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PILOT DESCRIPTION AND ASSESSMENT

Drava-Mura aquifer, Croatia

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LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate change
GWB	Groundwater body
GWDE	Groundwater dependent ecosystem

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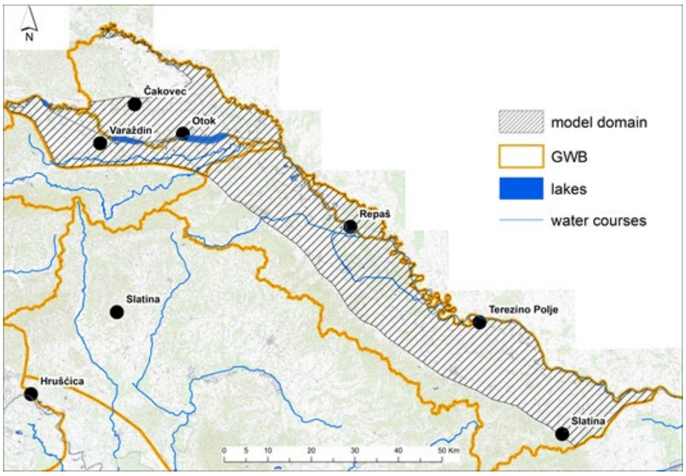
1 EXECUTIVE SUMMARY

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).

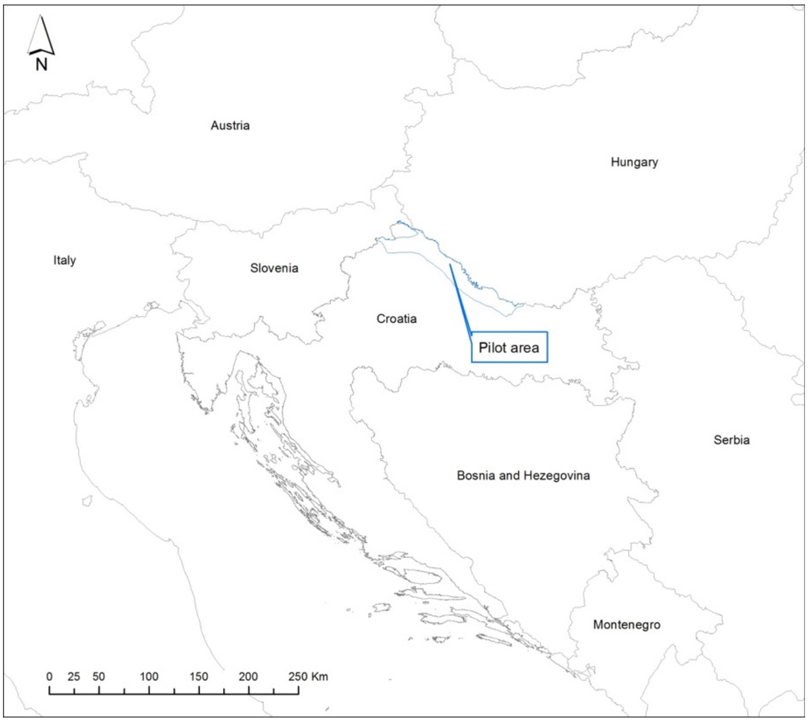


Figure 3.1. Location of the pilot area

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

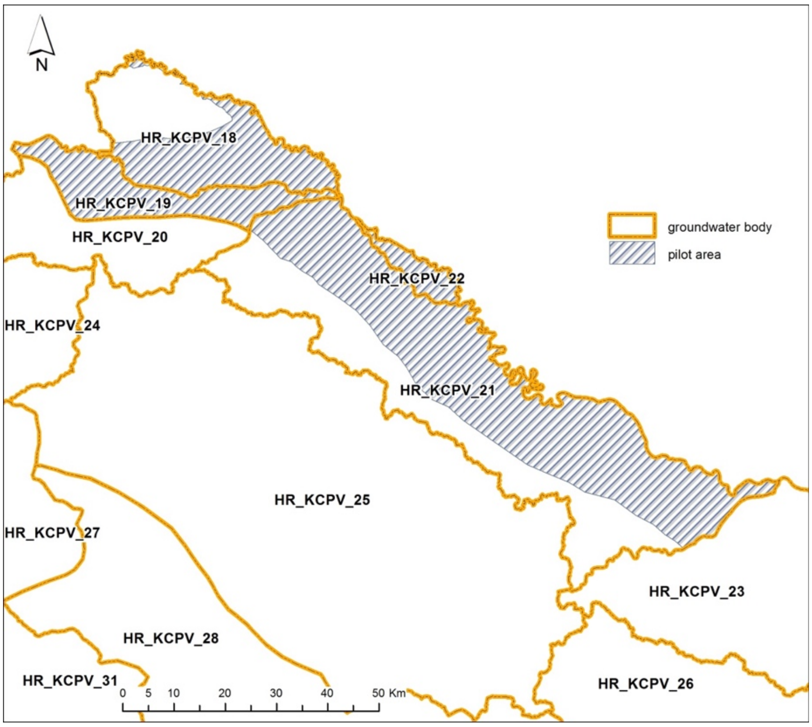


Figure 3.2. Pilot area and groundwater bodies

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.

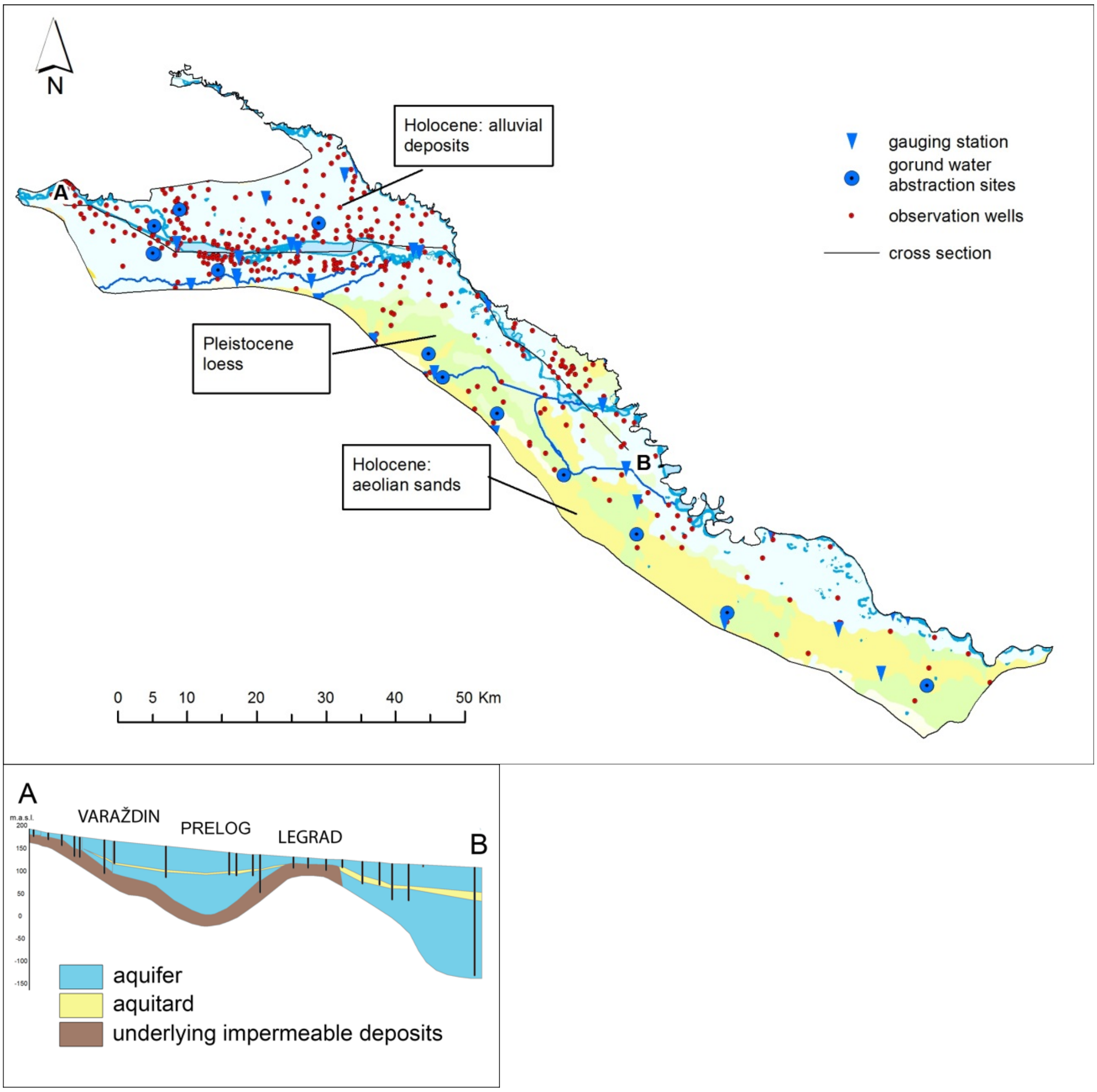


Figure 3.3: Geological map (HGI, 2009) and hydrogeological cross section

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.

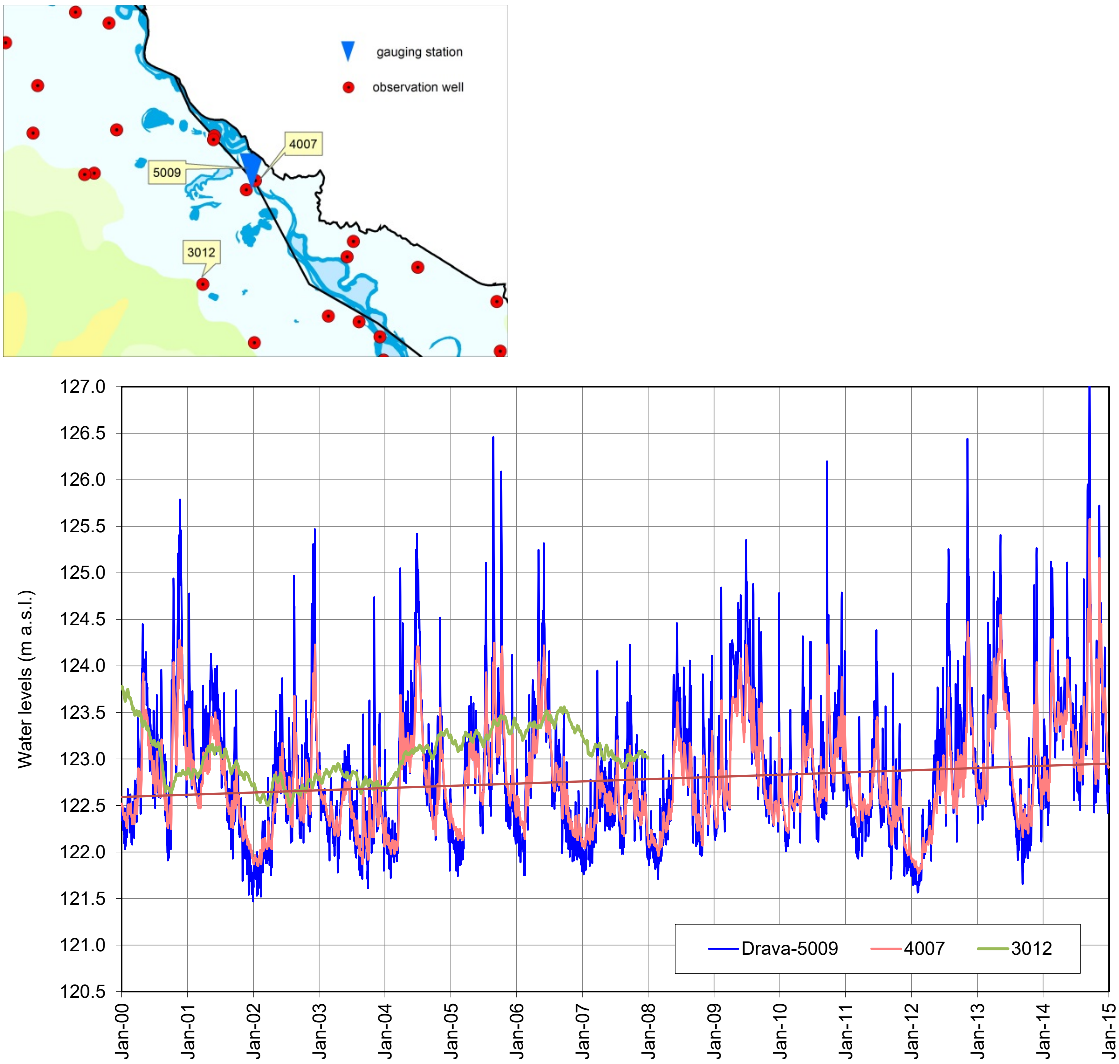


Figure 3.4. Drava river levels and groundwater levels at observation wells 4007 (450 m from the river) and 3012 (5 km from the river)

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.

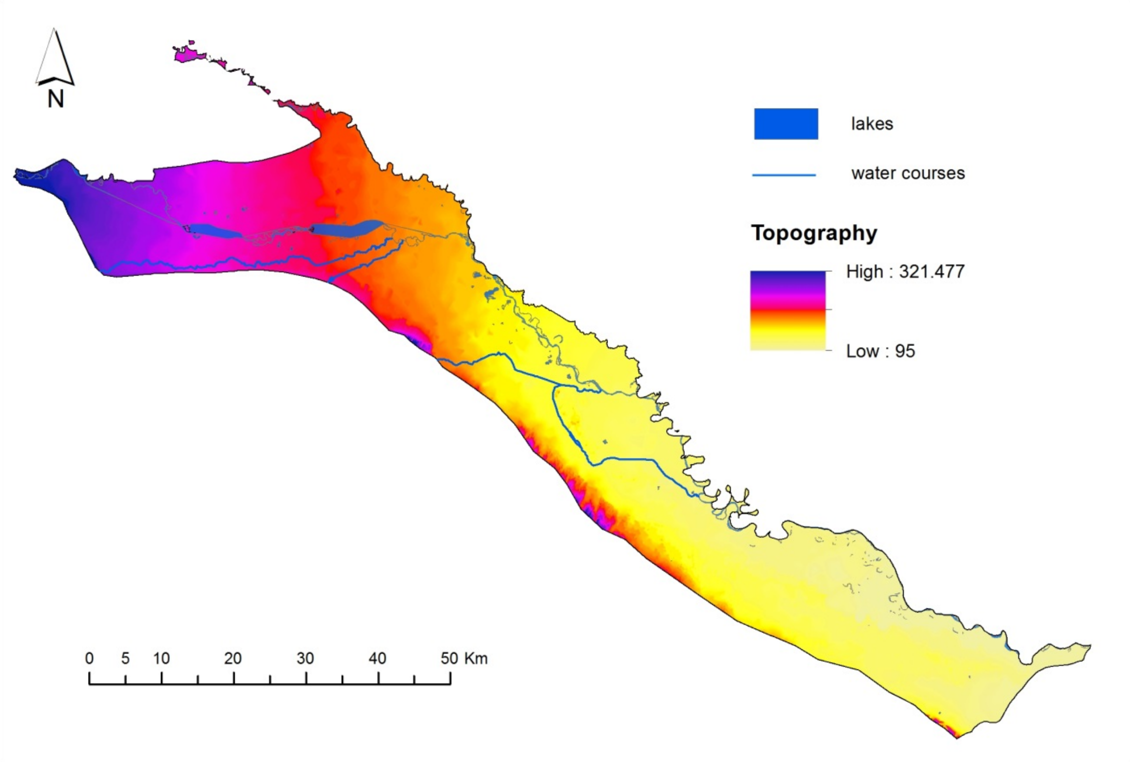


Figure 3.5. Topography

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 °C and average January temperature between 0 and 3 °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).

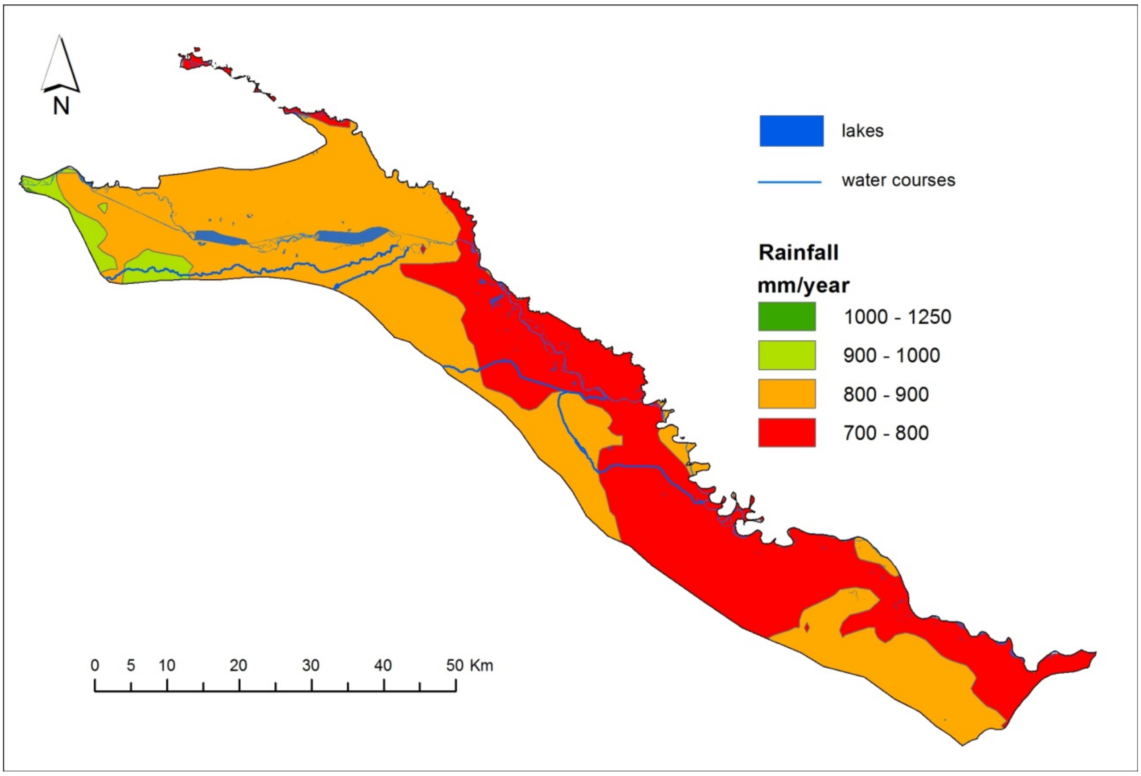


Figure 3.6. Spatial distribution of mean annual precipitation, 1961-1990 (Gajić-Čapka et al., 2003)

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.

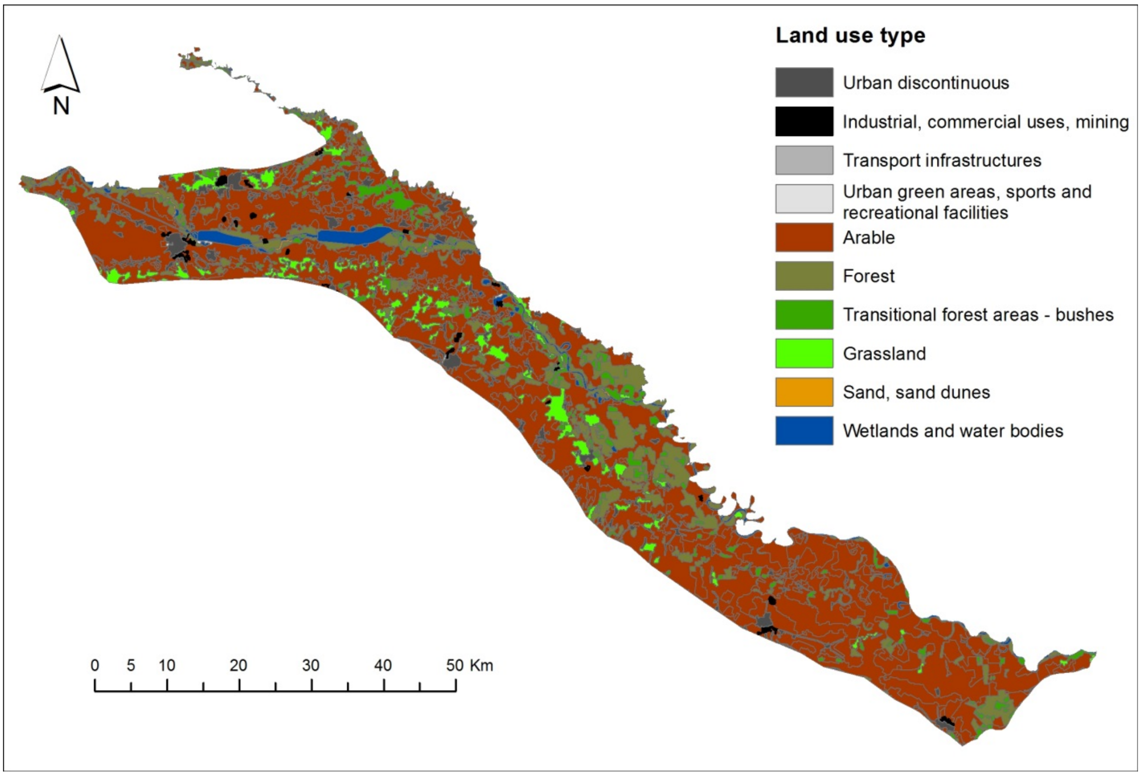


Figure 3.7. Map of land use over the pilot area (CLC, 2000)

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.

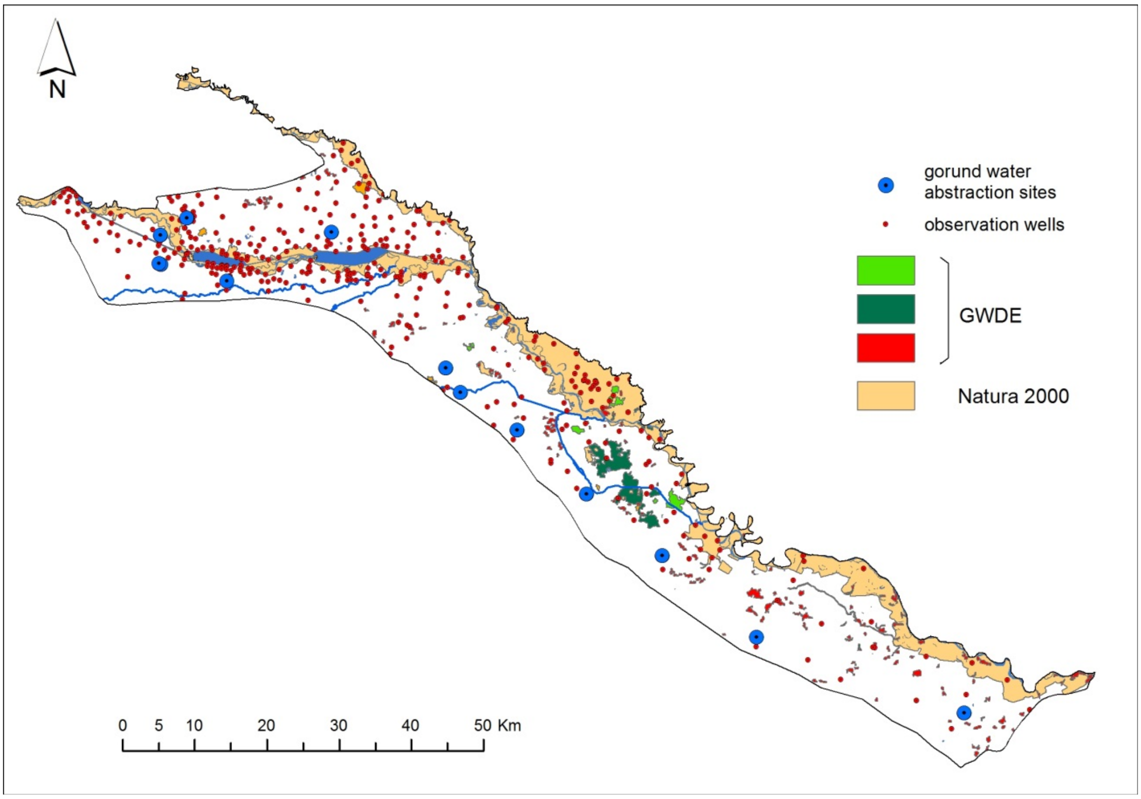


Figure 3.8. GWDEs and NATURA 2000 protected areas

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.

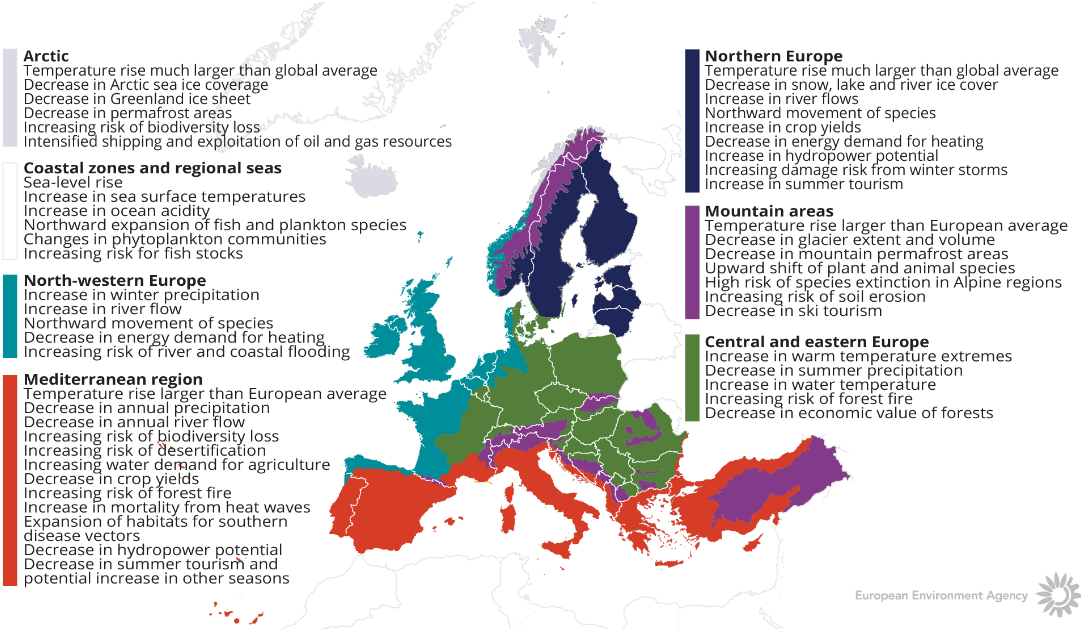


Figure 3.9. How is climate expected to change in Europe. The European Environment Agency map

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.

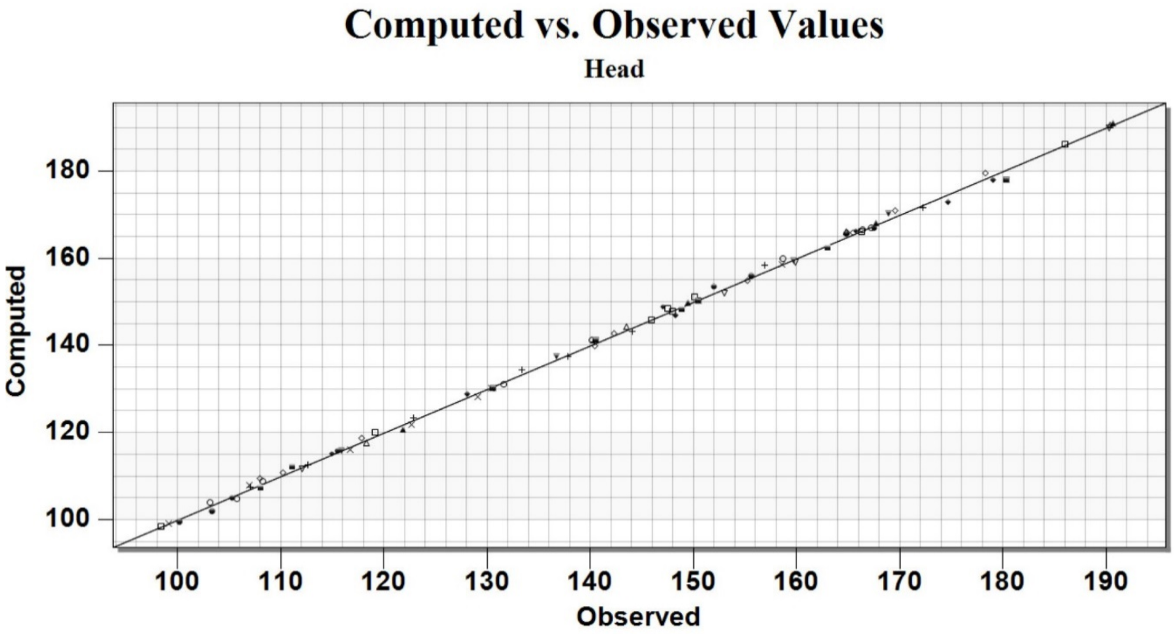


Figure 4.1. Calculated vs observed heads for steady state simulation

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%

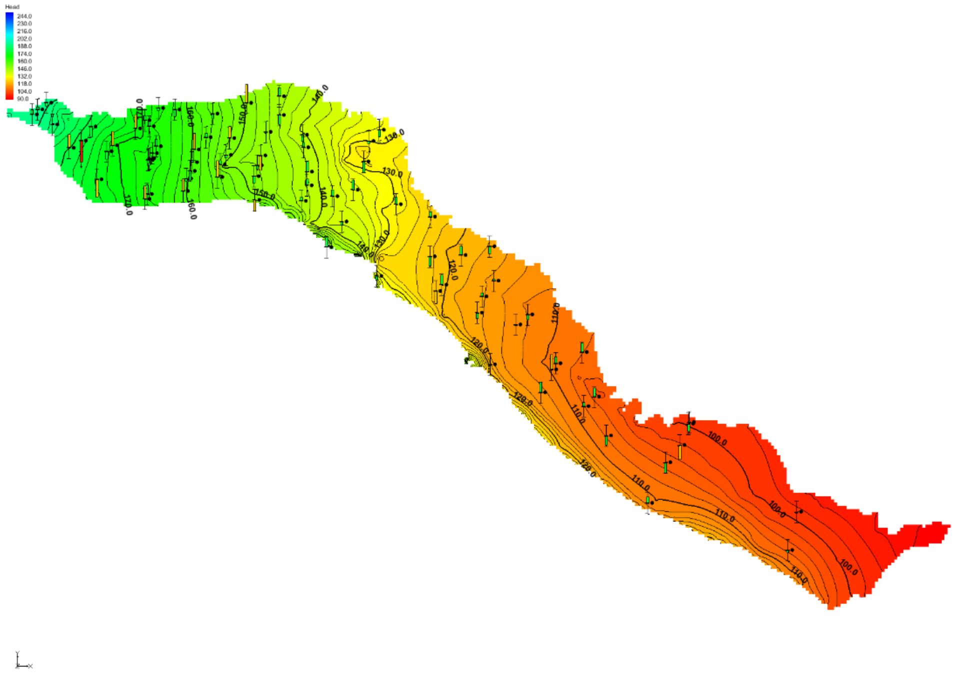


Figure 4.2. Hydraulic head in the upper aquifer – steady-state simulation

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).

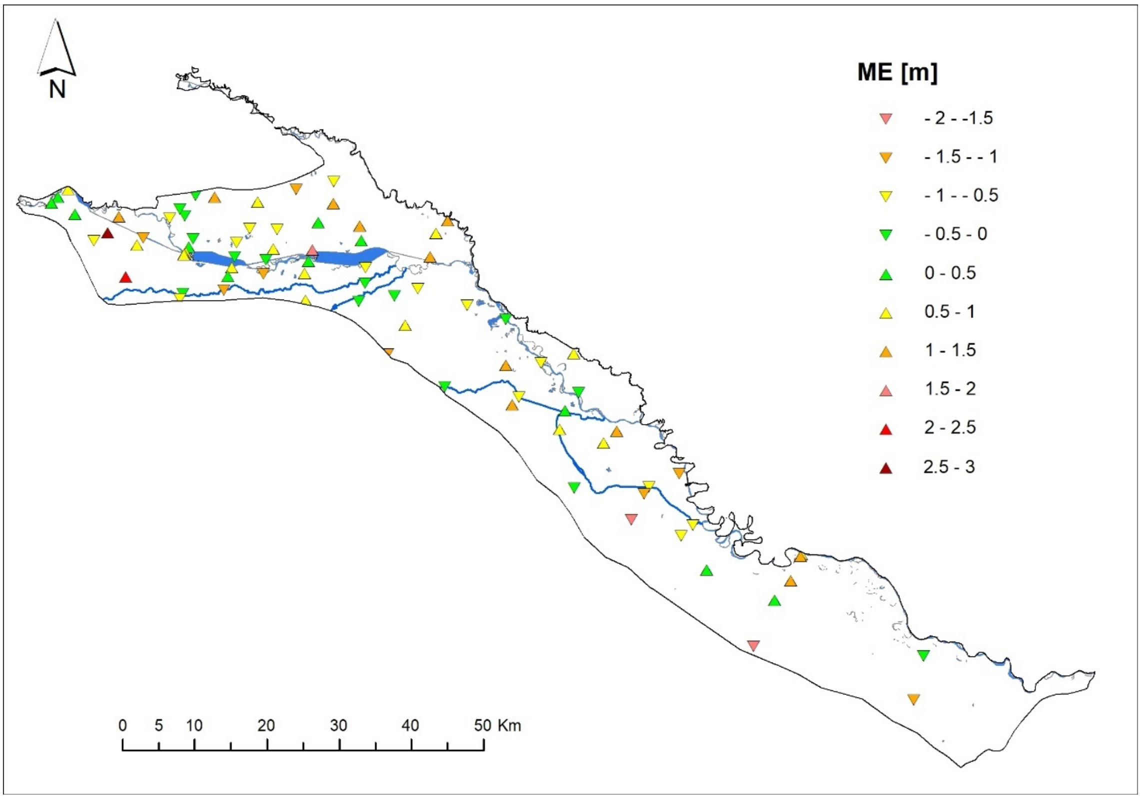


Figure 4.3. Mean error in the upper aquifer – transient simulation

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).

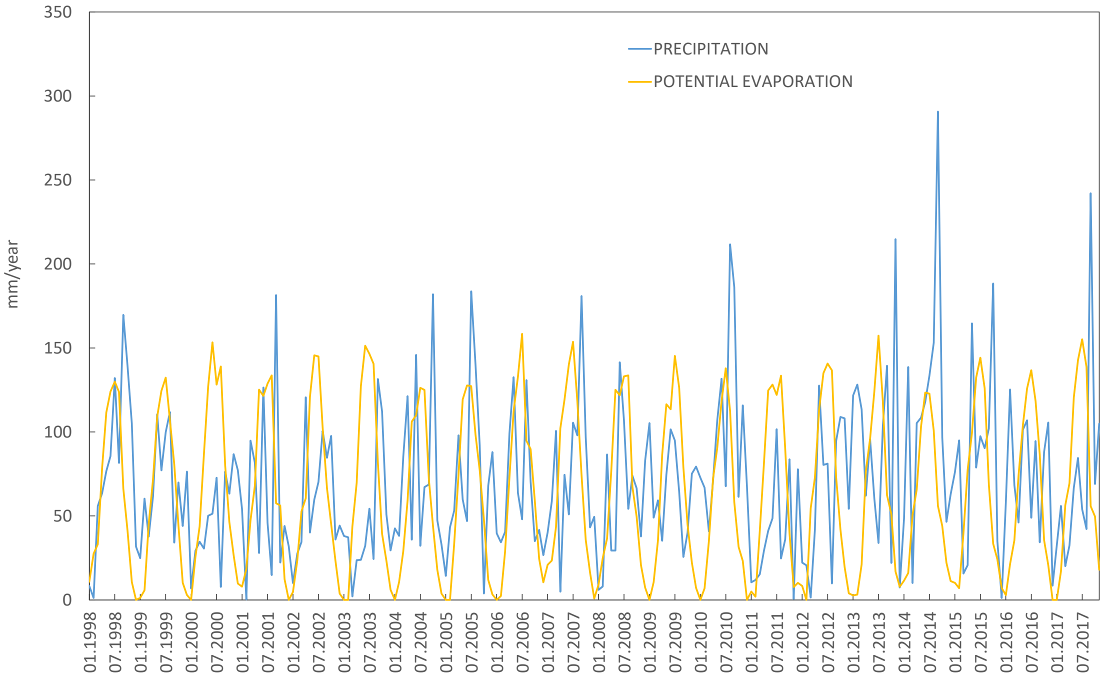


Figure 4.4. Precipitation and potential evapotranspiration

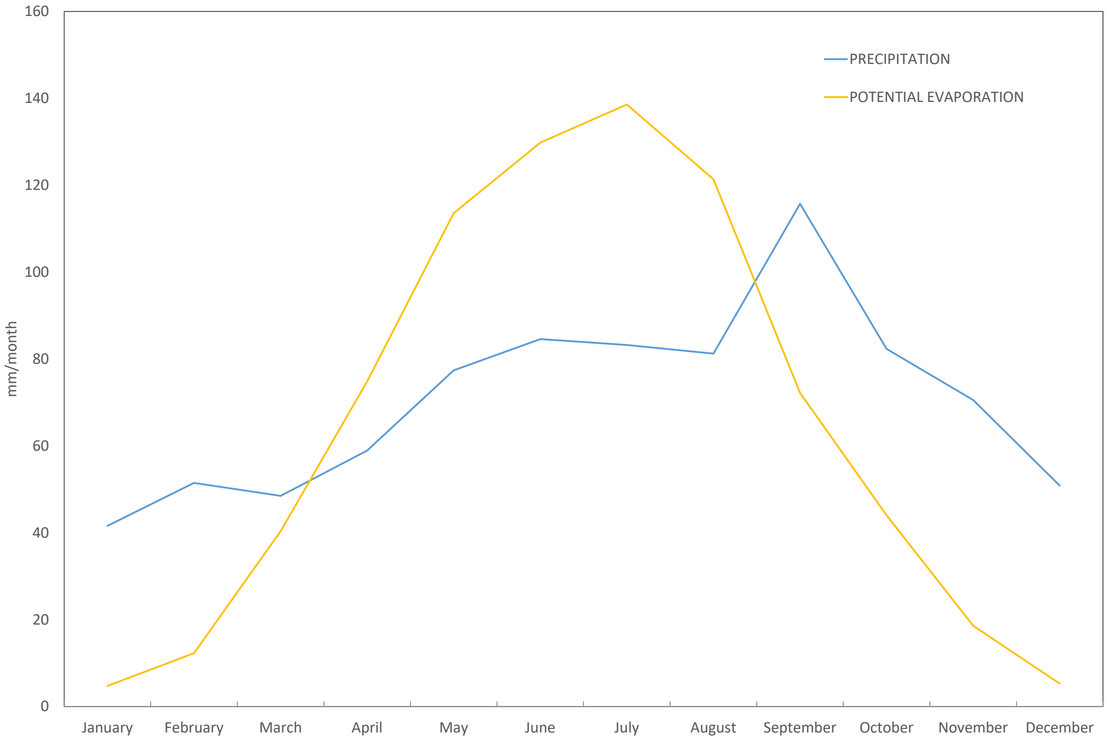


Figure 4.5. Monthly mean values of precipitation and potential evapotranspiration

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.

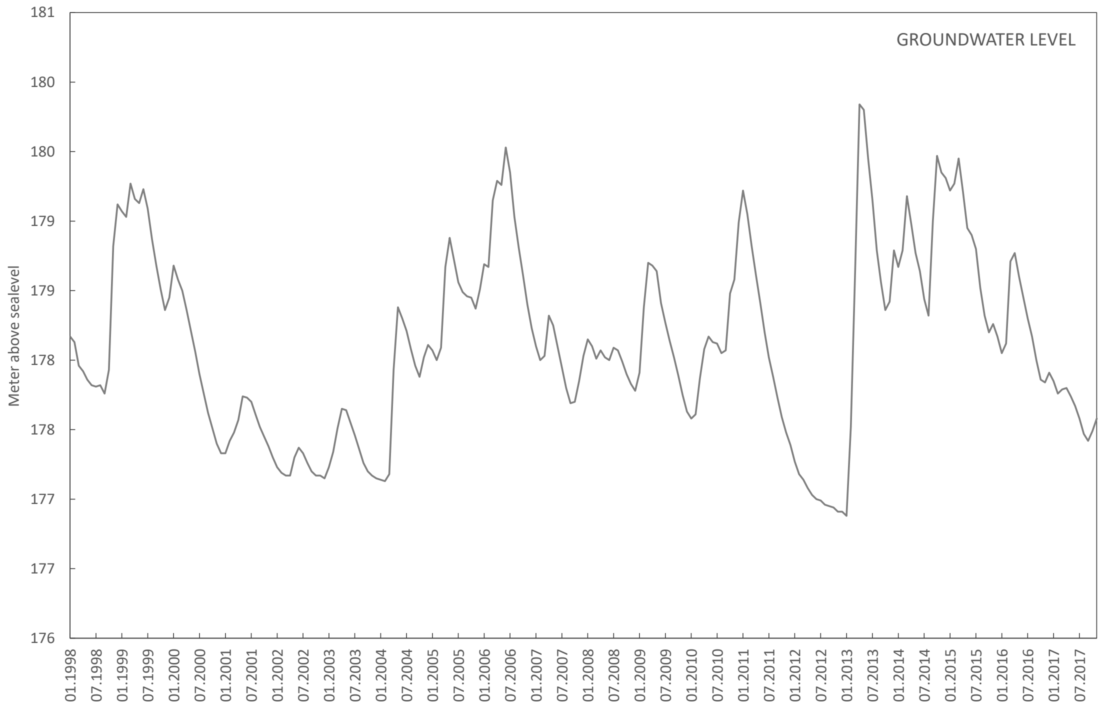


Figure 4.6. Groundwater levels

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

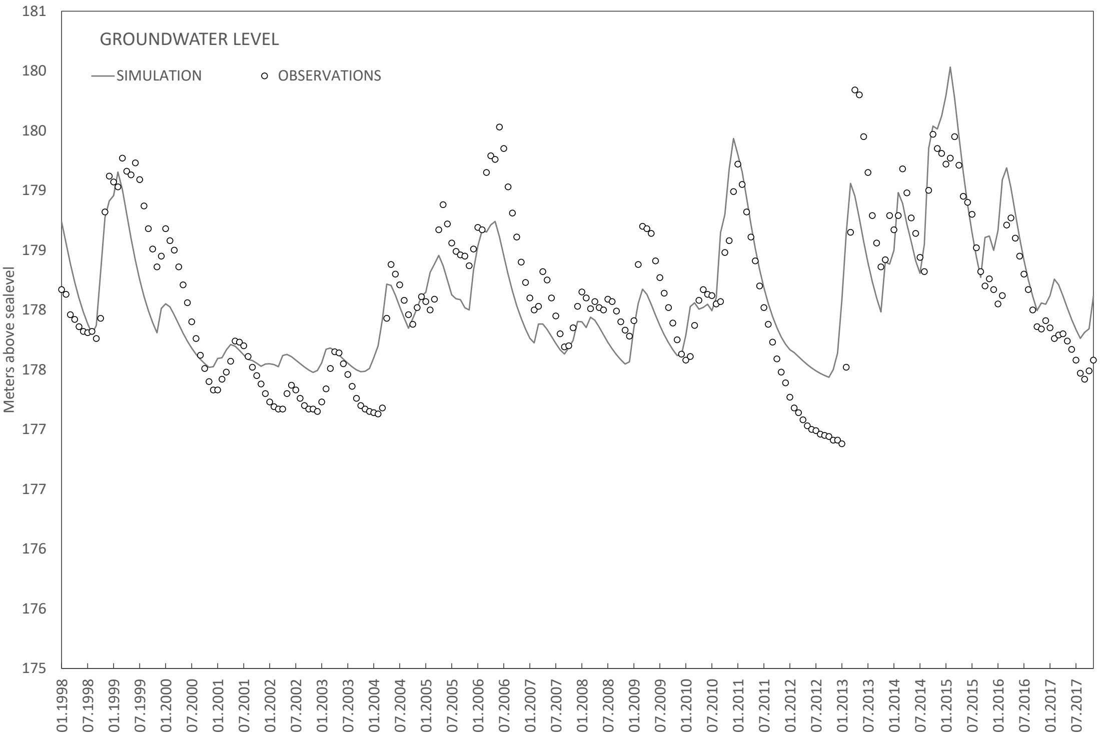


Figure 4.7. Simulated and observed groundwater levels

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.

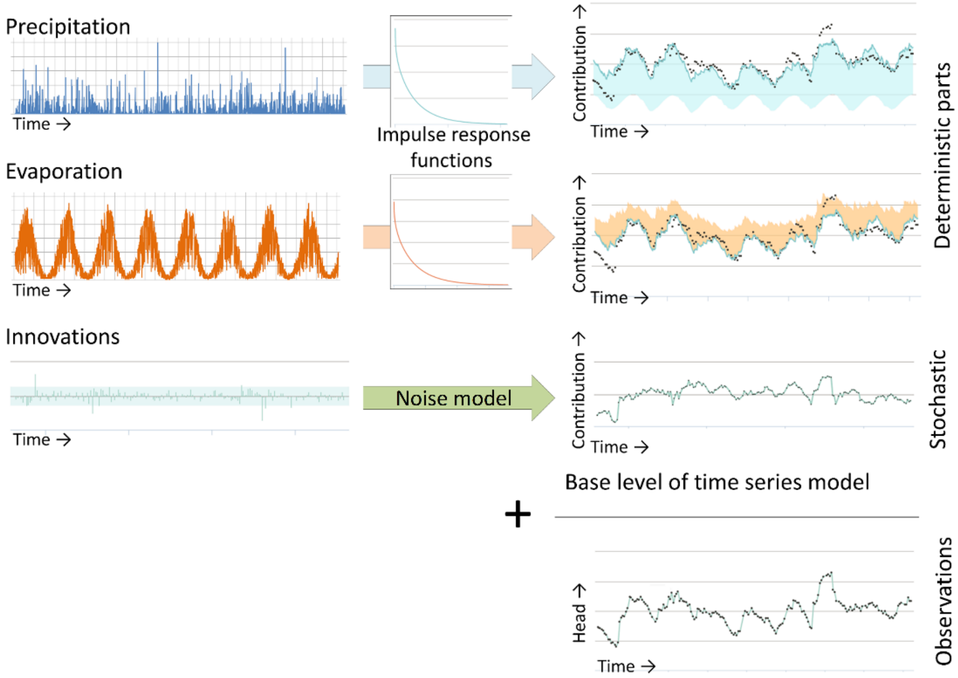


Figure 4.8. Metran setup

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.

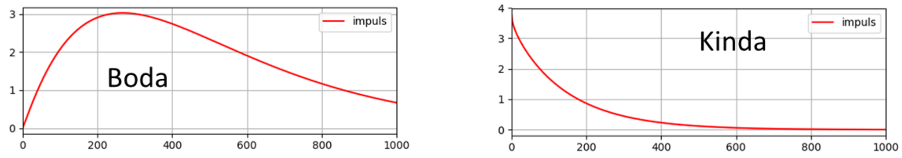
Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other daily time steps can be used, although Metran still has the limitation that the explanatory variables have a constant frequency. For the TACTIC simulations of series with monthly 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

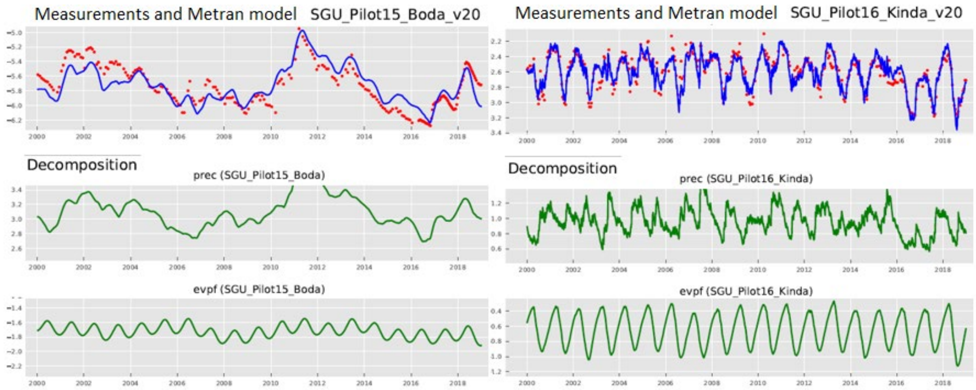


Figure 4.9. Impulse response functions and head time series for pilots in Sweden

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.

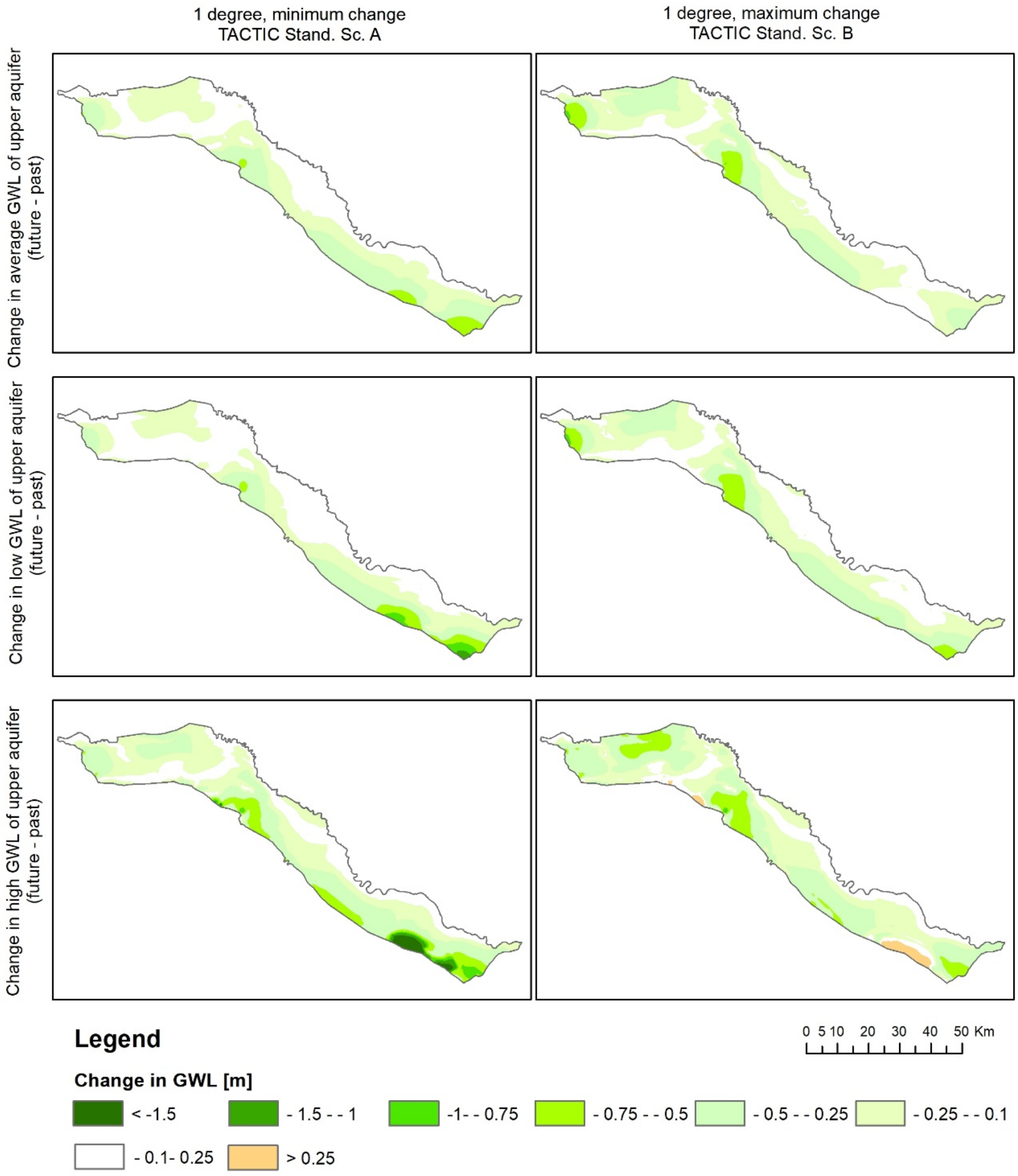


Figure 5.1. Changes in average, maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario.

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.

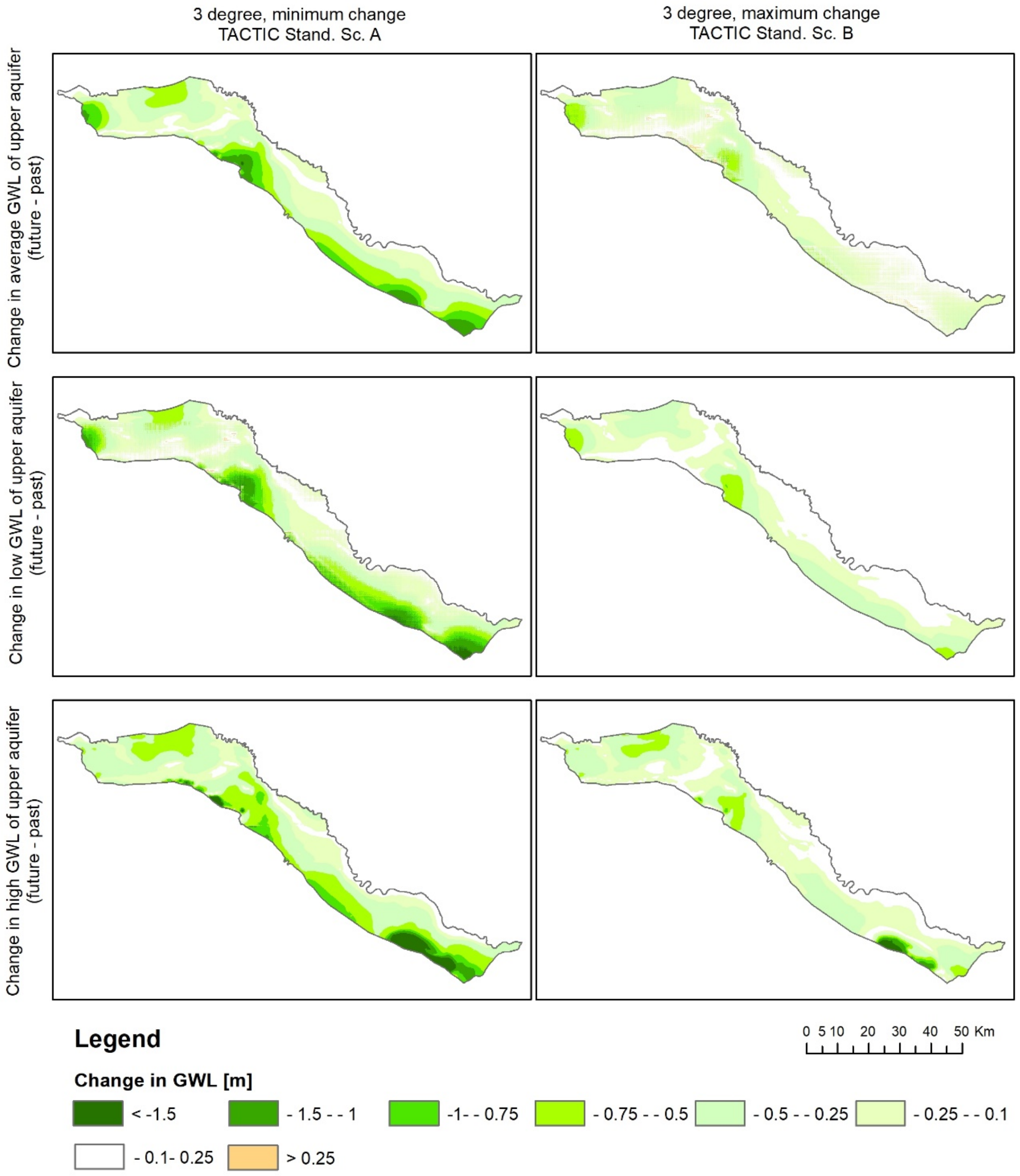


Figure 5.2. Changes in average, maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario.

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.

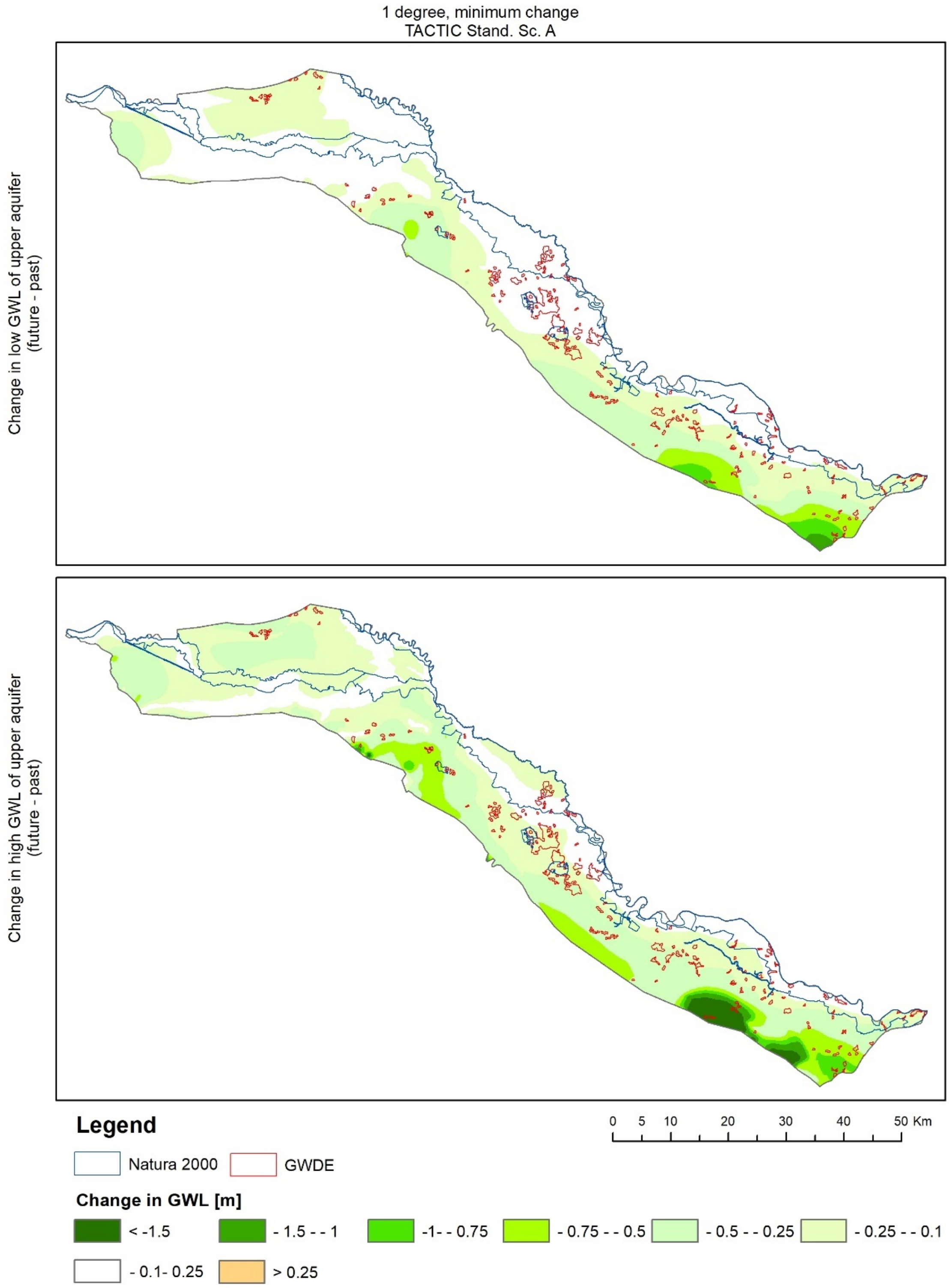


Figure 5.3. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario, minimum change.

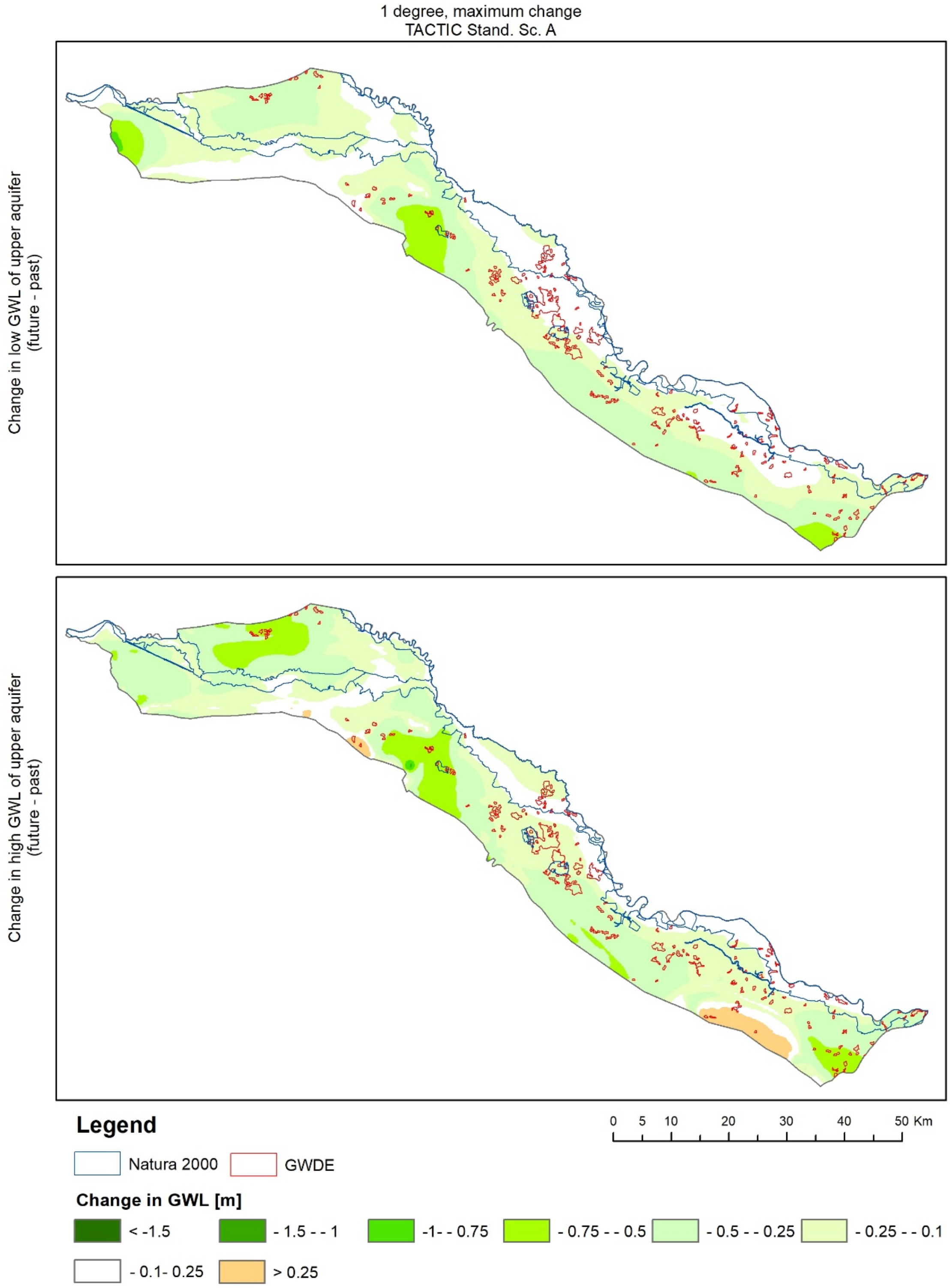


Figure 5.4. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 1-degree warming scenario, maximum change.

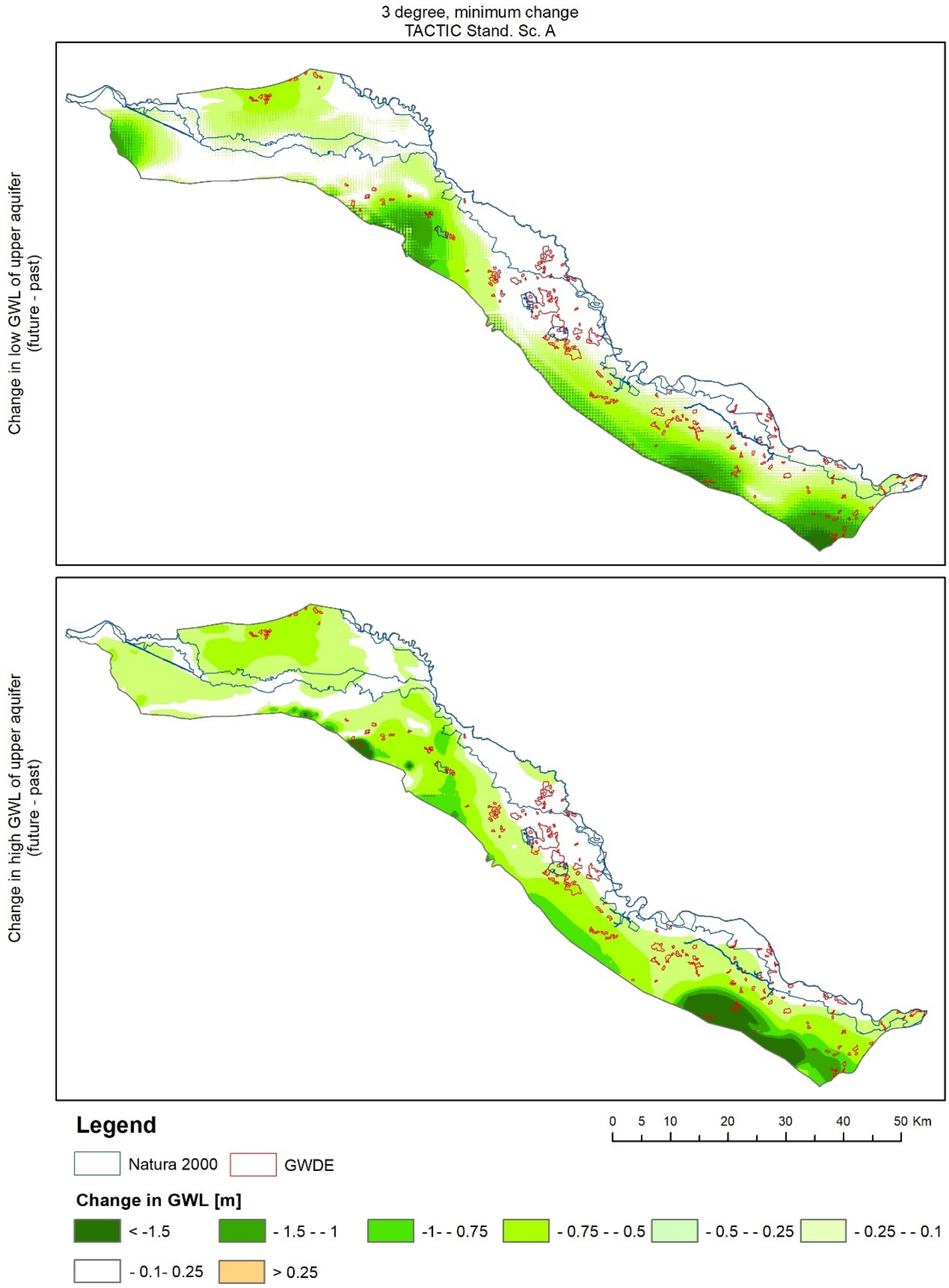


Figure 5.5. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario, minimum change.

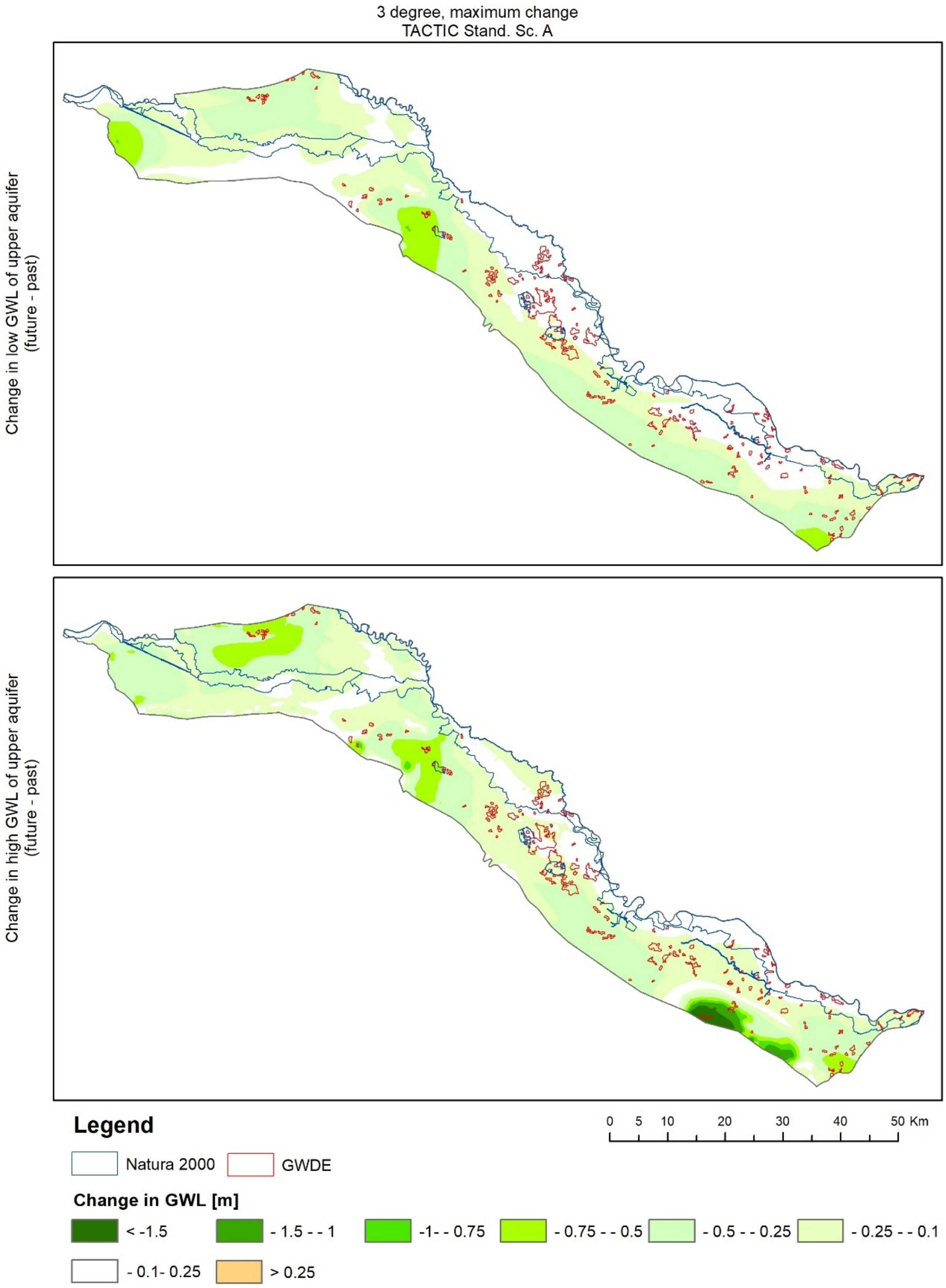


Figure 5.6. Natura 2000 protected areas, GWDEs and changes in maximum and minimum shallow groundwater levels simulated with the 3-degree warming scenario, maximum change.

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.

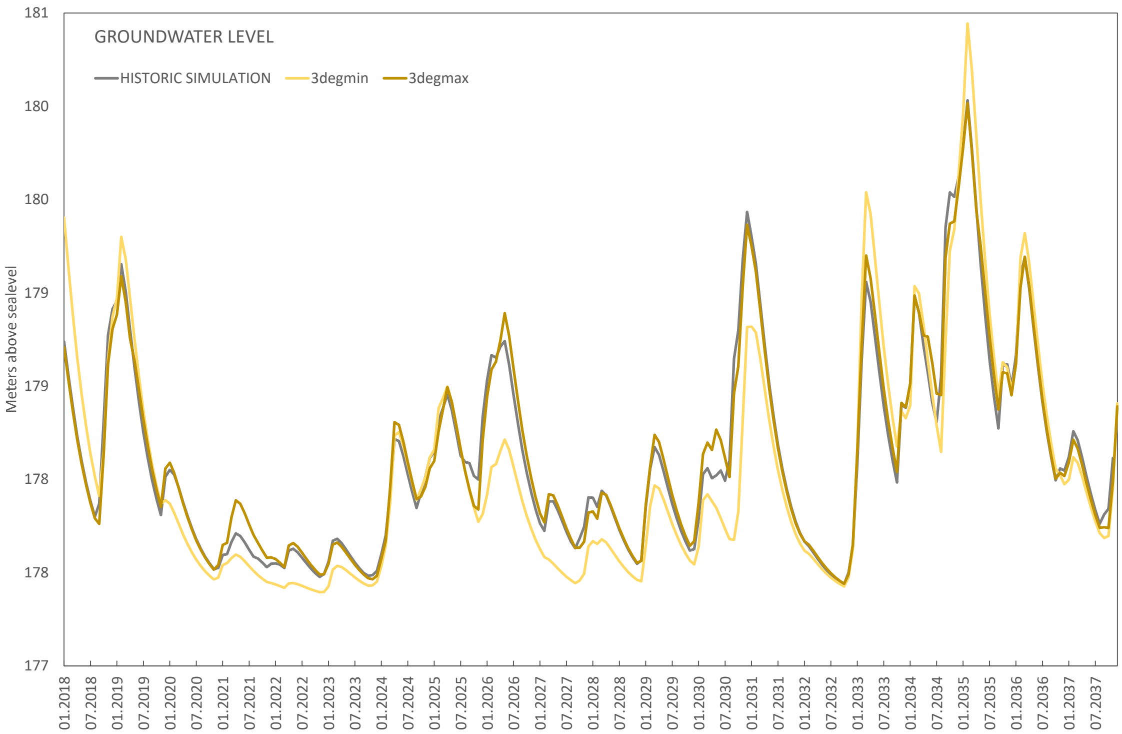


Figure 5.7. Groundwater level simulation for historic period and 3-degree minimum and maximum change.

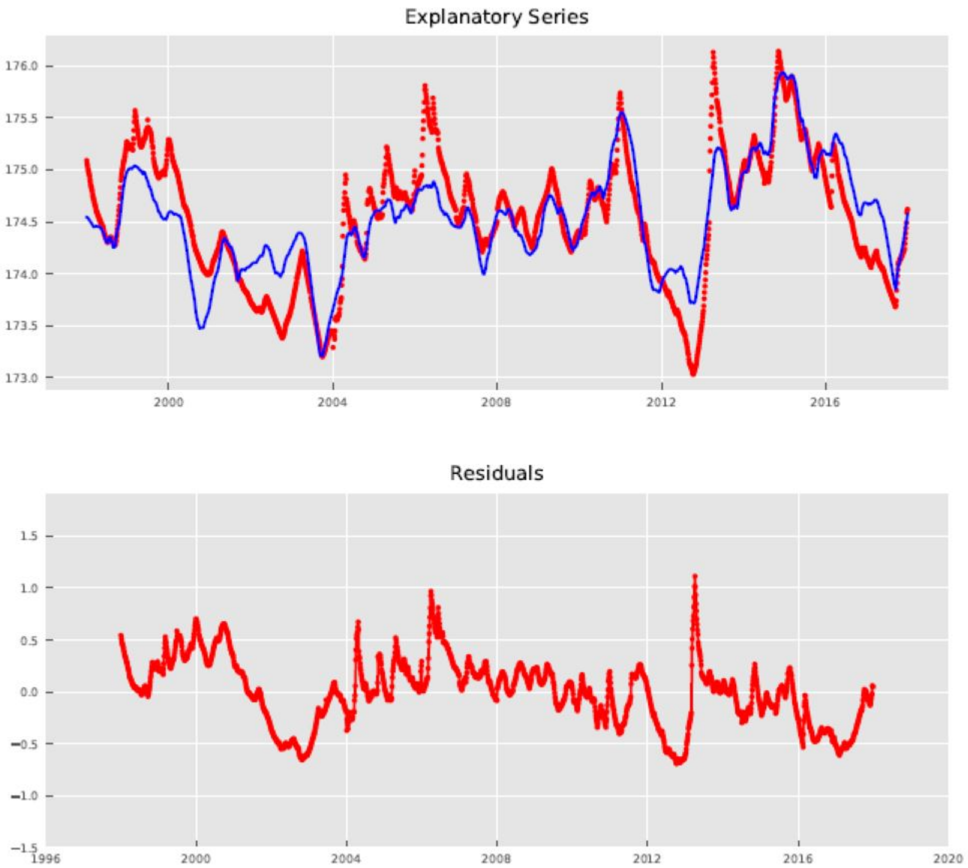
The results of the average monthly recharge from lumped hydrological model are shown in Table 5.1. For minimum change scenario recharge is 49% lower, while for the maximum change it is 4% higher, as compared to the reference period.

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.


Explanatory Series

Residuals

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.

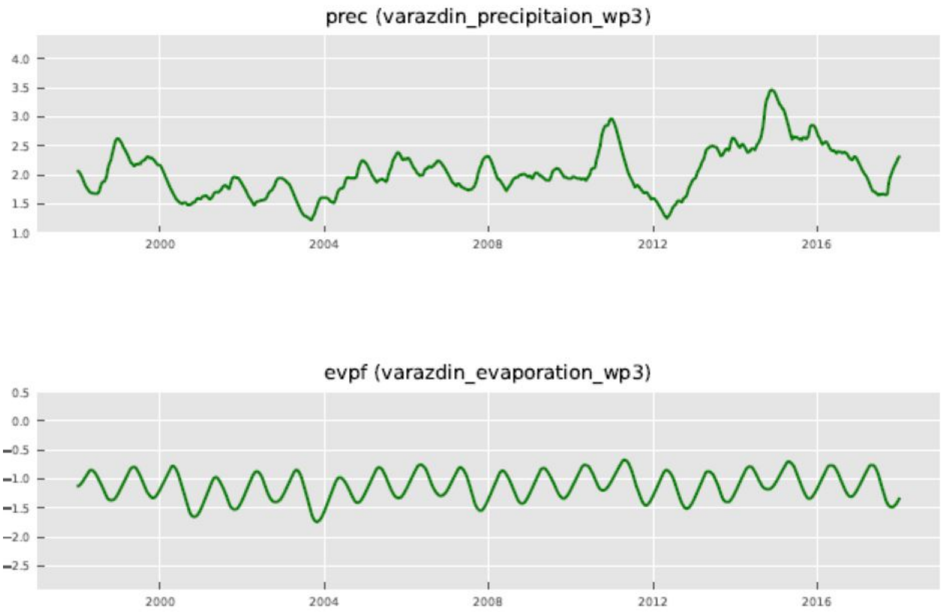


Figure 5.9. Contribution of precipitation and evaporation to the observed dynamics.

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.

6 REFERENCES

Besbes, M. & de Marsily, G. (1984): From infiltration to recharge: use of a parametric transfer function. Journal of Hydrology, 74, p. 271-293.

Brkić, Ž. (1999): Alluvial aquifer recharge through semipermeable covering deposits in northern Croatia. PhD thesis (in Croatian), University of Zagreb, 157 p.

Brkić, Ž., Larva, O., & Urumović, K. (2010): The quantitative status of groundwater in alluvial aquifers in northern Croatia. Geologia Croatica, 63/3, 283-298, Zagreb.

Croatian geological survey (2009): Geological map of Republic of Croatia 1:300000. HGI-CGS.

Doherty, J. (2015): Calibration and uncertainty analysis for complex wnvironmental models. Watermark Numerical Computing.

Gajić-Čapka, M., Perčec-Tadić, M. & Patarčić, M. (2003): Digitalna godišnja oborinska karta Hrvatske. Hrv. meteorol. časopis. [Digital map of annual precipitatins]. 38, 21-33, Zagreb.

Harbaugh, A.W. (2005): MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Harbaugh, A.W., Langevin, C.D., Hughes, J.D., Niswonger, R.N., and Konikow, L. F. (2017): MODFLOW-2005 version 1.12.00, the U.S. Geological Survey modular groundwater model: U.S. Geological Survey Software Release, 03 February 2017, http://dx.doi.org/10.5066/F7RF5S7G

Hill, M.C. (2006): The practical use of simplicity in developing ground water models. Ground Water, 44, 775-781.

Köppen, W. (1936): Das geographische System der Klimate. Handbuch der Klimatologie I, C. Berlin

Makjanić, B., Penzar, B., Volarić, B., Penzar, I. & Lisac, I. (1979): Klimatska karta Hrvatske prema Köppenovoj klasifikaciji za razdoblje 1950.-1977. [Climatic map of Croatia according to Köppen classification for the period 1950-1977]. Geofizički zavod PMF, Zagreb.

Miletić, P., Urumović, K., Capar, A., Bošković, D. & Mlakar, I. (1971): Analiza mjerenja podzemnih voda nizvodno od Virovitice – SR Hrvatska. [*Analysis of groundwater measurements downstream of Virovitica – SR Croatia – in Croatian*]. - Geol. vjesnik, 24, 155-159, Zagreb.

Patrčević, V. (1995) Hydrological analysis of vertical water balance of groundwater at the area of river alluvium. PhD thesis (in Croatian), University of Zagreb, 161 p.

Obergfell, C., Bakker, M., & Maas, K. (2019): Estimation of average diffuse aquifer recharge using time series modeling of groundwater heads. Water Resources Research, 55. https://doi.org/10.1029/2018WR024235

Šegota, T. & Filipčić, A. (1996): Klimatologija za geografe. [Climatology for geographers]. 3rd revised edition. Šk. knjiga, Zagreb.

Urumović, K., Hlevnjak, B., Prelogivić, E. & Mayer, D. (1990): Hidrogeološki uvjeti varaždinskog vodonosnika. [Hydrogeological conditions of the Varaždin aquifer]. Geol. vjesnik, 43, 149-158, Zagreb.

Urumović, K., Šarin, A. & Donadini, K. (1981): Groundwater balance in the river basin district Drava-Dunav for 1979-1980. IGI, Zagreb.

Zaadnoordijk, W.J., Bus, S.A.R., Lourens, A., Berendrecht, W.L. (2019): Automated Time Series Modeling for Piezometers in the National Database of the Netherlands. Groundwater, 57, no. 6, p. 834-843. https://onlinelibrary.wiley.com/doi/epdf/10.1111/gwat.12819.