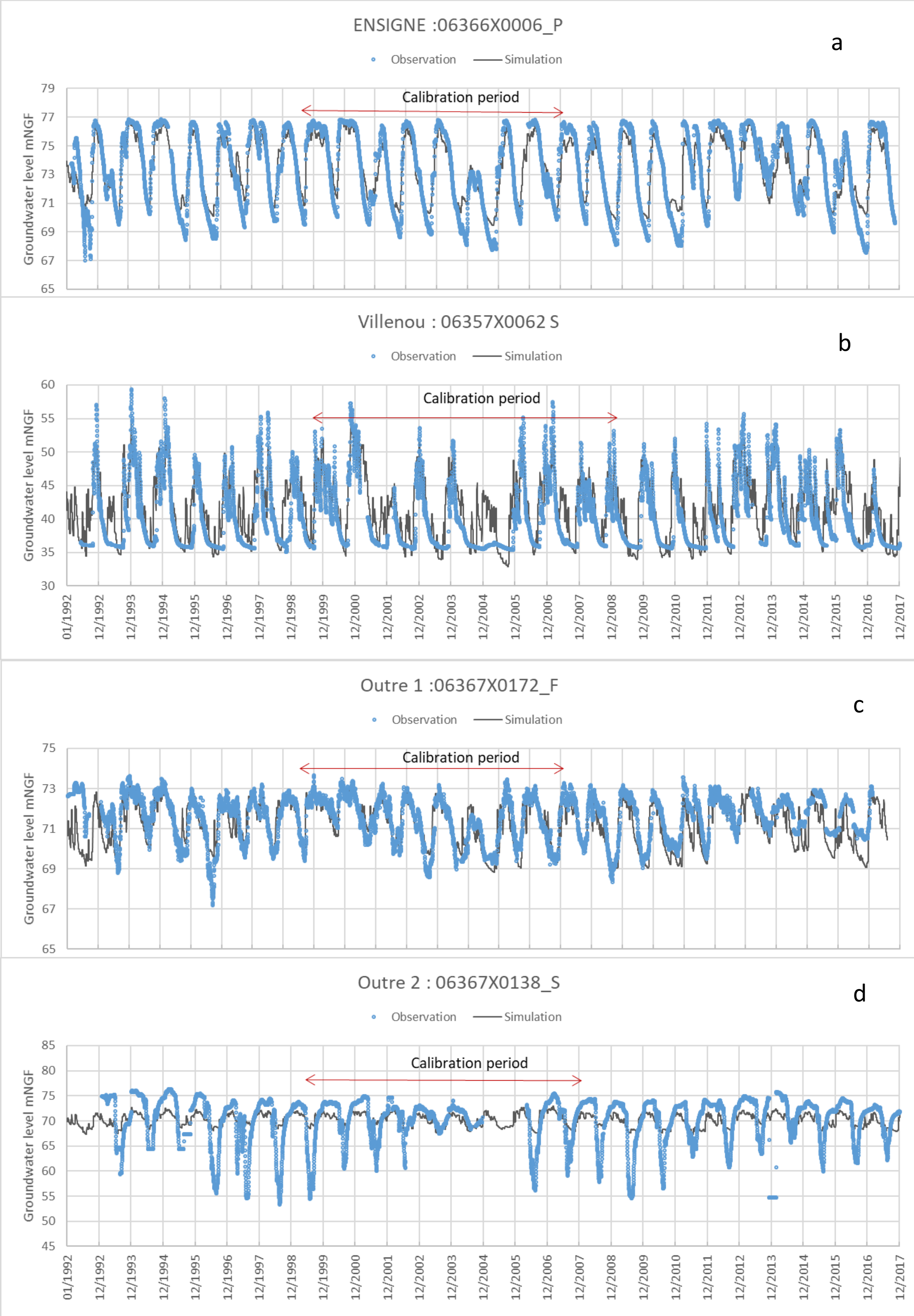
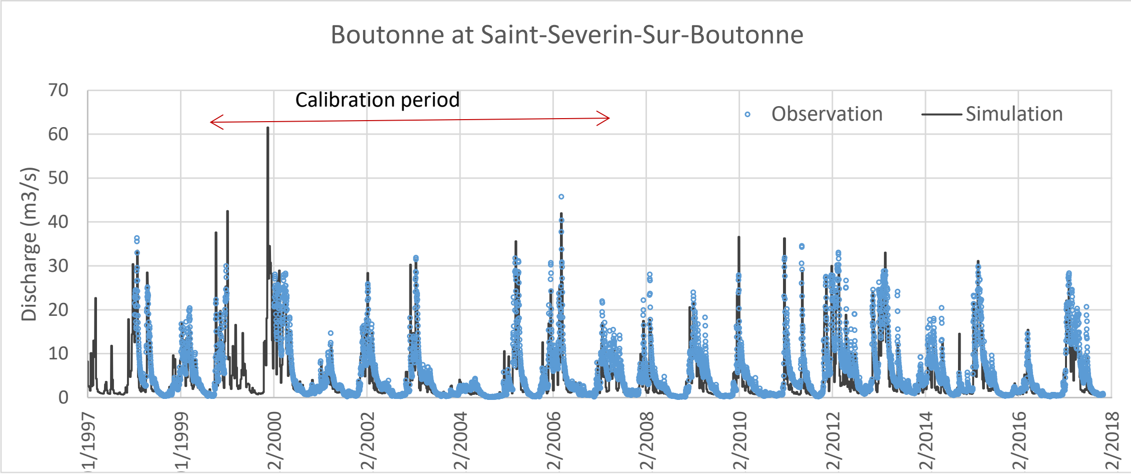


Figure 14 : Example of observed and simulated groundwater levels in piezometers located in Upper Jurassic aquifer (a and b), Dogger or Middle Jurassic aquifer (c) and in Infra-Toarcian aquifer (d).



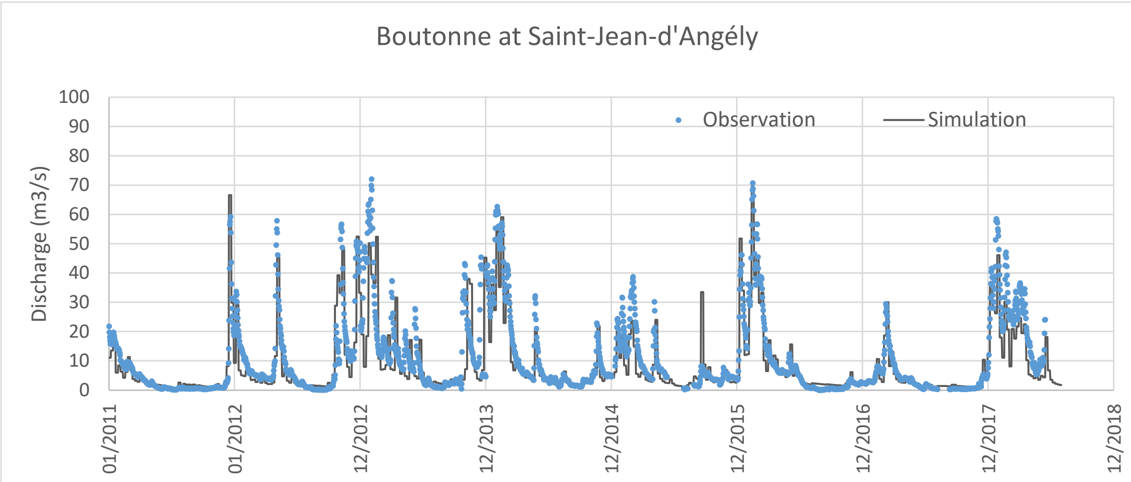


Figure 15 : Observed and simulated discharges in Boutonne River at two gauging stations.

		Groundwater level								River Discharge		
Aquifers and River name		Upper Jurassic				Dogger		Infra Toarcien		Boutonne River		
Observation points		ENSIGNE	VILLENOU	POIMIER	PAIZAY	OUTRE1	CHAIL	OUTRE2		Saint-Severin-Sur-Boutonne	Saint-Jean-d'Angély	
Statistical criteria	Time scale	Values	Values	Values	Values	Values	Values	Values	Unit			Unit
NASH SUTCLIFFE (NSE)	Monthly	0.86	0.79	-0.17	0.41	0.55	0.54	0.28		0.85	0.86	
ROOT MEAN SQUARE ERROR (RMSE)	Monthly	0.97	2.72	2.34	0.78	0.73	1.64	4.52	m	2.16	4.32	m3/s
MEAN ERROR (ME)	Monthly	-0.09	1.73	-0.43	-0.53	-0.31	0.70	0.03	m	-1.07	-1.52	m3/s

Figure 16 : Statistical criteria on various observations points for groundwater level and River discharge at the scale of Boutonne basin.

The Upper Jurassic and Dogger groundwater dynamics are well reproduced by model with a bias of -0.53 to 1.73 and a RMSE of 0.73 and 2.72 m respectively. For the Infra-Toarcian aquifer, mainly captive in the study area, the piezometers Outres 2 and Tillou are strongly impacted by pumpings located near the piezometers. Given that the model calculates a mean groundwater level over a 1-km resolution grid, the pumping influence cannot be reproduced at this scale. Note that the few observation points in the Dogger and Infra Toarcien aquifers make it difficult to assess the quality of the model in the middle and in the downstream area of the basin.

River discharges at Saint-Severin sur-Boutonne and at Saint-Jean-d´Angély stations are well reproduced by the model with a Nash criteria of 0.86 and 0.85 respectively; (NSE criterion is considered to be very good when it is greater than 0.7 and bad when it is lower than 0.5).

4.3 Uncertainty

The most important sources of uncertainty concern the data on groundwater and river water withdrawals, which volumes are not known before 2000. The assumption of averaged monthly withdrawals calculated from data known between 2000 and 2007 was considered for the period prior to 2000 and that subsequent to 2007.

Moreover, uncertainties linked to conceptual model should be underlined, they are linked to the ignorance of the Karst network upstream of the basin, therefore high hydraulic conductivities were considered in these areas to simulate the rapid flow generated by the Karst network. In addition, faults are not taken into account in the model but their impact on the aquifer geometry is considered.

5 RESULTS AND CONCLUSIONS

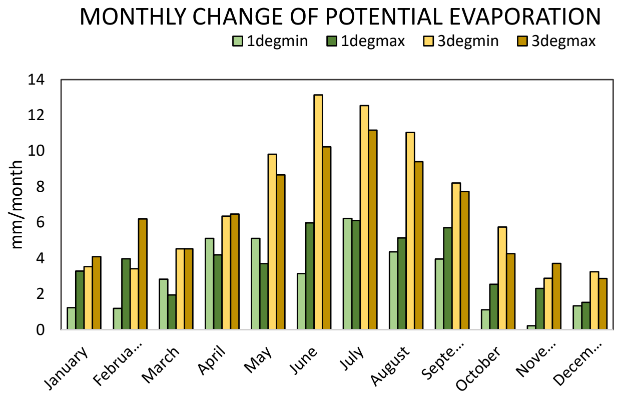
Climate change effects on groundwater recharge, groundwater levels in the Jurassic aquifers and the associated stream flows are assessed for Tactic standard scenarios. The impact is evaluated by comparing simulated results obtained with the data provided by each Tactic future standard scenario to those simulated on the reference period (1981–2010). Annual changes in mean groundwater recharge and mean, low and high groundwater levels are estimated, and the seasonal responses of the system are analysed at local scale for some piezometers and stream gauges.

5.1 Effects of change in future precipitation and Evaporation on groundwater recharge

The inter-annual averages of observed monthly precipitation and PET calculated for the reference period (1981-2010) were compared to those projected by the four Tactic scenarios. Change in monthly precipitation and PET are reported in Figure 17. An increase in autumn and winter precipitations is expected for 3 scenarios (+1°C wet, +3°C dry and wet). Precipitation rise is also expected in summer for +1°C wet and +3°C wet scenarios. Monthly change in PET shows an increase for all scenarios, particularly in summer under +3°C global warming.

30-years mean groundwater recharge calculated by the hydrogeological model for the reference and future (Tactic scenarios) periods are reported in Figure 18. It should be reminded that future changes in precipitation patterns, landscapes and land uses, which could affect the future groundwater recharge, are not included in the scope of this study.

Except the +1°C dry scenario, wich expects a slight drop in mean recharge, the other scenarios project an increase in future recharge. In fact, compared to mean recharge for historical period, the mean recharge over future period will increase by +6% for 1°C wet scenario, by +2% for 3°C dry scenario and by 19% for 3°C wet scenario.



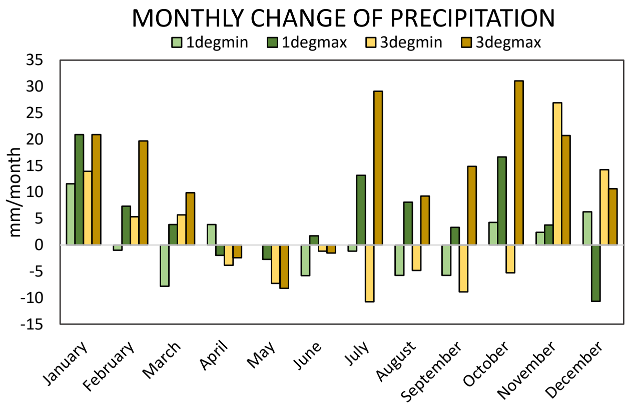


Figure 17: Monthly change of precipitation and Potential Evaporation under +1°C and +3°C for the 4 Tactic standard scenarios

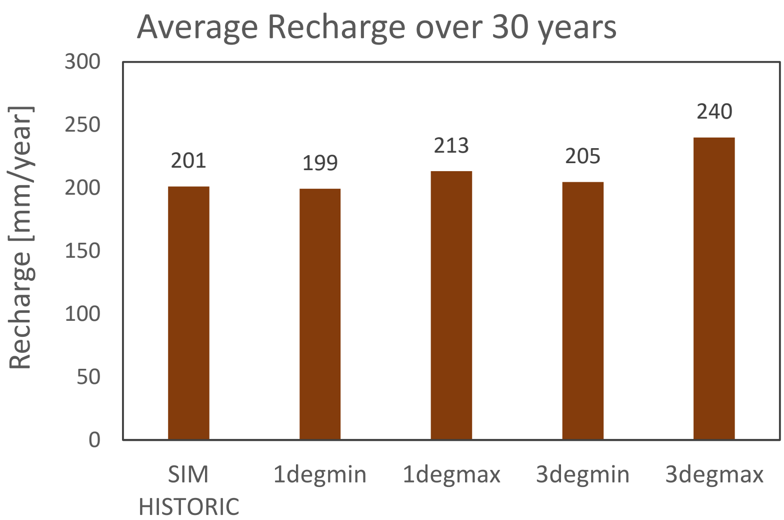


Figure 18 : 30-years mean groundwater recharge for the reference period (SIM Historic) and for the Tactic standard scenarios (under 1°C and 3°C global warming)

5.2 Effects on groundwater conditions and river flow

Results will focus on changes in shallow groundwater and river flow. Over the Boutonne basin, water abstractions are mainly carried out in the shallow groundwater of the upper Jurassic aquifers, in the Dogger aquifer and especially in the Infra-Toarcian for the upstream part of the basin. In addition, interactions with surface water occur with the upper Jurassic aquifer and in the northern part, in outcrop zones of the Dogger and Infra Toarcian aquifers.

5.2.1 Change in shallow groundwater

The mean shallow groundwater levels for the reference period (1981-2010) and for the future periods (two time slices in which the global annual mean temperature had increased by 1°C and 3°C compared to reference period) are calculated from the gridded simulated groundwater levels calculated by MARTHE over the simulation period and edited with a time interval of 30 days. Change in mean shallow groundwater levels is assessed for the 4 Tactic standard scenarios by comparing mean shallow groundwater levels for future periods with that of the reference period. In the same way, changes in dry and wet periods are also analysed.
The Figure 19 shows the relative changes in mean shallow groundwater levels between the four future Tactic simulations and the reference period (1981-2010) computed for each grid cell. in addition, the change of the 5% quantile of the simulated 30 periods (Future Q5 – Past Q5) and the 95% quantile (Future Q95 – Past Q95) are used to represent respectively the lowest groundwater level period and the highest groundwater levels during winter

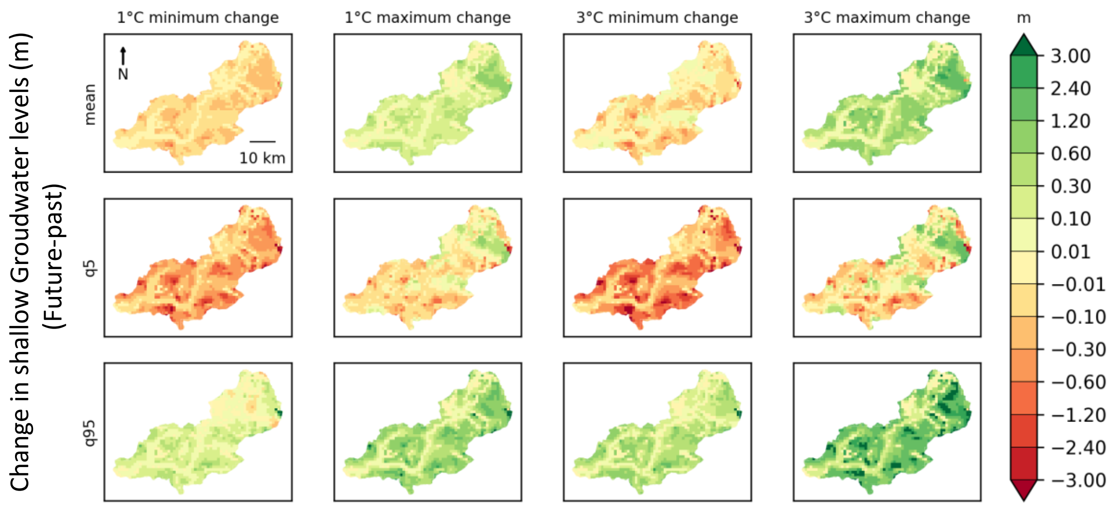


Figure 19 : Changes in mean, low and high shallow groundwater levels simulated with the four TACTIC standard scenarios.

The results are consistent with the wet and dry scenarios whether for the 1°C and 3°C scenarios and corroborate with changes in precipitations and groundwater recharge (see §5.1). It seems that for wet Tactic scenarios (1 degree max change and 3 degree max change), impact on mean groundwater levels under 3 degree is greater than under 1 degree warming with higher mean

groundwater levels. Nevertless, for dry Tactic scenarios, drop in mean groundwater level concern the whole basin under 1 degree warming whereas it is mainly located on plateaus under 3 degree warming.
The increase in mean groundwater levels over future period for 1 degree max change and 3 degree max change Tactic standard scenarios is explained by an increase in future recharge. Groundwater level rise is more marked on the plateaus than on the wet valley. The rise is more important for scenario 3°C wet (max change) and can reach locally more than 2 m.
Groundwater change in low water periods is more important compared to the mean and can reach -2.5 metres in plateaus. Decrease in groundwater level is more important for dry scenarios and for +3 degree.
Change in high groundwater level is more important for 1 degree and 3 degree wet scenarios and it remains significant for the 3 degree dry scenario.

5.2.2 Seasonal change in shallow groundwater levels

Seasonal changes in shallow groundwater levels are analysed for the 3 degree Tactic scenarios (dry and wet) over two piezometers located in the upper Jurassic aquifer (Ensigne) and in the Dogger aquifer (Outre 1) respectively. The monthly mean groundwater levels reported in Figure 20 were calculated from simulated groundwater levels over the reference period and for future climate.
This figure shows that for the upper Jurassic aquifer, for the dry scenario (3 degree min change), monthly mean water level increases slightly (0.20 m) in winter. On the other hand, the decrease in the water level is more marked in summer and in autumn (between -0.3 m and -0.5 m).The wet scenario (3 degrees max change) shows a more significant increase in the water table from August to the end of spring with a maximum reached in autumn (+0.8m).
For shallow Dogger aquifer, in the northern part of the basin, under dry scenario, monthly mean groundwater level is similar to that of historical period in winter but it is slightly lower for the other seasons. However, under wet scenario, monthly mean groundwater level is higher whatever the season.

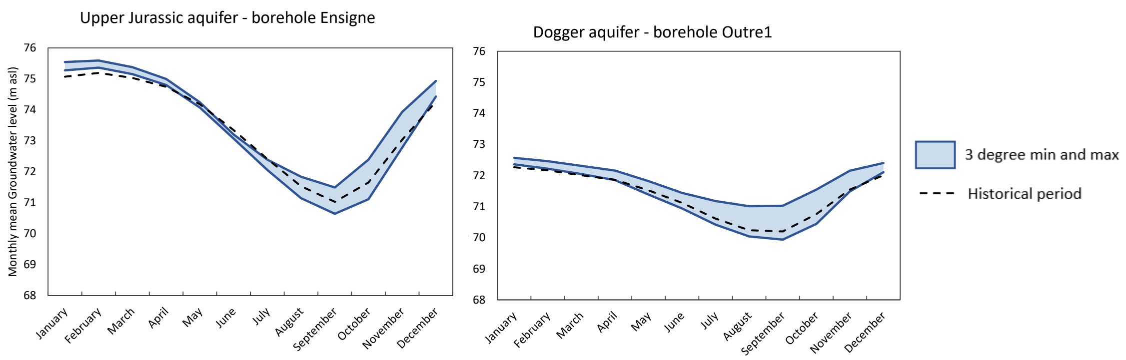


Figure 20 : Monthly mean groundwater level calculated over 30 years for historical period and under 3°C wet and 3°C dry Tactic standard scenarios.

5.2.3 *Change in river flow*

In the same way, monthly mean river flows were calculated over 30-years at two gauging stations located over the Boutonne river (Saint-Severin and Carillon at the basin outlet) for the historical period and for the future period of the four Tactic standard scenarios. The results are showns in Figure 21. For low flow periods (june to septembe), and under dry scenarios (1degree minchange and 3 degree minchange) slighly low water levels are expected. However, under wet scenarios, river discharges are expected to be higher than for the reference period. Otherwise, for high flow period (november to march), river discharges are expected to increase. This increase is more important for the 3 degrees scenarios (dry and wet).

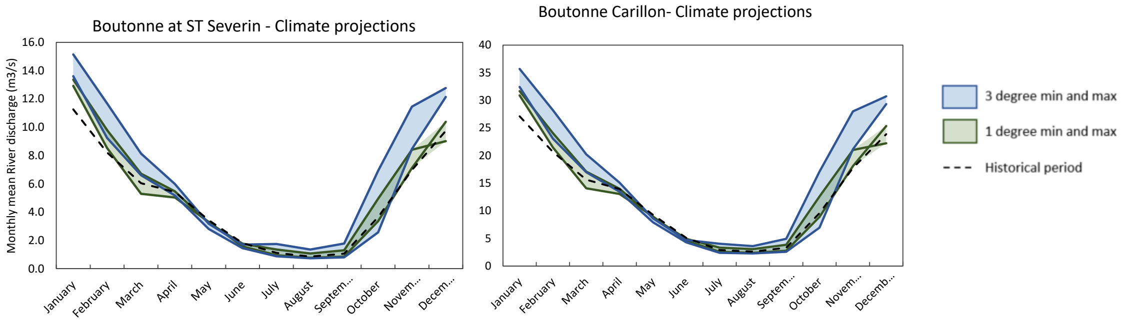


Figure 21 : Monthly mean river discharges at the two Boutonne gauging stations calculated over 30 years for the reference period and for the Tactic standard scenarios

As described above, the Tactic scenarios consider the same dynamic between different events in the historical dataset and in the dataset representing the future. Consequently, the impact will only concern the amplitude of the events and not their occurrences. For +3 degree scenarios (dry and wet) historical floods experienced by the Boutonne basin are expected to be greater in terms of amplitude. Figure 22 shows the historical flooding flood peaks (red circle) under the 3 degree minchange scenario.

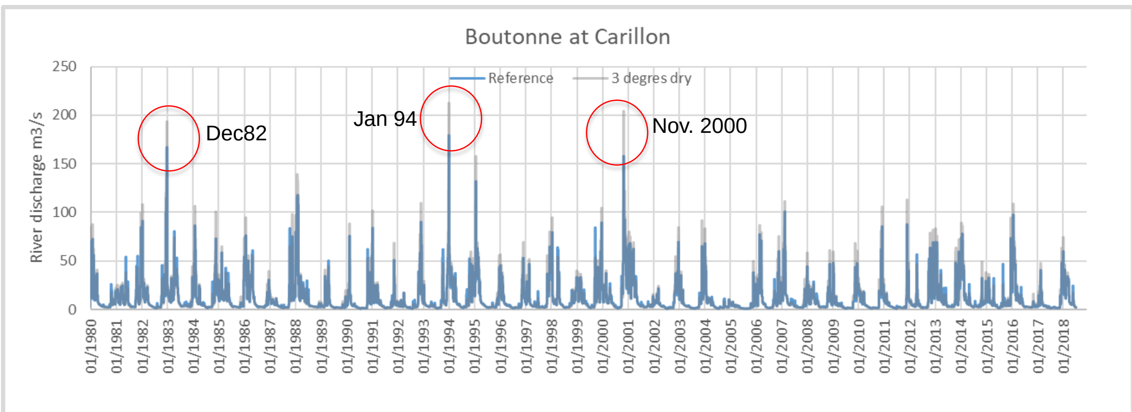


Figure 22 – Simulated river discharges values under current climate and for the +3 degree dry Tactic scenario.

5.3 Conclusion

Predictions of future groundwater reaction to TACTIC climate change scenarios are contrasted and depend on the evolution of future precipitation (dry scenario or wet scenario). Changes are amplified in the +3 degree, wet and dry scenarios, compared to the +1 degree scenarios. Results show that, for +3 degree scenarios, future mean groundwater recharge is expected to increase for both dry and wet scenarios (+2% and 19% respectively) compared to the mean groundwater recharge for historical period, leading to an increase of the mean shallow groundwater levels. Increases of shallow groundwater levels would concern all seasons, except spring in the case of the +3 degree wet scenario for the upper Jurassic aquifer, and all seasons for Dogger aquifer. However, decreases in the water level are more marked in summer and in autumn for the + 3 degree dry scenario.

River discharge is expected to increase in winter for all Tactic scenarios. Increase is more important for the +3 degree scenarios (dry and wet). However, for +1 degree and + 3 degree dry scenarios, low flows would be comparable to the reference period or slightly more severe.

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Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

Drava-Mura aquifer, Croatia

Authors and affiliation:

Ozren Larva

Croatian geological survey (HGI-CGS)

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

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Dissemination level	Public
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Work package	WP*3*
Lead WP/Deliverable beneficiary	*GEUS*
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Version	*Version 1*
Date	26/02/2021

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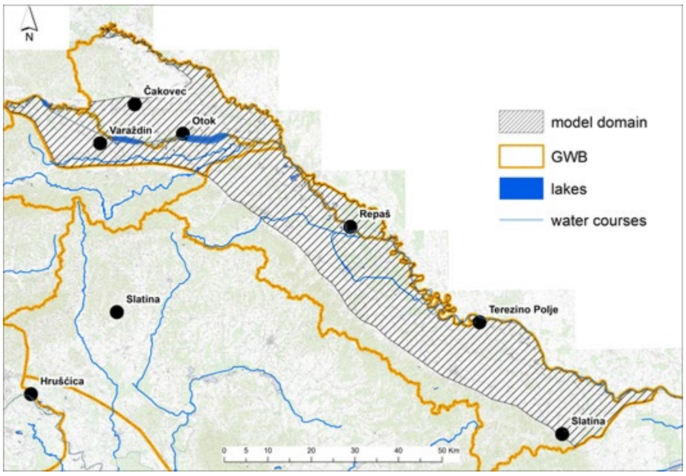
LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate change
GWB	Groundwater body
GWDE	Groundwater dependent ecosystem

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

Pilot name	Drava-Mura aquifer	
Country	Croatia	
EU-region	Central and Eastern Europe	
Area (km^2)	2500	
Aquifer geology and type classification	Sands and gravels (fluviatile deposits of major streams). Porous aquifer	
Primary water usage	Drinking water	
Main climate change issues	Groundwater dependent ecosystems (GWDEs) and Natura 2000 protected areas cover approximately 20% of the study area. GWDEs include phreatophytes that obtain a significant portion of water from the phreatic zone and capillary fringe. Hence, they are sensitive to the changes in groundwater levels which can be induced by climate change and/or anthropogenic factors.	
Models and methods used	Numerical groundwater flow model, lumped hydrological model, time series model	
Key stakeholders	Water supply companies, Croatian Waters	
Contact person	Ozren Larva, Croatian Geological Survey, olarva@hgi-cgs.hr	

The Drava-Mura pilot is situated in the northwestern part of Croatia, along the borders with Slovenia and Hungary. There is an aquifer system in the pilot area which is elongated along the Drava river valley. It represents the most important source of drinking water supply in the region, but it is also essential for the sustainability of the good status of Natura 2000 protected areas and the many of groundwater dependant ecosystems that are spread across the pilot. The thickness of the aquifer system increases in the southeast direction, from around 10 m at the utmost western part to 250-300 m in the central and eastern parts of investigated area. The vertical heterogeneity of the aquifer system increases in the same direction. The hydrographic network is well developed and there is generally a strong hydraulic connection between rivers and aquifer system. The aquifer is mostly unconfined and recharged by the infiltration of precipitation.

The assessment of the impact of climate change is focused on the upper aquifer, which is the most important in terms of drinking water supply and sustainability of GWDEs and NATURA 2000

protected areas. For this purpose, numerical model of groundwater flow in steady-state and transient condition is applied together with four standard climate change scenarios developed for the TACTIC project. The numerical model was set up using MODFLOW code and GMS modelling platform, whereas TACTIC standard scenarios was developed based on the ISIMIP (Inter Sectoral Impact Model Intercomparison Project) dataset. Other tools were also utilised, such as GARDENIA lumped hydrological model and METRAN time series model.
The modelling results are consistent for almost all applied climate change scenarios and point to the decrease of groundwater levels for characteristic hydrological conditions, except for 1-degree maximum change scenario and high waters, where the increase of groundwater levels is locally registered. The most affected region is the marginal part of the aquifer along the southern boundary. However, majority of the GWDEs is located in the central region of the pilot, which is overall less affected by climate change scenarios. This is particularly the case for the Natura 2000 protected sites, which are almost entirely situated along the Drava and Mura rivers.

2 INTRODUCTION

Climate change (CC) already has 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 Drava-Mura alluvial aquifer is located in the northwestern Croatia, along the state borders with Slovenia and Hungary. It represents the most important source of drinking water supply in the region. Besides, the aquifer system is vital for sustainability of the groundwater dependant ecosystems (GWDEs) and Natura 2000 protected areas. The assessment of the impact of climate change is focused on the upper aquifer. The key question is the direction of change in groundwater levels imposed by four different climate scenarios, the magnitude of the change and the spatial distribution, particularly in relation to GWDEs and Natura 2000 protected areas. The assessment was performed using numerical model of groundwater flow and standard climate change scenarios developed for the TACTIC project. The MODFLOW code and GMS modelling platform were used for groundwater flow modelling, while ISIMIP (Inter Sectoral Impact Model Intercomparison Project) dataset was utilized for development of TACTIC standard scenarios. Additionlally, the applicability of other tools was also checked, such as GARDENIA lumped hydrological model and METRAN time series model.

3 PILOT AREA

Drava-Mura aquifer represents the main source of groundwater for the drinking water supply in the region. Due to favourable hydrogeological conditions, several pumping sites have been developed over the years. Besides, there are a number of GWDEs and Natura 2000 protected areas, mostly spread along river banks of the Drava and Mura rivers. In this respect, the focus of investigation will be on the shallow aquifer system, i.e. on how future potential CC scenarios will influence the groundwater table depths. For the purpose of quantifying the impact of future climate scenarios on the aquifer system, the numerical groundwater flow model will be used for propagation of the CC to the investigated hydrogeological system. Prior to simulation of different effects of future CC scenarios, the model will be calibrated using historical data of groundwater levels observed within existing monitoring network.

3.1 3.1 Site description and data

3.1.1 Location and extension of the pilot area

The pilot area is located in the northwestern part of Croatia, along the borders with Slovenia and Hungary (Fig 1). It is a lowland area with developed hydrographic network. It belongs to Central and Eastern Europe region and covers 2500 km^2 (Figure 3.1).

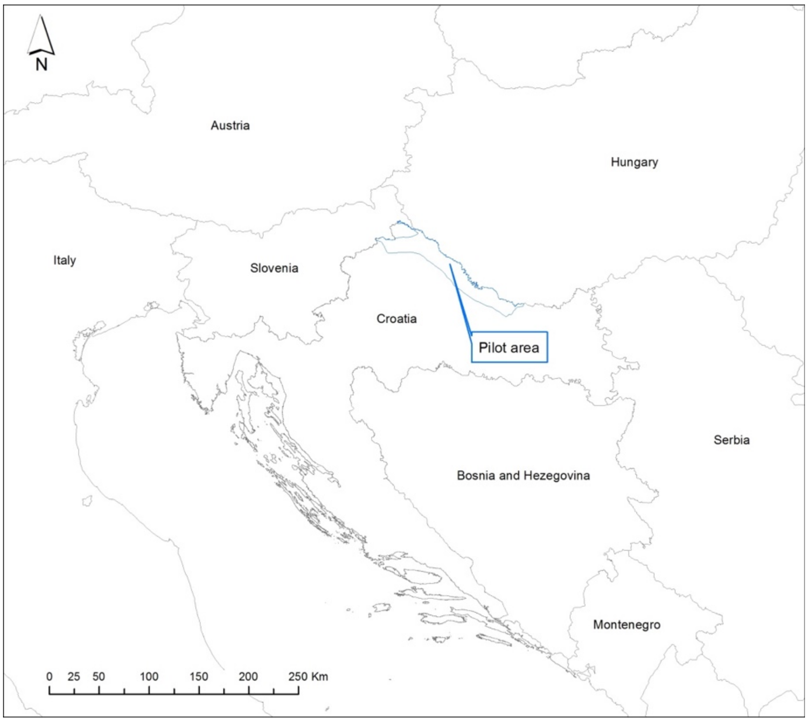


Figure 3.1. Location of the pilot area

Four groundwater bodies are, partly or completely, within the pilot domain – two of them entirely (Varaždinsko područje and Novo Virje), whereas the other two (Međimuirje and Legrad-Slatina) participate only with the parts where alluvial aquifer is developed (Figure 3.2, Table 3.1).

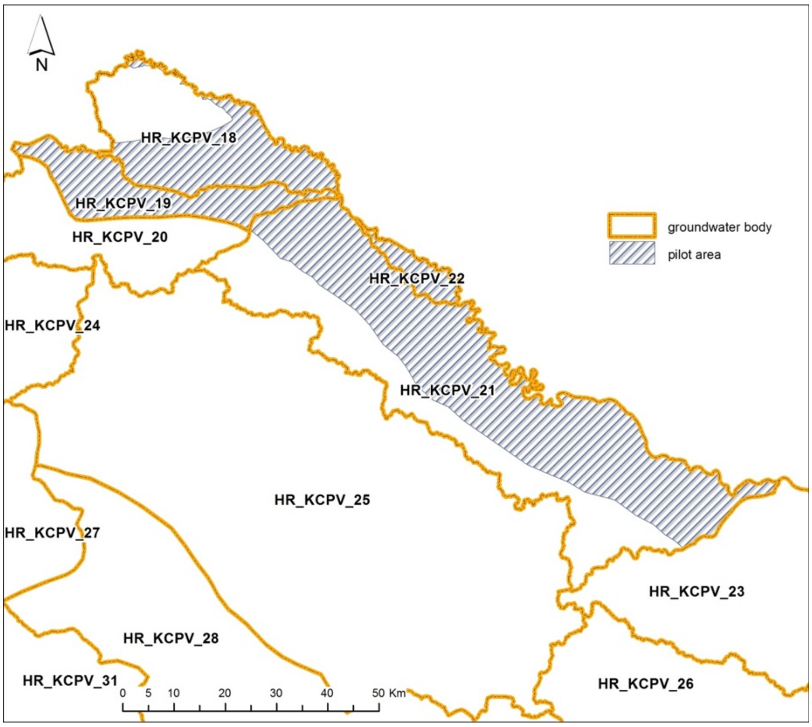


Figure 3.2. Pilot area and groundwater bodies

Table 3.1. Groundwater bodies within pilot area

Name	Code	GWB total area [km^2]	GWB area within the pilot area [km^2]
Međimurje	HR_KCPV_18	747	455
Varaždinsko područje	HR_KCPV_19	392	392
Novo Virje	HR_KCPV_22	97	97
Legrad-Slatina	HR_KCPV_21	2364	1516

3.1.2 Geology/Aquifer type

The Drava aquifer system is formed during Pleistocene and Holocene as a consequence of neotectonic activity and sedimentation of material which was transported mainly from the Alps by the Drava river. It is stretched parallel to the Drava river (Figure 3.3). There are three types of sediments at the ground surface, all of Quaternary age: Pleistocene loess, Holocene Aeolian sands and Holocene alluvial deposits which cover the majority of the pilot area.

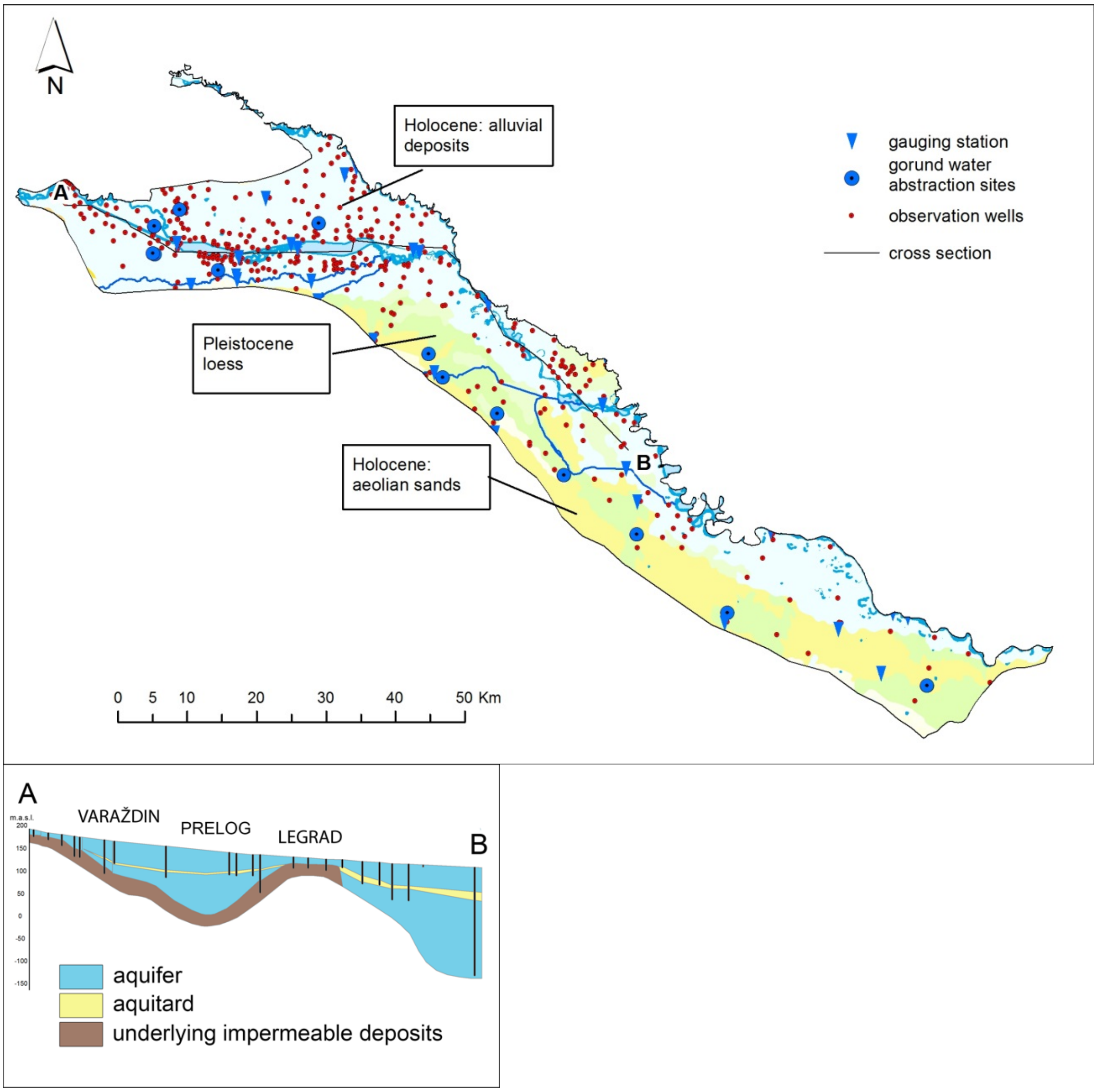


Figure 3.3: Geological map (HGI, 2009) and hydrogeological cross section

The thickness of the aquifer system increases in the southeast direction. It is around 10 m at the utmost western part of the pilot area. Further on downstream, it gets gradually thicker, reaching 150 m near Prelog (Urumović, 1990) and 250-300 m in the central and eastern parts of investigated area (Figure 3.3). In the same direction the average grain size decreases as a consequence of energy loss of the Drava river.

There is a covering aquitard at the top of the aquifer system which is composed of various shares of silt, clay and sand. In the westernmost area its thickness is generally low (< 1m) and in many places there is no cover at all. Further on downstream the thickness generally increases.

The general groundwater flow direction is toward the Drava river, apart from the western area where seepage from hydropower plants reservoirs (accumulation lakes) takes place. The aquifer is mostly unconfined. It is recharged by infiltration of precipitation and, only during high water levels, there is a seepage from the Drava river bed into the aquifer.

3.1.3 Surface water bodies

The hydrographic network is well developed at the pilot area. The Drava river with its left tributary Mura and right tributaries Plitivica and Bednja are the most prominent surface water bodies. But, there are also a number of smaller watercourses. Besides, there are also hydropower plant reservoirs (accumulation lakes) at the western part of the pilot area.

There is a strong connection between surface waters and groundwater, which is gradually diminished with the increase of distance from the river (Figure 3.4). Hence, any increase in groundwater levels far away from the Drava river is predominantly influenced by precipitation.

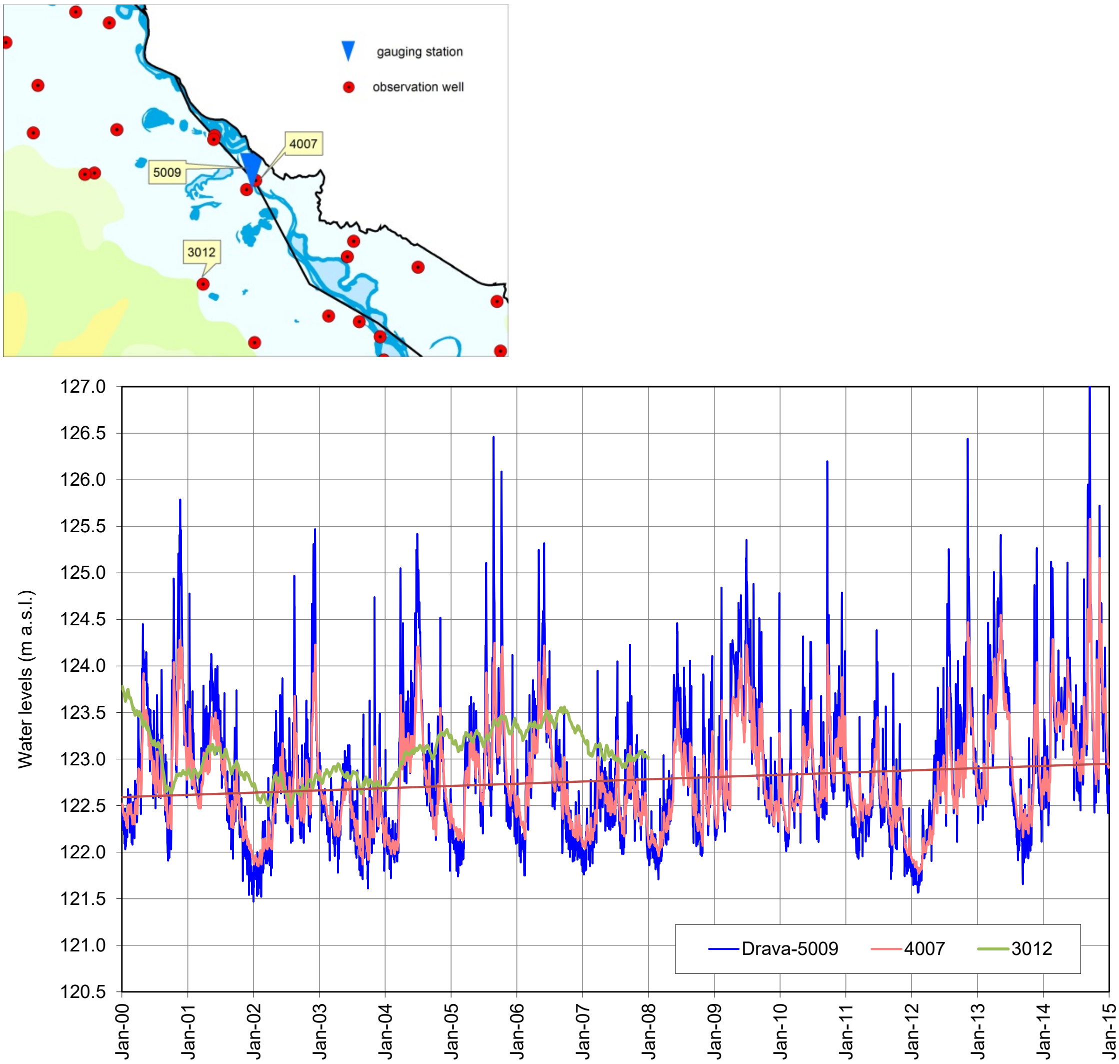


Figure 3.4. Drava river levels and groundwater levels at observation wells 4007 (450 m from the river) and 3012 (5 km from the river)

3.1.4 Topography

It is a lowland area with dominantly flat topography (Figure 3.5). The altitudes range from 200 m a.s.l. at the west to 100 m a.s.l. at the east.

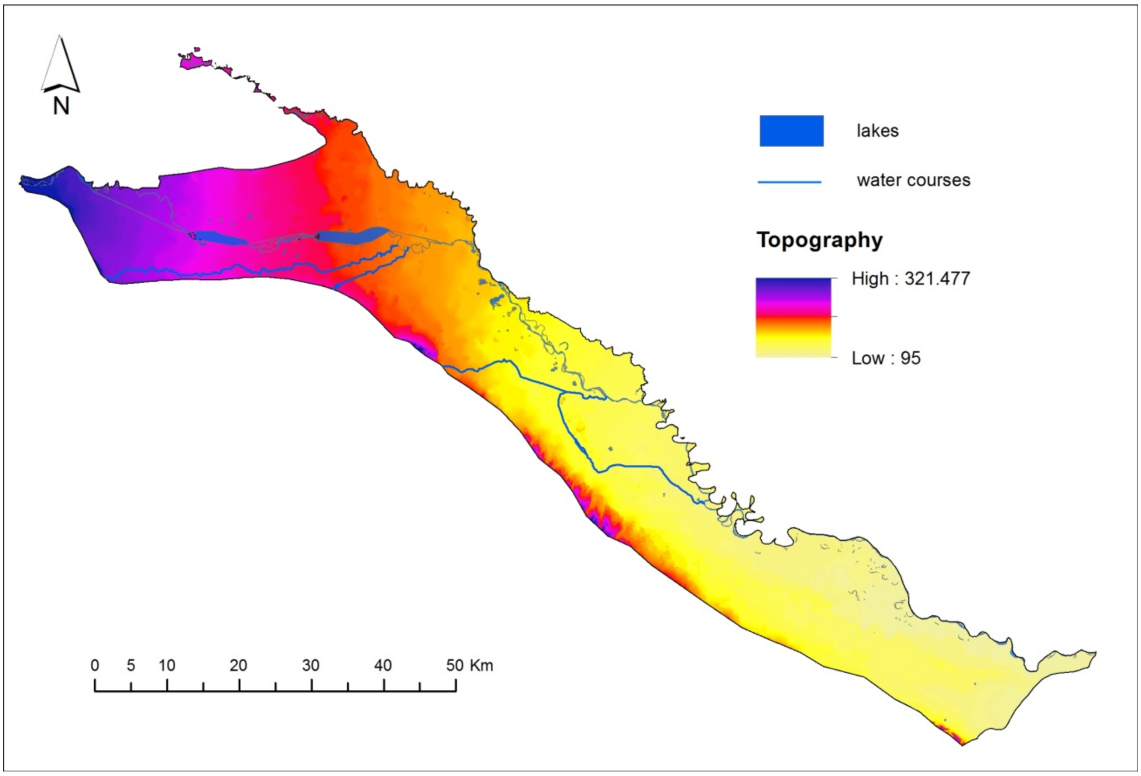


Figure 3.5. Topography

3.1.5 Climate

The climate in the pilot area is continental. According to Köppen classification system, it belongs to cfb type (Makjanić, 1979; Šegota & Filipčić, 1996). It is moderately warm, humid climate with warm summers. Average July temperature is between 20 and 22 ^{o}C and average January temperature between 0 and 3 ^{o}C.

Mean annual precipitation ranges from 700 – 1000 mm with maximum at the westernmost part of pilot area and with the slight decrease towards the southeast (Figure 3.6).

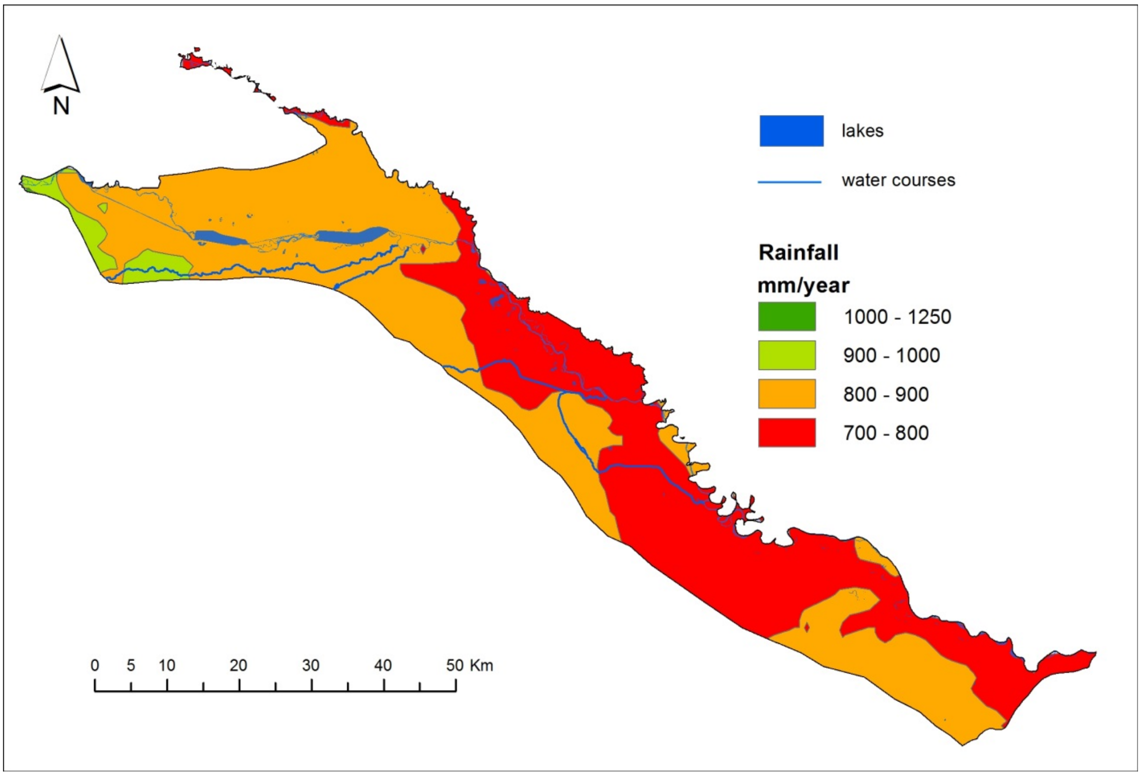


Figure 3.6. Spatial distribution of mean annual precipitation, 1961-1990 (Gajić-Čapka et al., 2003)

3.1.6 Land use

Land use mostly includes forest, arable land and grassland, with other categories having minor share. Figure 3.7 shows the spatial distribution of different categories (Corrina land cover, 2000) covering the pilot area.

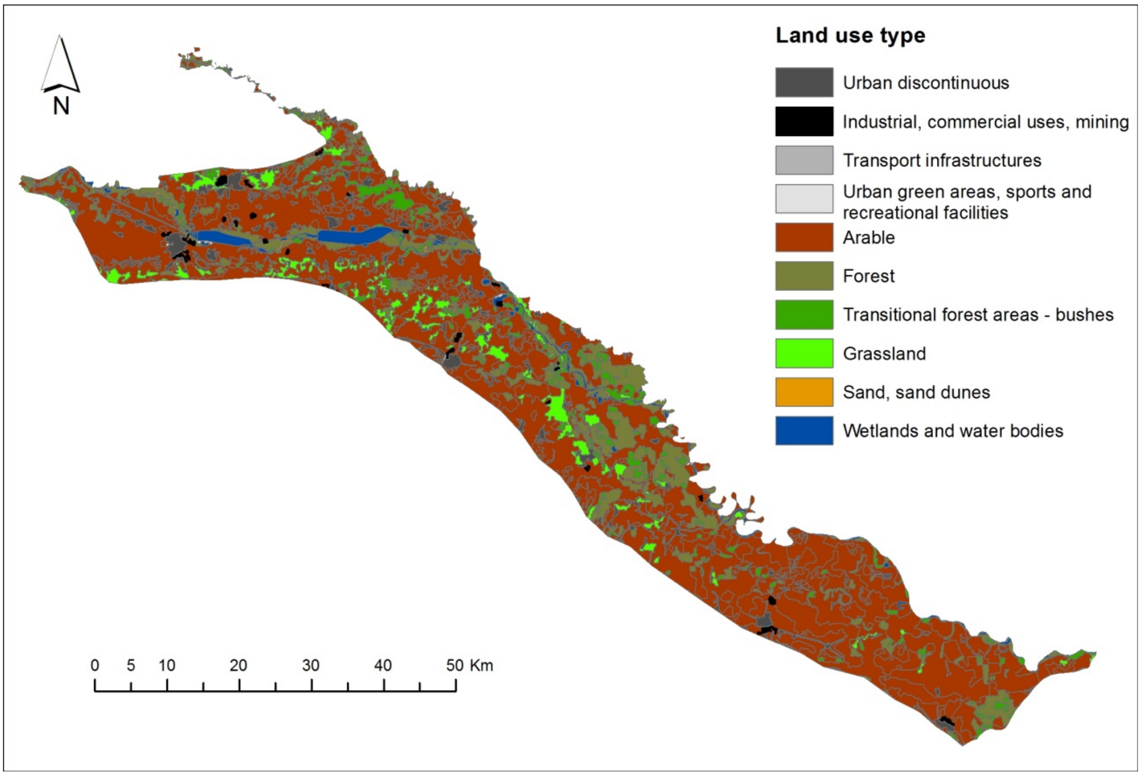


Figure 3.7. Map of land use over the pilot area (CLC, 2000)

3.1.7 Groundwater and surface water monitoring

National monitoring of groundwater and surface water levels has been carried out by State Meteorological and Hydrological Service (Figure 3.3). The frequency of measurements ranges from 2 times per week to continuous measurements by automatic logging devices. In addition, monitoring of groundwater levels has been also performed by waterworks at the catchment areas of groundwater sources for public drinking water supply. They are also keeping record of quantities of abstracted groundwater at the pumping sites. Generally, the density of monitoring wells is higher at the west (Figure 3.3), partly because of monitoring of hydropower plants operations. In the eastern area most of the observation wells are shallow and taps in some places more permeable deposits within covering aquitard (Miletić et al., 1971).

3.1.8 Abstraction/irrigation

Abstracted groundwater is primarily used for public water supply and it will not change in the near future since the water for irrigation, according to plan documents, will be mainly supplied from the Drava river. Table 3.2 shows quantities of abstracted groundwater in groundwater bodies.

Table 3.2. Abstraction rates in the period 2003-2013

Groundwater body	Abstraction rate [L/s]
Međimurje	150-280
Varaždinsko područje	270-370
Novo Virje	0
Legrad-Slatina	280

In the period 2003-2013 there was a negative trend of abstracted groundwater quantities in GWB Međimurje, whereas in GWBs Varaždinsko područje and Legrad-Slatina the abstracted quantities were mostly constant. There is no groundwater abstraction site in GWB Novo Virje.

3.1.9 Groundwater dependent ecosystems and Natura 2000

Majority of Natura 2000 protected areas are spread along rivers, while GWDEs are located both along the rivers and in the central parts of the pilot area (Figure 3.8). Phreatophytes within GWDEs are sensitive to the changes of groundwater levels because they obtain a significant portion of the water from the phreatic zone and the capillary fringe. Recent investigation has already pointed to the trend of lowering of groundwater levels in unconfined Drava aquifer in the period 1997-2007 (Brkić et al., 2010). Two factors have influenced such a trend: i) the decrease in the Drava river levels, which is influenced by morphological changes caused by the construction of hydrotechnical facilities and ii) a decrease in total annual precipitation from 1997 to 2008. According to some climate models, the trend of decrease in precipitation and increase of temperature could also prevail in the future which could lead to the increase in groundwater table depths and potentially negative consequences for GWDEs.

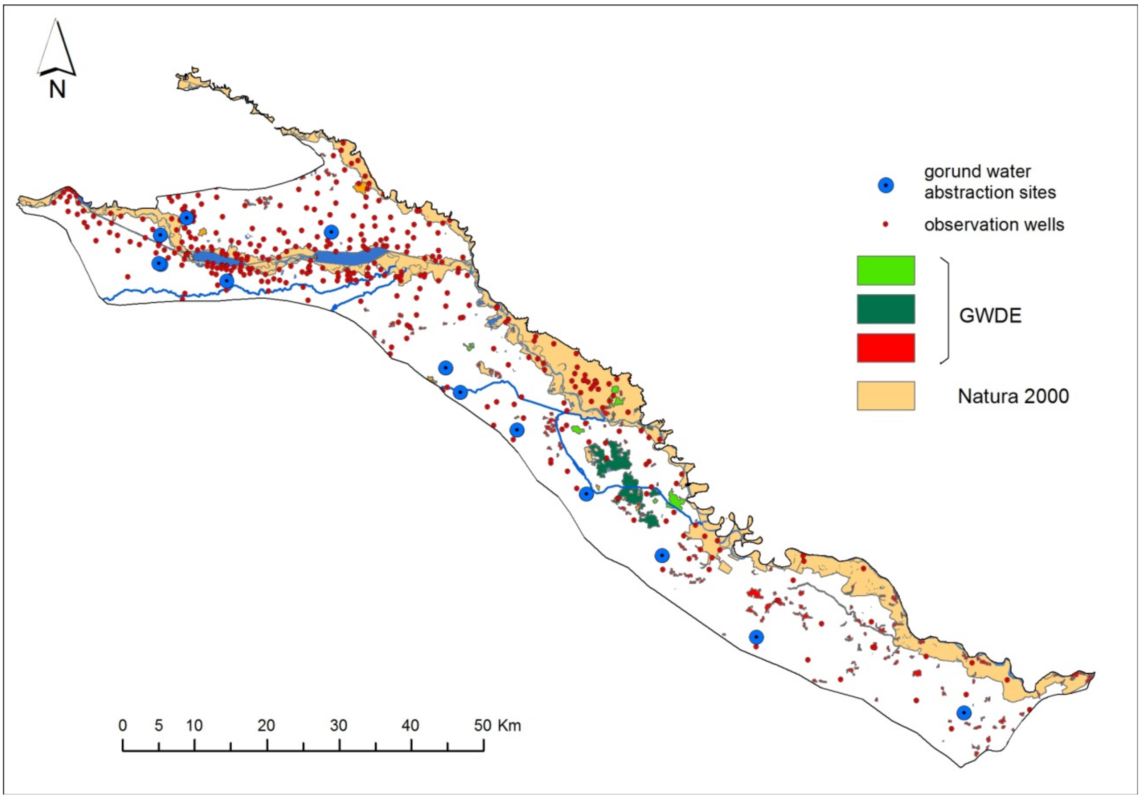


Figure 3.8. GWDEs and NATURA 2000 protected areas

3.2. Climate change challenge

According to the EEA map of expected CC in different European regions (Figure 3.9), the pilot area belongs to Central and eastern Europe where the increase in warm temperature extremes and decrease in summer precipitation are expected. Such circumstances could potentially have negative impact on groundwater regime and associated GWDEs. The main challenge is to assess the impact of CC on groundwater resources and find adequate adaptation and mitigation measures.

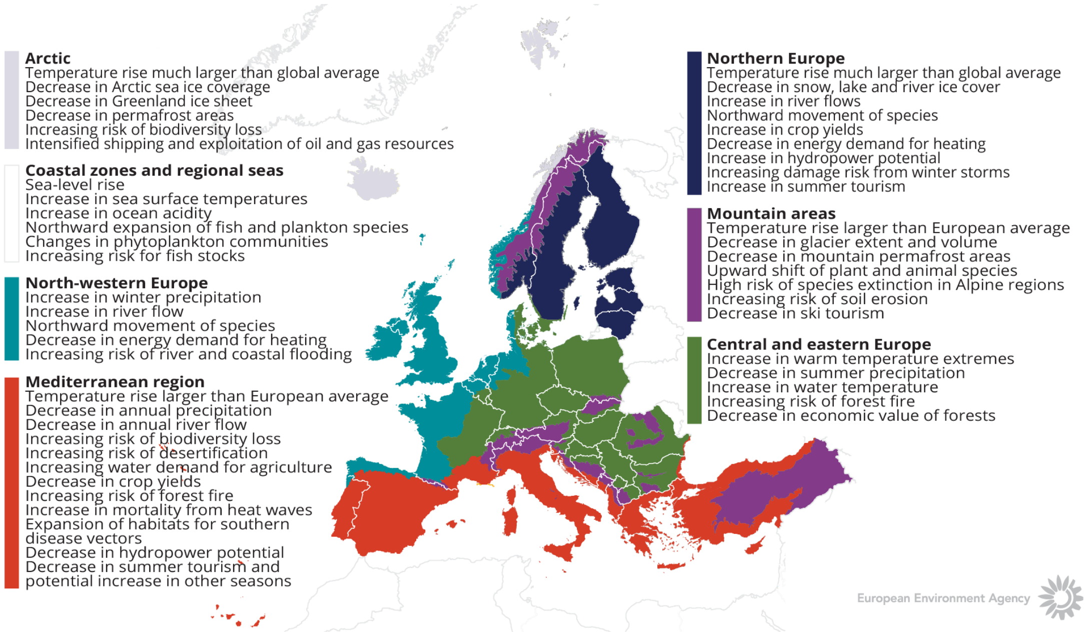


Figure 3.9. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

Distributed groundwater flow model, lumped hydrological model, time series model and TACTIC standard climate change scenarios were used for the purpose of evaluation of the climate change impact on groundwater levels and GWDEs in the pilot area.

4.1 Climate data

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"	6.0	gfdl-esm2m
	"Wet"	6.0	miroc-esm-chem
3-degree	"Dry"	8.5	gfdl-esm2m
	"Wet"	8.5	ipsl-cm5a-lr

4.2 Distributed groundwater flow model

Numerical groundwater flow model of the saturated zone of the Drava-Mura aquifer was developed and calibrated in steady-state and transient conditions. The purpose of the model is to assess the impact of climate change on the aquifer system and GWDEs. TACTIC standard scenarios results for the pilot area were applied on historical local data sets (precipitation, temperature, potential evapotranspiration) in a way that delta change values from TACTIC scenarios were multiplied / added to the local data sets in order to create input datasets for modelling of the impact of climate change.

4.2.1 Model description

Numerical modelling of groundwater flow was carried out with MODFLOW 2005 code (Harbaugh et al., 2017) using GMS modelling platform. The horizontal discretization of model domain was performed by a grid size 500 m x 500 m. Vertical discretization was obtained by four layers representing covering layer, upper aquifer, aquitard and lower aquifer (Figure 3.3).

There are different natural boundaries to groundwater flow in the study area for which appropriate mathematical descriptions were applied. In the south and south-west, groundwater flow boundaries include hills and mountains along which there is inflow into modelling domain that is simulated as specified flow boundary. The northern model boundary is represented by the Mura and Drava rivers, which are modelled as a head-dependent boundary. Besides, there are several power plant reservoirs with a strong influence on the groundwater flow net, which are also simulated as a head-dependent boundary. The same boundary condition was employed for rivers and drainage channels, while Neumann boundary condition was applied for recharge, which was estimated according to the previous studies (Patrčević, 1995; Brkić, 1999; Urumović et al., 1981) in the range from 20 to 30% of mean annual precipitation (Figure 3.6), and groundwater abstraction sites.

Model parameter values were initially assigned according to the results of pumping tests carried out mostly for the purpose of pumping sites development, and were subsequently adjusted during calibration process. Calibrated horizontal hydraulic conductivity values range from 40 to 250 m/day in the central part of the upper aquifer. Vertical anisotropy factor (Kh/Kz) is 10, while effective porosity is 0,23.

The 3D groundwater flow was simulated in steady-state and transient conditions. For steady-state simulation all boundary condition data were prepared in order to adequately represent average hydrological conditions. Transient simulation was performed for the period from 1998 to 2017 using monthly stress periods. Each stress period was divided into 10 time steps.

4.2.2 Model calibration

Steady-state model was calibrated against observed groundwater heads obtained from the network of observation wells (Figure 3.8, Figure 4.1, Figure 4.2). For calibration purpose, the parameter estimation tool PEST was used (Doherty, 2015). In accordance with parsimony principle (Hill, 2006), the model was kept as simple as possible, and the complexity was added in the process of calibration when necessary.

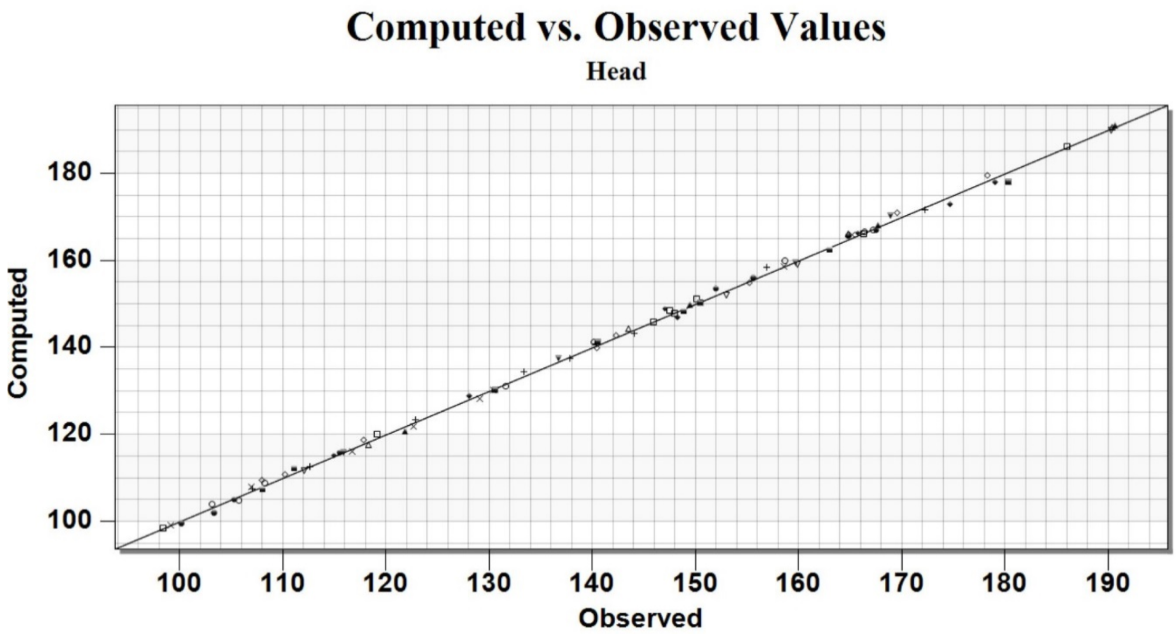


Figure 4.1. Calculated vs observed heads for steady state simulation

The calibration error statistics were calculated in order to evaluate the model performance. The goodness of fit between simulated and observed heads was evaluated using mean absolute residual (MAR), root mean squared residual (RMS) and normalised root mean squared residual (NRMS) (Table 4.2).

Table 4.2. Calibration error statistics

MAR	0.70 m
RMS	0.83
NRMS	0.90%

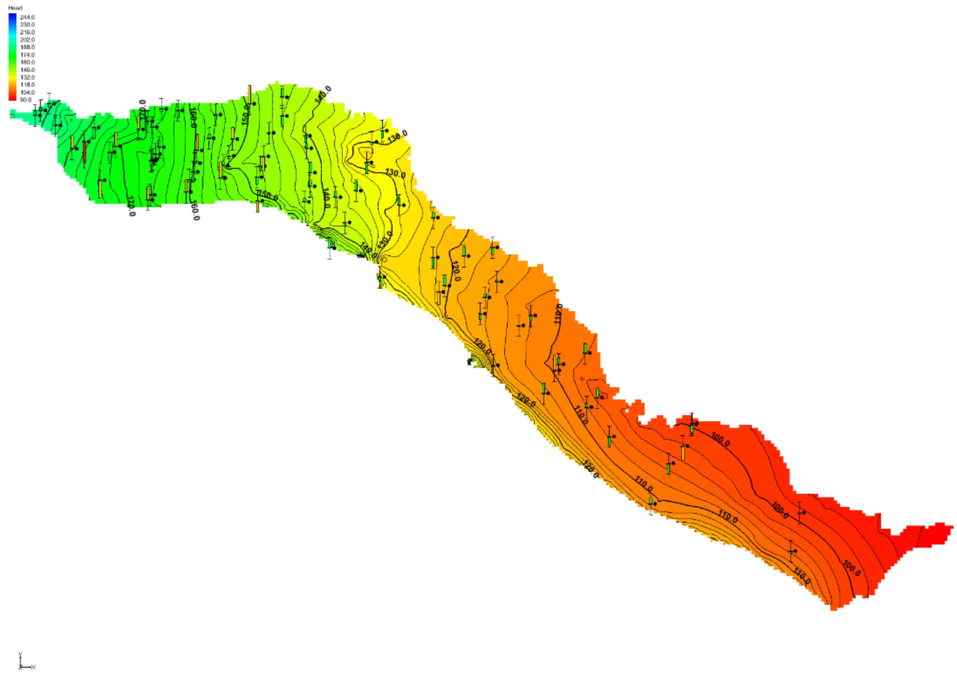


Figure 4.2. Hydraulic head in the upper aquifer – steady-state simulation

The model parameters calibrated in steady-state condition were applied in transient simulation. Cumulative annual recharge values for different zones in the modelling domain are kept the same as in steady-state, whereas monthly recharge values for each stress period were scaled by precipitations for the particular month, while taking into account air temperature and vegetation period. The transient simulation was set up for 20 years – 5 years as a warm up period, and 15 years for performance check, which was carried out by visual comparison of observed and simulated heads, groundwater flow nets and supported by summary statistics (Figure 4.3).

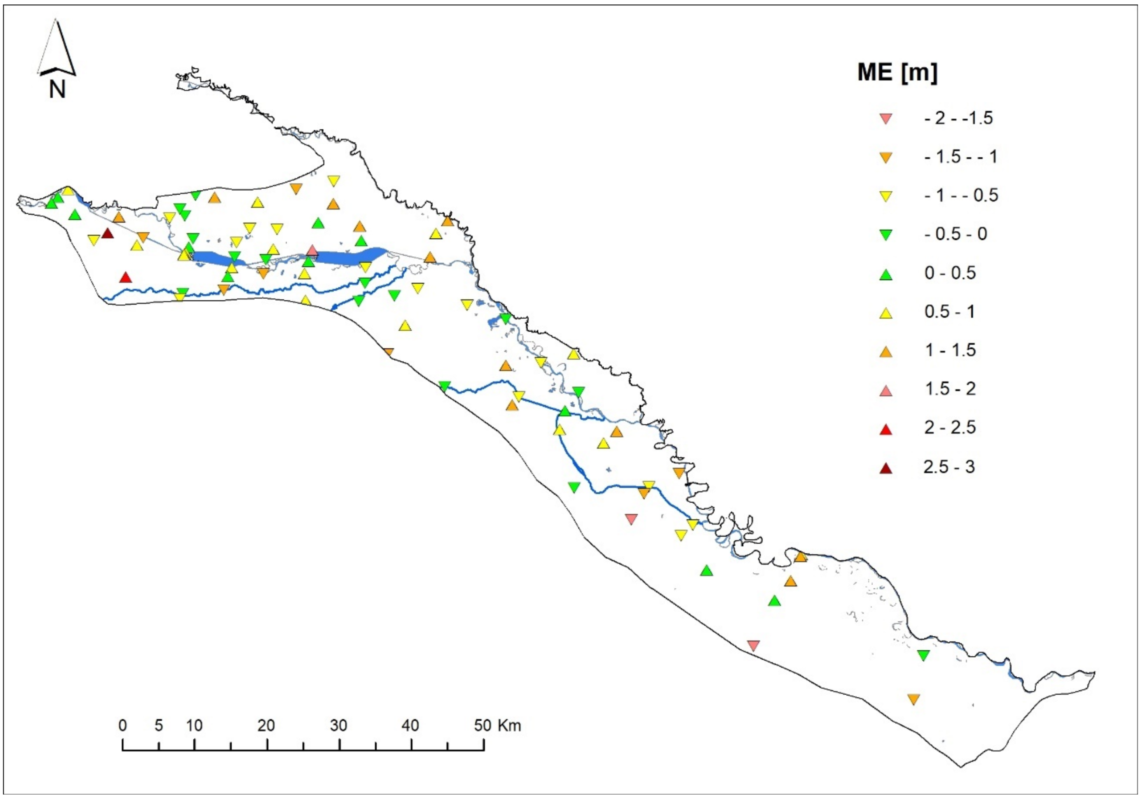


Figure 4.3. Mean error in the upper aquifer – transient simulation

4.3 GARDENIA lumped hydrological model

GARDENIA is an application developed by BRGM for lumped hydrologic modelling. It simulates the main water cycle mechanisms in a catchment basin (rainfall, evapotranspiration, infiltration, runoff) by applying simplified physical laws for flow through successive reservoirs. It uses meteorological data series related to catchment area (precipitation, potential evapotranspiration, air-temperature) to calculate:

- the flow rate at the outlet of a river (or spring);
- and / or the groundwater level at a given location in the underlying unconfined aquifer.

The calculations can be made at a daily, weekly, 10-day, or monthly time step. Users can also choose a much shorter time step, e.g. half-hourly or every five minutes.
Snowmelt can also be taken into account in the calculations.

The GARDENIA code can be used to:

- calculate the balance of rainfall, actual evapotranspiration, run-off and infiltration into the underlying aquifer,
- generate long series of flow rate or piezometric levels from historical rainfall data, after calibration for a relatively short period,
- analyse consistency between climate observations and observations of flow rates or piezometric levels.

Transfers from one reservoir to another are governed by simple laws described by the model's design parameters (retention capacity of the soil, transfer time, flooding thresholds, etc.).
Because of the global nature of the scheme and because of the complexity of the actual hydrological system, these parameters, although physically meaningful, cannot easily be deduced a priori from the physiographic characteristics of a basin at a given point (geology, plant cover, etc). These parameters must be therefore determined either:

- by calibration to one or two series of observations,
- or, exceptionally, by transposition from models of nearby catchment basins with similar characteristics.
-

The following data are required to calibrate the parameters:

- continuous time series used as input: rainfall and evapotranspiration (and air temperature if snowmelt is taken into account),
- in some cases, a time series of water abstraction (or injection) flows in the basin,
- one or two time series of observations (flow rates at the outlet and / or piezometric levels), not necessarily continuous but for the same period as the above series. The series (or two series) will be compared with the model output.

4.3.1 Model description

Gardenia lumped hydrological modelling has been performed in the utmost western part of the Drava-Mura pilot characterized by relatively small aquifer thickness, high effective infiltration and high hydraulic conductivity. The aquifer is unconfined and recharged by infiltration of precipitation. The covering aquitard is thin or non-existent.

The model was used to calculate the balance among rainfall, actual evapotranspiration and infiltration into the unconfined aquifer. The input datasets included precipitation and air temperature time series, while potential evapotranspiration was calculated using GARDENIA module and Turc equation (Figures 4.4 and 4.5).

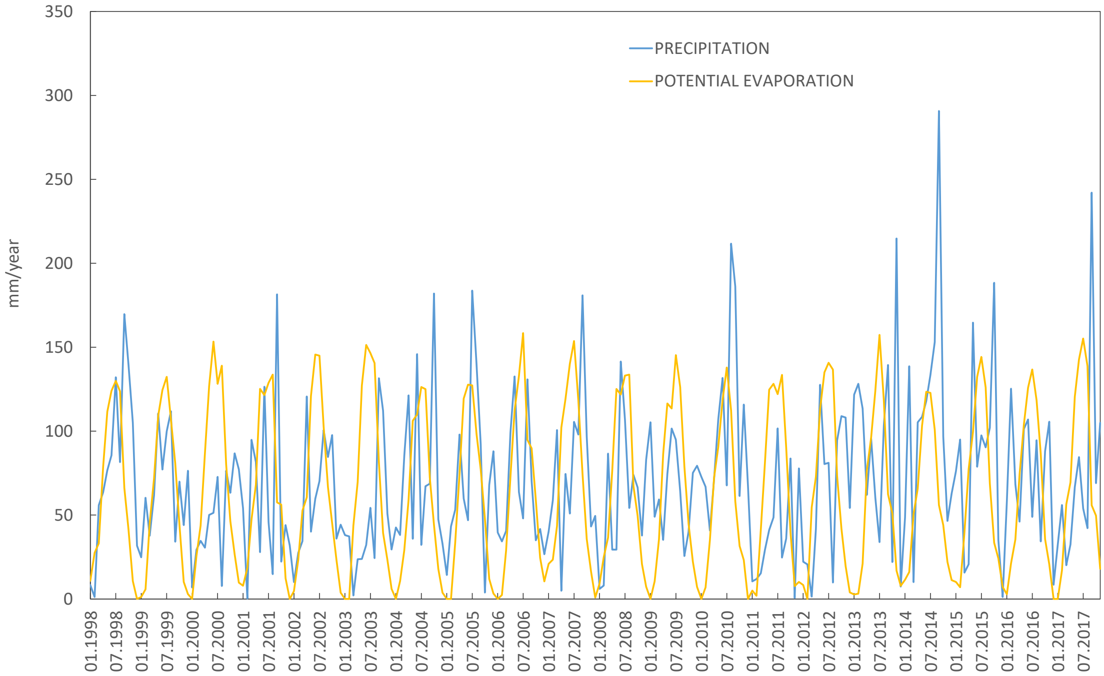


Figure 4.4. Precipitation and potential evapotranspiration

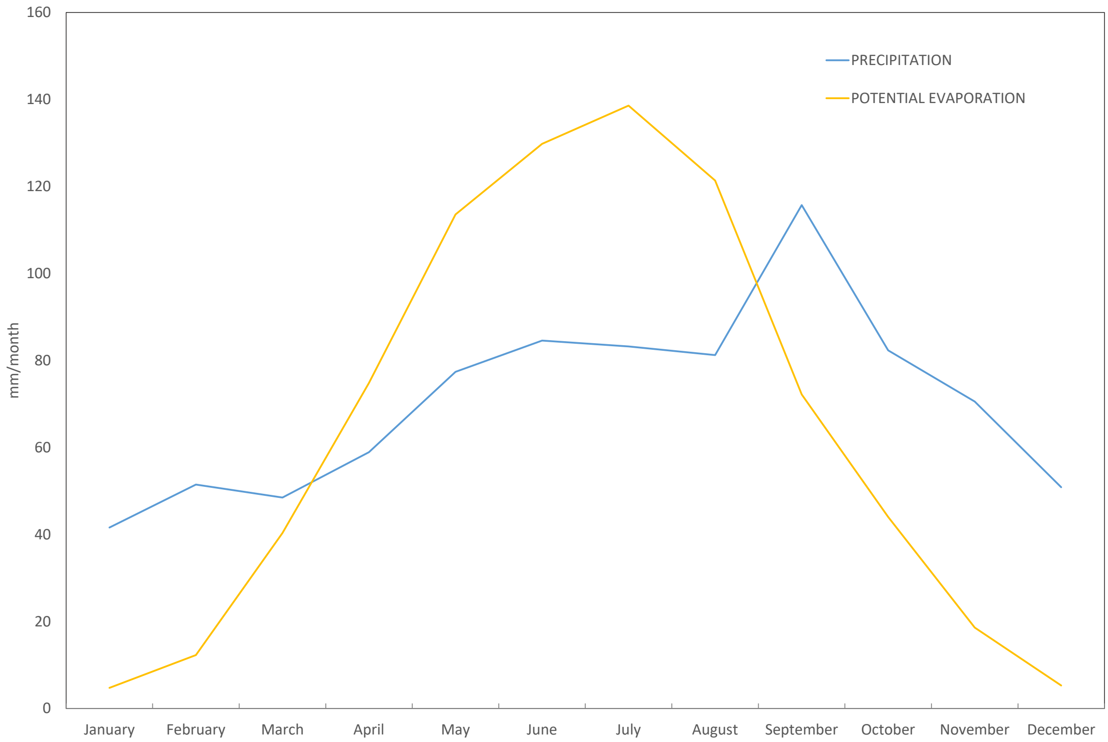


Figure 4.5. Monthly mean values of precipitation and potential evapotranspiration

4.3.2 Model calibration

The model was calibrated against mean monthly groundwater level dataset for the period from 1998-2018 (Figure 4.6). There are no groundwater abstraction site nor surface water courses in the immediate vicinity of the observation well used for model calibration.

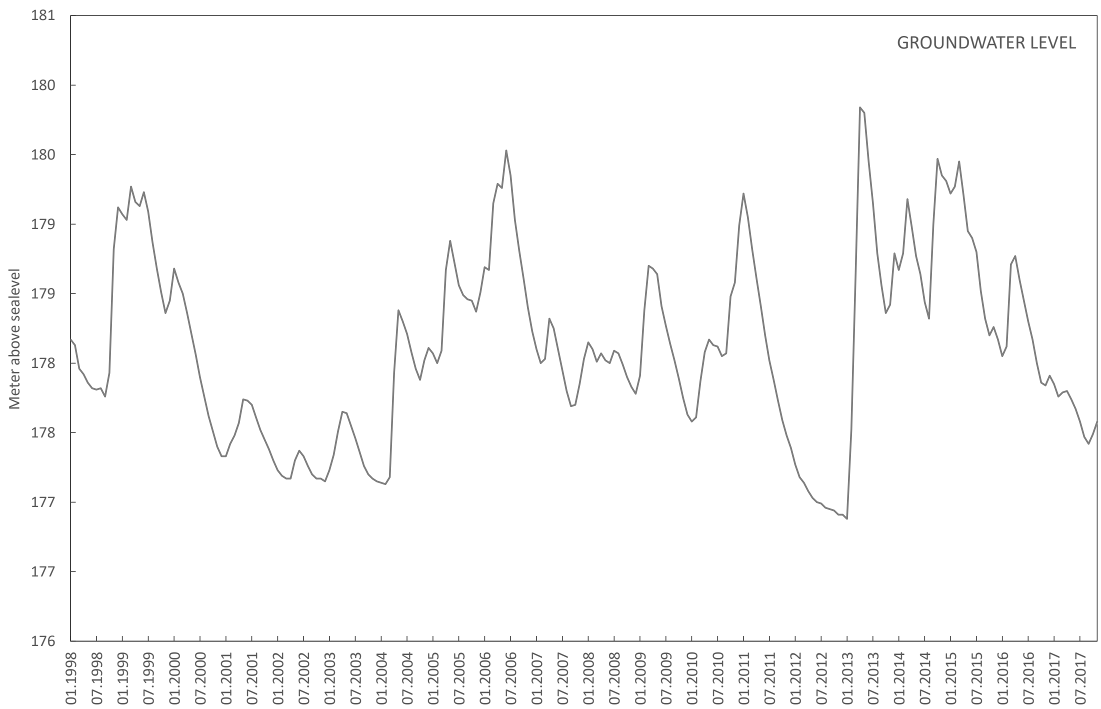


Figure 4.6. Groundwater levels

A reasonably good match between simulated and observed groundwater levels was obtained by the model (Figure 4.7). The calibration error statistics were calculated in order to evaluate the model performance (Table 4.3).

Table 4.3. Calibration error statistics

NSE	0.80 m
RMS	1.8 m
ME	0.7 m

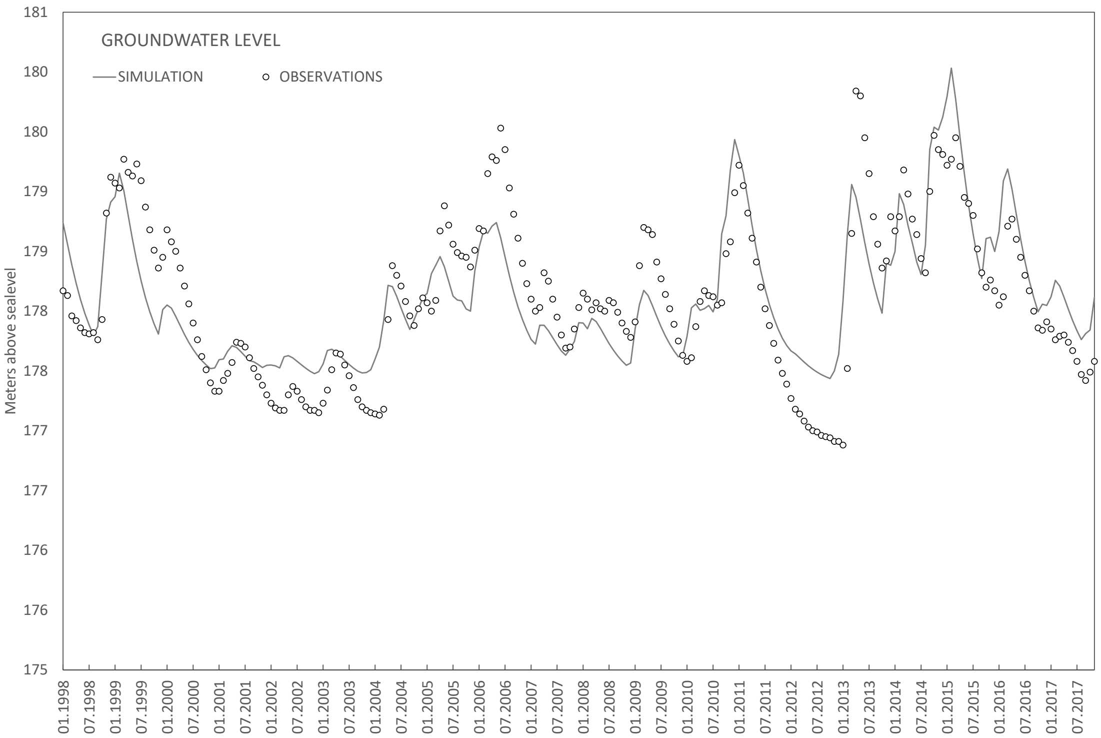


Figure 4.7. Simulated and observed groundwater levels

4.4 METRAN

Metran applies transfer function noise modelling of (groundwater head) time series with usually daily precipitation and evaporation as input (Zaadnoordijk et al., 2019). The setup is shown in Figure 4.8. If time series of other influences on the groundwater head are available, these contributions can be added to the deterministic part of the model. The stochastic part is the difference between the total deterministic part and the observations (the residuals). The corresponding input of the noise model should have the character of white noise.

The incomplete gamma function is used as transfer function. This is a uni-modal function with only three parameters that has a quite flexible shape and has some physical background (Besbes & de Marsily, 1984). The evaporation response is set equal to the precipitation response except for a factor (fc). The noise model has one parameter that determines an exponential decay. Thus, for the standard setup with precipitation and evaporation there are five parameters that have to be determined from the comparison with the observations: the three parameters of the precipitation response, the evaporation factor, and the noise model parameter (actually the time series model has a fifth parameter, the base level, but this is determined from the assumption that the average of the calculated heads is equal to the average of the observations). There are three extra parameters for each additional input series, such as pumping.

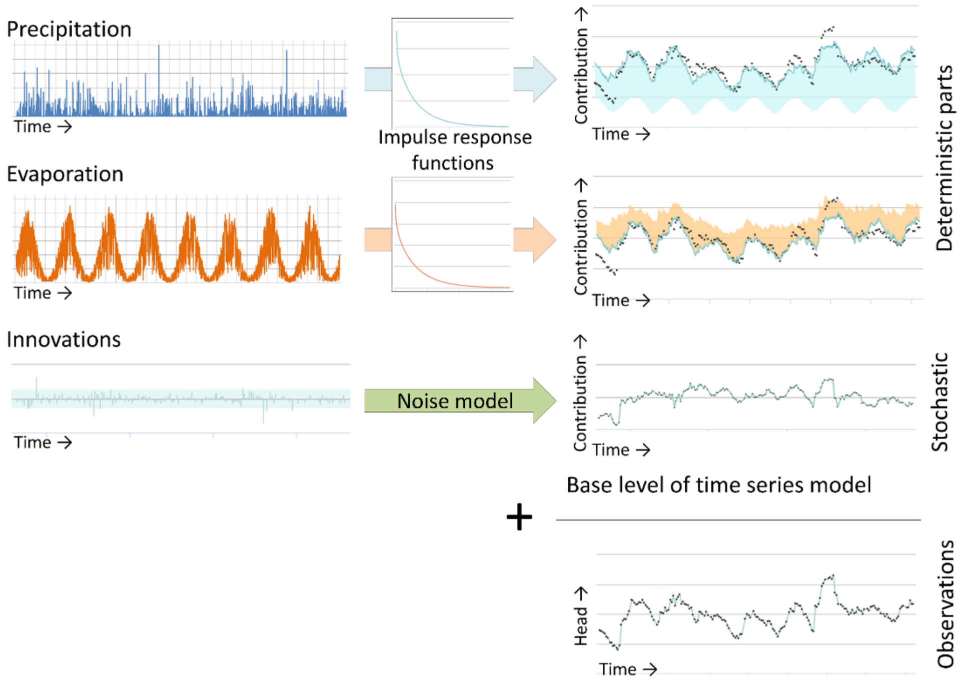


Figure 4.8. Metran setup

Metran's time series model is linear. So, the model creation breaks down when the system is strongly nonlinear. This can occur e.g. when drainage occurs for high groundwater levels, when the ratio between the actual evapotranspiration and the inputted reference evaporation varies strongly, or when the groundwater system changed during the simulated period.

Metran can also not find a decent time series model when the response function is not appropriate for the groundwater system.

Finally, the parameter optimization of Metran uses a gradient search method in the parameter space, so it can be sensitive to initial parameter values in finding a solution.

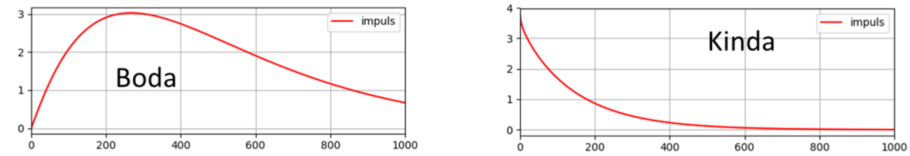
Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other daily time steps can be used, although Metran still has the limitation that the explanatory variables have a constant frequency. For the TACTIC simulations of series with monthly or decadal meteorological input series, the time step has been set to 30 and 10 days, respectively. This time step has been applied from the end date backward.

The heads may be irregular in time as long as the frequency is not greater than the frequency of the explanatory series.

As an output model creates several columns. The column fc is the evaporation factor and it gives the importance of evapotranspiration compared to precipitation.

M0 gives the total precipitation response, which is equal to the area below the impulse response function and the final value of the step response function.

The average response time is another characteristic of the precipitation response. The influence is illustrated in Figure 4.9 with the impulse response functions and head time series for two models with very different response times for time series of SGU in Sweden.



M0prec	mu_pr	fc	name
502	75073	0.80	SGU_Pilot16_Kinda_v20
2128	1105396	0.46	SGU_Pilot15_Boda_v20

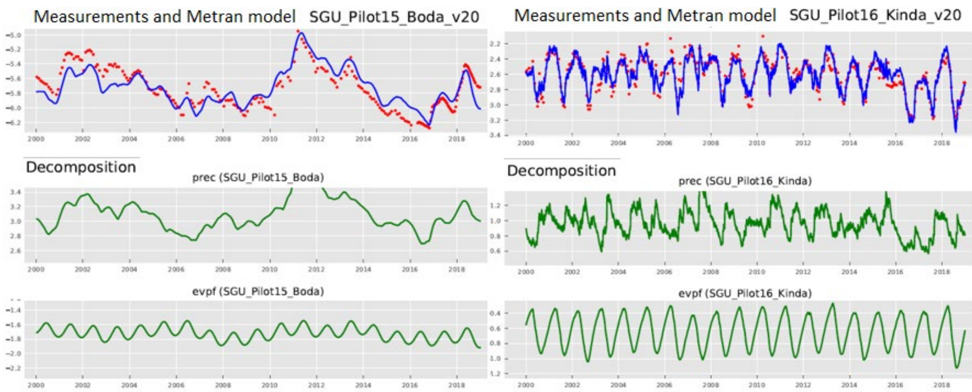


Figure 4.9. Impulse response functions and head time series for pilots in Sweden

Metran judges a resulting time series model according to a number of criteria and summarizes the quality using two binary parameters Regimeok, Modok (Zaadnoordijk et al., 2019):

- Regimeok =1 : highest quality
- Modok = 1 (and Regimeok = 0) : ok
- Both zero = model quality insufficient

More detailed information on the model quality is given in the form of scores for two information criteria (AIC and BIC), a log likelihood, R2, RMSE, and the standard deviations and correlations of the parameters.

Although the transfer-noise modelling of Metran determines statistical relations between groundwater heads and explanatory variables, we like to think of the results in physical terms. It is tempting to interpret the evaporation factor, as the factor translating the reference into the actual evapotranspiration. Then, we can calculate a recharge as
$R = P - f\,E$
where R is recharge, P precipitation, E evapotranspiration, and f the evaporation factor. Following the definitions used in the TACTIC project, this recharge R actually is the effective

precipitation. It is equal to the potential recharge when the surface runoff is negligible. This in turn is equal to the actual recharge at the groundwater table if there also is no storage change or interflow. In such cases it may be expected that this formula indeed corresponds to the meteorological forcing of the groundwater head in a piezometer, so that it gives a reasonable estimate of the recharge Obergfell et al. (2019) showed this for an area on an ice pushed ridge in the Netherlands.

However, this assumes that all precipitation recharges the groundwater, which cannot be done in many places.

In Dutch polders with shallow water tables and intense drainage networks, it is reasonable to assume that the actual evapotranspiration is equal to the reference value. In that case, the factor f becomes larger than 1 because 1 mm of evaporation has less effect than 1 mm of precipitation (because part of the evaporation does not enter the ground but is immediately drained to the surface water system). In that case, we can calculate recharge as:

$R = P - f\,E \qquad (f \leq 1)$

$R = P/f - E \qquad (f > 1)$

5 RESULTS AND CONCLUSIONS

5.1 Distributed groundwater flow model

The impact of climate change on the aquifer system was assessed by the means of distributed groundwater flow model and TACTIC standard climate change scenarios. The aquifer system mainly consists of two aquifers, which are separated by aquitard. Overall, groundwater table is close to the surface, and only occasionally exceeds several meters – mainly close to the groundwater abstraction sites and along the southern boundary of the aquifer system. The focus of climate change impact assessment was on the upper aquifer which is a key to interaction and sustainability of GWDEs and at the same time is the major source of drinking water.

5.1.1 *TACTIC scenarios: Upper aquifer*

The transient simulations of groundwater flow for historic and future periods were performed with monthly stress periods. The minimum, maximum and average groundwater heads across the entire simulation period were calculated within GMS modelling platform. The resulting rasters were then used for calculation of differences in groundwater heads between future and reference periods.

Figure 5.1 and 5.2 shows the differences in groundwater heads for 1-degree and 3-degree warming scenarios, respectively. Clearly, the negative direction of change prevails across all analysed hydrological conditions and both simulated scenarios. The only difference is in the magnitude of change. The opposite direction of change is only registered for high waters and 1-degree maximum change scenario along the southern aquifer boundary, particularly in the utmost southwestern part where high recharge rates are simulated.

Figure 5.1 shows that minimum and maximum changes within 1-degree warming scenario result in similar differences in groundwater heads between future and reference periods. Mostly, the decrease in groundwater heads is between 0 and 0.75 m. Maximum change shows somewhat lower heads in in the northwestern area of the pilot for low hydraulic conditions, whereas the opposite situation is in the southeastern area. Overall, the largest decrease in groundwater heads is obtained for minimum change and high hydraulic conditions in the southeastern area of the pilot, where groundwater heads drop is below -1,5 m. The increase of groundwater heads above 0,25 m is simulated for high waters and 1-degree maximum change in the utmost southwestern part of the pilot.

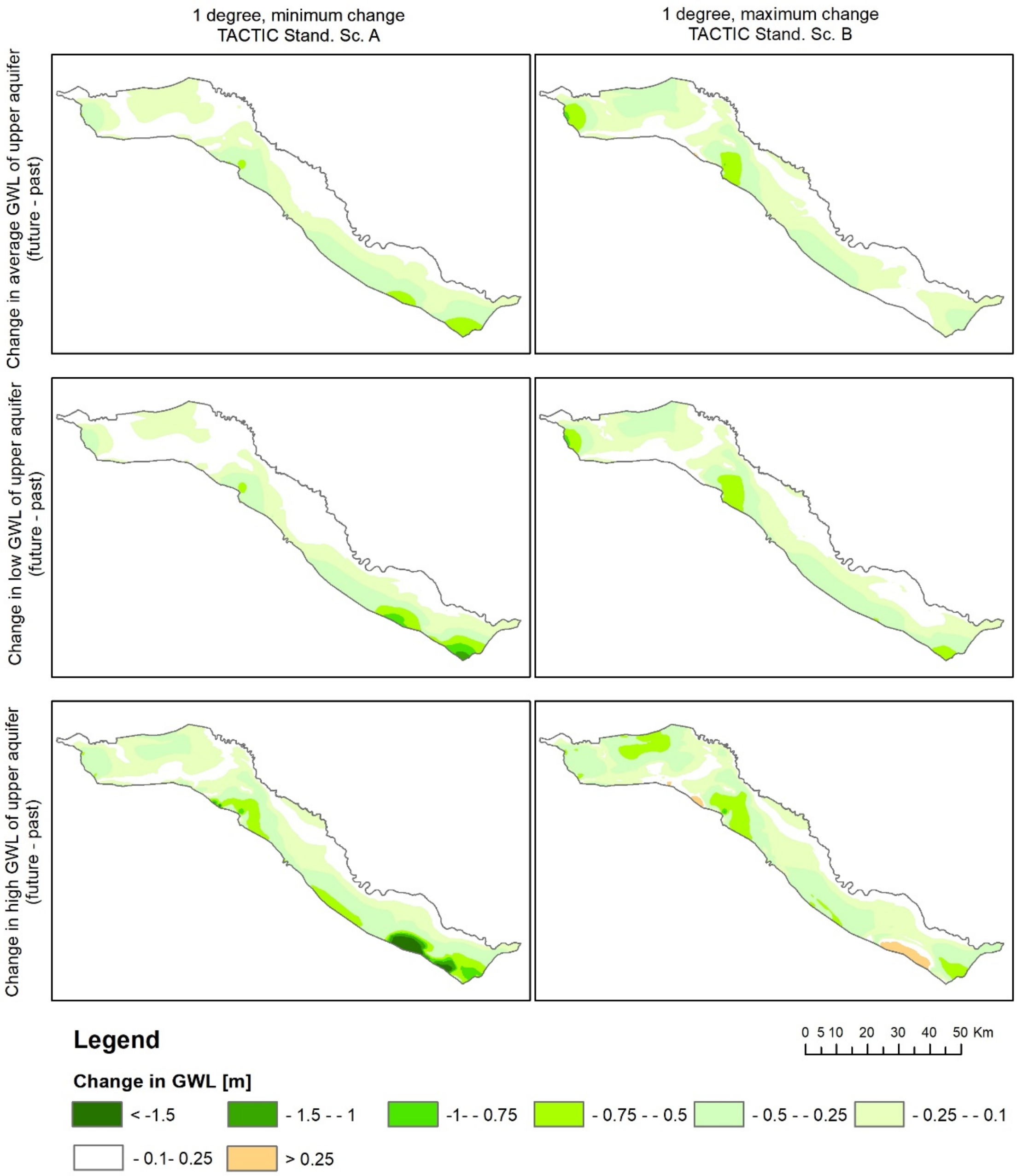


Figure 5.1. Changes in average, maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario.

The modelling results for 3-degree scenario, shown in Figure 5.2, is consistent with the results for 1-degree scenario. The direction of change is the same for the both minimum and maximum change scenarios, but the magnitude of change is larger for 3-degree scenario, as expected. The areas with the decrease in groundwater heads between 0 and -0.1 are significantly smaller in comparison with 1-degree warming scenario, whereas pilot areas with groundwater drop below -1 m are larger.

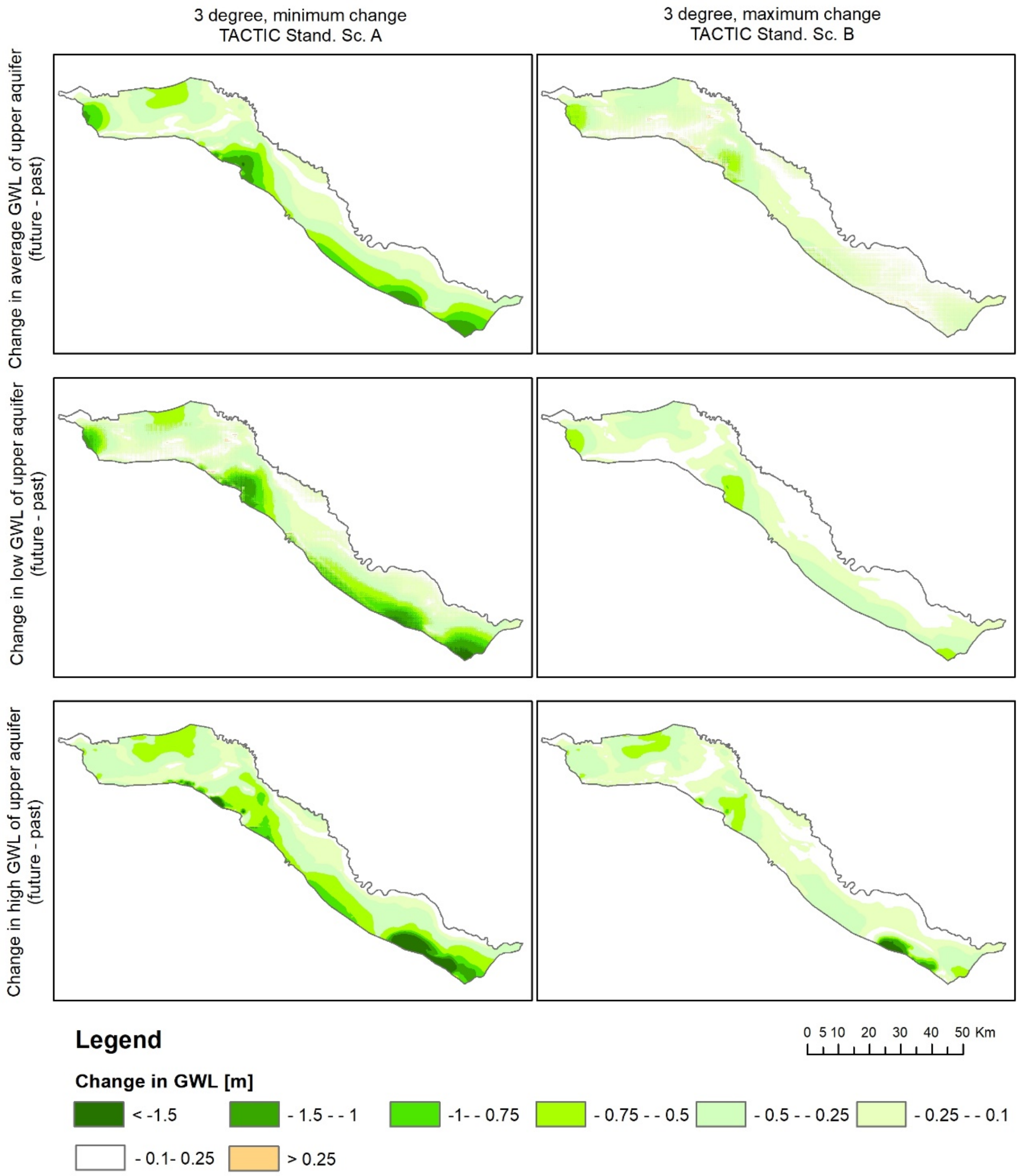


Figure 5.2. Changes in average, maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario.

Figures 5.1 and 5.2 shows that the minimum change in groundwater levels for both 1-degree and 3-degree scenarios is nearby the Drava river. This is a consequence of the fact that the same river stages were applied for historic and future periods. Since the Drava river is in direct contact with groundwater in most of the pilot area, it controls groundwater levels in the vicinity of the river bed.

5.1.2 TACTIC scenarios: Groundwater dependent ecosystems

Natura 2000 protected areas and a number of GWDEs are spread across the pilot area (Figure 3.8). It is well known that phreatophytes are sensitive to the changes in groundwater levels. However, exact depths and magnitudes of oscillation of groundwater levels that are required for the good status of GWDEs are yet to be established. Therefore, the focus of the impact assessment of climate change scenarios in the pilot areas occupied by Natura 2000 protected areas and GWDEs was on identification of the relative change of groundwater levels.

Both 1-degree and 3-degree warming scenarios yield the decrease in groundwater levels, apart from 1-degree maximum change scenario results for high hydrologic conditions, which show opposite direction of change locally along southern aquifer boundary. Natura 2000 protected areas and GWDEs are mainly scattered in central region of the Drava river valley, which is characterized by the smallest difference in groundwater levels between historic and future periods (Figures 5.3 – 5.6). The decrease in groundwater levels in in that area ranges from less than -0,25 m to -0,5 m, locally up to -1 m in low hydrologic conditions and 3-degree minimum change scenario (Figure 5.5). However, there are several GWDEs located along southern and northern aquifer boundaries. These areas are characterised by larger decrease in groundwater levels. The largest difference is registered along the southeastern aquifer boundary, where it reaches more than -1,5 m in low water condition and 3-degree minimum change scenario. The similar drop in groundwater levels in that area is registered for high waters and 1-degree minimum change, 3- degree minimum change and 3-degree maximum change scenarios.

Overall, it can be concluded that majority of GWDEs and Natura protected sites should not be significantly affected by climate change scenarios under consideration. It especially applies for 1-degree and 3-degree maximum change scenarios and central region of the pilot where the majority of protected areas are located. However, the results of 3-degree, minimum change scenario are somewhat of concern for those GWDEs located closer to the southern aquifer boundary, because the simulated groundwater level drop reaches more than -0,75 m for high and low hydrologic conditions. Such circumstances could be dangerous for those phreatophytes that require their roots to be submerged during a certain period of year.

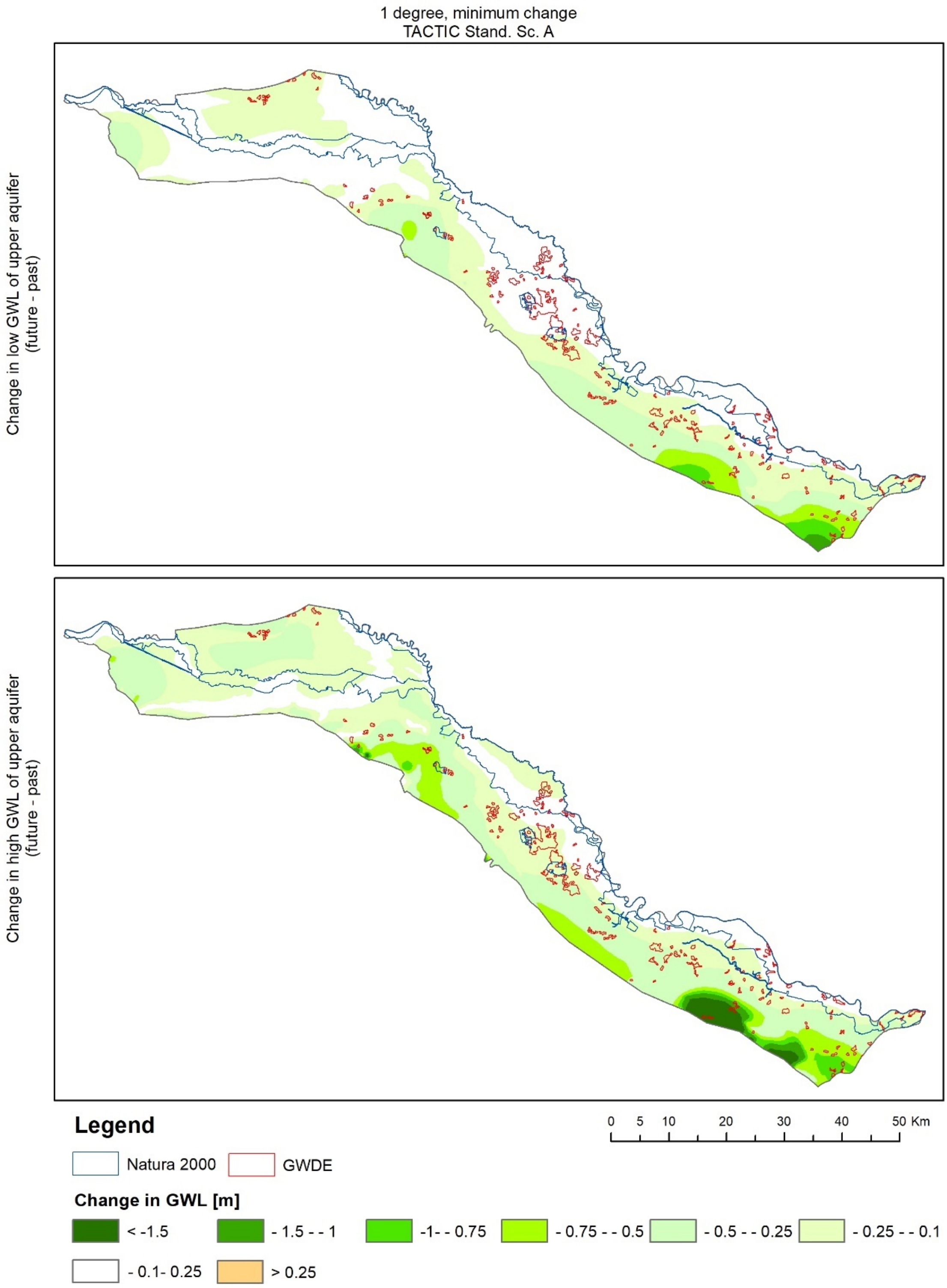


Figure 5.3. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario, minimum change.

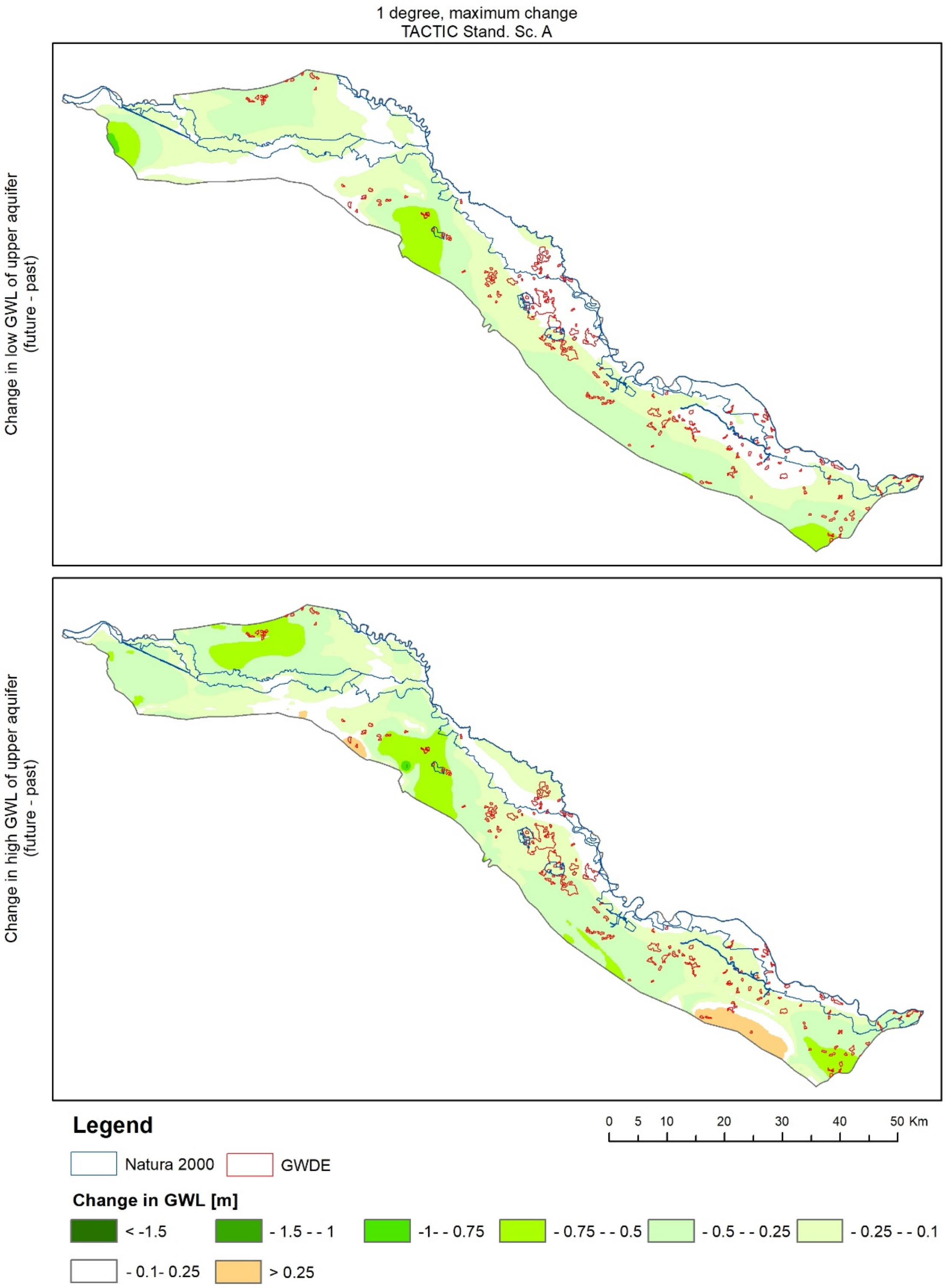


Figure 5.4. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario, maximum change.

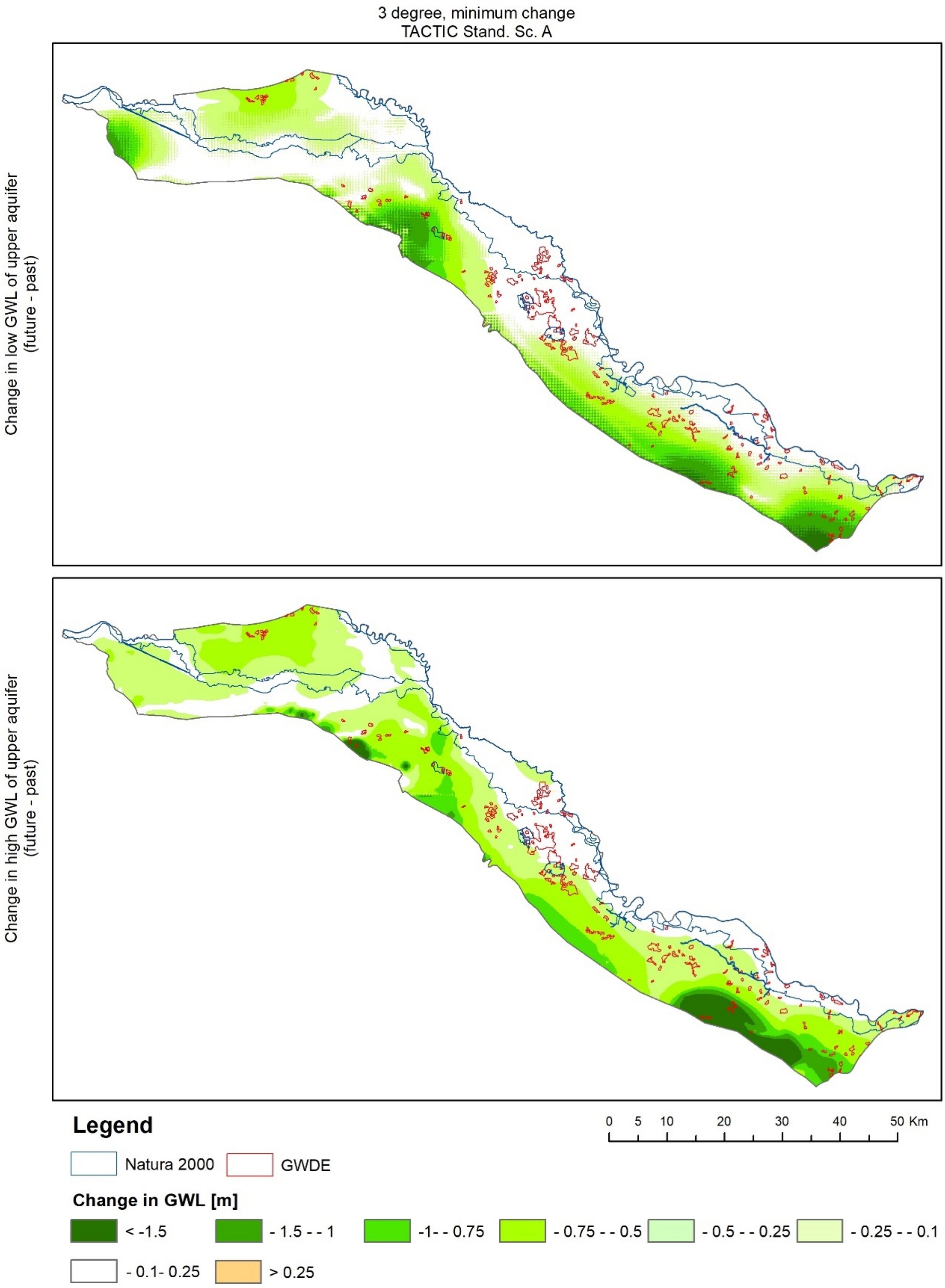


Figure 5.5. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario, minimum change.

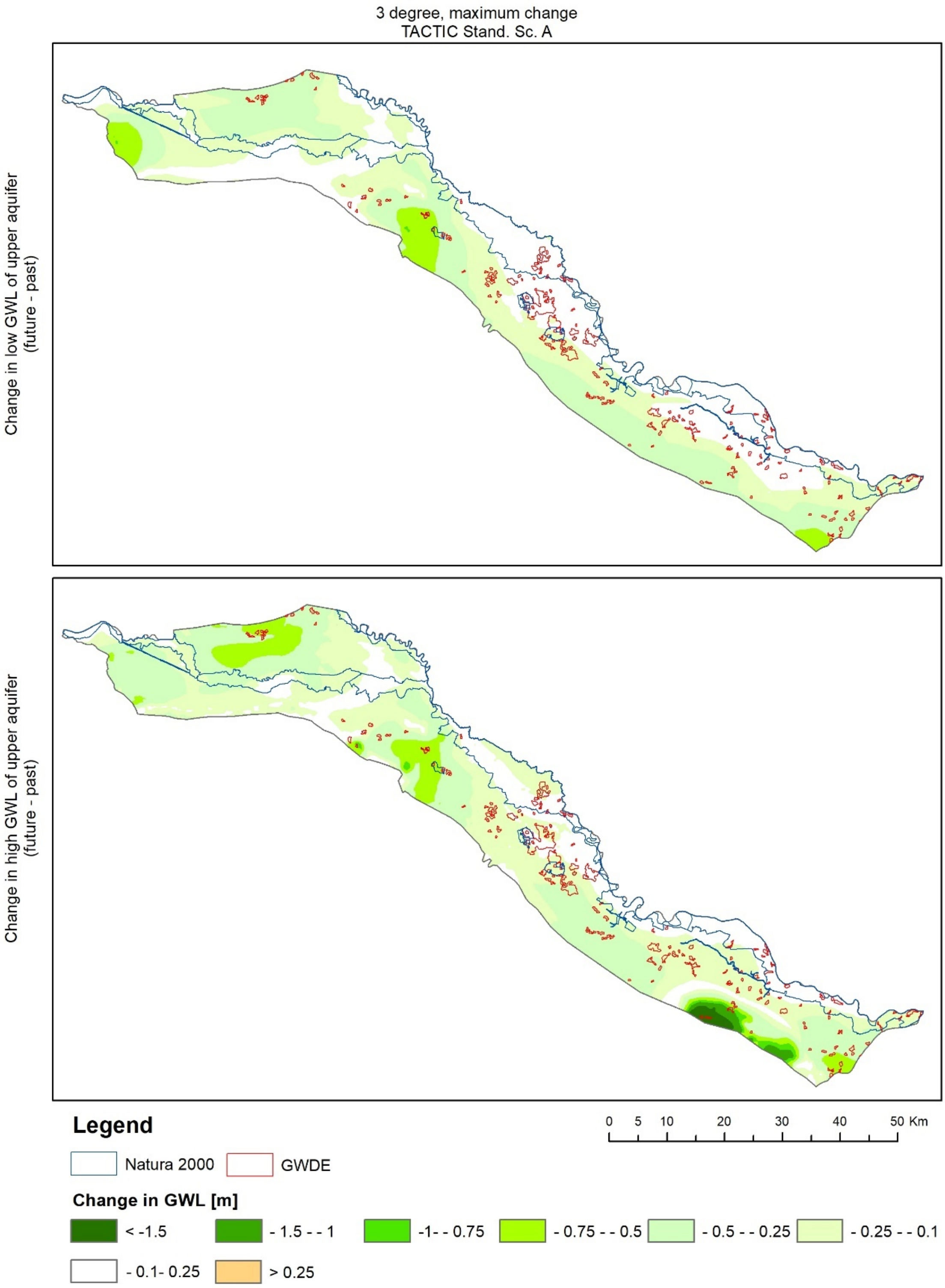


Figure 5.6. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario, maximum change.

5.2 GARDENIA lumped hydrological model

The calibrated lumped hydrological model was applied for generation of future groundwater level time series for 3-degree minimum and maximum change scenarios (Table 4.1). Simulated groundwater levels for minimum change scenario are mostly below historic values, whereas the difference between groundwater levels for maximum change scenario and historic simulation is overall rather small.

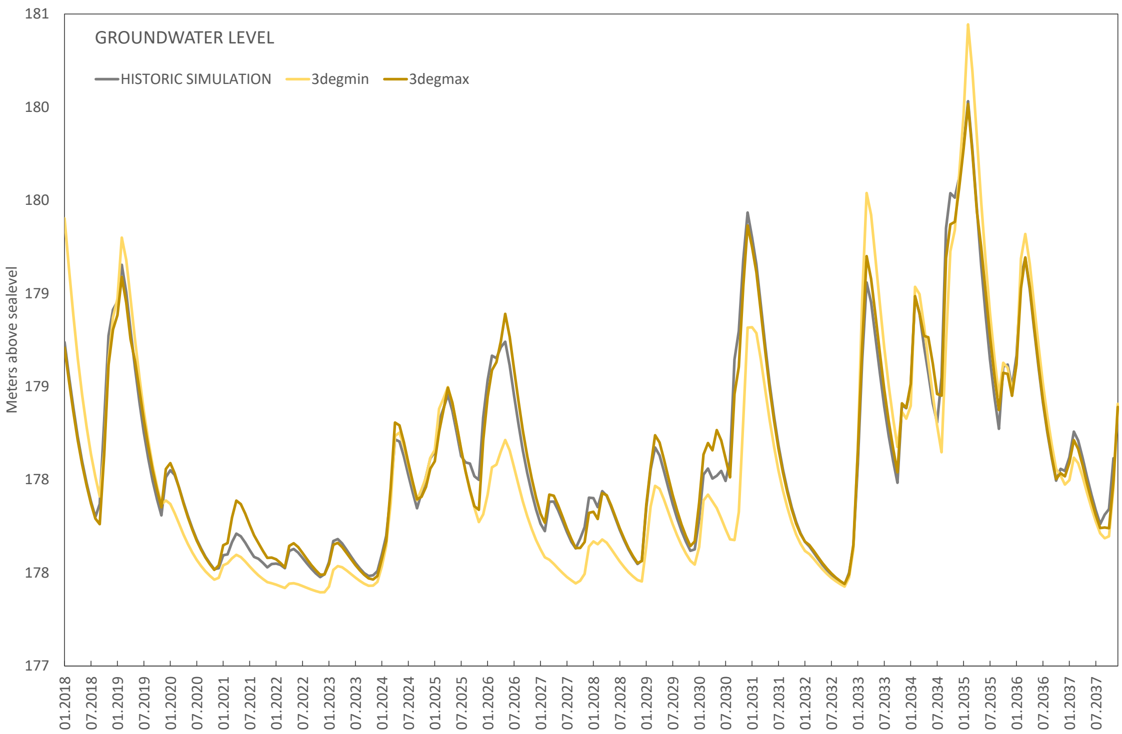


Figure 5.7. Groundwater level simulation for historic period and 3-degree minimum and maximum change.

The results of the average monthly recharge from lumped hydrological model are shown in Table 5.1. For minimum change scenario recharge is 49% lower, while for the maximum change it is 4% higher, as compared to the reference period.

Table 5.1. Average recharge – lumped hydrological model

Average recharge [mm/m]		
Reference period	3-degree minimum change	3-degree maximum change
11.7	6.0	12.2

5.3 METRAN

Figure 5.8 shows results of transfer function noise modelling of groundwater head time series at the utmost western area of the Drava-Mura pilot. Daily precipitation and evaporation were used as input.

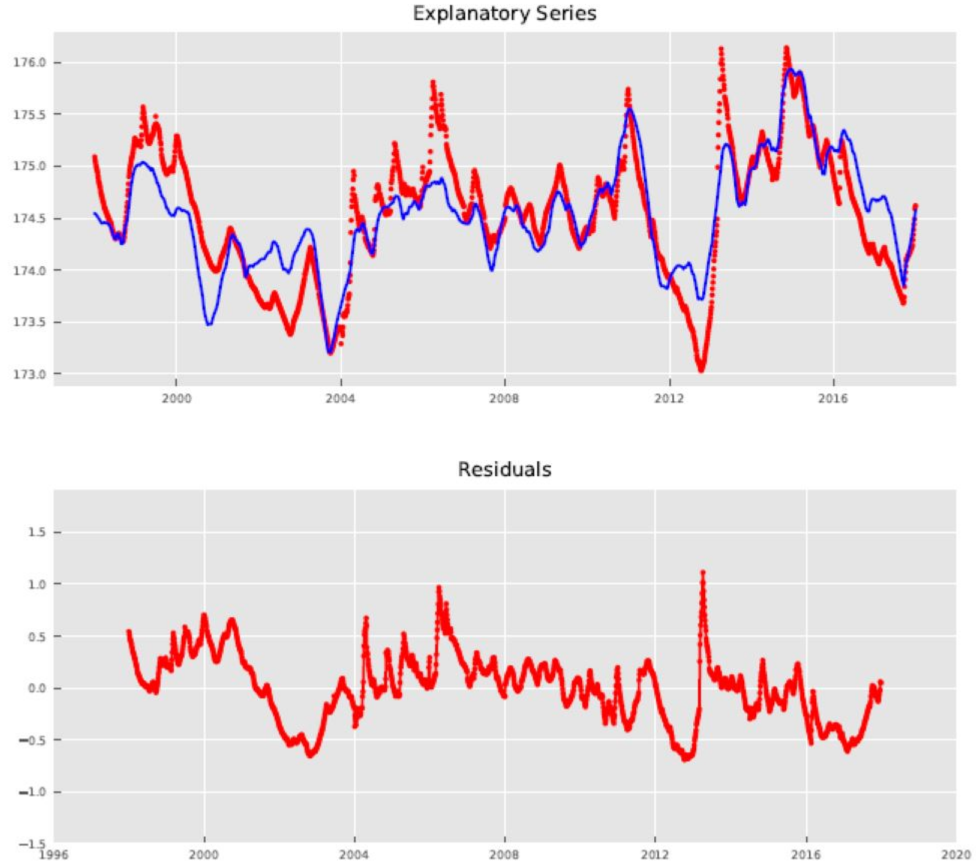


Figure 5.8. Head time series (blue – simulated, red – observed) and residuals.

The contribution of the precipitation and evaporation to the observed dynamics are shown in Figure 5.9.

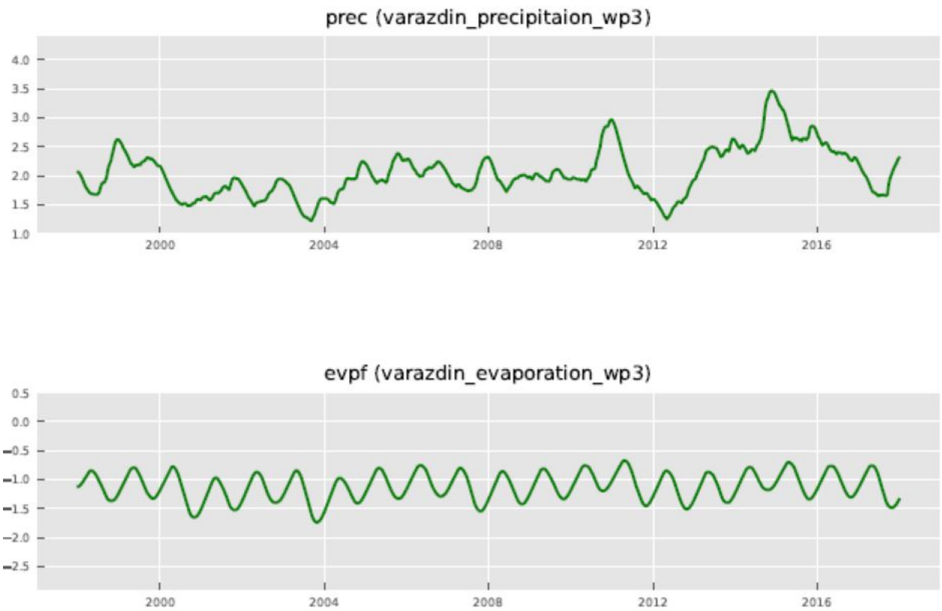


Figure 5.9. Contribution of precipitation and evaporation to the observed dynamics.

According to the indicators shown in Table 5.2, the model performs reasonably well.

Table 5.2. Model performance indicators.

Regimeok	1
Modok	1
R2	0.73
RMSE	0.32 m

The results of time series model point out that average monthly recharge for the observation well under consideration is 12,17 mm lower and 1.21 mm higher for 3-degree minimum change and 3-degree maximum change, respectively, as compared to the reference period. The *fc* value stands for evaporation coefficient (Table 5.3).

Table 5.3.

fc	Average recharge [mm/m]		
	Reference period	3-degree minimum change	3-degree maximum change
0.5	31,94	19.77	33,15

5.4 Conclusions

The report contains results of the climate change impact assessment on the upper alluvial aquifer of the Drava-Mura pilot area and associated GWDEs and Natura 2000 protected areas. For that purpose, distributed groundwater flow model, GARDENIA lumped hydrological model and METRAN time series model were applied together with four combinations of RCPs-GCMs from TACTIC standard scenarios, which are based on ISIMIP datasets.

The results of climate change signals propagation through distributed groundwater flow model showed that:

- Negative direction of change between future and historic groundwater heads prevails for both 1-degree and 3-degree warming scenarios. The opposite direction is only registered locally along southern boundary of the aquifer system for 1-degree maximum change scenario and high-water conditions.
- Magnitude of change in groundwater levels is higher for 3-degree warming scenario, as expected.
- Central region and along the Drava river show minimum change in groundwater heads for both climate change scenarios, which is partly due to the fact that the climate change impact on river discharges was not simulated.
- Most GWDEs should not be significantly affected by climate change scenarios, except for those located closer to the southern aquifer boundary where results for different scenarios show a local drop for specific hydrological conditions below -0,75 m.

Comparison of average monthly recharge values obtained by application of different tools at the utmost western part of the pilot area showed that:

- Gardenia lumped hydrological model simulated recharge values that are 25% lower for historic period, 42% lower for 3-degree minimum change and 3,3% higher for 3-degree maximum change scenarios, as compared to the values from distributed model of groundwater flow;
- Metran time series model simulated recharge values that are 104% higher for historic period, 90% higher for 3-degree minimum change and 180% higher for 3-degree maximum change scenarios, as compared to the values from distributed model of groundwater flow.
-

The study has been performed at regional scale, with the grid size of the distributed groundwater flow model 500x500 m. Therefore, the results are unsuitable for the application in assessing the impact of climate change at local scales.

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

Denmark

Authors and affiliation:

Ida Karlsson

Jacob Kidmose

Geological Survey of Denmark and Greenland

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data	
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Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	WP3
Lead WP/Deliverable beneficiary	Institution
Deliverable status	
Version	Version no 3
Date	Date 22. Feb 2021

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LIST OF ABBREVIATIONS & ACRONYMS

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

TABLE OF CONTENT

1 EXECUTIVE SUMMARY

Pilot name	Denmark	
Country	Denmark	
EU-region	NW, CE	
Area (km^2)	43000	
Aquifer geology and type classification	Sand and gravel, chalk	
Primary water usage	Drinking	
Main climate change issues	Rising shallow groundwater table, groundwater flooding	
Models and methods used	Integrated hydrological model	
Key stakeholders	Government, Regional and local authorities, water suply companies	
Contact person	Jacob Kidmose (jbki@geus.dk)	

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

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

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

2 INTRODUCTION

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

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

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

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

3 PILOT AREA

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

3.1 Site description and data

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

Table 3.1 Subcatchments of Denmark

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

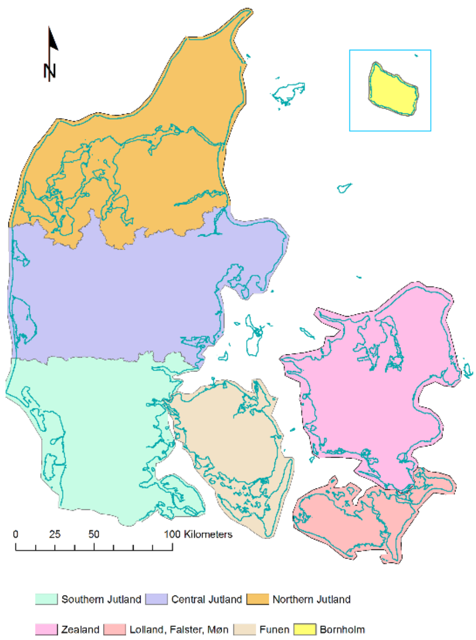

Figure 3.1 Denmark and the seven subareas. The Island of Bornholm is located east of Zealand in the Baltic Sea.

3.1.1 Climate

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

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

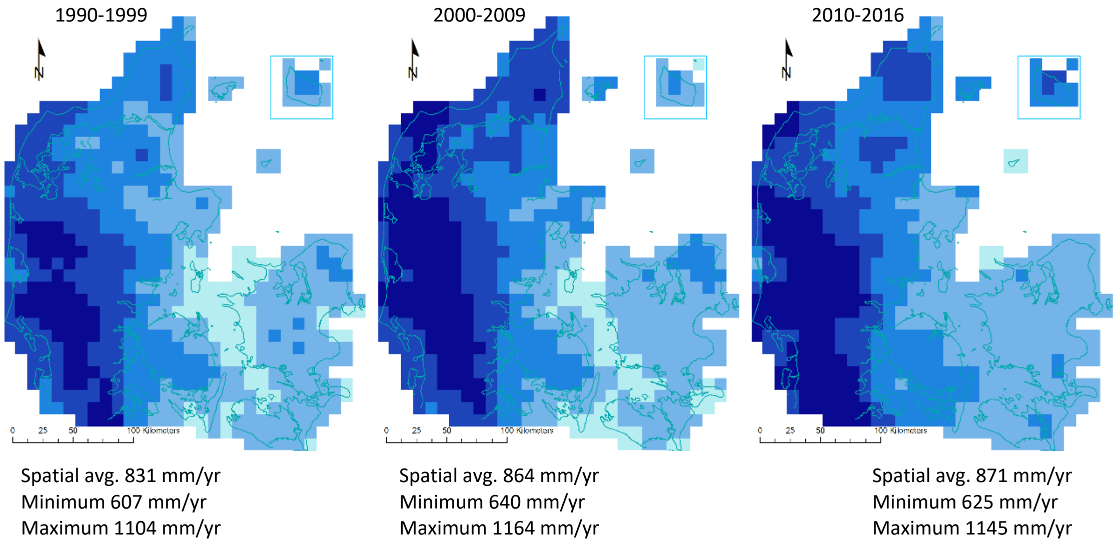

Figure 3.2 Mean yearly precipitation 1990-1999, 2000-2009, and 2010-2016 (lower left is the same as the upper figure

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

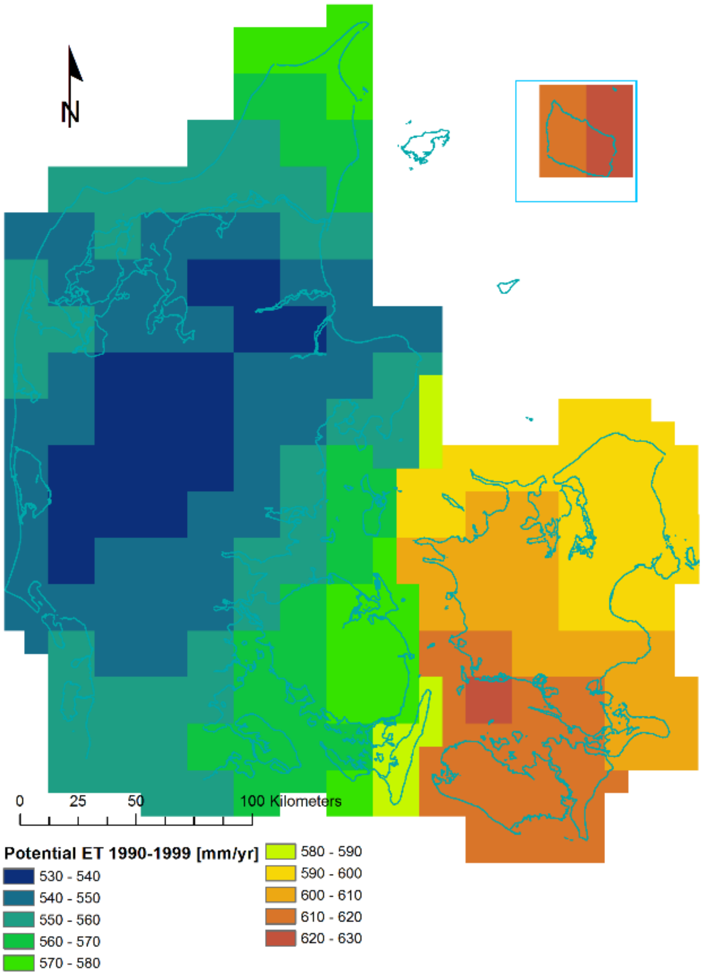

Figure 3.3 Potential evapotranspiration, mean value from 1990-1999 (min=528, max=624, spatial mean=568 mm/yr).

3.1.2 Topography

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

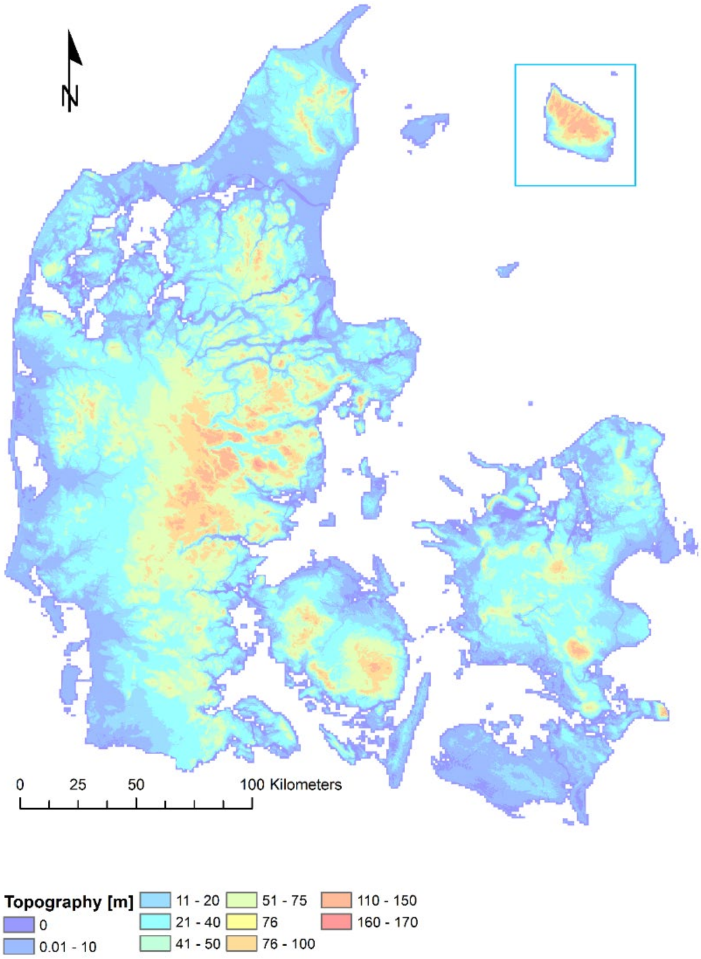

Figure 3.4 Topography of Denmark. Elevation is shown according to meters above mean Danish sea level (DNN).

3.1.3 Soil types

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

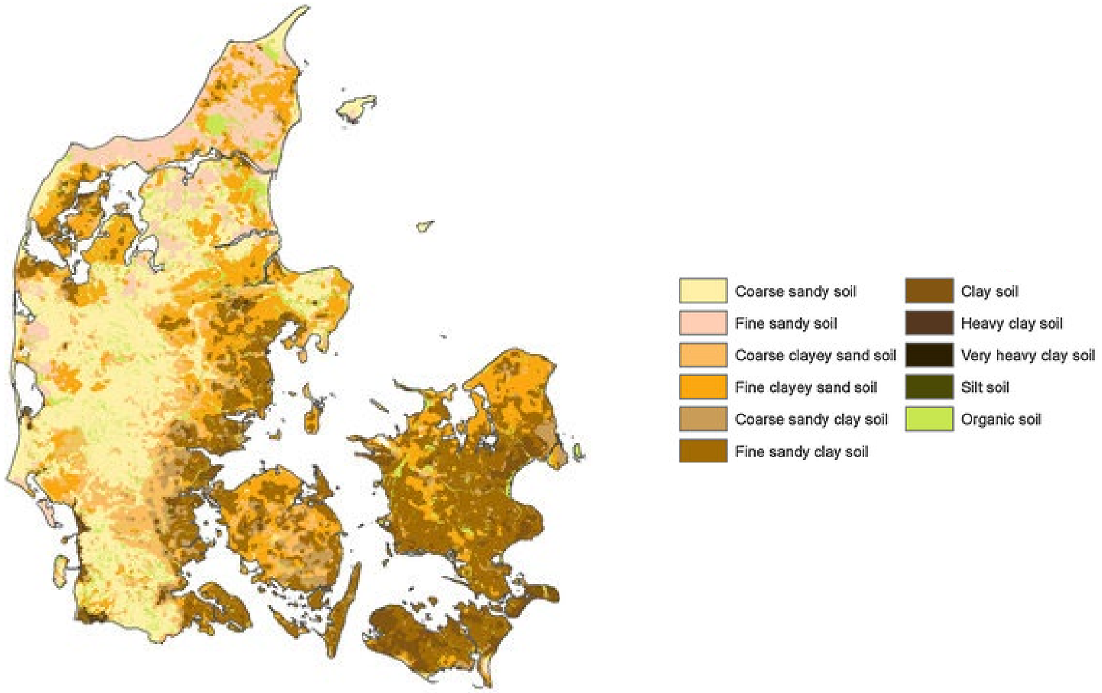

Figure 3.5 Map of the Danish soil types from Odgaard et al. (2017) and Greve et al. (2007)

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

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

3.1.4 Land use

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

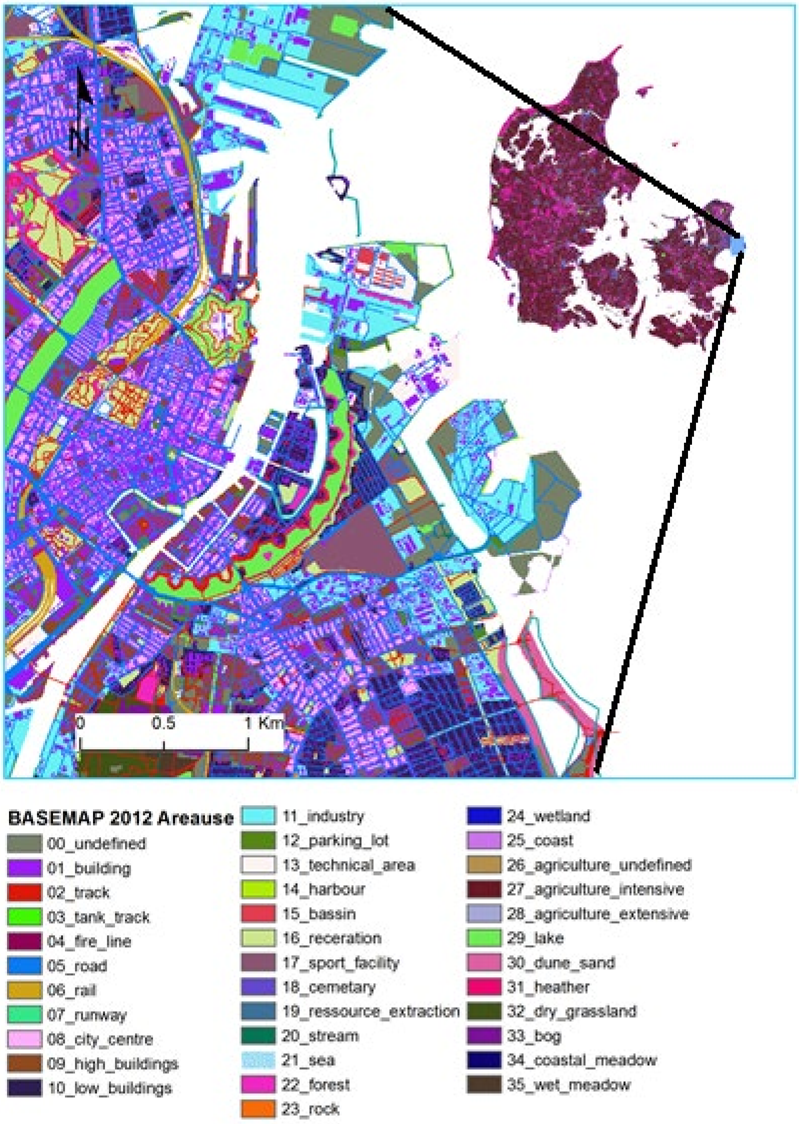

Figure 3.7 Area use in Denmark based on the 10x10 m raster dataset by Levin et al. 2012.

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

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

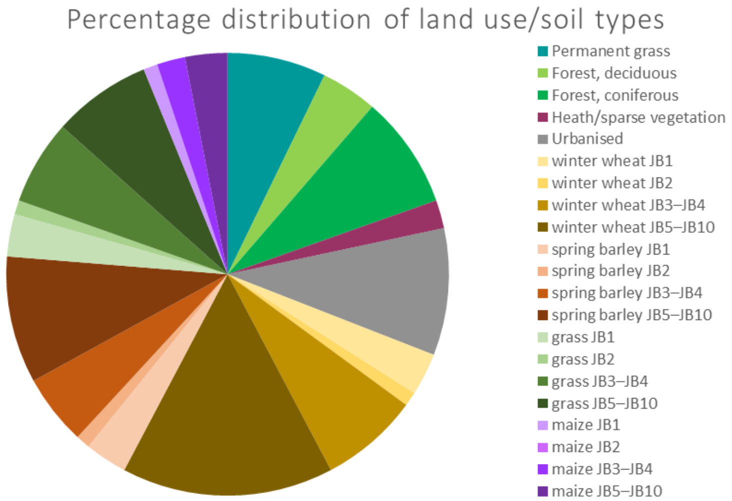

Figure 3.9 Distribution of land use types with soil type classification in farmlands (surface water bodies not included) data from Stisen et al. (2012)

3.1.5 Geology/Aquifer type

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

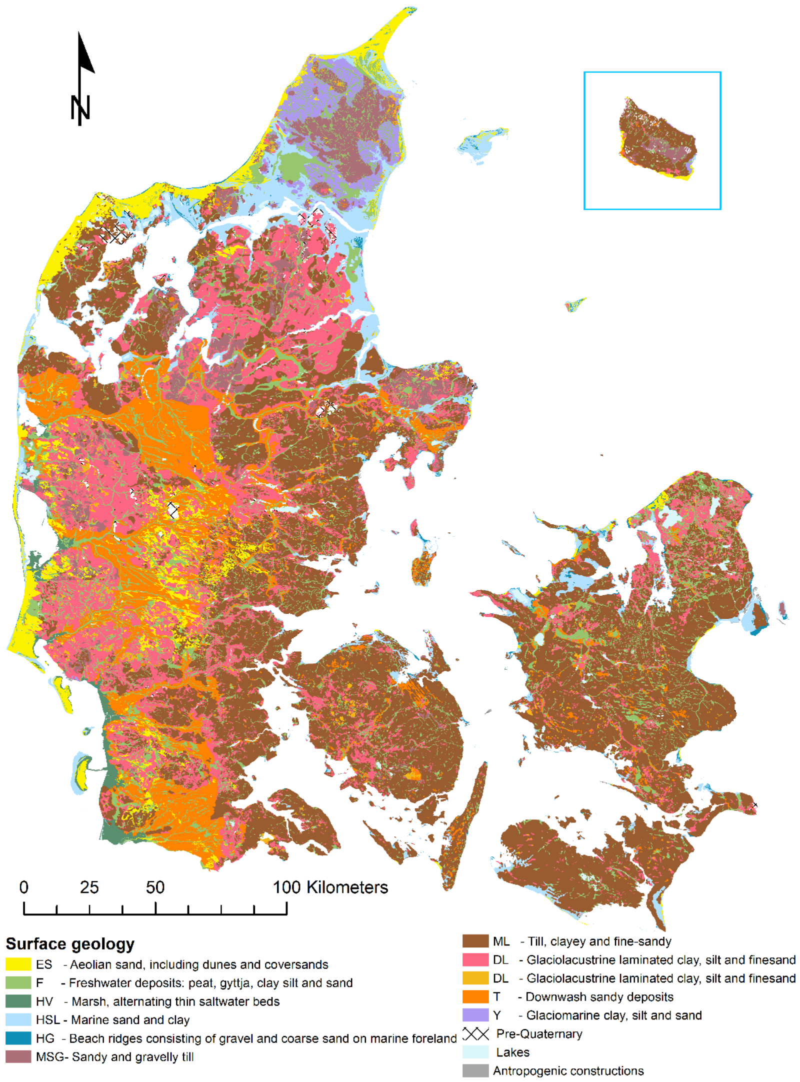

Figure 3.10 Surface geology of Denmark.

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

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

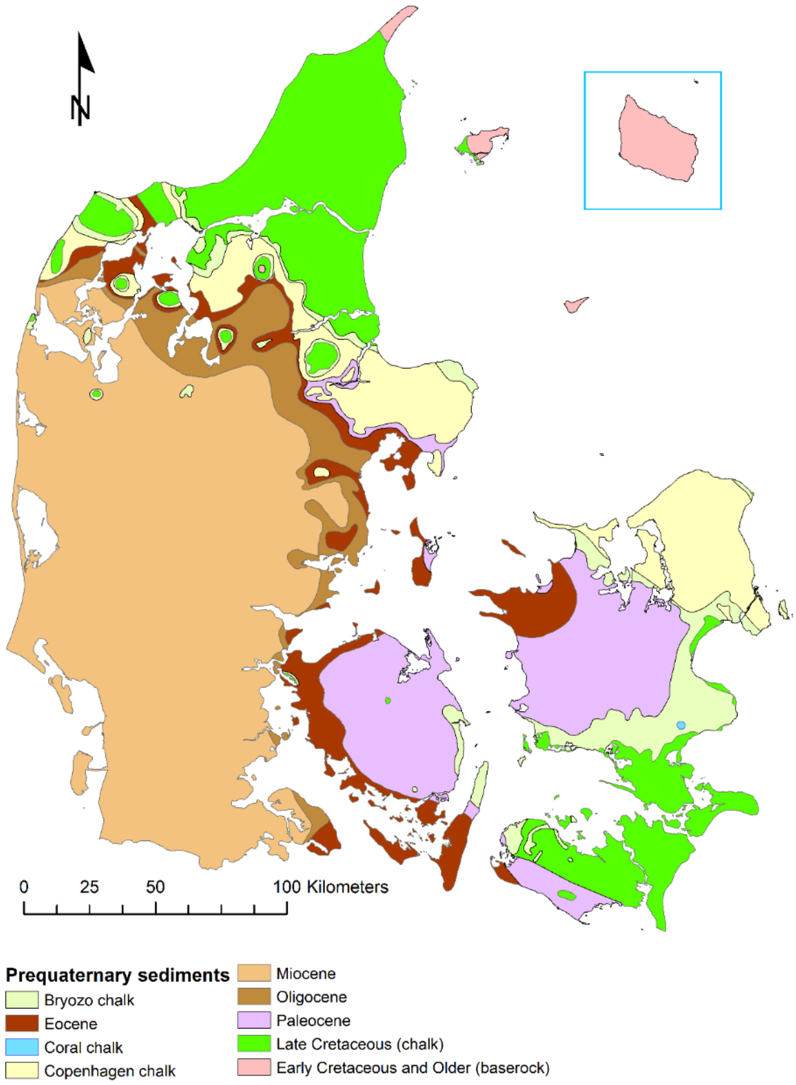

Figure 3.11 Prequaternary surface in Denmark.

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

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

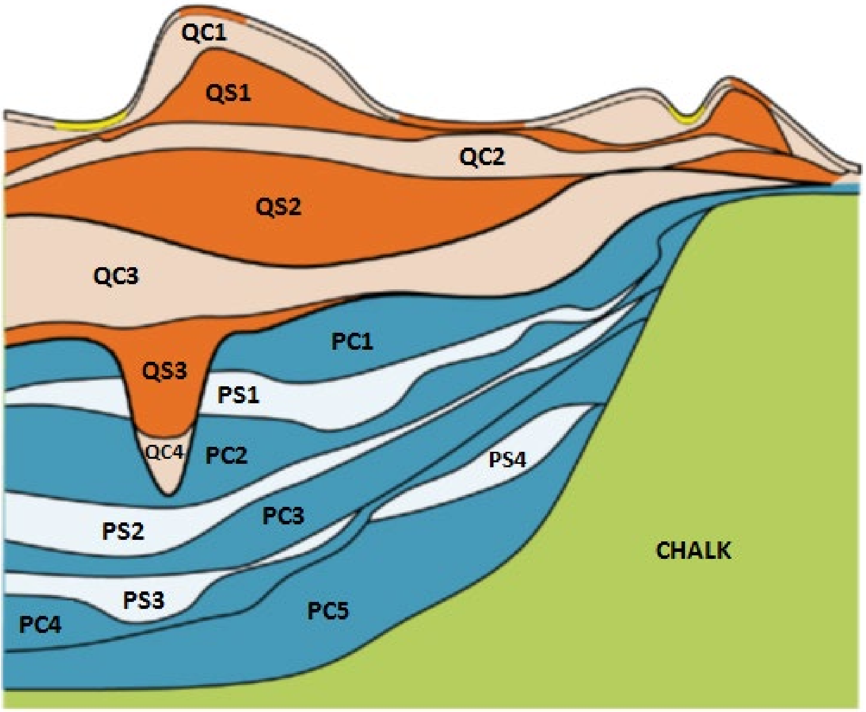

Figure 3.12 Sketch of the principal behind the hydro-stratigraphical model for Jutland. Layers are number from ground surface. QS: Quaternary sand, QC: Quaternary clay, PC: Prequaternary clay, PS: Prequaternary sand.

3.1.6 Groundwater level

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

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

3.1.7 Surface water

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

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

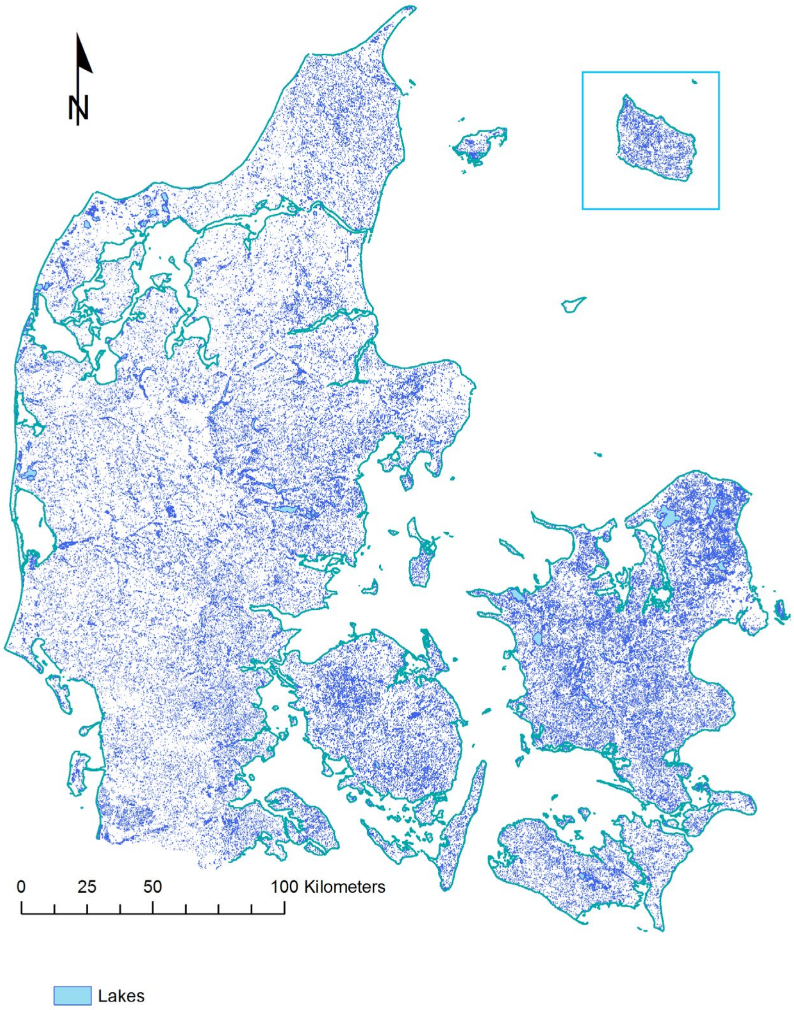

Figure 3.14a Lakes in Denmark

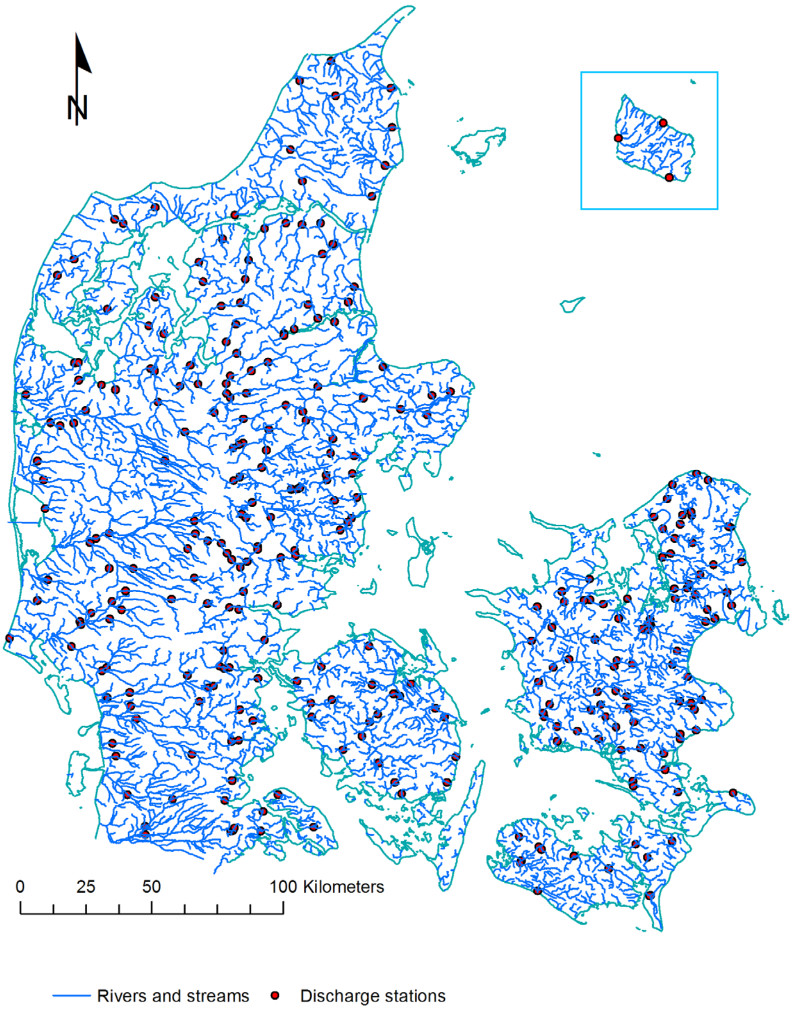

Figure 3.144b River network in DK model and locations of river discharge measurements.

3.1.8 Abstractions/irrigation

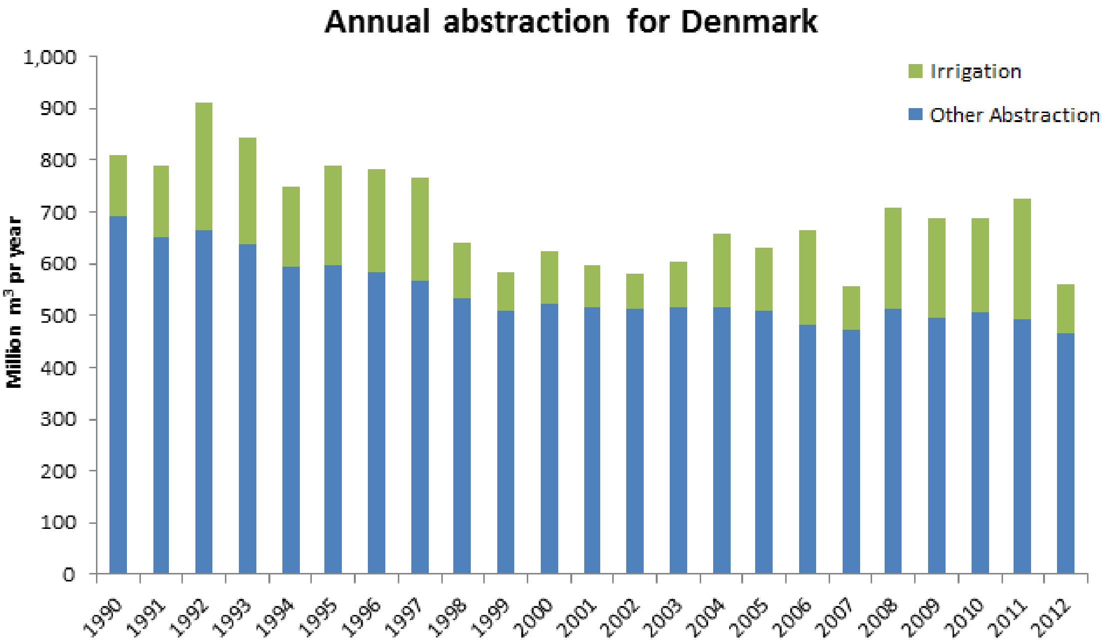

Figure 3.15: Abstraction rate in Denmark from 1990-2012, two abstraction types are differentiated; abstraction for irrigation purposes (green) and abstraction for all other water uses (blue).

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

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

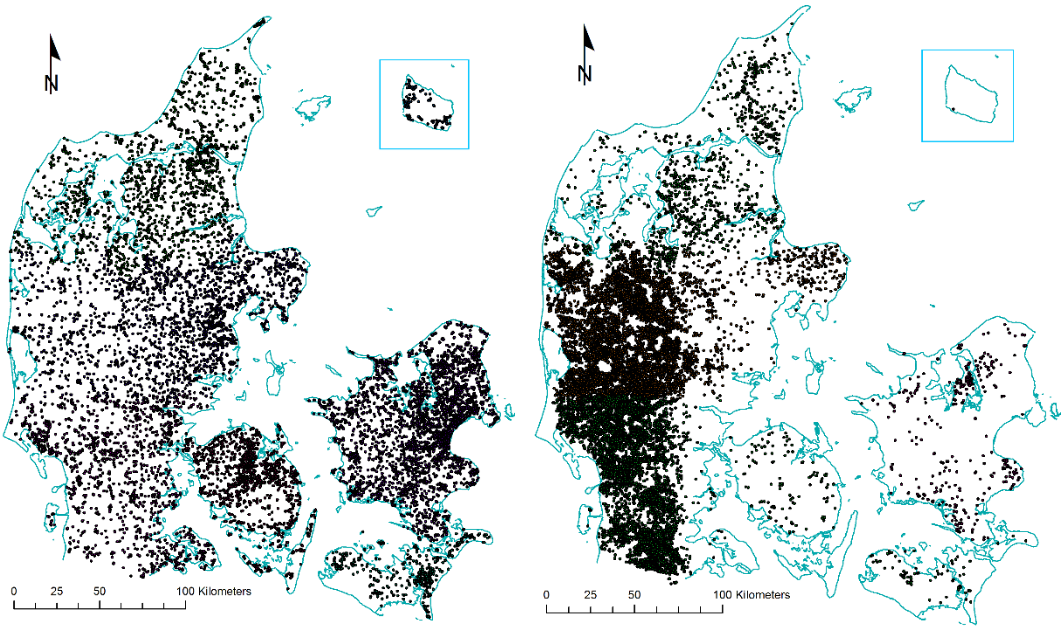

Figure 3.16: Groundwater abstraction for the seven model domains for general abstraction (left) and for field crop irrigation (right).

3.2 Climate change challenge

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

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

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

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

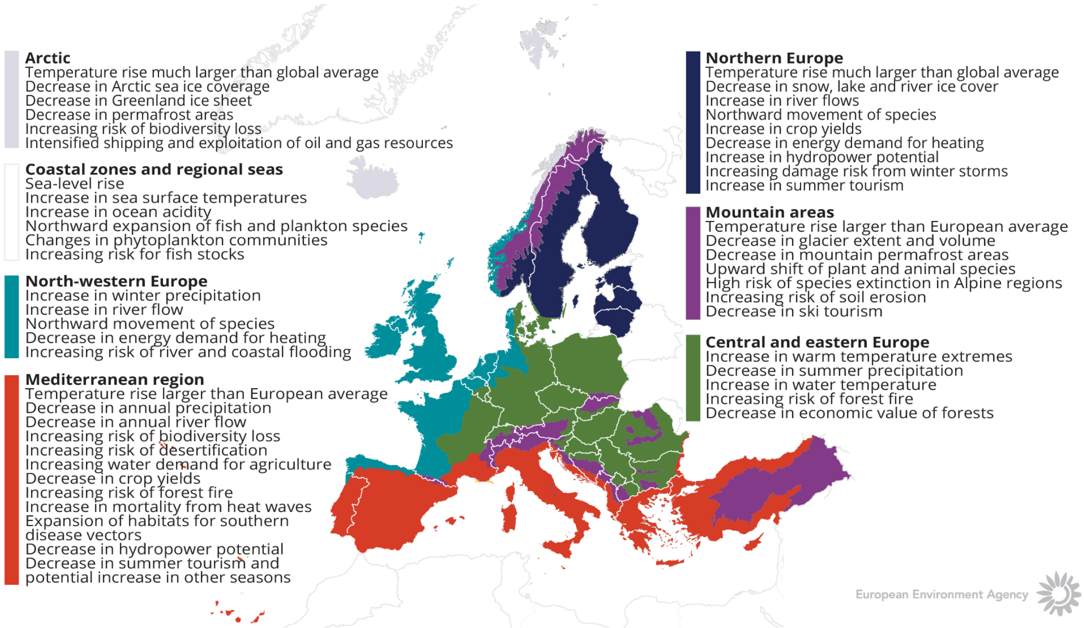

Figure 3.17 European Environment Agency map of projected climate change for Europe

4 METHODOLOGY

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

4.1 Climate data

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

4.1.1 TACTIC standard Climate Change scenarios

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

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

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

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

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

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

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

4.1.2 Euro-CORDEX

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

Table 4.2 The Euro-CORDEX climate change ensemble

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

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

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

4.1.3 Differences between the climate change scenarios

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

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

4.2 Integrated hydrological modelling of climate change

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

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

4.2.1 Model description

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

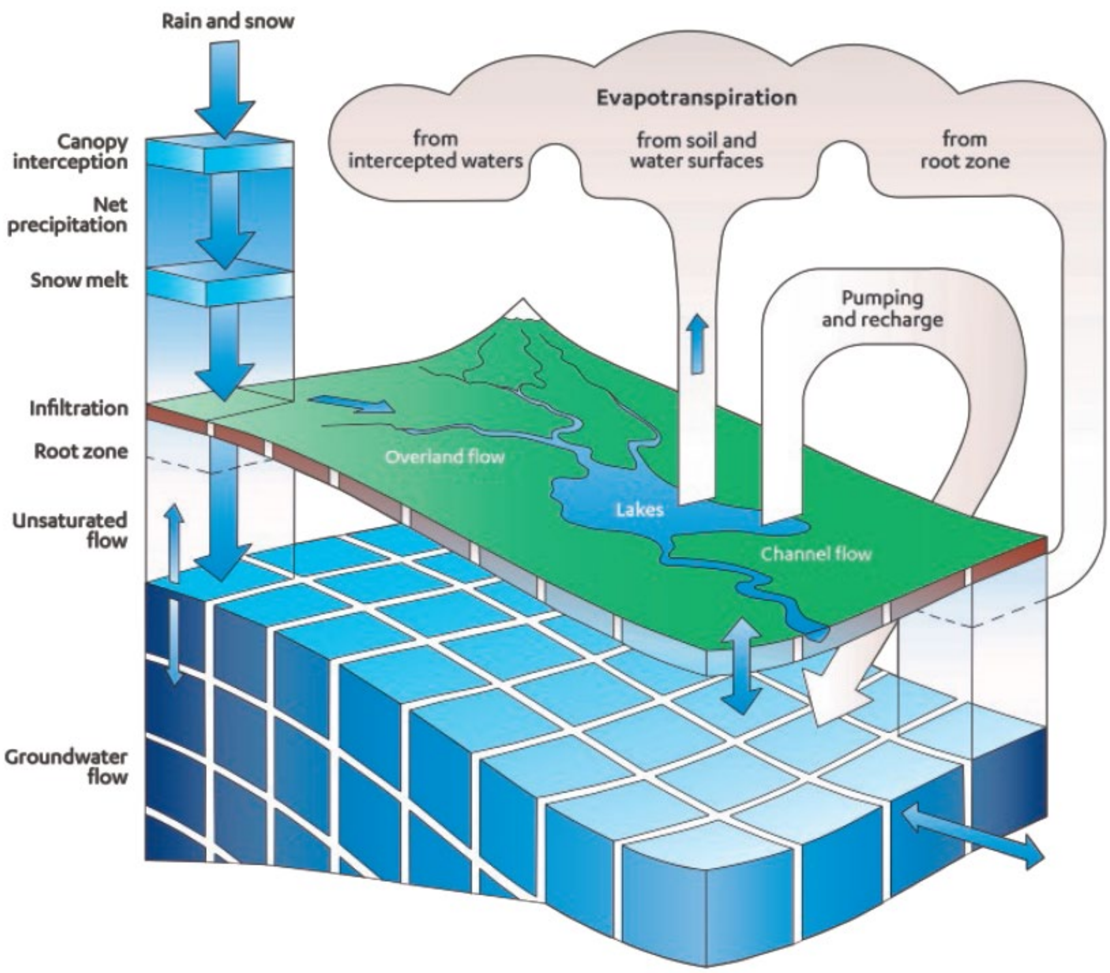

Figure 4.1 MIKE SHE model: Simulated hydrological water fluxes.

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

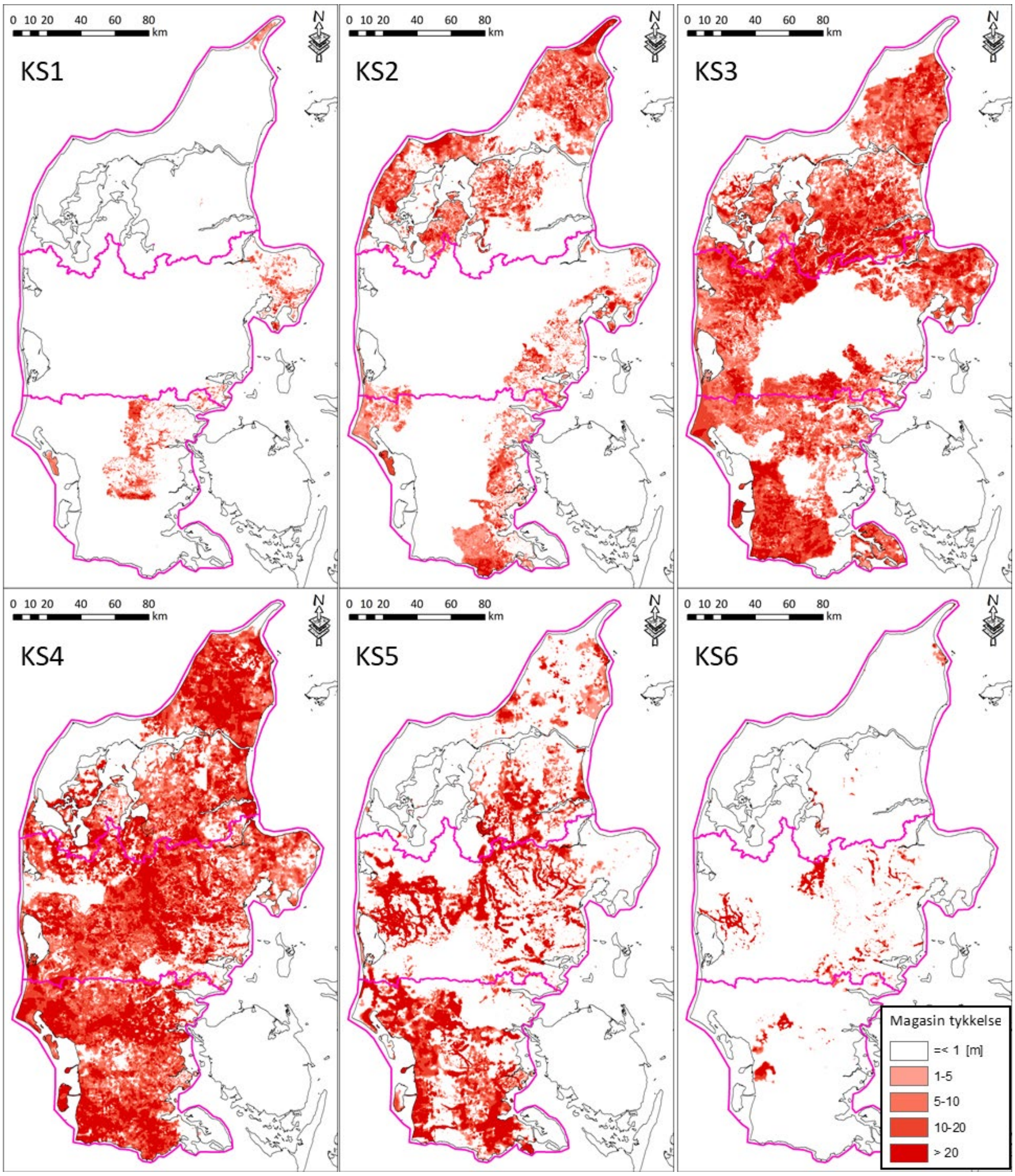

Figure 4.2 Quaternary sand aquifers KS1-6 and their thickness across Jutland. Figure is from Stisen et al. 2019.

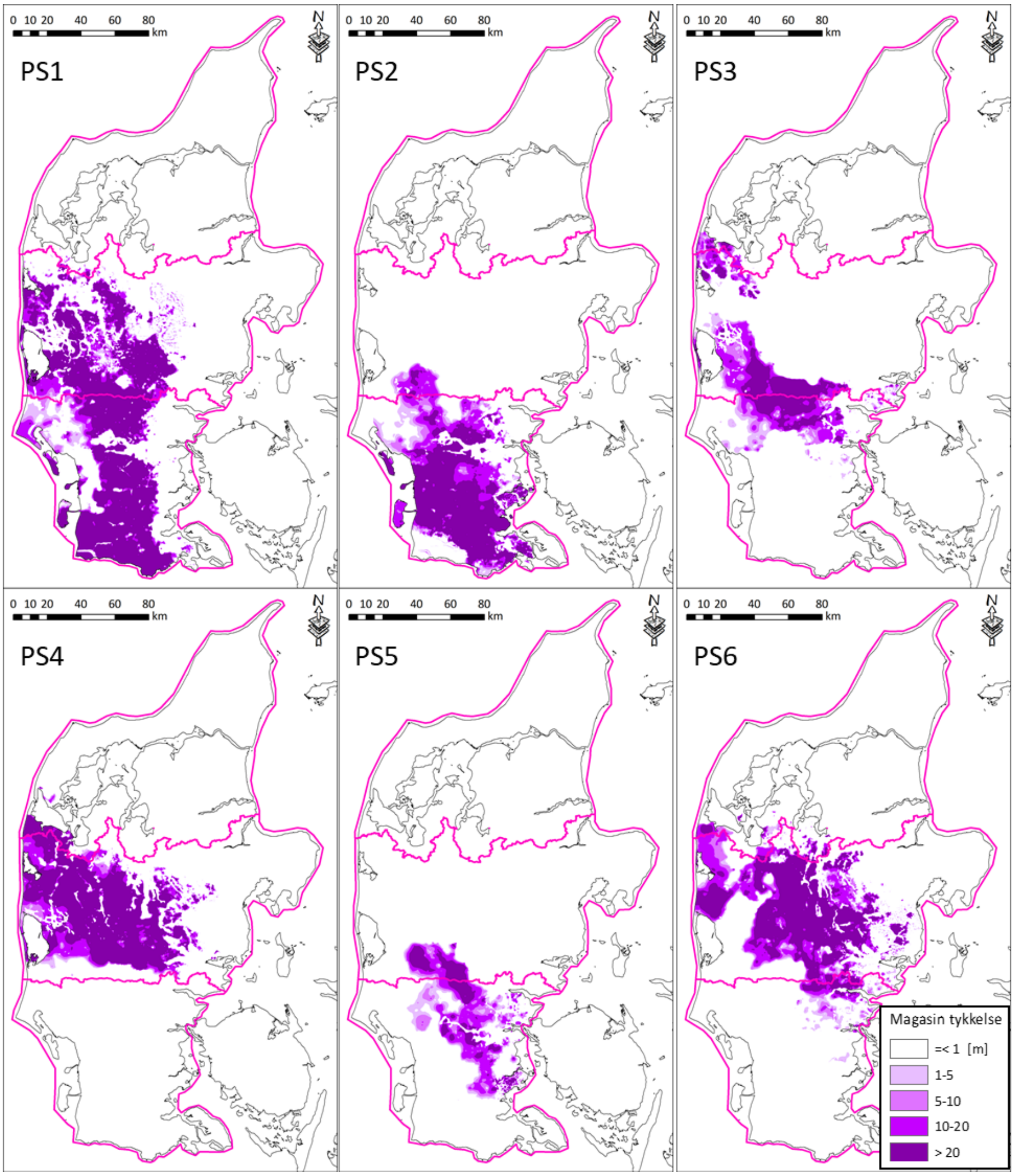

Figure 4.3 Miocene sand aquifers PS1-6 and their thickness across Jutland. Figure is from Stisen et al. 2019.

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

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

4.2.2 Model Calibration

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

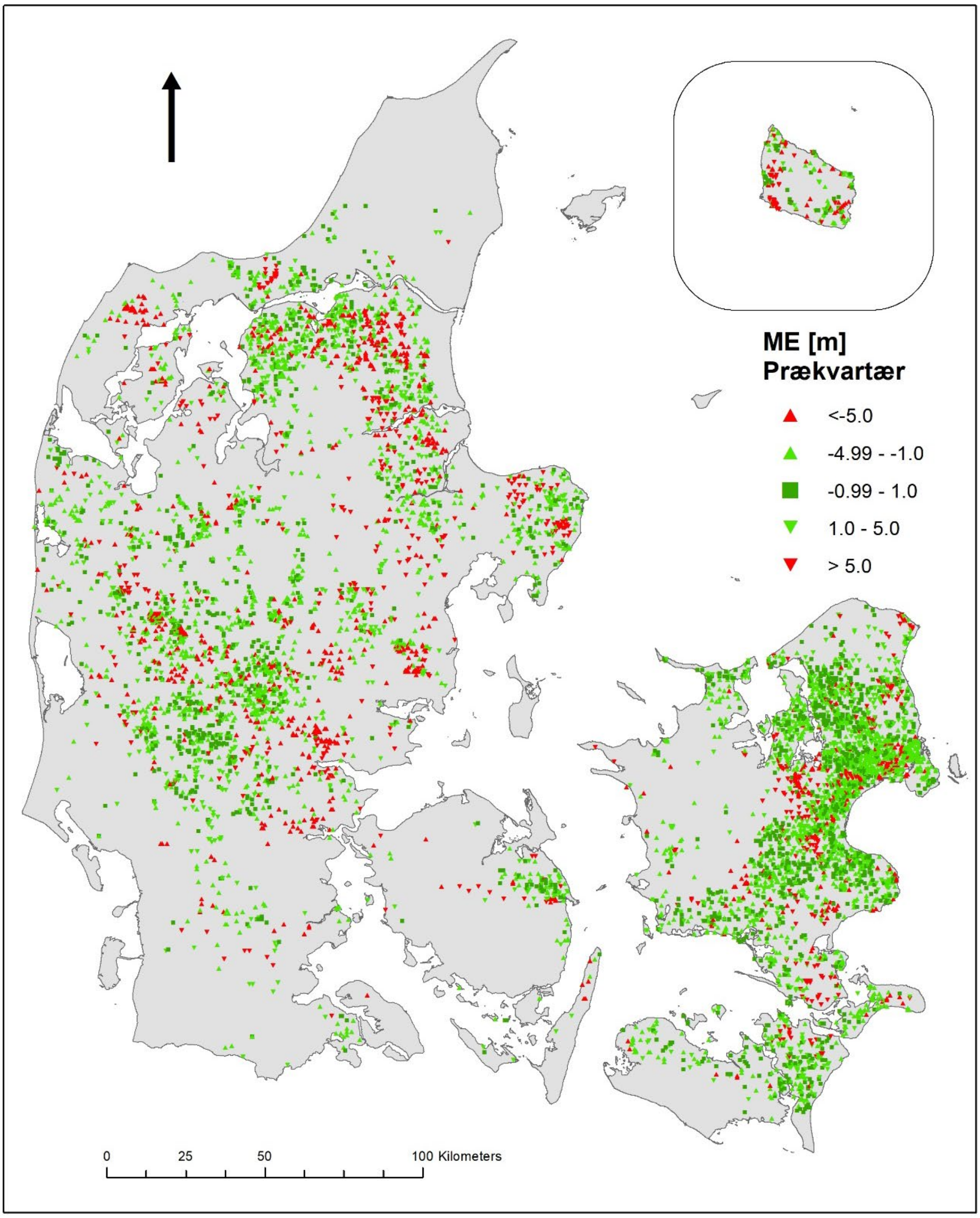

Figure 4.4 Spatial distribution of mean error, pre-Quaternary layers, in the calibration period. Figure is from Stisen et al. (2019).

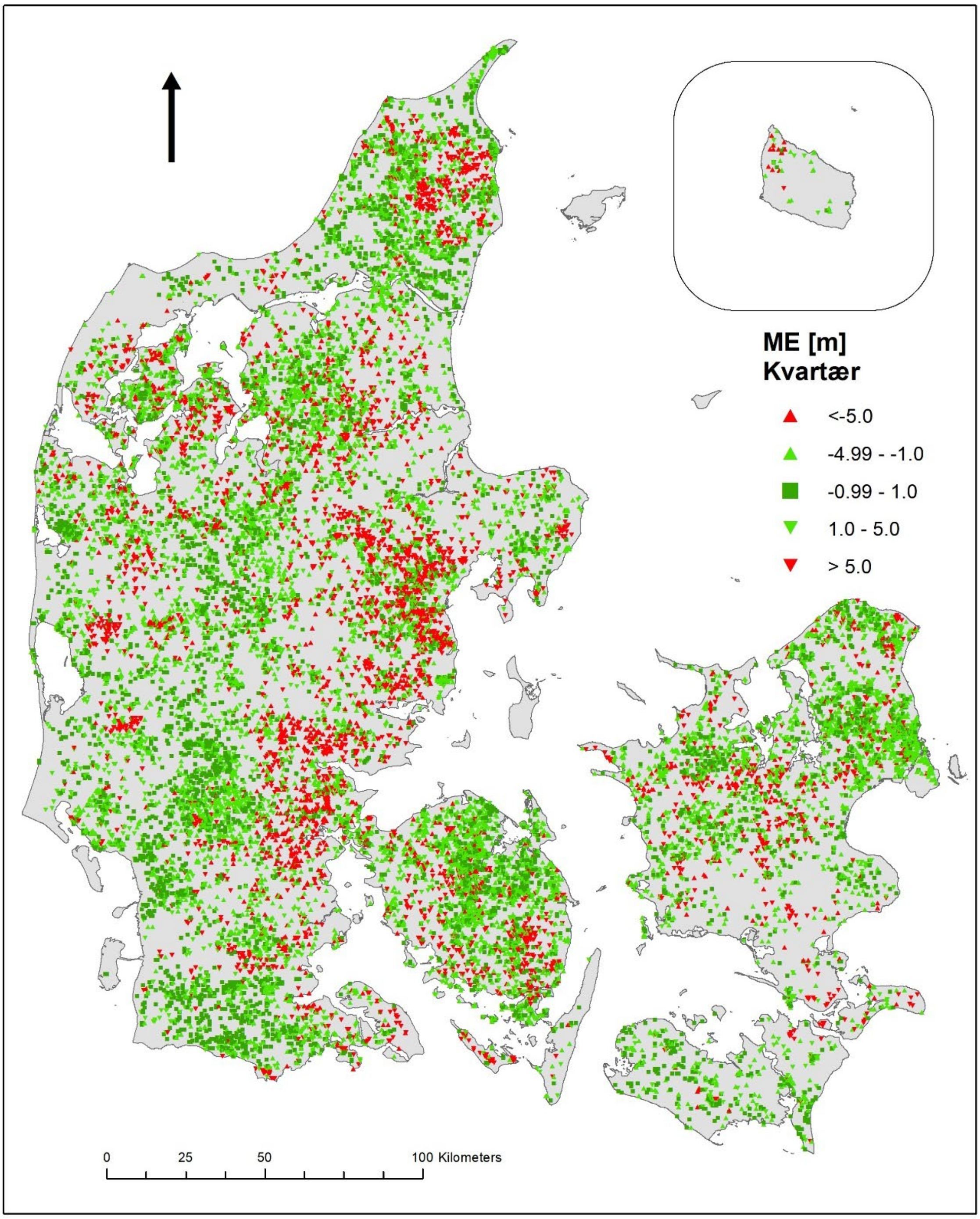

Figure 4.5 Spatial distribution of mean error, pre-Quaternary layers, in the calibration period. Figure is from Stisen et al. (2019).

5 RESULTS AND CONCLUSIONS

5.1 Integrated hydrological modelling

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

5.1.1 TACTIC scenarios: Shallow groundwater

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

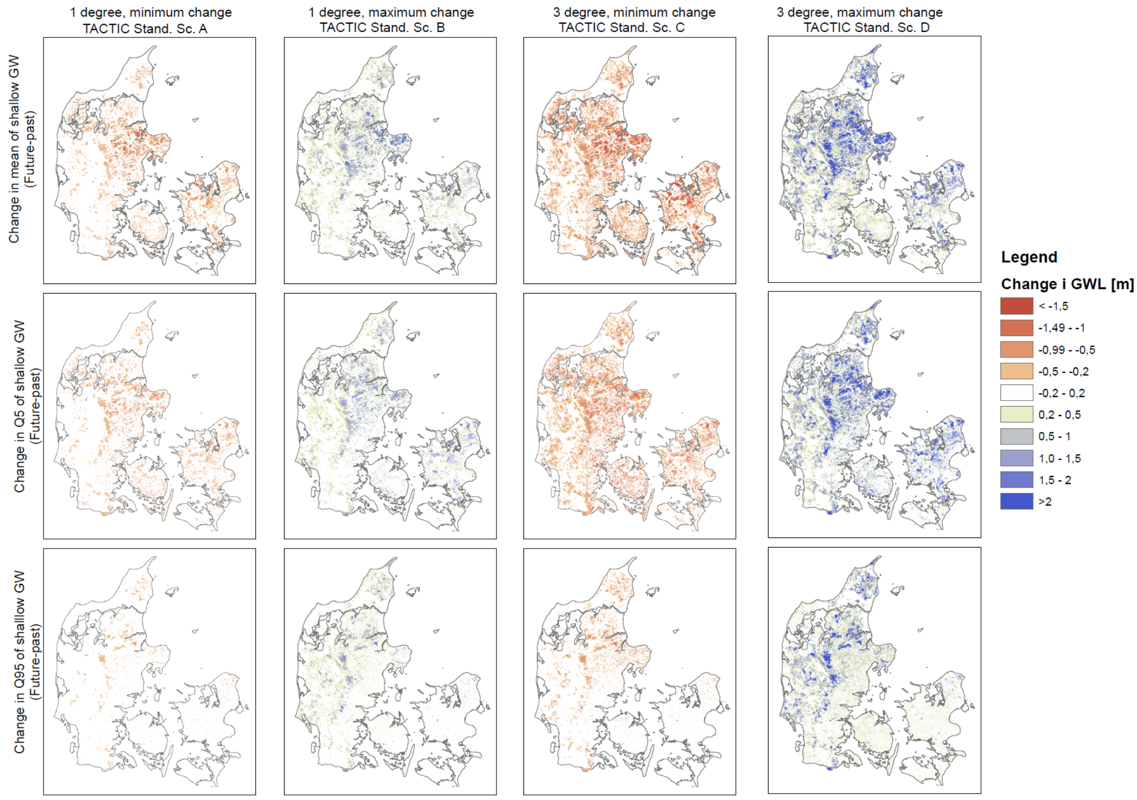

Figure 5.1 Changes in mean, high and low shallow groundwater levels simulated with the 4 TACTIC standard scenarios.

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

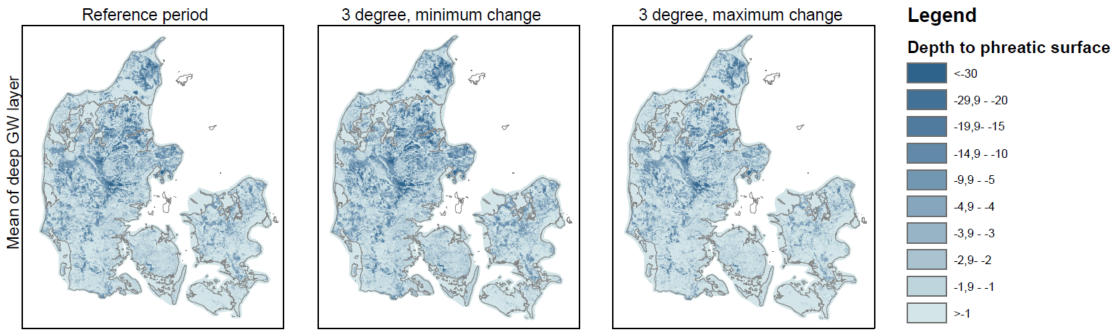

Figure 5.2 Shallow groundwater levels for the reference period (left) and the future period for the 3 degree change scenarios. 3 degree minimum in the middle and 3 maximum to the right.

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

5.1.2 TACTIC scenarios: Deep groundwater

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

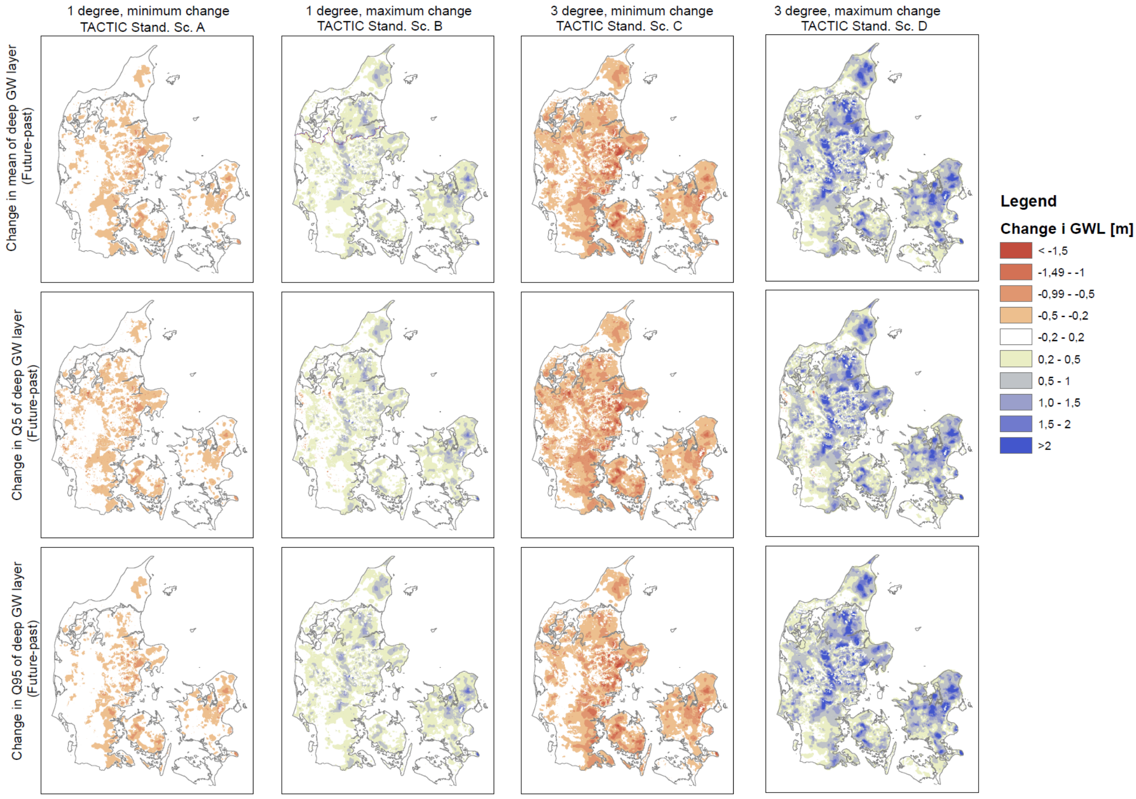

Figure 5.3 Changes in mean, high and low shallow groundwater levels simulated with the 4 TACTIC standard scenarios for the deeper aquifers.

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

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

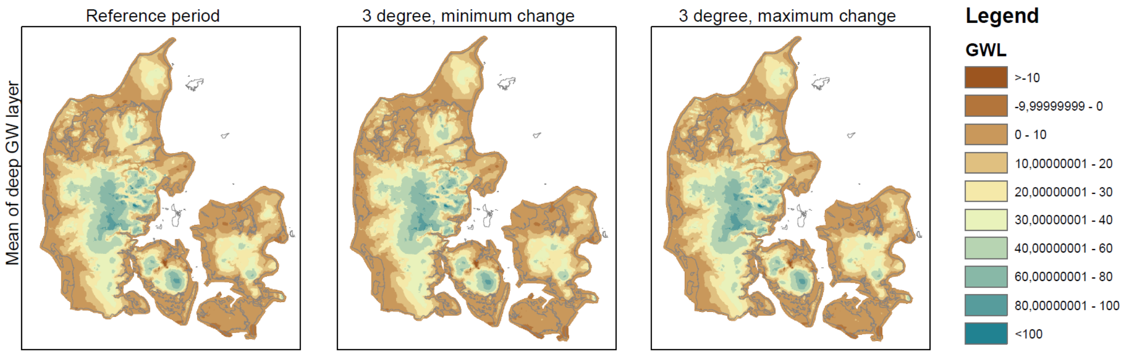

Figure 5.4 Deep groundwater levels for the reference period (left) and the future period for the 3 degree change scenarios. 3 degree minimum in the middle and 3 maximum to the right.

5.1.3 *Euro-CORDEX*

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

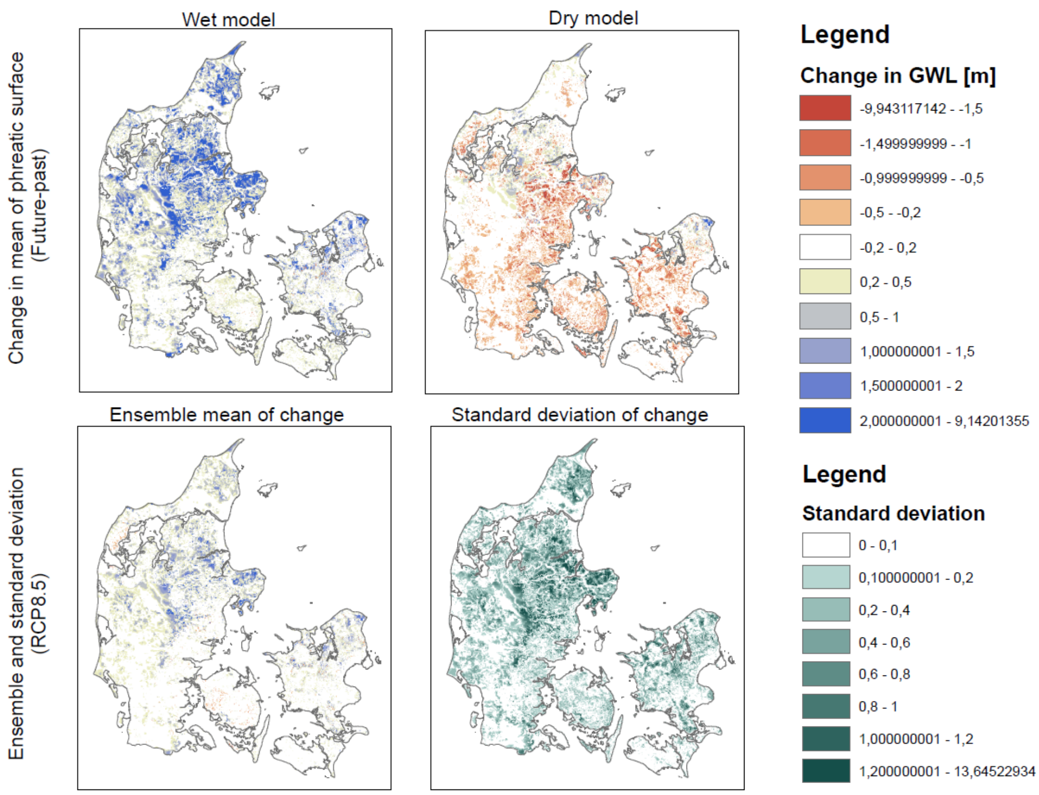

Figure 5.5 Changes of shallow groundwater levels for a wet and a dry ensemble member (upper left and right), and the ensemble mean of the change between past and future

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

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

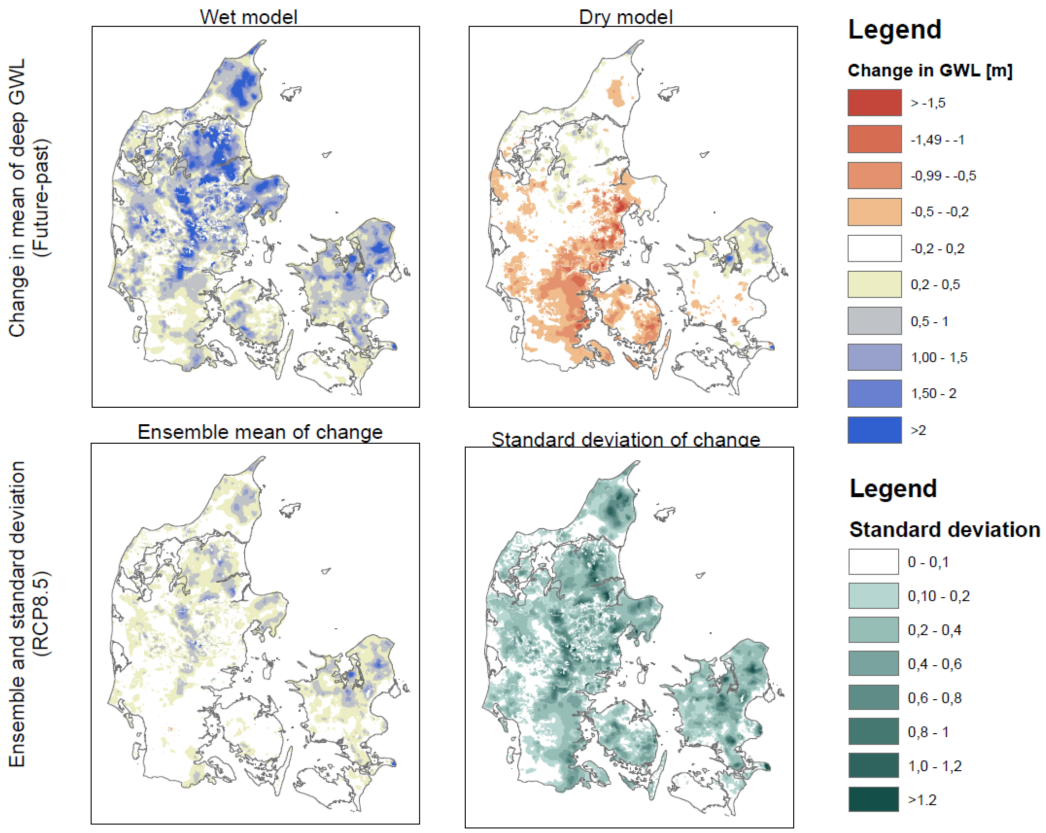

Figure 5.6 Changes of deeper groundwater levels for a wet and a dry ensemble member (upper left and right), and the ensemble mean of the change between past and future (lower left). The standard deviation of change (lower right) show where the members of the ensemble differs most. Based on the Euro-CORDEX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

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

5.1.4 Conclusions of the assessment based on integrated hydrological modelling

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

6 REFERENCES

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2

PILOT DESCRIPTION AND ASSESSMENT

HUNGARY

Authors and affiliation:

Éva Kun, Péter Szabó, György Tóth, Lilian Fejes, Attila Kovács

Mining and Geological Survey of Hungary

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LIST OF ABBREVIATIONS & ACRONYMS

TABLE OF CONTENTS

1 EXECUTIVE SUMMARY

Pilot name	Hungary	
Country	Hungary	
EU-region	Central Europe	
Area (km^2)	93000	
Aquifer geology and type classification	Sands and gravels, Limestones/dolomites, Volcanic rocks	
Primary water usage	Irrigation/Industry	
Main climate change issues	By the end of the 21st century in 100 years, the mean annual temperature in Hungary may increase by 3.5-4 °C and by 2.2 °C following the RCP8.5 and RCP4.5 scenarios, while precipitation results indicate that a small increase of 5% is projected by 2071–2100.	
Models and methods used	Modular modelling (hydrological model with WHI UnSat Suite software HELP module, hydrogeological model-series Visual Modflow)	
Key stakeholders	Water supply companies, farmers, water authorities	
Contact person	Éva Kun, Mining and Geological Institute of Hungary	

A dynamic modular approach was developed in order to quantitatively simulate the groundwater table under various climate conditions. The applied methodology included:

1. Determination of climate zones based on measured and simulated climate variables;
2. Determination of recharge zones (Hydrological Response Units, HRU's) based on surface geology, land use, and slope conditions.
3. Calculation of recharge for each recharge zone using 1D analytical hydrological model series.
4. Simulation of the groundwater table under various climate conditions using numerical groundwater flow models.

The climate data used in our hydrological modelling comprised gridded daily observed data from the CARPATCLIM-HU and CORDEX database and projections of different regional climate model.

Results of recharge calculation indicate that recharge could decrease up to 50 mm/year by the end of the 21st century in the elevated areas, while in other climate scenario we can presume wetter climate. Slight recharge increase is projected in parts of the Great Hungarian Plain and the Transdanubian Hills. Water levels most probably will increase over the Alpokalja, Mecsek, Transdanubian and Northern Mountain Ranges. Moderate water level drops in the Duna-Tisza

Interfluve and Tiszántúl areas are probable, while slightly rising groundwater levels are projected in parts of the Great Hungarian Plain and the Transdanubian Hills.

Our studies have highlighted the high degree of uncertainty in climate models. As a result, there has been both drought and a wetter climate trend and this can often vary from area to area. It has shown spatial and temporal fluctuations in precipitation and other climatic parameters, so the long-term trend may result opposite changes compared to the short or even medium-term.

The presented outputs were determined at the regional scale and as such cannot be used for local investigations. The presented methodology though can be applied for modelling the climate impact both at the regional and local scales for assessing the climate vulnerability of groundwater resources.

2 INTRODUCTION

Groundwater resources are impacted by global climate change through the modification of water balance. The changes of rainfall and temperature have direct effects on recharge and evapotranspiration conditions, and indirect influence on groundwater extractions. The purpose of this study was the development of a methodology for the assessment of direct impacts of climate change on shallow groundwater resources and its country-scale application in Hungary. A modular methodology was applied, which included the delineation of climate zones and recharge zones, the calculation of recharge using hydrological models and the simulation of groundwater table for various climate scenarios using numerical groundwater models. Observed climate parameters and historical groundwater level data were applied for the groundwater model calibration. Results from regional climate model projections were applied for the future groundwater simulations and for two future time slices.

3 PILOT AREA

3.1 Site description and data

The pilot area covers the entire Hungarian territory. Hungary is located in Central Europe, within the Carpathian Basin. It measures about 250 km from north to south and 524 km from east to west. It has 2,106 km of borders, shared with Austria to the west, Serbia, Croatia and Slovenia to the south and southwest, Romania to the southeast, Ukraine to the northeast, and Slovakia to the north.

Hungary has three major geographic regions (which are subdivided to seven smaller ones).
The Great Plain, a flatland lying east of the Danube River; Transdanubia, a hilly region lying west of the Danube and extending to the Austrian foothills of the Alps; and the North Hungarian Mountains, which is a mountainous and hilly country north of the Great Plain.

A great part of Hungary is a basin filled with marine and fluvial deposits, sometimes as thick as several kilometres (Figure 1). The marine deposits situated at larger depth are mainly clays and clayey marls with low water yield. The alluvial sediments deposited in the Pannonian Sea comprise sand and sandstone layers with a thickness of 1-2 kilometres.
In the Quaternary fluvial sediments were deposited with silty, sandy and gravel deposits. The thickness of these sediments can reach up to 1 km in the Kisalföld and in the southern region of the Great Hungarian Plain. The edges of the basin fans contain gravel aquifers. Their thickness is usually only a few tens of metres, however in the Szigetköz region their thickness is several hundred meters. Some rivers flow across these formations and their water is in direct contact with the water contained in the gravel layers.

One of the most significant group of aquifers comprise coarse sand and gravel layers of the clastic basin deposits. At larger depth, sandstone replaces the loose sandy layers. These aquifers can be found in more than three quarter of the country's area facilitating local drinking water production, and also the abstraction of thermal water from greater depths (usually deeper than 500 m).

From the shallow gravel aquifers along the riverbanks, bank-filtered water is extracted. The upper layers down to the depth of 10 to 20 m are of fine-grained formations with the possibility of local production of small discharges only. The majority of dug wells in the villages and countryside homesteads are producing water from such formations.

Another main type of aquifers is karstic rocks that can be found in highland areas covering one fifth of Hungary's territory. These comprise Mesozoic limestones and dolomites. While these are important drinking water resources, at large depth they contain thermal water, part of which come to the surface in the form of the well-known thermal springs (Héviz, Budapest, Eger, etc.).

Besides the main groundwater types (bank-filtered, shallow and deep groundwaters and karst waters), water can also be exploited to a smaller extent from other geological formations.

Parts of the highland regions are built up of fractured rocks (crystalline and volcanic) which feed smaller springs of local significance.

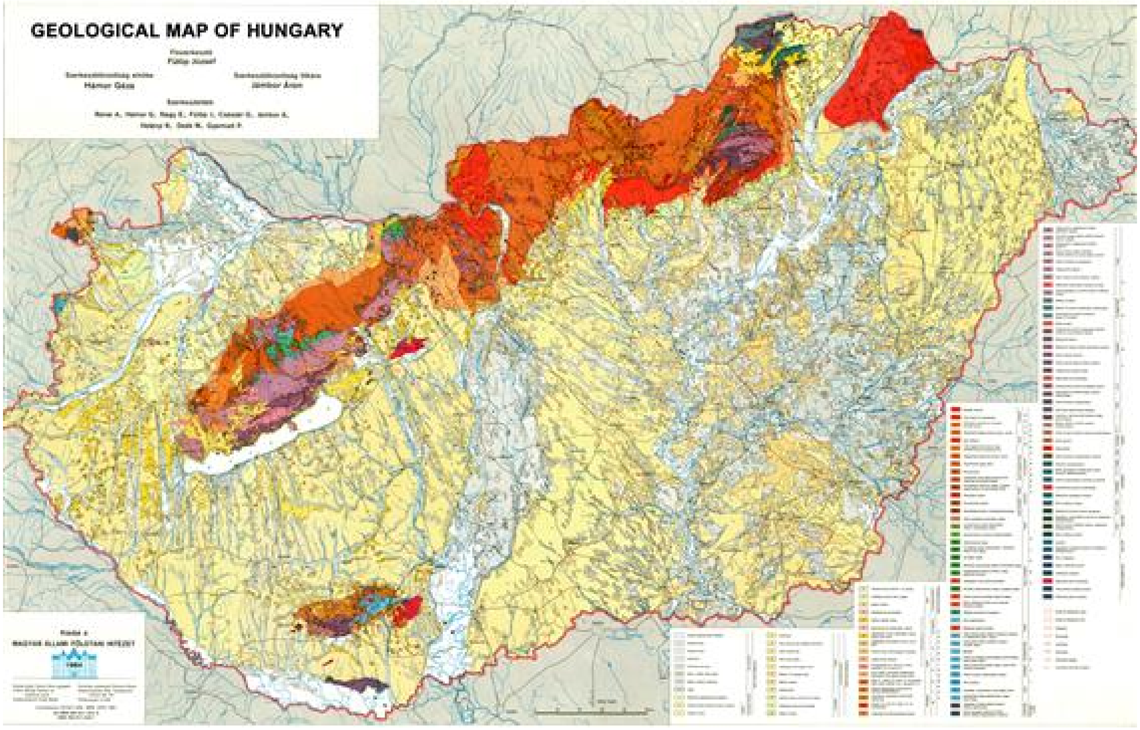

Figure 1. Geological map of Hungary

The total area of Hungary is 9,303,000 ha, of which 79% or 7,356,000 ha is agricultural land, and 48.2% or 4,502,000 ha is arable land. The topsoil textures of Hungarian soils can be characterised by sand 15%, sandy loam 12%, loam 47% and loamy clay or clay 26%.

About 85% of Hungary's territory is suitable for different purposes in agriculture and forestry, depending on the fertility of soils. Accordingly, agriculture is the largest user of land. The quality of cultivated lands, soil types, physical features, slope and climatic conditions are good for various agricultural production with substantial regional differences.

Hungary has a continental climate, with hot summers and cold winters. Mean annual temperature is between 10-11 °C. All-time temperature extremes are 42 °C in the summer and −35 °C in the winter. July is the hottest month with mean temperature above 21 °C, and January is the coldest with below -1 °C. The average rainfall sum is around 600 mm per year, June being the wettest month, February the driest on average. The mean annual temperature of Hungary between 1973–2004 is shown in Figure 2, while annual rainfall distribution for 1973–2004 is indicated in Figure 3.

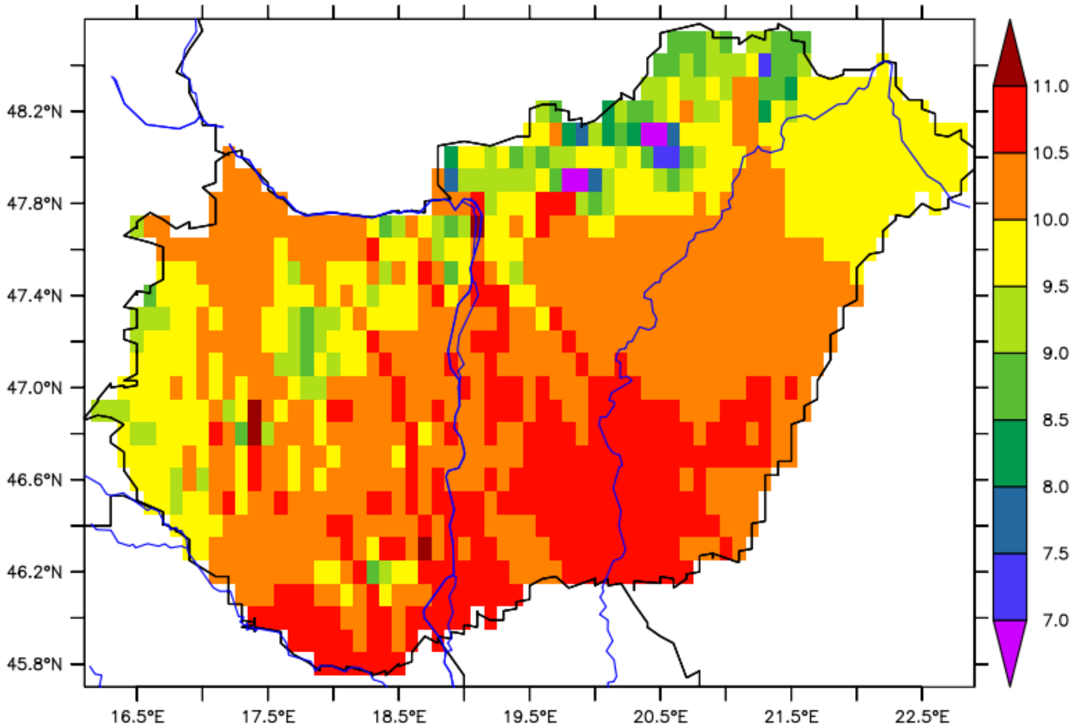

Figure 2. Mean annual temperature distribution for 1971–2000 [°C]

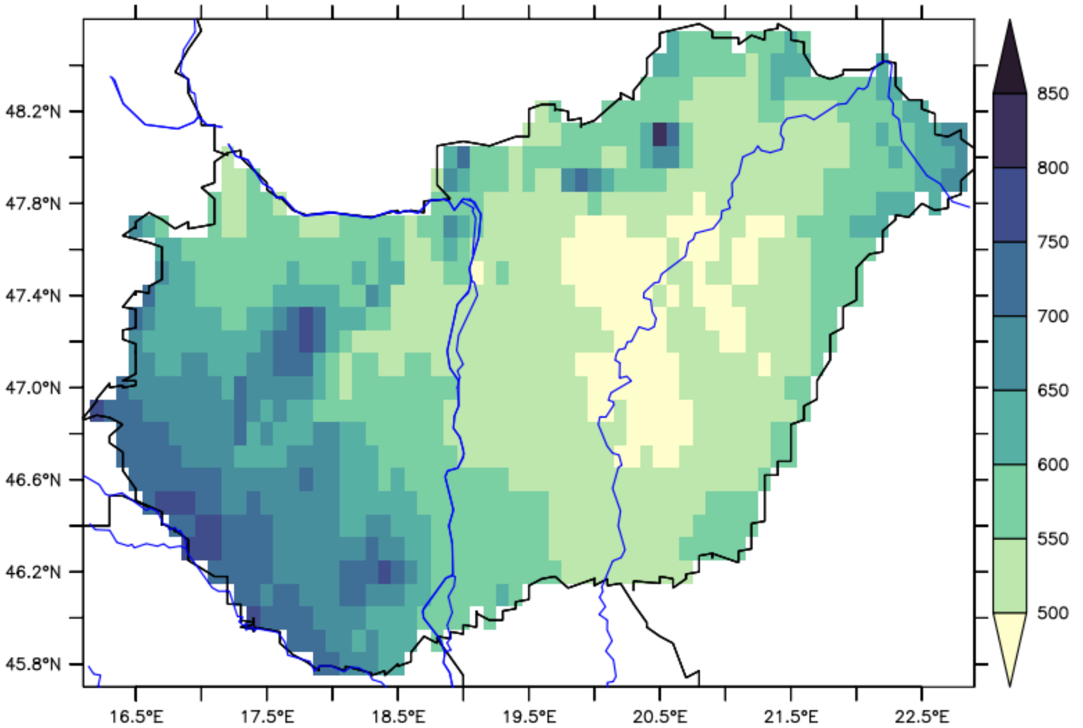

Figure 3. Annual average precipitation distribution for 1971–2000 [mm/yr]

3.2 Climate change challenge

In Central Europe, both warm and cold tails of the temperature distribution in all seasons warmed over the entire 20th century regardless of maximum and minimum temperature, though the largest increase in the cold tail occurred for the minimum temperature.

The analysis of observed climate data indicates a general tendency of more frequent, longer, and more intense heatwaves in the entire Carpathian region. On the other hand, the cold-waves show a general tendency to become less frequent and less intense. The Carpathian region and the Mediterranean are the two European hotspots showing a drought frequency, duration and intensity increase from 1990 onwards (Spinoni et al., 2013).

The amount of annual precipitation decreased (with around 5-10%) since the beginning of the 20th century. The strongest decrease happen during spring, while the summer precipitation amount did not change and the autumn and winter precipitation also decreased. The precipitation also became more intense, which is likely to increase run-off rates and flood risks, and decrease recharge rates and groundwater resources.

The results of two locally run models, the ALADIN-Climate and RegCM regional climate models following the SRES A1B medium scenario (Nakicenovic and Swart, 2000) indicate that annual mean temperature in Hungary is expected to rise by 3-3.5 °C by the end of the 21st century. Highest warming is expected in summer (Illy et al., 2015). Regarding four RCA4 regional climate model simulations from the EURO-CORDEX initiative (Jacob et al., 2014), one could conclude that the results from the RCP4.5 scenario provide significantly lower warming (around 2-2.5 °C) than RCP8.5 (Meinshausen et al., 2011), which could reach 4-4.5 °C by 2071–2100 (higher values coming from the EC-EARTH global model conditions). Temperature increase is stronger for the North of the country (Figure 4).

Following the two locally run climate simulations, ALADIN-Climate and RegCM, a small decrease ((-5)%) of the annual rainfall amount is projected by the end of the 21st century (Illy et al., 2015). The currently wettest season, summer could become around 20% drier, while the fall will most probably be 5-10% wetter besides other seasons being uncertain in the direction of change for 2071–2100. Regarding the four RCA4 climate simulations from the EURO-CORDEX, we can see a different change pattern: regardless of the scenario and the global model conditions, simulations show a small annual precipitation increase almost for all of Hungary. One model results have higher positive change for the RCP8.5, while the other one for the RCP4.5 scenario run. This signal reaches 5-12% values, and only small parts of the country are around zero change (Figure 5).

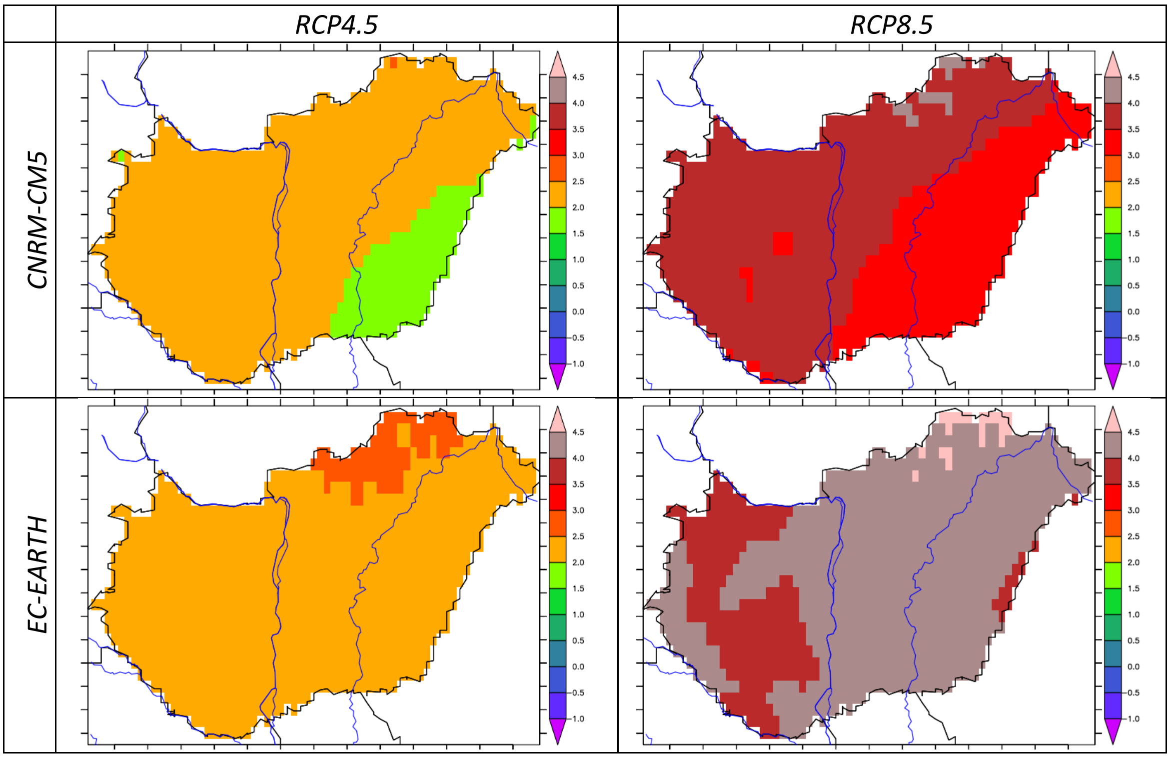

Figure 4. Annual temperature change [°C] between 1971–2000 and 2071–2100 based on four RCA4 regional climate model simulations (following the RCP4.5 and RCP8.5 scenarios and using two different global climate model boundary conditions, CNRM-CM5 and EC-EARTH)

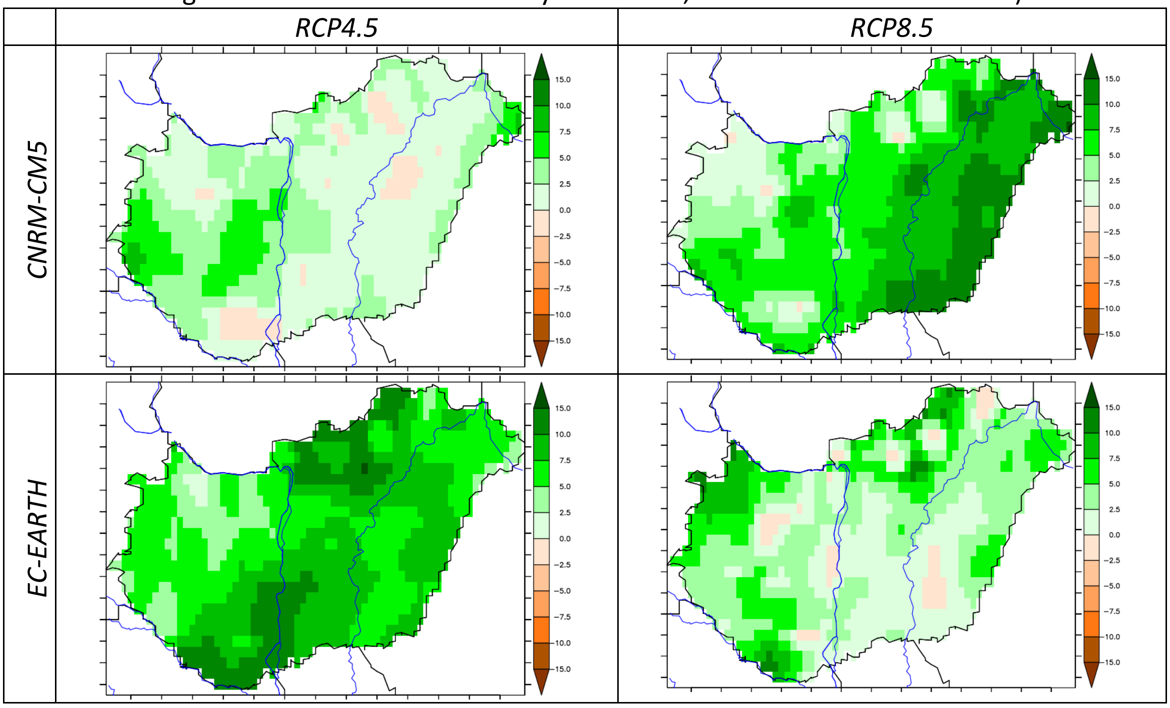

Figure 5. Annual precipitation change [%] between 1971–2000 and 2071–2100 based on four RCA4 regional climate model simulations (following the RCP4.5 and RCP8.5 scenarios and using two different global climate model boundary conditions, CNRM-CM5 and EC-EARTH)

4 METHODOLOGY

Within the frameworks of the project, a dynamic modular approach was developed in order to quantitatively simulate the groundwater table under various climate conditions. The calculations were done in 2 phases (maps can be found at: https://map.mbfsz.gov.hu/nater/; documentation at: https://nater.mbfsz.gov.hu/). In the 1st phase climate conditions were derived from the ALADIN-Climate regional climate model and Thornthwaite's climate zones were applied. The observed and simulated climatic parameters per grid point was not yet possible due to the large amount of data and the current performance of the given software and Thornthwaite's zones were too rough in some places. In the 2nd phase (Figure 6) new improved concept was applied: four regional climate projections were used, new territorial units on the gridpoint level and new infiltration calculations for done.

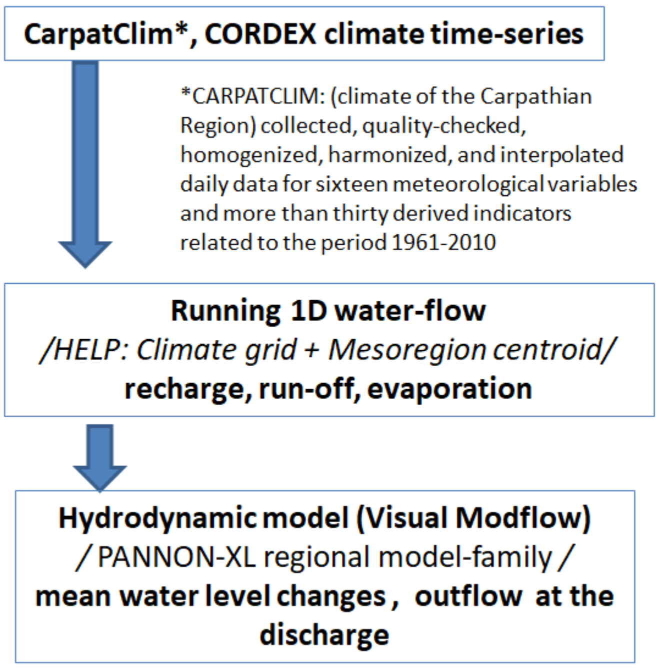

Figure 6. Simplified workflow of the second phase of the project

The climate data applied in our hydrological calculations comprised gridded daily observed data from CARPATCLIM-HU (Bihari et al., 2017), while future climate conditions previously from the ALADIN-Climate (Illy et al., 2015) and in the 2nd phase from RCA4 (Jacob et al., 2014).

Recharge zones (HRU's) were determined based on surface geology, landuse, slope and climatic conditions. The HELP hydrological model (Schroeder et al., 1994) used for calculation of 1D water balance for recharge zones. The MODFLOW numerical groundwater modelling (Waterloo Hydrogeologic Inc., 2005) was applied for the calculation of the water table under various climate conditions. The groundwater simulations for the past were undertaken based on both CARPATCLIM-HU observed conditions and on projections from ALADIN-Climate and RCA4 outputs.

4.1 Methodology and climate data

The CARPATCLIM-HU (Lakatos et al., 2013) observational database was applied as the past input parameters for the hydrological models. CARPATCLIM-HU is a homogenized, gridded dataset interpolated from climate observations inside and outside of Hungary. It was derived from weather observations at 258 regular stations and 727 rain gauge ones from the involved 9 countries (Czech Republic, Slovakia, Poland, Ukraine, Romania, Serbia, Croatia, Austria and Hungary). Solely from Hungary 37 regular and 176 precipitation stations were used (Lakatos et al., 2013). This database has a horizontal resolution of 0,1° (around 10 km) and temporal resolution of a day for the basic meteorological variables from 1961 to 2010. The gridding was obtained by the Multiple Analysis of Series for Homogenization software (MASH version 3.03; Szentimrey, 2008) and the Meteorological Interpolation based on Surface Homogenized data (MISH, version 1.03; Szentimrey and Bihari, 2007).

Meteorological data of mean temperature, precipitation were used on a daily basis, while global radiation, evapotranspiration, mean wind speed and relative humidity were used on a monthly or seasonal basis averaged for each recharge polygon and served as input parameters in the hydrological model of HELP for the recharge calculations.

Using the same meteorological variables on the same temporal resolution mentioned above, future simulations were based on outputs of the ALADIN-Climate regional climate model and the RCA4 model. ALADIN-Climate was developed within an international framework at Météo France (Csima and Horányi (2008)). RCA4 model (Samuelsson et al. (2014)) is a Swedish regional climate model and its results are freely available to download within the EURO-CORDEX framework (Jacob et al., 2014).

The future anthropogenic activity was considered as hypothetical emission scenarios for the climate models and the SRES A1B (considered as a medium one) emission scenario (Nakicenovic et al., 2000) and the RCP4.5 and RCP8.5, medium and high-end scenarios, respectively were applied (Meinshausen et al., 2011). The below table summarizes the used climate model outputs for the different phases of the project.

regional climate model	**boundary conditions from a global climate model**	**simulation run**
ALADIN-Climate	ARPEGE-Climat	1961-1990 SRES A1B scenario
RCA4	CNRM-CM5	1975-2004 RCP4.5 scenario RCP8.5 scenario
RCA4	EC-EARTH	1975-2004 RCP4.5 scenario RCP8.5 scenario

4.1.1 *Climate classification*

Climate classification was necessary as soil water balance is necessary for the assessment of groundwater conditions. Out of the internationally accepted biophysical climate classification methods, the Köppen (1936), the Holdridge (1947) and the Thornthwaite (1948) methods were applied in Hungary. The comparative analysis of these methods were made by Szelepcsényi et al. (2009) and proved that Thornthwaite's method is appropriate for the mezo-scale characterization of the climatic diversity of Hungary (Ács and Breuer, 2012). The methodology described in Ács and Breuer (2013) was applied for the calculation in the first step of Thorntwaite climate zonation. A detailed description of the calculation scheme applied is provided in Kovács et al. (2015a,b). In the second step, climatic zones were prepared for grid points and simplified for the centroid of mesoregions.

Climate zones were determined for different time periods using mean monthly values of climate variables.

4.1.2 *Recharge zones*

Recharge zones used in this study are hydrogeological units, in which recharge conditions are assumed to show an insignificant variability. Recharge zones are also called Hydrological Response Units according to the SWAT modelling methodology (Neitsch et al. 2002).

Recharge zones were delineated as a superposition of four data layers including climate zones, surface geology, landuse and slope conditions.

The surface geological map constructed by Gyalog and Síkhegyi (2005) was applied in the first data layer. Geological formations were reclassified into six lithological categories such as fractured, dolomite, limestone, fine porous, coarse porous and surface waters.

Landuse polygons were derived from the CORINE (EEA, 2006) map. The large number of original landuse categories were regrouped into six main classes such as urban areas, arable land, pastures, permanent crops, forests, and water bodies.

Slope categories were determined based on the 50 m resolution Digital Elevation Model of Hungary. Two slope categories were applied such as flat areas (0-5%) and slopes (> 5 %). The resulting map of recharge zones is indicated in Figure 7 .

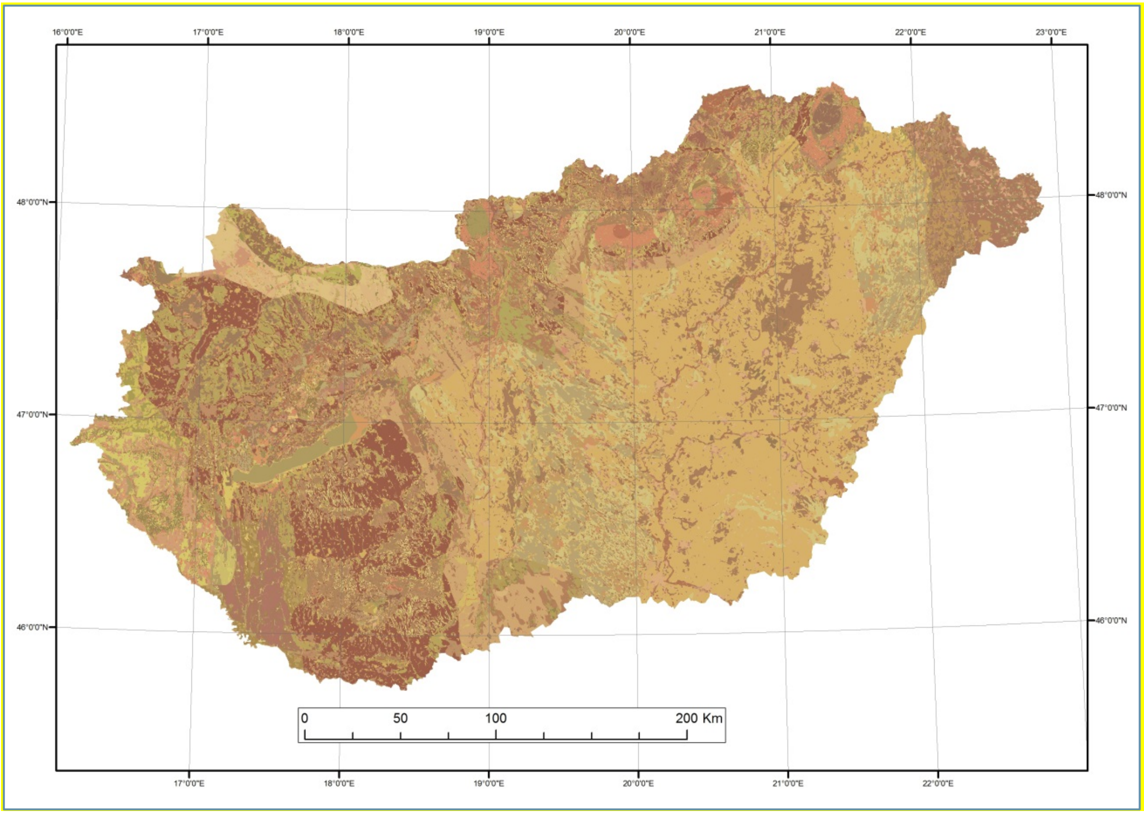

Figure 7. Applied recharge zones

4.1.3 Hydrological modelling

The potential effects of climate change on groundwater conditions were represented via water budget calculations for each recharge unit (HRU). The HELP model (Schroeder et al., 1994) was applied to calculate daily water balances. The applicability of this model is well known from the literature (Gogolev, 2002; Jyrkama and Sykes, 2007) and the methodology has successfully been applied in Hungary. The simulated percolation rates (recharge values) were imported into the numerical groundwater flow model aimed at simulating the groundwater table.
HELP (Hydrologic Evaluation of Landfill Performance) is a hydrologic numerical model developed by the United States Environmental Protection Agency for landfills. The model uses a water-balance approach to model evapotranspiration and drainage through soil layers. The model is often used for simulating the effects of various climate scenarios.
The weather generator of the HELP model needs several meteorological variables, such as daily and monthly average mean temperature, daily and monthly accumulated total precipitation, monthly average horizontal wind speed, daily global radiation and monthly relative humidity.
Besides meteorological input, the HELP code requires the definition of soil profiles for the calculation of one-dimensional transient water balance. Soil profiles were defined by analyzing grain size distributions of soil samples collected systematically as part of the national soil mapping campaign, and organized in a soil logging database. A characteristic soil profile was assigned to each lithological category. Based on grain size distribution data, soil layers were classified according to the United States Department of Agriculture (USDA) soil classification triangle. Default hydraulic parameters defined in HELP were assigned to each soil category.

As the uppermost three metres of observed soil profiles show negligible vertical variability, and the average depth of groundwater is within this range, homogeneous soil profiles were applied. The applicability of homogeneous profiles was verified and confirmed through extensive sensitivity analysis.
Simulated percolation rates (recharge) were verified against literature annual values and were also compared with monitoring well hydrographs of selected test sites. Default soil parameters were fine-tuned through calibration against observed water level fluctuations.

Table 1. Adjusted hydraulic parameters applied for different soil types throughout the HELP simulation of recharge rates.

Parameter	**Profile**				**Unit**
	Fine porous (Silty Loam)	**Coarse porous (Loamy Sand)**	**Karst (Sand)**	**Fractured (Fine Sand)**	
Total porosity	0.46	0.43	0.44	0.38	vol/vol
Field capacity	0.23	0.20	0.05	0.20	vol/vol
Wilting point	0.12	0.08	0.02	0.03	vol/vol
Sat.hydr.conductivity	5	10	500	8	cm/day
Subsurface inflow	0	0	0	0	cm/day
Evapotranspiration zone depth	115	125	125	125	cm

Calibrated soil parameters for each type profile are indicated in Table 1. The effects of landcover and slope were simulated using a range of runoff curve numbers. The runoff curve number (also called a curve number or simply CN) is a lumped empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess. It is widely used and is an efficient method for determining the approximate amount of direct runoff from a rainfall event in a particular area. Applied curve numbers were adjusted in order to obtain realistic recharge rates for each type profile.
Recharge rates were simulated using the finalised soil profiles for each recharge zone applying spatially averaged climate parameters for the corresponding climate zones.
Differences in recharge between the simulated periods and future time periods are indicated in Figure 8. – Figure 12.

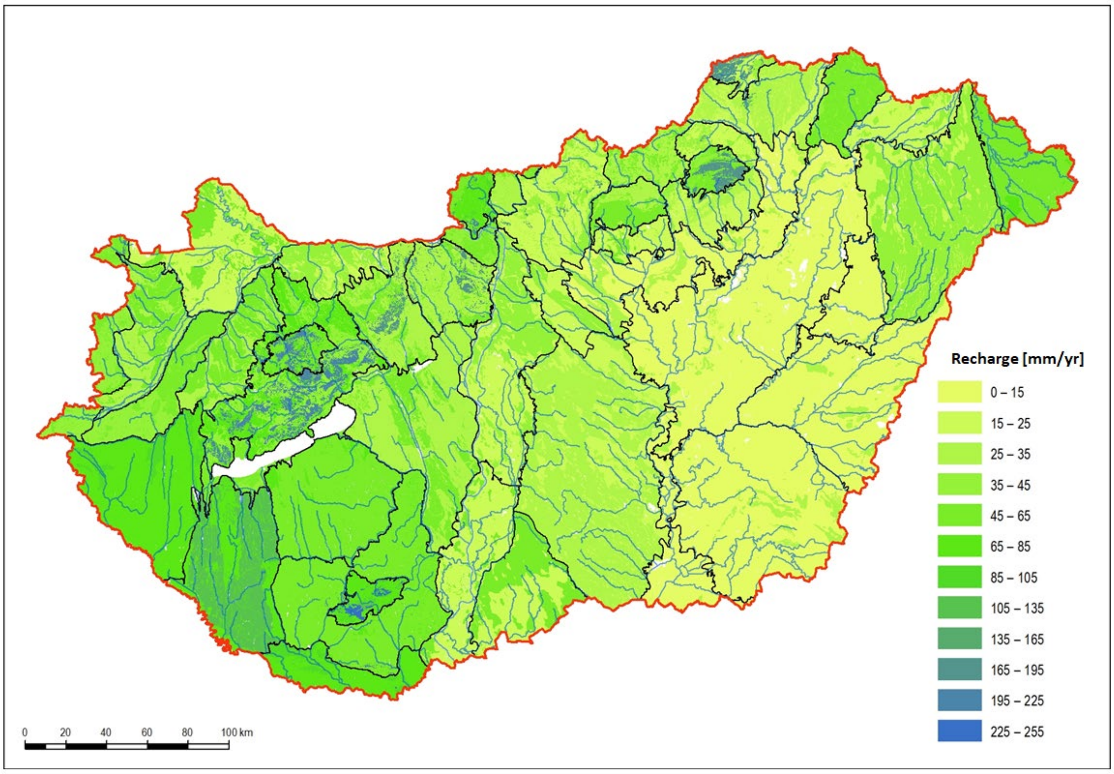

Figure 8. Simulated mean **recharge distribution** for 1975-2004 based on the CARPATCLIM-HU observations.

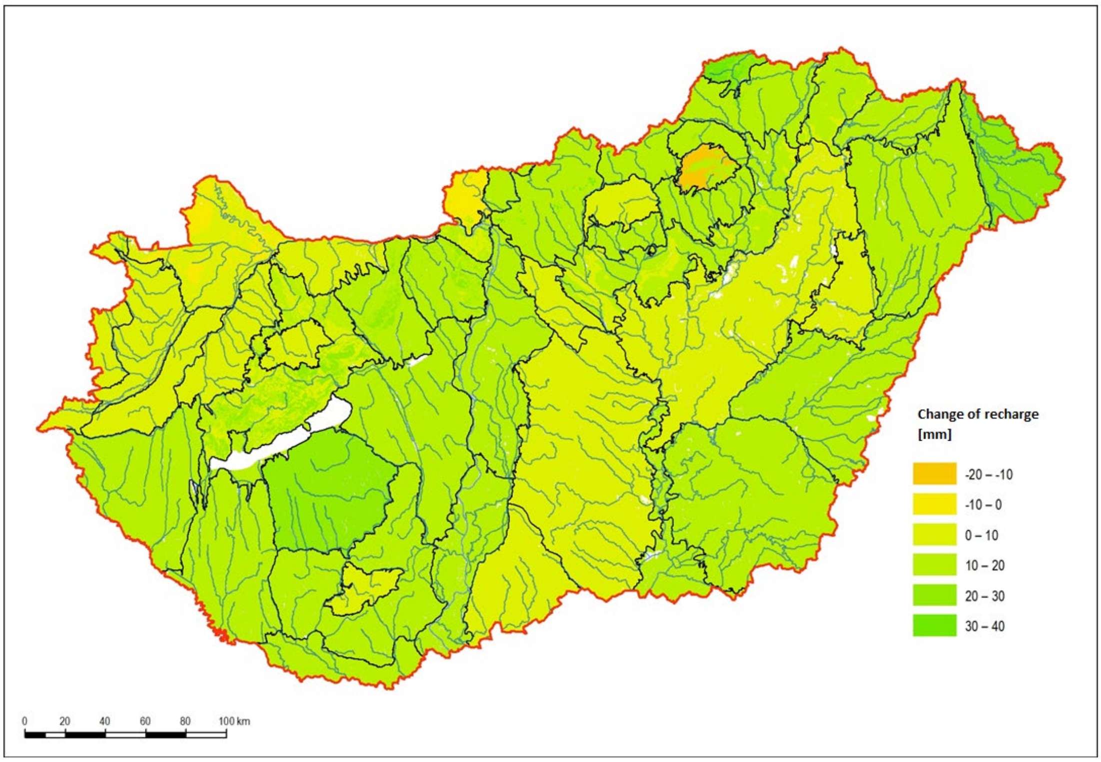

Figure 9. Simulated recharge change between 1975-2004 and 2071-2100. RCA.C (Calculated based on RCP45 model scenario)

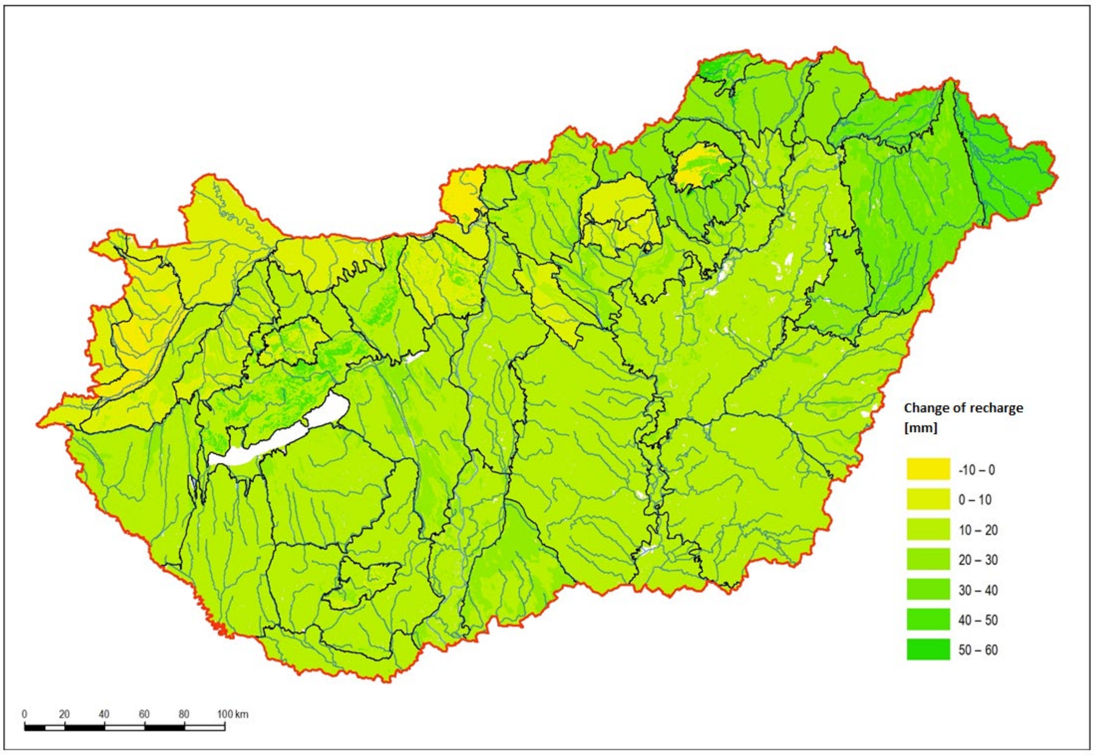

Figure 10. Simulated recharge change between 1975-2004 and 2071-2100. RCA.C Calculated based on RCP85 model scenario

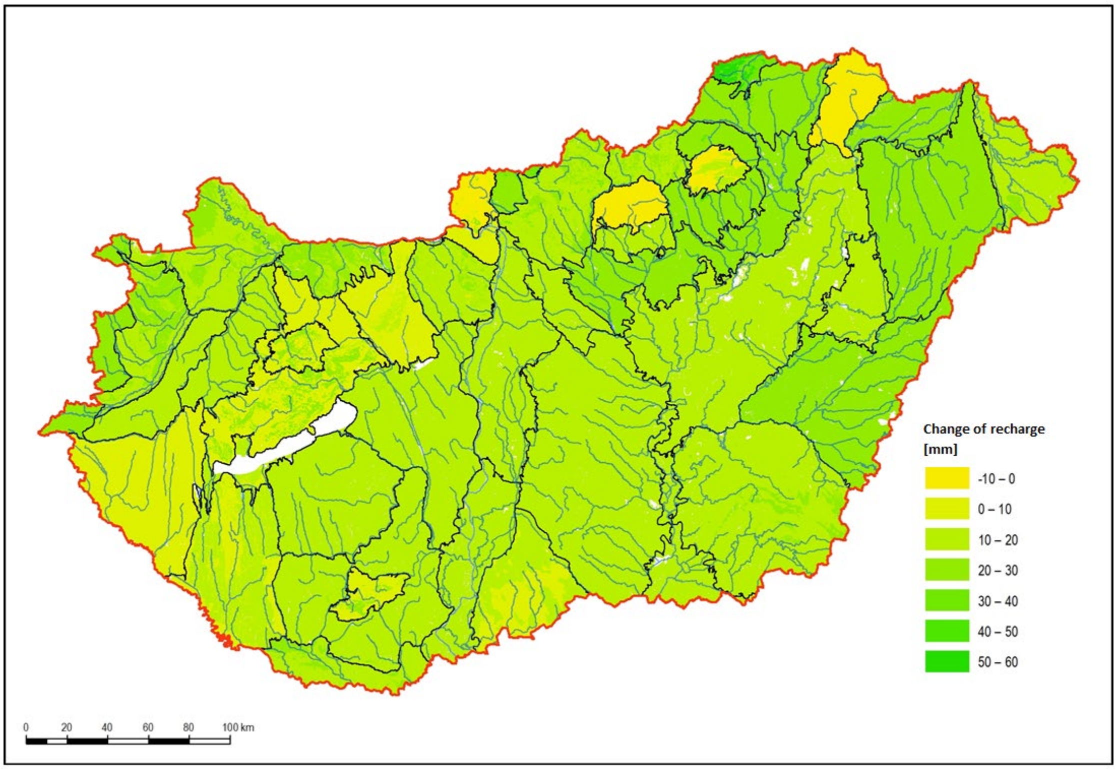

Figure 11. Simulated recharge change between 1975-2004 and 2071-2100 based on RCA.E RCP85 model scenario

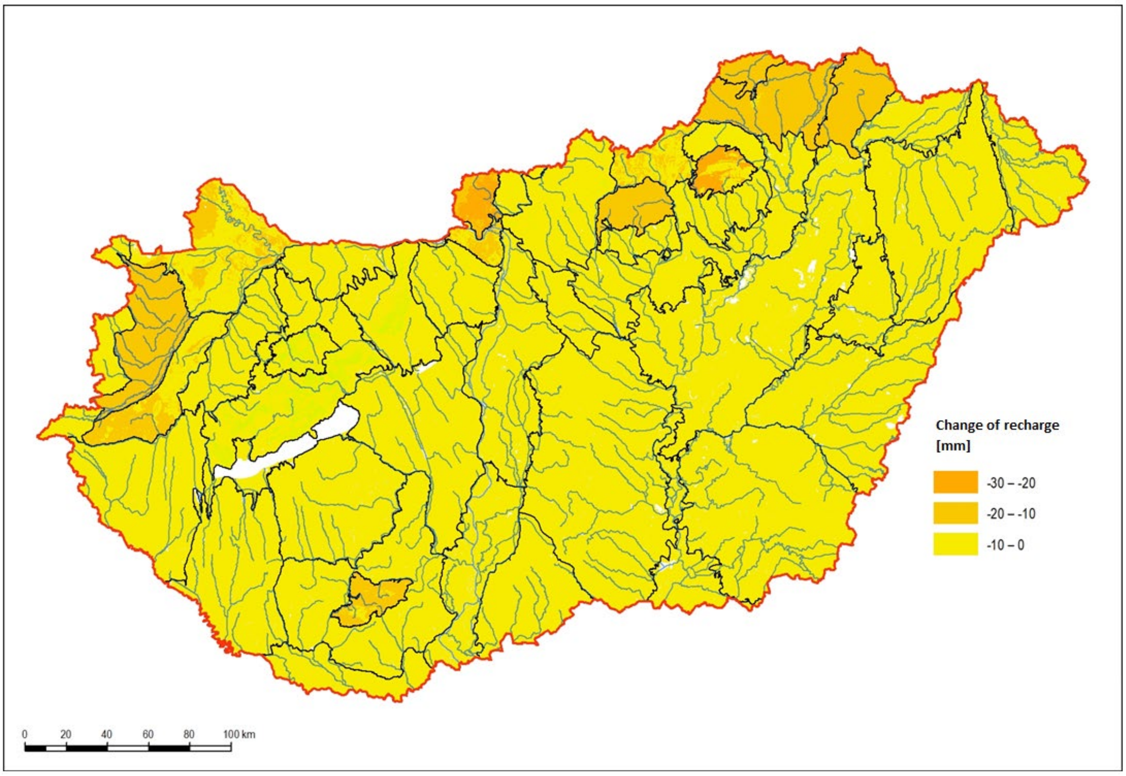

Figure 12. Simulated recharge change between 1975-2004 and 2023-2052 based on RCA.C RCP45 model scenario

The difference maps basically show the increase in recharge for the largest area of the country between the first and last simulation period for all model scenarios. The average rate of growth is 10-30 mm/year, but in the eastern part of the country it can be 40 mm/year. However, in the mountainous regions – mainly in Bükk and Börzsöny – the RCA.C scenarios show a decrease in infiltration of about 10 mm / year. The RCA.E scenarios predict the infiltration change differently in mountainous regions. While in the RCP45 scenario the infiltration shows an increase here as well, in the RCP85 scenario the infiltration in the Northern Mountain Ranges is expected to decrease.

We would like to draw the attention to the map version that illustrates the 30-year average infiltration changes calculated from the RCA.C RCP45 model scenario between 1975-2004 and 2023-2052 (Figure 12). In this version, unlike other versions, the recharge change is negative. This scenario could have a rather negative impact on both groundwater-dependent ecosystems and increasing irrigation needs in terms of opportunities.

4.2 Tool(s) / Model set-up

4.2.1 *Groundwater modelling*

The overall aim of groundwater modelling was to simulate water table distribution under various climate conditions. For this reason a two and also three dimensional steady-state numerical model was developed.
The MODFLOW numerical groundwater flow model has been chosen for this study, operating under the Visual Modflow v.4.6 software package (Waterloo Hydrogeologic Inc., 2005). MODFLOW is widely accepted numerical groundwater flow modelling code. The application of a finite-difference code ensured a simple data transfer between input and output data grids and the model interface.
In mountainous areas of open karst terrain, where shallow aquifers are absent, karst water table was simulated, and was considered to be hydraulically connected to adjacent shallow groundwater bodies. Model extent included the political borders of the country, and the model domain had a rectangular geometry.
The main boundary conditions applied in the model comprised surface streams, water bodies and drainage zones. The model was calibrated against water level monitoring stations, spring elevations and river stages.
Artificial influences on the groundwater system such as water extractions were not incorporated in the model scenarios. Simulated water tables are thus hypothetical distributions which are intended to demonstrate direct effects of climate impacts rather than to predict future groundwater levels.

4.3 Tool(s)/ Model calibration/ test

In the first step the natural-state model simulated average groundwater conditions for the period 1961-1965. It was assumed that shallow groundwater conditions were determined by climatic conditions during this period and that artificial influences were negligible. The natural-state model served for calibrating hydraulic properties against measured water levels. Calibrated parameters were applied for the simulation of predictive scenarios.
Shallow aquifers were regrouped into larger hydrogeological units to facilitate model calibration. Transmissivity values were adjusted to obtain an acceptable match between measured and simulated groundwater heads.
The objective of the model calibration process was to determine model-scale hydraulic parameters that reproduce the hydraulic functioning of the groundwater system. Transmissivity values were adjusted to obtain an acceptable match between measured and simulated groundwater heads.
The calibration process involved the continual adjustment of hydraulic transmissivity until the closest match between model predicted water levels and field measured water levels was obtained. Model calibration was undertaken with the assumption that field measured time-averagred water levels represent steady state (equilibrium) of the groundwater system.
Model calibration was performed by means of automated calibration using PEST. PEST (WNC, 2005) is a nonlinear parameter estimation code. Parameter optimisation is achieved using the

Gauss-Marquardt-Levenberg method to drive the differences between model predictions and corresponding field data to a minimum in a weighted least squares sense. The implementation of this search algorithm in PEST is particularly robust; hence PEST can be used to estimate parameters for both simple and complex models including large numerical spatial models with distributed parameters.

4.4 Uncertainty

The primary method for quantitatively assessing the goodness of fit of calculated data is through calculation of the Scaled Root Mean Square Error (RMS). The RMS error (or standard deviation) is the square root of the average of the squared differences in measured and simulated heads, expressed as (Eq. 1):

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(x_{calc} - x_{obs})^2}{n}} \qquad \text{(Eq. 1)}$$

where n is the number of measurements. The Scaled Root Mean Square Error (SRMS) is the RMS divided by the range of observed values, or (Eq. 2):

$$SRMS = \frac{RMS}{(X_{obs})_{\max} - (x_{obs})_{\min}} \qquad \text{(Eq. 2)}$$

where Xobs is the measured head, and Xcalc is the calculated head.

The scatter plot of simulated versus observed groundwater levels of the natural-state model is indicated in Figure 13.
According to international standards, the required calibration accuracy is generally set in accordance with the model complexity. For a medium complexity regional model such as this, an SRMS error of approximately 3.3 % is considered to be an acceptable calibration.

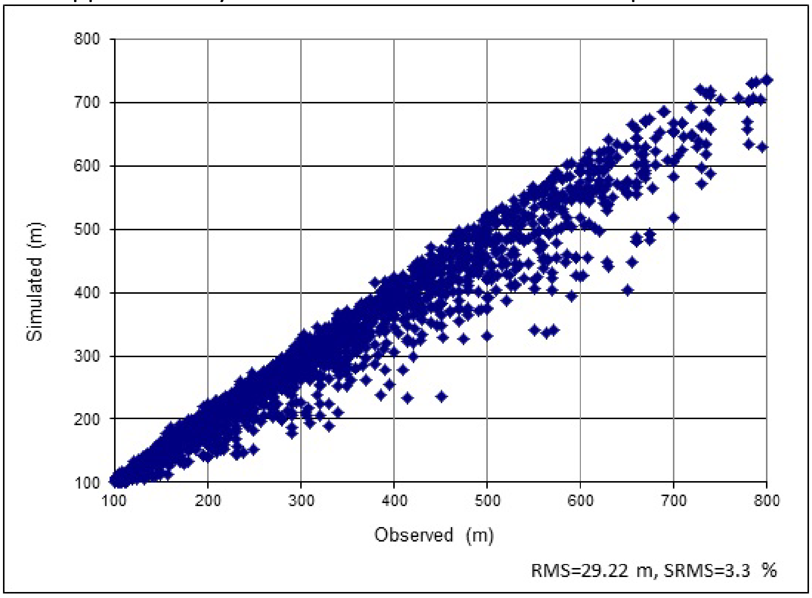

Figure 13. Scatter plot of simulated vs. observed groundwater levels of the natural-state model.

5 RESULTS AND CONCLUSIONS

5.1 Results of hydrogeological modelling

Using the Pannon XL v.3.0 version, in the 2nd step, we performed 22 runs based on the recharge distributions described above with no production (“natural”) and production (2008-15 average values). The result maps contain the levels and water management elements of the groundwater flow systems for different climate scenarios and periods (surface net recharge, recharge, discharge [mm / year]). Here are some typical variations of this series of maps:

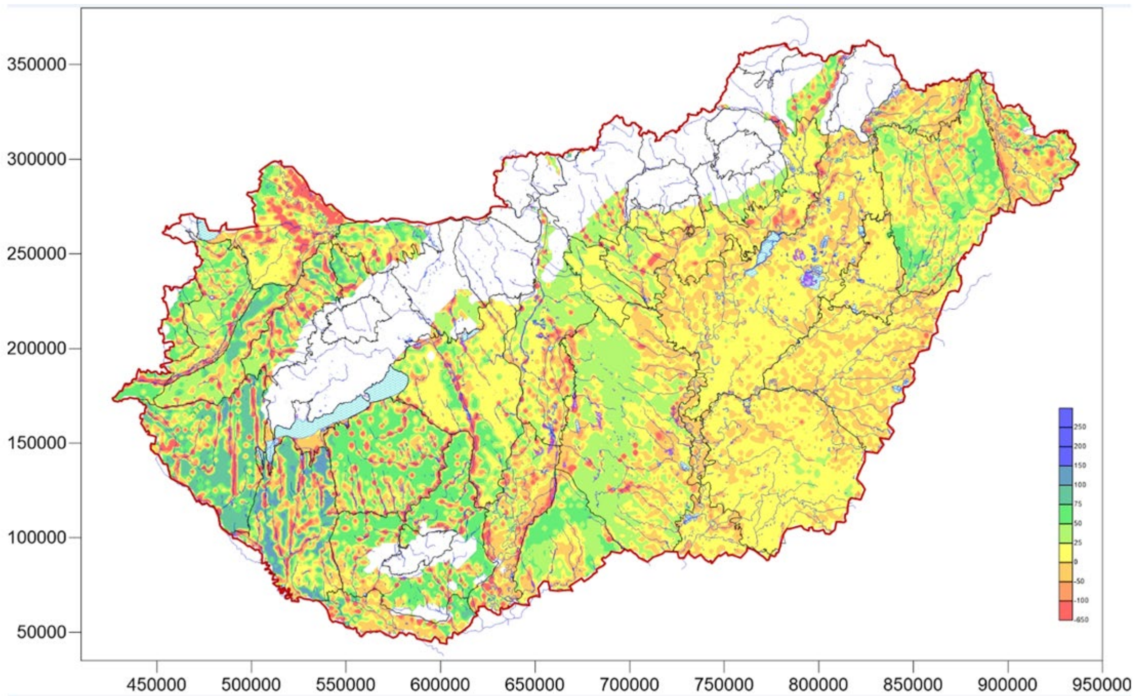

Figure 14. Net recharge on the surface (Pannon-XL v.3.0 - production version) modelled on the basis of calculated climate data of the near future (2023-2052) IPCC RCP 4.5 excluded mountainous areas [mm/year]

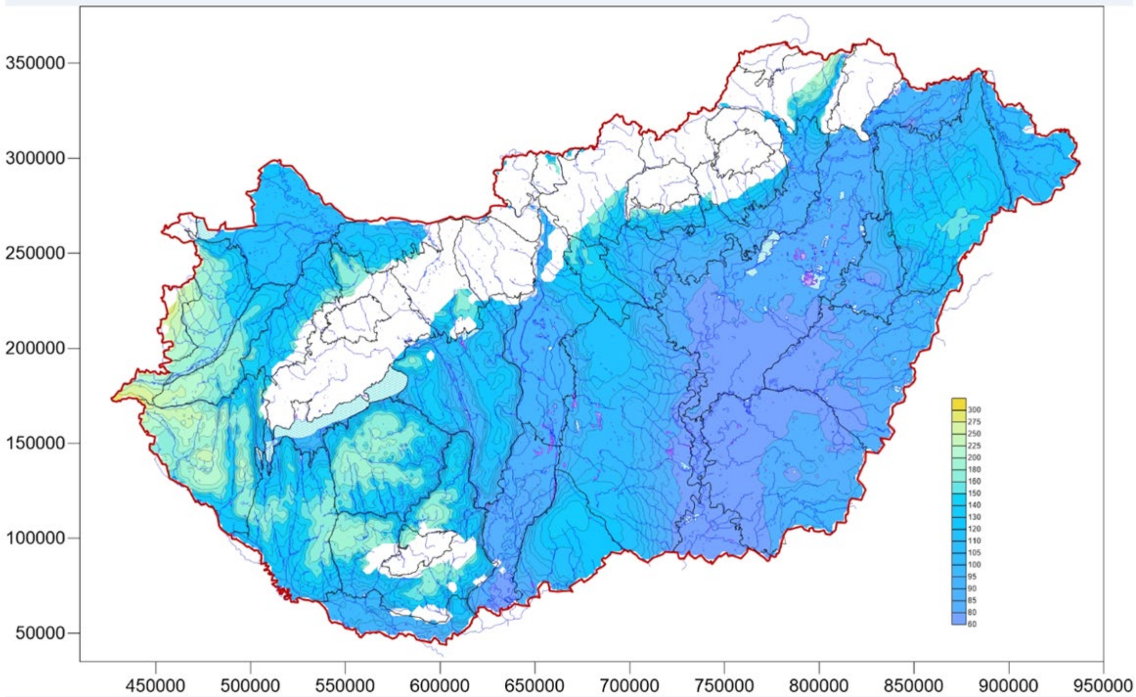

Figure 15. Groundwater level distribution modelled on the basis of climatic data measured for the reference period (1973-2004) CC-HU (Pannon-XL v.3.0 – production version) excluding mountainous areas [masl]

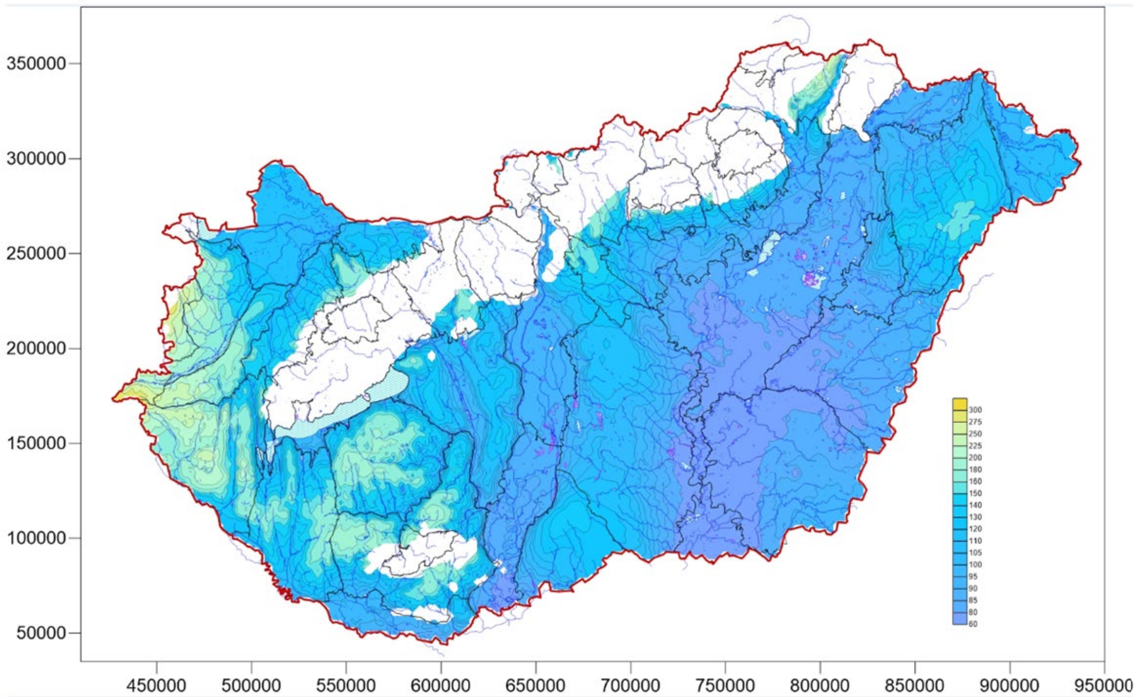

Figure 16. Groundwater level distribution modelled for the reference period (1973-2004) calculated on the basis of climatic data calculated by IPCC RCP4.5 (Pannon-XL v.3.0 - production version) excluding mountain areas [masl]

5.2 Conclusions

The present paper summarises a methodology developed for the calculation of groundwater table distributions from climate parameters. The goal of water table modelling was to develop a methodology which can be applied for calculation of the water table under different climate conditions. This was done in order to facilitate climate impact assessment and the evaluation of climate sensitivity of groundwater aquifers.

A dynamic modular approach was developed in order to quantitatively simulate the groundwater table under various climate conditions. The applied methodology included:

1. Determination of climate zones based on measured and simulated climate variables;
2. Determination of recharge zones (Hydrological Response Units, HRU's) based on surface geology, land use, and slope conditions.
3. Calculation of recharge for each recharge zone using 1D analytical hydrological model series.
4. Simulation of the groundwater table under various climate conditions using numerical groundwater flow models.

The climate data used in our hydrological modelling comprised gridded daily observed data from the CARPATCLIM-HU and CORDEX database and projections of different regional climate model.

Results of recharge calculation indicate that recharge could decrease up to 50 mm/year by the end of the 21st century in the elevated areas, while in other climate scenario we can presume wetter climate. Slight recharge increase is projected in parts of the Great Hungarian Plain and the Transdanubian Hills. Water levels most probably will increase over the Alpokalja, Mecsek, Transdanubian and Northern Mountain Ranges. Moderate water level drops in the Duna-Tisza Interfluve and Tiszántúl areas are probable, while slightly rising groundwater levels are projected in parts of the Great Hungarian Plain and the Transdanubian Hills.

Our studies have highlighted the high degree of uncertainty in climate models. As a result, there has been both drought and a wetter climate trend and this can often vary from area to area. It has shown spatial and temporal fluctuations in precipitation and other climatic parameters, so the long-term trend may result opposite changes compared to the short or even medium-term.

The presented outputs were determined at the regional scale and as such cannot be used for local investigations. The presented methodology though can be applied for modelling the climate impact both at the regional and local scales for assessing the climate vulnerability of groundwater resources.

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Deliverable 3.2 and 6.3

PILOT DESCRIPTION AND ASSESSMENT

Segura Basin

Authors and affiliation:

Juan de Dios Goméz-Gómez, AJ. Collados-Lara, David Pulido-Velazquez, Leticia Baena-Ruiz,.

Geological Survey of Spain (IGME)

This report is part of a project that has received funding by the European Union's Horizon 2020 research and innovation programme under grant agreement number 731166.

Deliverable Data	
Deliverable number	D3.2 & D6.3
Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	**WP3:** INTEGRATED GROUNDWATER - SURFACE WATER ASSESSMENT OF CLIMATE CHANGE **and WP6:** GROUNDWATER ADAPTATION STRATEGIES

Lead WP/Deliverable beneficiary	WP3 (GEUS); WP6 (IGME)
Deliverable status	
Version Date	Version 1 14/11/2018

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LIST OF ABBREVIATIONS & ACRONYMS

SB: Segura Basin
CU: Conjunctive Use

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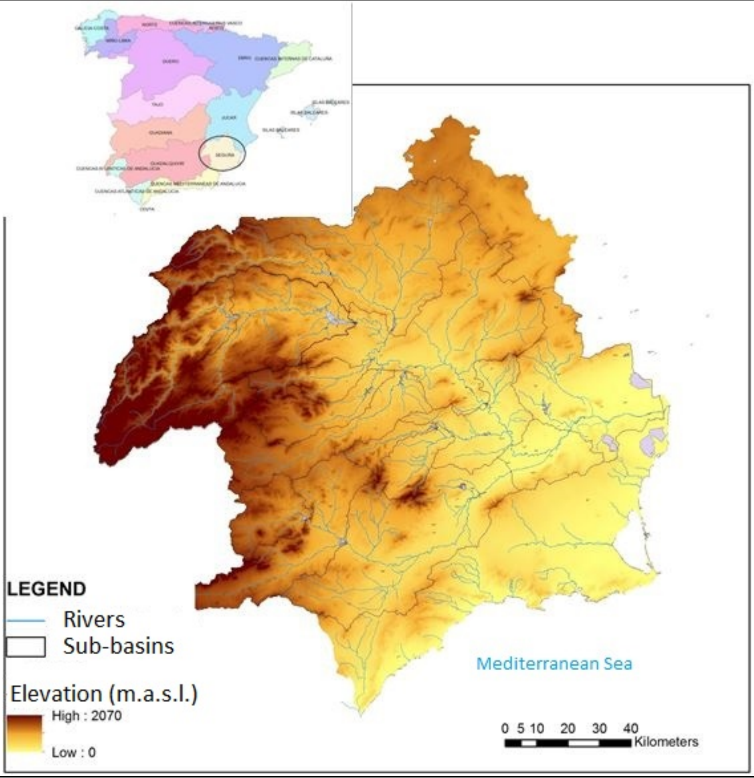
1 EXECUTIVE SUMMARY

Pilot name	SEGURA BASIN	
Country	Spain	
EU-region	Mediterranean region	
Area (km^2)	14778 km^2	
Aquifer geology and type classification	Detrital and carbonated. Sedimentary & karstic.	
Primary water usage	Irrigation / Drinking water / Industry	
Main climate change issues	This coastal basin is an example of a Mediterranean area with a significant water demand, mainly for irrigation but also for urban supply (with an important seasonal component for the touristic sector), and low availability of resources. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of resources taking into account the interaction between surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin and addicional supply from desalination plants. Global change will exacerbate these problems by reducing the availability of resources and increasing irrigation requirements (higher temperatures and lower precipitations). It will also cause an incraese in the magnitude and frequency of extreme phenomena such as floods and droughts. An integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model is proposed to help in the decision making process.	
Models and methods used	Generation of local future climate change scenarios to analyse droughts following the method proposed in the framework of this project (Collados-Lara et al., 2018) and definition of adaptation scenarios. Propagation with a chain of auxiliary models (recharge, agricultural) to generate inputs for a CU management model at basin scale, defined with the AQUATOOL code; Assessment of different types of drought and its propagation.	

Key stakeholders	Segura River Basin Authority, farmers associations, Canal del Taibilla (public water supply company), Regional Authorities, Environmental Conservation Groups.
Contact person	J.D. Gómez, D. Pulido, L. Baena, A.J. Collados. IGME (Spain): j.dedios@igme.es; d.pulido@igme.es; l.baena@igme.es; aj.collados@igme.es

This pilot is an example of a Mediterranean coastal basin with a significant water demand, mainly for irrigation but also for urban supply (with an important seasonal component for the touristic sector), and low availability of resources. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of resources taking into account the interaction between surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin and addicional supply from desalination plants. Global change will exacerbate these problems by reducing the availability of resources and increasing irrigation requirements (higher temperatures and lower precipitations). It will also cause an incraese in the magnitude and frequency of extreme events such as floods and droughts. An integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model is proposed to help in the decision making process.

Local future climate change and adaptation scenarios has been developed to analyse droughts following the method proposed in the framework of this project (Collados-Lara et al., 2018). They have been propagated with a chain of auxiliary models (recharge, agricultural) to generate inputs for a CU management model at basin scale, defined with the AQUATOOL code. Finally different types of drought and its propagation have been assesed.

Results observed for the whole Segura Basin system for the period 2071-2100 show lower resources available to meet the different demand elements, which means higher deficits for that demands. Higher pumping rates in aquifers are estimated for future scenarios and the impacts would also be reflected on lower guarantees to meet demands. The four studied scenarios show important reduction of precipitation and increase of temperature and large increments of the number, duration, intensity and magnitude of droughts. The study of the correlation of hydrological and meteorological droughts shows significant correlations for a gap from 0 to 6 months depending of the scenario considered. However the correlation of meteorological and operational droughts shows a maximum of correlation for a gap around 4 months for all cases.

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 Segura basin pilot is one of the basin scale pilots that have been analysed in Tactic, focusing on climate change impacts and adaptation strategies with special attention to the propagation of drought events. So the main challenge of the pilot is to perform an integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model.

3 PILOT AREA

The Segura basin is a representative case of a Mediterranean basin with semi-arid climate. It is located in one of the driest regions of Spain, with low availability of resources but significant water demand. Agriculture is the main socioeconomic activity in the middle and lower basin together with the touristic activity in the coast. The supply reliability in this case depends on an appropriate conjunctive use (CU) operation of surface and groundwater resources. In fact, it is a deficitary system that needs water transfers from Tagus Basin (in Central Spain), causing social conflicts between regions, and addicional supply from desalination plants. This problem might be exacerbated in the future due to climate change impacts (higher temperatures, lower precipitations and more extreme phenomena). So the aim of this case study is to perform an integrated analysis of future climate change impacts and adaptation strategies based on some indexes obtained from the results of a system management model.

3.1 Site description and data

- Location, extension and topography of the pilot area

The case study cover and area of 14778 km^2 located in Southeastern Spain, in the Mediterranean region of the EU (See Fig. 3.1). The River Segura is the main stream of the basin together with its tributaries Mundo, Argos, Quípar, Mula and Guadalentín. The main city of the system is Murcia with a population of 440,000 inhabitants, and also Alicante (330,000) is partially supplied by the system.

The altitude ranges from 2070 m.a.s.l. at the Sierra de Segura mountains (Northwest) to 0 m.a.s.l. at the seashore.

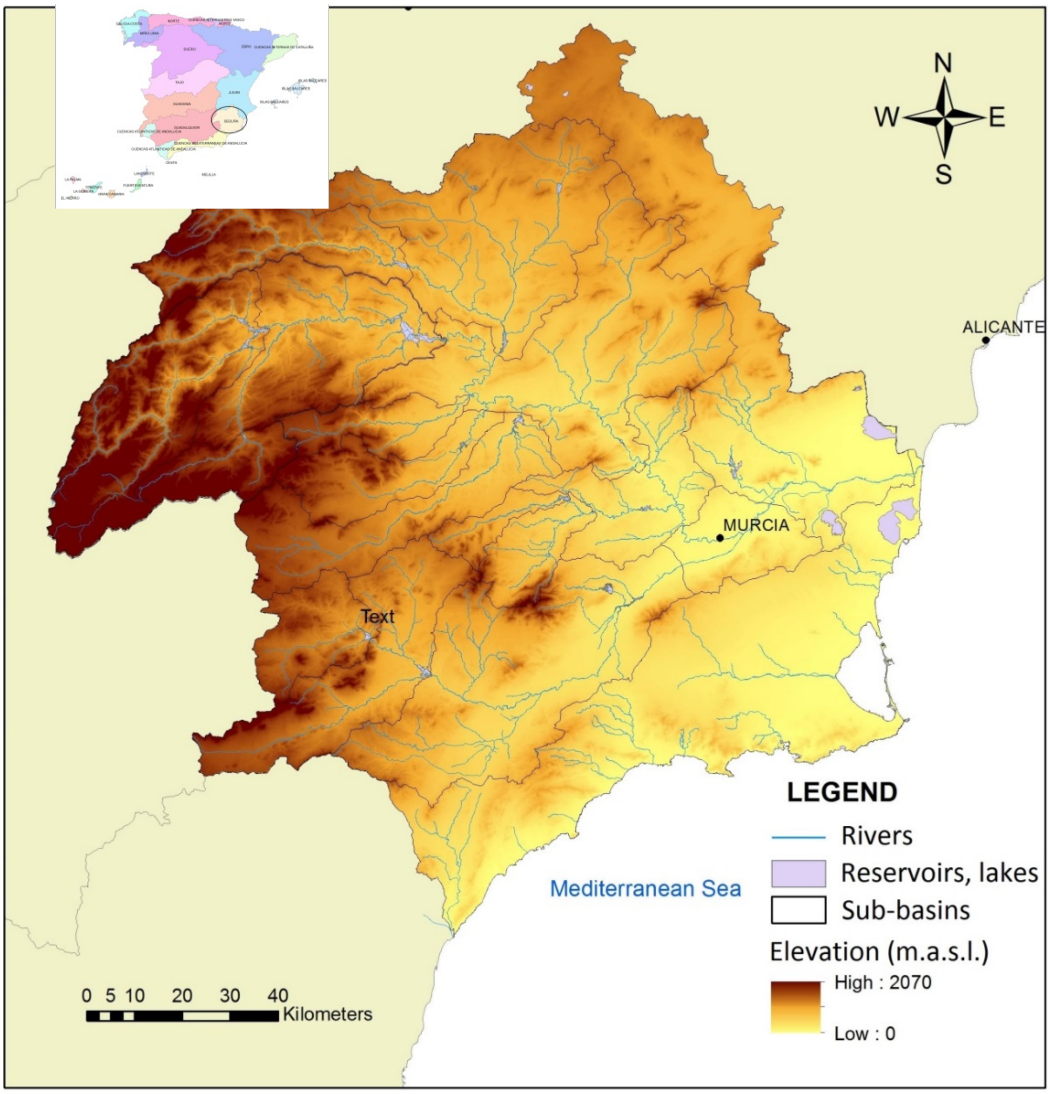


Fig. 3.1. Location of the pilot area

- Geology/Groundwater bodies type

The Segura Basin is almost totally included in the geological domain of the Bética Mountain Range. Only in its northern part, materials from the tabular cover overlying the Hercynian basement can be found. The Bética Mountain Range is the group of mountain chains generated by the Alpine folding that extends across Andalusia, Murcia and south of Valencia.

A total of 60 GW bodies are included in the Segura Basin, with a complex geology and different lithologies such detrital as carbonate and mixed (see Fig. 3.2).

One of the main groundwater bodies in the system is the Middle-Lower Segura Plain, a Plioquaternary aquifer located in the lower part of the basin, partially connected to the sea, wich concentrates most of the urban and agricultural water demands of the system. It has been thoroughly studied and described, and several models have been developed.

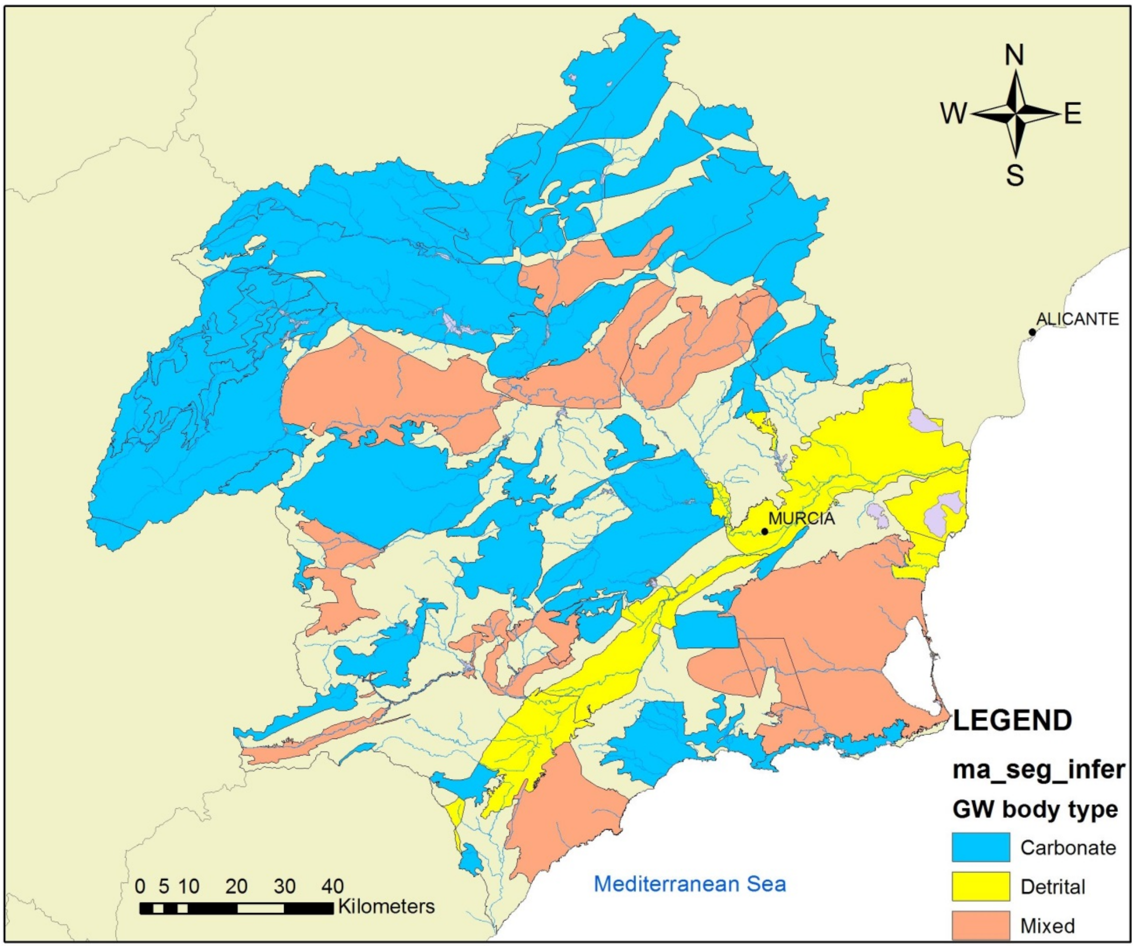


Fig. 3.2 Groundwater bodies type

CODE	NAME	EXTENSION (KM2)	GROUP	TIPOLOGY
070.001	CORRAL RUBIO	170	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.002	SINCLINAL DE LA HIGUERA	210	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.009	SIERRA DE LA OLIVA	73	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.005	TOBARRA-TEDERA-PINILLA	151	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.008	ONTUR	155	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.004	BOQUERÓN	283	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.007	CONEJEROS-ALBATANA	159	CARBONATE	Folded sedimentary (Mesozoic and

				Cenozoic)
070.013	MORATILLA	29	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.012	CINGLA	379	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.003	ALCADOZO	505	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.024	LÁCERA	8	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.023	JUMILLA-YECLA	264	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.010	PLIEGUES JURÁSICOS DEL MUNDO	985	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.006	PINO	48	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.011	CUCHILLOS-CABRAS	209	MIXED	Carbonate and detrital
070.027	SERRAL-SALINAS	97	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.017	ACUIFEROS INFERIORES DE LA SIERRA DE SEGURA	1524	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.021	EL MOLAR	288	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.022	SINCLINAL DE CALASPARRA	332	MIXED	Carbonate and detrital
070.025	ASCOY-SOPALMO	369	MIXED	Carbonate and detrital
070.026	EL CANTAL-VIÑA PI	40	MIXED	Carbonate and detrital
070.029	QUIBAS	137	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.028	BAÑOS DE FORTUNA	86	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.020	ANTICLINAL DE SOCOVOS	751	MIXED	Carbonate and detrital
070.030	SIERRA DEL ARGALLET	6	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.031	SIERRA DE CREVILLENTE	20	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.036	VEGA MEDIA Y BAJA DEL SEGURA	705	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.035	CUATERNARIO DE FORTUNA	19	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.034	ORO-RICOTE	66	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.032	CARAVACA	677	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.033	BAJO QUÍPAR	61	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.040	SIERRA ESPUÑA	630	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.019	TAIBILLA	69	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)

070.042	TERCIARIO DE TORREVIEJA	169	DETRITAL	Tabular detrital from Neogene basins
070.041	VEGA ALTA DEL SEGURA	27	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.039	BULLAS	279	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.018	MACHADA	43	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.038	ALTO QUÍPAR	181	MIXED	Carbonate and detrital
070.051	CRESTA DEL GALLO	25	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.053	CABO ROIG	62	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.052	CAMPO DE CARTAGENA	1240	MIXED	Carbonate and detrital
070.037	SIERRA DE LA ZARZA	17	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.050	BAJO GUADALENTÍN	324	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.055	TRIÁSICO DE CARRASCOY	108	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.047	TRIÁSICO MALÁGUIDE DE SIERRA ESPUÑA	30	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.048	SANTA-YÉCHAR	42	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.043	VALDEINFIERNO	152	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.049	ALEDO	73	MIXED	Carbonate and detrital
070.046	PUENTES	121	MIXED	Carbonate and detrital
070.054	TRIÁSICO DE LOS VICTORIA	110	MIXED	Carbonate and detrital
070.045	DETRÍTICO DE CHIRIVEL-MALÁGUIDE	93	MIXED	Carbonate and detrital
070.044	VÉLEZ BLANCO-MARÍA	72	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.057	ALTO GUADALENTÍN	275	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.058	MAZARRÓN	284	CARBONATE	Metamorphic
070.063	SIERRA DE CARTAGENA	66	CARBONATE	Metamorphic
070.061	ÁGUILAS	379	MIXED	Carbonate and detrital
070.056	SIERRA DE LAS ESTANCIAS	7	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)
070.059	ENMEDIO-CABEZO DE JARA	50	CARBONATE	Metamorphic
070.060	LAS NORIAS	18	DETRITAL	Alluvial, litoral and other Pliocuaternary deposits
070.062	SIERRA DE ALMAGRO	20	CARBONATE	Folded sedimentary (Mesozoic and Cenozoic)

Table 3.1. Groundwater bodies in the SB system.

- ***Surface water bodies***

The River Segura is the main stream of the basin together with its tributaries Mundo, Argos, Quípar, Mula and Guadalentín. Traditionally, surface water in this basin has been strongly regulated due to the water scarcity in the region and the extreme events (such droughts as floods) that historically have afected it. A complex network of reservoirs and canals has been set up in the system to regulate internal and external water resources (water transfer from Tagus basin), and more recently to also incorporate desalination resources.

So the flow series measured at most gauges are in altered regime, and only in the upper basin can be found a natural regime. However the series have been restored to natural regime by the River Basin Authority and in some IGME project.

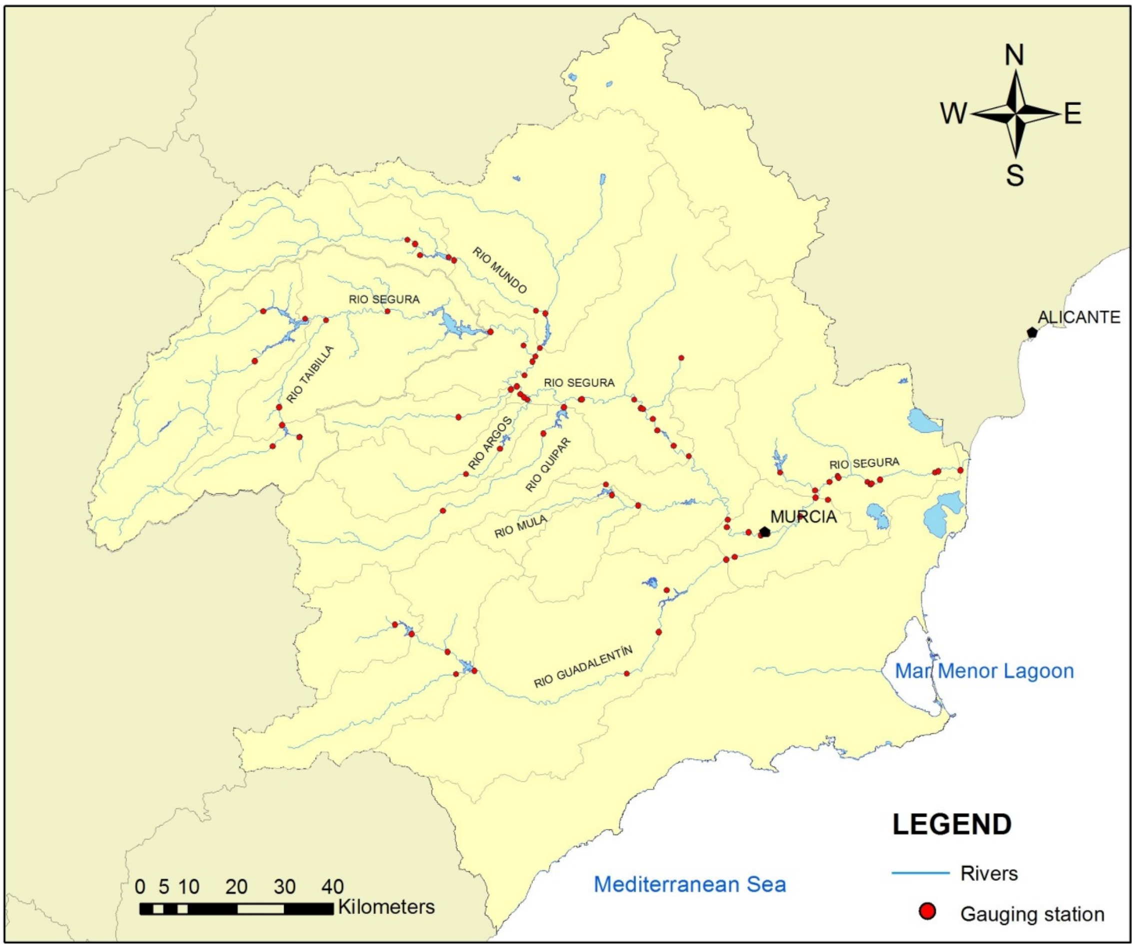


Figure 3.3. Surface water bodies and stream gauges.

- ***Climate***
  - *climate type*

    The general predominant climate in the Segura Basin is Mediterranean, with specific tipologies in different areas. So half of the basin, the highest lands at the North and West, has a temperate Mediterranean climate. At middle altitudes the climate becomes continental Mediterranean, and at the rest of the territory (second in extension) it is subtropical Mediterranean, except in a coastal strip at the South where it is semi-arid subtropical Mediterranean (CHS, 2018).

- *precipitation, temperature and evapotranspiration*
  The annual average rainfall in the basin is 382 mm according to historical series (1940/41-2005/06) and 362 mm considering the short period (1980/81-2005/06). The regime of precipitation is extremely variable in space and time, with clear differences between the upper and lower basin.

  The mean potential evapotranspiration is around 700 mm and the mean real evapotranspiration is estimated about 328 mm for the long period series. The overall mean runoff has been calculated as 13% of the overall mean precipitation, which is the lowest in the Iberian Peninsula.

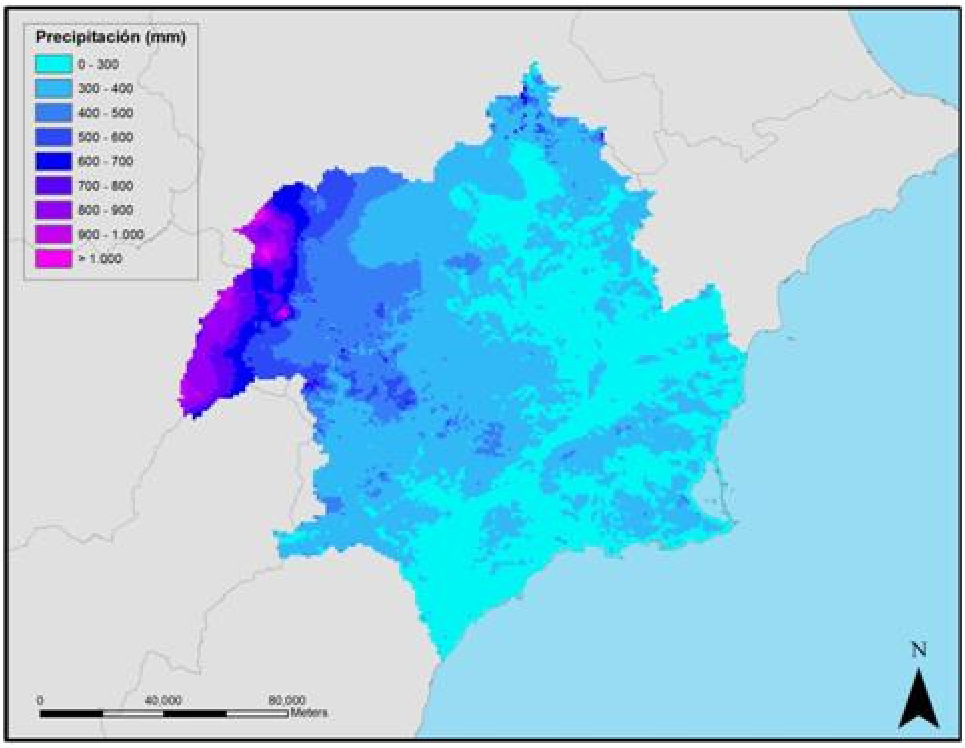


Figure 3.4. Mean annual precipitation distribution in the Segura Basin District (CHS, 2018)

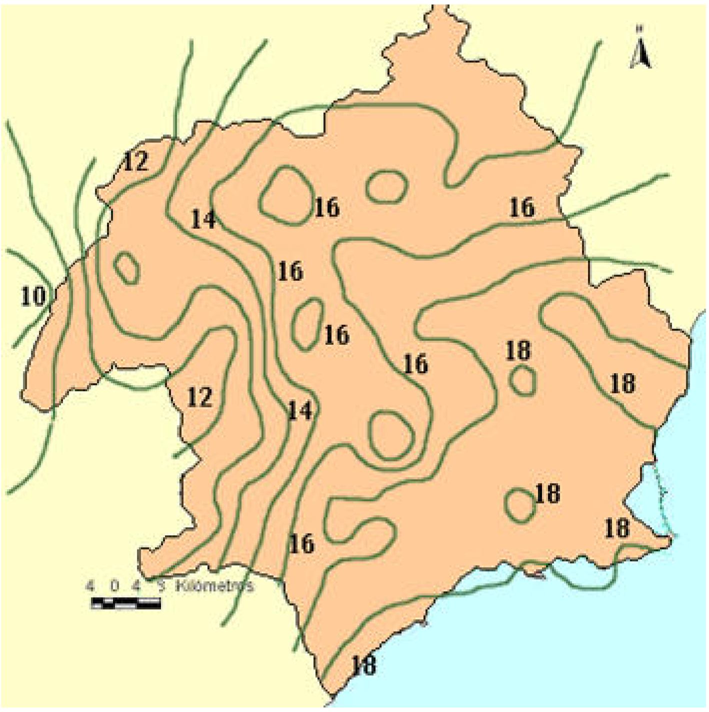


Figure 3.5. Mean annual temperature distribution in the Segura Basin District (CHS, 2018)

- Land use

The main socioeconomic activity is irrigated agriculture, traditionally concentrated in the alluvial and coastal plains. The main crops are citrus and fruit trees, and also green and other vegetables.

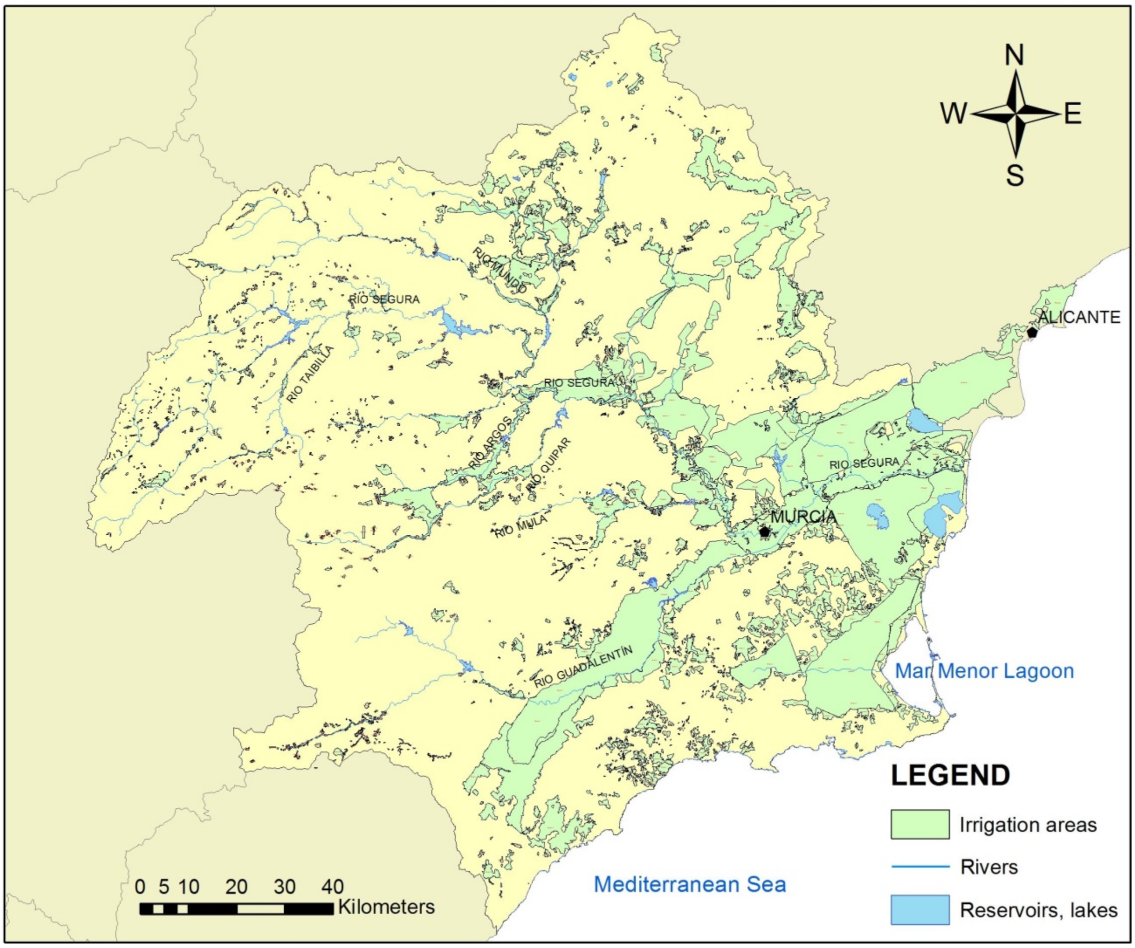


Fig. 3.6 Irrigation areas

- ***Management scheme***

This complex conjunctive use system includes different types of water resources such as groundwater, surface water, external water transfer from Tagus basin (Central Spain) and unconventional resources (wastewater reuse and desalination). The system integrates a network of reservoirs and canals in order to regulate and distribute such resources and meet the different demands. The simplified topologic scheme of the lower part of the system shows such complexity (see Fig. 3.7).

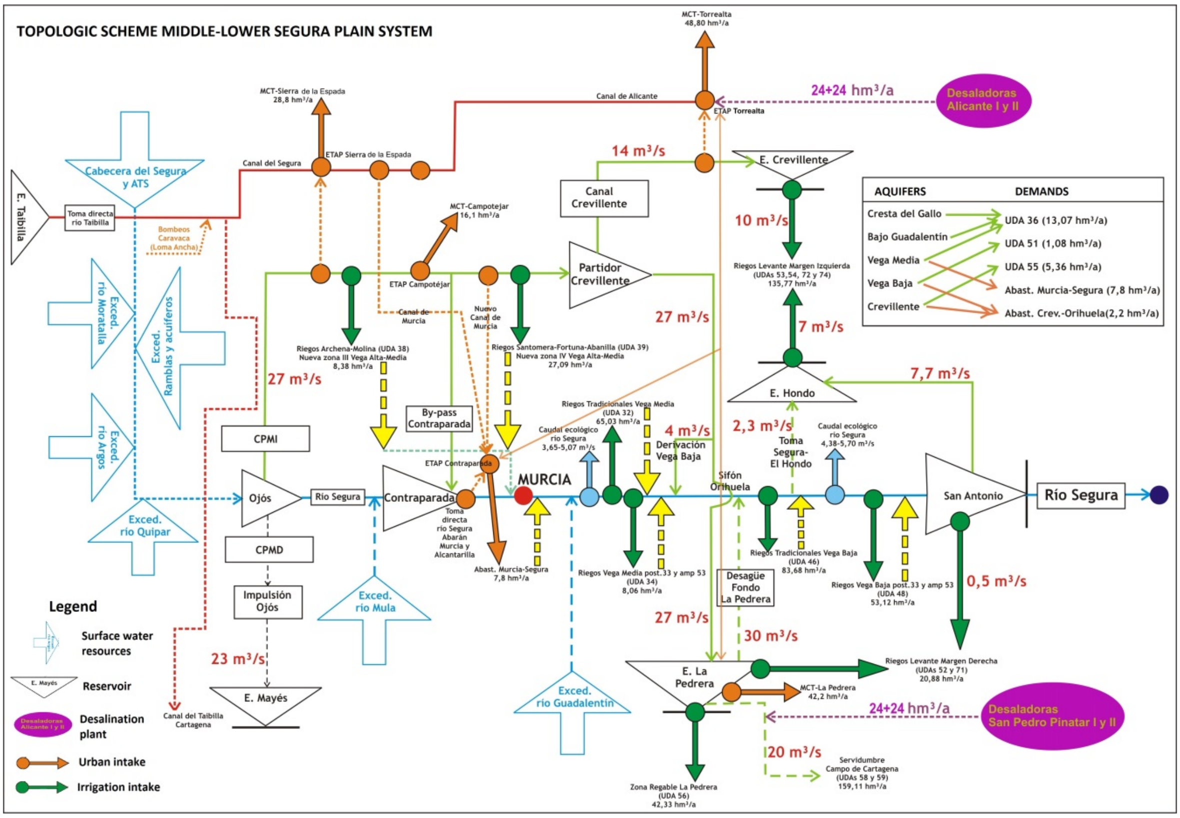


Fig. 3.7 Topologic scheme of the water management system (modified from Gómez-Gómez et al., 2016)

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to climate change in this case study are those described in the Figure 8 for the Mediterranean regions. Existing national estimates show also a significant reduction (around a 20% for the RCP8.5 emission scenario in the horizon 2071-2100) of the aquifer recharge in the area (see Pulido-Velazquez et al., 2018)

The main challenge is to find adaptation measures to maintain a sustainable use of groundwater bodies and the other water resources with a balance between supply and water demands (different uses) under future climate change conditions.

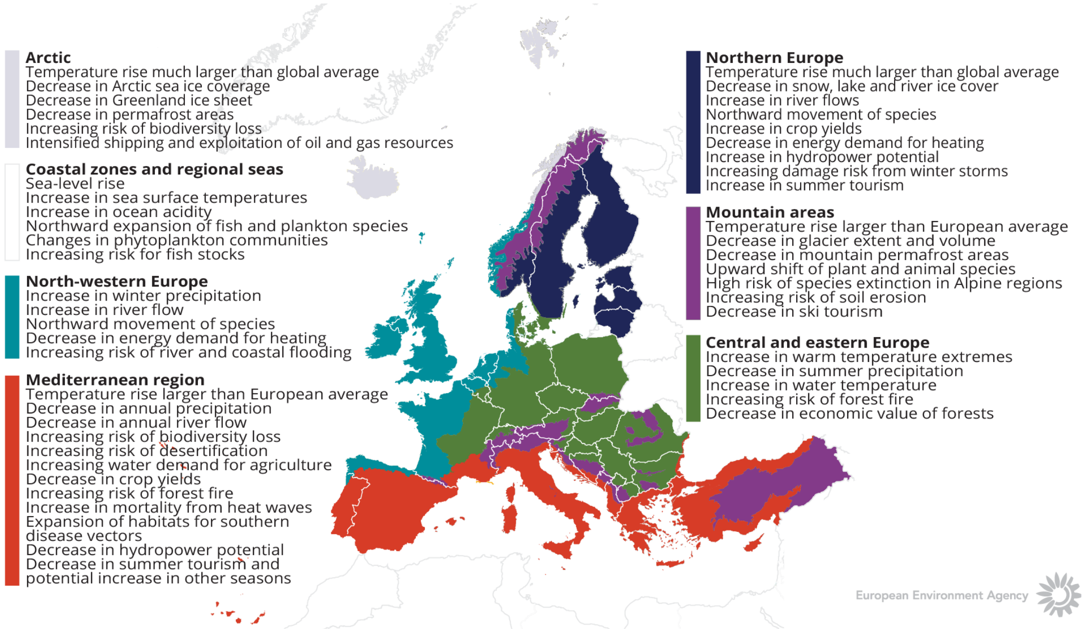


Figure 3.8. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

The assessment of climate change impacts on the Segura basin water resources management system (groundwater, surface water and alternative water sources) have been performed using the climate change scenarios from Euro-Cordex (RCP8.5 emission scenario) and the integrated hydrological management model of the basin. The Segura Basin management model is based on the AQUATOOL code, coupled with a rainfall-runoff model (Temez) and a CROPWAT model for irrigation demands assessment (TACTIC toolbox reference).

4.1 Climate data

The present pilot study relies on the Euro-CORDEX regional climate models to reflect future climate conditions. The TACTIC standard CC scenarios have not been used for this pilot.

4.1.1 Euro-CORDEX climate change scenarios

Future climatic series (temperature and rainfall) have been generated applying a statistical downscaling technique for the period 2071-2100. The applied method have been "delta-change" type. It intends to obtain series considering the differences between control and future of the regional climate models and to apply them to the historical series (Fowler et al., 2007). More specifically we have been followed the methodology proposed by Pulido-Velazquez et al., 2011.

The regional information about climate change has been got from CORDEX project, which has resolution about 12,5x12,5 Km for version EUR-11. In this project four emissions scenarios are considered. They are called Representative Concentration Pathways (RCP) and they are related to a possible range of radiative forcing (FR) values in the year 2100 depending on CO2 concentration values. The most pessimistic scenario (RCP8.5) has been considered in this study.

Nine regional climate models nested to different global climate models (see Table 4.1), with RCP 8.5 emission scenario, were used to assess future conditions for the Segura Basin pilot area.

Table 4.1. Euro-CORDEX climate change ensemble.

RCM \ GCM	CNRM-CM5	EC-EARTH	MPI-ESM-LR	IPSL-CM5A-MR
CCLM4-8-17	X	X	X	
RCA4	X	X	X	
HIRHAM5		X		
RACMO22E		X		
WRF331F				X

We tested several statistical techniques to generate local scenarios from the considered RCMs (correction of first- and second-order moments, regression approach, quantile mapping) under two different conceptual approaches: bias correction and delta change techniques. The bias corrections intend to apply a perturbation of the control series obtained with the RCM

simulations to reduce their statistical differences with the historical ones. Future series will be generated by assuming that this bias with the real values will be maintained invariant also in the future. The delta change corrections are defined by using the relative difference in the statistic of future and control of the RCM simulations to perform a perturbation of the historical series in accordance with these estimated changes. It assumes that the RCM simulation approach properly the deltas due to climate change, but not the absolute values.
We considered four options to define the most representative future scenarios by applying different ensembles of the potential scenarios deduced from the available climate models. Two ensemble scenarios were considered by combining, as equi-feasible members, all the future series (that correspond to different RCM simulations) generated by delta change (E1) or bias correction (E2). Two other options were defined by combining only the non-eliminated models (E3) (in delta change approach) or the non-eliminated combinations of models and correction techniques (E4) (bias correction techniques), assuming that we do not trust on the eliminated ones. We eliminated the projections considered as 'inferior' in terms of goodness of fit (see detail of the method in Collados-Lara et al., 2018). The criteria employed to identify the inferior approaches is the next one: An approach is inferior if any other approach provides approximations significantly better for all the statistics (basic and drought statistics).

4.1.2 Differences between the TACTIC standard CC scenarios and the used Euro-CORDEX climate change scenarios

The methodology of the assessment of climate change impacts on groundwater conditions are slightly different between the TACTIC standard scenarios and the Euro-CORDEX ensemble. Whereas the TACTIC scenarios apply four selected scenarios representing a 1 and 3 degree temperature change in the 2nd most dry and 2nd most wet scenario, the Euro-CORDEX uses a larger ensemble with no specific attention to most wet or dry scenario. Furthermore, the TACTIC scenarios are not targeted to a specific future time-period but to a specific temperature rise relative to the reference period, of 1 and 3 degrees, respectively. The Euro-CORDEX scenarios targets the specific time-period of 2071-2100, or the changes between this future period and the reference period. The reference period for the CORDEX approach has been 1971-2000.

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

4.2 Integrated hydrological management modelling of climate change

The Segura Basin management model is based on the AQUATOOL code, coupled with a rainfall-runoff model (Temez) and a CROPWAT model for irrigation demands assessment (TACTIC toolbox reference).

It is based in a previous integrated model developed for the Vega Baja del Segura system (Gomez-Gomez et al. 2016), and subsequently updated and extended to the whole Segura basin.

4.2.1 Model description

The decision support system of Segura Basin (SB) was developed using the code AQUATOOL, and specifically its module SIMGES (Andreu et al. 1996).

This is a software for integrated management modelling of water resources at a basin scale (similar to MIKE BASIN), appropriate for simulation of the river-aquifer interaction, regulation elements such as reservoirs and aquifers, and many other elements involved in water management such as river flows, demands, return flows, ecological flows, canals and other conections, pumpings and artificial recharge. The simulation uses a monthly time step.

The Segura alluvial plain (Fig. 4.1) aquifer has been integrated in the conjunctive use model by means of a flow model made with the code AQUIVAL, which simulate transient state groundwater flow by the eigenvalues method (Pulido-Velazquez et al. 2007).

The activities carried out to develop the model can be grouped into three phases:

- Characterisation of the SB hydrological system, setting and describing the different elements to be considered, available resources (surface water, groundwater and alternative resources), demands to be met and current hydraulic infrastructures.

- Once the integrated management model was set up with SIMGES, the current management scenario was calibrated and simulated for the historical period.

- The generated future CC scenarios were applied to the model to analyse the impacts on the different elements of the hydrological management system (aquifers, satisfaction of demands, river flows…), with special focus on drought propagation.

Different types of water resources such as groundwater, surface water, external water transfer from Tagus basin (Central Spain) and unconventional resources (wastewater reuse and desalination) have been considered in the model. The system integrates a network of reservoirs and canals in order to regulate and distribute such resources and meet the different demands. The simplified topologic scheme of the lower part of the system shows such complexity (see Fig. 3.7).

A total of 60 GW bodies are included in the Segura Basin integrated management model, with a complex geology and different lithologies such detrital as carbonate and mixed (see Fig. 3.2). Special attention has been paid to the Middle-Lower Segura Plain, a Plioquaternary aquifer located in the lower part of the basin partially connected to the sea, which concentrates most of the urban and agricultural water demands of the system.

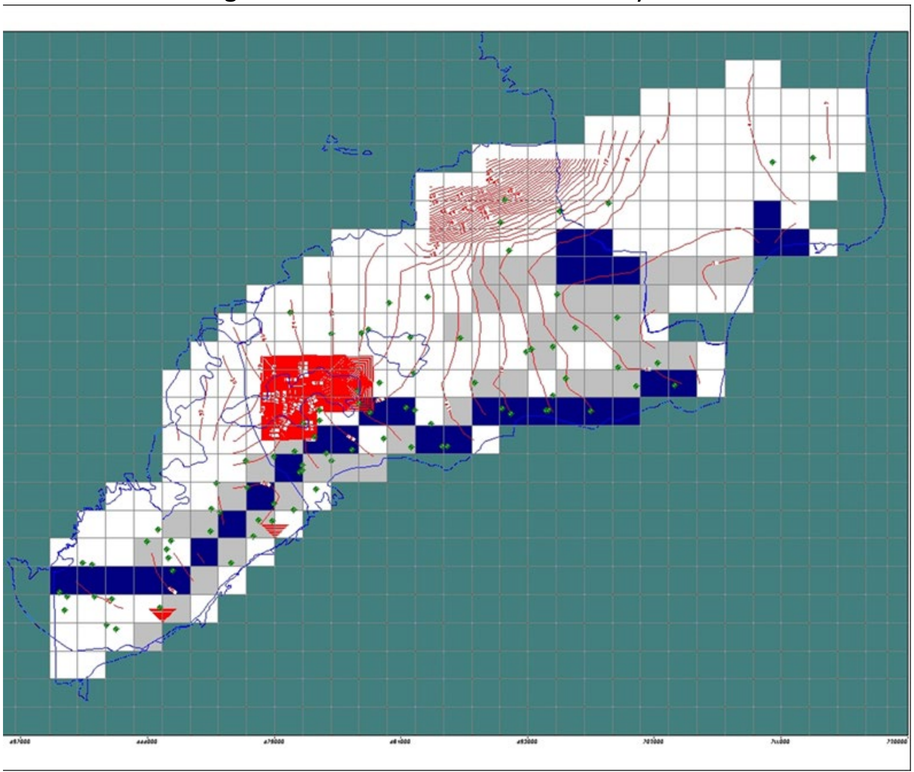


Figure 4.1. Discretization of the Segura alluvial plain aquifer

The basin has been divided into 11 subbasins for different Segura reaches and tributaries: Guardamar, Beniel, Contraparada, Paso de los Carros, Puentes, Baños de Mula, Cenajo, Camarillas, Alfonso_XIII, Argos and Archena. A rainfall-runoff model (Témez) has been developed to calculate river flow series for the subbasins.

Figure 4.2. River subbasins and gauge stations to calibrate TEMEZ model.

A total of 103 demand elements have been included in the model considering urban, industrial, agricultural, environmental and golf demands. Irrigation areas corresponding to agricultural demands are shown in figure 3.6.

Table 4.2. Total annual demands by uses (Mm3)

Urban	Agricultural	Environmental	Industrial	Golf
244.31	1582.38	273.36	10.79	6.20

Surface water regulation infrastructure has also been considered. 15 reservoirs have been included in the model.

4.2.2 Model calibration

The integrated model has been calibrated with a total of 70 gauge stations (Fig. 4.2) for the surface water flow (Temez rainfall-runoff model) and 82 observation wells for the Vega Media-Baja del Segura aquifer (Fig. 4.3).

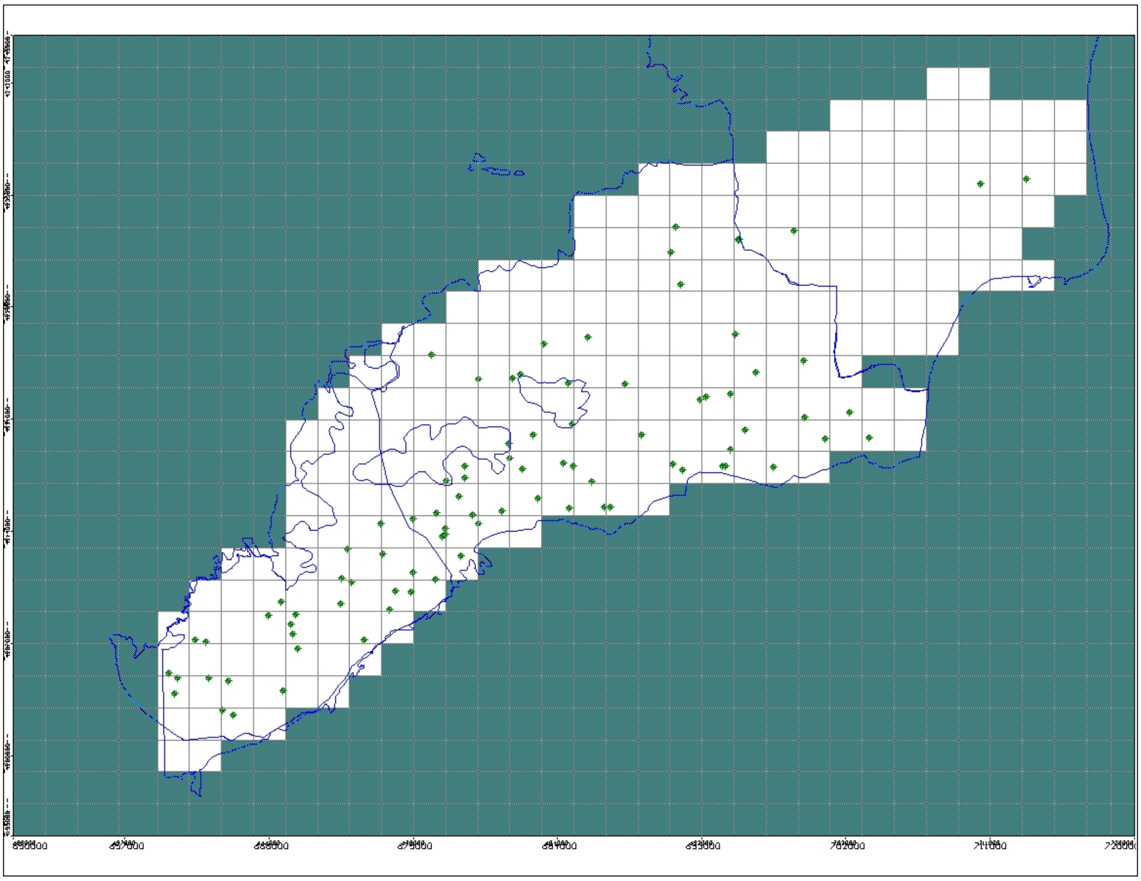


Figure 4.3. Observation wells in Vega Media-Baja del Segura aquifer.

The calibration period was 1994-2010 for the groundwater flow model of Vega Media-Baja del Segura aquifer and 1972-2001 for the rainfall-runoff model of the basin.

Fog 4.4 shows the simulated pezometric levels for September-2010 in Vega Media-Baja del Segura aquifer.

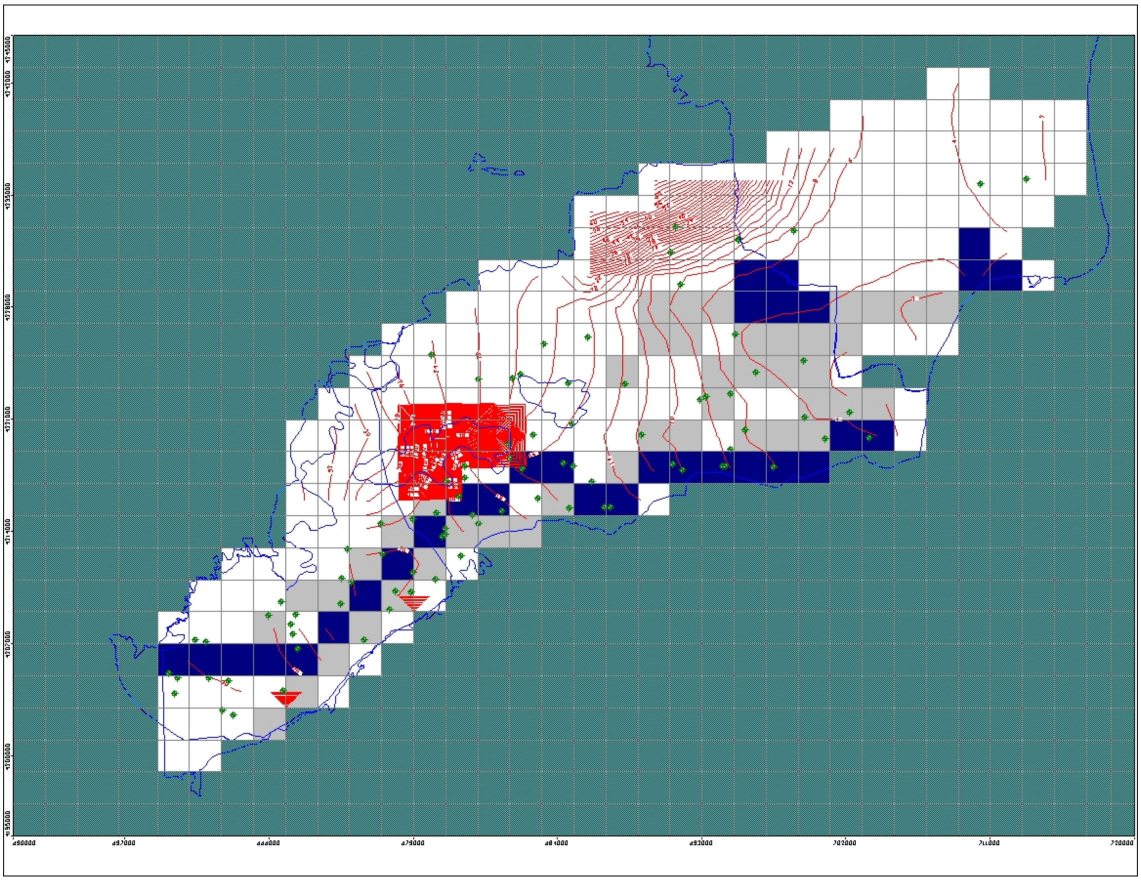


Figure 4.4. Calculated piezometric levels for sep-2010 in Vega Media-Baja del Segura aquifer.

4.3 Assessment of droughts and their propagation

In order to assess meteorological, agricultural and hydrological droughts we will employ the next series of inputs and outputs of the hydrological models: precipitation, humidity and streamflow. The operational drought was assessed by considering a “demand satisfaction index”, which is obtained for each month dividing the total supply by the total demand.

The first step needed to assess droughts from the series of outputs of the model is to aggregate them at a yearly scale for each proposed spatial homogeneous units. For all these aggregated series of results (precipitation, humidity, streamflow, and satisfaction indices) we propose to apply the same statistical procedure, the standard precipitation index (SPI), in order to identify and assess the main statistical properties (duration, magnitude or intensity) of the different types of drought in each spatial unit. Note that the probability of occurrence of precipitation for the SPI calculation, in the control and future simulations, was obtained using parameters calibrated from the observed series, in order to perform an appropriate comparison. From the SPI series, the statistics (number of droughts, duration, magnitude and intensity) were obtained by applying run theory

We also studied the temporal correlation of different kinds of drought assuming different time lags. We intend to identify which is the time lag that provides the best correlation between the meteorological drought and the other types of droughts (agricultural, hydrological and

operational). It allows us to estimate the inertial or time lags between each type of droughts and the meteorological ones.
We also propose to perform a sensitivity analyses to the spatial scale, assessing droughts and temporal correlations also for the whole basin that integrates different homogeneous units.

5 RESULTS AND CONCLUSIONS

5.1 Results based on the integrated hydrological modelling

Once the model was calibrated, the generated future series (P, T) of four climatic scenarios for the period 2071-2100 were applied. Results were obtained for the whole Segura Basin system in terms of lower resources available to meet the different demand elements, which means higher deficits for that demands.

Results were also obtained and analysed with a monthly step on water volumes stored in reservoirs and aquifers, river flows, piezometric levels in Vega Media-Baja aquifer, pumpings, demands and supplies. Propagation of drought events were also analysed for the four future scenarios. All these results were aggregated by subbasins to be analysed.

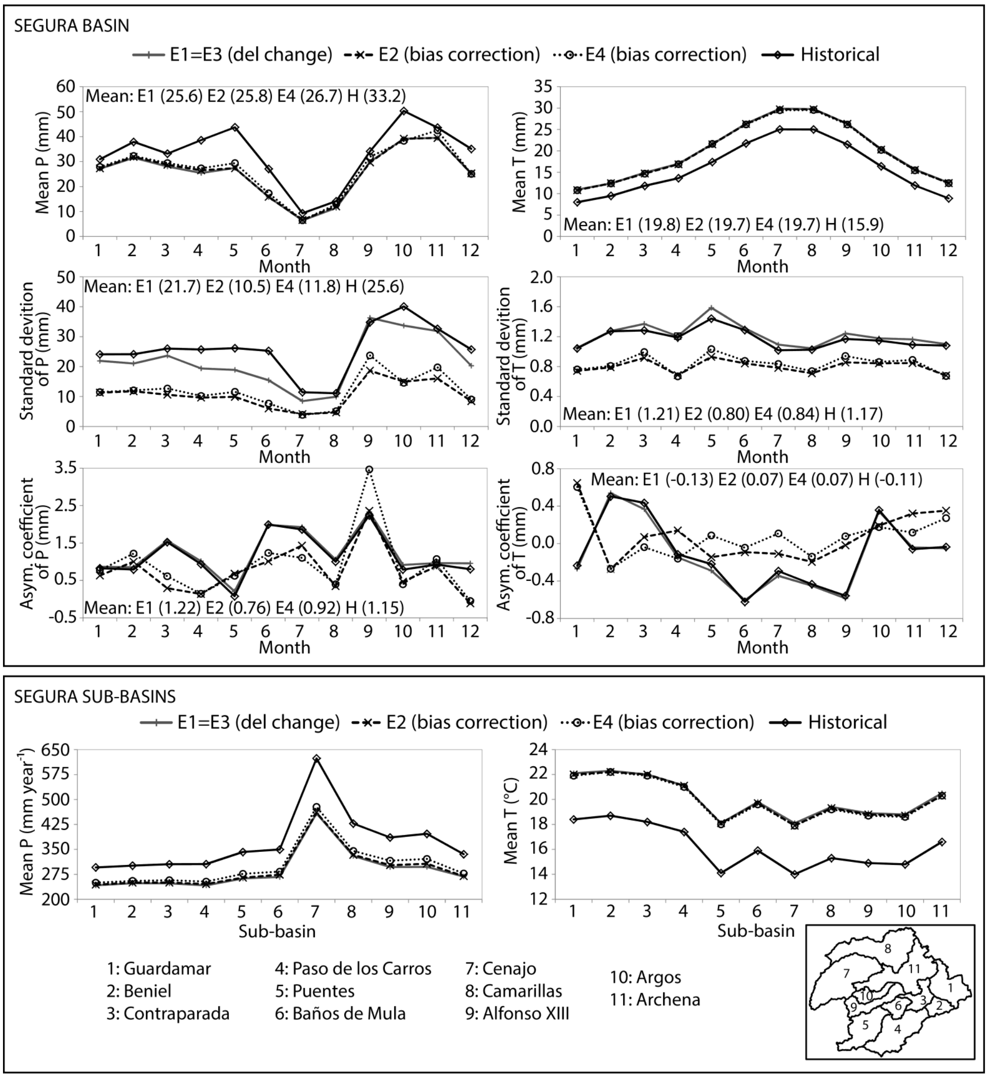


Figure 5.1. Future P and T series for the four ensembles

Statistics of precipitation and temperature for the four scenarios (E1 to E4) are shown in figure 5.1. Main statistics on runoff and demands are also reflected for these four scenarios and compared to historical data (Fig. 5.2) both for the whole Segura Basin and for the subbasins.

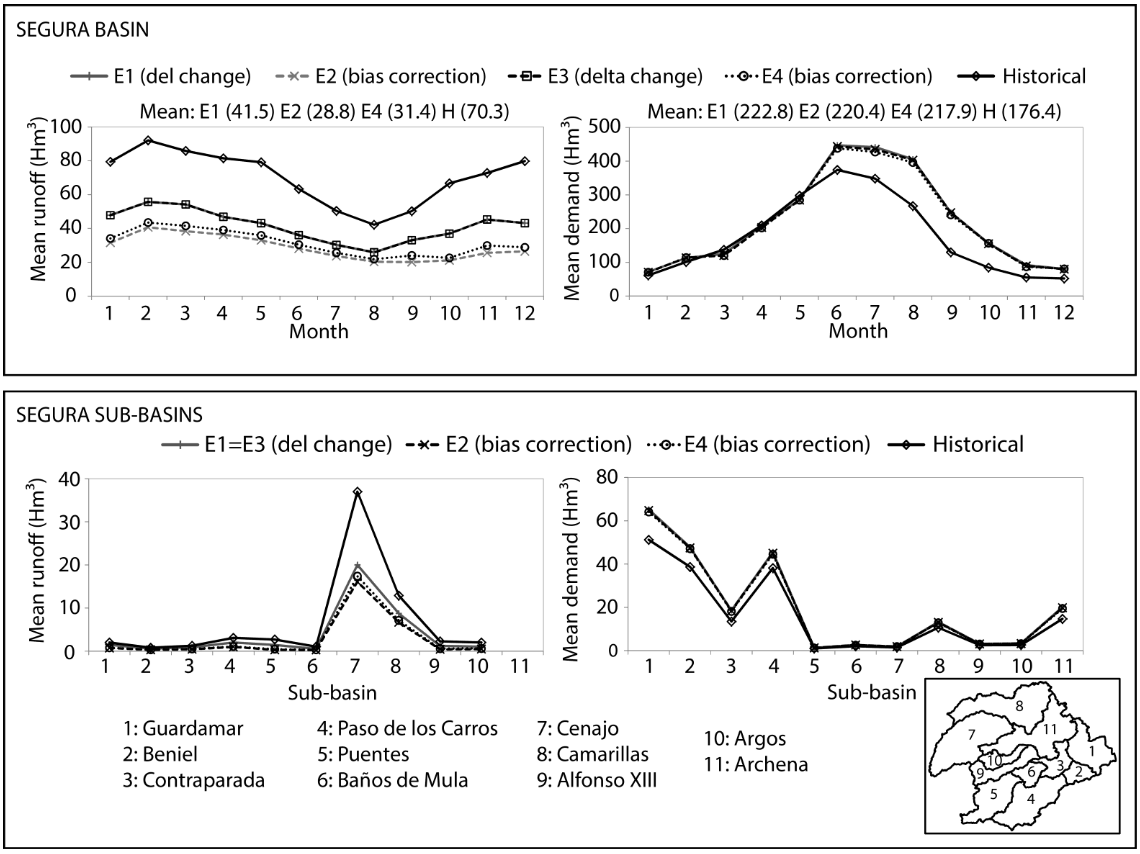


Figure 5.2. Runoff and demand for the four scenarios

A summary of results respect to guarantees of satisfaction of demands are reflected in table 5.1. Once again, these results are aggregated for the whole Segura Basin and the different subbasins. We can observe how guarantees are estimated to decrease significantly for the three future scenarios. The worst scenario is E2 with more than 21% of reduction of guarantee for the whole basin.

Table 5.1. Mean monthly volumetric guarantees (supply/demand)

Basin-Subbasin \ Scenario	Historical	E1=E3	E2	E4
Total Basin	**96.25%**	**77.61%**	**75.02%**	**76.04%**
S. 1 Guardamar	99.58%	86.28%	86.02%	86.59%
S. 2 Beniel	98.89%	92.32%	91.52%	92.10%
S. 3 Contraparada	95.83%	62.87%	55.40%	56.95%
S. 4 Paso de los Carros	90.36%	66.35%	63.84%	65.15%
S. 5 Puentes	70.35%	55.79%	51.30%	52.69%

S. 6 Baños de Mula	83.46%	67.20%	66.19%	66.71%
S. 7 Cenajo	95.36%	62.48%	56.58%	59.35%
S. 8 Camarillas	96.35%	67.98%	61.61%	63.09%
S. 9 Alfonso_XIII	95.55%	68.07%	64.66%	66.17%
S. 10 Argos	83.46%	52.71%	47.20%	48.90%
S. 11 Archena	96.23%	73.25%	68.26%	69.50%

Future CC scenarios would also have a negative impact in aquifers according to the results obtained on groundwater pumpings (table 5.2). For the worst scenario (E2) there would be an increase of 275 Mm3 in groundwater exploitation for the whole basin.

Table 5.2. Mean annual pumping in aquifers (Mm3)

Basin-Subbasin \ Scenario	Historical	E1	E2	E4
Total Basin	**645.84**	**880.84**	**921.47**	**908.29**
S. 1 Guardamar	63.99	134.27	134.56	133.39
S. 2 Beniel	84.06	137.99	137.15	136.20
S. 3 Contraparada	56.42	62.48	64.12	63.45
S. 4 Paso de los Carros	126.85	126.63	127.86	127.33
S. 5 Puentes	10.41	10.53	10.53	10.53
S. 6 Baños de Mula	19.25	19.72	19.77	19.70
S. 7 Cenajo	0.00	0.00	0.00	0.00
S. 8 Camarillas	41.26	59.11	64.33	63.32
S. 9 Alfonso_XIII	3.33	3.73	3.83	3.76
S. 10 Argos	51.33	71.91	80.10	77.75
S. 11 Archena	188.96	254.48	279.22	272.86

Finally figures 5.3, 5.4, 5.5 and 5.6 show a summary of results obtained for the propagation of droughts according to different parameters: meteorological, agricultural, hydrological and operational respectively. These results are showed for the different Segura basins and homogeneous areas. We observe important increases of the number of droughts and its duration, magnitude and intensity for the period 2071-2100 with respect the historical period for the different series studied (precipitation, humidity, streamflow and demand satisfaction index).

We also studied the correlation between the different types of droughts (Figure 5.7). Meteorological droughts show a good correlation with hydrological and operational droughts. The maximum correlations are reached for different gaps in each case. In the case of hydrological the maximum correlation is obtained without gap and in the case of operational the gap is 3-4 months.

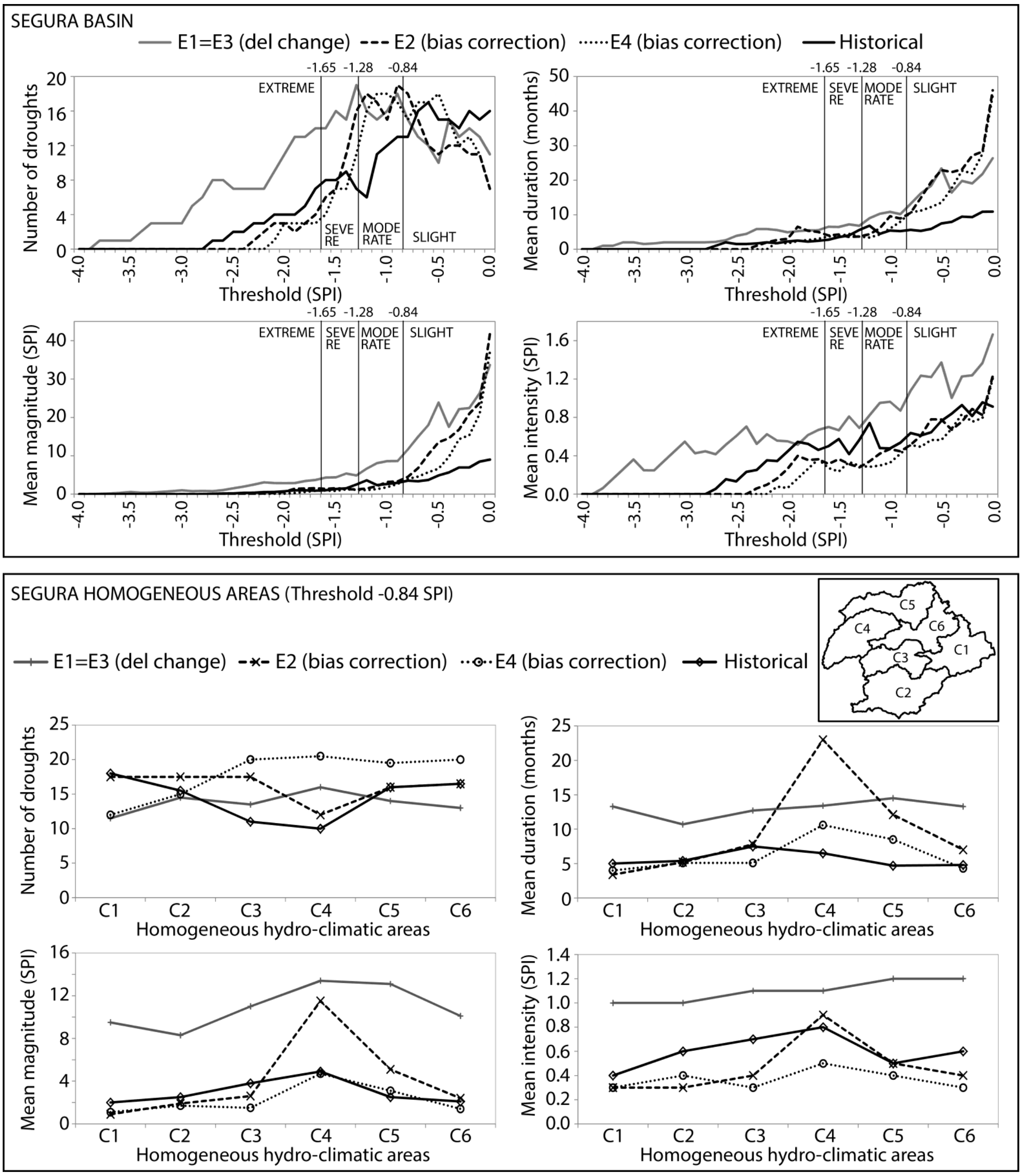


Figure 5.3. Statistics of meteorological droughts (Precipitation)

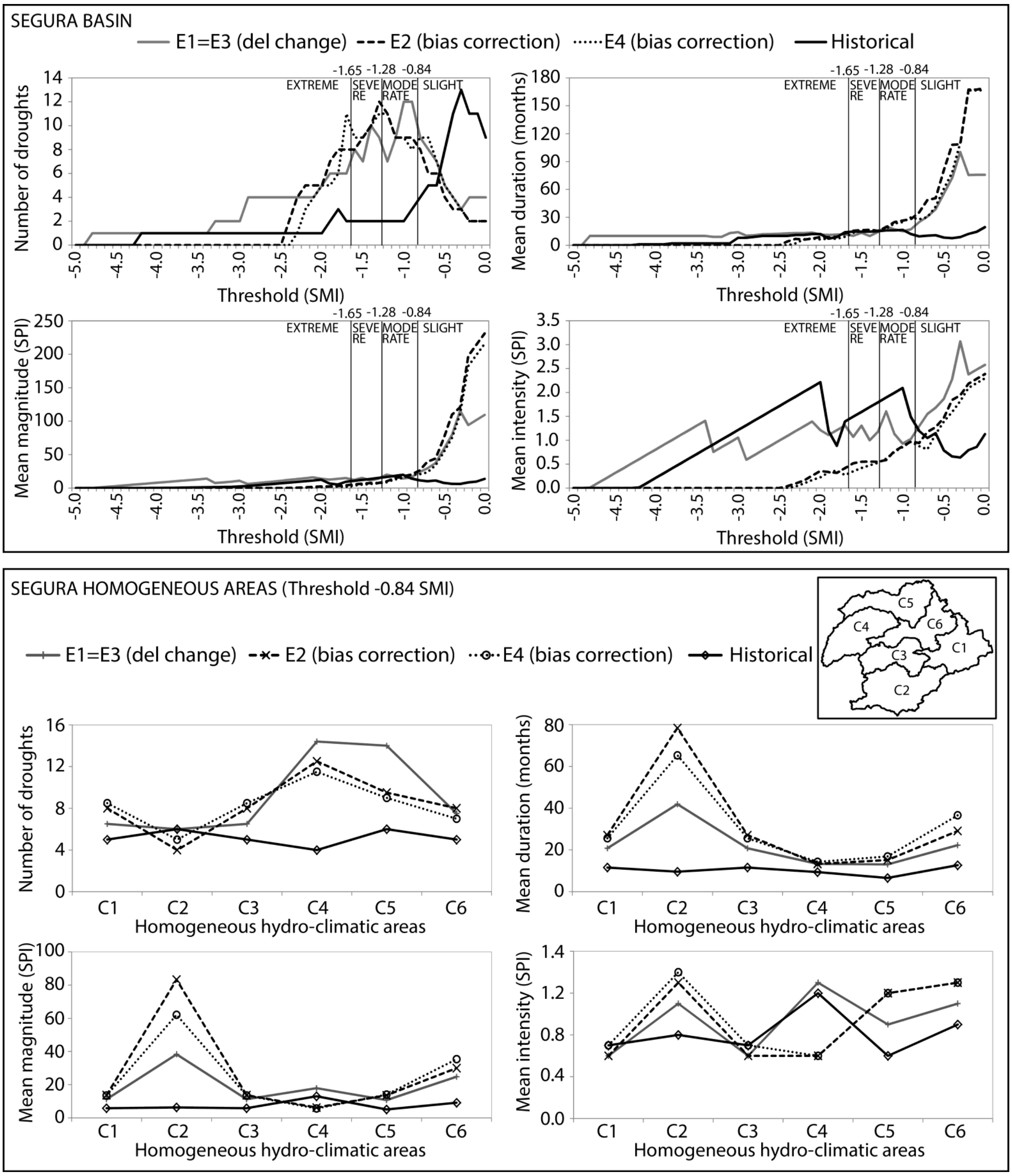


Figure 5.4. Statistics of agricultural droughts (Moisture)

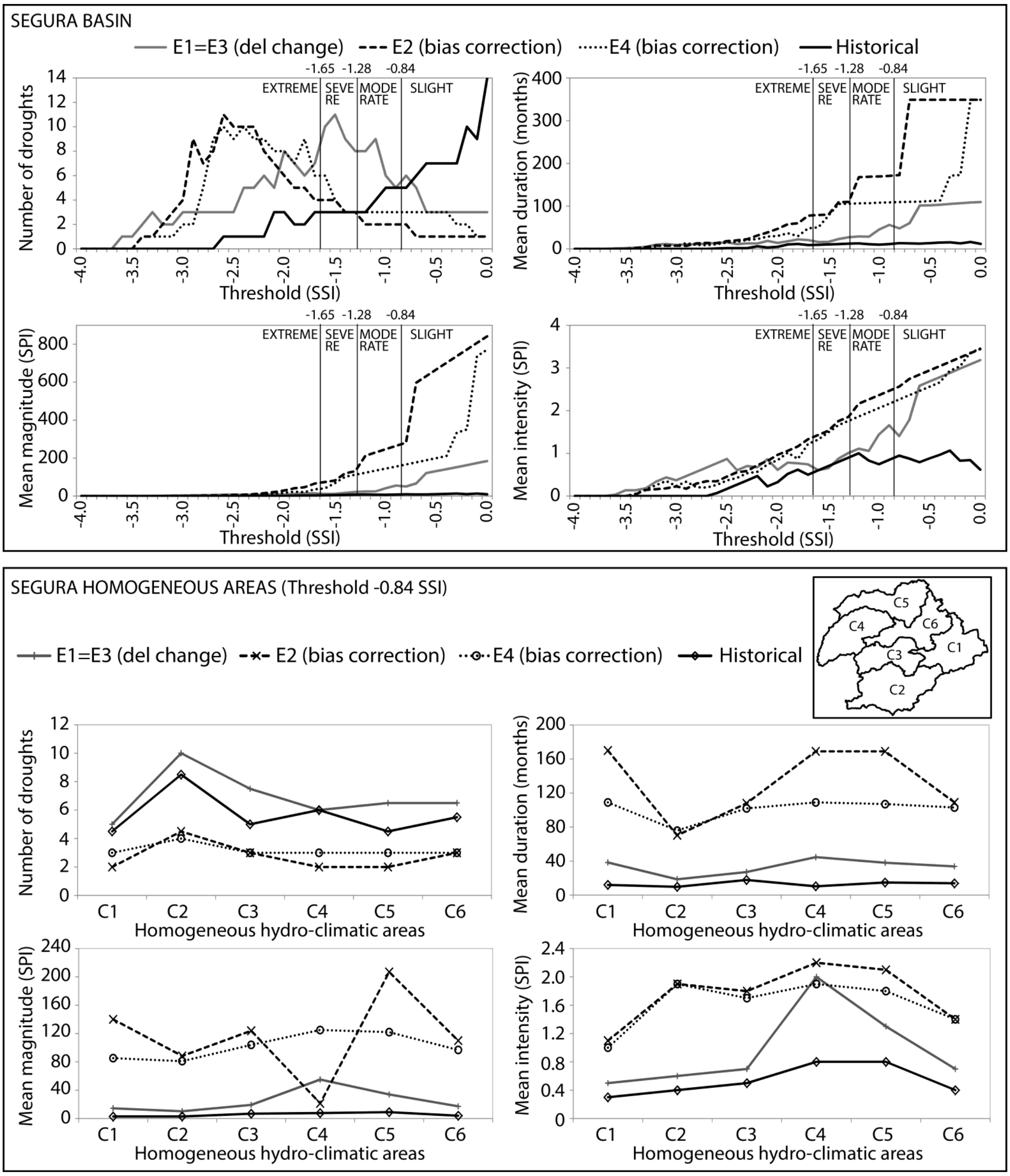


Figure 5.5. Statistics of hydrological droughts (Streamflow)

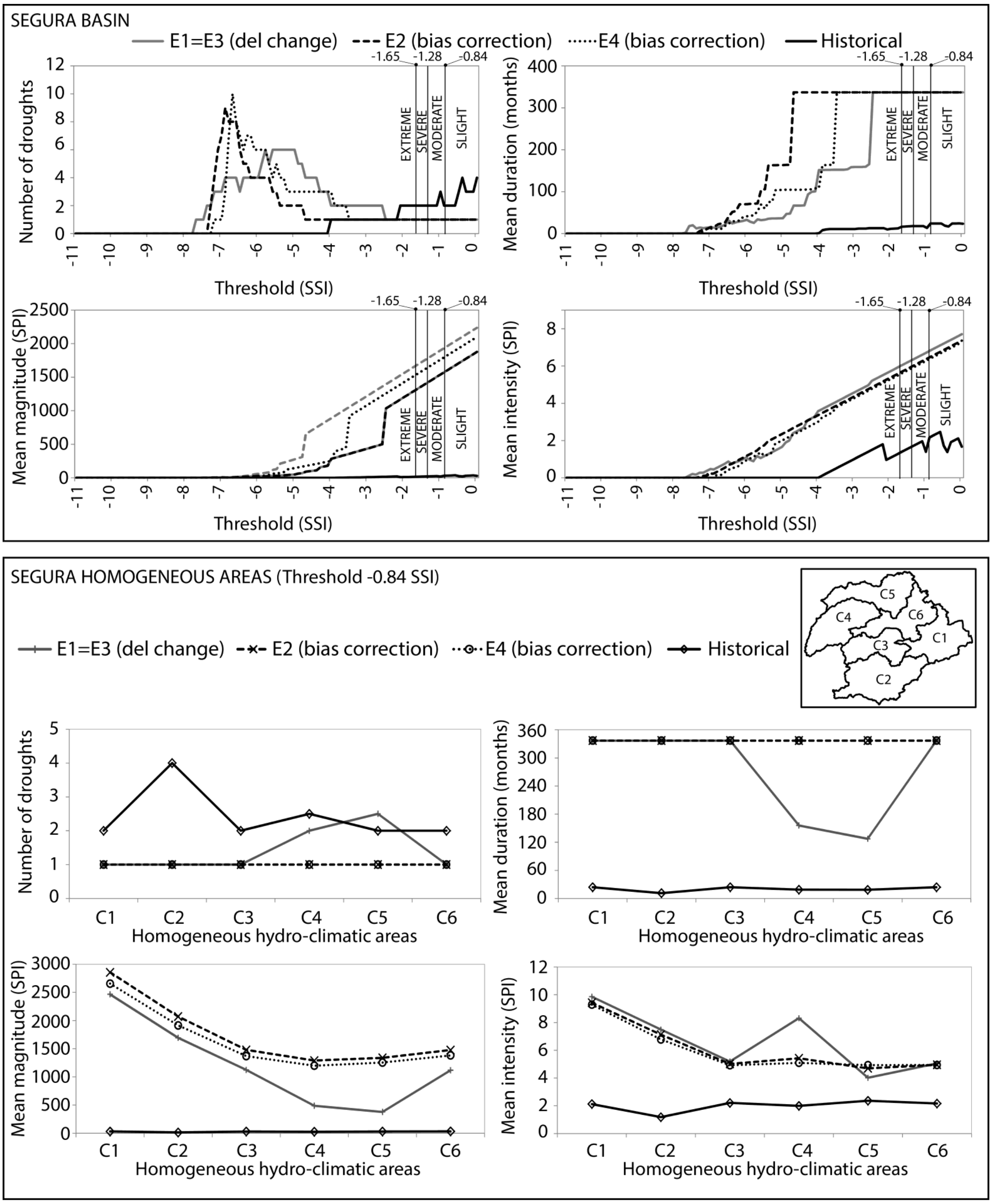


Figure 5.6. Statistics of operational droughts (Satisfaction)

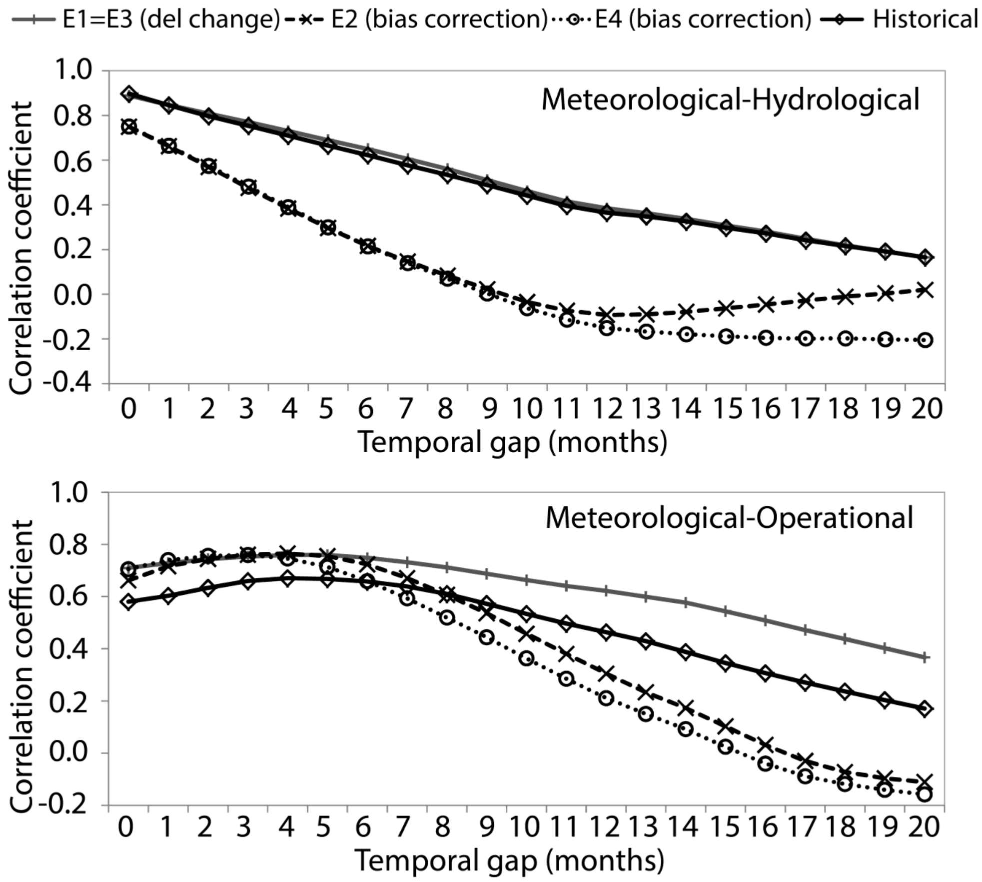


Figure 5.7. Droughts correlation

5.2 Conclusions of the assessment based on integrated hydrological modelling

This method has been applied to assess impacts of future potential climate change scenarios on the Segura Basin management system and on meteorological, agricultural, hydrological and operational droughts providing consistent pictures of monthly plausible future scenarios taking into account basic and drought statistics of the historical series and the climatic model simulations.

Results observed for the whole Segura Basin system with the four climatic scenarios for the period 2071-2100 show lower resources available to meet the different demand elements, which means higher deficits for that demands. Higher pumping rates in aquifers are estimated for future scenarios and the impacts would also be reflected on lower guarantees to meet demands. Scenario E2 has the worst impacts on the system according to this assessment.

The four studied scenarios show important reduction of precipitation and increase of temperature and large increments of the number, duration, intensity and magnitude of droughts. The study of the correlation of hydrological and meteorological droughts shows significant correlations for a gap from 0 to 2 months in E2 and E4 cases and for a gap from 0 to 6 months in historical and E1=E3 cases. However the correlation of meteorological and operational droughts shows a maximum of correlation for a gap around 4 months for all cases.

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TACTIC GROUNDWATER

GeoERA

Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

Deliverable 3.2 and 6.2

PILOT DESCRIPTION AND ASSESSMENT

Storåen-Sunds, Denmark

Authors and affiliation:

Jacob Kidmose

Geological Survey of Denmark and Greenland

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Version	*2*
Date	28/02/2021

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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

TABLE OF CONTENTS

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.

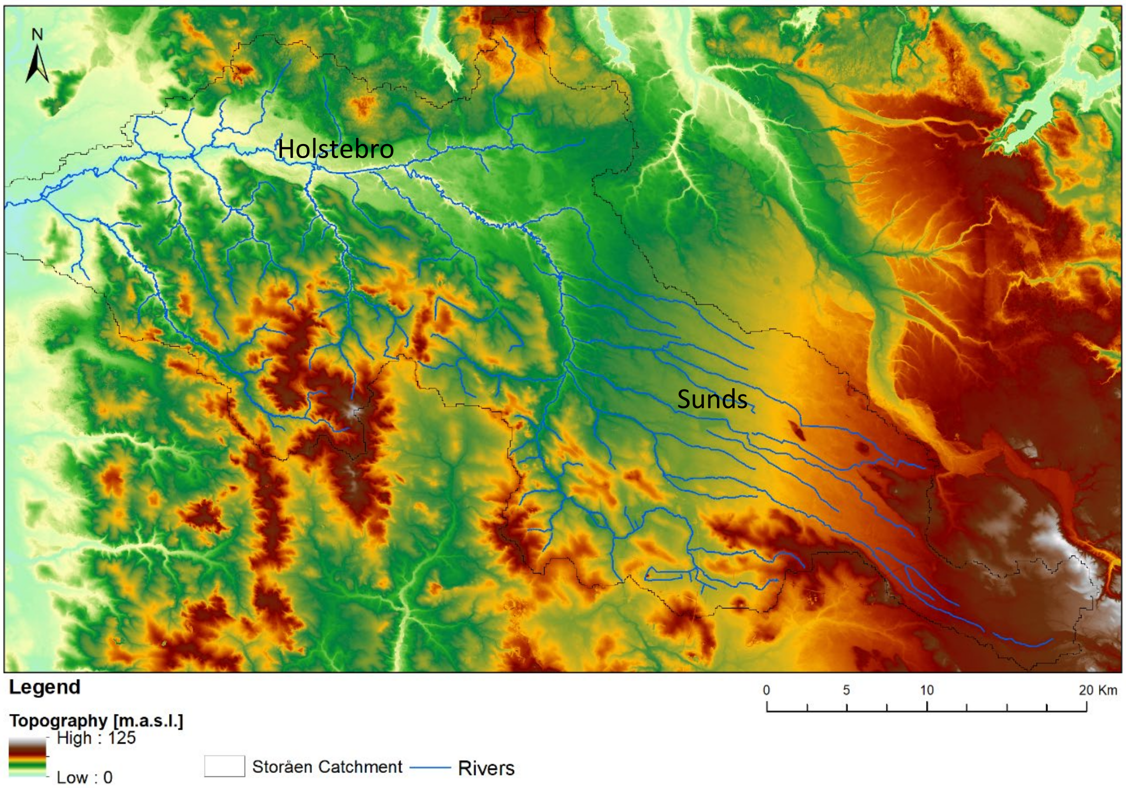

Figure 3.1 Storåen catchment. Sunds city is located in the upper part of the Storåen catchment. Topography in the Storåen catchment varies from 110 m a.s.l. (meters above sea level) to 0 m a.s.l. at Nissum Fjord, where Storåen discharges to, which is connected to the sea.

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).

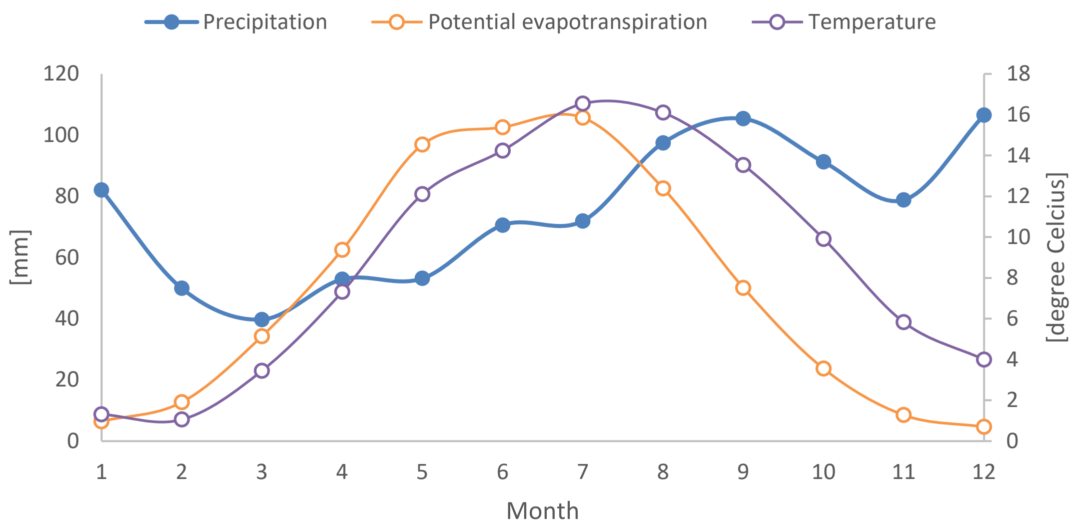

Figure 3.2 Monthly variation in precipitation, potential evapotranspiration and temperature. Average monthly values are derived from the grid-based dataset for the period of 2011-2018.

3.1.2 Area use

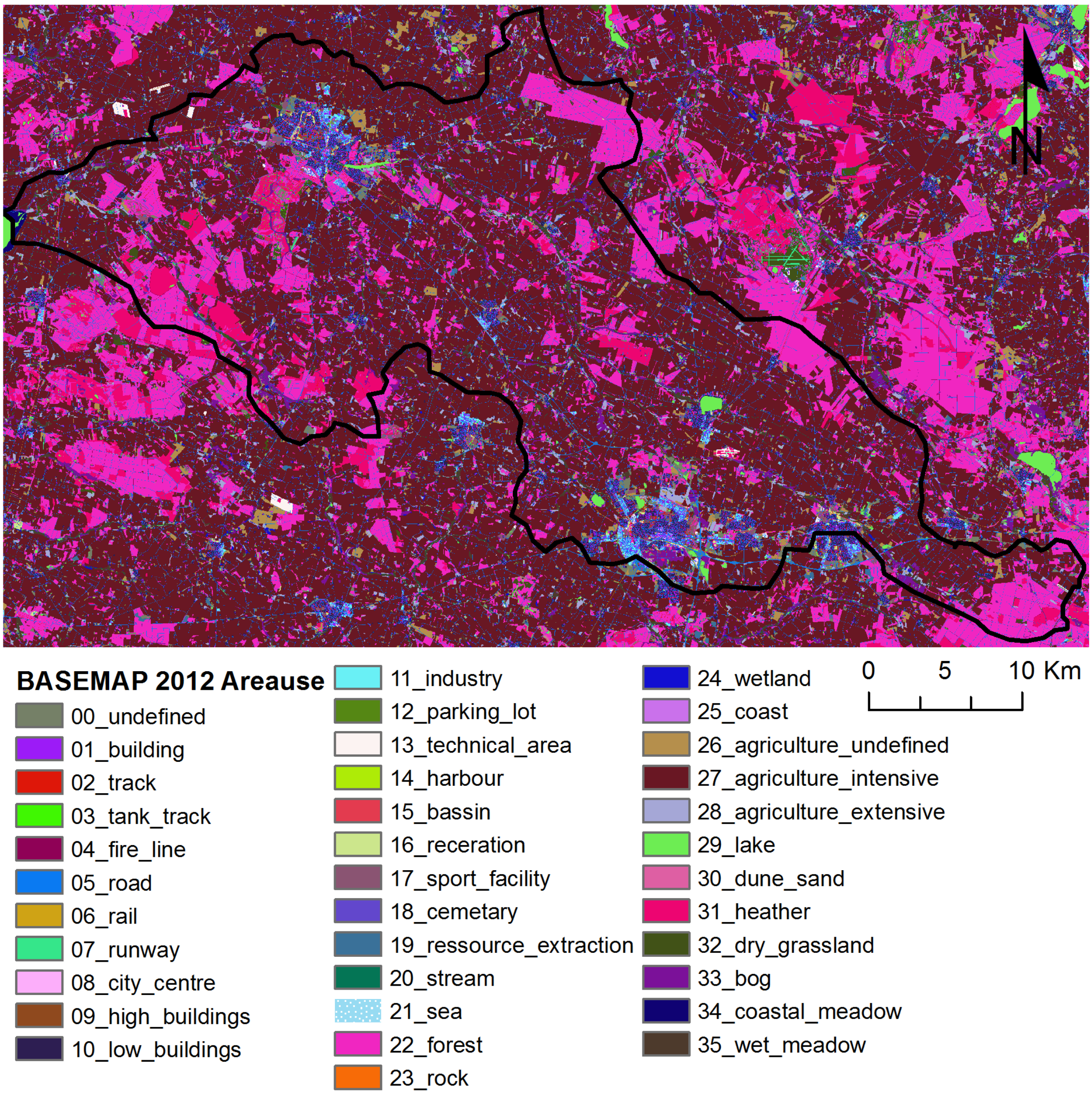

Figure 1.3 Area use in Storåen-Sunds (datasource: Danske Miljøportal 2018).

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*

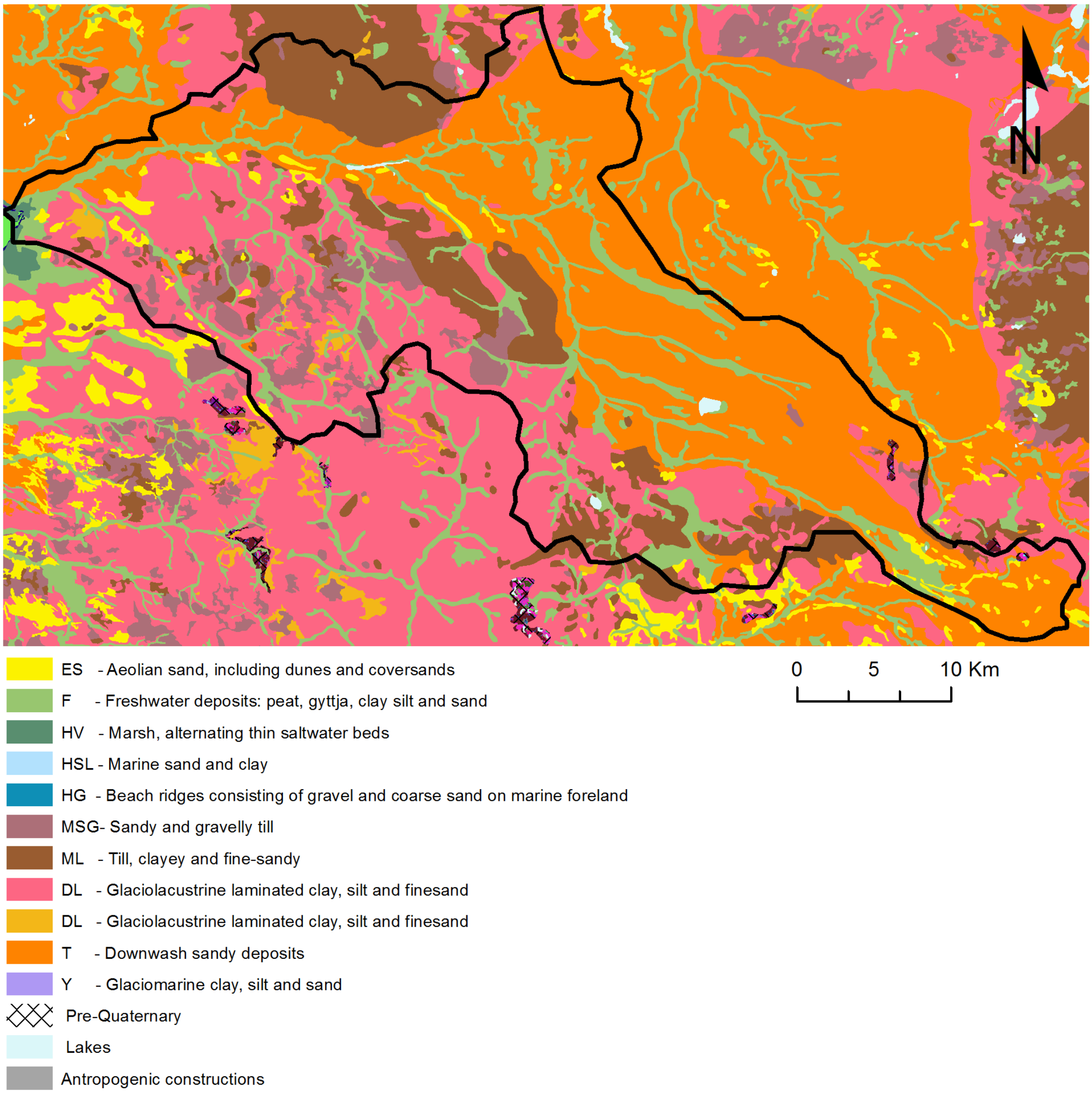

Figure 3.2 Geology at the surface (datasource: GEUS).

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.

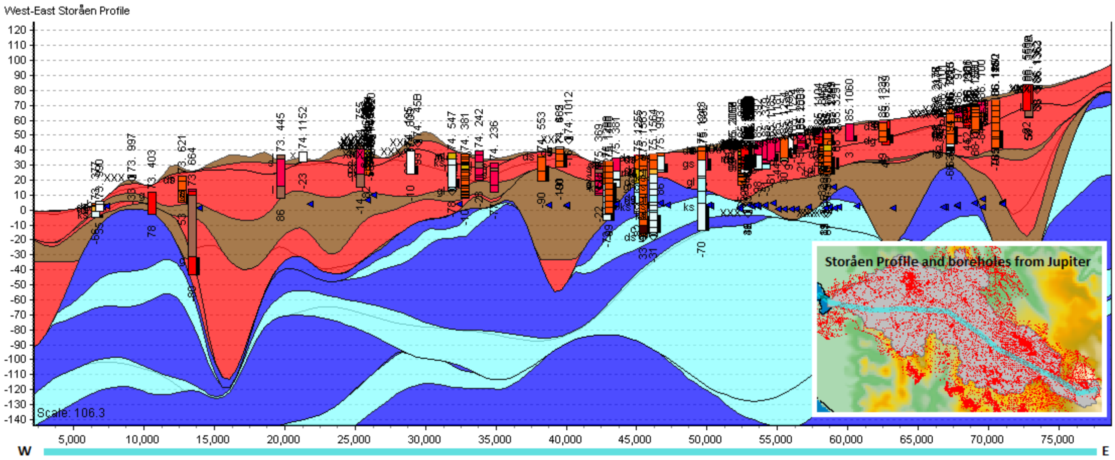

Figure 3.3 Geological profile of the Storåen catchment. Upper quaternary clays (brown), sands (red), and pre-quaternary sands (light blue) and clays (blue).

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

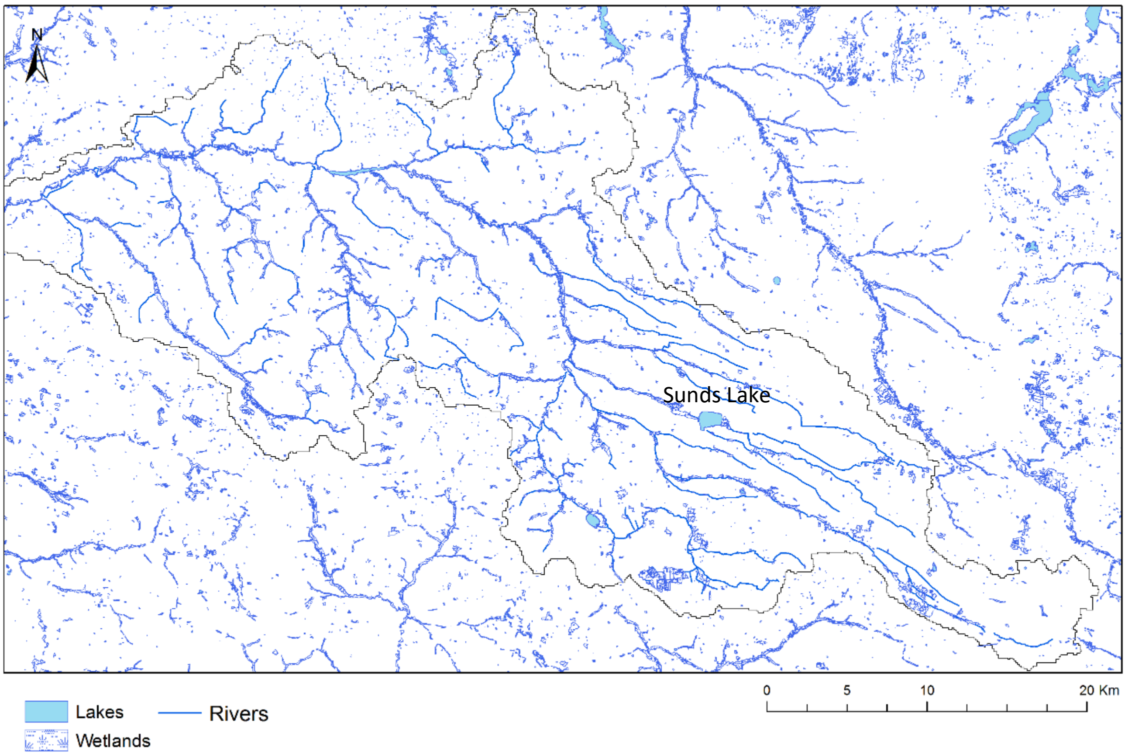

Figure 3.4 Surface waters at Storåen catchment (datasource: Dansk Miljøportal 2018).

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

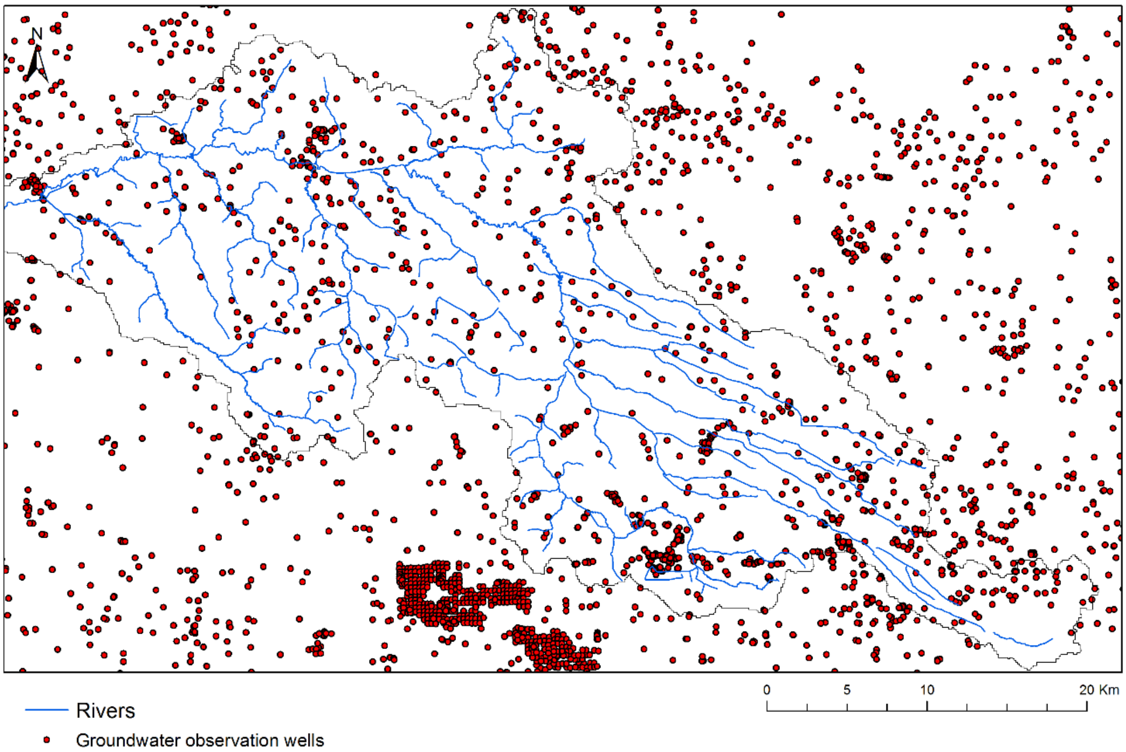

Figure 3.7 Wells with groundwater-level observations at Storåen Catchment.

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.

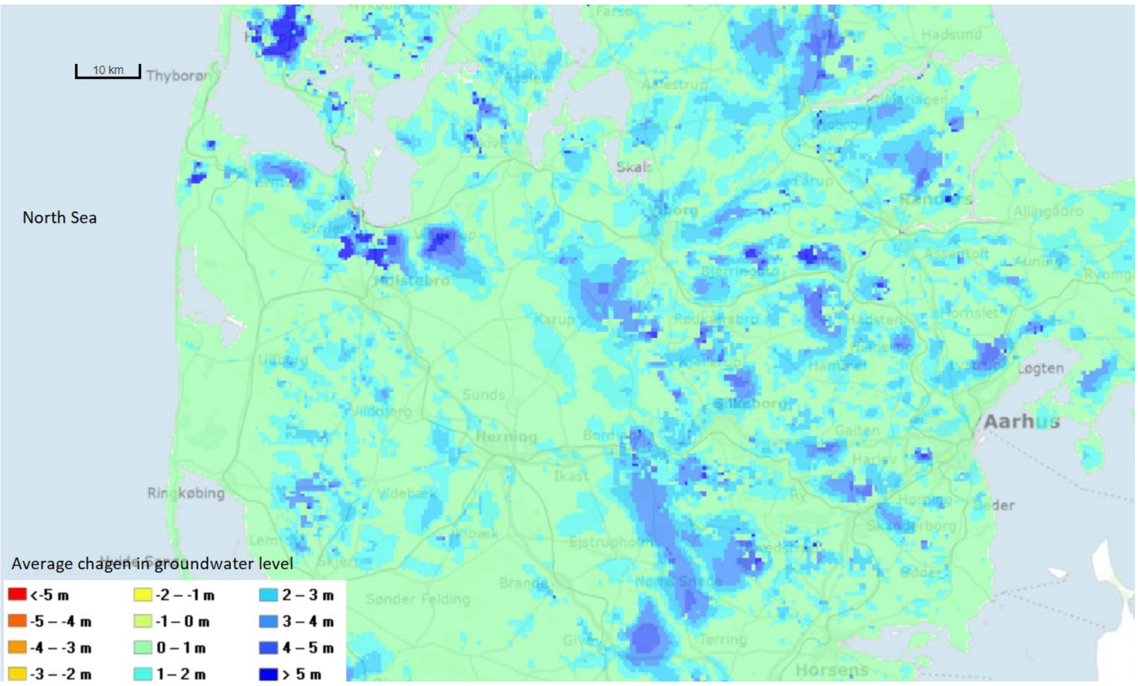

Figure 3.5 Climate change impact on groundwater. Groundwater changes between the historic period of 1961-1990 and the future period of 2021-2050. Results are shown from Central Jutland in meter of change between present and future mean groundwater table (Source: Klimatilpasning.dk 2011).

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.

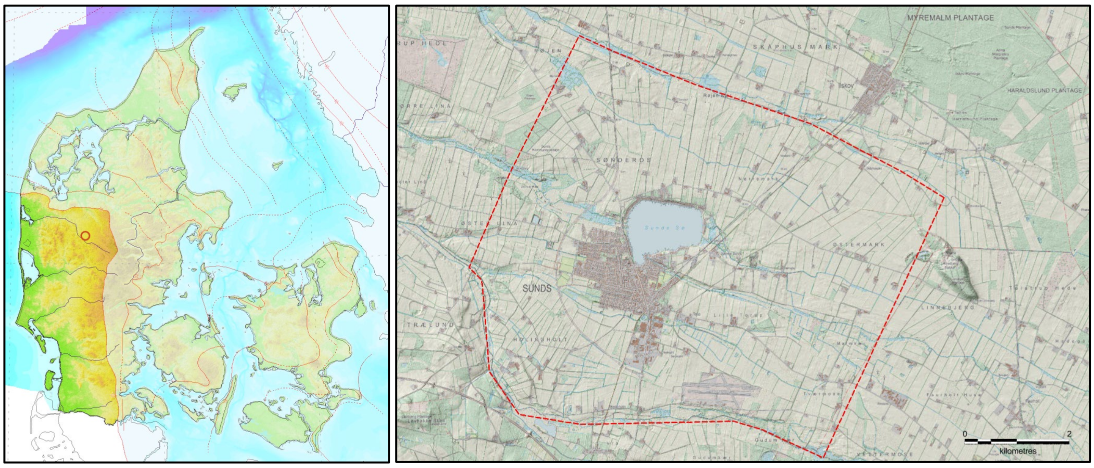

Figure 4.1 Location of Sunds in Denmark (left), and model boundary (red polygon to the right)

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.

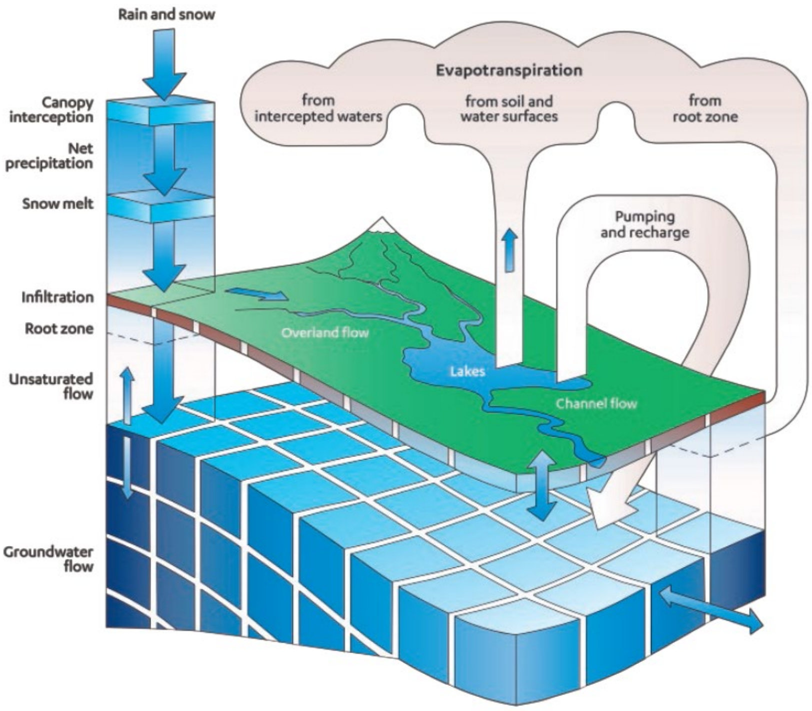

Figure 4.2 MIKE SHE model: Simulated hydrological water fluxes.

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.

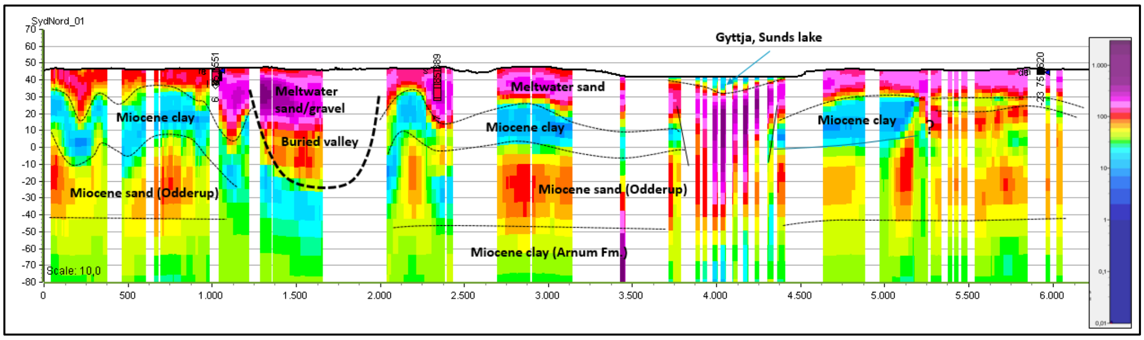

Figure 4.3 The geology of the Sunds model is based on geophysical measurements, Rasmussen et al. 2020.

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.

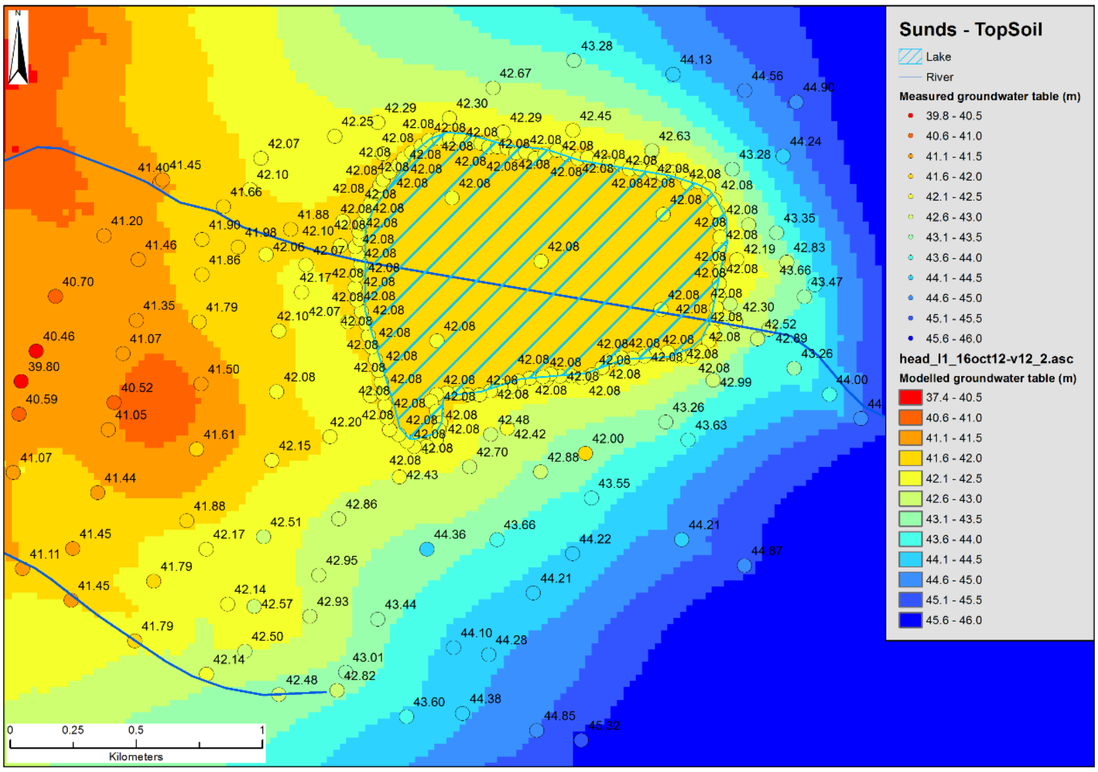

Figure 4.4 Groundwater head elevations from the calibrated hydrological model (colour contours) and the observed groundwater heads and water levels of Sunds Lake (coloured circles and numbers). Rasmussen et al. 2020.

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

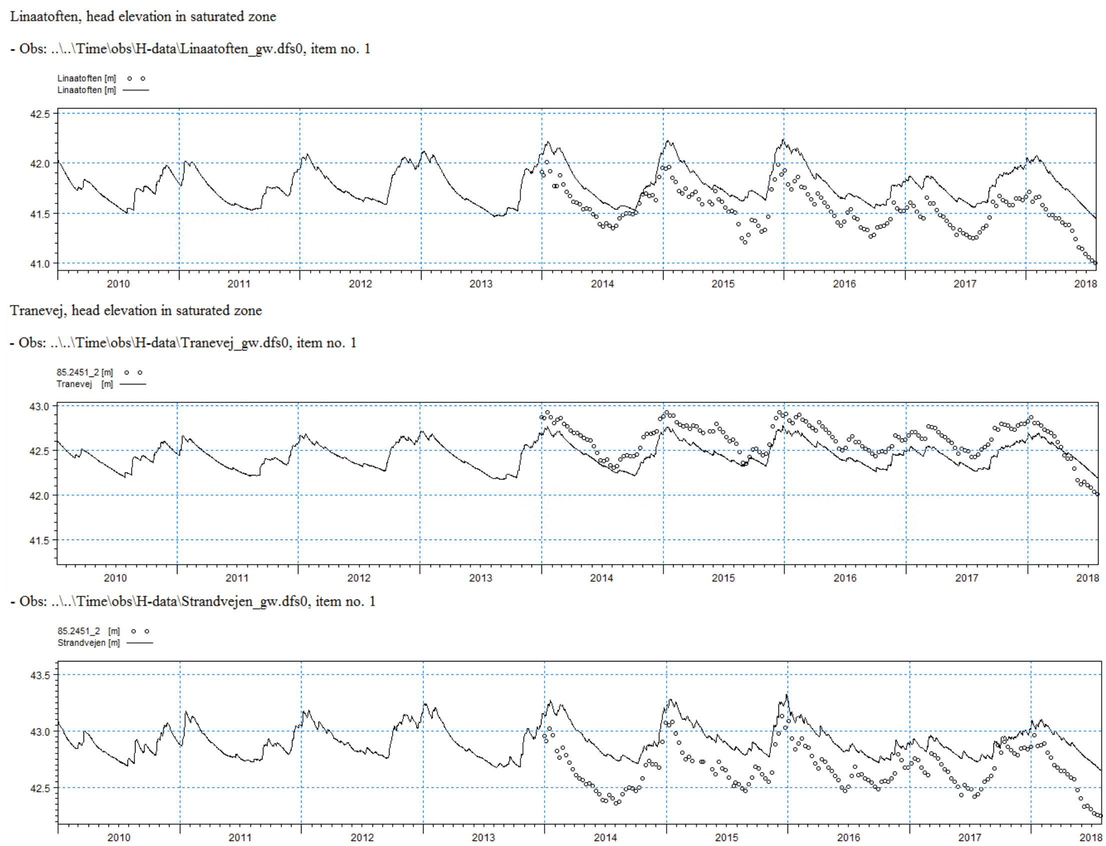

Figure 4.5. Modelled (solid lines) and observed groundwater head (circles) at station Linaatoften, Tranevej, and Strandvejen. Rasmussion et al. 2020.

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).

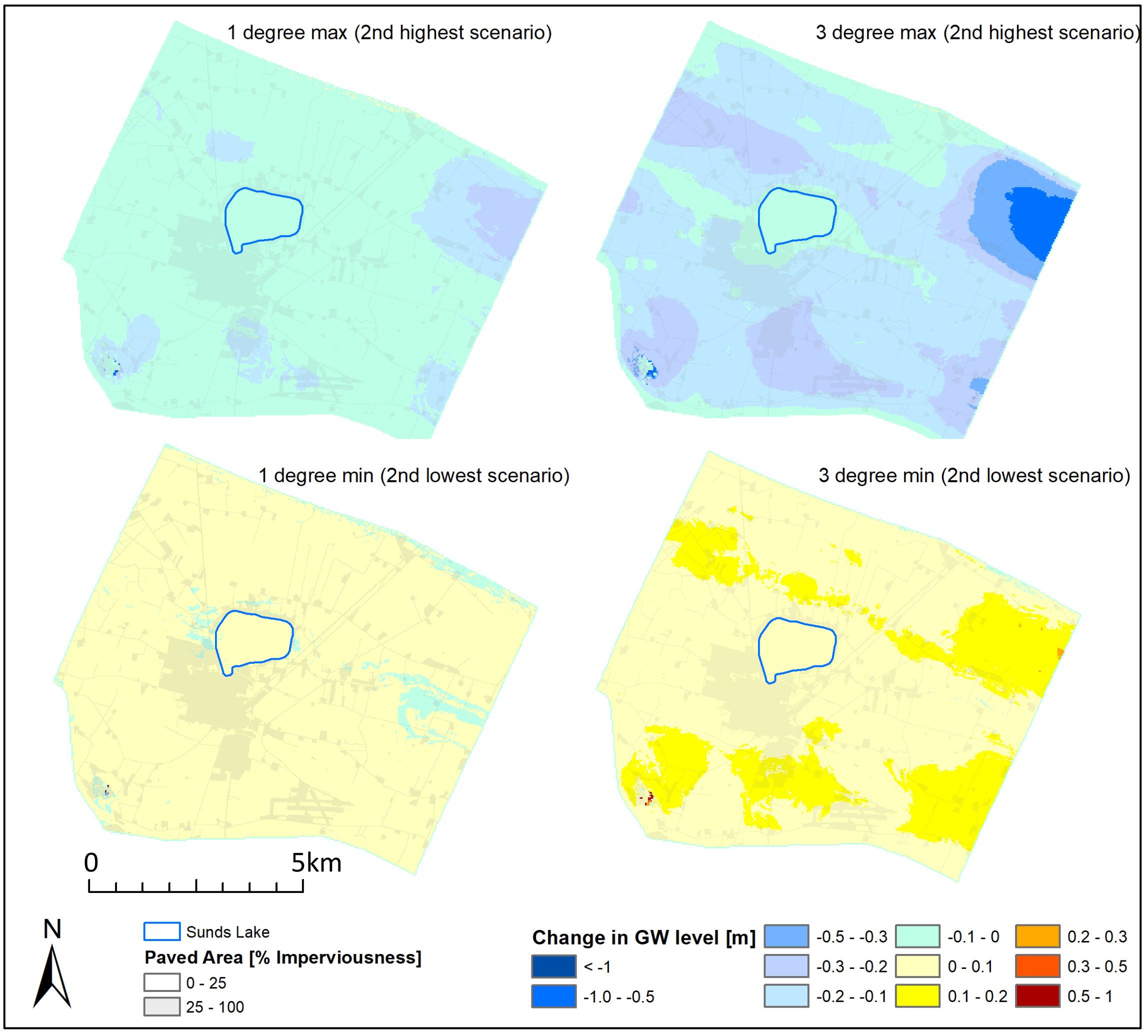

Figure 4.6 Change in groundwater levels for the four TACTIC climate change standard scenarios. The lower ones are the dry scenarios where groundwater levels mostly decrease (yellow-red colour) and the upper ones are the wet where groundwater levels increase (blue colour). Negative numbers (-) indicate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

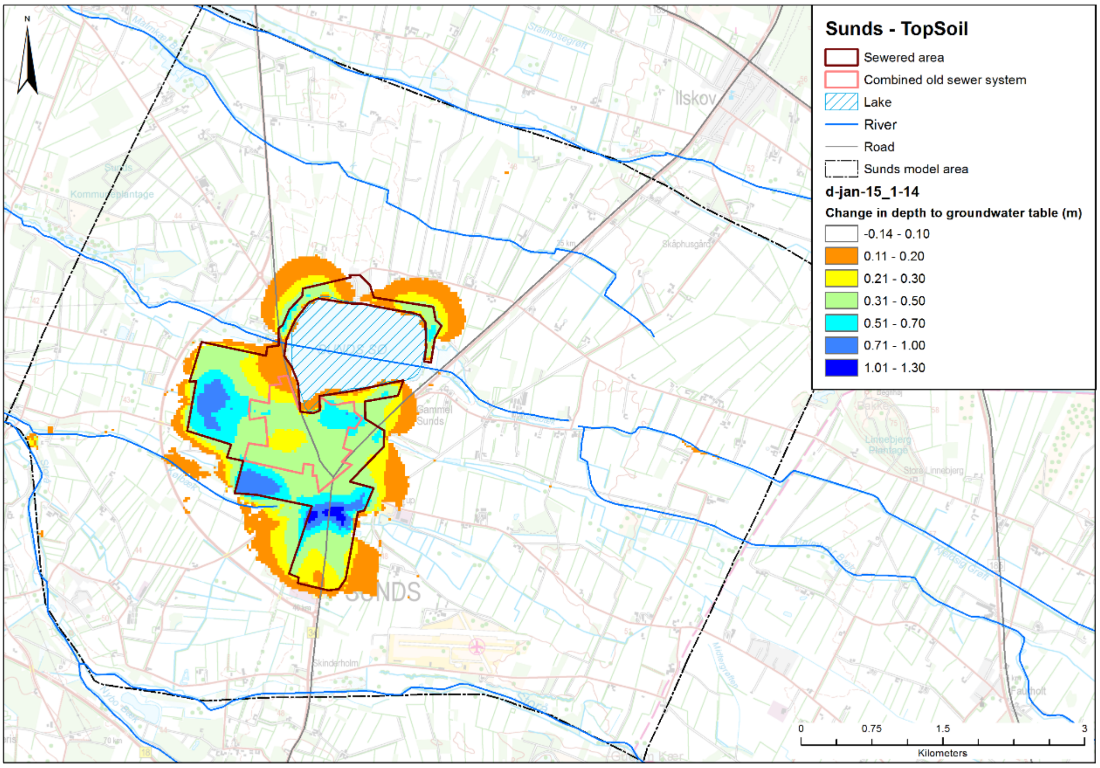

Figure 4.7 Effect on depth to groundwater table if establishing drains (3rd pipe) in the whole town. The figure shows the situation for a January situation with high groundwater table. Rasmussen et al 2020.

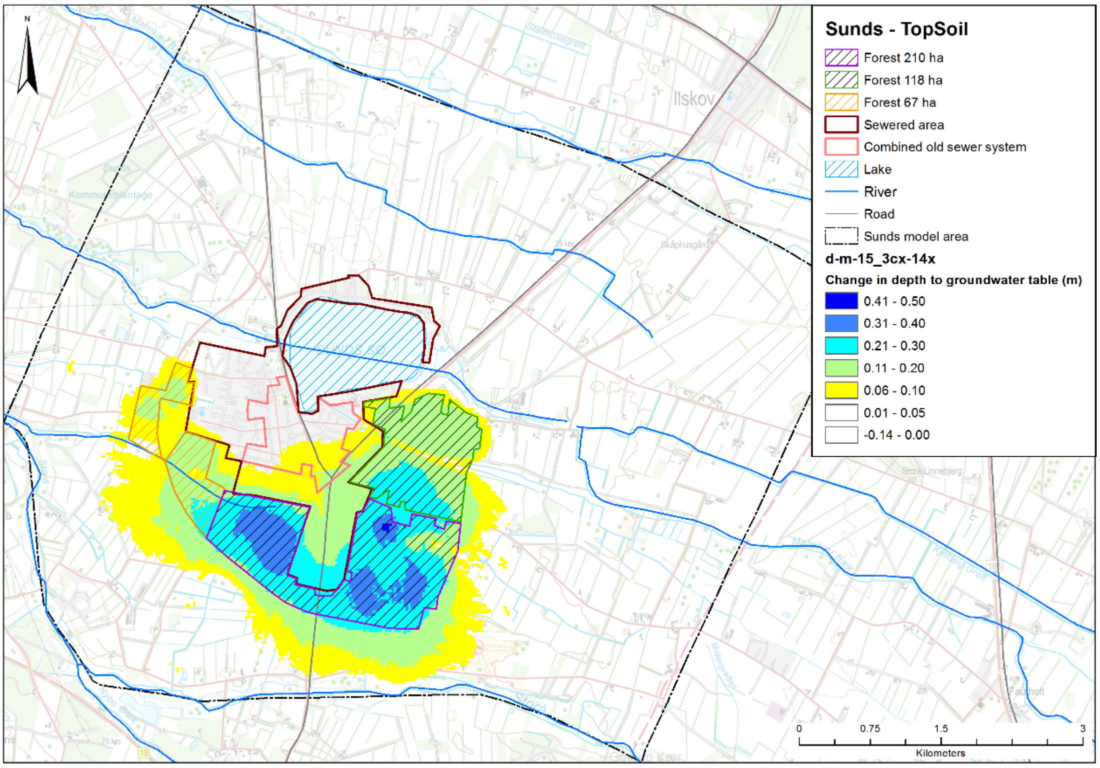

Figure 4.8 Effect on groundwater table with plantation of coniferous forest on 395 ha west, south, and east of town. Rasmussen et al 2020.

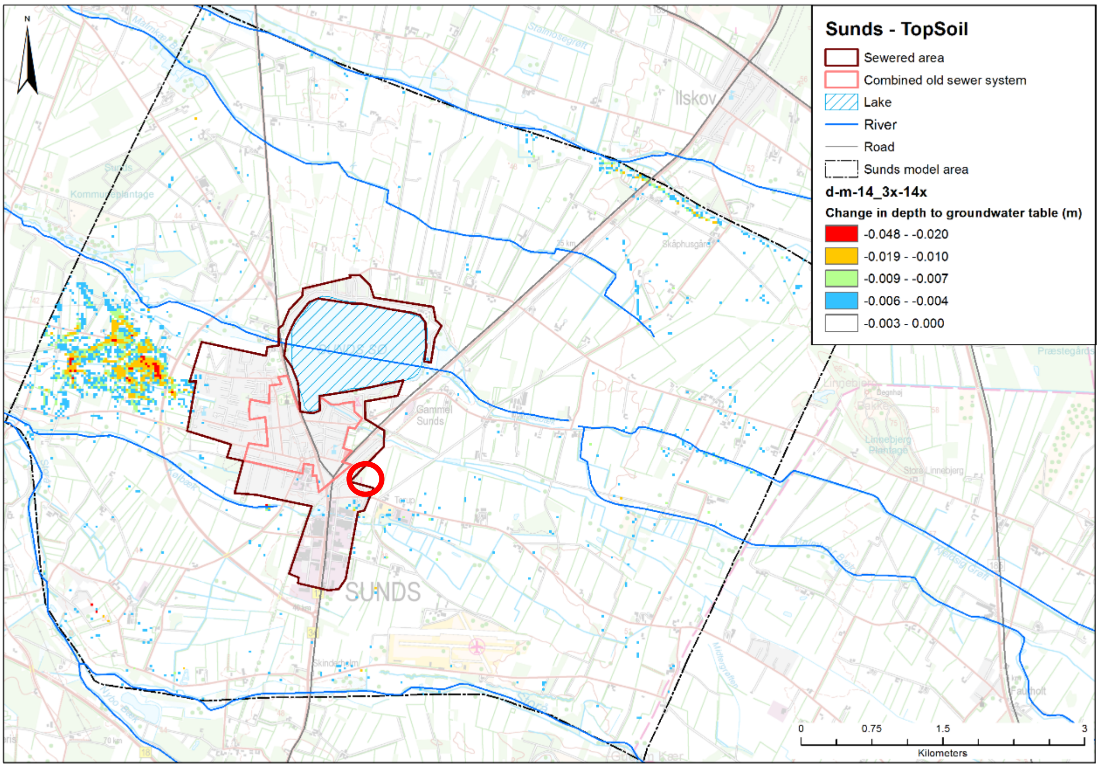

Figure 4.1 Effect on depth to groundwater table if groundwater abstraction for Sunds Waterworks stops. Minus in the numeric scale indicates a rise in groundwater table. Red circle shows the location of the waterworks wellfield. Rasmussen et al 2020.

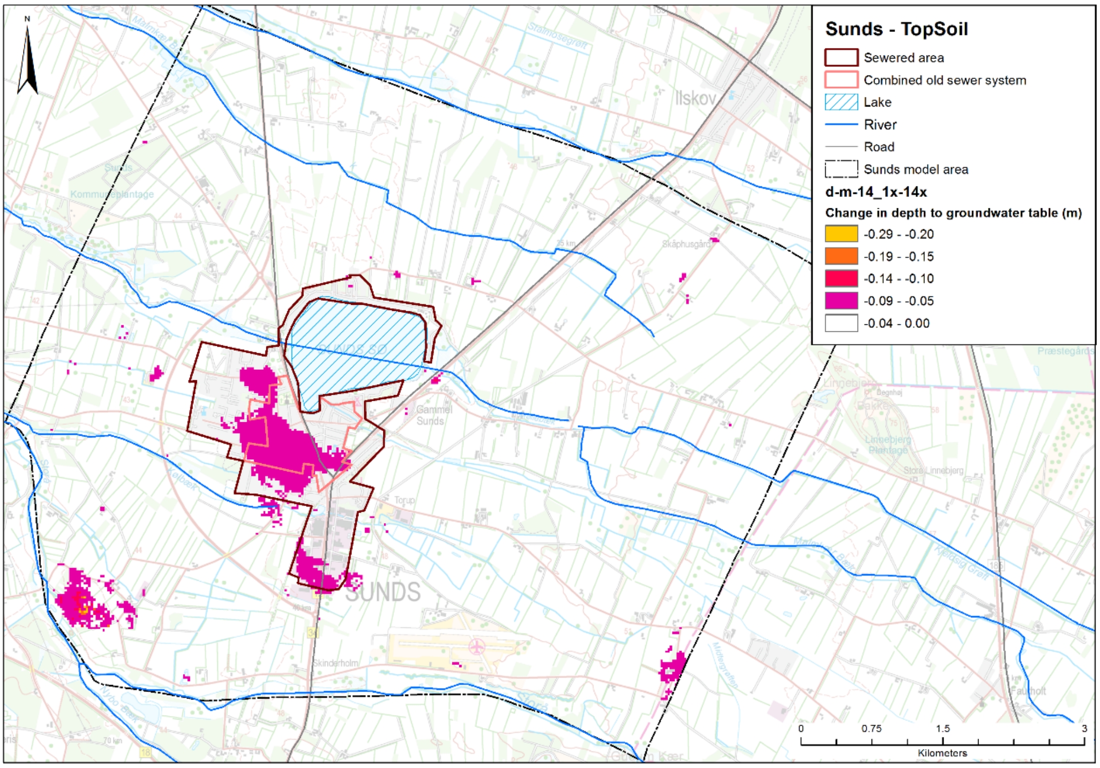

Figure 4.10 Change in depth to groundwater for the scenario with an increase of local rainwater infiltration in the whole town from 25% to 50%. Rasmussen et al 2020.

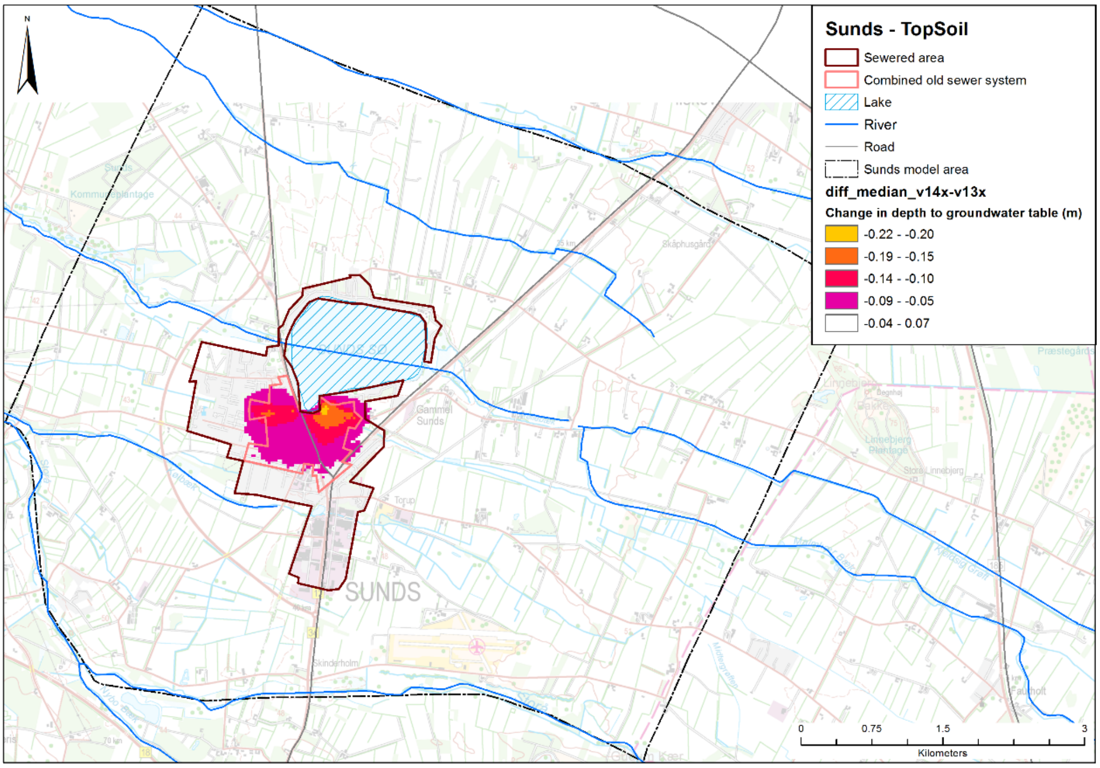

Figure 4.11 Change in depth to groundwater table after renovation of sewers in the centre of town (area inside light red lines). Rasmussen et al 2020.

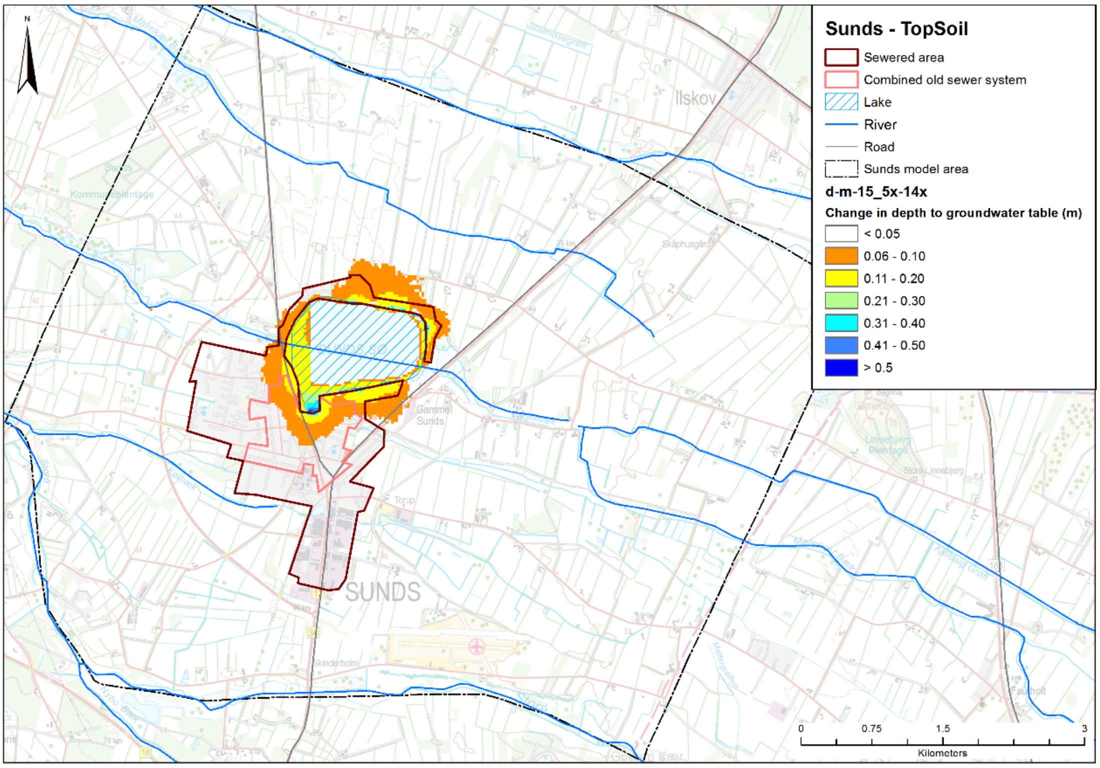

Figure 4.12 Lowering the water table in Sunds Lake to a constant elevation of 41.6 m, "the summer level". The figure shows the situation for a median groundwater table. Rasmussen et al 2020.

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.

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Deliverable 3.2 & 6.3

PILOT DESCRIPTION AND ASSESSMENT

Upper Guadiana Basin (Spain)

Authors and affiliation:

David Pulido-Velazquez, Leticia Baena-Ruiz, Africa de la Hera Portillo, Miguel Mejias, AJ. Collados-Lara, Juan de Dios Goméz-Gómez.

Geological Survey of Spain (IGME)

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Deliverable Data	
Deliverable number	D3.2 & D6.3
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Deliverable name	Pilots description and assessment report for groundwater-surface water/ Pilots description and assessment report for adaptation
Work package	WP3 & WP6
Lead WP	GEUS (WP3), IGME (WP6)
Deliverable status	
Version	Version 1
Date	14/11/2018

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
FAO	Food and Agriculture Organization of the United Nations
GSOs	Geological Survey Organisations
MS	Management scenario
SAC-SMA	Sacramento Soil Moisture Accounting
UGB	Upper Guadiana Basin

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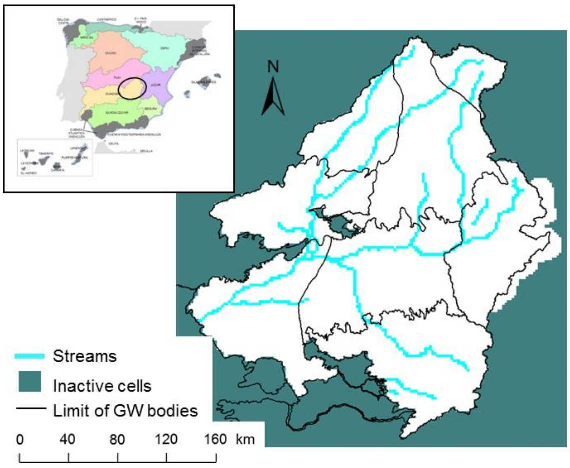
1. EXECUTIVE SUMMARY

Pilot name	UPPER GUADIANA BASIN	
Country	Spain	
EU-region	Mediterranean region	
Area (km^2)	14000 km^2	
Aquifer geology and type classification	Detrital and carbonated. Sedimentary & karstic.	
Primary water usage	Irrigation / Drinking water / Industry	
Main climate change issues	Decrease in piezometric levels and some negative environmental impacts upon groundwater-dependent wetlands, streams and rivers. Identify and assess climate change adaptation measures for a sustainable management of the Basin.	
Models and methods used	Generation of local future climate change scenarios and definition of adaptation scenarios (by applying top-down and bottom-up approaches). Propagation with a chain of auxiliary models (recharge, agricultural) to generate inputs for a distributed flow model defined with the MODFLOW code; Propagation of impacts on laggoons by using regression models that include climatic and hydrological explanatory variables.	
Key stakeholders	Guadiana River Basin Authority, farmers associations (farmers are a highly heterogeneous group, whose interests often cannot be generalised; this implies a wide range between those associations working at institutional level and those working at political scale representation), water supply companies, Environmental Conservation Groups.	
Contact person	L. Baena, D. Pulido, A. de la Hera, M. Mejias, JD Goméz, Aj Collados-Lara. IGME (Spain), l.baena@igme.es; d.pulido@igme.es; a.delahera@igme.es; m.mejias@igme.es; j.dedios@igme.es; Aj.collados@igme.es	

Eight groundwater bodies compose the Upper Guadiana Basin (UGB), including detrital and carbonated aquifers with a complex geology. The intensive groundwater use mainly for irrigation has trigger abundant social and economic benefits; however, it has also produced a significant decrease in piezometric levels and some negative environmental impacts upon groundwater-dependent wetlands, streams and rivers. The Basin shows strong natural interaction between groundwater and surface water gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve; under semi-natural conditions wetlands totalled about 25000 ha. However, this area is now reduced to only 7000 ha. In addition, some rivers and streams that were naturally fed by the aquifers now have become net losing rivers. Some climate change (CC) predictions forecast an increase in temperature and a decrease in precipitation, which will cause a decrease in water contributions and an increase in the magnitude and frequency of extreme phenomena such as floods and droughts. In front of these scenarios it will be necessary to design adaptation strategies able to be impemented with the acceptation and support of all groundwater users.

The overall objective of this study is to assess and summarise impacts of potential future CC scenarios on the quantitative status of aquifers and groundwater depend lagoons. This assessment will require the generation of local future CC scenarios. Their impacts are assessed by propagating them with a chain of auxiliary models (recharge, agricultural) that generate inputs for a distributed flow model defined with the MODFLOW code. A regression model is also applied to estimate impacts on laggoons. Finally, we identify and analyse potential adaptation strategies by applying top-down and bottom-up approaches.

Results show that some CC scenarios would imply a reduction in the recharge due to higher temperature and lower precipitation. This entails an increase in pumping to maintain the irrigation area. These scenarios will produce a decrease of the water table regarding the reference year (2015), producing a reduction of the discharge and therefore, a smaller surface water in wetlands. Other scenarios estimate a slightly increase in both precipitation and temperature. It will imply an increase in groundwater recharge. For those scenarios, although the increase in pumping to maintain irrigated area (due to the higher temperature) will produce groundwater depletion in some areas, the groundwater discharge could increase regarding the mean historical discharge.

2. INTRODUCTION

CC already have widespread significant impacts in Europe, which are 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 CC 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, identification, and analyses of potential adaptation strategies.

TACTIC is centred on 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 UGB pilot (Spain) represents one of the pilots in TACTIC where the impacts from CC on groundwater and dependent ecosystems will be adressed. The general challenge of the pilot is to assess future potential groundwater levels and changes in the surface of groundwater dependet lagoons. We will also study potential adaptation strategies by using a mixed top-down and bottom-up approach.

3. PILOT AREA

In the UGB strong natural interactions between groundwater and surface water are observed, which gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve. This pilot area also highlights the strong conflict between groundwater-dependent ecosystems and groundwater pumping to supply demands (mainly irrigation demands). This problem might be exacerbated in the future due to CC impacts. In this project we intend to assess potential future impacts, considering different potential CC scenarios and adaptation strategies.

3.1 Site description and data

3.1.1 Location and extension of the pilot area

The case study cover and area of near 14000 km^2 located in the Mediterranean region of EU (See Figure 3.1 and Table 3.1). It has traditionally been one of Spain's most intensively pumped groundwater systems, due to a predominantly dry climate and to the prevalence of irrigated agriculture, as well as to the fact that it stores large amounts of accessible groundwater (Martínez-Santos et al., 2018). It represents a unique example of a semiarid region where groundwater use has helped transform a largely poor rural region into a prosperous agricultural and industrial center (Hernández-Mora, 2002; Llamas, 2005).

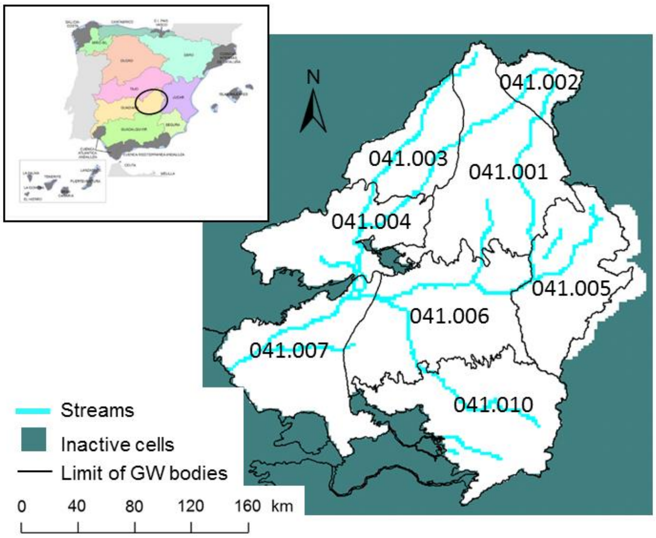


Fig. 3.1: Location of the pilot area.

Table 3.1: Groundwater bodies in the UGB according to UGB (2018, 77).

Name	Code	Extension (km^2)
Sierra de Altomira	041.001	2575
La Obispalía	041.002	490
Lillo-Quintanar	041.003	1102
Consuegra-Villacañas	041.004	1606

Rus-Valdelobos	041.005	1459
Mancha Occidental II	041.006	2536
Mancha Occidental I	041.007	2003
Campo de Montiel	041.010	2200

3.1.2 Geology/Aquifer type

The geology of the UGB is complex including detrital and carbonated aquifers (see Figure 3.2). One of the main groundwater bodies is the Mancha Occidental Aquifer, located in the central part of the UGB. Groundwater connectivity between the different aquifers in the UGB is structurally complex, however, the Mancha Occidental Aquifer is known to be on the receiving end of the system (IGME, 2004; Martínez-Cortina, 2003; Martínez-Santos et al., 2008) and it has been thoroughly described from the hydrogeological viewpoint in several works (IGME, 2004, 2005; ITGE, 1989; Martínez-Santos et al., 2008).

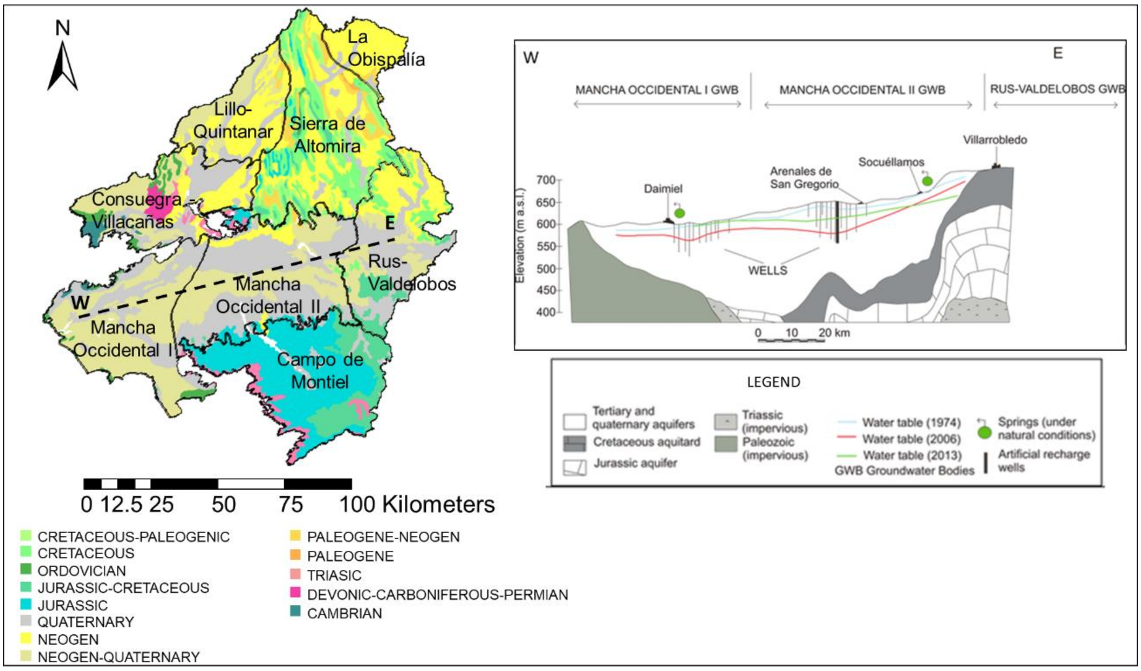


Fig. 3.2: Geological map and cross sections.

3.1.3 Topography and soil types

The area is predominantly flat, sloping gently over 150 km, from the northeast (elevation 730 m.a.s.l.) to the southwest (600 m.a.s.l.) (Figure 3.3, left). The soils (Figure 3.3, right) in the basin mainly belong to the calcisol group according to the FAO classification (1998). It also be found Regosol and others such as luvisol and podzol can be found in the southeast area (Conan et al. 2003).

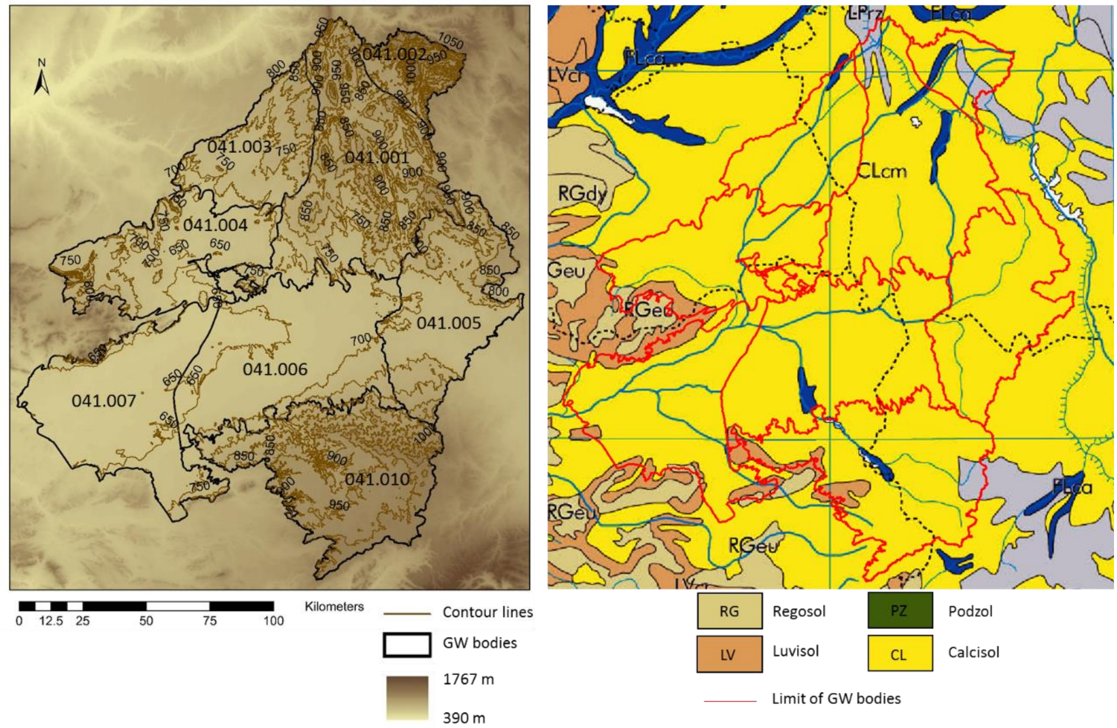


Fig. 3.3: Left: Topography (Digital Elevation Model map with a resolution of 100m); right: soil map from IGN (E 1:3000000).

3.1.4 Surface water bodies

The Basin shows strong natural interaction between groundwater and surface water which gives rise to over one hundred wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve (see Figure 3.4); under semi-natural conditions wetlands totalled about 25000 ha. However, this area is now reduced to only 7000 ha (De la Hera, 2003) due to intensive groundwater pumping. The most part of them are groundwater-dependent wetlands. The current groundwater management implies that a good number of them are at risk to survive. Intensive groundwater withdrawal depleted the water table by more than 20 m between the mid-1970s and the first decade of the new century (IGME, 2004). Although an important and unexpected recovery of the Mancha Occidental aquifer has occurred recently, there are still uncertainties with regard to ecosystems functionality and provision of ecosystem services.

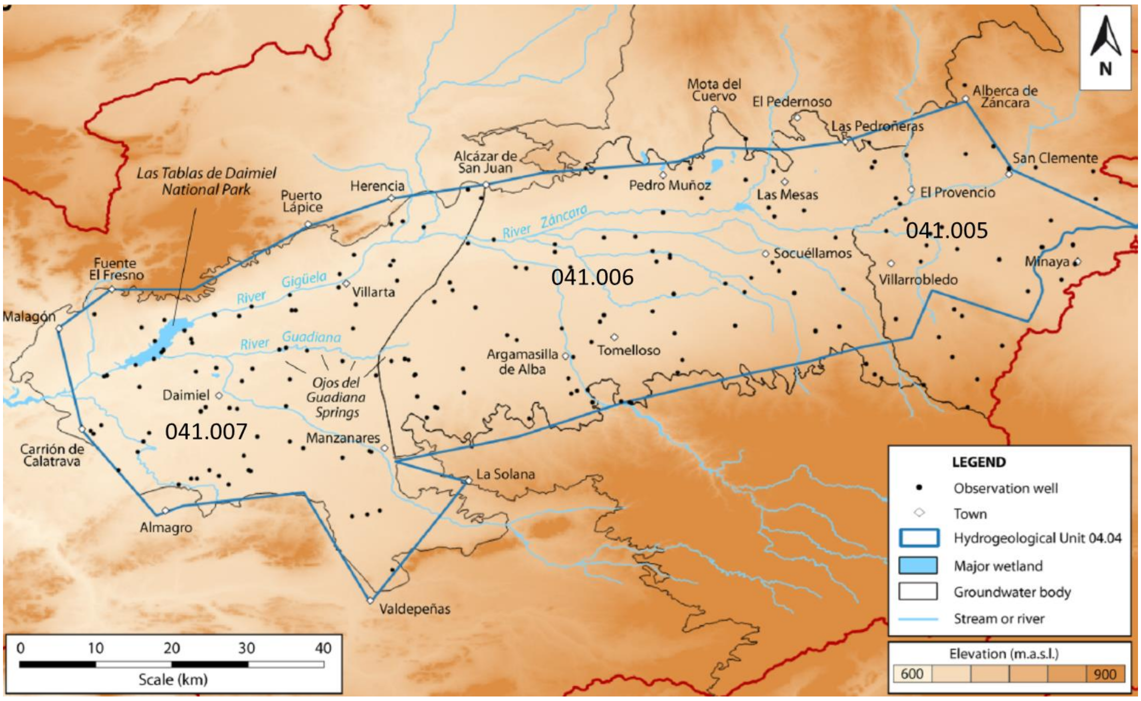


Fig. 3.4: Wetlands that make up UNESCO's Mancha Húmeda Biosphere Reserve.

There are some flow gauges in which the streamflows of some sub-basins are measured even in nearly natural conditions. The location, resolution and period covered by them are represented in Table 3.2 and Figure 3.5.

Table 3.2: Statistics of the flow gauges.

Flow gauges	Average Q(m^3/s)	Period	Temporal resolution	Surface (km^2)
4004	2.17	1973-2015	Daily	847
4101	0.44	1973-1996	Daily	674
4201	1.22	1973-2012	Daily	1080
4202	1.01	1973-2015	Daily	3120
4224	0.67	1975-2015	Daily	2090

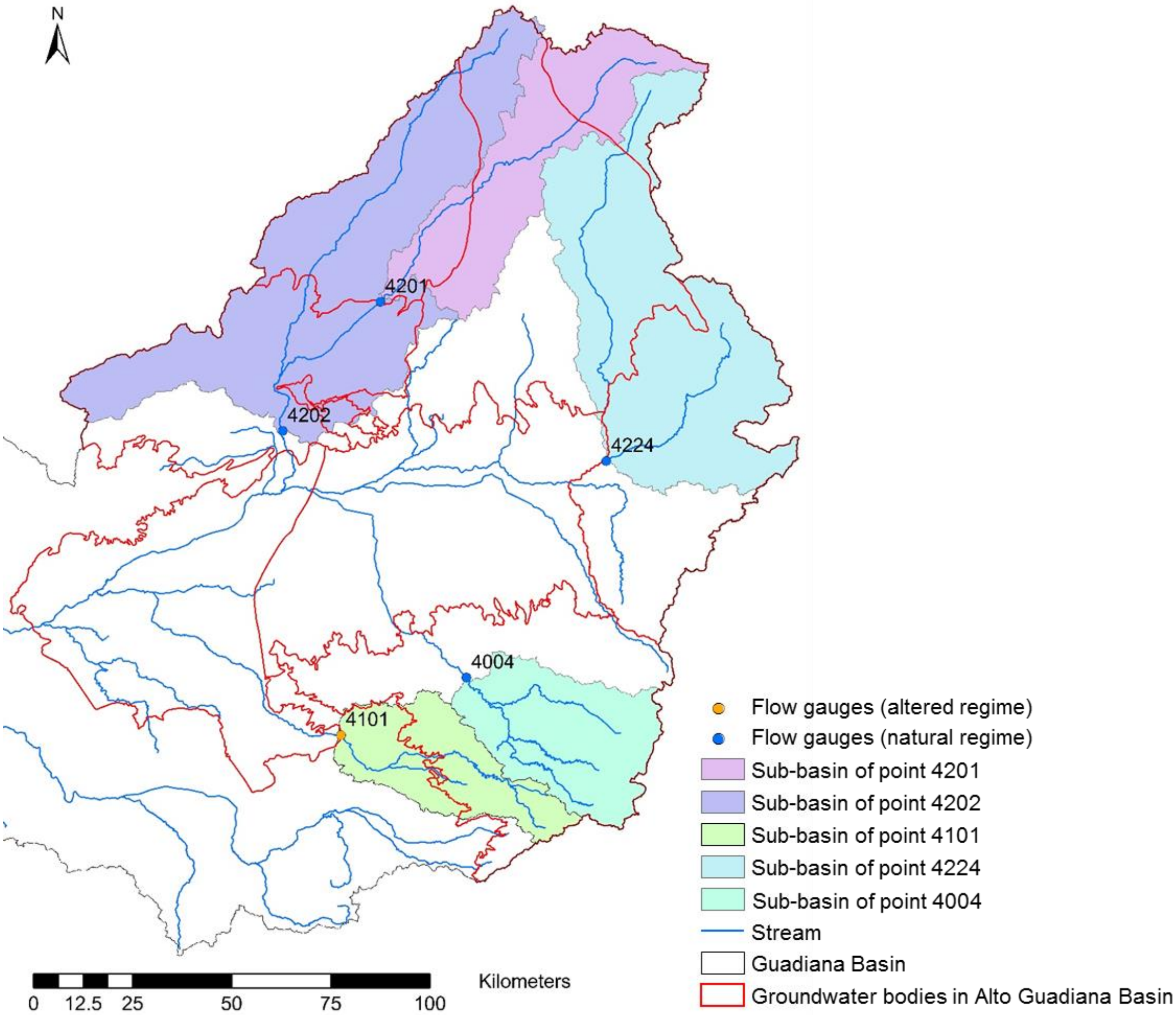


Fig. 3.5: Flow gauges distribution.

3.1.5 Hydraulic head evolution

The intensive groundwater withdrawal depleted the water table by more than 20 m between the mid-1970s and the first decade of the new century (IGME, 2004). In Figure 3.6 we represent the location of the observation points, the maximun observed drawdowns and the temporal evolution in some relevant observation wells.

Aquifers located in the central part of th UGB (Mancha Occidental I and Mancha Occidental II) have experienced a spectacular recovery of its piezometric levels in recent times; in fact, it is currently close to full storage, to the point that its wetlands, artificially maintained for decades, have experienced natural groundwater discharge again for the first time since the early 1980s (Martínez-Santos et al., 2018).

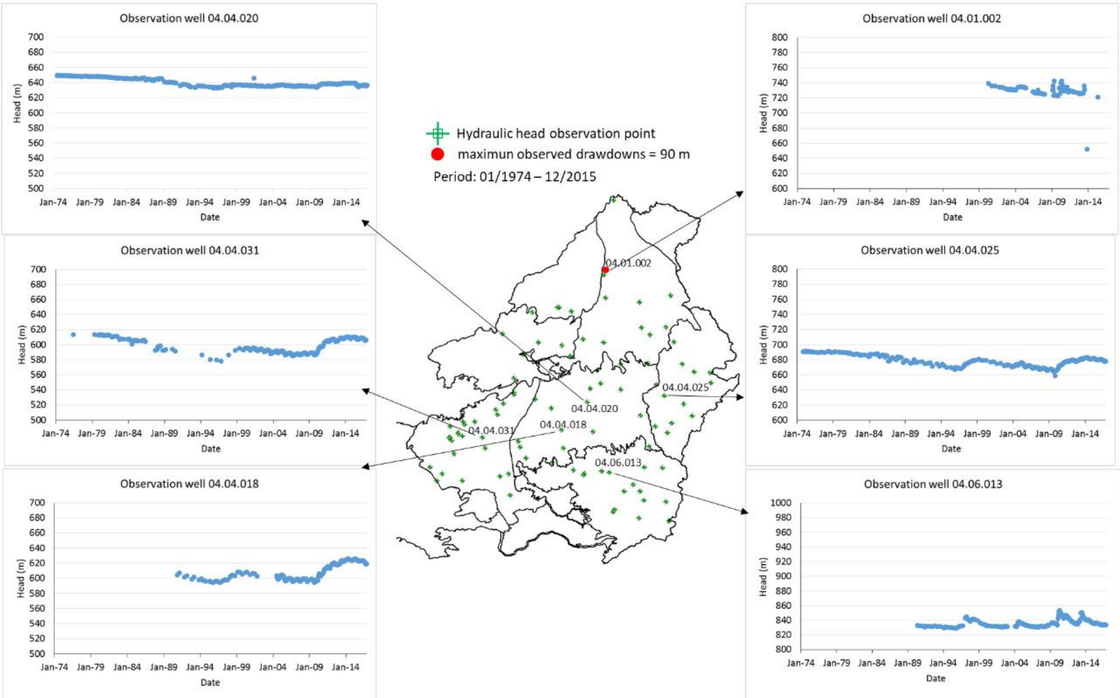


Fig. 3.6: Location of hydraulic head observation points.

3.1.6 Climate

Although this pilot is located in the Mediterranean Region in accordance with the EEA maps, the climate conditions are typically continental and semiarid. Summers are hot and dry, and winters are short and generally mild (Martinez-Santos et al., 2018).

The precipitation is irregularly distributed in the time (see Figure 3.7). The annual average value in the period 1904-2014 is 405 mm (Martinez-Santos et al., 2018). The mean annual temperature is 14.7 °C, oscillating between a maximum mean value of 25.5 °C in July and a minimum of 5.4°C in January. The mean potential evapotranspiration is 700 mm/year. Rainfall is the main source of aquifer recharge.

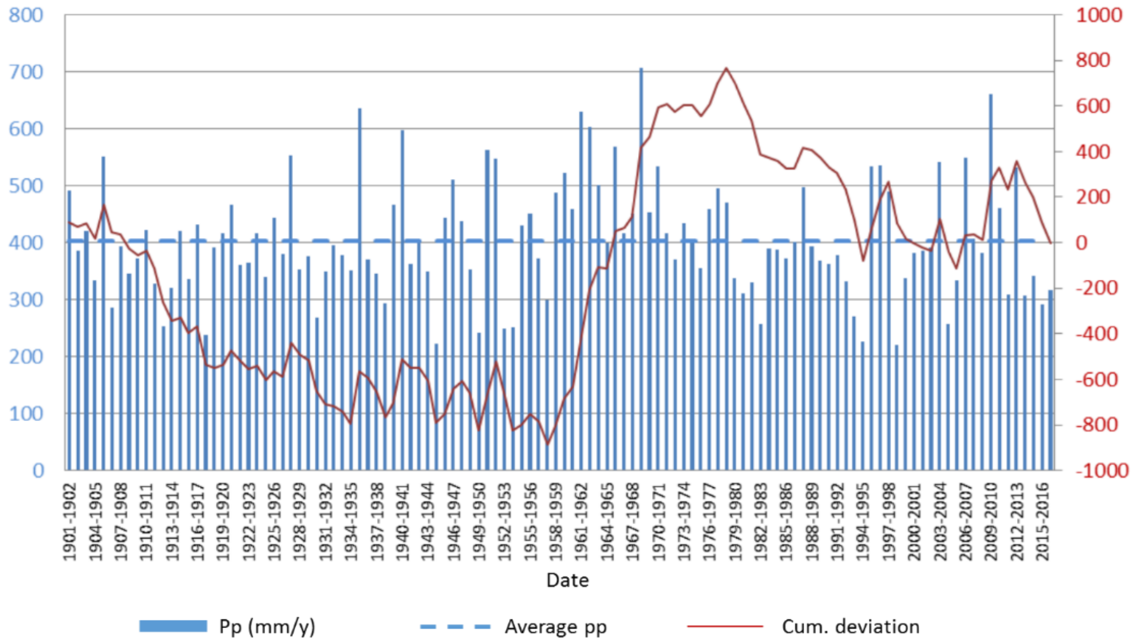


Fig. 3.7: Temporal evolution of the Precipitation (mm/year).

3.1.7 Land use

The main land use is agriculture (see Figure 3.8), which has been expanded in this area since early seventies. The main crops are winter cereals, vineyards and olives (Conan et al. 2003). Although non-irrigated agriculture is the most extensive, there are important irrigation areas mainly located in the central part of the basin.

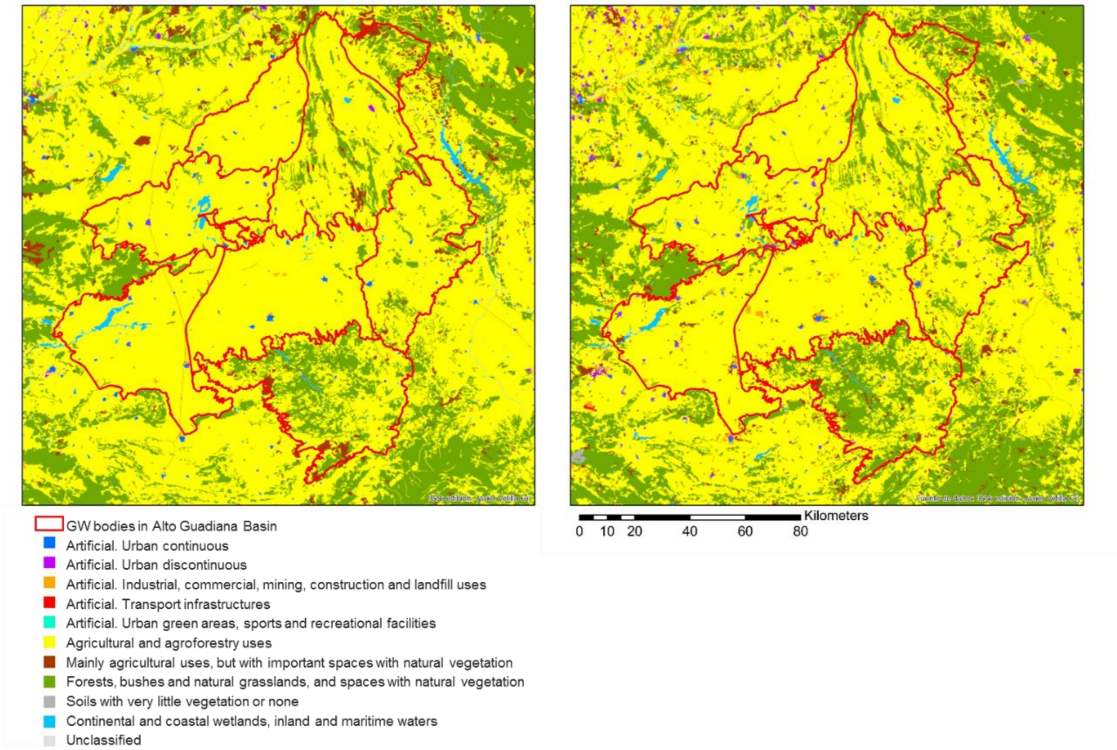


Fig. 3.8: Land use maps from CORINE (1990 and 2012).

3.1.8 Abstractions/irrigation

Currently, pumping-based irrigation accounts for over 90 % of the total water uses. The intensive groundwater pumping in turn led to the desiccation of most groundwater-dependent ecosystems, including Ramsar-listed Las Tablas de Daimiel National Park (Castaño-Castaño et al., 2008), and triggered a series of measures to constrain irrigation. This intensive groundwater pumping is partly due to inadequate management and partly to the presence of thousands of illegal wells. Figure 3.9 and Figure 3.10 show the annual historical temporal evolution of the pumping applied in the MODFLOW model and the spatial distribution in the UGB.

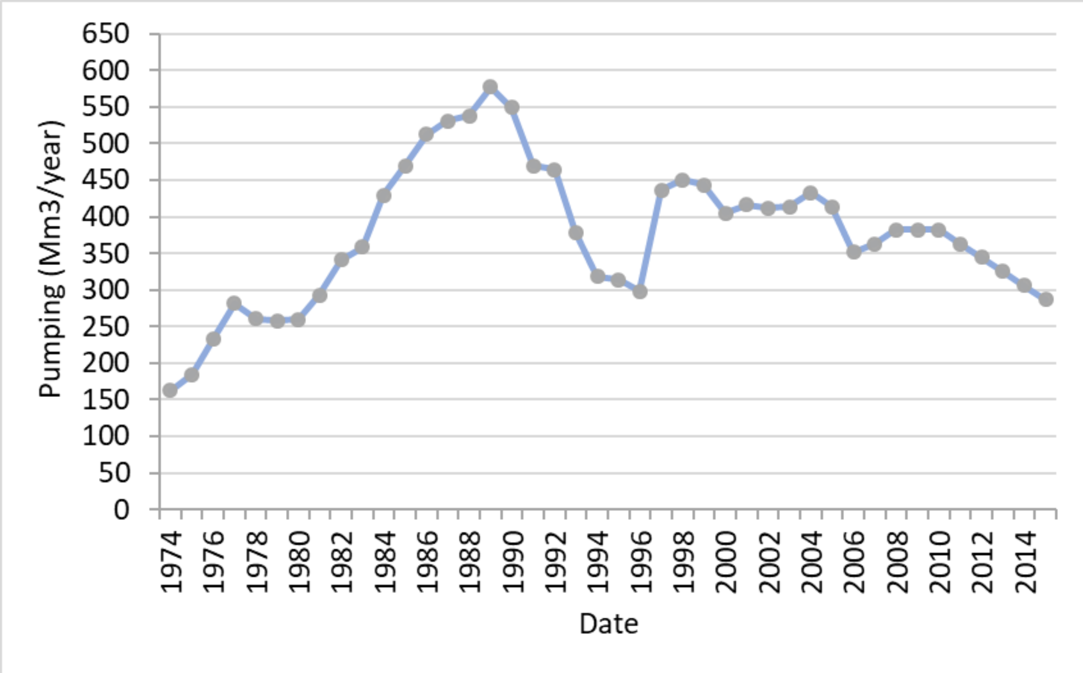


Fig. 3.9: Historical temporal evolution of pumping (Mm^3/y).

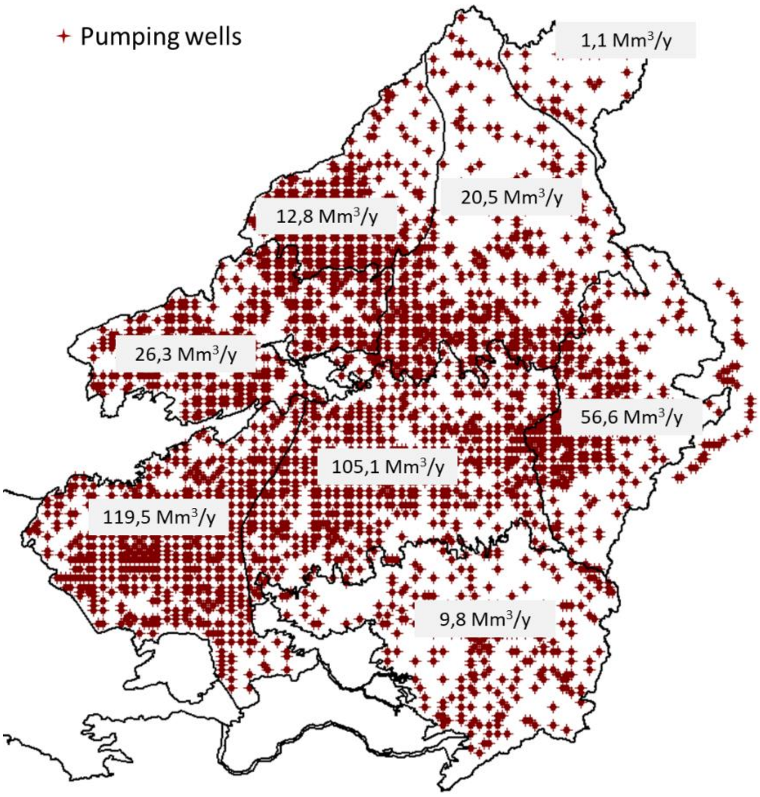


Fig. 3.10: Spatial distribution of the pumpings and mean pumping rates in each GW body in the period (2006-2015).

3.1.9 Flow balance components

The evolution of the main components of the flow balance in the UGB is sumarized in (Table 3.3).

Table 3.3. Approximate water balance in the Upper Guadiana Basin.

Inflow/outflow	Inflows (Mm^3/y)		Outflows (Mm^3/y)			
Date	Rainfall recharge	Recharge from streams	Groundwater pumping	Evapotranspiration from the water table	Discharge to rivers	Lateral transfer to Júcar
1976-1980	771.8	29.3	244.6	985.2	411.8	-19.5
1981-1985	481.2	31.6	347.9	279.5	148.0	18.9
1986-1990	628.5	32.7	489.1	177.4	123.4	47.2
1991-1995	237.4	22.6	328.7	80.2	79.9	52.4
1996-2000	742.6	31.6	336.2	180.5	127.5	68.5
2001-2005	484.0	27.8	340.9	116.1	100.2	72.9
2006-2010	620.6	29.7	375.5	93.5	87.8	0.9
2010-2015	591.1	31.4	327.8	163.1	126.3	0.3
1976-2015	**569.7**	**29.6**	**348.8**	**259.4**	**150.6**	**30.2**

3.2 Climate change challenge

In accordance with the EEA map the main expeted issues due to CC in this case study are those described in the Figure 3.11 for the Mediterranean regions. Existing national estimates show also a significant reduction (around a 20% for the RCP8.5 emission scenario in the horizon 2071-2100) of the aquifer recharge in the area (see Pulido-Velazquez et al., 2017).

The main challenge is to find adaptation measures to maintain a sustainable use of the groundwater bodies with a balance between supply water demands (different uses) under future CC conditions and maintaining a good status in the related ecosystem.

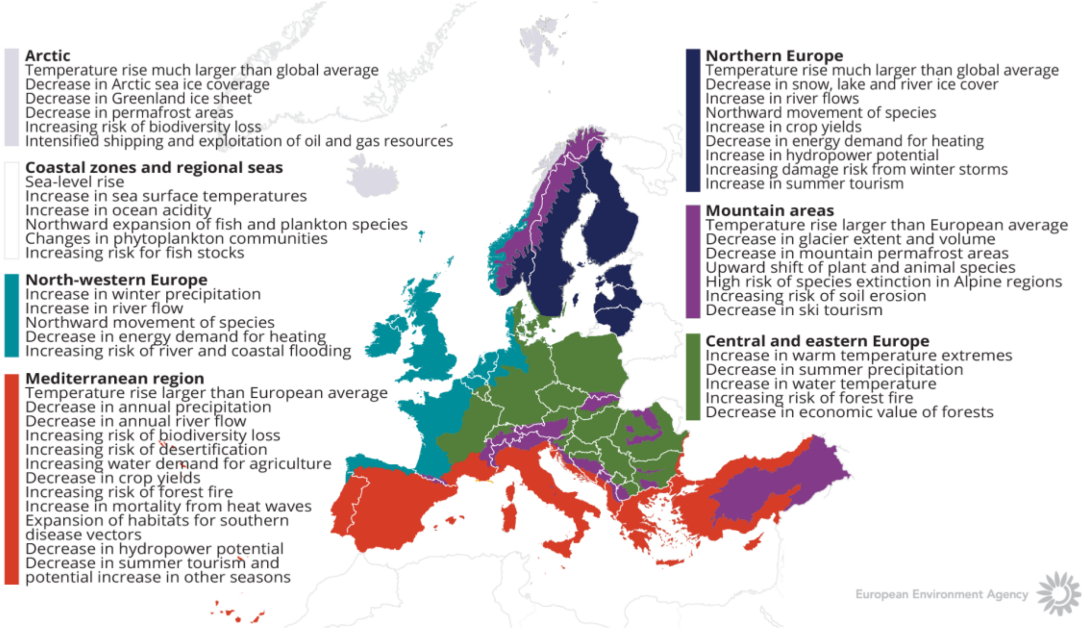


Figure 3.11: European Environment Agency map of projected CC for Europe.

4. METHODOLOGY

The assessment of CC impacts on groundwater and dependent wetlands in the UGB are performed using the TACTIC standard CC scenarios and a chain of hydrological, agricultural and groundwater flow models.

On the other hand, the monitoring and estimation of the water surface in wetlands (groundwater dependent ecosystems) is an important issue in the UGB due to the high environmental value that these lagoons have in the ecosystem functionality. A regression model is applied to estimate the impacts of CC on laggoons.

Finally, we identify and analyse potential adaptation strategies by applying top-down and bottom-up approaches through a participatory process involving groundwater users and skateholders.

The modelling framework is summarised in Figure 4.1.

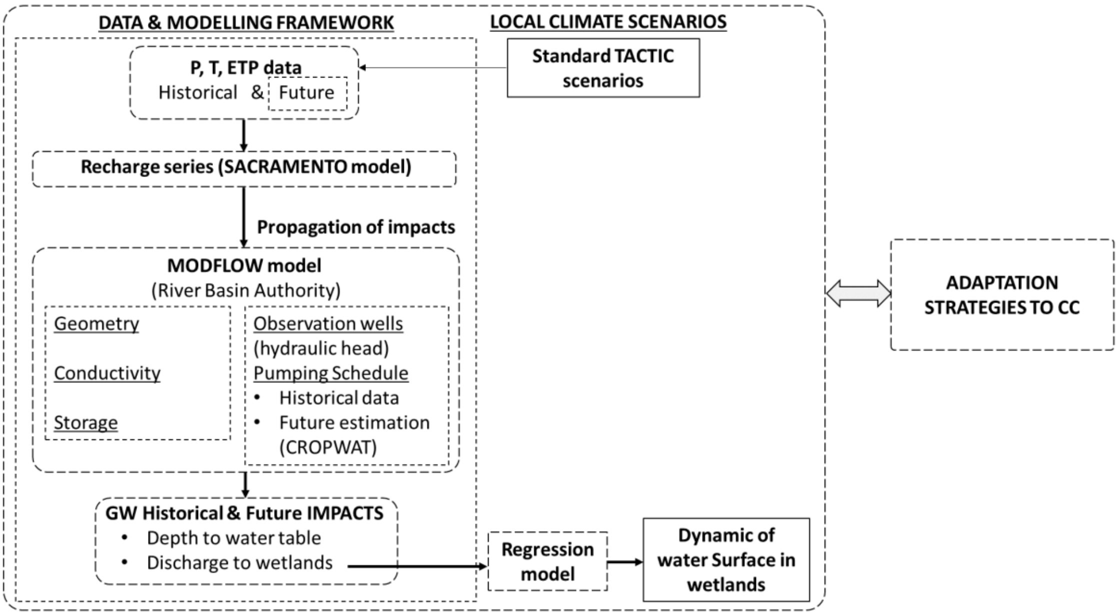


Figure 4.1: Modelling framework.

4.1. Climate data

The present study relies on the TACTIC standard CC 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 CC 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	gfdl-esm2m
	“Wet”	4.5	noresm1-m
3-degree	“Dry”	8.5	miroc-esm-chem
	“Wet”	6.0	ipsl-cm5a-lr

4.2. Integrated hydrological modelling of CC (method 1)

The assessment of impacts of CC is performed by propagating the local climate scenarios within a chain of auxiliary models (recharge, agricultural) that generate the inputs for a distributed flow model defined with the MODFLOW code.

The numerical groundwater flow (Modflow) model was developed by the River Basin Authority in 2010 and it has been has been updated until 2015 (SURGE, 2018). The Modflow model simulates the groundwater flow and river-aquifer relationship in the eight groundwater bodies that compose the UGB. It covers a total area around 14000 km^2 and the cell size is 1000x1000

m. The model is discretized into three layers to simulate the different hidraulic properties in some areas of the model.
The model was calibrated against hydraulic head data from the River Basin Authority and the Spanish Geological Survey (IGME) in the period 1974-2015. It was not possible to perform an automated model optimization (with PEST calibration tool) probably due to the complexity of the model. The groundwater levels were adjusted in 23 piezometers (of the 91 available in the UGB) by varying hidrogeological parameters (within reasonable ranges) through a trial-error procedure. Figure 4.2 shows some xamples of results of the calibration of the Modflow model in the UGB in terms of groundwater levels.

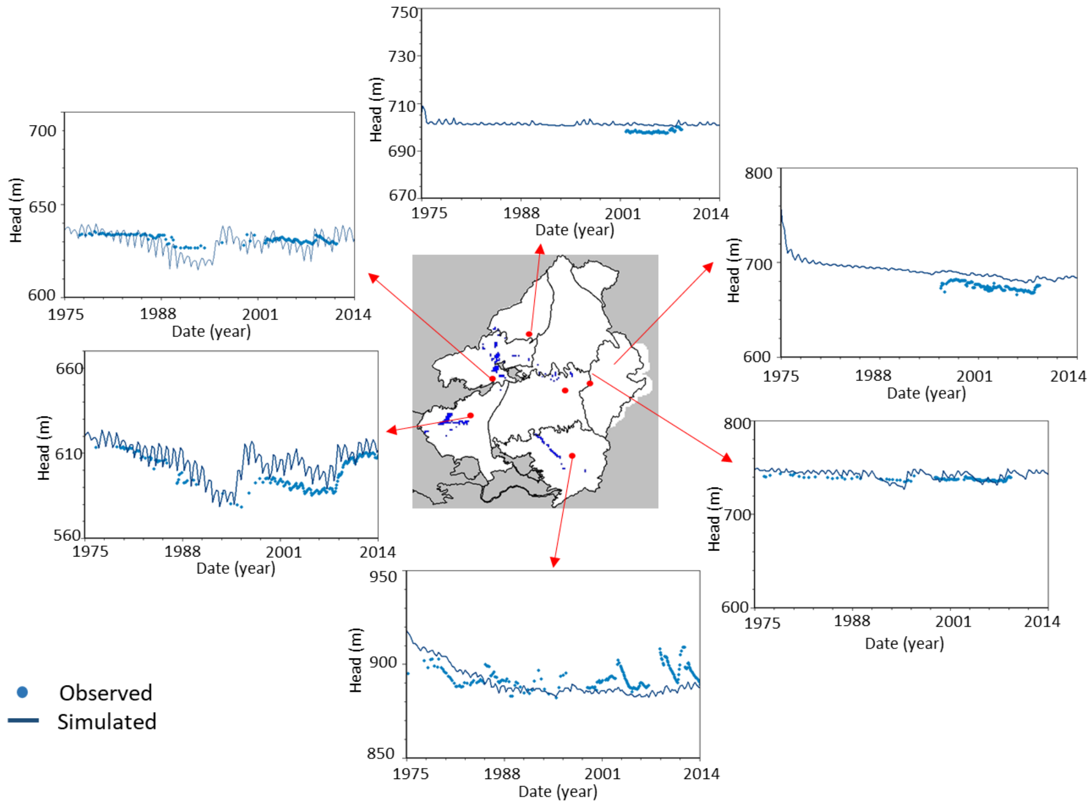


Figure 4.2: Examples of observed and simulated groundwater levels in the Modflow model (UGB).

The flow model requires recharge series as input, which are obtained from a calibrated Sacramento Soil Moisture Accounting (SAC-SMA) model of the US National Weather Service River Forecast System. This model uses precipitation and evapotranspiration time series as input, along with parameters on soil moisture states and the basin's relative permeability to estimate the amount of water that enters, is stored in, and leaves the basin. Five SAC-SMA models were calibrated in the historical period (1974-2015) by a trial and error process to fit the simulated flow rates to the observed ones from five flow gauges in the UGB (see Figure 3.5). Climate series of precipitation came from Spain02 (Herrera et al., 2016) and evapotranspiration series were calculated by using Hargreaves formulation. The period of calibration for each subbasin varied depending on the data availability. The Nash-Surcliffe and R^2 were used to compare the simulated and observed flow for the five subbasins.

Figure 4.3 shows the results of calibration of SAC-SMA model in subbasin EA4004.

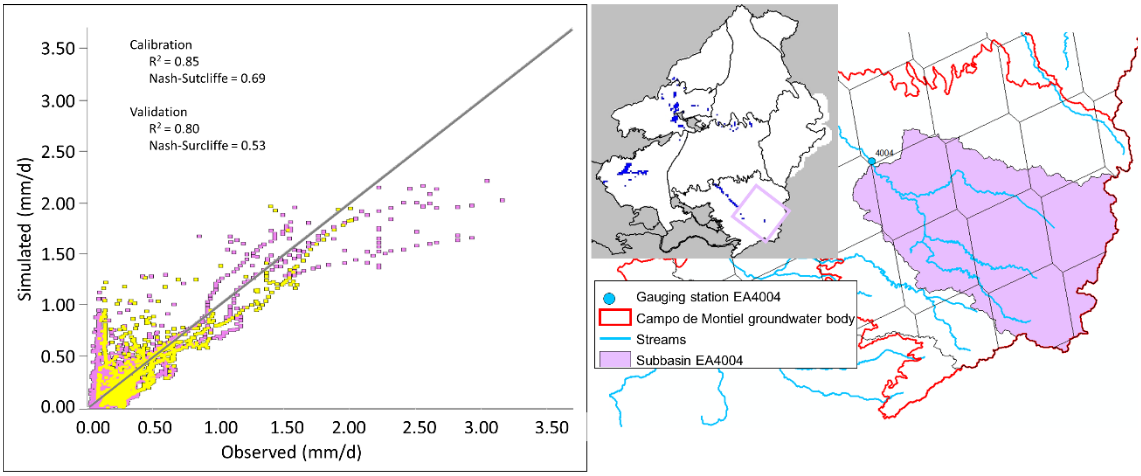


Figure 4.3: Results of SAC-SMA model calibration in subbasin EA4004 in the UGB.

The calibrated SAC-SMA models are used to propagate the impacts of CC on recharge, which is used as input data in the Modflow model.

The future pumping schedule in the Modflow model is generated by using the CROPWAT model (Smith, 1992) to calculate net irrigation demands according to the CC scenario. This tool allows estimating water requirements for each kind of crop from precipitation and temperature data. Thus, the future climatic series has been applied to two management scenarios (MS) with different objectives:

- Maintaining the current (2015) pumping schedule in the future (MS 1).
- Maintaining the current (2015) spatial crop distribution in the future (MS 2);

The Modflow model is used in this study to propagate the impacts of CC on groundwater levels and discharges to wetlands.

4.3. Estimation of the dynamic of surface water in wetlands (method 2)

The monthly dynamic of surface water in Lagunas de Ruidera wetlands in Campo de Montiel (South of UGB) has been estimated from an ensemble of regression models that were calibrated by using satellite data and hydro-climatological variables. Figure 4.4 shows the location of Lagunas de Ruidera in the UGB.

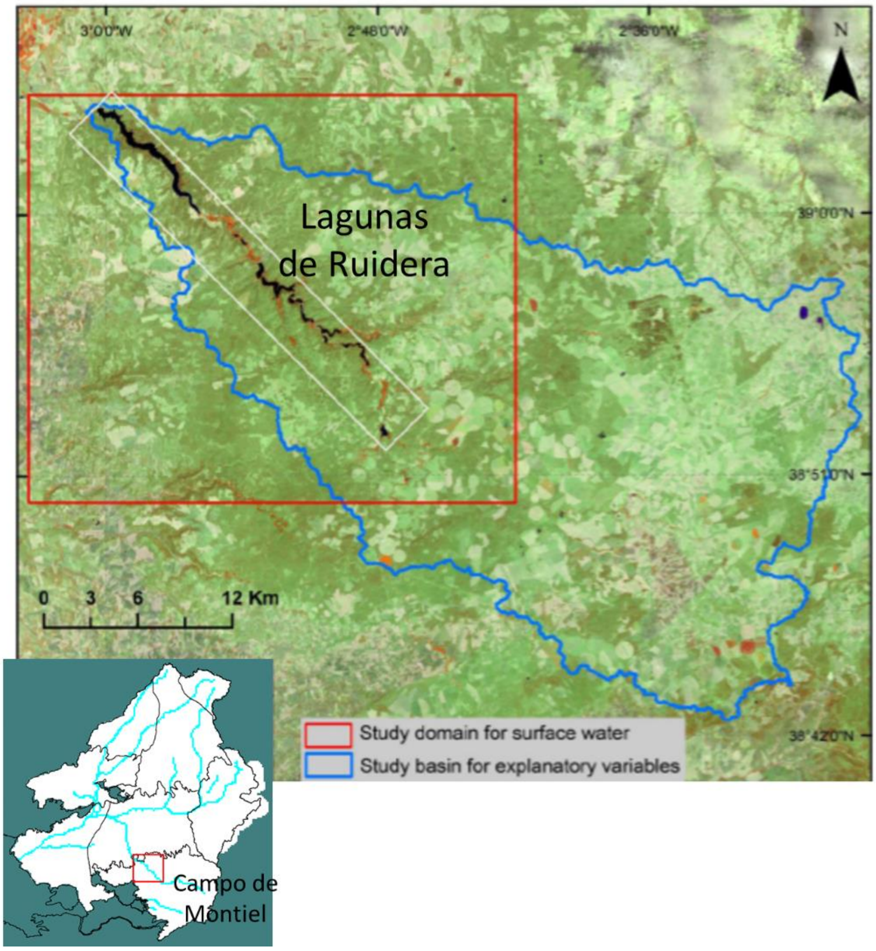


Figure 4.4: Location of the pilot area for the estimation of the dynamic of surface water in the UGB.

The purpose of these regression models is to complete the information provided by satellite data in order to obtain long monthly series of surface water in small lagoons that require high spatial resolution information. This ensemble of regression models also allows estimating future changes in surface water on lagoons due to CC.

The explanatory variables used for the calibration of the multiple regression model were: precipitation; effective precipitation; temperature; potential evapotranspiration; and aquifer discharge in the period 1984 to 2015.

4.4. Adaptation strategies to CC (method 3)

In this project, a participatory method has been designed to define local future socio-economic scenarios, establish adaptation strategies and validate the model developed in the pilot area. This participatory process involves local agents of agricultural communities in the UGB including farmers, the Guadiana River Basin Authority, the General Directorate of Agriculture and Natural Environment of Castilla La Mancha, local municipalities, national environmental officers and environmental organizations.

Three local scenarios were defined and presented in a workshop that was held in the study area (Bolaños de Calatrava), were some exercises were carried out to elicit their knowledge in relation to the previous results obtained with the physical flow model. The three socio-economic scenarios are:

1) Business as usual: a vision of future evolution with current trends;
2) Innovation and globalization: trend to globalization and opening of borders and markets with reinforcing economic subsidies, promoting environmental practices and crops and a high rural innovation;
3) Fragmentation and protectionism: the European Union promotes market protectionism and the economic subsidies support for productivity.

5. RESULTS AND CONCLUSIONS

Results from the work in the UGB pilot (Spain) will focus on changes on shallow groundwater levels and the impacts on dependent ecosystems. This pilot area reveals the strong conflict between groundwater-dependent ecosystems and groundwater pumping to supply demands (mainly irrigation demands). This problem will be exacerbated in the future due to CC impacts, although some CC scenarios show hopeful results.

The ensemble of regression models calibrated to estimate the water surface in wetlands are useful to understand the impacts of CC in groundwater dependent ecosystems.

The knowledge of these impacts (groundwater levels and dependent ecosystems) allows us to establish and assess adaptation measures, which are defined in the framework of a participatory process that includes all groundwater users of the area.

5.1. Climate data: TACTIC standard CC scenarios

The TACTIC standard scenarios show differences in the mean value of climatic variables. The mean annual precipitation in the historical period (1974-2015) was 433 mm/year and the mean annual temperature was 14.6 °C (Herrera et al., 2016). All the CC scenarios estimate an increase in the mean temperature (between 0.8 and 3.1 °C). The minimum change scenarios (1 and 3 degree) show a decrease in mean annual precipitation (drier conditions) whereas the maximum change scenarios (1 and 3 degree) show an increase in this variable (wetter conditions).

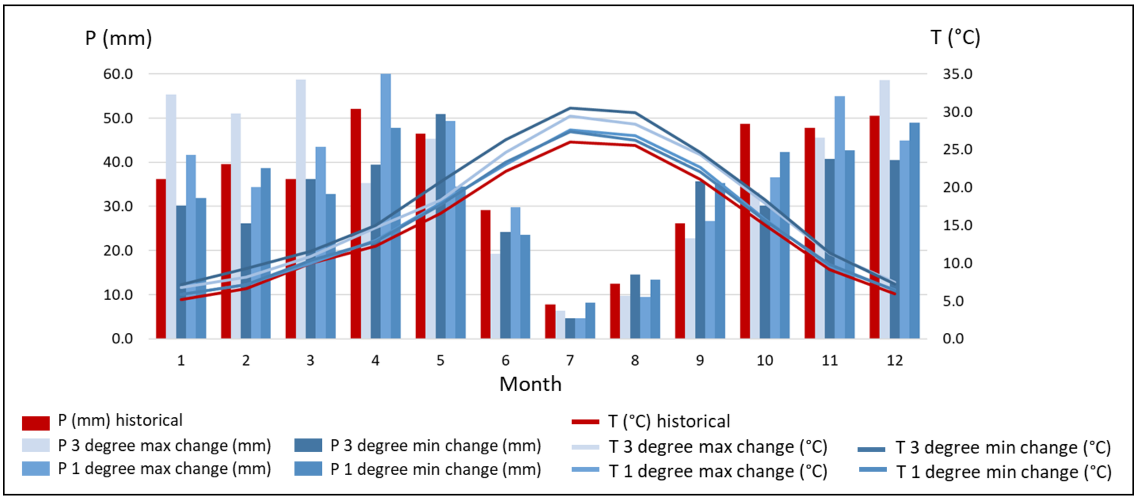


Figure 5.1: Monthly mean historical and future estimated climatic variables (precipitation P (mm) and temperature T (°C)) for the four TACTIC standard CC scenarios.

5.2. Integrated hydrological modelling of CC (method 1)

The results generated by the TACTIC standard scenarios are consistent for the minimum and maximum changes between the 1 and 3 degree scenarios. The minimum change shows "drier" conditions in the future and the maximum changes show "wetter" conditions in the future. As expected, the 3 degree minimum scenario is the most extreme and therefore, it will cause a higher decrease in rainfall recharge (figure 5.2).

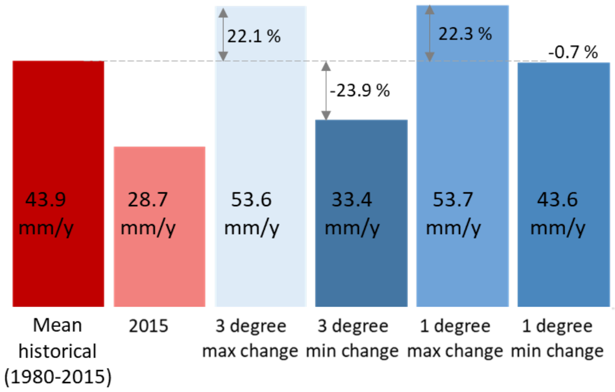


Figure 5.2: Recharge obtained by SAC-SMA models and change (Δ%) caused by CC scenarios regarding to the mean historical recharge.

The MS simulated by using CROPWAT model also show different results depending on the CC scenario (Figure 5.3), although all of them move in the same direction regarding the reference year (2015).

Although maximum change scenarios (1 and 3 degree) estimate an increase in groundwater recharge, the increase in the mean annual temperature will produce higher crop water requirements. If the pumping schedule is maintained in the future as in the year 2015 (MS 1), the CC will led to decrease the irrigation area. The reduction in the irrigation area will be larger in the most extreme CC scenario (3 degree, minimum change) and it will be smaller under the 1 degree maximum change scenario.

The MS 2 will require an increase of groundwater abstractions in order to maintain the irrigation area as in 2015. Under this MS, 3 degree minimum change CC scenario will mean the highest increase in pumping whereas 1 degree maximum change CC scenario will imply the smallest increase in pumping.

Although the 3 degree maximum change scenario estimates a significant increase in future groundwater recharge, the strong increase in mean temperature (2.3 °C above the historical mean temperature) will imply a drastic reduction in the irrigation area (MS 1) or a large increase in pumping (MS 2), depending on the MS. On the contrary, the 1 degree minimum change scenario estimates a slight reduction in future groundwater recharge (regarding the mean historical) and the small increase in the mean temperature (0.8 °C above the mean historical temperature) will contribute to moderate changes in both irrigation area and pumping in the future.

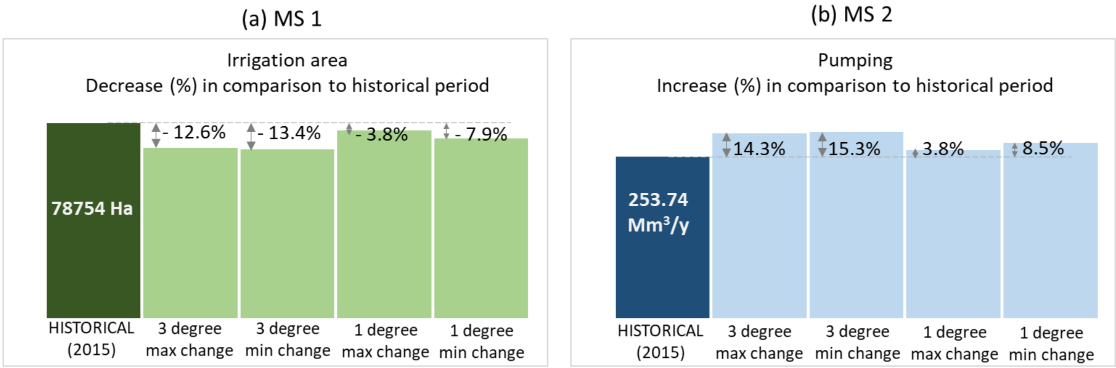


Figure 5.3: Changes (%) in irrigation area (a) and pumping (b) regarding to the reference year (2015) caused by CC scenarios.

Figure 5.4 shows the distributed impacts of the most adverse CC scenario (3 degree minimum change) on the pumping and/or the irrigated area under the two MS. All the groundwater bodies will experiment similar changes in irrigation area and pumping except La Obispalía, which will require a large increase in pumping to maintain the irrigation area as in 2015.

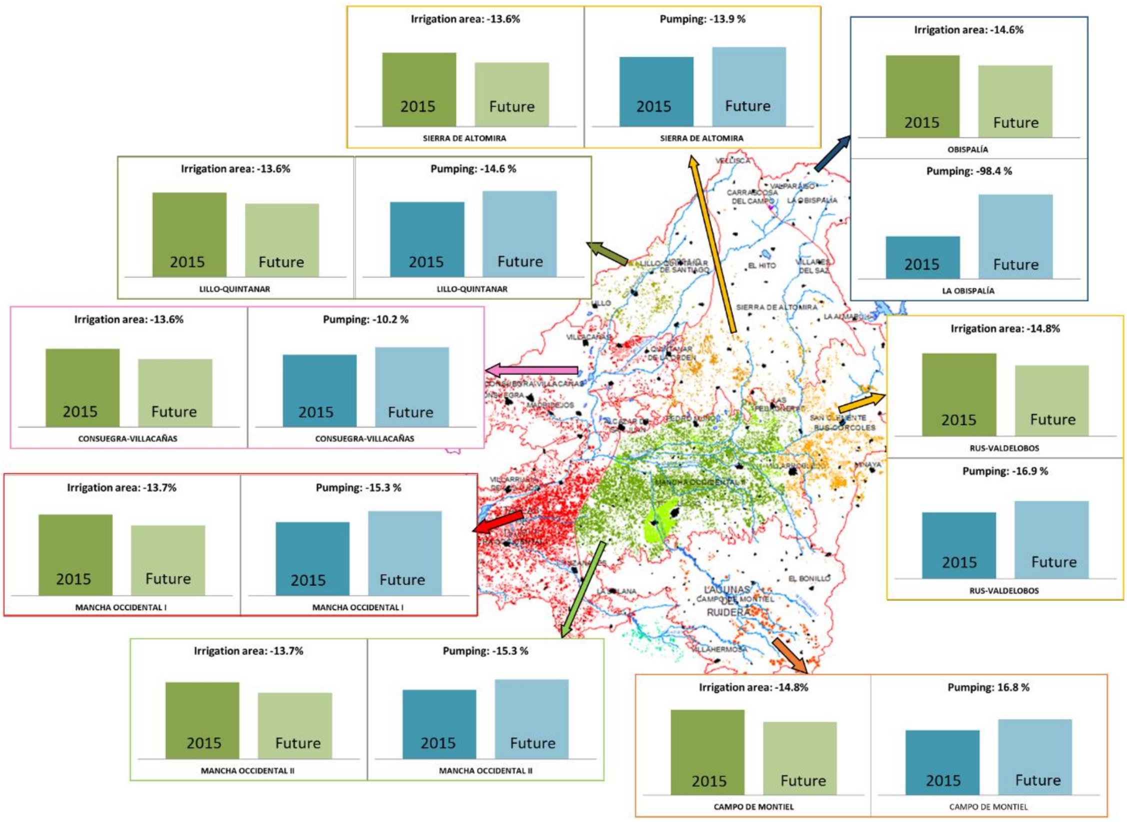


Figure 5.4: Impacts of 3 degree, minimum change CC scenario on irrigation area and pumping regarding the reference year (2015).

These MS and CC scenarios will reflect their impacts in the groundwater levels producing changes of different magnitude and direction (Figure 5.5).

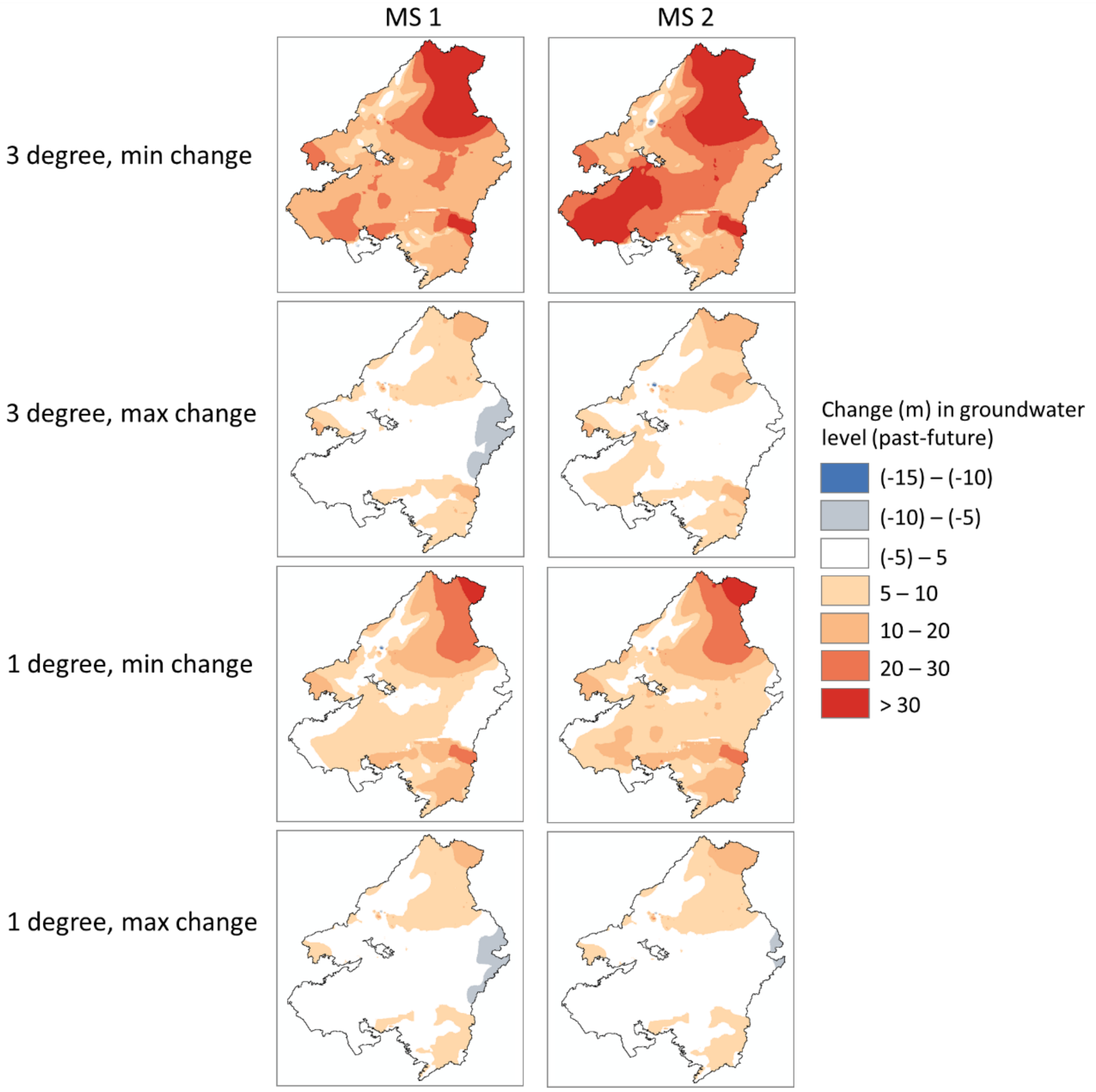


Figure 5.5: Maximum changes regarding 2015 in groundwater levels simulated with the 4 TACTIC standard scenarios

The minimum change scenarios shows “drier” conditions (lower groundwater levels) in the future regarding the maximum change scenarios (1 degree and 3 degree). Maximum change scenarios show “wetter” conditions (higher groundwater levels) in the future in some zones in the pilot area. As expected, the 3 degree scenarios are more extreme for both the minimum and maximum change than the 1 degree scenarios.

In general, the most adverse scenario would be 3 degree maximum change CC scenario in combination with the MS 2. On the contrary, the MS 1 under the 1 degree maximum change scenario would be the most favourable. For this scenario, a large area will maintain the groundwater level as the past (or it will experiment slight changes, between (-5) – 5 meters).

Under this scenario, some aquifers mainly in northern and southern areas will decrease the groundwater level and a small area in the east will increase the groundwater level.

5.3. Estimation of the dynamic of surface water in wetlands (method 2)

The ensemble of regression models calibrated in Lagunas de Ruidera wetland area (Campo de Montiel, UGB) is used to estimate the water surface under CC scenarios. Figure 5.6 shows the future estimation for the most extreme CC scenario (3 degree, minimum change). The water surface is expressed in pixels with a resolution of 30x30 m. This CC scenario will involve a decrease of the water surface of 12.6% regarding the mean historical water surface. It might lead the disappearance of the smallest lagoons in this area.

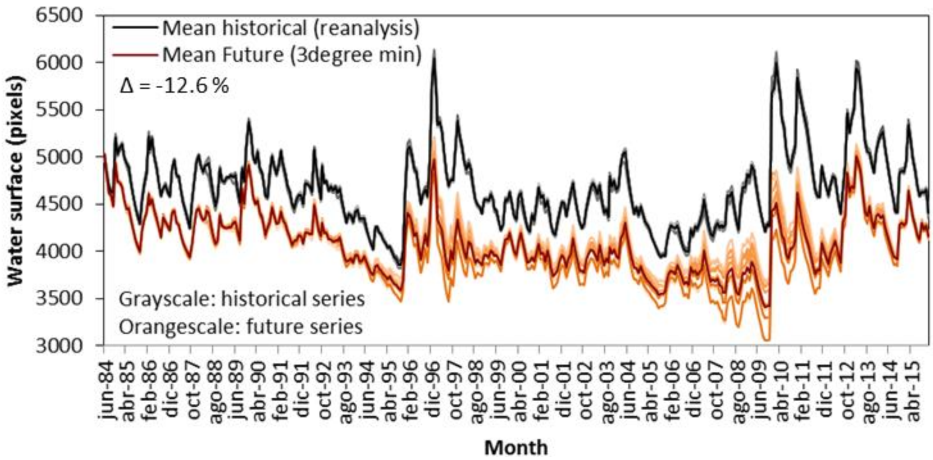


Figure 5.6: Monthly time series of the surface water for the historical period and future estimation

5.4. Adaptation strategies to CC (method 3)

In the workshop held with skateholders in the UGB, the participants discussed the main environmental, social, economic characteristics and the expected evolution of some indicators of the three proposed local scenarios. Most of the participants were aware of the need to preserve the groundwater status and dependent ecosystems and they revealed the importance of the wetlands to the region development.

Some of the most valued adaptation strategies in the workshop were the land use change through the development of other activities and the improvement of the control of the extractions, among other measures (innovation, optimization of crop water use, etc).

Some of these measures will lead to a reduction of the irrigation area, which could be materialized through the MS 1 described in Sections 4.2 and 5.2.

Figure 5.5 shows that MS 1 will help to counter the CC impacts and it will be possible to maintain and/or increase the groundwater levels in some areas in the UGB.

The impacts of the reduction of the irrigated area are also analysed in terms of discharge to wetlands in Figure 5.7.

These results are also consistent for the minimum and maximum changes between the 1 and 3 degree scenarios. Two CC scenario (3 degree, minimum change and 1 degree, minimum change) show a decrease in groundwater discharge to wetlands regarding the discharge in the reference year (2015). Although the recharge in 2015 was notably lower than the mean historical, the groundwater bodies have experimented a recovery due to the decrease in pumping since 2010 (see Figure 3.9). However, in the past (1980-2015), the overexploitation in the UGB lead to some wetlands to disappear due to the reduction in the discharge.

Under the MS1, the CC scenarios with higher recharge will experiment also an increase in discharge to wetlands.

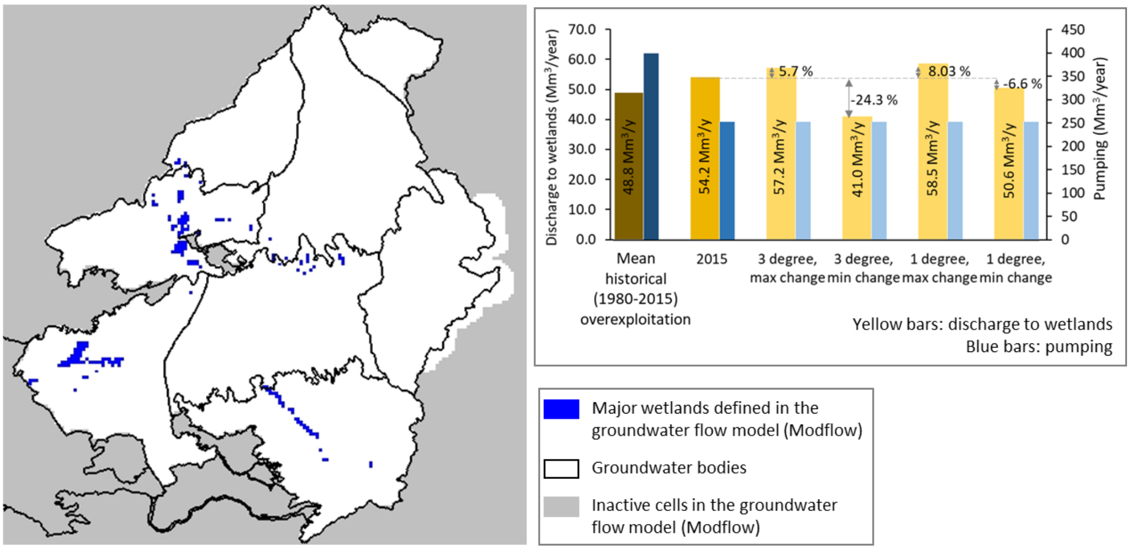


Figure 5.7: Location of the major lagoons in the UGB and mean future groundwater discharge to wetlands simulated with the 4 TACTIC standard scenarios

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Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe

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PILOT DESCRIPTION AND ASSESSMENT

The Netherlands
&
De Raam, Netherlands

Authors and affiliation:

Willem J. Zaadnoordijk (TNO-GSN)
Timo Kroon (Deltares)
Eva Schoonderwoerd (Deltares)
Janneke Pouwels (Deltares)

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Deliverable Data	
Deliverable number	D3.2, D4.2
Dissemination level	Public
Deliverable name	Pilot description and assessment
Work package	WP3, WP4
Lead WP/Deliverable beneficiary	GEUS
Deliverable status	
Version	3
Date	26/03/2021

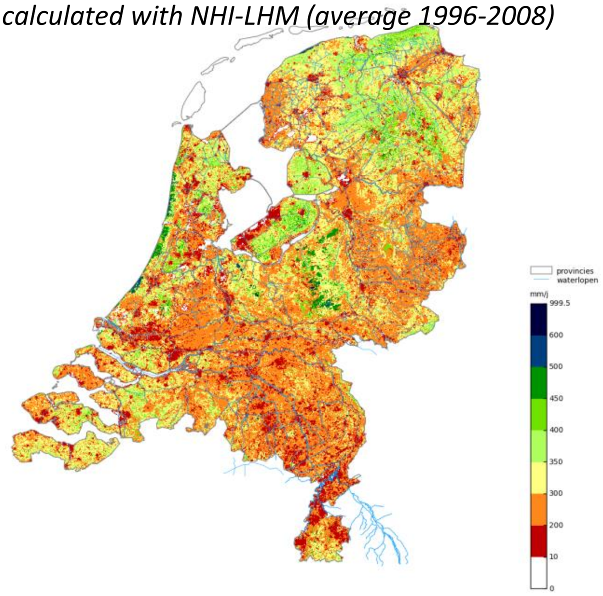
LIST OF ABBREVIATIONS & ACRONYMS

AHN	Open Source Data set with Actual Elevation Levels for the Netherlands (in Dutch “Actueel Hoogtebestand Nederland”)
BIS	Data base with Dutch soil characteristics (in Dutch: “Bodemkundig Informatie Systeem”).
Deltares	Dutch research institute.
iMOD	Open Source modelling software of Deltares, based on the MODFLOW model (USGS), adapted to apply for large datasets, and including a user interface.
LGN	Data set with land use for the Netherlands (in Dutch: ”Landelijk Grondgebruik Nederland”)
Metran	Tool for transfer noise modelling and dynamic factor analysis of groundwater head time series.
NAP	National Dutch Datum (equal to mean sea level; in Dutch: “Normaal Amsterdams Peil”)
NHI	Netherlands Hydrological Instrument (integrated hydrological model based on iMOD).
NHI-LHM	National Hydrological Model of the NHI (in Dutch: “Landelijk Hydrologisch Model”).
TNO-GSN	TNO Geological Survey of the Netherlands.

TABLE OF CONTENTS

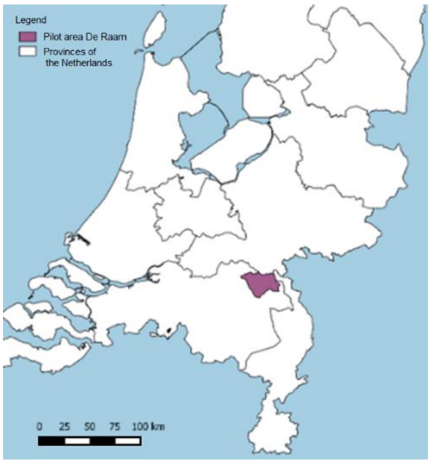
1 EXECUTIVE SUMMARY

TNO Geological Survey of the Netherlands (TNO-GSN) and Deltares together contribute two pilots to the TACTIC project: a national pilot “Netherlands” and a regional pilot “de Raam”.

Pilot name	Netherlands	*Example of groundwater recharge (mm/year) calculated with NHI-LHM (average 1996-2008)* 
Country	Netherlands	
EU-region	North-western Europe	
Area (km²)	40 500	
Aquifer geology and type classification	Sand and gravel – Porous; Chalk – Fissured	
Primary water usage	Drinking water / Irrigation / Industry / Ecology	
Main climate change issues	Climate change (change of precipitation, evaporation, incoming river discharges and sea level rise), combined with socio-economic developments	
Models and methods used	Integrated Hydrological model (national application of the Netherlands Hydrological Instrument; NHI-LHM), Time series analysis (using Metran)	
Key stakeholders	Rijkswaterstaat, Ministry of Infrastructure and Water (including Delta Programme), Ministry of Economic Affairs and Climate policy. Further the waterboards, provinces and drinking water companies are involved in development and application of the hydrologic instrument.	
Contact persons	Timo Kroon, Deltares, timo.kroon@deltares.nl Willem Jan Zaadnoordijk, TNO, willem_jan.zaadnoordijk@tno.nl	

This pilot considers the groundwater and interaction with the surface water system at a national scale with the national hydrologic model for the Netherlands (NHI-LHM). Usually this integrated model for simulations in the subsurface and surface water in the Netherlands is applied for national water management and national policy making (quantity and water quality). Water management on a national level with the model relates to national water supply and measures for drought prevention, such as setting of the weirs in the main water system in the (branches of) the Meuse and Rhine, and the management of the storage in lake IJsselmeer, which serves during drought as the largest fresh water reservoir in the Netherlands.

Within TACTIC simulations with the national model are presented for the current climate and for four climate change scenarios. The calculated heads are compared at a few locations with simulations from linear transfer noise models (created using Metran, the groundwater dynamics tool of http://www.grondwatertools.nl).

Pilot name	De Raam	
Country	Netherlands	
EU-region	North-western Europe	
Area (km^2)	224	
Aquifer geology and type classification	Sand and gravel – Porous	
Primary water usage	Irrigation / Ecology / Drinking water	
Main climate change issues	climate change (change of precipitation, evaporation, incoming river discharges and sea level rise), combined with socio-economic developments	
Models and methods used	Integrated Hydrological model (regional model, based on iMOD), Time series analysis (using Metran)	
Key stakeholders	Waterboard Aa en Maas, province of Noord-Brabant and drinking water company Brabant Water	
Contact person	Timo Kroon, Deltares, timo.kroon@deltares.nl Willem Jan Zaadnoordijk, TNO, willem_jan.zaadnoordijk@tno.nl	

For the regional pilot in the Netherlands, ‘de Raam’ a regional model is applied. This model has been developed for regional management of groundwater and surface water and is a refined version of the national instrument (NHI). It is used by the waterboard, province and drinking water company to investigate the effects of regional and local measures in the current and future (climate change) situation.

Within TACTIC the regional groundwater model has been used to simulate the current climate and for the TACTIC climate change scenarios. A comparison between the results from the regional and the national integrated hydrological model is presented.

At the location of a few monitoring wells, the calculated heads are compared with simulations from linear transfer noise models from Metran. Also time series modelling has been carried out for a few piezometers influenced by an accident on the river Meuse during which the river level was 3 meters lower than normal.

The transfer noise modelling of monitoring of measured groundwater heads reproduces the measured heads better than a distributed physically based model at the location of the piezometer. However, a physically based model is better suited for scenario calculations, even if the scenarios only involve changes in the explaining variables of the transfer noise model. The reason for this, is the non-linearity of the groundwater system or change of system behaviour when the situation differs from the calibration period. The simulations of time series near the river Meuse illustrated this with different responses to the river level for the normal situation and during an accident with much lover water levels.

The transfer noise models using only groundwater heads as calibration variables do not provide a useful estimate of groundwater recharge. Moreover, transfer noise modelling of time series itself does not provide information in between piezometers – for the best spatial estimation of historic groundwater heads a combination of time series and a physically based distributed model provides the best results.

Lastly, a comparison of a fine resolution regional model and a coarse resolution national model indicates that the fine resolution is necessary to study local variations. This also corresponds to the different purposes of these models. The national model is used for the management of the main rivers and for national policy development. The model for De Raam is intended for improving the regional water management, e.g. by evaluating concrete local measures.

2 INTRODUCTION

The Netherlands is bordered by Belgium, Germany and the North Sea. The land area is 40 500 km^2. The surface topography is relatively flat ranging from below sea level in polders in the Western and Northern parts to 300 meters above in the South-eastern corner.

The large scale differences in the elevation of the phreatic groundwater level are related to the net groundwater replenishment from precipitation areas with relatively little drainage and surface water in the higher mostly Pleistocene inland part of the country and the drainage in polders and other lower areas mostly with a Holocene cover. The drainage is strongly influenced by anthropogenic surface waters.

The fresh groundwater of meteoric origin in this system in the Netherlands reaches its largest depths in the Holocene coastal dunes (tens of metres depth), the Pleistocene ice-pushed hills (Veluwe and Utrechtse Heuvelrug) in the central and Eastern part of the country (up to few hundred metres depth), and in the supra-regional groundwater flow system in the South-eastern part of the country (≥ 600 m). These fresh parts of the groundwater flow systems occur in unconsolidated sedimentary sequences of dominantly Holocene and Pleistocene to Neogene age.

The availability of groundwater in the Netherlands is influenced by the surface waters. Surface water is mainly supplied from the catchment areas of the Rhine and the Meuse (see figure 2.1).

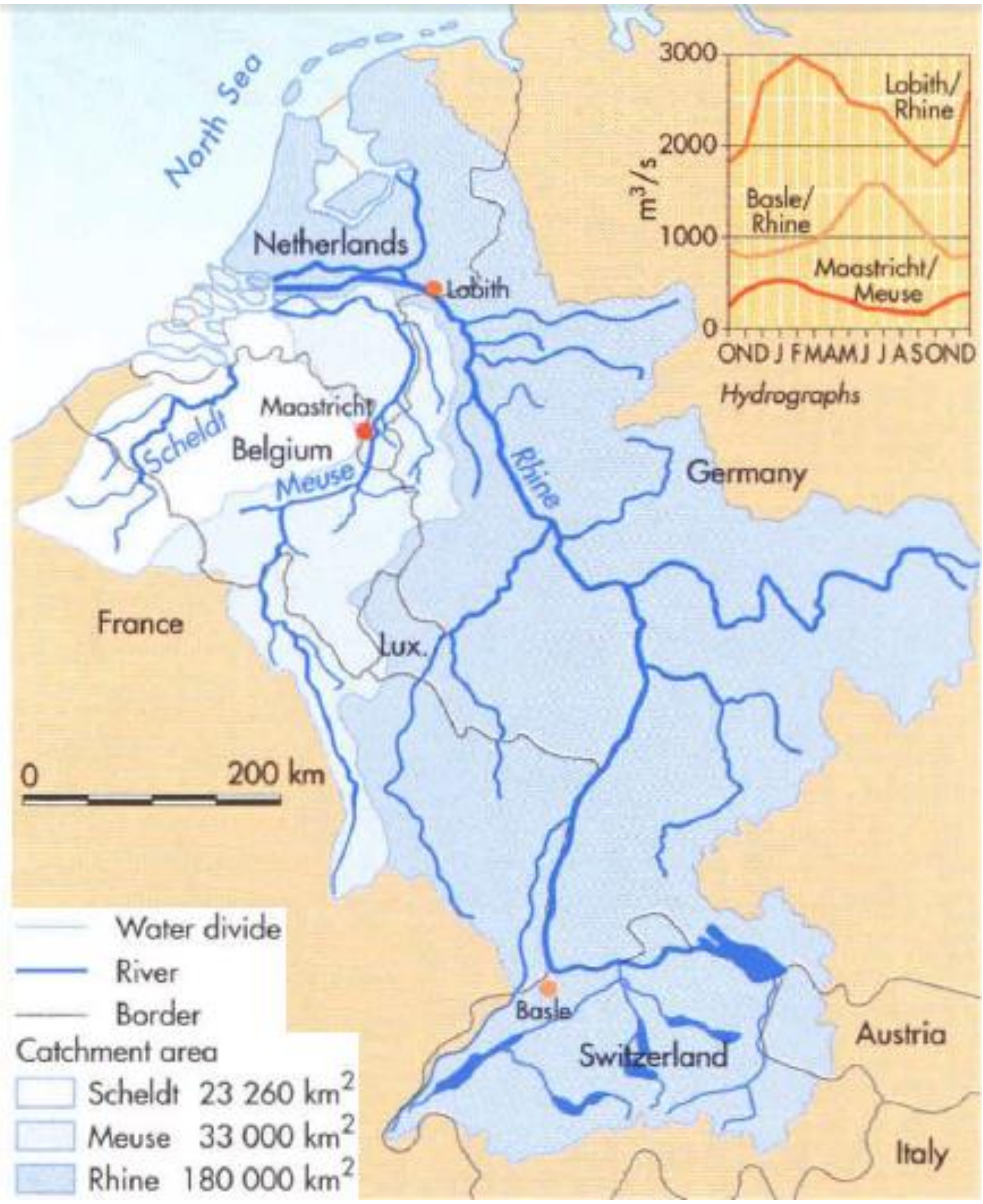


Figure 2.1 The Netherlands situated in the catchment of the river Rhine and Meuse

Deltares and TNO Geological Survey of the Netherlands contribute two pilots to the TACTIC project: a national and a regional pilot. For both pilots, two types of models are applied:

- Integrated hydrological model;
- Time series model.

The integrated models are based on the Netherlands Hydrological Instrument, NHI (de Lange et al., 2014). The time series models have been created using Metran (Berendrecht & van Geer, 2016).

The Netherlands Hydrological Instrument (NHI) (https://www.nhi.nu) is used for integrated hydrological modelling. It contains data and software for both the surface water and groundwater, based on iMOD (Vermeulen et al, 2020). The nationwide modelling is carried out with the LHM (National Hydrological Model) (Janssen et al., 2020), but the NHI also contains several regional models.

Metran is a tool for transfer noise modelling of groundwater head time series (Berendrecht & van Geer, 2016). It is applied to the groundwater head time series in the Dutch national subsurface database (https://www.dinoloket.nl/en/subsurface-data) on the groundwater tools website http://www.grondwaterstandeninbeeld.nl (Zaadnoordijk et al., 2019).

The National pilot of the Netherlands focusses on the groundwater simulations and interaction with the surface water at a national scale, based on 250 m grid cell calculations. On this scale the national hydrologic model (NHI-LHM) is typically applied in national policy studies in the Netherlands, for example to explore the effects of measures and climate change on the water quantity or water quality (salinity or nutrients). On this scale the model is also applied for national water management during drought, to decide on possible measure, for example concerning the weirs in the main water system in the (branches of) the Meuse and Rhine, and the management of the storage in lake IJsselmeer, which serves during drought as large fresh water reservoir in the Netherlands.

The regional pilot in the Netherlands, ‘de Raam’, uses a regional model of NHI (the GRoundwater model of waterboard Aa en Maas, ‘GRAM’, Deltares & Aa en Maas, 2020), which has been developed for regional water management. The concepts and data are based on the same instrument (NHI) as the national model, but the model is applied with extra and more detailed information and on a higher resolution, typically on 25 m grid cell basis. This model is used in several projects for regional water management, for example to decide on measures in the regional water system, to explore the effects of land use (mostly agricultural and natural) and the regional effects of climate change on the regional groundwater and surface water system.

3 PILOT AREAS

3.1 Site description and data

Two pilot areas will be explained in this chapter: The Netherlands and The Raam. The Raam is a catchment area of the stream with the same name, situated in the province of Noord-Brabant. Figure 3.1 shows the location of The Raam within the Netherlands.

Figure 3.1 The location of pilot area The Raam within the Netherlands.

Data needed for physically-based distributed groundwater modelling are available as open data via the NHI data portal (https://data.nhi.nu/) and additional data sources within the Netherlands:

- Meteorological data is available from the Royal Dutch Meteorological Institute KNMI (http://www.knmi.nl/nederland-nu/klimatologie-metingen-en-waarnemingen),
- Data about the large surface waters from Rijkswaterstaat (http://waterinfo.rws.nl)
- Subsurface data including groundwater head measurements are available via TNO Geological Survey of the Netherlands (https://www.DINOloket.nl).
- Soil data: http://www.bodemdata.nl/

3.1.1 Meteorological data

According to the Köppen system, the Netherlands has a temperate maritime climate (type Cfb) with relatively mild winters, mild summers and rainfall throughout the year. The precipitation of 890 mm per year (climate period 1981-2010) is quite evenly distributed throughout the year, see table 3.1. The evaporation is on average 540 mm per year.

Figure 3.2 shows the spatial distribution of the precipitation and evaporation in the Netherlands. Higher precipitation can be found in some Eastern parts in the North, middle and South of the country, as well as some polder areas in the Western part of the country. The Southwest of the Netherlands has the highest evaporation, with a decrease in evaporation in the North-eastern direction.

Meteorological time series are available from 35 weather stations (hourly and daily precipitation and evaporation) and about 300 precipitation stations (daily precipitation) in the Netherlands. Those data are used in the ground water modelling.

Table 3-1 Monthly precipitation in the Netherlands, averaged over 1981 – 2010 (Bot, 2016).

Month	Average precipitation [mm]
January	75
February	59
March	74
April	45
May	65
June	68
July	84
August	77
September	81
October	89
November	96
December	84

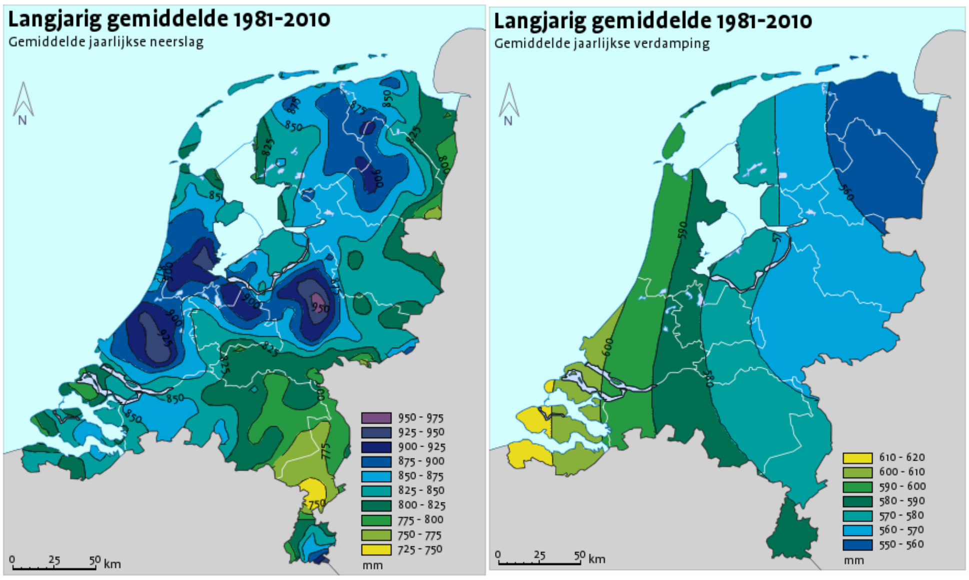


Figure 3.2 The average precipitation (left) and evaporation (right) for the period 1981 – 2010 in the Netherlands (KNMI, 2011).

3.1.2 Topography

Figure 3.3 shows the surface elevation of the Netherlands, based on public data for the Netherlands (AHN). Part of the Netherlands is below sea level; the lowest level is 6.7 m below mean sea level. In the South and East, the height of the landscape is relatively high. The maximum elevation in the central area of the Netherlands is about 100 meters above mean sea level; in the Southeast the highest elevation is 322 meters above mean sea level.

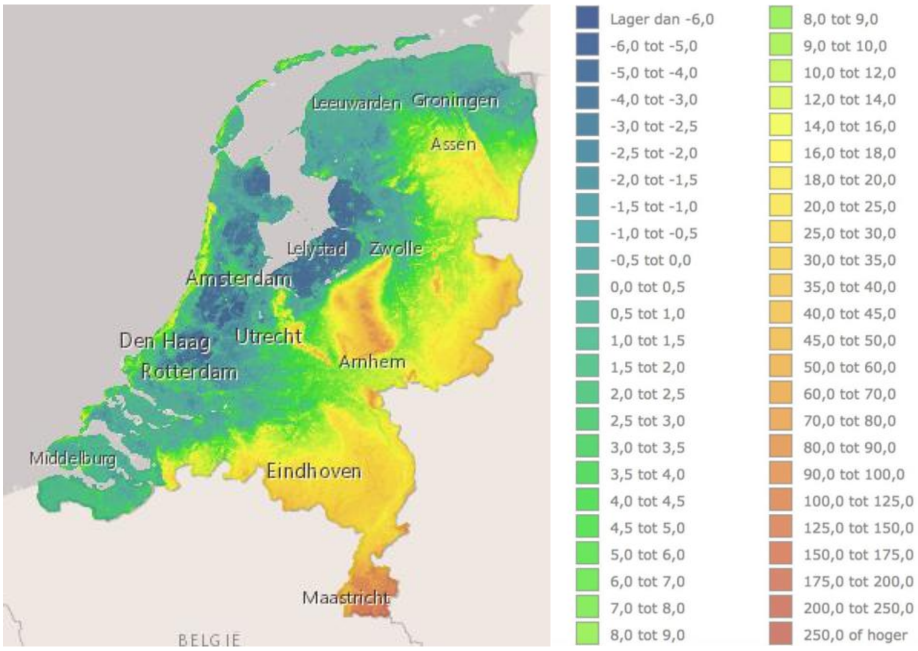


Figure 3.3 Surface elevation of the Netherlands, in meter above mean sea level (m+ NAP). Source: https://www.ahn.nl.

Figure 3.4 shows the surface elevation in the pilot area of De Raam (located between the cities of Arnhem and Eindhoven shown in Figure 3.3).

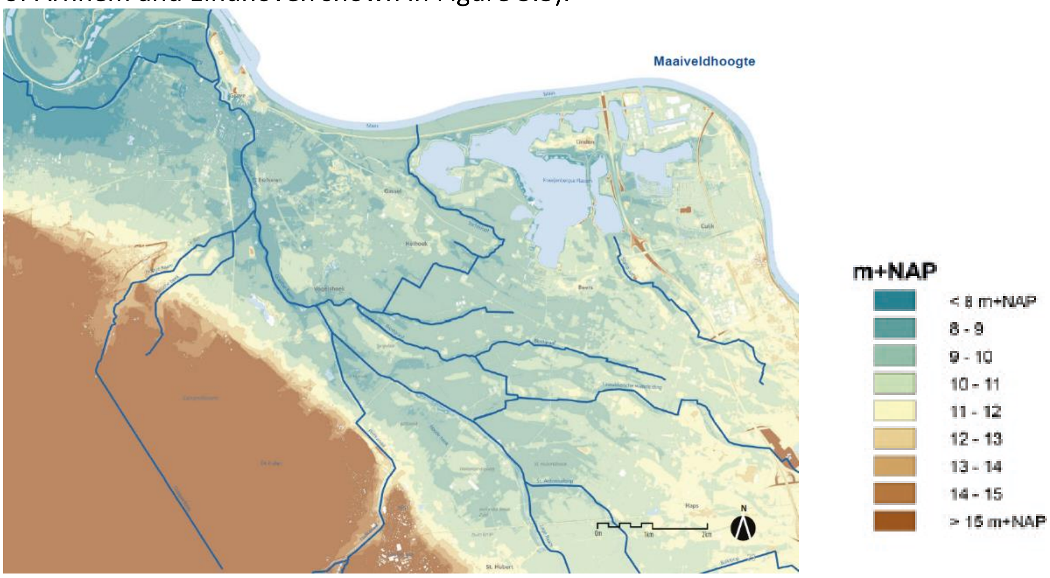


Figure 3.4 Surface elevation (m+NAP) of the area "De Raam" (Besselink, 2018).

3.1.3 Geology/Aquifer type

The Netherlands is located in the North Sea basin. Groundwater resources are limited primarily mainly to deposits of Quaternary age, which are the result of the interplay of rivers (Rhine, Meuse, Scheldt, and the previous Baltic river system Eridanos) and the North Sea.

Figure 3.5 gives a hydrogeological section across the country. It shows the Holocene confining layer, which is present in the Western and Northern parts of the country, the ice pushed ridges in the centre, and the clayey units of the marine Formations of Maassluis (MSk), Oosterhout (Ook), and Breda (BRk) which usually act as hydrological base depending on the location and context.

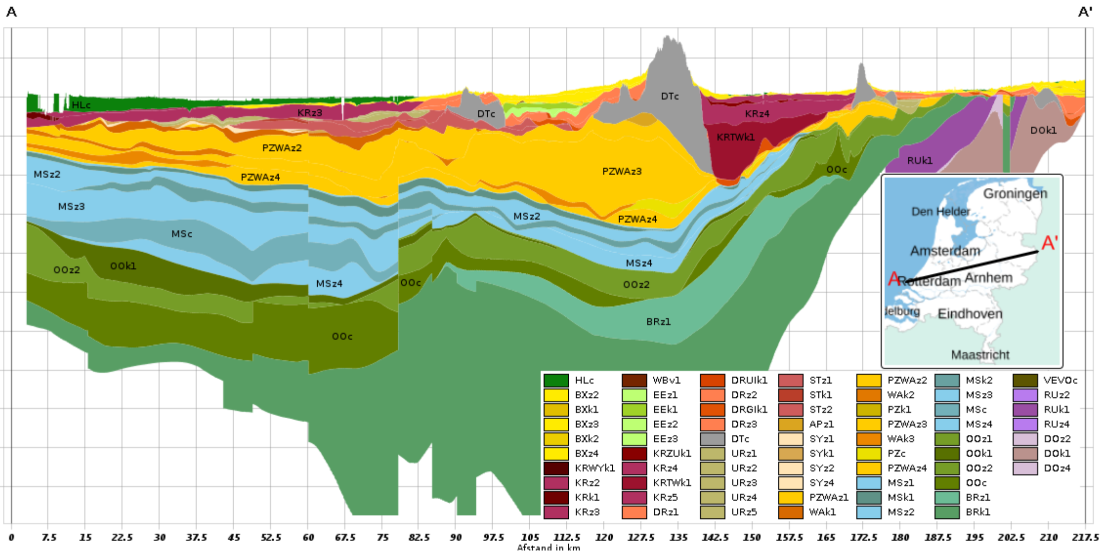


Figure 3.5 Hydrogeological units of the regional hydrogeological model REGIS II (see https://www.dinoloket.nl/en/subsurface-models) with the last two characters indicating sandy (z), clayey (k), or complex (c) units within the geological units.

The sandy units of the Formations of Kreftenheye and Peize & Waalre are important aquifers. Background information on the geological units can be found in the online stratigraphic nomenclator: https://www.dinoloket.nl/en/stratigraphic-nomenclature.

The South-eastern corner of the Netherlands has the highest elevations and also the subsurface is different from the rest of the country (Figure 3.6 and figure 3.3). There is a cover of loss and older geologic units come close to the surface, notably the chalk aquifers of the Formations of Gulpen (GUq), Maastricht (MTq), and Houthem (HOq).

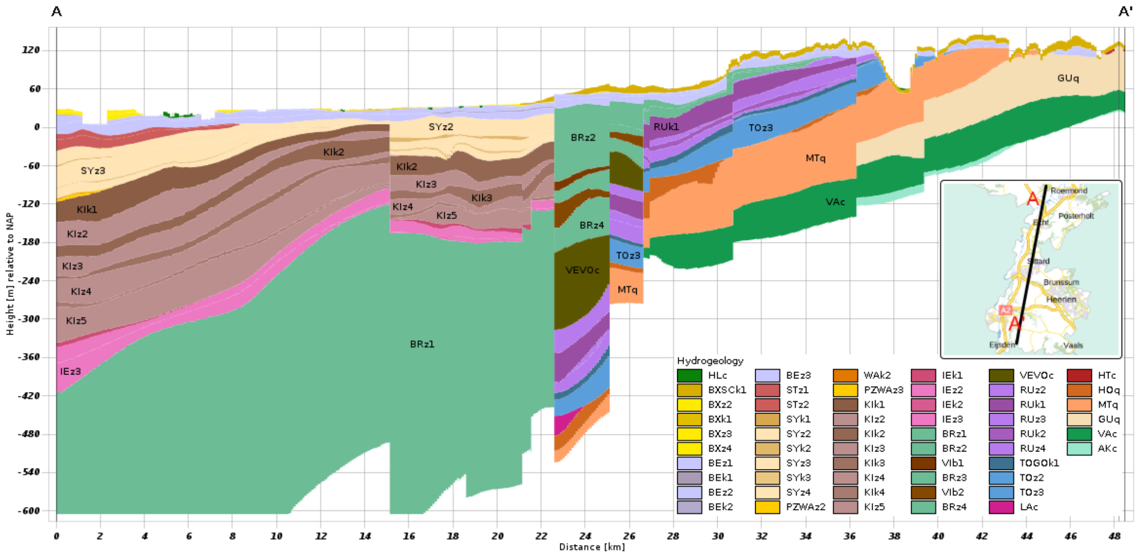


Figure 3.6 REGIS II section in South-eastern corner of the Netherlands with the highest elevation and the oldest deposits of the Netherlands.

3.1.4 Soil types

Figure 3.7 shows a soil map of the Netherlands, based on BIS (the Dutch Soil Database). The sandy soils occur in the South and East of the country. Along the main rivers, in the Southwest and in the North of the Netherlands, clayey soils can be found. The purple areas have peat soils and in the South-eastern corner, loamy soils occur. In the Raam area clayey soils can be found near the river Meuse in the North, and sandy soils in the South.

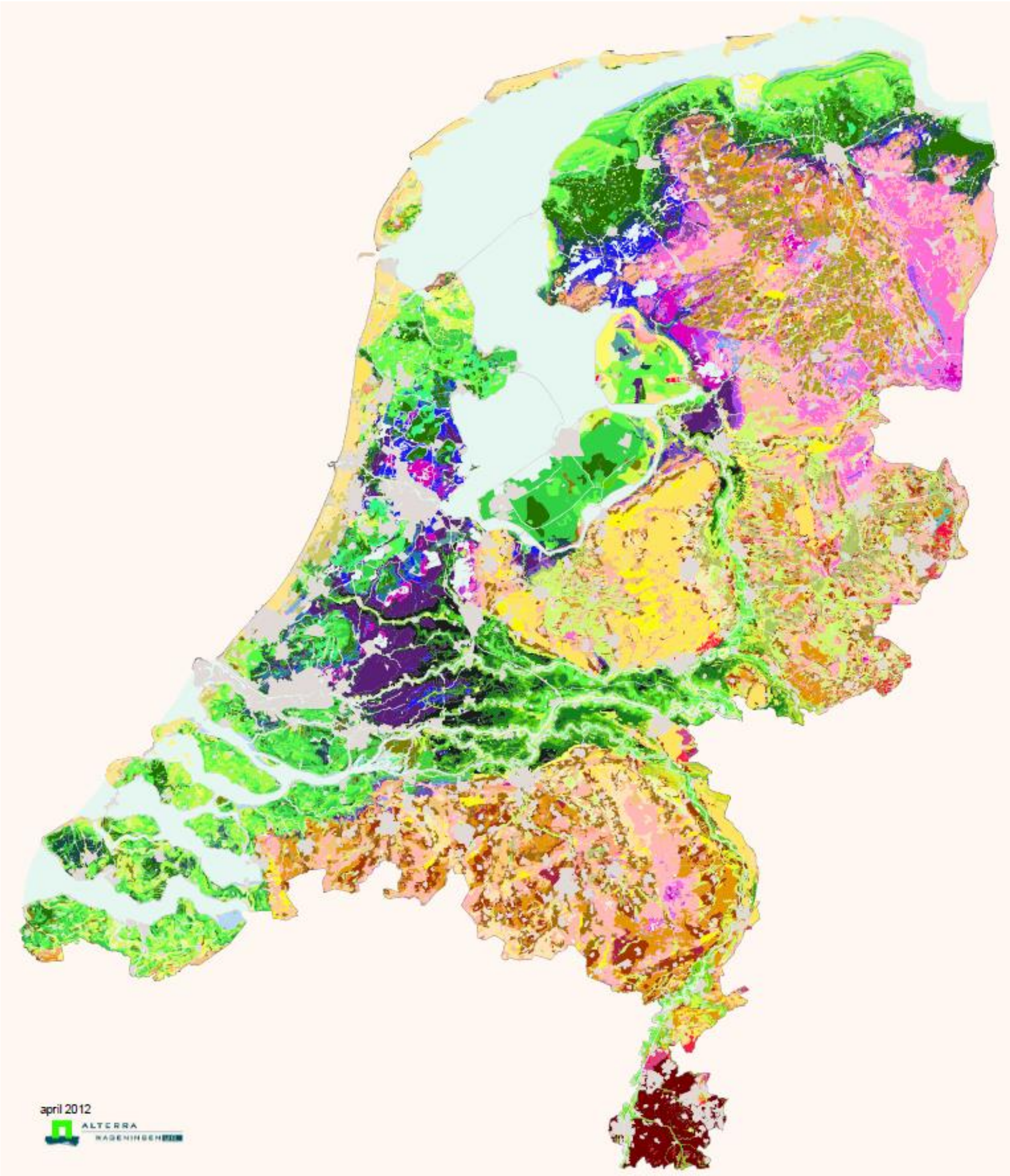


Figure 3.7 Soil types of the Netherlands (Wosten et al., 2012). The purple/blue colours are peat soils, the yellow/brown colours are sandy soils and green colours are clay soils. The dark brown colour in the South-eastern corner are loamy soils.

3.1.5 Surface water bodies

Figure 3.8 shows the largest surface water bodies in the Netherlands, including the larger river systems coming in from the East (Rhine) and Southeast (Meuse) (see also figure 2.1). The Scheldt flows from Belgium into an estuary in the Southwest. In the central West and North of the Netherlands lakes can be found, which are the result of peat extractions in the past. A larger zone in the North and the West of the country have many smaller water courses and ditches, mainly in the lower areas (see *Figure 3.3*) with clay and peat soils (see *Figure 3.7*). These water bodies have a controlled surface water level and strongly influence the phreatic groundwater level, often in combination with tube drainage. This way inundation is prevented in winter and for the polders with large upward seepage also in summer. The surface water system serves as a water supply system in times of drought. In the sandy areas in the East and the South, less water bodies are present and these do not provide water in times of drought. These regions are more dependent on precipitation and irrigation from groundwater.

Figure 3.8 Surface water bodies (Topografische Dienst Kadaster, 2019)

3.1.6 Land use

Figure 3.9 shows the different types of land use in the Netherlands. A large part of the area in the Netherlands is used for agriculture. Urban area is most concentrated in the central Western part, whereas in the Eastern part larger areas with forest and dry nature occur.

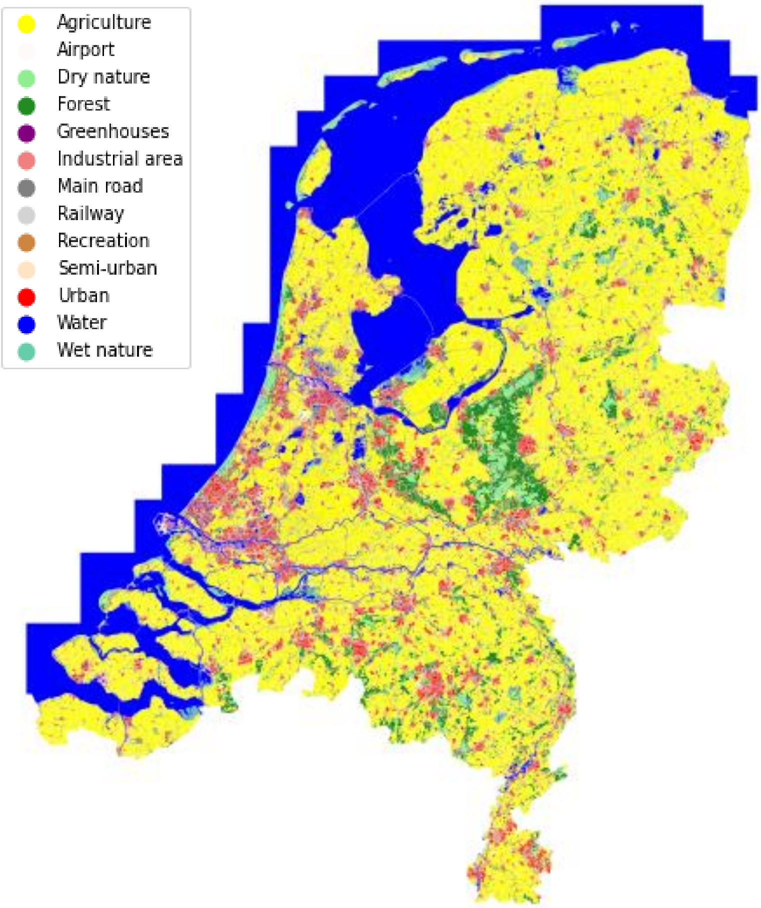


Figure 3.9. Land use types in the Netherlands (source: Dutch Statistical Bureau, CBS).

Figure 3.10 shows the different types of land use in De Raam, where mostly agricultural land can be found. Also, some urban areas and forests occur. The lakes in the Northeast are connected to the river Meuse, which is the North-eastern boundary of the area of De Raam.

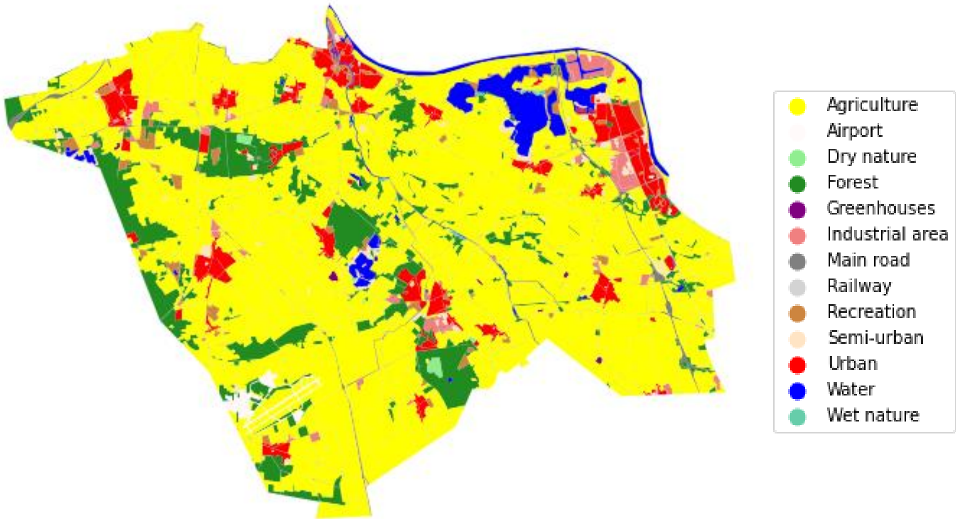


Figure 3.10 Land use types in the pilot De Raam

3.1.7 Abstractions/irrigation

Groundwater abstraction occurs in the Netherlands for drinking water production, industry and agriculture (for livestock and (overhead) irrigation). *Figure 3.11* shows the wells fields used for drinking water production. They are located in areas with fresh water aquifers, which mostly coincide with higher surface elevations (cf. *Figure 3.3*).

Figure 3.11: Blue dots indicate well fields for drinking water supply, yellow is groundwater extraction at the riverbank, orange are water infiltration locations, green is drinking water supply from surface water and red are emergency wells. The different areas indicate the regions of the drinking water supply companies (Vewin, 2017).

Figure 3.12 shows the locations of irrigation wells together with the locations where surface water is used for irrigation.

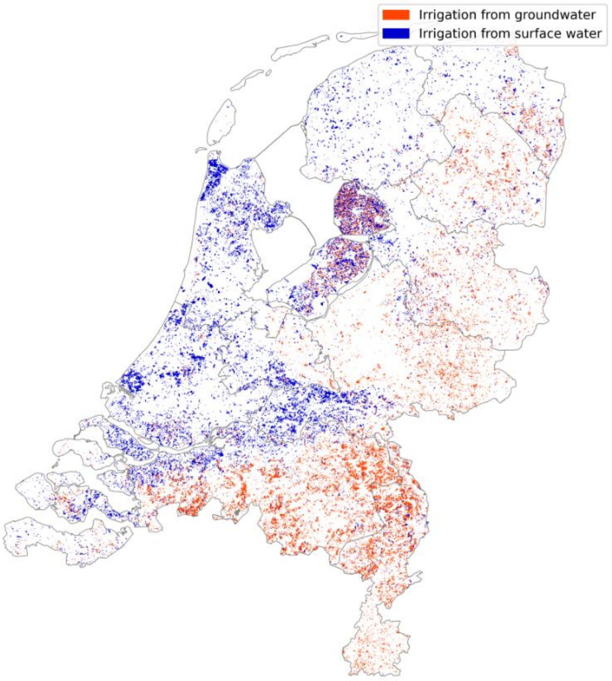


Figure 3.12: Locations of irrigation wells and irrigation from surface water (data available at https://www.nhi.nu).

3.2 Climate change challenge

3.2.1 How is the climate expected to change in the Netherlands

The Royal Dutch Meteorological Institute prepares climate change scenarios for the Netherlands. According to the most recent scenarios, climate change is expected to cause the following effects in the Netherlands (KNMI, 2015):

- Temperature will rise;
- Mild winters and hot summers will occur more often;
- Precipitation and extreme precipitation in the winter will increase;
- The intensity of extreme summer precipitation will increase;
- Hail and thunder will become more intense;
- Changes in wind speed are small;
- The amount of foggy days will decrease.

These predicted effects are aligned with the European Environment Agency map that describes the expected climate change across the different areas in Europe as shown in *Figure 3.13*. Scenarios for future climate change in the Netherlands are described by KNMI (KleinTank et al., 2015). In those scenarios the most likely changes in the Netherlands are described according to the latest insights.

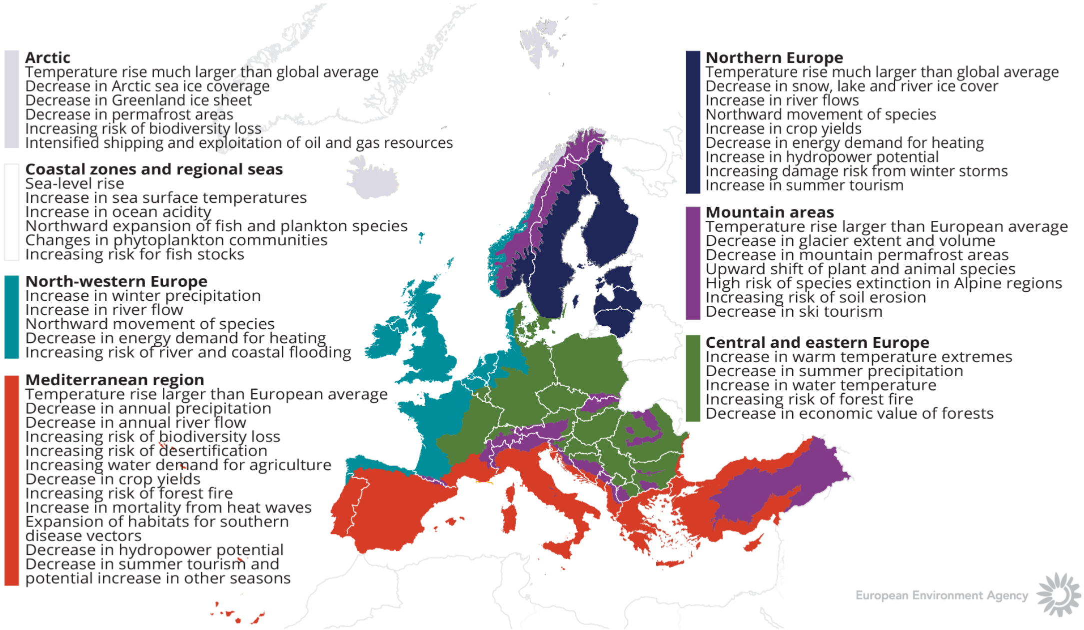


Figure 3.13. How is climate expected to change in Europe. The European Environment Agency map

3.2.2 What are the challenges related to the expected climate change?

Water shortage is one of the challenges from the extended droughts expected to result from climate change. This impacts many sectors, such as agriculture, ecology, and drinking water production, industrial water use, electricity production (because of restriction for cooling water), and transport (because of reduced depth of the rivers which are main waterways for shipping). Degradation of peat and emission of greenhouse gases threatens the peat areas (see *Figure 3.7*). In the Netherlands, lowering of the groundwater table in historical cities poses a special risk, because of wooden foundations of buildings that decay when they are no longer below the groundwater table.

Another major challenge is extreme precipitation, which can cause flooding. The threat from flooding is most severe in urban areas, where it is likely to be caused directly by precipitation. Streets can be covered by water, the ground floor of buildings may be flooded, and water can flow into basements. In addition, the sewer system may be overloaded, leading to sewage spilling into the surface water and causing water quality problems.

Sea level rise makes the coastal area more vulnerable for floods, and rivers more vulnerable for sea water intrusion.

4 METHODOLOGY

4.1 National Hydrological Model NHI-LHM

In 2005, Dutch national research institutes and the water authorities (both national and regional) started to combine their water expertise and financial means to construct a national water model: the Netherlands Hydrological Instrument NHI (https://www.nhi.nu). This had to replace various separated, partially parallel modelling efforts, such as the national models NAGROM (de Lange, 1991) and LGM (Lieste et al., 1993), and the regional model GMN (Iwaco, 1992). It started by bringing together the available data and technologies, resulting in a first version of the national model in 2008. In 2013, a next main version of NHI was achieved, based on the consensus of all national and regional water management organizations. An extensive description of the NHI can be found in De Lange et al. (2014).

The nationwide modelling is carried out with the LHM (National Hydrological Model), but the NHI also contains several regional models. The NHI contains a coupling of four sub-models, which together can simulate the groundwater, surface water and the vadose zone (see *Figure 4.1*). The groundwater is modelled with the use of iMOD (Vermeulen et al., 2020), which includes a Graphical User Interface developed by Deltares and an adapted version of MODFLOW 2005, to enable fast calculations in large domains. The surface water is divided into the regional surface water, modelled with the use of Mozart, and national surface water, which uses DM (Distribution Model) (De Lange et al, 2014). The vadose zone is modelled with the use of MetaSWAP (van Walsum et al., 2017). The grid cell size that is used in the NHI-LHM model is 250x250 m.

An important aim of the NHI is computing the water demand and allocation for different water users in periods of water scarcity. Therefore, the LHM is used within the National Water Model, a constellation of different models including water quality and effect modules for agriculture, terrestrial nature and other sectors. Besides, a special version of NHI is available for modelling salinity transport in the subsurface (Delsman et al, in prep 2021).

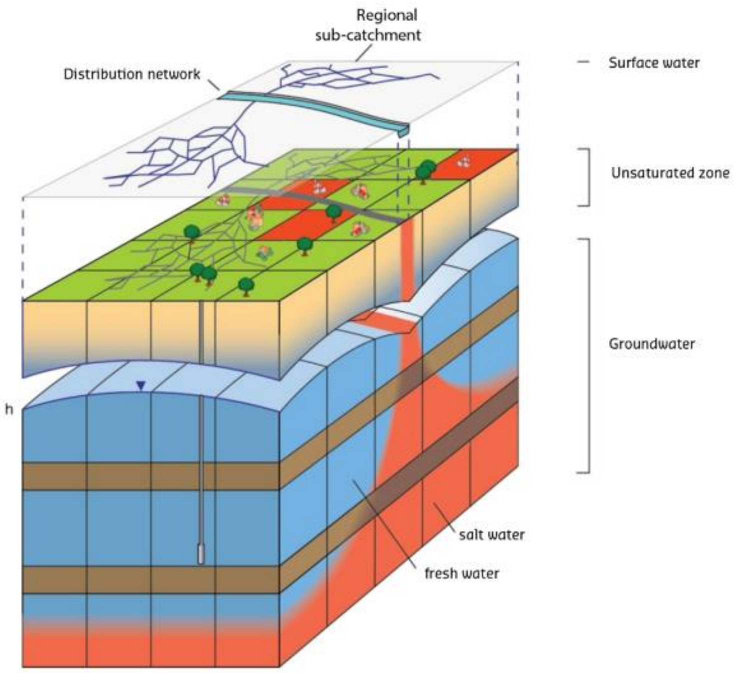


Figure 4.1 The hydrological components of the Netherlands Hydrological Instrument (NHI)

4.1.1 NHI components and coupling

The surface water is modelled on a large, national, scale with the Distribution Model (DM) and on local scale with Mozart. DM allocates water to various water users by optimizing the water demands. The allocation of water is calculated with water distribution rules, based on water management practice. This includes a prioritizing scheme for water scarcity, where first water is allocated to the most important category and then to the categories with lower priorities. These categories are as follows: 1: water safety (like dikes) or irreversible damage to nature areas. 2: public utilities (drinking water & energy). 3 & 4: for example agriculture, industry and recreation. MOZART is a lumped model, which calculates a balance for the surface water by accounting for withdrawals and discharges. MOZART is applied to every small catchment, resulting in a calculated surface water level that is coupled with the surface water levels in the corresponding MODFLOW cells.

The unsaturated zone is modelled with the use of MetaSWAP. This model computes the transfer of water between the saturated zone and the atmosphere, while also incorporating the root zone and vegetation. The coupling procedure is described by Van Walsum and Veldhuizen (2011). Recently the coupling procedure within NHI is improved by a BMI-coupling procedure, which is implemented in the original MODFLOW 6 code (Hughes et al., 2021, in prep.).

The groundwater, modelled with MODFLOW, interacts (drainage or infiltration) with the surface waters in MOZART. Other top system components in MODFLOW, the phreatic storage coefficient, phreatic head and the flux to and from the unsaturated zone, are based on information of MetaSWAP. Furthermore, the irrigation demand is calculated by MetaSWAP which results in a water demand for surface water in MOZART or groundwater in MODFLOW.

Recently, the national model has been extended with the crop growth model WOFOST (Hunink et al., 2019). This detailed crop model is coupled to MetaSWAP. By using WOFOST, the crop growth is not fixed input for the groundwater model, but calculated dynamically, depending on the condition in the soil and the atmosphere. This enables improved calculations of evapotranspiration, also for climate changes, because effect of changing temperatures and higher CO_2 concentrations on the crop growth can be taken into account.

The calculation of actual evapotranspiration of the crops within the combination MetaSWAP-WOFOST is based on Penman-Monteith, which is not directly compatible with the TACTIC climate scenarios with the delta change factors. Also, these scenarios do not contain carbon dioxide concentrations. This means that within the climate scenarios for TACTIC, the WOFOST option is not used.

4.1.2 NHI-LHM version and calibration

The national modelling is carried out with LHM version 4.1 (Janssen et al., 2020). The geohydrological schematization is represented by 8 model layers within NHI-LHM, based on geohydrological models of the Netherlands: REGIS II V2.2 (TNO-GSN, 2021a) and GeoTOP (TNO-GSN, 2020b).

NHI-LHM (version 4.1) has been calibrated in steady state mode using the average groundwater heads for the period 2011-2018 of piezometers available in the national subsurface database (https://www.dinoloket.nl/en/subsurface-data). The calibration was carried out by using the iPEST software, which an implementation in iMOD (Vermeulen et al., 2020) of the parameter estimation package PEST (Doherty, 2015). The calibrated parameters were the aquifer transmissivities, aquitard resistances, drainage conductances, and the conductances of the groundwater-surface water exchange.

To evaluate the reliability of the model, NHI currently is extensively validated, in close collaboration with a broad group of stakeholders (Rijkswaterstaat, provinces, water boards and drinking water companies) covering the entire country, each bringing in their system knowledge and validation field data (Klopstra et al., 2021 in prep, Janssen et al., 2021 in prep). Recommendations for model improvement resulting from this validation will be implemented in the next version of the national model.

4.2 Regional groundwater model used in de pilot Raam

The regional NHI model of De Raam is developed by Waterboard Aa en Maas, based on the same software and data as in NHI-LHM 4.1. However, the spatial discretization is more refined and more detailed information is used. Therefore, the model is better equipped for regional analysis than the national model. The most important differences with the national model are:

- The grid size is 25x25 m (instead of 250 m);
- The subsurface is divided into 19 layers (instead of 8 layers);

- The meteorology is based on data from Meteobase (http://www.meteobase.nl), which includes extra radar data (instead of data from weather and precipitation stations of the Royal Dutch Meteorological Institute KNMI);
- The surface water levels in the smallest water bodies (the small ditches) are derived from a detailed Digital Elevation Model (DEM: the surface elevation along the ditch). This yields more detailed information for the surface water levels compared to the database of the waterboards used in the national model;
- The regional modules for the unsaturated zone (MetaSWAP) and for groundwater (MODFLOW) can be coupled to a hydraulic model for the surface water (instead of using only surface water routing through MOZART and the Distribution Model DM). Note that this has not been applied for the analysis of the TACTIC climate change in this report.

The groundwater model has been calibrated, based on measurements of groundwater heads in the period 2007 - 2016 (Bos-Burgering and Hunink, 2020).

4.3 Metran

The software Metran (Berendrecht & van Geer, 2016) is used for the time series modelling (Zaadnoordijk et al., 2019). The groundwater level time series is split into a deterministic part and a stochastic part (*Figure 4.2*). The deterministic part represents the variation due to the specified explanatory variables. For the models on the 'groundwatertools' website (http://www.grondwaterstandeninbeeld.nl), these are precipitation and potential evapotranspiration. It is possible to include additional influences, like surface water levels or a general trend. The difference between the deterministic part and the measurements is called the model residual.

A noise model is used for the stochastic part. The purpose is to remove the autocorrelation in the residuals. The smaller the time steps between the measurements, the larger the autocorrelation. The existence of autocorrelation decreases the reliability of the model. We use a noise model with an exponential decay. The inverse of the noise model is applied to the residuals to obtain so-called "innovations".

The explanatory variables are convoluted with an impulse response function (see e.g. Kreyszig, 2012): the value of each day is multiplied by the response function and the results are summed. An incomplete gamma distribution is used for the impulse response function (Berendrecht & Van Geer, 2016). It has three parameters, a multiplication factor A* and two shape parameters a and n (Besbes & de Marsily, 1984). For the groundwatertools website, the same function is used for precipitation and potential evapotranspiration except for a factor. This leads to five parameters to be optimized: three of the precipitation response, one evaporation factor, and one noise model parameter. The parameters are determined by a minimization procedure for the innovations.

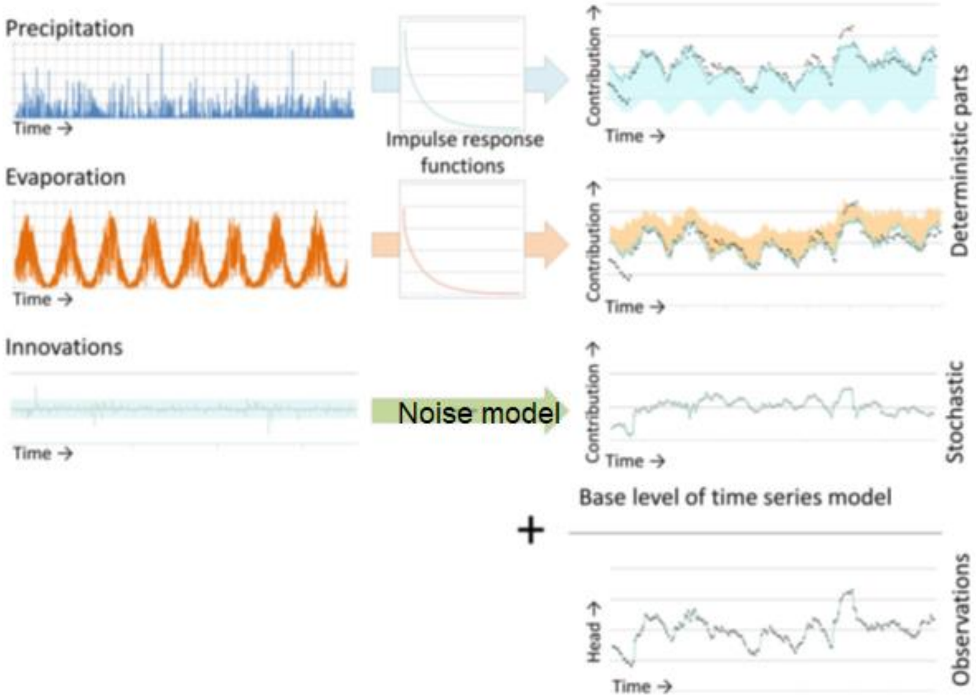


Figure 4.2 Setup of transfer function-noise model used for modelling head time series in Metran

The resulting time series models are evaluated using model evaluation criteria among which the explained fraction of the groundwater variation (Zaadnoordijk et al., 2019). Three classes are distinguished: bad models, reasonable models, and good models. The bad models are not shown on the website. The analysis in this report uses only the good models.

4.4 Climate change scenarios

In order to arrive at results that are inter-comparable for all of Europe a new procedure for selection of climate change scenarios has been developed within TACTIC.

The climate change scenarios have been based on climate data from the Inter-Sectoral Impact Model Inter-comparison Project (ISIMIP). These data consist of ensembles of 15 models: three Representative Concentration pathways (RCP) applied to five Global Climate Models. The spatial resolution is 0.5° and the temporal resolution 1 day. Two criteria were used to select an ensemble member (Sperna Weiland et al., 2021, in prep.):

- a global warming level of +3 degrees and +1 degrees, relative to a reference period (1980-2010);
- the 2nd highest and 2nd lowest scenario are selected, using the following indicators for regional climate change response: European mean temperature change, regional (case specific) precipitation change, regional net precipitation change and regional temperature change.

4.4.1 TACTIC standard Climate Change scenarios

The TACTIC standard scenarios are developed based on the ISIMIP (Inter Sectoral Impact Model Inter-comparison Project, see www.isimip.org) datasets. The resolution of the data is 0.5°x0.5° 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.

Table 4-1 shows the RCP-GCM combinations employed for the analysis of the Dutch pilots in the TACTIC project. The average delta change factors for precipitation and evaporation for the national pilot and the pilot De Raam are shown in *Table 4-2* and *Table 4-3*, respectively.

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

Table 4-2. Average delta change factors per climate change scenarios for the national pilot.

Netherlands	P	PET
1ºC min	0.986	1.087
1ºC max	1.056	1.086
3ºC min	0.969	1.082
3ºC max	1.139	1.087

Table 4-3. Average delta change factors per climate change scenarios for pilot De Raam

Pilot area: Raam	P	PET
1ºC min	0.985	1.089
1ºC max	1.051	1.093
3ºC min	0.973	1.081
3ºC max	1.146	1.094

The yearly averaged factors in *Table 4-2* and *Table 4-3* show only small differences for the national pilot and the regional pilot De Raam. The monthly factors show some more variation as can be seen in *Figure 4.3*. This illustrates the deviations that may be expected when applying a single set of change factors for an area as large as the Netherlands.

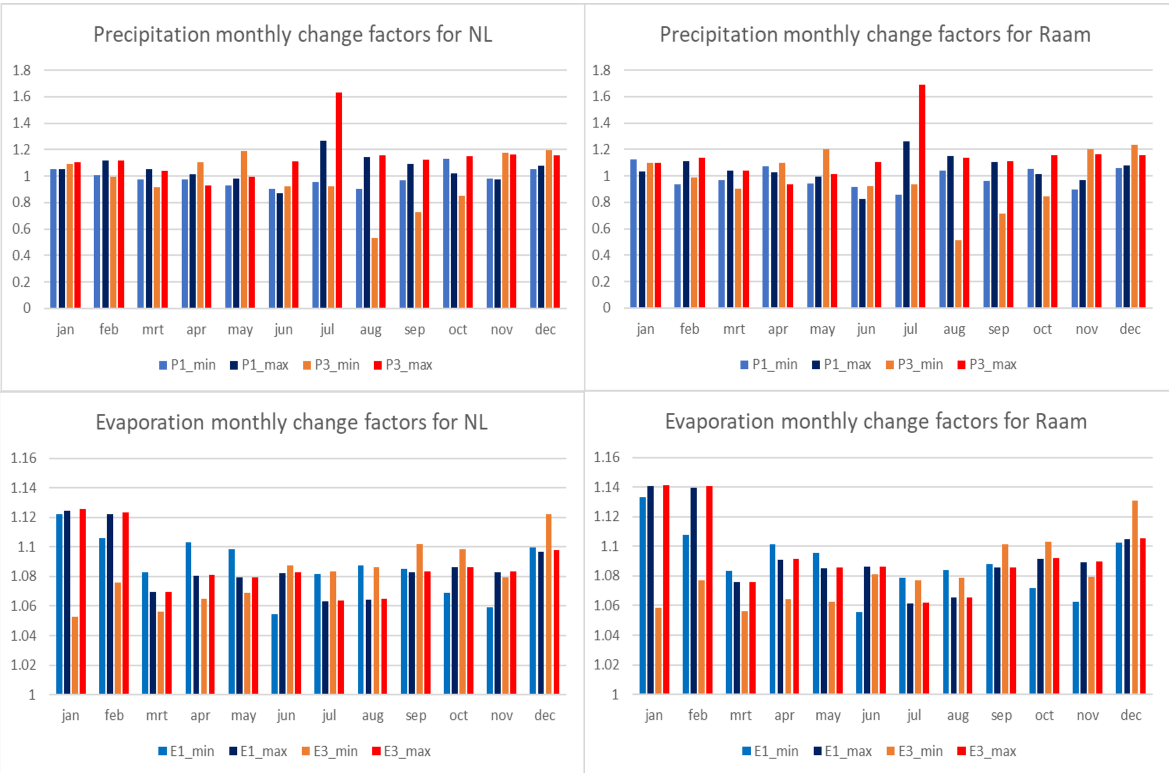


Figure 4.3. Delta change factors per month for the Netherlands (left) and De Raam (right).

5 RESULTS

This chapter presents the results for the national pilot and the pilot De Raam in separate sections (Section 5.1 and 5.2). Within these sections, results are presented for the reference period and the climate scenarios. Within these subsections the Integrated hydrological modelling (NHI) and the time series modelling are discussed independently.
Comparisons between the results in the various subsubsections are presented in the Discussion chapter (Chapter 6).

5.1 National pilot

The national pilot covers the entire country of Netherlands.

5.1.1 Reference period results

5.1.1.1 Integrated hydrological model

This subsubsection gives the results of the integrated model (NHI-LHM, see Section 4.1) of the national pilot. The model simulations have been carried out with LHM version 4.1. Although larger time series have been calculated with the model for the reference period, from 1980 - 2020, the following analysis focusses on the results in the period 2011 – 2018. This period is used more often for analyses of results of the national model, because extensive measurement sets are also available for this period, which allows extended validation of the model results. Besides, for this period also results are available for the regional pilot, which makes it easier to compare the national and regional approach.

In Figure 5.1, the phreatic head distribution and the deep groundwater heads are shown, averaged over the simulation period 2011 – 2018. The deep groundwater heads are the heads in Layer 4 of the model. Layer 4 is chosen, because this layer contains most of the groundwater abstraction wells in the Netherlands. In *Figure 5.2*, the typical winter and summer phreatic head are shown. The left picture is the typical winter head, which can be considered as the highest mean. This is a typical Dutch statistic of the water table depth. It is calculated as the yearly mean of the three highest phreatic heads calculated on every 14th and 28th day in a month, which is then averaged over the simulation period (in this analysis: 2011-2018). Similarly, the typical summer head (figure on the right), is calculated as the mean of the three lowest phreatic heads within a year, which is subsequently averaged over the same simulation period.

The average phreatic head illustrates the differences between the low-lying and higher parts of the Netherlands. In the reclaimed parts of the Netherlands (some typical polder areas mainly in the central and Western part of the Netherlands), the phreatic groundwater table is close to the ground surface. In the sandy ridges, the water table is at a higher depth below the surface area. A clear example is the Veluwe in the middle of the country, with phreatic heads at a depth of over 10 meter below ground level. In those typical infiltration areas with deep ground water levels, also higher model errors (> 1 m) might be found, when validation the model with measurements (figure 5.3). The typical winter and summer phreatic heads show the dynamics of the groundwater levels during a year. In the winter, the ground water level is almost at surface level in the Western and Northern parts of the Netherlands. In the driest period in the summer, the water table in these regions is about 1 meter lower compared to the winter situation.

Figure 5.1 shows that the deep groundwater heads in the regions with a low elevation are very high, often above surface level. This indicates that there is an upwards seepage flux in these areas.

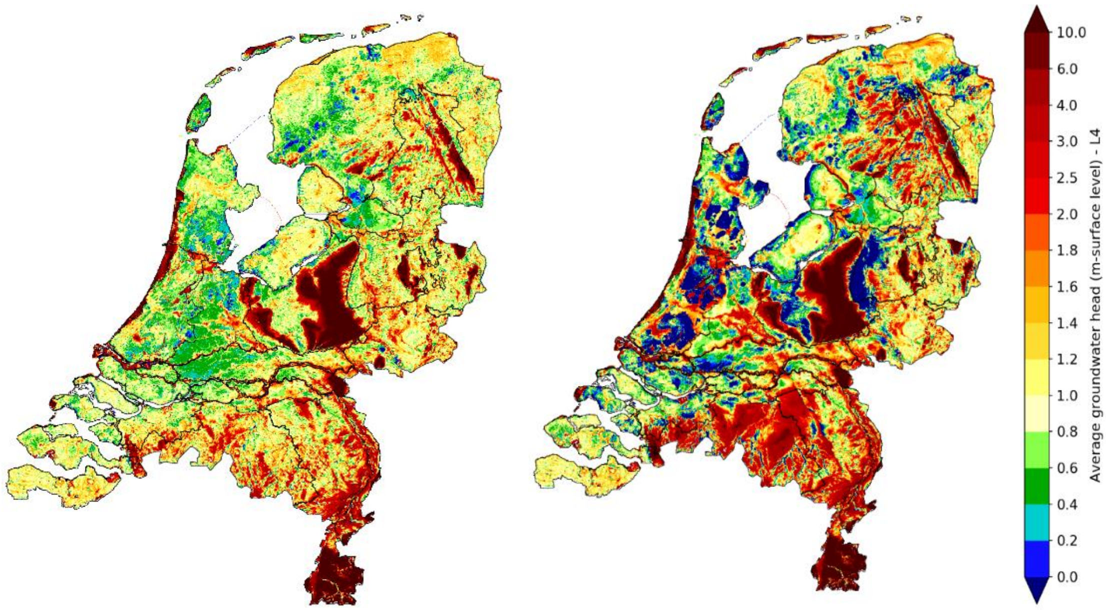


Figure 5.1. Average phreatic head (left) and deep groundwater head (model layer 4) in m below surface level.

Due to the seasonal variation mostly of evaporation and water use, the groundwater heads have a seasonal dynamic. This is illustrated by the high and low groundwater levels in *Figure 5.2*. These are the depth below the surface of approximately the 87.5th and 12.5th percentile of the groundwater table.

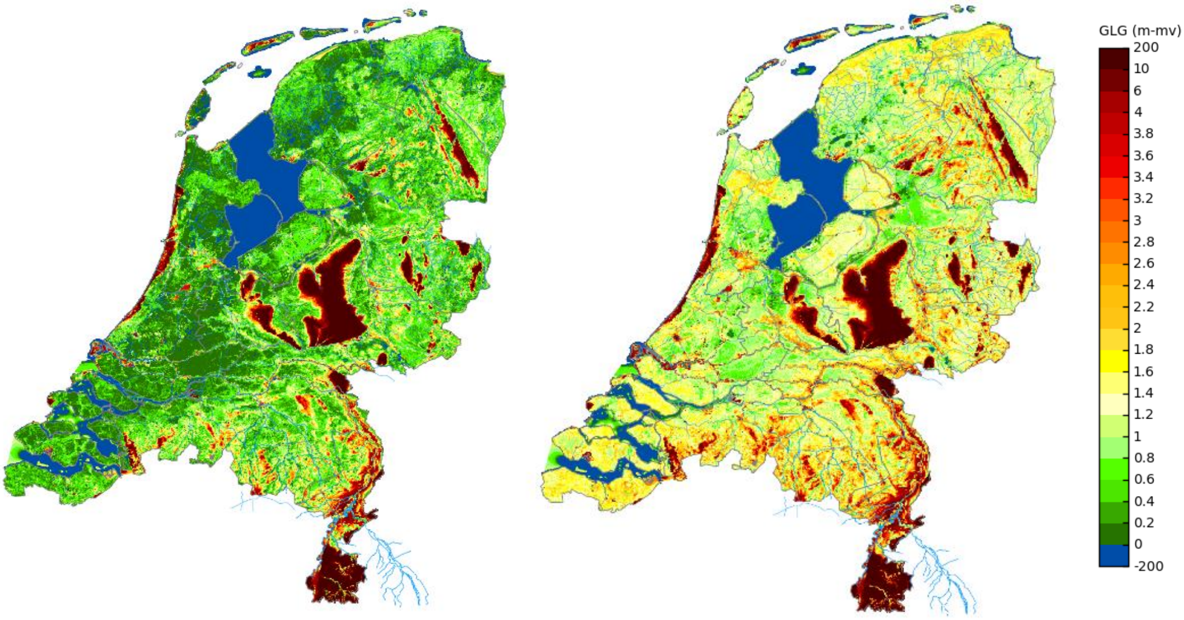


Figure 5.2. Average high (left) and low (right) groundwater levels in m below the surface level (approximately the 87.5th and 12.5th percentile).

The average high (GHG) and low (GLG) groundwater table is used for validation. *Figure 5.3* gives an example of the comparison of calculated and measured values for NHI-LHM version 4.1 for GHG, GLG and the difference between these (yearly dynamic).

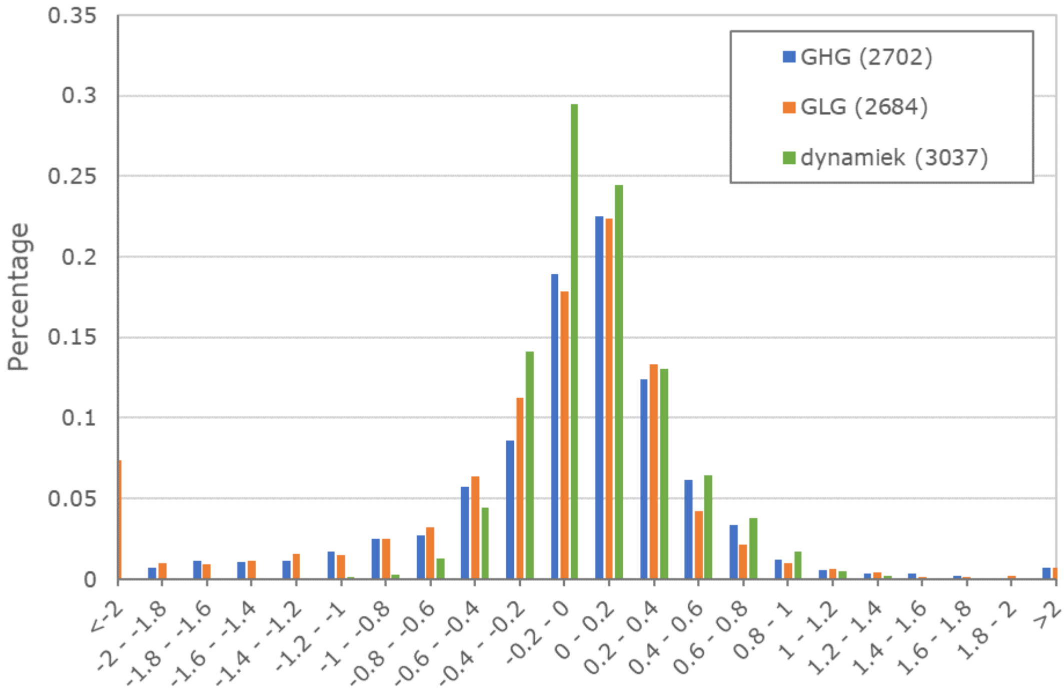


Figure 5.3. Example of validation of the calculated groundwater levels in LHM 4.1: the distribution (percentage on vertical axis) of prediction errors of calculated phreatic heads expressed in average high levels (GHG, approximately 87.5th percentile), average low (GLG, approximately 12.5th percentage), and the difference between GHG and GLG (yearly dynamics: "dynamiek"). Source: Berendrecht (2021).

NHI-LHM does not only calculate heads, but also fluxes. Due to the amount of detail in the schematization of the top system, groundwater recharge can be determined according to various definitions. *Figure 5.4* gives two examples: the effective precipitation and the recharge at the groundwater table.

The yearly effective precipitation is calculated as the difference between the yearly precipitation and the yearly potential evaporation. The left picture in *Figure 5.4* shows the average effective precipitation according to the national model (LHM) in the period 2011-2018. The reference situation shows that on a yearly basis, the Western and Northern part of the Netherlands are the areas that receive most precipitation. In these regions, the yearly average of the effective precipitation is positive. The South and East are dryer, where a small region stands out with negative effective precipitation (the higher potential evaporation is higher than the precipitation).

The groundwater recharge is calculated as the difference between the precipitation and the evapotranspiration and surface runoff, as calculated within the coupled models MetaSWAP and MODFLOW. This groundwater recharge which enters the upper boundary of the MODFLOW model is shown in the right picture of *Figure 5.4*. The reference situation shows that the calculated recharge is slightly higher in the lower part of the Netherlands: the Western and Northern areas. In the higher, sandy parts of the Netherlands, the recharge is slightly lower. These spatial differences are similar to the distribution of a high and low effective precipitation.

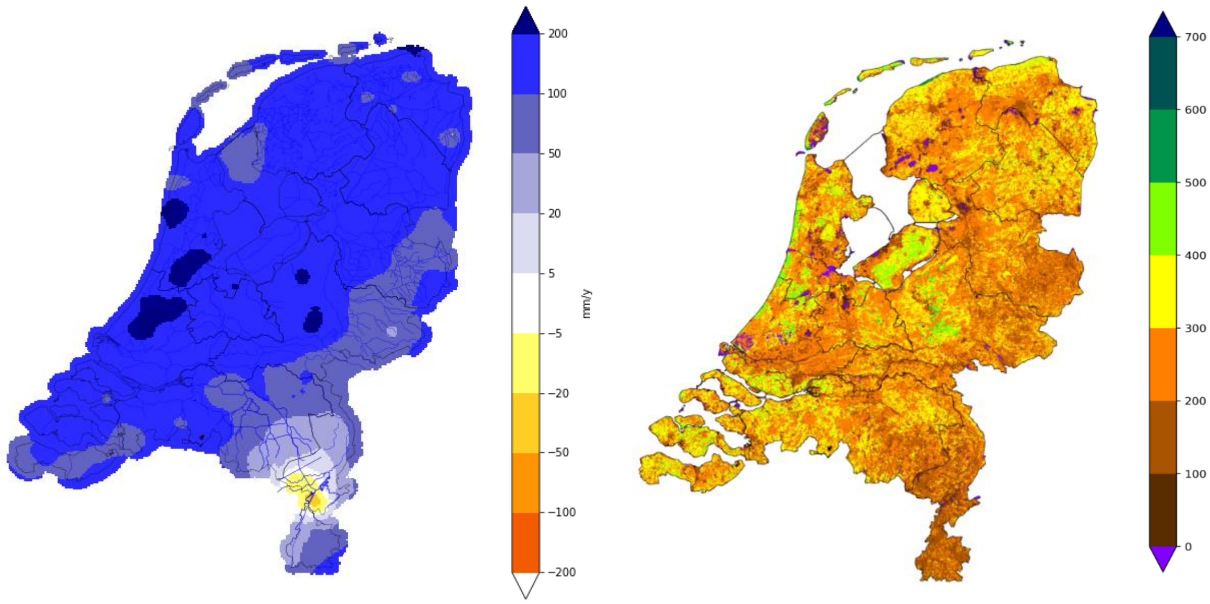


Figure 5.4. The average yearly effective precipitation in mm/year for the LHM (left) and average groundwater recharge in mm/year for the LHM (right)

Figure 5.4 illustrates that the recharge differs significantly from the net precipitation surplus, which mainly indicates large differences between reference evaporation (meteorological input for the model) and actual evapotranspiration (hydrological output of the model).

The surface water discharges, which are shown in *Figure 5.5*, contain the fluxes for all surface water systems as calculated by MODFLOW (DRN and RIV systems). The direction of these fluxes are relative to the groundwater system. This means that a negative flux describes water that is abstracted from the groundwater, whereas a positive flux is water that infiltrates the groundwater system. The discharge flux is generally negative, meaning the surface water bodies gain water from the groundwater. The West and North of the country have a very high density of surface water bodies, whereas the East and South show larger areas without surface water discharge.

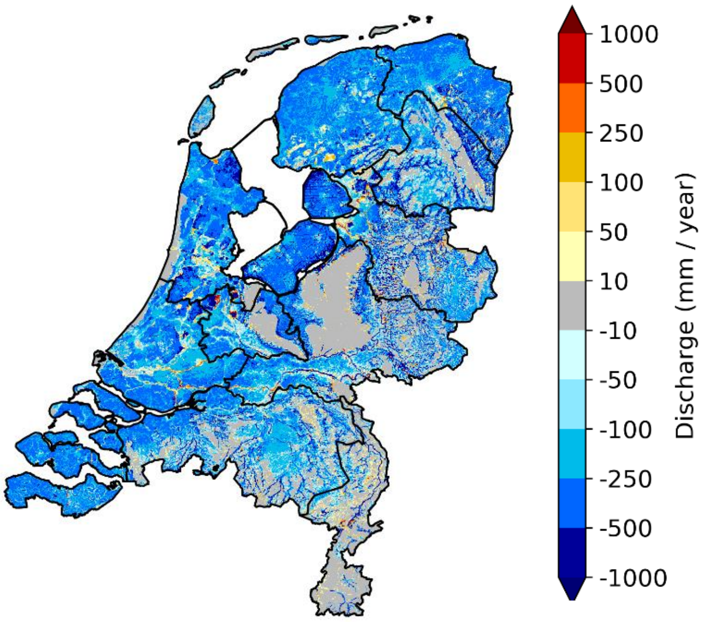


Figure 5.5. Average discharge of all surface water systems in mm/year

5.1.1.2 Time series models

The ground water tools website http://www.grondwaterstandeninbeeld.nl provides time series models for all groundwater head time series of the piezometers in the national database with subsurface data https://www.DINOloket.nl/en/subsurface-data. The time series models have been created by Metran (see Section 4.3). The precipitation response is related to the properties of the groundwater system (Zaadnoordijk & Lourens, 2019). The response can be characterized by the total response (or unit step response, i.e. the final value of the groundwater head change due to unit step change of the precipitation) and the median response time. These values usually are reliable for the models of good quality (Zaadnoordijk, 2018). See Section 4.3 and Zaadnoordijk et al., 2019 for the quality assessment of the time series models.

Figure 5.6 shows the total response from the piezometers in the upper regional aquifer of NHI-LHM with a good time series model.

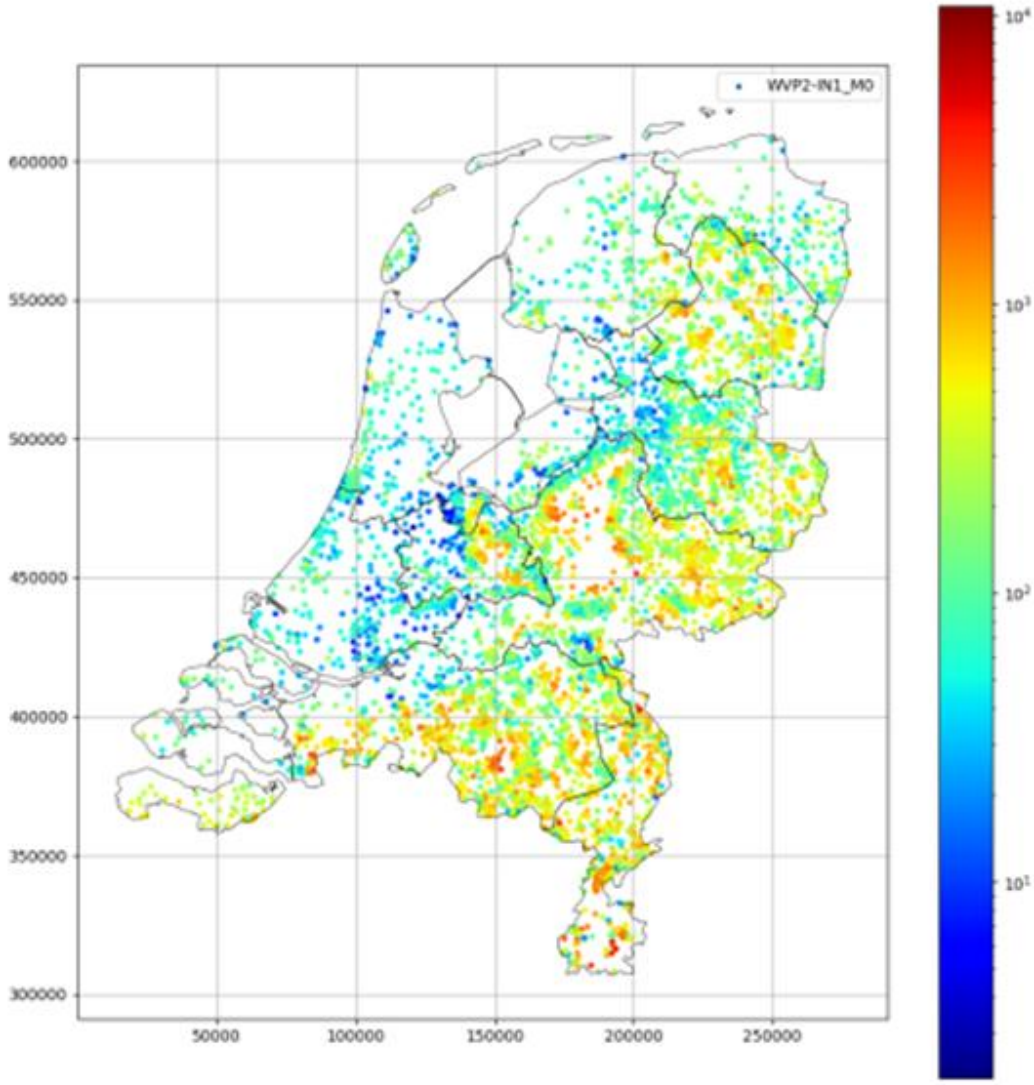


Figure 5.6 Total precipitation response (M0 or unit step response [100 day] groundwater head in cm over precipitation in meters per day) in the transfer-noise models for the upper regional aquifer (NHI-LHM code WVP2). Source: Zaadnoordijk & Lourens, 2019).

The pattern of the median precipitation response time in *Figure 5.7* is similar to that of the total response (*Figure 5.6*) with higher values in the East and South.

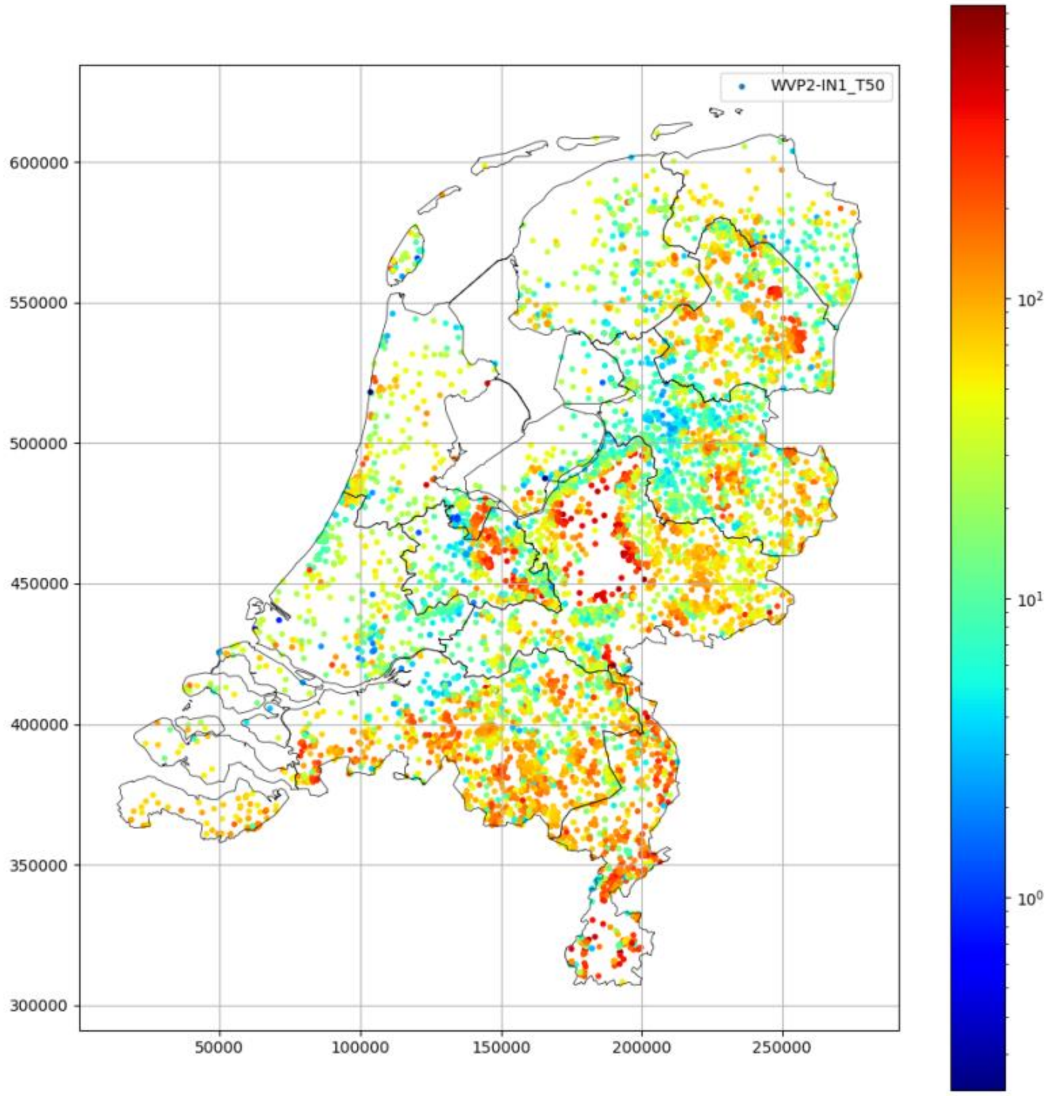


Figure 5.7 Precipitation response time (t50 [days]) in the transfer-noise models for the upper regional aquifer (NHI-LHM code: WVP2). Source: Zaadnoordijk & Lourens, 2019.

Under various assumptions, the evaporation coefficient of the Metran models can be used to determine a crude estimate of the long term average recharge (Obergfell et al., 2019). *Figure 5.8* and *Figure 5.9* show the values on a map for the piezometers located in the two upper model aquifers of NHI-LHM. The maps do not show an apparent spatial pattern. Comparisons of the Metran estimates with the groundwater recharge calculated by NHI-LHM are given in Sub-subsection 6.4.2.1 .

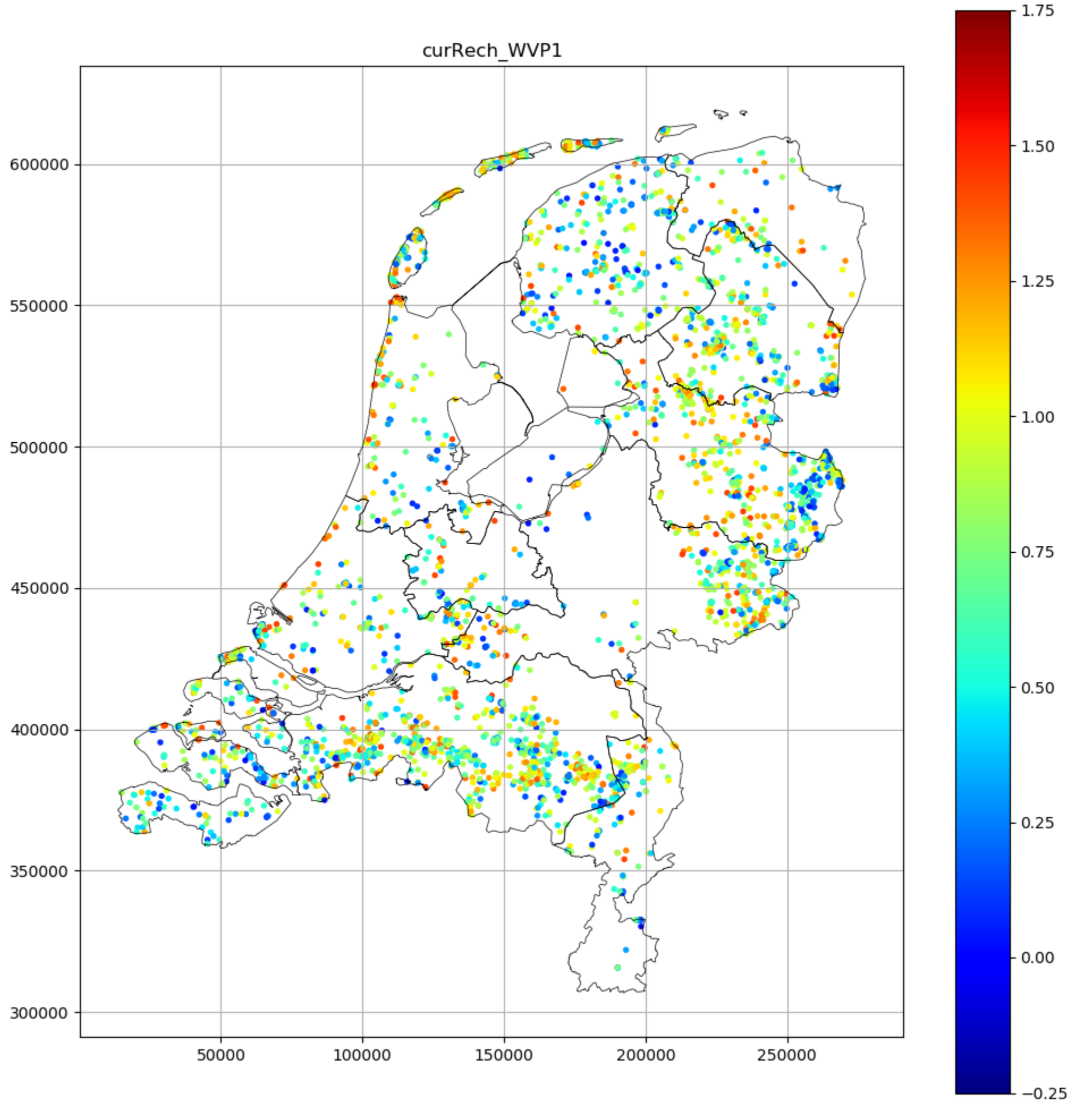


Figure 5.8 Crude estimate of groundwater recharge [mm/day] from evaporation factor in Metran models of piezometers in NHI-LHM modelaquifer 1 (phreatic water table aquifer).

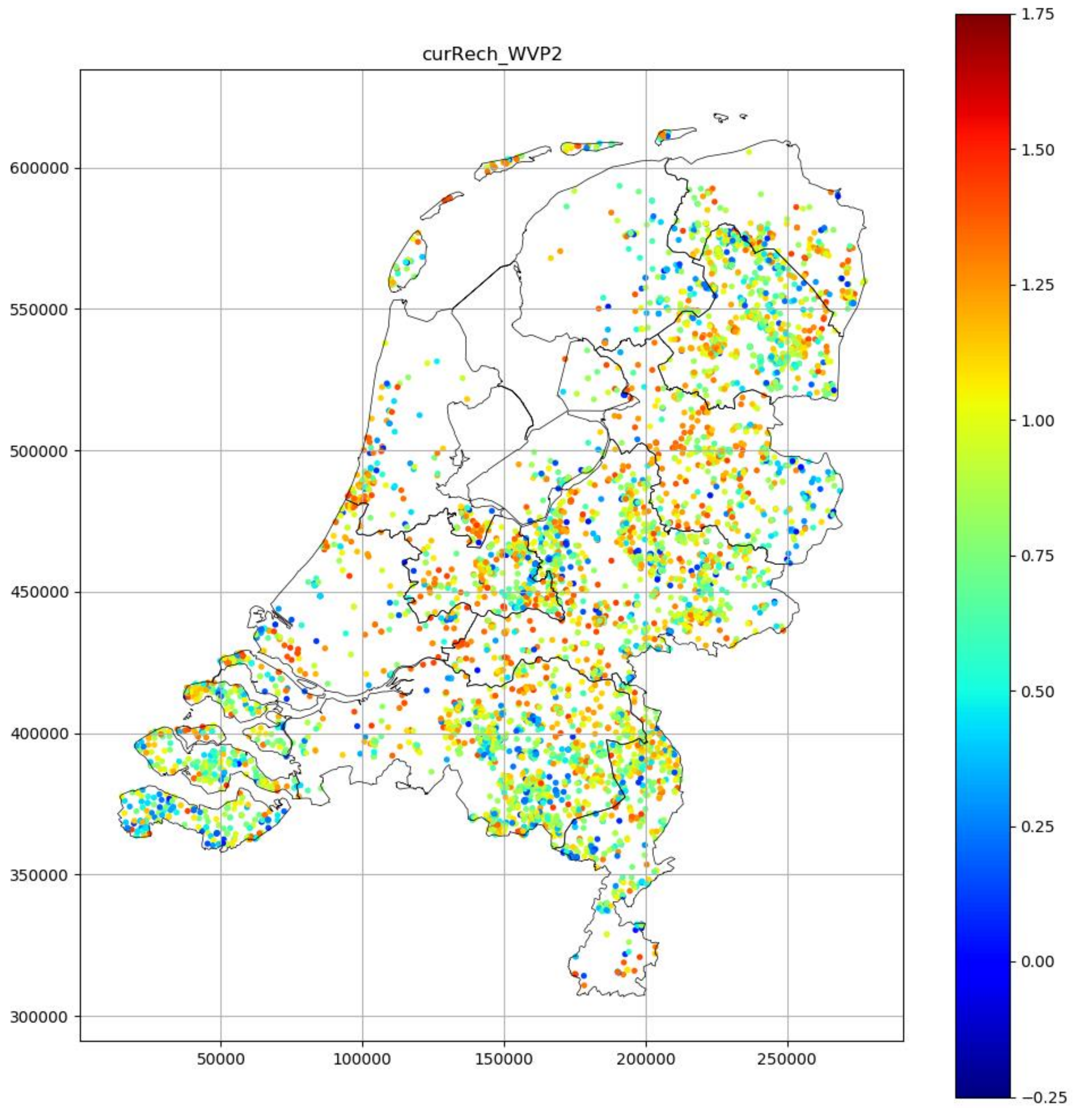


Figure 5.9 Crude estimate of groundwater recharge [mm/day] from evaporation factor in Metran models of piezometers in NHI-LHM modelaquifer 2 (the upper regional aquifer)

5.1.2 Climate change scenario results

This subsection contains results for the climate change scenarios described in section 4.4.

5.1.2.1 Integrated hydrological model

The effective precipitation in the reference situation and under the different climate scenarios is shown in *Figure 5.10*. The climate scenarios have a different impact on the effective precipitation. The regional differences that are visible in the reference situation remain the same: the North and West have a higher effective precipitation compared to the South and East of the Netherlands. The ‘dry’ scenarios of both temperature rise scenarios (1° min and 3° min) reduce the effective precipitation. In the 3° min scenario, almost the whole South-eastern half of the country will have on average a negative effective precipitation. The ‘wet’ scenarios (1° max and 3° max) increase the effective precipitation. The national variation of the effective precipitation in the 1° max scenario is comparable to the reference situation, but the whole country has a positive effective precipitation. In the 3° max scenario, the effective precipitation is over 200 mm/year for a large part of the country. The differences between the minimum and maximum variants of the climate scenarios are mainly caused by a strongly varying precipitation flux for the different variants.

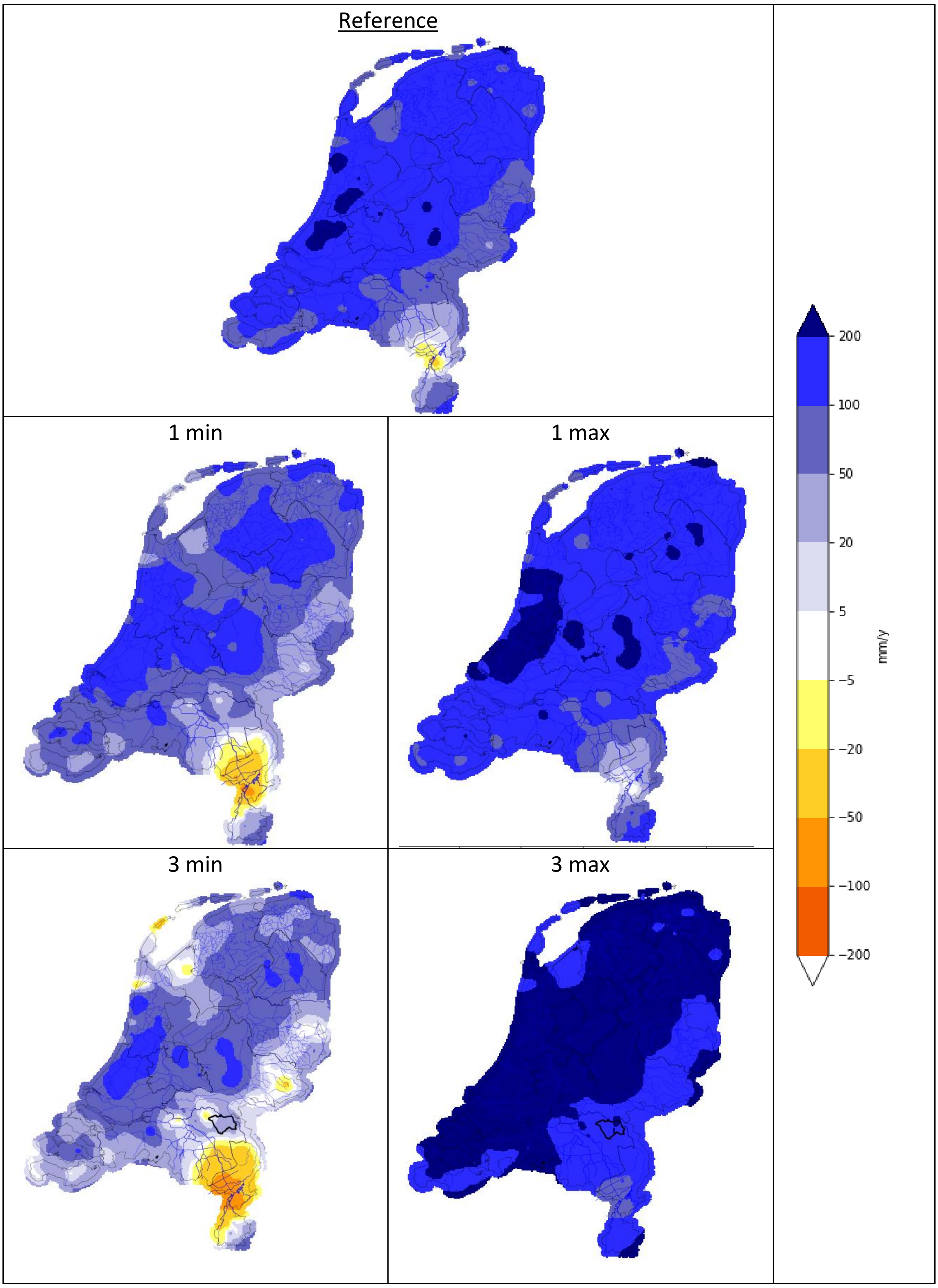


Figure 5.10. Average yearly effective precipitation (mm/year) for the reference situation (top) and the effect of the different climate scenarios (middle and bottom)

Figure 5.11 illustrates the effect of the climate scenarios on the phreatic groundwater head and *Figure 5.12* shows deeper groundwater heads. Generally, the 'dry' variants of the climate scenarios result in a decrease in the groundwater head, which means that the water table level decreases. On the contrary, the 'wet' scenarios result in an increase of the groundwater head and therefore increases the level of the water table.

The differences in heads due to climate change are larger in the South and East of the country compared to the low-lying areas in the North and West. The hydraulic head in these low-lying areas is generally very little affected in the 1^{o} min scenario. In this scenario, only the regions with high surface elevations (the Veluwe and the South-eastern corner of the country) experience a decrease in phreatic head of about 0.5 – 1.0 m. For the 'dry' variant of 3 degrees temperature increase (3^{o} min), the phreatic head is influenced in almost the whole country. This means that the phreatic head is lowered with at least 5 cm and locally up to 2 meters. The locations with the largest decrease in head in the 3^{o} min scenario, are also the locations with the largest increase in phreatic head in the 3^{o} max scenario. These sandy locations (the Veluwe for example) function as typical infiltration areas, where (change in) effective recharge directly leads to change in heights because the absence of surface waters. The increment in the phreatic head may locally exceed 2 m. In contrary, in the West of the Netherlands the changes are damped by the abundancy of surface waters.

The 3^{o} max scenario hardly leads to changes in ground water heads, because the surplus of water is easily drained by the intensive drainage systems. The lower net precipitation in the 3^{o} min scenario does have effect the ground water heads in the Western part of the Netherlands, because the lower net precipitation can't sufficiently be compensated by a surface water supply, while this can still be compensated in the 1^{o} min scenario. This stresses the importance to have combined calculations for groundwater and availability of surface water for the Netherlands.

The 1^{o} max scenario stands out from the other scenarios in the sense that there are regions that show an increase in head, as well as regions with a decreasing hydraulic head. The areas react differently in this scenario due to a difference in net precipitation, land use and geohydrological properties.

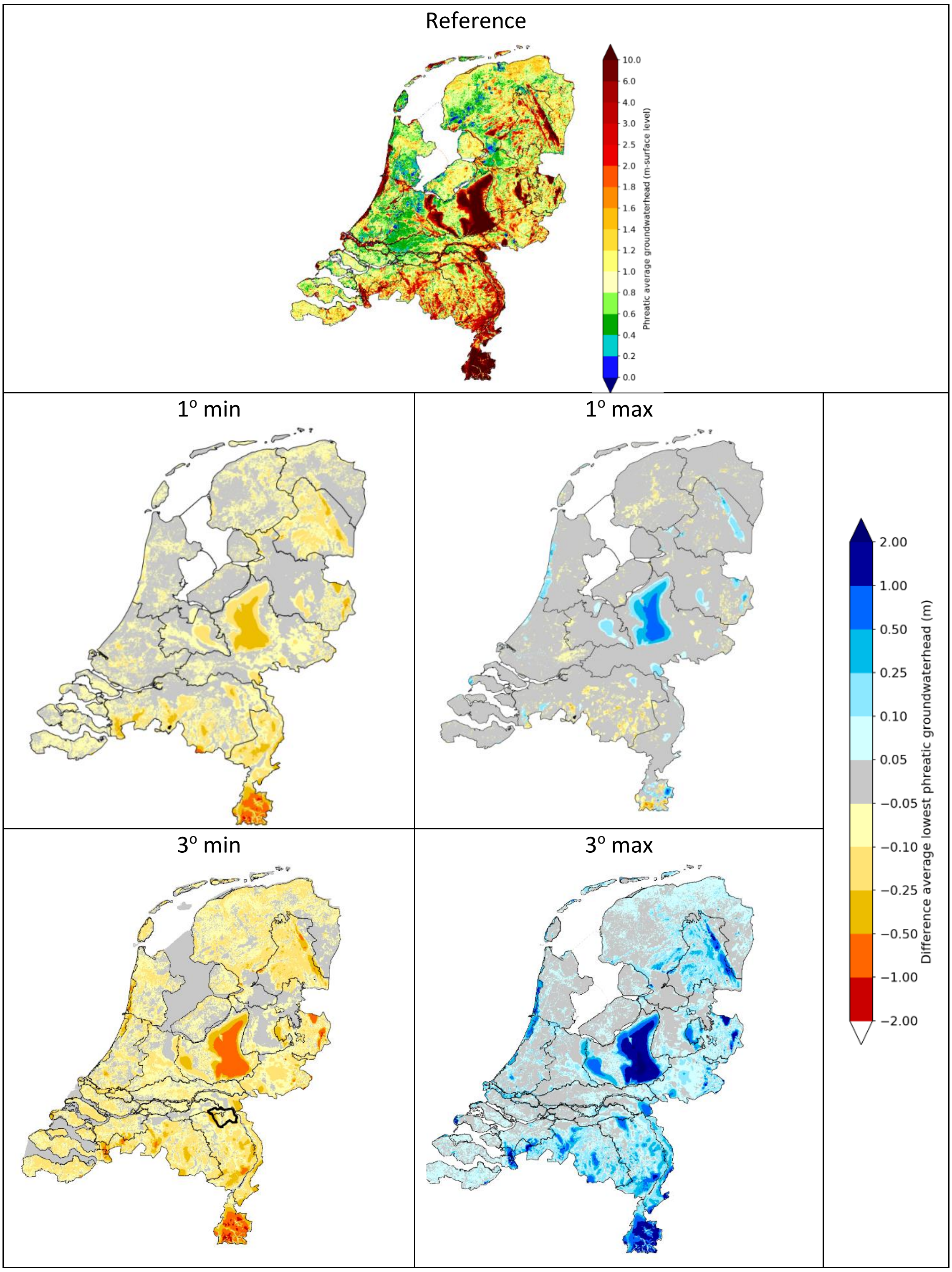


Figure 5.11. Average mean phreatic groundwater head in m below surface level (top) and the differences in mean phreatic groundwater head for all climate scenarios compared to the reference situation

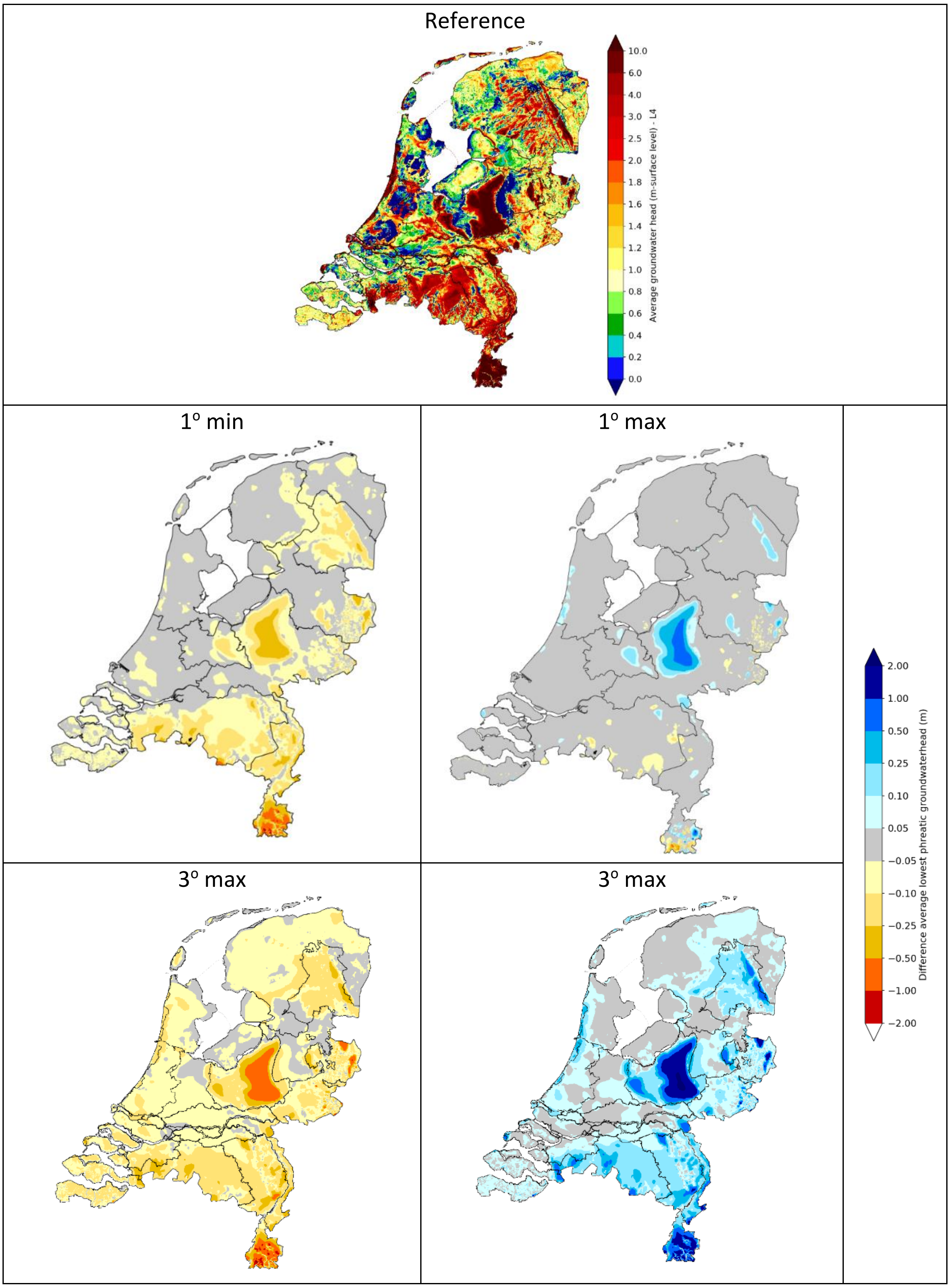


Figure 5.12. Average mean deep groundwater head (model layer 4) in m below surface level (top) and the differences in mean deep groundwater head for all climate scenarios compared to the reference situation.

The average groundwater recharge for the climate scenarios is shown in *Figure 5.13*. In the 1° min scenario, the recharge slightly decreases, mainly in the North-eastern part of the country. The 1° max scenario shows both an increase as a decrease in recharge, which is similar to the effect as shown for the heads. The regions where the hydraulic head increases, are also the regions with an increasing groundwater recharge. The 3° min scenario shows a decrease in recharge in almost the whole country, although this decrease is almost negligible in the very South. The 'wet' scenario (3° max) illustrates an increase in groundwater recharge, which is highest in the Northeast.

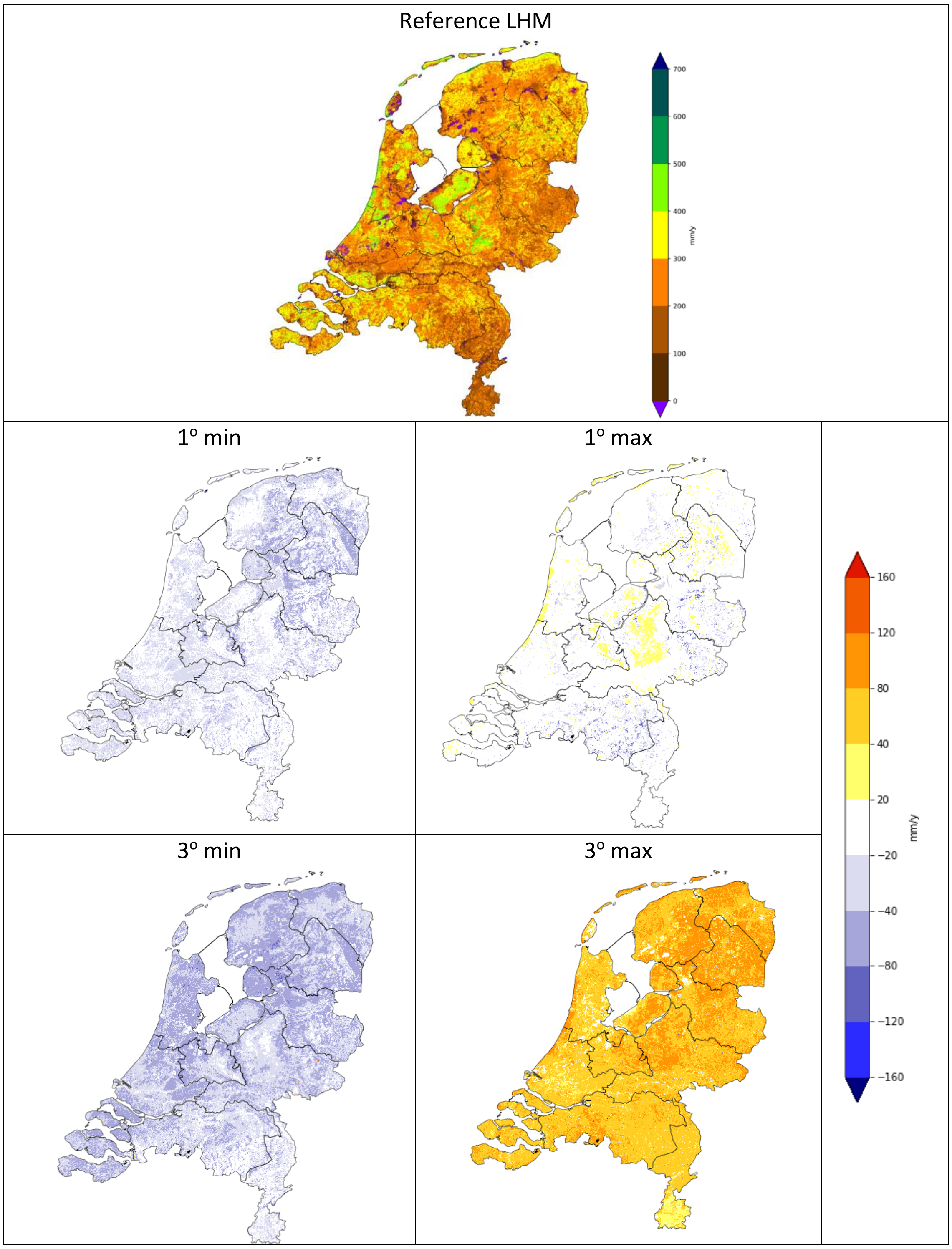


Figure 5.13. Average groundwater recharge in mm/year in 2011-2018. Top: groundwater recharge (mm/year) in the reference situation. Middle and bottom: difference in average groundwater recharge (mm/year) for the different climate scenarios compared to the reference situation.

In *Figure 5.14* the average nationwide recharge is plotted. The top left picture shows the average for every month in the whole simulation period, and compares the climate scenarios. Clearly, the biggest differences occur in the summer period (April – September). The 1° min and 3° min scenario have a lower recharge every month except for November and December, when the 3° min recharge exceeds the reference recharge. The 3° max scenario is clearly the wettest scenario, with a positive value in all months except April, May and June. The 1° max scenario shows an interesting pattern: it has the highest negative recharge in April, May and June, but abruptly switches to a slightly positive value in July.

The other graphs in *Figure 5.14* show the differences in recharge over the different years. To derive these graphs, the average recharge per month is calculated for every simulation year between 2011 and 2018. The lowest and highest value that is found for every month is shown as respectively the minimum and maximum value in *Figure 5.14*. These graphs show that the variation in recharge between years can be substantial. For example, the recharge in August was almost -0.5 mm/day in 2003, but more than +0.5 mm/day in 2004. In general, the 'dry' climate scenarios (1° min & 3° min) decrease this variability between years, whereas the 'wet' climate scenarios show an increased variability. To compare: the difference in the minimum average and maximum average recharge in August is in the reference situation about 1 mm/d, in the 3° min scenario about 0.5 mm/d and in the 3° max scenario about 1.25 mm/d.

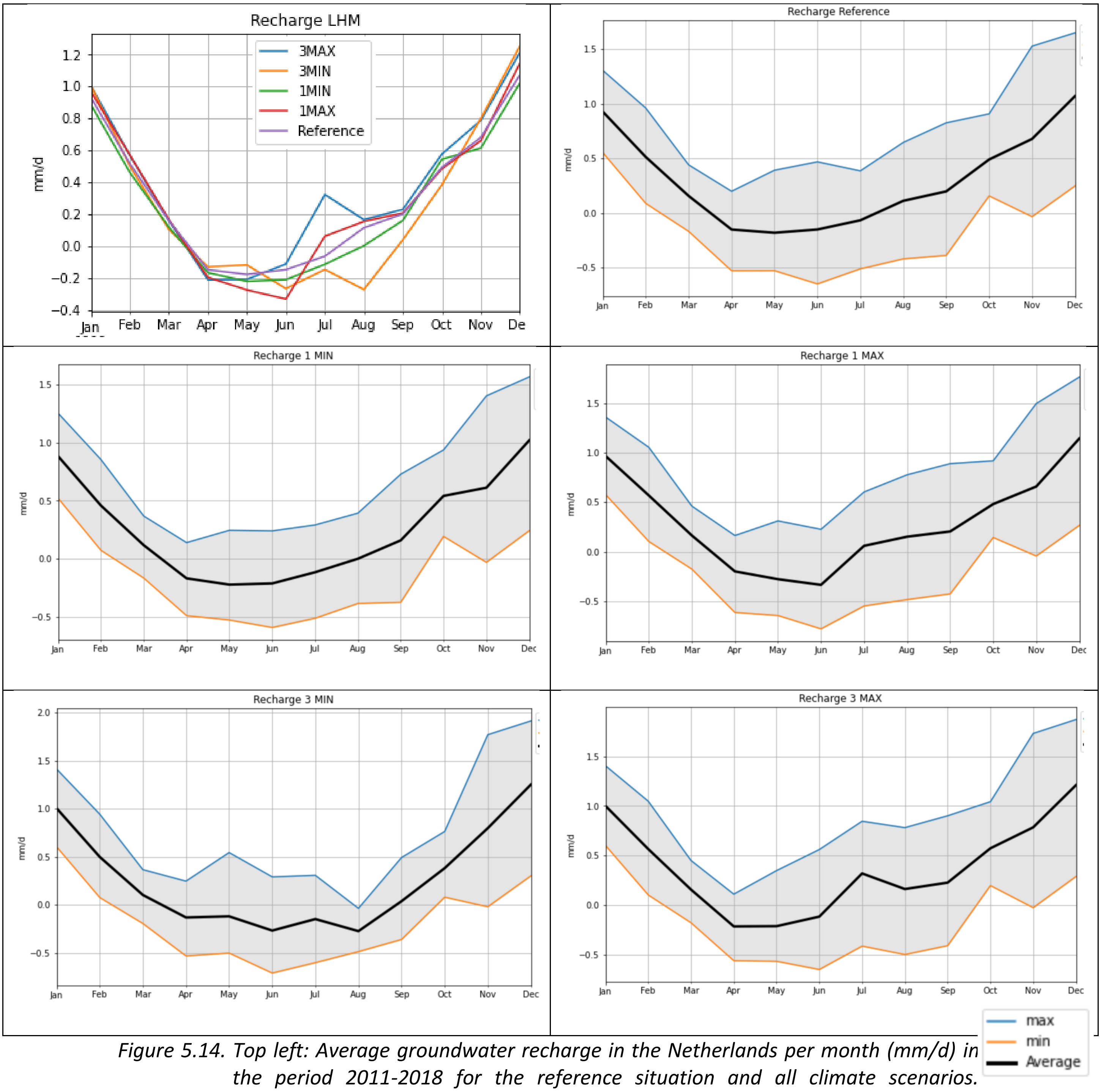


Figure 5.14. Top left: Average groundwater recharge in the Netherlands per month (mm/d) in the period 2011-2018 for the reference situation and all climate scenarios. Top right, middle and bottom row: average groundwater recharge per month and the maximum and minimum average groundwater recharge per month in the reference situation (top right) and the climate scenarios (middle and bottom row).

The effect of climate change on the discharges is relatively minor for the scenarios based on one degree temperature change, but may be significant for 3 degree temperature change (see *Figure 5.15*). In the latter case, differences in discharge reach up to 50 mm/year in many areas due to climate change, which is significant compared the total discharge of about 250 – 500 mm/year. The dry climate variants (the min scenarios) show a positive increase in the discharge flux. This means that the flux becomes less negative and the total discharge decreases. In the 1 degrees scenario, only the discharges in a limited amount of water bodies are affected; in the Western part of the Netherlands the effect is limited by the damping effect of the surface water systems. In the 3° min scenario, all surface water bodies are affected.

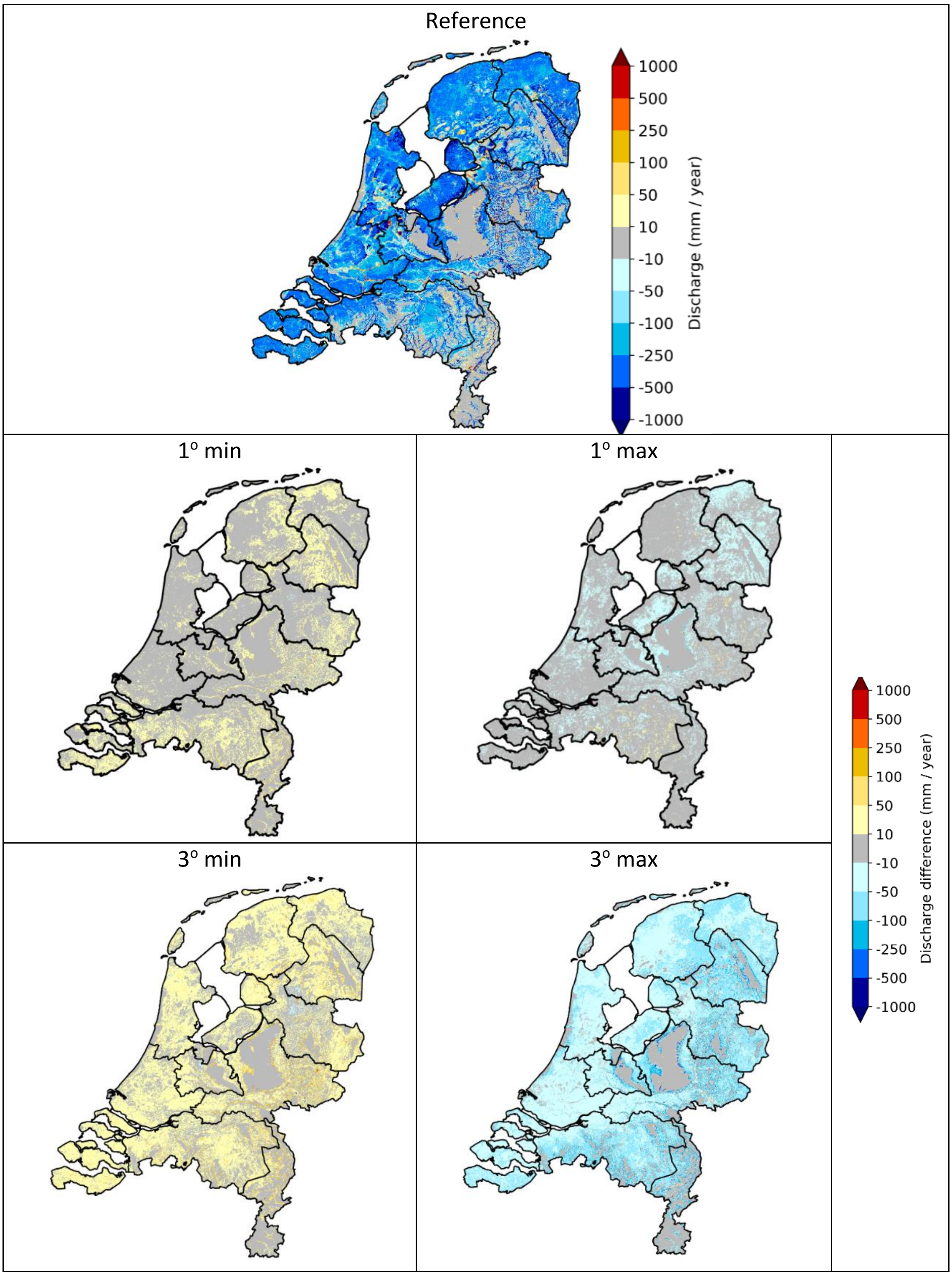


Figure 5.15. Average discharge of all surface water systems in mm/year in the reference situation (top) and the differences in discharge for all climate scenarios compared to the reference situation

5.1.2.2 Time series models

The piezometers selected for the regional pilot (subsection 5.2.1.2) have been simulated with the national climate change factors (in addition to the regional factors – see subparagraph 5.2.2.2) and compared to the results of the national integrated model NHI-LHM. The results are inter-compared in section 6.3.

Furthermore, long term average recharges have been calculated for the climate scenarios. The results offer only an indication of the change, with little spatial variation, due to the crude calculating and the usage of uniform meteorological data for the entire country (*Figure 5.16*).

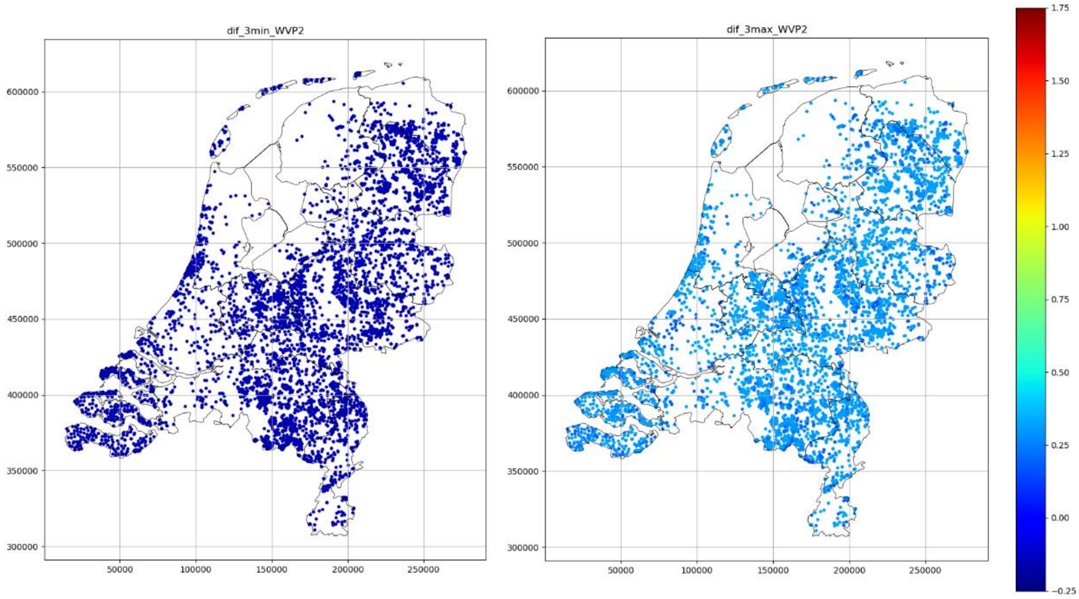


Figure 5.16 Change of the crude estimate of groundwater recharge from Metran models of piezometers in NHI-LHM model aquifer 2 for climate change scenario 3° min (left) and 3° max (right).

5.2 De Raam

5.2.1 Reference period results

5.2.1.1 Integrated hydrological model

The phreatic head distribution in pilot area 'De Raam' is shown in *Figure 5.17*. The Western part of the area has phreatic heads that a relatively far below the surface level. This is due to the fact that the surface elevation sharply increases towards this region: the elevation difference is about 8 m. Furthermore, the phreatic heads near the river Meuse are also relatively deep (far below surface level).

The groundwater recharge is shown in *Figure 5.18*. This picture shows that the groundwater recharge is quite uniform across the whole area. In the areas with land use type 'urban area' and 'forest' have the lowest groundwater recharges.

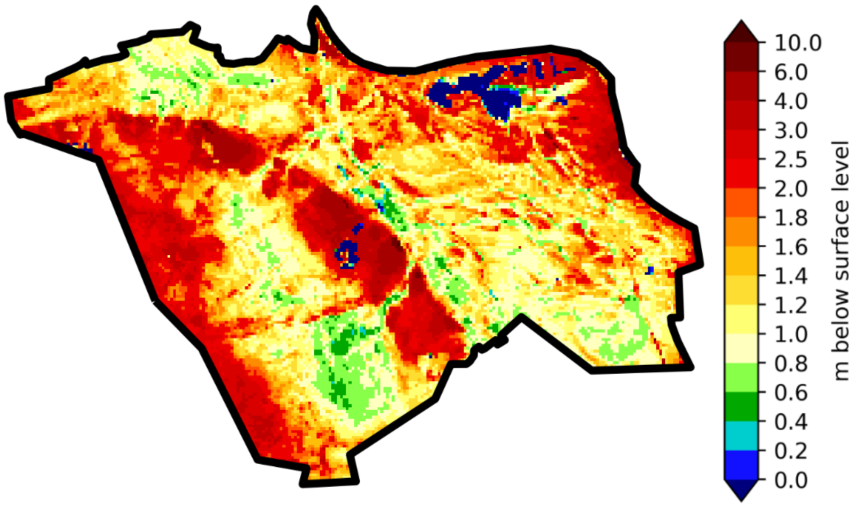


Figure 5.17. Average phreatic head in pilot area 'De Raam' in m below surface level.

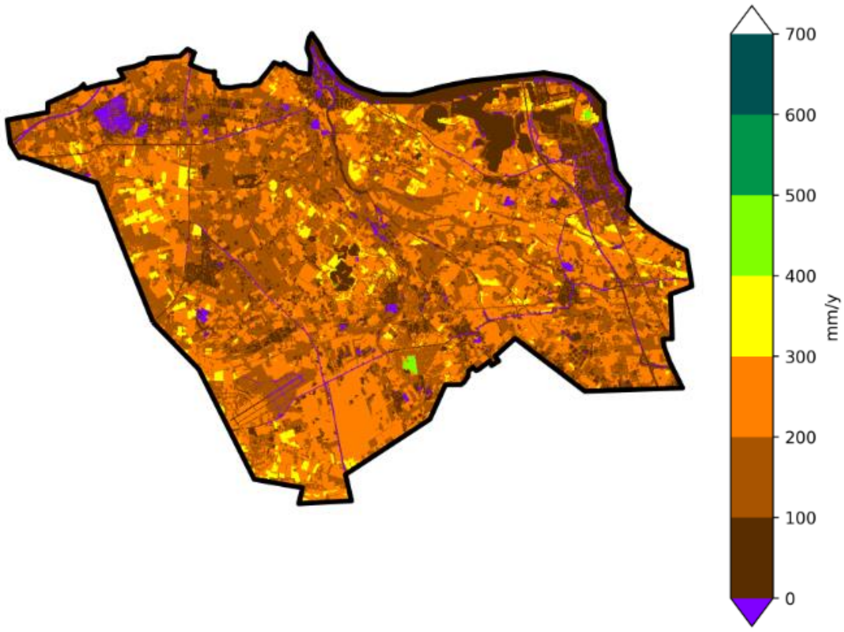


Figure 5.18. Average groundwater recharge in pilot area De Raam (mm/year) in period 2011-2018

5.2.1.2 Time series models

Metran (see section 4.3) has been used to create time series models for selected time series using precipitation and evaporation as explanatory variables to determine the precipitation response and to perform simulations for the climate scenarios (see subsubsection 5.2.2.2).

Also some time series along the river Meuse have been modelled with the river water level as a third explanatory variable in order to investigate the linearity of the river response under different circumstances.

Three monitoring wells have been selected to create time series models (see *Figure 5.19*). The wells have multiple piezometers at various depths.

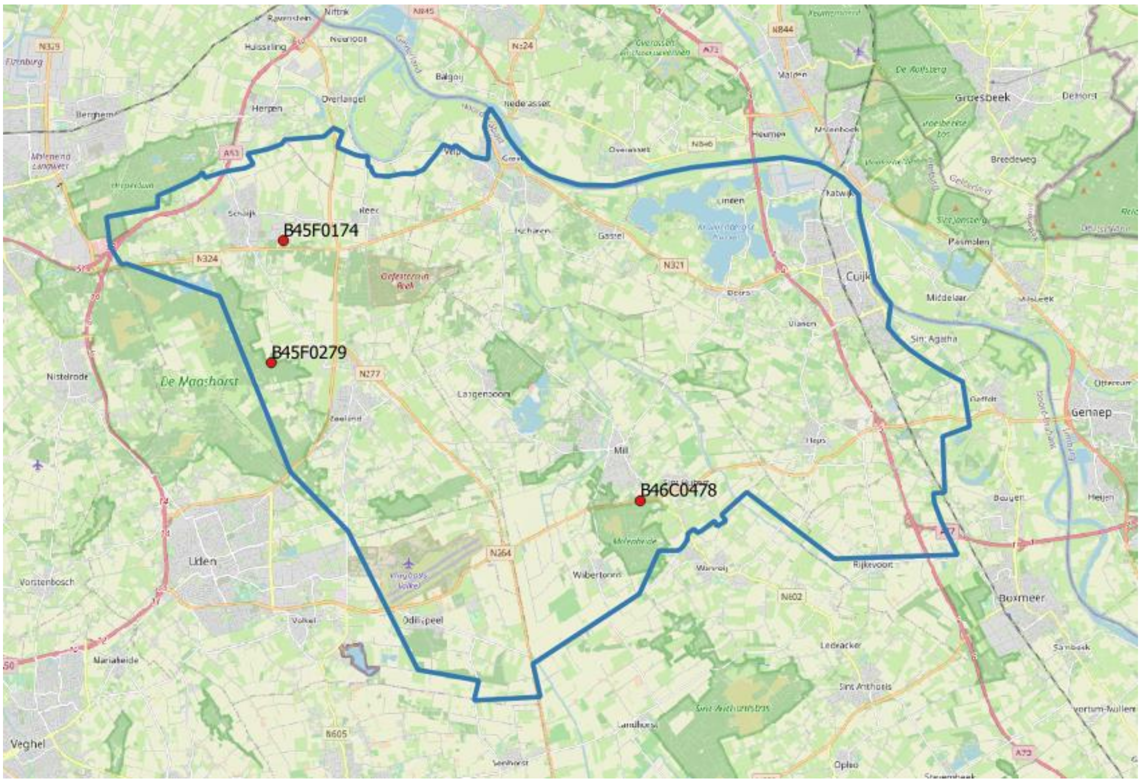


Figure 5.19 selected multi-piezometer monitoring wells for pilot de Raam.

Figure 5.20 and *Figure 5.21* show the median precipitation response time and the total precipitation response from the Metran models, respectively. The results show that these characteristics of the precipitation response are quite similar for all piezometers. They vary more in lateral direction compared to the vertical direction. This is due to the lack of aquitards with a high resistance and differences in conditions at the locations of piezometers.

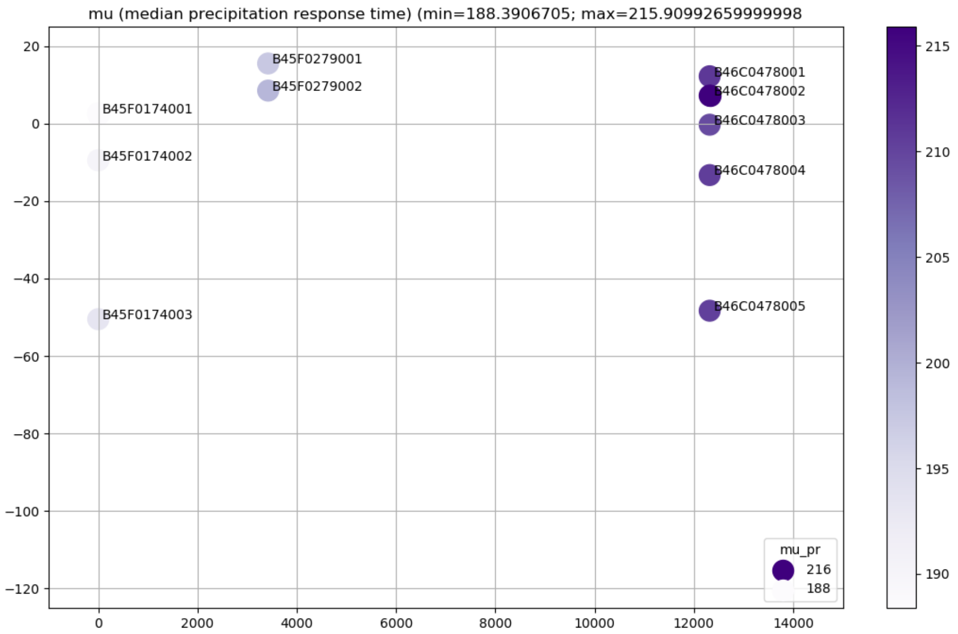


Figure 5.20 median precipitation response time [days] from Metran models of groundwater head time series with vertical coordinates in meters.

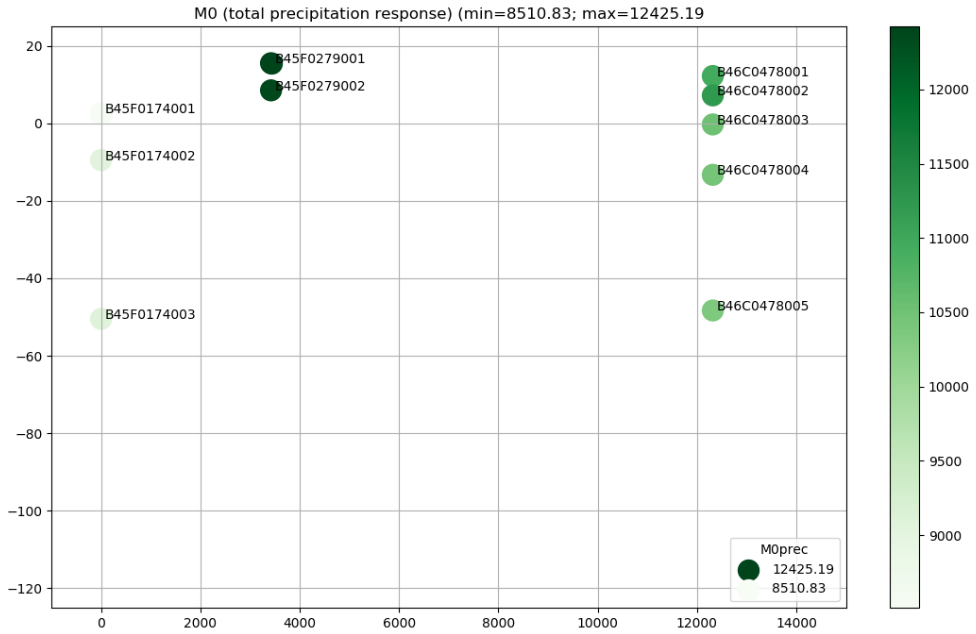


Figure 5.21 Total precipitation response [0.1 d] = [mm/(cm/d)] from Metran models of groundwater head time series with vertical coordinates in meters.

Time series modelling of groundwater response to river water levels

A shipping accident on the river Meuse in December 2016 offered an opportunity to look at the performance of Metran under unusual consequences. A ship rammed the weir in the river Meuse at the Western boundary of the pilot area of de Raam (downstream). This caused a drop of the Meuse water level of 3 meters (*Figure 5.22*), while the normal fluctuation is much smaller (and mostly upward during high discharge events).

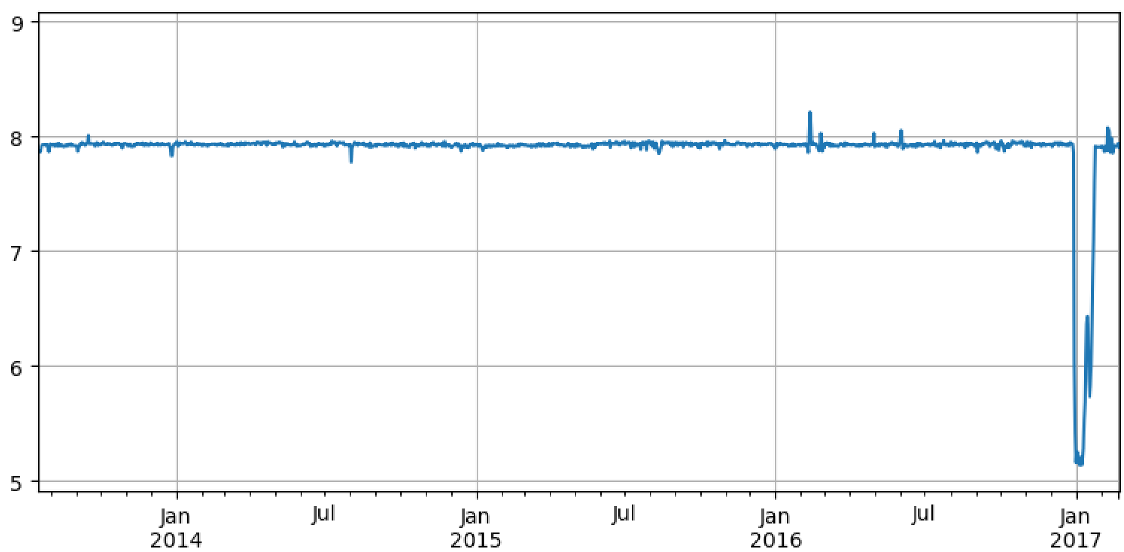


Figure 5.22 Meuse river level in meters above NAP

The groundwater in piezometer B46A1559001 at 160 meters from the Meuse reacts very quickly to the river level. Metran can match the slower response to precipitation and evaporation much better, but the timing and direction of the river response can be represented (*Figure 5.23*).

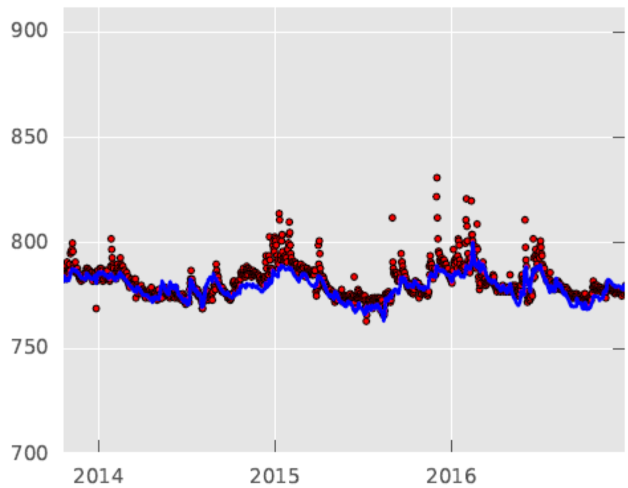


Figure 5.23 Calibration of Metran model for piezometer B46A1559001 during normal Meuse water levels.

This Metran model has been used to simulate the groundwater levels after the accident using the same explanatory variables: precipitation, evaporation, and Meuse water level (*Figure 5.24*).

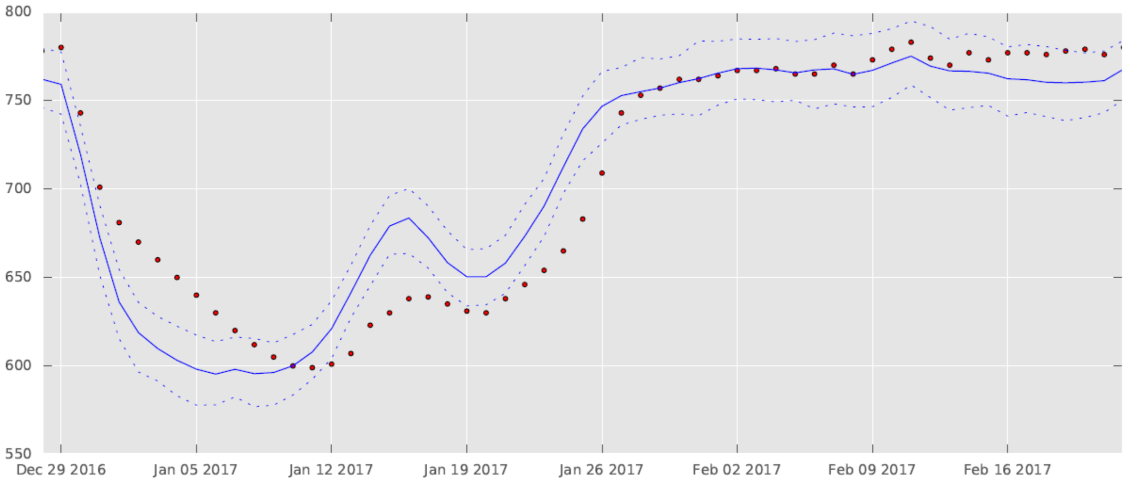


Figure 5.24 Simulation of Metran model (in blue; with 10- and 90-percentile as dotted lines) for piezometer B46A1559001 during unusual change of Meuse water levels (measurements in brown dots).

For this situation, Metran does not simulate the proper timing of the decline and the shape of the recovery also differs ostentatiously. One cause of these deviations is the fact that the

situation is outside the range of groundwater heads and river levels in the calibration period. Another reason is that the response to these extreme river levels is different from the normal response. This may be due to non-linearities and hysteresis in the groundwater system.
This deficiency of the model is illustrated by the fact that the measurements (brown dots in *Figure 5.24*) lie outside the confidence interval created by the stochastic part of the model (the dotted blue lines in *Figure 5.24* represent the 10- and 90-percentile of the simulation).

5.2.2 Climate change scenario results

5.2.2.1 Integrated hydrological model

The effect of the climate scenarios on the groundwater recharge as calculated by the regional model of pilot area De Raam is shown in *Figure 5.25*. No further results are presented in this Subsubsection, but comparisons of De Raam with NHI-LHM are discussed in subsection 6.4.1.

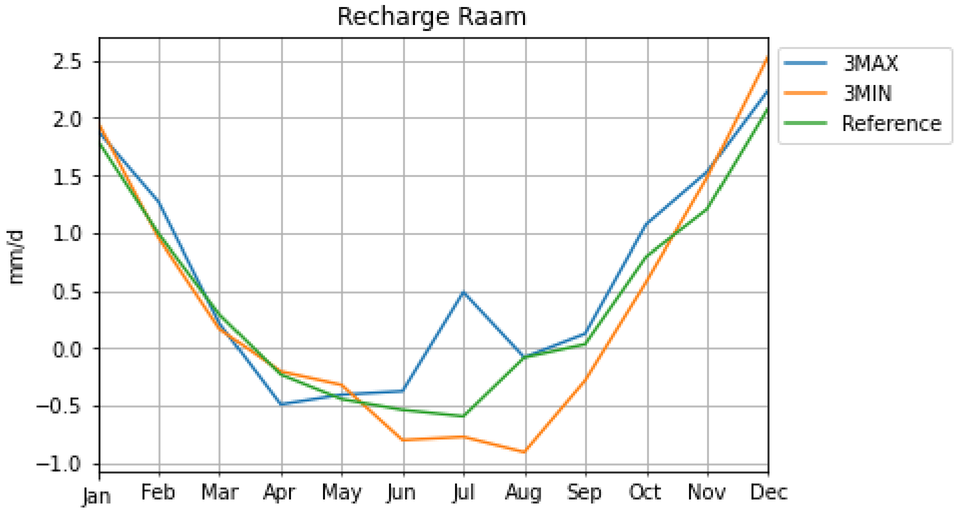


Figure 5.25. Average groundwater recharge as calculated by the regional model of De Raam per month (mm/d) in the period 2011-2018 for the reference situation and the 3 min and 3 max climate scenarios

5.2.2.2 Time series models

The Metran models for the selected piezometers from subsubsection 5.2.1.2 have been used for simulations of the climate change scenarios. The precipitation and evaporation series of the Volkel weather station of the Royal Dutch Meteorological Institute KNMI have been changed using the local change factors for the area of de Raam (see section 4.4).

6 DISCUSSION

6.1 NHI-LHM

The average effective precipitation and average groundwater recharge per month is shown in *Figure 6.1*. These graphs show the average value of the whole country, as an average for every month in the period 2011-2018. Clearly, there is a difference between the effective precipitation and the actual groundwater recharge. The effective precipitation has a much stronger variation throughout the year compared to the groundwater recharge. These differences can be explained by the fact that the actual evaporation is often lower than the potential evaporation and because a part of the precipitation will flow away as surface runoff.

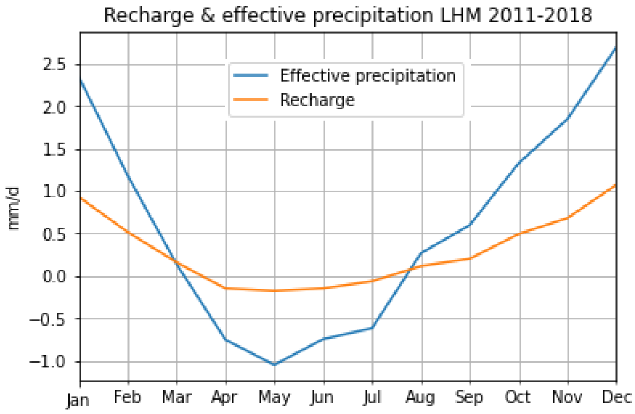


Figure 6.1. Monthly average of effective precipitation and recharge in mm/d

Including an atmosphere-plant model like WOFOST in an integrated model improves the estimation of the actual evapotranspiration. Moreover, the effect of higher CO_2 concentrations on the crop growth can be taken into account, in addition to the change in temperature. Depending on the schematization of the atmosphere-plant model, additional meteorological (and crop) information is needed as input, e.g. WOFOST is based on Penman-Monteith needing daily mean temperature, wind speed, relative humidity, and solar radiation as meteorological input. Because these were not available for the TACTIC climate scenarios, these were simulated without WOFOST.

The use of WOFOST can have a large impact on the model results. For example, a comparison of evapotranspiration in 2003 as modelled with or without WOFOST can result in a change up to 50 mm/year. This influences the calculated groundwater heads; in a relatively dry year they might increase up to 0.25 m compared to a run without WOFOST (Hunink et al., 2019).

The groundwater recharge in urban areas is not well known (Witte et al., 2019). The presence of buildings and pavement has a strong influence on the routing and infiltration of precipitation, with often a large portion going directly into storm sewers or surface water. Also, leaking sewers and drinking water infrastructure can have a large influence (e.g. Foster et al., 1998). In the Netherlands, urbanisation generally leads to a reduction of groundwater recharge because of the implementation of drainage and the fact that in most urban areas, sewers start to act as drains when they age (Witte et al., 2019). The change of groundwater levels in urban areas may have high financial risks due to flooding, moisture problems (also a health risk), subsidence and deterioration of foundations.

6.2 De Raam

The model for De Raam has been created specifically to support the waterboard in their regional water management. This includes evaluation of local measures to improve the water availability during dry periods. Therefore, a resolution was used that allows for modelling at the parcel scale.

So far, changes in extreme precipitation have not been taken into account in the analysis of climate scenarios for GeoERA. If precipitation intensity changes due to the climate scenarios, an extension of the rapid discharge components might become important, as demonstrated within the Raam pilot.

Within the Lumbricus program in the Netherlands, the software of the regional groundwater model of De Raam has been coupled to a detailed hydraulic surface water model, D-FLOW FM (1D and 2D), through which fluxes between the various model components are dynamically exchanged on an hourly time step basis. This allows the calculation of refined interaction between groundwater and regional surface waters, which especially might be important for extreme rainfall events. The developments with this coupled software will be continued in 2021, especially the tuning of the different model parameters so that the linked models better match the measurements for groundwater and surface waters.

The interim results of the pilot De Raam (for the small river de Hooge Raam) demonstrates that inclusion of detailed processes of surface runoff (encountered in the 2D model, see *Figure 6.2*) and detailed hydraulic 1D calculations (*Figure 6.3*) affects the calculation results of the groundwater calculations. This development might be important for analyzing the effect of climate change on groundwater, if precipitation intensity might increase in the future.

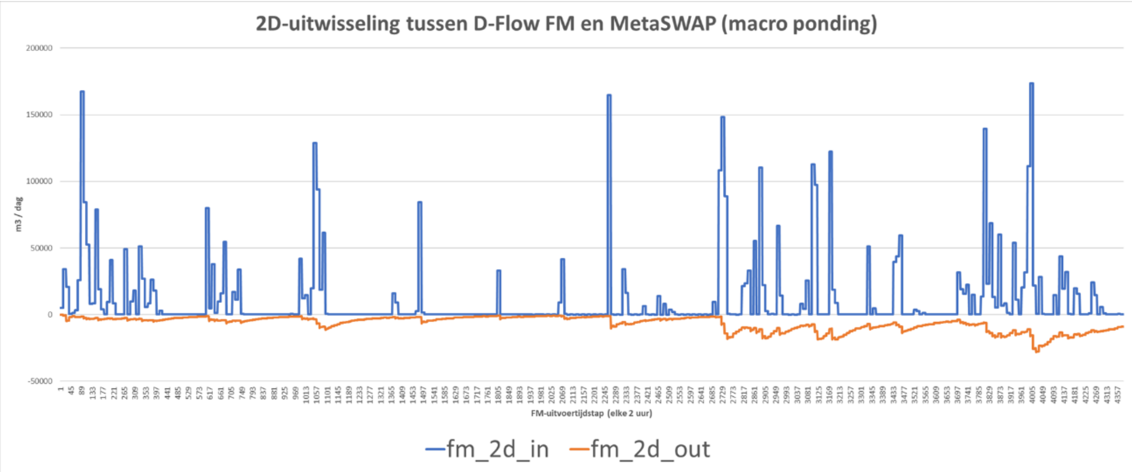


Figure 6.2 Example of exchanges of fluxes between the detailed 2D overland flow (in D-FLOW FM) and the coupled model for the unsaturated zone (MetaSWAP-MODFLOW). Blue: inflow D-FLOW FM, orange: outflow D-FLOW FM.

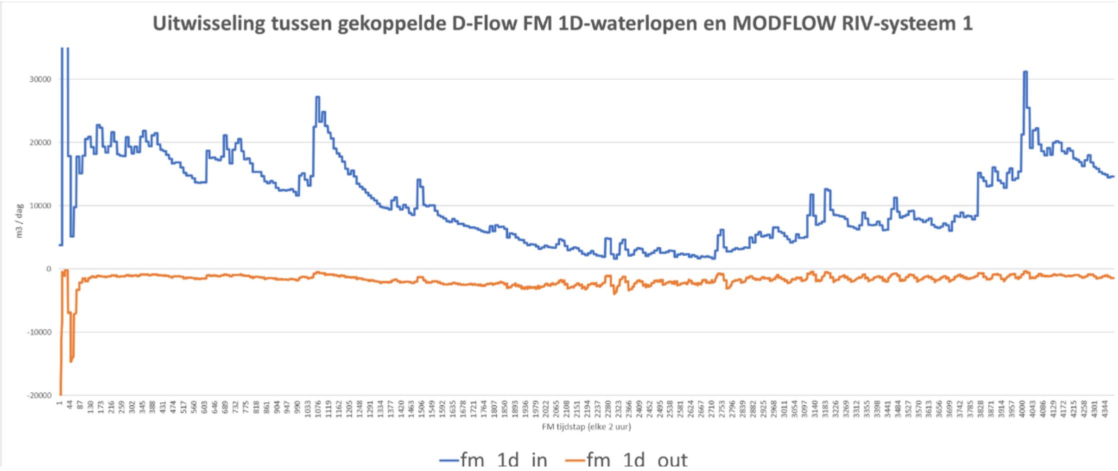


Figure 6.3 Example of exchanges of fluxes between the 1D hydraulic model (D-FLOW FM) and the river systems in the MODFLOW, as a result of the coupled software applied for the Raam region. In blue: inflow D-FLOW FM, orange: outflow MODFLOW.

The accident at the weir of Grave in December 2016 leading to exceptionally low water levels in the River Meuse for the first weeks of 2017 may provide a good opportunity to test the physically based model outside the normal situation it has been calibrated. Although the direct practical purpose may seem limited, it would provide insight into the performance outside of the calibration range. A potentially important aspect would be the release of water from storage and the subsequent refilling of the storage and the hysteresis that may be expected. The accident might provide a future test case for the coupled models of surface water and groundwater.

6.3 Metran

The physical basis of the transfer-noise modelling of time series is limited. The main aspects are the choice of explanatory variables and the shape of the response function. Metran uses an incomplete gamma function, which is connected to a physical schematization (Besbes & de Marsily, 1984).

Also, the output can illuminate physical patterns. The median response time of the groundwater head to precipitation has a similar pattern as the distance between surface waters and surface elevation (*Figure 6.4*).

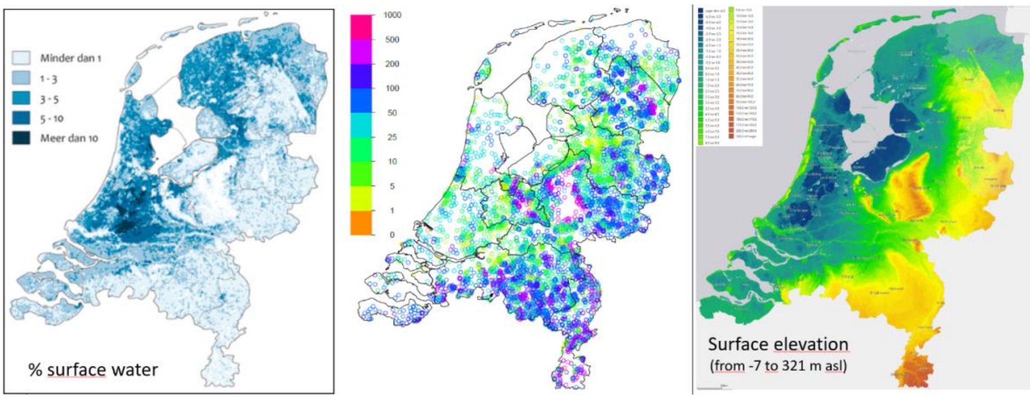


Figure 6.4 Precipitation response time [days] (centre, Figure 5.7), surface percentage of surface water (left) and surface elevation (right)

Comparison of *Figure 5.6* with *Figure 6.4* or *Figure 5.7* shows that the total response also has a similar pattern. However, the correlation between both quantities decreases for larger values (*Figure 6.5*).

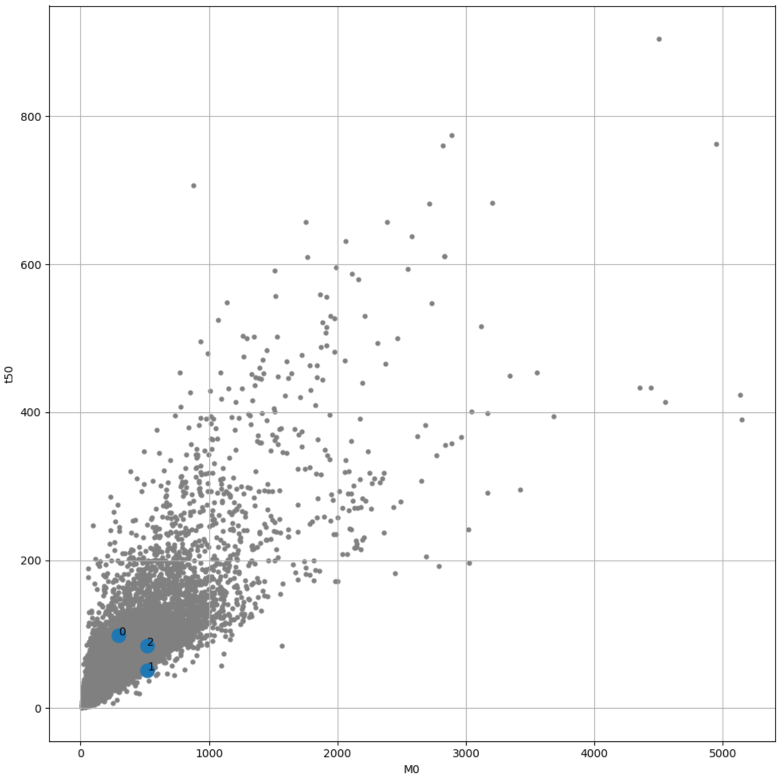


Figure 6.5 Mean precipitation response time t50 [days] as function of the total precipitation response M0 [cm per m/d] for all good time series models together with K-means cluster centers for the upper regional aquifer (WVP2 in NHI-LHM).

The connection between these characteristics of the precipitation response and the physical properties of the groundwater system is not well known and is topic of research (e.g. Haaf et al., 2020). Here, K-means clustering (Pedregosa et al., 2011) has been used to obtain insight in the variation of ratio between the total precipitation response M0 and the mean precipitation response time t50 in *Figure 6.5*. The time series models of Cluster 2 have an average ratio of M0 and t50. The response time is relatively high in cluster 0 and relatively low in cluster 1.

The map in *Figure 6.6* shows the clusters for piezometers in the upper regional aquifer. The Western part of the Netherlands contains mostly cluster 0. This mainly is relatively low lying polder area where the upper regional aquifer is covered by a Holocene confining layer. In the higher areas without a confining layer, the clusters 1 and 2 are interspersed.

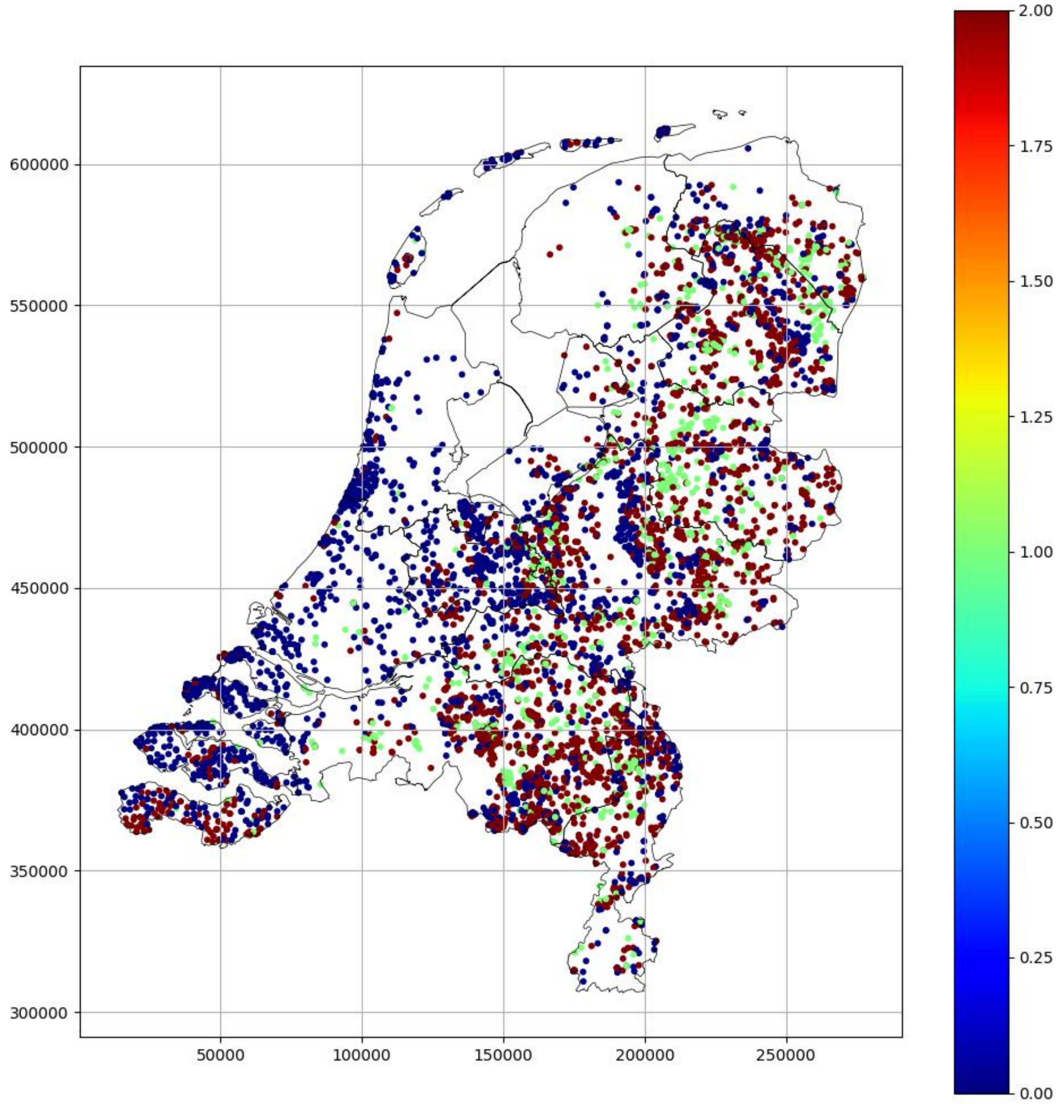


Figure 6.6 K-means clusters for the total precipitation response M0 (relative to the average M0) and ratio of M0 over the median response time t50 for the upper regional aquifer (WVP2 in NHI-LHM).

The piezometers selected for the regional pilot (subsubsection 5.2.1.2 have been simulated with Metran and the results are compared with heads from the national model NHI-LHM in section 6.3.

6.4 Comparison between models

6.4.1 Regional and national physically based distributed models

Figure 6.7 shows the difference between the effective precipitation for the national model and regional model. This figure illustrates that there are differences following from the way the meteorology has been created, using only data from weather and precipitation stations for the national model, but also radar information for De Raam. Also, the discretisation was different. The differences are small. The effective precipitation for the Raam model is about 3.5 mm/year higher than the effective precipitation of the national model, which is about 100 mm/year.

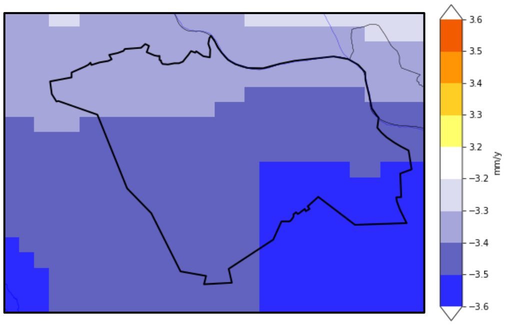


Figure 6.7. The difference between the effective precipitation of the LHM and De Raam model (mm/year). Calculated as LHM minus De Raam.

Figure 6.8 *s*hows the depth of the phreatic groundwater table below the surface for both model for the three degrees climate scenarios.

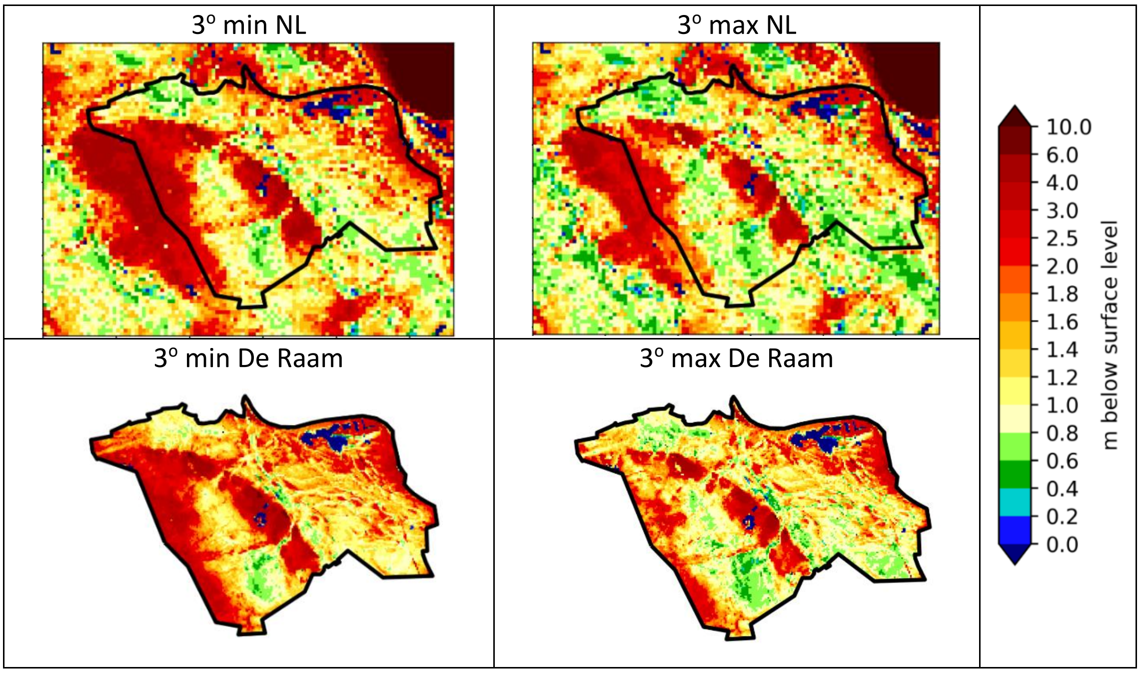


Figure 6.8. Phreatic head in m below surface level for the 3 min (left) and 3 max scenario (right). The top row are the results from the national model, the bottom row are the results of the local model of De Raam.

The phreatic head distribution of both models (see *Figure 6.8*) are similar, although there are some differences. The phreatic heads according to the regional model of De Raam are slightly lower compared to the national model, meaning that they are further below surface level. Moreover, due to the fine grid size of the regional model, a much more detailed head distribution can be distinguished.

The average groundwater recharge as computed by the national and regional model is spatially compared in *Figure 6.10*. In *Figure 6.9* the average groundwater recharge in the whole area for every month is plotted. Both figures clearly indicate that the groundwater recharge according to the regional model is lower, at some points up to 200 mm/year. This corresponds to the differences that were seen in the results of the phreatic head, where it was shown that the phreatic heads according to the regional model are lower. This shows that the coarse resolution of the national model attenuates the effect of climate change.

In *Figure 6.11*, the recharge of the simulations with the 3° min and 3° max scenarios for the regional model and national model are compared to their reference situations. These figures show that the effect of the climate scenarios is slightly different for both models. Especially for the 3° max scenario: some regions that have a relatively large increase in recharge (at the west boundary) according to the national model, have a relatively low increase according to the regional model.

The variation of the groundwater recharge during the year as calculated by the regional model (see *Figure 5.25*) and for the national model (see *Figure 5.14*) also compare quite well.
Spatially the differences are more distinct, as can be seen in *Figure 6.10* and *Figure 6.11*.

In general, it can be concluded that the finer grid size for the regional model results in a much more detailed image of the effect of climate change in the pilot area. The national model results are only useful to describe a general effect of climate change in the area. Due to the fine grid size of the regional model, also the regional differences within the pilot area become known.

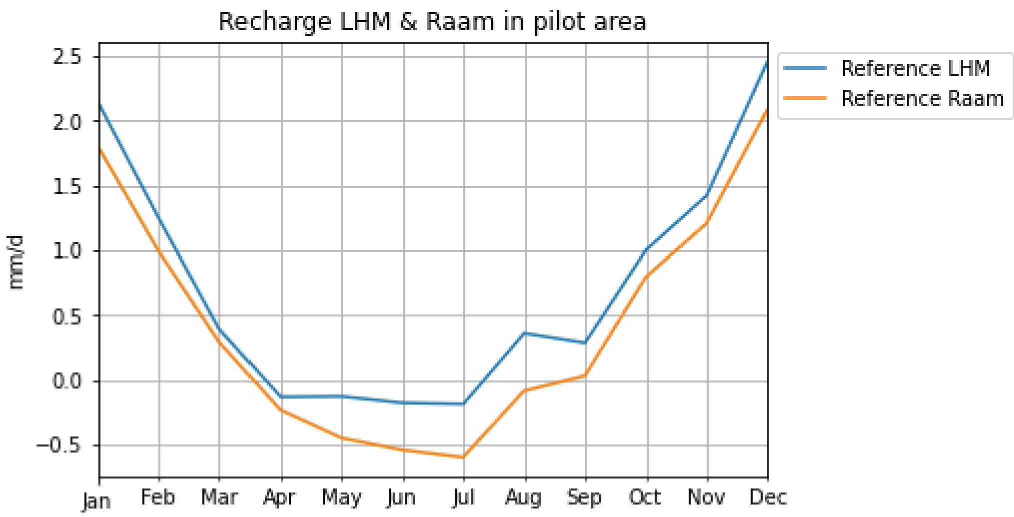


Figure 6.9. Average monthly recharge in the period 2011-2018 in pilot area De Raam as calculated by the national model (LHM, blue) and regional model (Raam, orange)

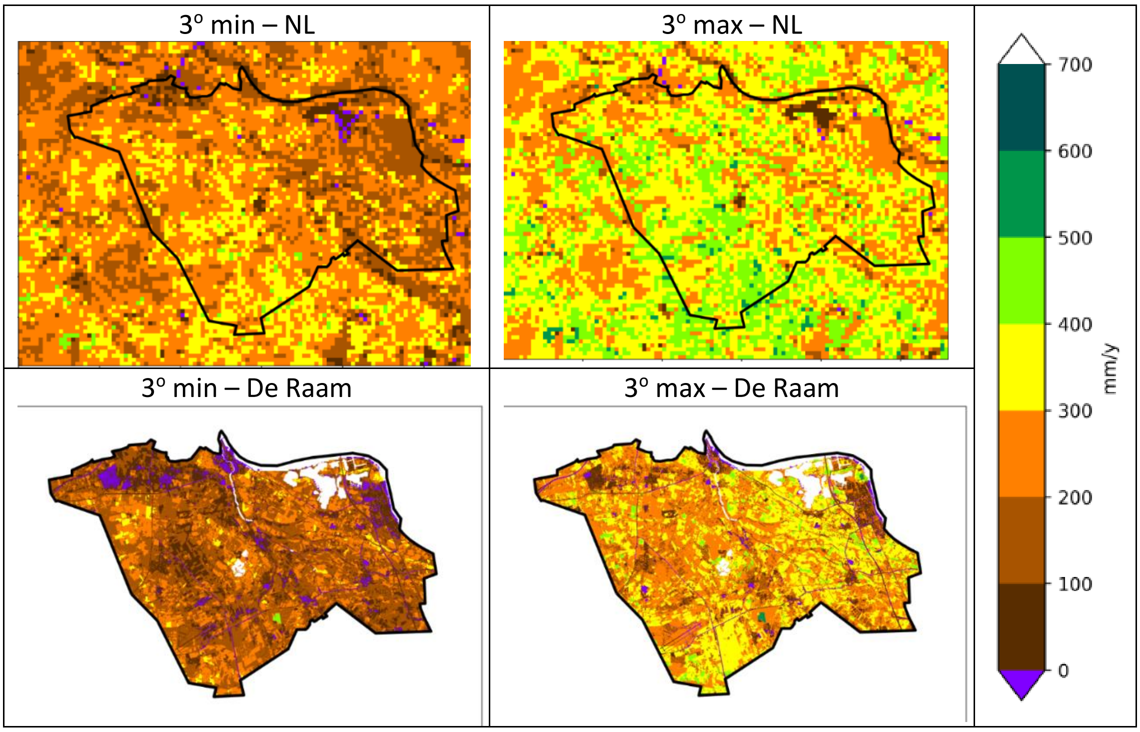


Figure 6.10. Groundwater recharge in mm/year for the 3° min scenario (left) and 3° max scenario (right). The top row are the results from the national model, the bottom row are the results of the regional model of De Raam

3° min – NL	3° max – NL	

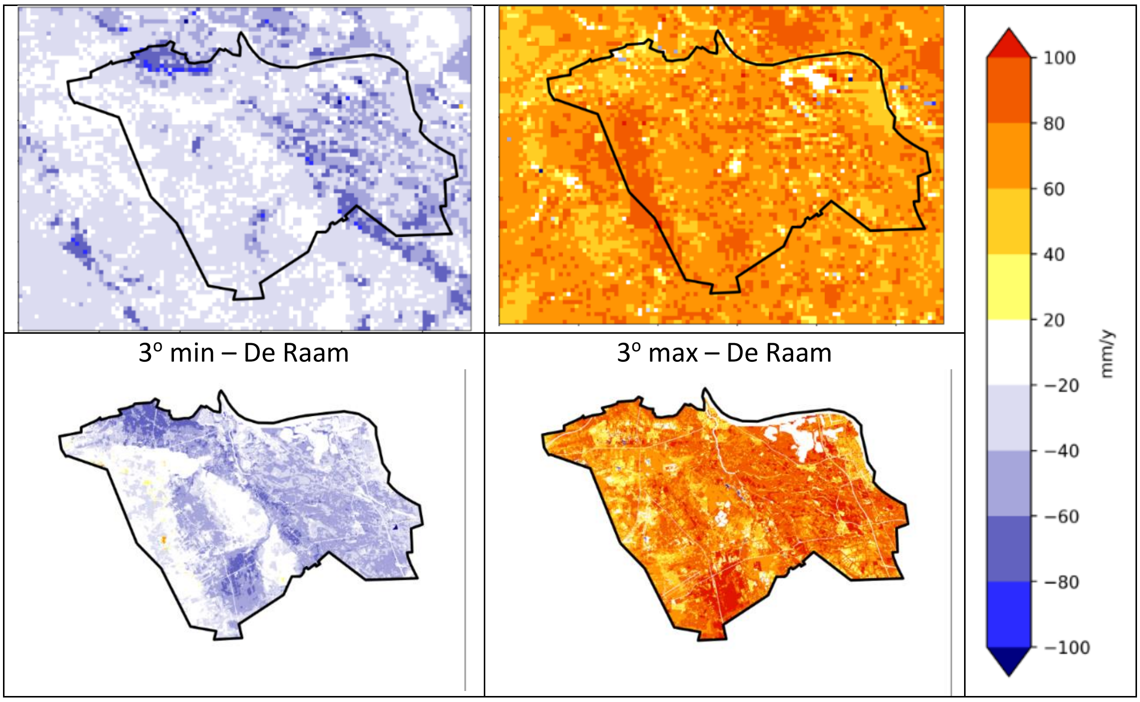


Figure 6.11. Groundwater recharge change in mm/year compared to the reference situation of the national model (top) and regional model (bottom) for the 3° min (left) and 3° max (right) scenario.

6.4.2 Physically based distributed models and time series models

The physically based distributed models NHI-LHM and de Raam have been built up from a conceptual model of the hydrology and the subsurface together with a parametrization derived from the knowledge of this physical system. The Metran models have a very limited physical base: the use of the incomplete gamma function as transfer function (Besbes & de Marsily, 1984) and the selection of explaining variables. This leads to differences in the results.

6.4.2.1 Reference situation

Figure 6.12 shows the measurements of the first piezometer of monitoring well B45B0174, which is located about 10 meters below the surface of 13.62 meters (from 3.51 to 1.5 m NAP).

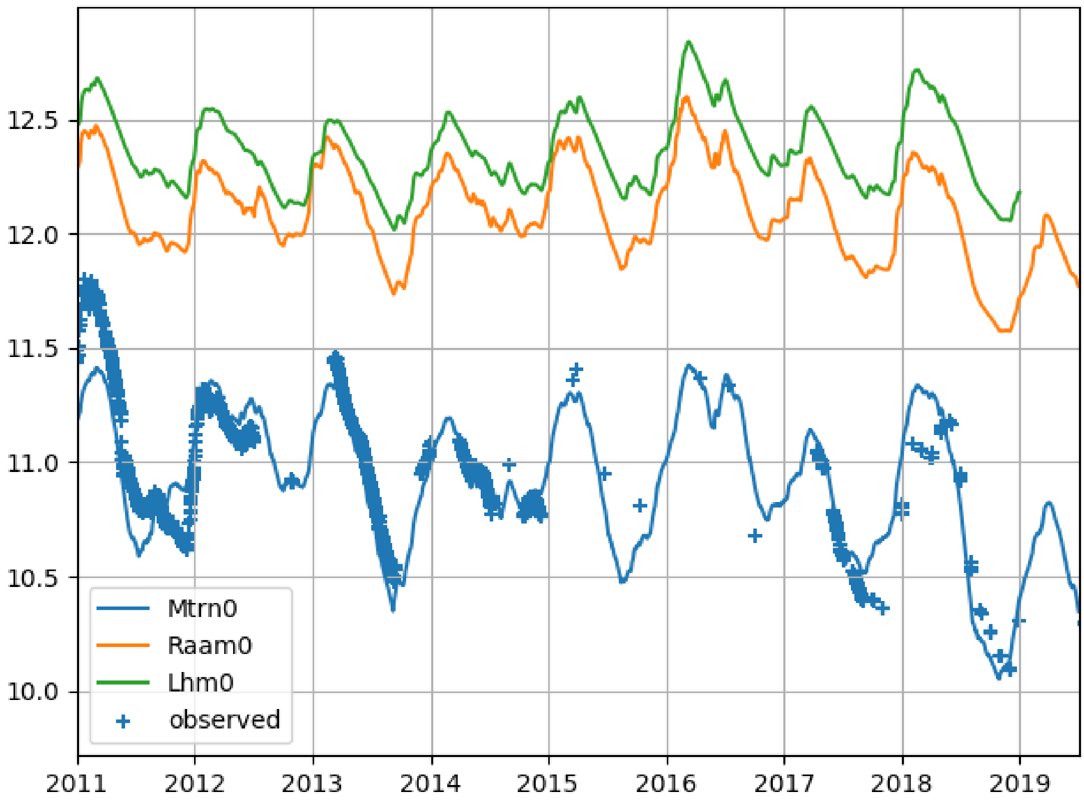


Figure 6.12 Measured groundwater heads for B45F0174001 together with simulated values from Metran (Mtrn0), de Raam model (Raam0), and NHI-LHM (Lhm0).

The main difference between the modelled heads in *Figure 6.12* is the average level. That of the Metran model corresponds well with the measurements. A deviation is to be expected for the distributed models because of the spatial discretization, which leads to representative values of cells of 250 m x 250 m and 25 m x 25 m for the national and the regional model respectively. In these models the recharge processes depend on the depth of the groundwater below the surface. The difference between the actual surface elevation and the model value is 1.35 meter for the national model and 0.23 m for the regional model (see Table 6-1). This corresponds to the difference in averages of the model heads in *Figure 6.12* for the National model. So, the surface processes may be simulated adequately, despite the deviation from the heads measured at this specific point.

Table 6-1 surface elevation from metadata of piezometer and models (m NAP).

Location	surface	NHI-LHM	De Raam
B45F0174	13.62	14.97	13.85
B45F0279	20.51	20.77	20.83
B46C0478	17.16	17.53	17.71

The fluctuation of all three models is less than the measured fluctuation of the groundwater heads in *Figure 6.12*, especially in the first three years of the graph. The drop of the head in the dry summer of 2018 is simulated better by Metran than the distributed models.

Figure 6.13 shows a similar graph for the upper piezometer of monitoring well B46C0478. The piezometer is perforated between 13.19 and 11.19 m NAP, while the surface elevation here is 17.16 m NAP.

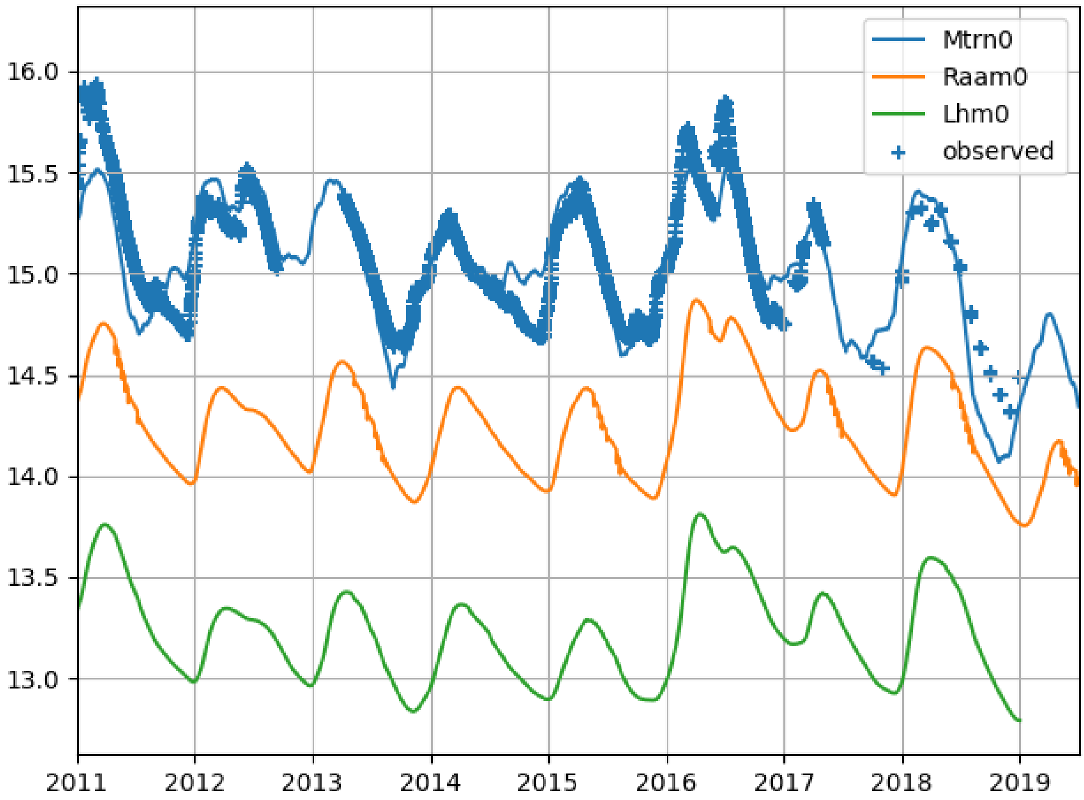


Figure 6.13 Measured groundwater heads for B46C0478001 together with simulated values from Metran, de Raam model, and NHI-LHM.

Figure 6.13 also shows a systematic difference between the models. Now the heads from the distributed models are lower, while the surface elevation is again higher (see Table 6-1). The regional model de Raam matches the measured heads much better than the national model. The distributed models simulated the fluctuation of the heads better for the year 2011. Metran overestimates the drop of the heads in 2018 and the minimum is off in timing. The distributed models underestimate the drop slightly, and model the timing better than Metran. This could be due to non-linear behaviour that the physically based models can reproduce, while the Metran model is linear.

6.4.2.2 Climate change scenarios

Figure 6.14 and *Figure 6.15* show comparisons for integrated model results with time series models simulations for climate change scenarios in the upper piezometer of two monitoring wells.

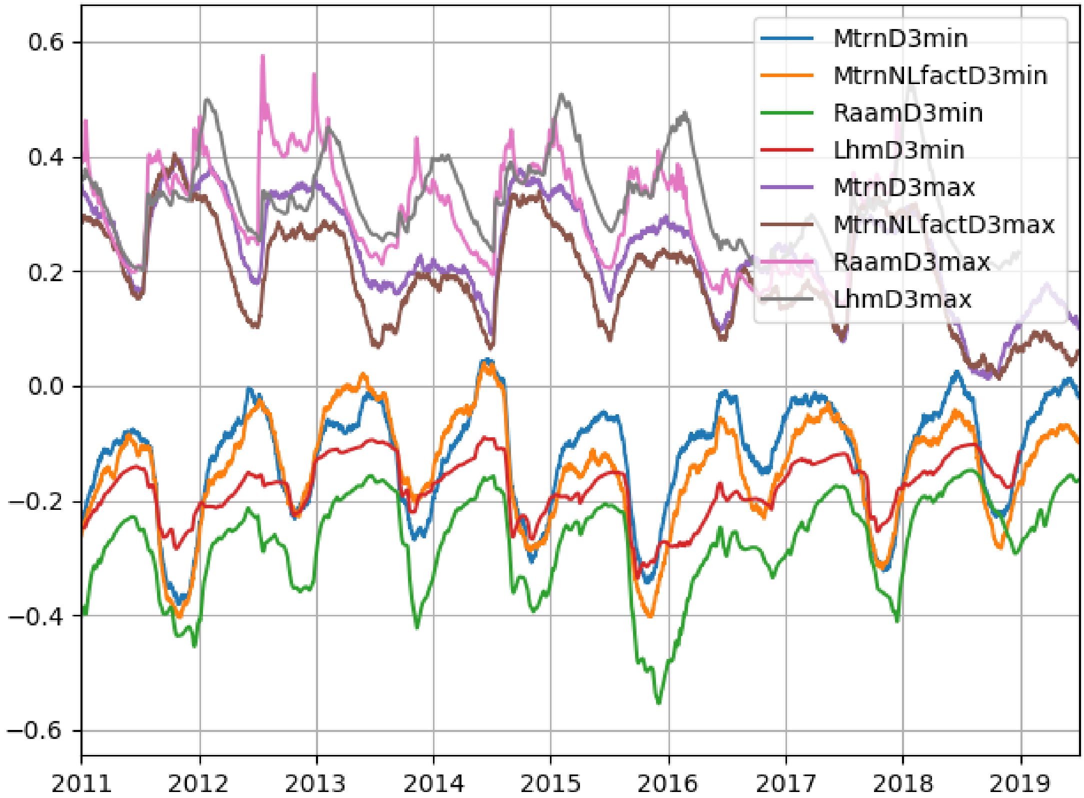


Figure 6.14 Calculated changes for the 3min and 3max climate change scenarios with respect to the reference simulation for piezometer B45F0174001.

There is some impact of the change factors visible in the two Metran simulations (Mtrn with De Raam factors, and MtrnNLfact with national factors). The difference in change factors is also contained in the integrated models. Moreover, the simulations for De Raam seem to benefit from the more detailed regional model.

The physical relations in the integrated models create different dynamics of the groundwater table than the relatively simple extrapolation of the current situation in the time series models. Because of this the changes from the integrated models are probably more reliable than from the time series models. However, given the larger deviation from the measurements for the current situation, the absolute values should be used with care.

This probably can be improved by constructing more accurate maps of the reference groundwater head by combining the measurements or time series models together with the integrated model results. This can be done by kriging with model output as a trend surface (e.g. Zaadnoordijk et al., 2021). The changes simulated by the integrated model are subsequently superimposed on this reference head map.

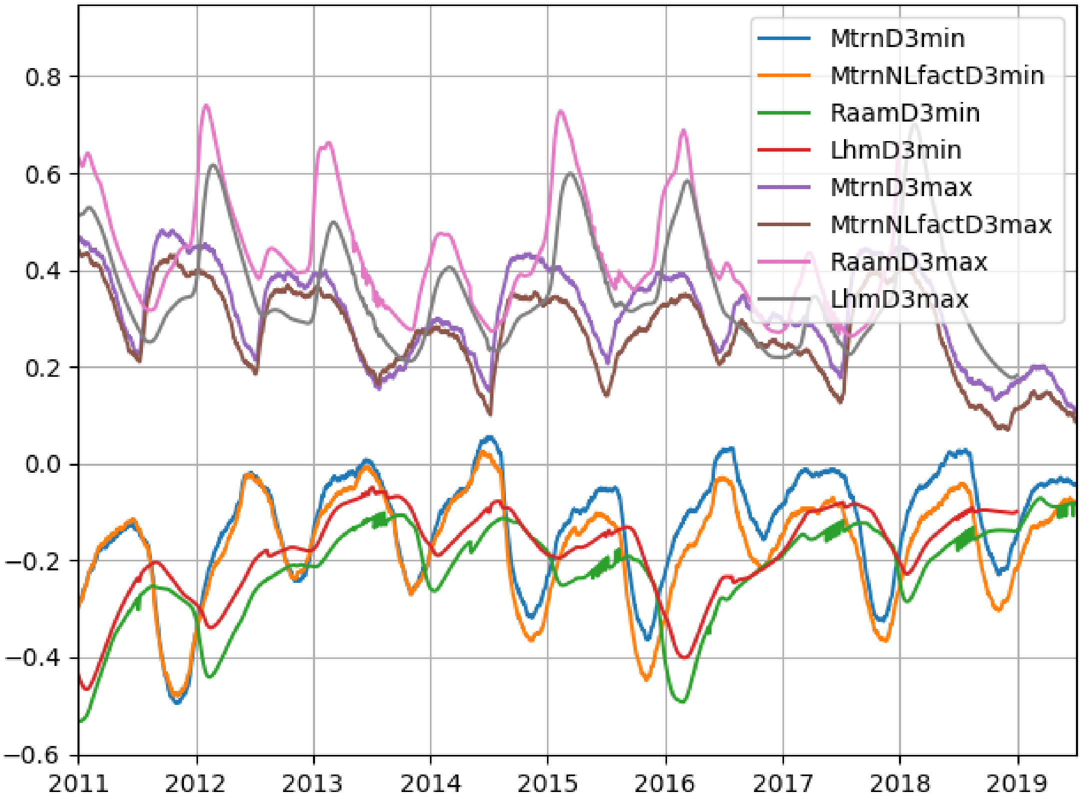


Figure 6.15 Calculated changes for the 3min and 3max climate change scenarios with respect to the reference simulation for B46C0478001.

The fact that simulations with time series models assume that the groundwater system does not change (and in case of the Metran simulations presented also assumes a linear behaviour) does limit their usefulness for propagation of climate change in the groundwater system, compared to the integrated models. On the other hand, making separate time series models for different periods is an easier way to detect whether the groundwater system has changed or temporarily behaves differently.

7 CONCLUDING REMARKS

Two pilots in the Netherlands have been investigated using integrated physically-based distributed hydrological modelling and transfer-noise time series modelling. The national pilot and the regional pilot De Raam have a large difference in resolution (250 m x 250 m and 25 m x 25 m, respectively), related to the different purposes. The national model is used for the management of the main rivers and for national policy development. The model for De Raam is intended for improving the regional water management, e.g. by evaluating concrete local measures.

A comparison of the results of the national and regional pilot has indicated that the finer resolution is necessary to study local variations within the pilot area. The national model is only able to roughly describe the effect of climate change in the pilot area. Moreover, the effect of climate change according to a regional model is also slightly more profound compared to the national model.

The time series modelling provides information only at locations of monitoring wells, although it is possible to create spatial images of various outputs.

The time series models provide more accurate history matching at the well locations, while the integrated models are better predictors for future scenarios.

The recharge calculated by the integrated models is more reliable than that of time series models calibrated only on groundwater heads. The time series model allows for an estimation of the correlation of the groundwater levels with surface water levels, which provides a limited insight in the groundwater-surface water interaction compared to the integrated models.

Both types of models can simulate climate change scenarios, albeit results of the integrated models are much more trustworthy, provided the important processes are included with an adequate parametrisation. It can be useful for climate analysis to further detail the processes within the integrated models, for example coupling with detailed crop models if crop evaporation might change in the future situation, or with detailed surface water models if the intensity of precipitation changes significantly.

The effort to setup and maintain the integrated model is much larger than for time series modelling. Combined use provides extra benefits e.g. improved spatial continuous history matching, determining important processes to include in the integrated model by time series modelling with known influences, and selection (and weighing) of piezometers to use for calibration.

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