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PILOT DESCRIPTION AND ASSESSMENT

Posavina (Serbia)

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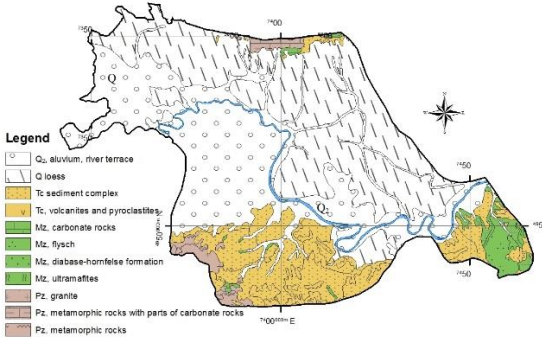
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LIST OF ABBREVIATIONS & ACRONYMS

TABLE OF CONTENTS

LIST OF ABBREVIATIONS & ACRONYMS	5
1 EXECUTIVE SUMMARY	5
2 INTRODUCTION	7
3 PILOT AREA	8
3.1 Site description and data	8
3.2 Climate	9
3.2.1 Climate type	9
3.2.2 Precipitation and evapotranspiration	9
3.3 Topography	9
3.4 Land use	10
3.5 Geology/Aquifer type	11
3.6 Surface water bodies	13
3.7 Abstractions/irrigation	13
3.8 Climate change challenge	14
4 METHODOLOGY	15
4.1 Methodology and climate data	15
4.1.1 AquiMod	15
4.1.2 Metran	15
4.1.3 Climate data	16
4.2 Tool(s) / Model set-up	18
4.2.1 AquiMod	18
4.2.2 METRAN	20
4.3 Tools/ Model calibration/ test	21
4.3.1 Calibration of AquiMod models	21
4.3.2 Calibration of Metran models	23
4.4 Uncertainty	23
5 RESULTS AND CONCLUSIONS	25
5.1 Performance to historical data	25
5.2 Future projections	25
REFERENCES	28
Appendix A: AquiMod methodology	29
The soil moisture module	30
The unsaturated zone module	30
The saturated zone module	31
Limitations of the model	32
Model input and output	33
Appendix B: Metran methodology	34
Limitations	35
Time step	35
Model output	35
Model quality	36
Recharge	36

1 EXECUTIVE SUMMARY

Pilot name	Posavina (Sava River Basin)	
Country	Serbia	
EU-region	Central and Eastern Europe	
Area (km ²)	5250 km ²	
Aquifer geology and type classification	Sand and gravel. Porous aquifer	
Primary water usage	Irrigation/ Drinking/ Industry	
Main climate change issues	The catchment of Sava River has a history of high and low groundwater and surface water levels due to increase of temperature, extreme weather conditions, floods (due to heavy rainfall) and even droughts (in some years). Therefore, the three main potential impacts of climate change on water resources in the area are related to the problems of water availability, water quality and frequency of floods and droughts. Changes in the water regime with these three aspects would inevitably influence water management.	
Models and methods used	AquiMod, METRAN	
Key stakeholders	Ministry of Mining and Energy of the Republic of Serbia, Ministry of Agriculture, Forestry and Water Management, Ministry of Environmental Protection, water supply and utility companies	
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Posavina Pilot area is situated in the area of the Sava River Basin in Serbia. From the border with Croatia on the West, to Belgrade in the East, Fruška Gora Mountain to the North and Cer Mountain in the South. The area includes part of Vojvodina (Pannonian Basin) - Srem, then Macva and parts around Belgrade, the capital city.

Besides capital city, groundwater is the only source of water supply in this area. Recharge is mainly from the Sava River, and infiltration from precipitation and surface waters from irrigation canals. In addition, there is a small infiltration of groundwater from the terrace sediments into the aquifer. Groundwater discharges into the Sava riverbed at low water levels. In the area of the alluvial plain in the semi-permeable layer, an accumulation of groundwater was formed, which is in direct hydraulic connection with the shallow aquifer. Depth to groundwater table is 2-6 m. Groundwater level fluctuations are driven by infiltration recharge and by evapotranspiration (Josipović and Soro, 2012).



The impact of climate change is focused on the shallow aquifer, which is the most important in terms of drinking water supply in this area. For research purposes Aquimod and Metran time series models were applied. However, the Aquimod models were tested at the five boreholes and could not obtain the satisfactory results, mostly because of the great influence of Sava River water levels. Metran, on the other hand, succeeded in groundwater simulations and recharge estimation only when the river water levels were added as an additional input signal. A Metran model applied at one borehole was used to estimate the long term average historical recharge value as well as the projected recharge values using four standard climate change scenarios developed for the TACTIC project. The TACTIC standard scenarios were developed based on the ISIMIP (Inter Sectoral Impact Model Inter-comparison Project) dataset.

Geological Survey of Serbia has groundwater monitoring net only for the purposes of creating the Basic Hydrogeological Maps, and therefore monitoring is conducted for a hydrologic year. Hence for the purposes of the time series analyses the groundwater data, precipitation, evapotranspiration, and temperature for the Posavina area are taken from the Republic Hydrometeorological Service of Serbia (RHMS).

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts on Europe's hydrological systems including groundwater bodies, which is expected to intensify 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. 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 infrastructure 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>).

3 PILOT AREA

The major groundwater reserves in Serbia are accumulated in thick Quaternary and Neogene aquifers. Alluvial aquifers of large rivers are particularly important and widely used for drinking water supply. This study focuses on groundwater resources in the area of the Sava River Basin. The main purpose of investigating this area is to define general water balance (surface water, precipitation, and groundwater). General water balance is of utmost importance for understanding hydrogeological and agricultural features of the terrain. Assessing the impact of climate characteristics and surface water to the shallow aquifer, will allow efficient planning of measures for sustainable use and protection of shallow groundwater.

Significant climate change observations on the territory of Serbia in the past 20 years, especially in the area of Sava River Basin, have led to conclusion that the major floods (for example in 2014), winter and summer droughts (in 2000, 2012) had great impact to the groundwater table and arable land in this area.

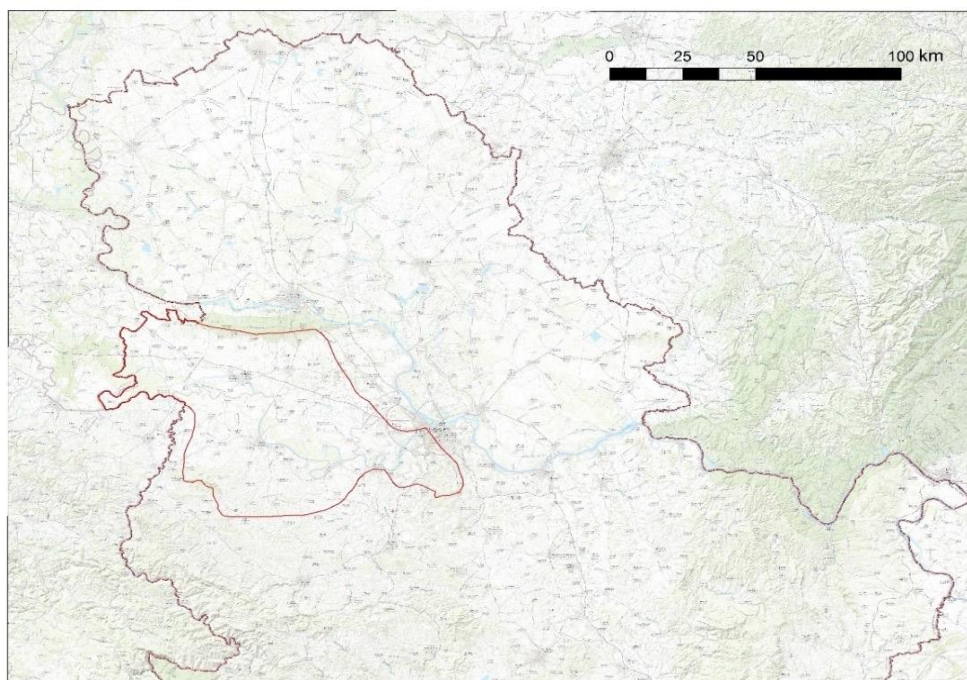


Figure 1. Pilot area

3.1 Site description and data

The area of research covers the Sava River Basin in Serbia. This area stretches from the border with Croatia on the West to Belgrade in the East, and from Fruška Gora Mountain to the North to Cer Mountain in the South (Figure 1). The area includes a significant part of Srem, Macva and parts around Belgrade, the capital city. The territory covers an area of about 5250 km², and Sava River catchment size in Serbia is 9057,29 km². Posavina includes a large part of Srem (Vojvodina, Pannonian Basin) and a large part of the Macva (except the part along River Drina).



3.2 Climate

3.2.1 *Climate type*

The climate in the area is continental, with cold winters, and hot, humid summers with well-distributed rainfall patterns.

The climate data of the Republic Hydrometeorological Service of Serbia were used. The climate elements, air temperature, precipitation, and PET for the period 1997-2016 at the meteorological stations Sremska Mitrovica, Sabac, and Belgrade were analysed.

A comparative analysis of air temperature for meteorological stations Sremska Mitrovica, Sabac and Belgrade (for the period 1997-2016) was performed in order to examine the elements of climate (air temperature) of the terrain and environment. Based on data obtained from RHMSS, which were monitored between 1997 and 2016 the average air temperature at meteorological stations is: 11.2 °C for Sremska Mitrovica; 11.3°C for Sabac; and 12.7 °C for Belgrade.

3.2.2 *Precipitation and evapotranspiration*

In order to assess the amount of precipitation in the pilot site, a comparative analysis of the amount of precipitation for meteorological stations Sremska Mitrovica, Sabac and Belgrade was performed.

Based on the data obtained from the RHMSS, which were monitored between 1997 and 2016 the sum of rainfall at meteorological stations are: 624 mm for Sremska Mitrovica, 681 mm for Sabac, 706 mm for Belgrade.

By comparison, the mean values of precipitation for the period between 1997 and 2016 on these three stations and significant deviation of differences in precipitation quantities were observed. Notable amount of precipitation in the area is registered, especially for 2014 (sum 1095 mm).

Evapotranspiration is very low between November and March, more or less strong the rest of the year according to the RHMSS. The PET for these three locations is calculated using the Penman- Monteith method.

3.3 Topography

Posavina is a spacious floodplain of Srem and Mačva and parts of the terrain are peripheral parts of Fruška Gora and Cer mountains. The orographic peculiarities of the terrain are a direct consequence of its creation and, the slopes of the mountain hills in the south and north are part of the Pannonian basin filled with young lacustrine deposits.

The largest hydrographic potential is Sava River and its tributaries, as a very important waterway and strategic traffic direction in this part of Europe. The Sava River flows through Serbia in a length of 206 km, mostly through Srem, and its entire length is navigable. Bosut River is the significant watercourse in the area, and there are several artificial reservoirs and irrigation canals.

Neotectonic movements formed tectonic trenches and depressions in which the accumulation process during Neogene was intense. Thickness of the deposits reaches up to two and three thousand meters. Lower non-structural blocks and intensive accumulations continues throughout the Quaternary. Horst of Fruška Gora rises at a rate of 2 mm per year.

In the zone of the Sava River, there are also the most important urban and industrial centres, thus in the same area are the most important sources of water supply.

3.4 Land use

The area is in state ownership managed by Public Enterprise Vojvodina sume, predominantly covered by the forests (95%, see Figure 3). Public Enterprise Vode Vojvodine manages some land in state ownership. Serbian Armed Forces manages the area for hunting and fishing tourism - VU Morović. The rest is private agricultural land (Zingstra, et al. 2010).

A dyke along the Sava protects the largest part of the site but the water regime of the area is managed through a dam in the River Bosut. Flooding of the site is not regular, but managed depending mostly upon needs of agriculture and flooding protection of settlements and towns in the vicinity and downstream. Due to high level of ground water in spring, significant part of the forest area protected by the dyke is regularly waterlogged. Oldest natural forest remnants cover only 1% of the site and are under protection in form of six separated Strict Nature Reserves. Dominant land use is forestry (Zingstra, et al. 2010).

Most of the Pilot area was under influence of frequent inundations from the Sava and Bosut rivers until the dyke was built in the 1930s. Thanks to low altitude and strategic importance of oak forest present in the area, the site remained in close-to-natural state, with gradually, but not obvious changes in land cover and land use. During 20th century, most of area around the site was converted from forests into arable land. Nowadays, during dry summer season, the forests and wetlands suffer from insufficient groundwater. Water management is not adjusted to forest needs, even though it would not cause damage to arable land. Modification of water management is necessary in order to maintain good forest health and biodiversity of the area. Extensive grazing is necessary for maintaining open wetland areas, which used to be present before the changes in natural processes (flooding) and traditional land use activities (Zingstra, et al. 2010).

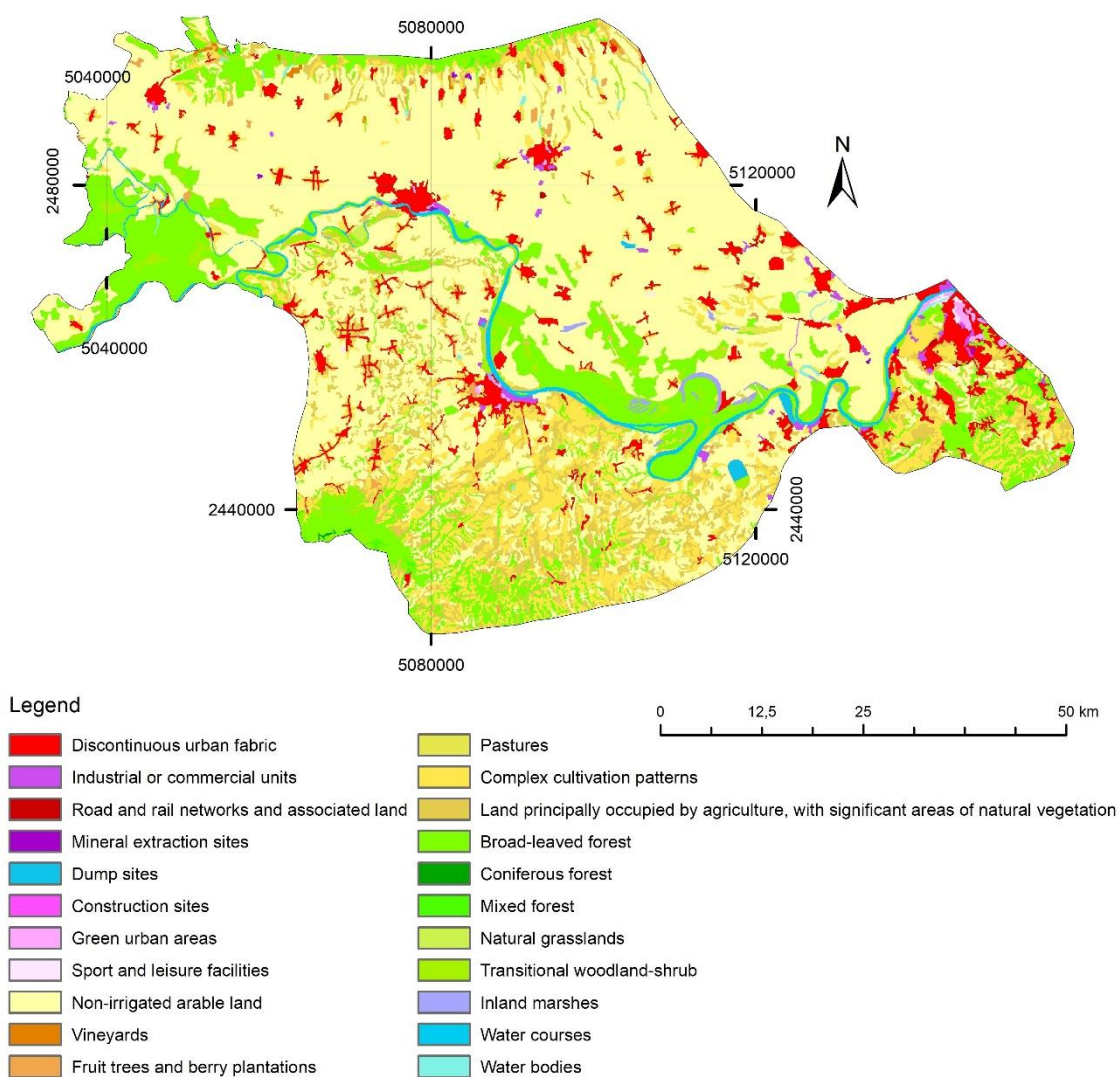


Figure 3. Corine land use map of Pilot area

3.5 Geology/Aquifer type

Pilot area is mostly covered with Quaternary sediments (Figure 4). On the territory of Republic of Serbia, the Sava River makes an extensive alluvial plain. Such an extensive plain enabled the



formation of an abundant aquifer. According to hydrogeological researches, alluvial formations of this aquifer are made of gravel-sand and sand sediments that represent the basic groundwater collector, while fine-grained and slurry sands and clays make upper layer. The depth of the water-bearing layer varies between 12 m and 20 m, in some cases even 25 m (Stojadinović, et al. 2005)

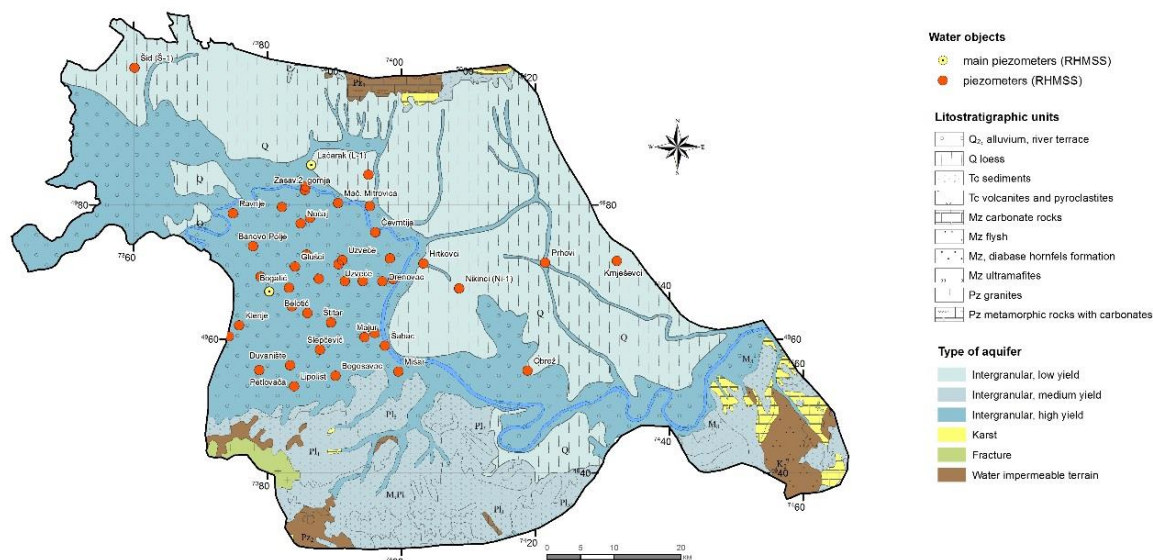


Figure 4. Hydrogeological map of the Pilot area with observation boreholes

Gravel-sand sediments, as a water-bearing environment, have good filtration properties with the infiltration rate of 10—4 m/s. Groundwater recharge is mainly from precipitation and groundwater inflow. To some extent, irrigation also recharge the aquifer. However, main inflows of the water to this aquifer are from the surface water of the Sava River. The analysis of the groundwater regime points out that groundwater table weakens with the distance from Sava. Generally, groundwater table is 3 m below the ground, while in the zone of exploitation wells dynamic level is between 3.5—4.0 m below the surface. Significant depth of alluvial formations, favorable filtration characteristics of the water-bearing layer and the way of its recharge enable the occurrence of an abundant aquifer that is thoroughly in use (Stojadinović, et al. 2005). Figure 5 shows the average groundwater levels interpolation using groundwater levels observed over the period from 1997 to 2016.

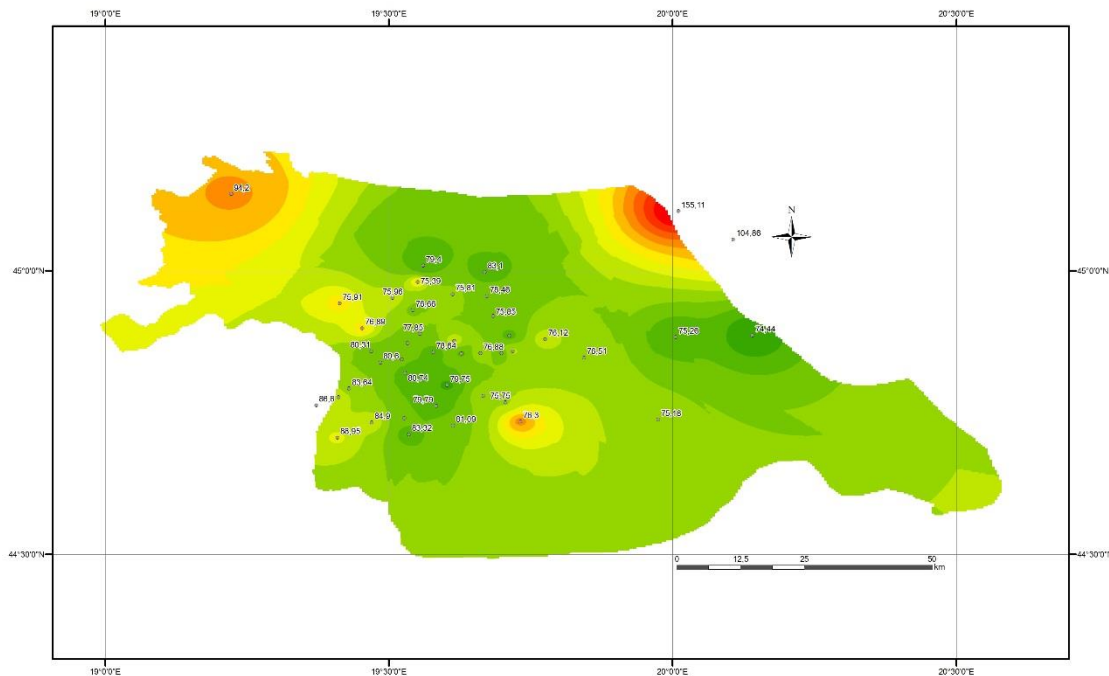


Figure 5. Interpolation of average groundwater levels for the 1997-2016 period

3.6 Surface water bodies

The Sava River is one of the most complex as well as interesting rivers in Europe. The river attracted international attention due to a historic flood in 2014. It originates in the Slovenian mountains and flows into the Danube in Belgrade. Sava River basin is 926 km long – together with tributaries and it is the best preserved and most diverse river systems in Europe: from narrow gorges, to areas with extensive gravel banks, to huge alluvial forests with oxbows and species-rich alluvial meadows (Schwarz, 2016).

3.7 Abstractions/irrigation

Water from aquifers that are formed in alluvial deposits is one of the main sources of water supply worldwide. Basic characteristic of river- bank infiltration type of water source is depending on hydraulic connection between surface water and groundwater. Intensity of this connection has a direct influence on quality of water. River always carry a load of suspended material that has been deposited on the contact between river and riverbed and riverbanks. Infiltration rate of surface water could decrease and initial capacity of water source can be depleted because of the clogging process.



Alluvial aquifer is a major potential source of water supply (of population and industry) in Serbia. However, the shallow aquifer is highly dependable on amount of infiltrated water from precipitation and river water and thus susceptible to negative effects of climate change.

3.8 Climate change challenge

Obvious effect of climate change is an increase of mean annual air temperature and decrease of precipitation. Decrease of annual quantity of precipitation will be followed by its irregular distribution during the year. Decreased precipitation, along with the temperature rising, will negatively affect groundwater balance due to reduced infiltration of surface water and intensified evapotranspiration. Recharge of aquifers will be reduced and groundwater reserves will be endangered.

The most affected aquifers are shallow (alluvial). During analysis of possible climate changes and their effect, the two possible scenarios must be taken into consideration such as long drought period and flood occurrence.

Figure 6 describes the expected climate change across the different areas in Europe as prepared by the European Environment Agency.

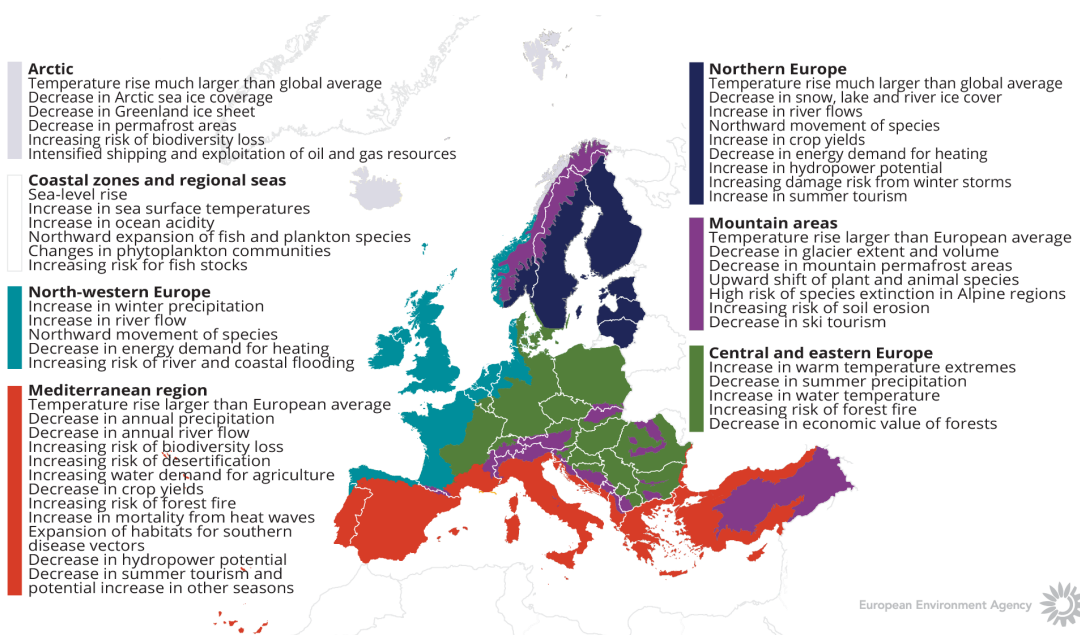


Figure 6. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 *AquiMod*

AquiMod is a lumped parameter computer model that has been developed to simulate groundwater level time series at observational boreholes (Mackay et al., 2014a). It is based on hydrological algorithms that simulate the movement of groundwater within the soil zone, the unsaturated zone, and the saturated zone. The lumped models neglect complexities included in distributed groundwater models but maintain some of the fundamental physical principles that can be related to the conceptual understanding of the groundwater system (Mackay et al., 2014b).

The primary aim of AquiMod is to capture the behaviour of a groundwater system through the analysis of the available groundwater level time series. Once calibrated the model can be run in predictive mode and be used to fill in gaps in historical groundwater level time series and to calculate future groundwater levels. In addition to groundwater levels, it also provides predictions of historical and future recharge values and groundwater discharges.

The mathematical equations that are used to simulate the movement of groundwater flows within the three modules are detailed in Appendix A. The model uses rainfall and potential evaporation time series as forcing data. These are interpreted by the soil module representing the soil zone. The soil module calculates the rainfall infiltration and pass it to the unsaturated zone module. This module delays the arrival of the infiltrating water to the saturated zone module. The latter calculates the variations of groundwater heads and flows accordingly.

The model is calibrated using a Monte Carlo approach. It compares the simulated and observed groundwater level fluctuations and calculates a goodness of fit. The AquiMod version used in this work employs the Root Square Mean Error (RMSE) or the Nash Sutcliffe (NSE) performance measures to assess the performance of the model. The user sets a threshold value to accept all the models that perform better than the specified threshold. The possibility of producing many models that are all equally acceptable, allows the user to interpret the results from all these models and calculate uncertainty.

The recharge values calculated from AquiMod are those that reach the aquifer system and drive the groundwater levels. However, the recharge was not calculated using Aquimod for this Pilot area since the NSE results were unsatisfactory.

4.1.2 *Metran*

Metran applies a transfer function-noise model to simulate the fluctuation of groundwater heads with precipitation and evaporation as independent variables (Zaadnoordijk et al., 2019). The modelling approach consists mainly of two impulse functions and a noise model. The first impulse function is used for convolution with the precipitation to yield the precipitation contribution to the piezometric head. The second is for evaporation which is either a separately estimated function, or a factor times the function used for precipitation. The noise model is a stochastic noise process described by a first-order autoregressive model with one parameter



and zero mean white noise. Further information about the model is given in Appendix B with the model setup shown in the Figure B1.

Metran allows the addition of other processes affecting the behaviour of the groundwater heads, for example pumping or the presence of surface features such as rivers. The contributions from these processes are added to the deterministic part of the model.

Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other time step lengths can be applied. However, the explanatory variables must still have a constant frequency.

The model is calibrated automatically; however, the model uses two binary parameters, Regimeok and Modok, to judge a resulting time series model. Regimeok cross-examines the explained variance R^2 (> 0.3), the absolute correlation between deterministic component and residuals (< 0.2), and the null hypothesis of non-correlated innovations (p value > 0.01). If all these criteria are satisfied, Regimeok returns a value of 1 indicating highest quality. Modok also cross-examines the explained variance R^2 (> 0.1) and the absolute correlation between deterministic component and residuals (< 0.3) as well as the decay rate parameter (> 0.002) and if all these criteria are satisfied, it is given a value of 1. If Modok = 1 and Regimeok = 0, the model is still considered acceptable. If both these parameters are 0, the model quality is insufficient and the model is rejected.

Metran's time series model is linear and the model creation fails when the system is strongly nonlinear. It is also limited to the response function being appropriate for the simulated groundwater system. Metran uses a gradient search method in the parameter space, so it can be sensitive to initial parameter values in finding an optimal solution.

The model calculates an evaporation factor f that gives the importance of evapotranspiration compared to precipitation. It is possible to use this factor to calculate the recharge values as shown by Equation B2 in appendix B. However, it must be noted that the use of Equation B2 is based on too many assumptions that are easily violated. Because of this, the equations should be applied only to long-term averages using only models of the highest quality.

Following the definitions used in the TACTIC project the recharge quantity corresponds to 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 is also no storage change or interflow.

4.1.3 Climate data

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 $0.5^\circ \times 0.5^\circ$ global grid and at daily time steps. As part of ISIMIP, much effort has been made to standardise the climate data (e.g. bias correction). Data selection and preparation included the following steps:



1. Fifteen combinations of RCPs and GCMs from the ISIMIP data set were 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 between 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 were 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 occurs 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 on the various parts of Europe. The scenarios showing the lowest/highest precipitation were avoided, as these endmembers often reflect 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 1. Combinations of RCPs-GCMs used to assess future climate

		RCP	GCM
1-degree	"Dry"	rcp6p0	ipsl-cm5a-lr
	"Wet"	rcp4p5	miroc-esm-chem
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp8p5	miroc-esm-chem

4.2 Tool(s) / Model set-up

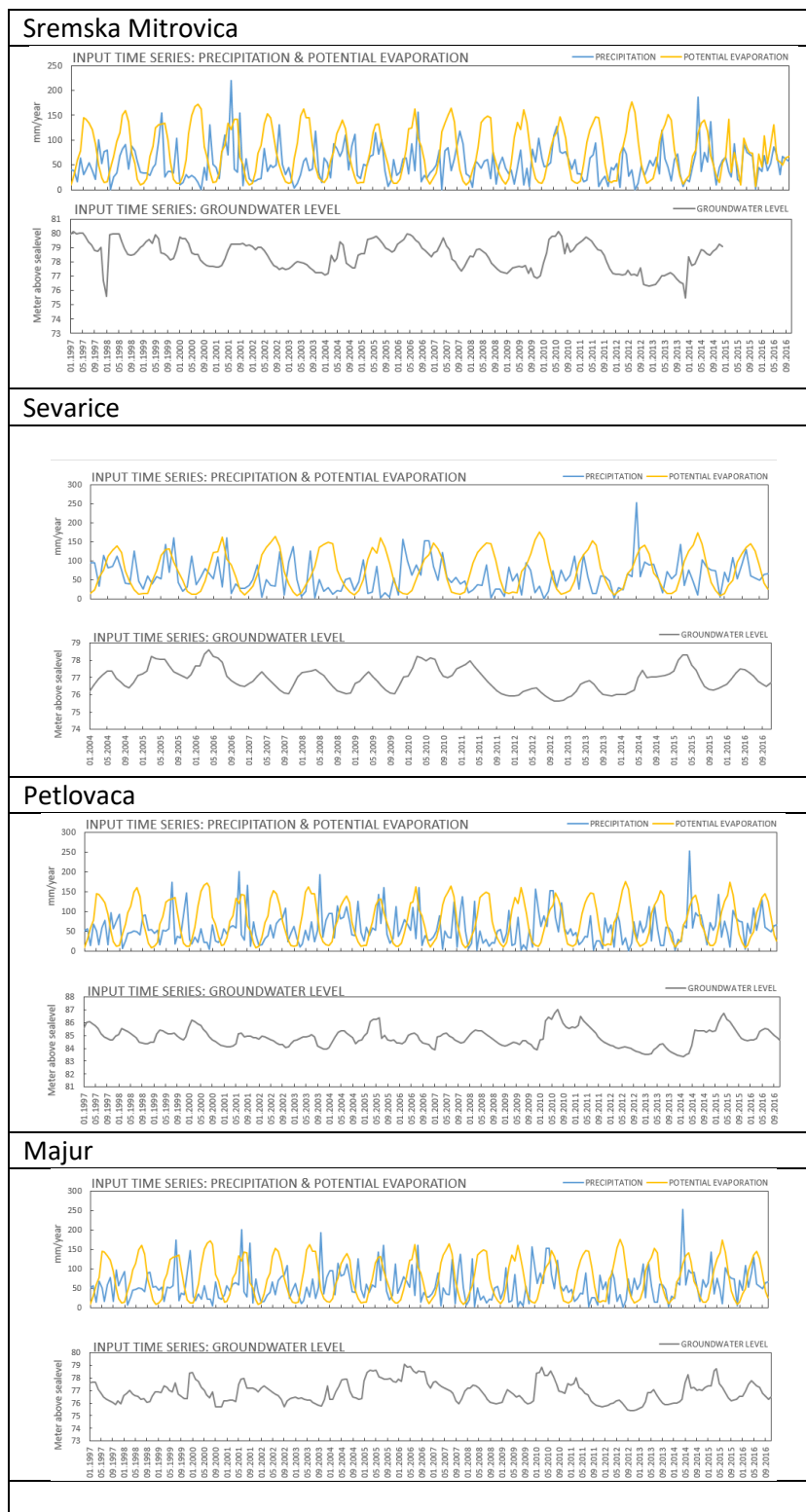
4.2.1 *AquiMod*

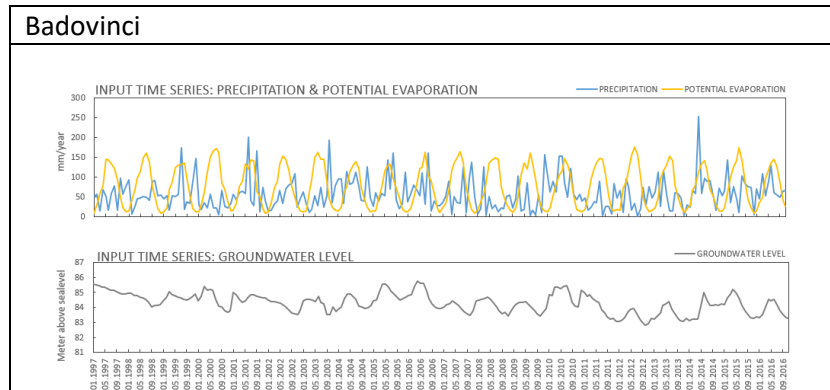
Aquimod model setup relies mainly on two input files. The first input file “Input.txt” is a control file where the module types and model structure are defined. AquiMod is executed first under a calibration mode where a range of parameter values of the different selected modules are given in corresponding text files and a Monte Carlo approach is used to select the parameter values that yield best model performance. “Input.txt” also controls the mode under which AquiMod is executed, the number of Monte Carlo runs to perform, the number of models to keep with an acceptable performance, and the number of runs to execute in evaluation mode.

The second file AquiMod uses is called “observations.dat”. This file holds the forcing data mainly the potential evaporation and rainfall. However, it is also possible to include the anthropogenic impact on groundwater levels by including a time series of pumping data in this file. None of the boreholes studied here includes pumping data. The observed groundwater levels that are used for model calibration are also given in this file. The data are provided to the model on a monthly basis, and this forces AquiMod to run using a time step length of one month. The table 2 shows daily time series of rainfall and potential evaporation values (mm/month) as well as the fluctuations of water table at the different boreholes.

All AquiMod models built for the boreholes in Table 2 use the FAO Drainage and Irrigation Paper 56 (FAO, 1988) method in the soil module, and employ the two-parameter Weibull probability density function to control the movement of infiltrated water in the unsaturated zone (Appendix A1). The groundwater module structures vary between the different boreholes. The best groundwater module structure is found by trial and error during the calibration process. The simplest structure, one layer with one discharge feature, is selected first and then the complexity of the module structure is increased gradually to see if the model performance improves. The structure with best model performance should be selected to undertake the recharge calculations. However, in Posavina the structures that gave the best performance at the selected boreholes are mainly of one layer except at the Badovinci borehole..

Table 2. Figures showing time series of daily rainfall and potential evaporation values (mm/month) as well as the fluctuations of water table at the different boreholes.





4.2.2 METRAN

Metran applies transfer function noise modelling with daily precipitation and evaporation as input and of groundwater levels as output (Zaadnoordijk et al., 2019). The setup is shown in [Figure 1](#)[Figure 7](#). If time series of other influences on the groundwater head are available, these contributions can be added to the deterministic part of the model. An input file that holds the monthly information of precipitation, potential evaporation and groundwater levels is prepared for each borehole. Plots of these data are shown in Table 2. Metran calculates the characteristics of the impulse functions and the corresponding parameters automatically.

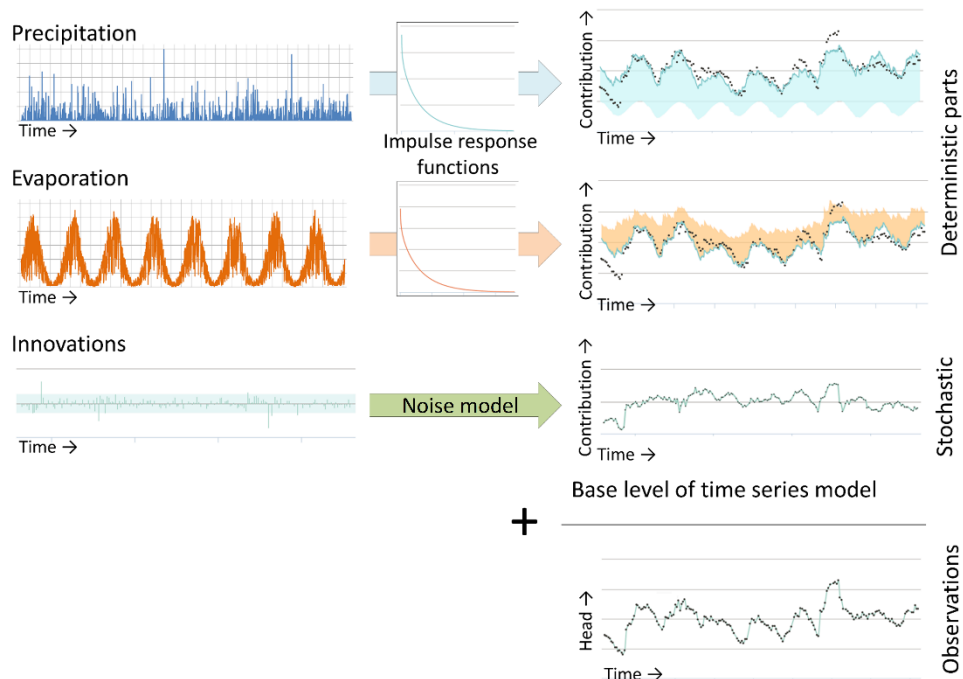


Figure 17. Illustration of METRAN setup

4.3 Tools/ Model calibration/ test

4.3.1 Calibration of *AquiMod* models

The calibration of *AquiMod* is performed automatically using the Monte Carlo approach. The user populates the files of the selected modules with minimum and maximum parameter values and then the model randomly selects a value from the specified range for any given run. The selection of the minimum and maximum values is physically based depending on the characteristics of the study area. For example, the minimum and maximum values of the root depth in the soil module are set to 15 cm and 60 cm respectively for a study area covered with grass, while these values are set to 120 cm and 200 cm for a woodland area. The storage coefficients bound of a groundwater module are set to much lower values in a confined aquifer compared to those used for an aquifer under unconfined conditions.

A conceptual hydrogeological understanding must be available before the use of *AquiMod*, since this is necessary to set the limits of the parameter values for the calibration process. In some cases, it is not possible to obtain a good performing model with the selected values and that necessitates the relaxation of these parameters beyond the limits informed by the conceptual understanding. In such cases, the parameter values must feed back into the conceptual understanding if better performing models are obtained.

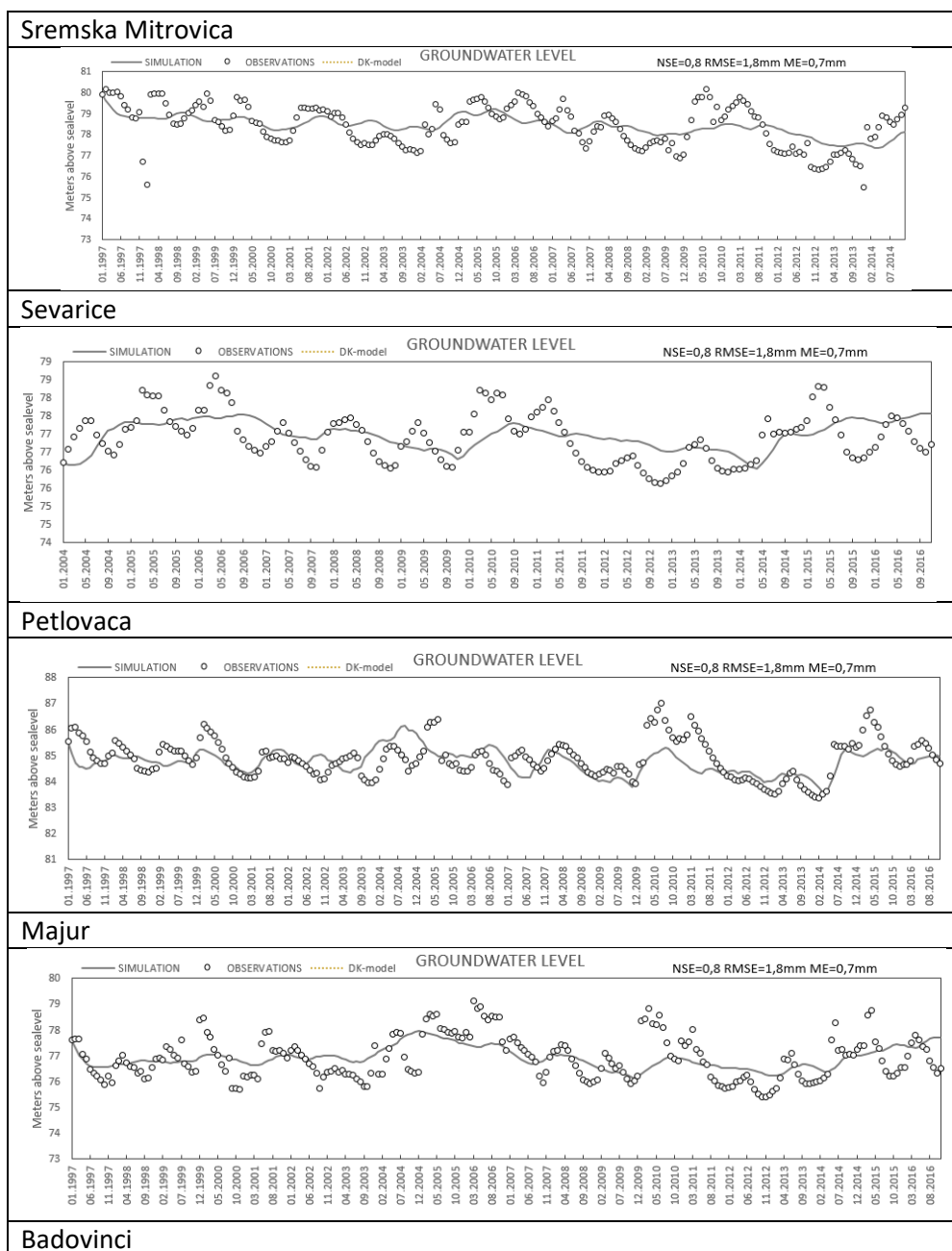
AquiMod execution time is relatively small, which allows the calibration of the model using hundreds of thousands of runs in couple of hours. The performance measure used to assess the quality of the simulation is the Nash Sutcliffe Error (Appendix A) that takes a maximum value of unity for a perfect match between the simulated and observed data. The threshold at which models are accepted is set to a value of 0.6. However, in Pilot area none of the models achieved the NSE higher than 0.6.

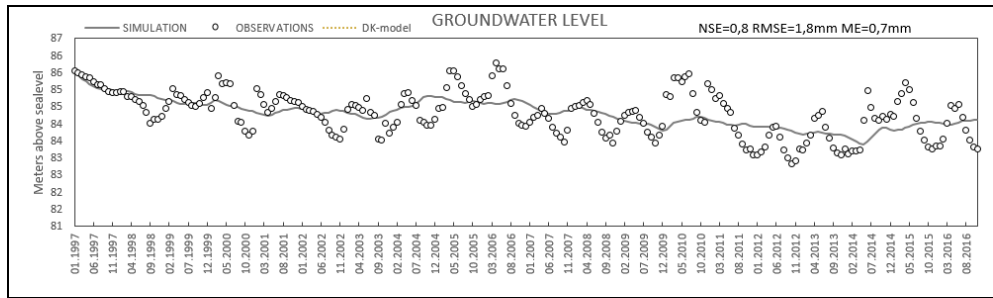
Table 3 shows the best Nash Sutcliffe Efficiency (NSE) measures attained at the selected boreholes using the *AquiMod* model. According to these values, it is clear that the match between the simulated and observed groundwater levels have not been achieved. The plots in table 4 show the comparison between observed groundwater levels and those simulated using *AquiMod*. In this case, the best NSE value of 0.32 is obtained at Sremska Mitrovica borehole. The structures selected for these boreholes are of one layer (Sremska Mitrovica, Sevarice, Petlovaca, Majur) or two layered systems (Badovinci). Because of these low NSE values, these models were not selected to undertake the recharge calculations.

Table 3. Nash Sutcliffe Error measure at Posavina boreholes

Borehole name	NSE
Sremska Mitrovica	0.32
Sevarice	0.17
Petlovaca	0.20
Majur	0.22
Badovinci	0.255

Table 4. Comparison between the simulated and observed groundwater levels at Posavina boreholes





4.3.2 Calibration of Metran models

For the standard setup with precipitation and evaporation, five parameters have to be determined during the calibration of the model. Three parameters are related to the precipitation response, the evaporation factor, and the noise model parameter (Appendix B). There are three extra parameters for each additional input series, such as Sava River levels in this case. The parameter optimization of Metran uses a gradient search method in the parameter space to reach a global minimum. As explained in Appendix B, two parameters indicate if Metran succeeded with producing a match between the simulated and observed data. These are called the Regimeok and Modok. When Regimeok is equal to one, the calibration is of highest quality. If Modok is equal to one and Regimeok is equal to zero, the calibration is of acceptable quality. Finally, if both parameters are equal to zero, the calibration quality is insufficient.

Metran also failed to produce an acceptable model at the selected boreholes. However, the inclusion of the fluctuations of the nearby river stage with time as an input signal to Metran, has led to significant improvement to the match between the simulated and observed groundwater levels. The inclusion of river stage time series was trialled at Sremska Mitrovica only. Metran output showed highest quality (Medok 1, Regimeok 1, RMSE 0.6 and R^2 0.6) and the model was used for recharge calculations at this borehole. However, due to the limited availability of time and resources, it was not possible to check the performance of Metran with this third river stage included at the remaining boreholes.

4.4 Uncertainty

Aquimod is designed to simulate the groundwater levels as described in Appendix A. The model represents the groundwater system as a closed homogeneous medium, with no impact from any outer boundary or feature, whether physical or hydrological, such as the presence of rising and falling river stage. However, the Pilot area there is a great impact on groundwater recharge from Sava River, because of their hydraulic connection. Therefore, the good models with application of Aquimod with only groundwater levels could not be obtained.

In the beginning, the same happened with the application of Metran. Firstly, we used the input files with groundwater levels and precipitation only for the same five boreholes (Sremska Mitrovica, Sevarice, Petlovaca, Majur, and Badovinci). Afterward we added data of PE, however, we could not obtain the good fit. The fit of high quality was obtained only after adding the data



of surface water levels. Therefore, recharge and future simulations were taken into consideration for Sremska Mitrovica borehole where we have achieved the satisfactory model.

5 RESULTS AND CONCLUSIONS

5.1 Performance to historical data

As mentioned previously, the AquiMod failed to reproduce the behaviour of the groundwater level time series at all the selected boreholes. The model was not used for recharge calculation. Throughout the calibration, all parameters and model structure combinations that were trialled could not meet the NSE-criteria. The reason for AquiMod failure is anticipated to the fact that river stage fluctuations have significant influence on the fluctuations of groundwater levels. This is clearly demonstrated by Metran, which also failed to produce an acceptable model at all the boreholes but was successful when river stage fluctuations are included as an additional input signal.

Metran uses formulas that are based on assumptions that can be violated (Appendix B). It is better to use the infiltration coefficient f_c with the long-term average values of rainfall and potential evaporation to calculate long-term average values of recharge and using only model of the highest quality. Time series of recharge values, from the analysis undertaken using Metran are not produced. However, the long-term average recharge values were calculated using Metran as shown in table 5.

As the infiltration coefficient is less than unity, the recharge was calculated using the following equation (Appendix B):

$$R = P - fE$$

where R is recharge, P precipitation, E evapotranspiration, and f the evaporation factor.

Table 5 Recharge values calculated using the recharge factors estimated by Metran

Borehole name	Average precipitation (mm/day)	Average potential evaporation (mm/day)	Recharge factor	Recharge (mm/day)
Sremska Mitrovica	1.72	2.47	0.29 ± 0.67	1.15

Metran estimates an upper and a lower value for the infiltration coefficient f_c as shown in Table 5. This can be used as an indication of uncertainty associated with the calculated f_c value. Unfortunately the upper and lower bounds are significantly large compared to the initial value of f_c . Therefore, it is impossible to calculate an upper and lower recharge bounds in this case. In addition, these bounds indicate that the estimated recharge value should be treated with care.

5.2 Future projections

The forcing data, rainfall and potential evaporation, are altered using the change factors of the climate models (see Section 4.1.3.). For the Posavina area, there is set of monthly change factors, used with the data driving Metran. These change factors are used as multipliers to both the historical rainfall and potential evaporation values (Table 6).



The historical time series are altered using these factors first and then the long-term average rainfall and potential evaporation values are calculated using Metran. The recharge coefficient f_c values are calculated from the calibration of Metran model using the historical data, then applied to calculate the projected long-term average recharge values.

Table 6. Monthly change factors as multipliers used for the borehole data

	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	1° Min	0.76	0.98	1.12	1.08	0.98	0.97	0.85	0.91	1.04	1.04	0.90	0.99
	1° Max	1.02	0.95	0.89	1.16	1.18	1.20	1.01	1.09	0.92	1.08	1.34	1.10
	3° Min	1.28	1.03	1.13	1.26	0.96	0.89	0.46	0.66	0.72	0.78	1.14	0.93
	3° Max	0.95	1.07	1.15	1.00	1.04	1.15	0.98	0.90	0.88	1.17	0.85	1.19
PE	1° Min	1.10	1.09	1.03	1.04	1.05	1.06	1.05	1.05	1.06	1.04	1.07	1.04
	1° Max	1.16	1.12	1.11	1.09	1.04	1.06	1.07	1.07	1.09	1.09	1.07	1.16
	3° Min	1.19	1.17	1.21	1.15	1.09	1.07	1.10	1.08	1.10	1.09	1.13	1.13
	3° Max	1.33	1.35	1.29	1.29	1.14	1.09	1.09	1.11	1.12	1.13	1.16	1.22

Table 7. Long-term average recharge values calculated for the period 1997-2016

name	calibration	1min	1max	3min	3max
6_SREMSKA-MITROVICA-GWLcleaned_v10	1,15	1,07	1,26	0,94	1,11

Table 7 shows the historical and future long-term average recharge values calculated using the best performing Metran model and using the data observed at Sremska Mitrovica borehole. It is clear that the highest reduction in recharge values are observed when the 3° Min rainfall and evaporation data are used, while the highest increase in recharge values are observed when the 1° Max rainfall and potential evaporation data are used.

Figure 8 shows the data listed in Table 7. It is clear that in almost all the cases, the recharge values become lower than the historical values when the 1° Min, 3° Min, and 3° Max data are used and they become higher than the historical values when the 1° Max is used. While the reduction in recharge values are expected with the use of the 3° Min and 1° Min change factors as these scenarios represent drier scenarios, the reduction of recharge when the 3° Max comes as a surprise as this is expected to be the wettest scenario. This behaviour could be related to the complex effect of the use of the change factors, which may reduce both the rainfall and potential evaporation at the same period but at different rates. However, additional investigations are required to confirm this behaviour.

The same applies for the groundwater head simulations produced by Metran. Figure 9 shows historical and future long-term groundwater head simulations for Sremska Mitrovica with climate change projections. Here, groundwater levels simulated using the 3° Max change factors fluctuates at a lower levels than those simulated using the 1° Max change factors. This is counter intuitive as the 3° Max scenario is expected to be a wetter scenario than the 1° Max scenario. These results must be treated with care until they are verified by future research work.



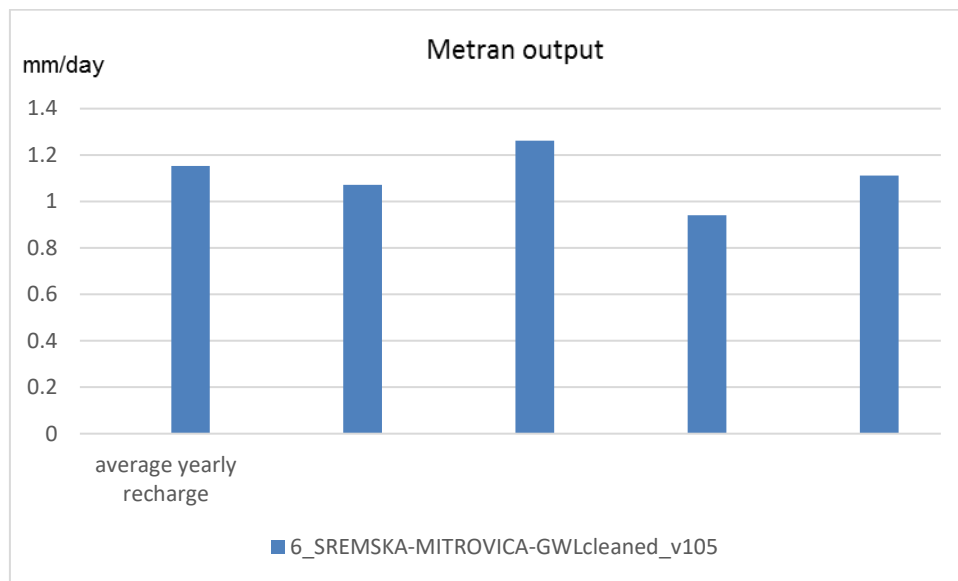


Figure 8. Historical and future recharge projections produced by Metran

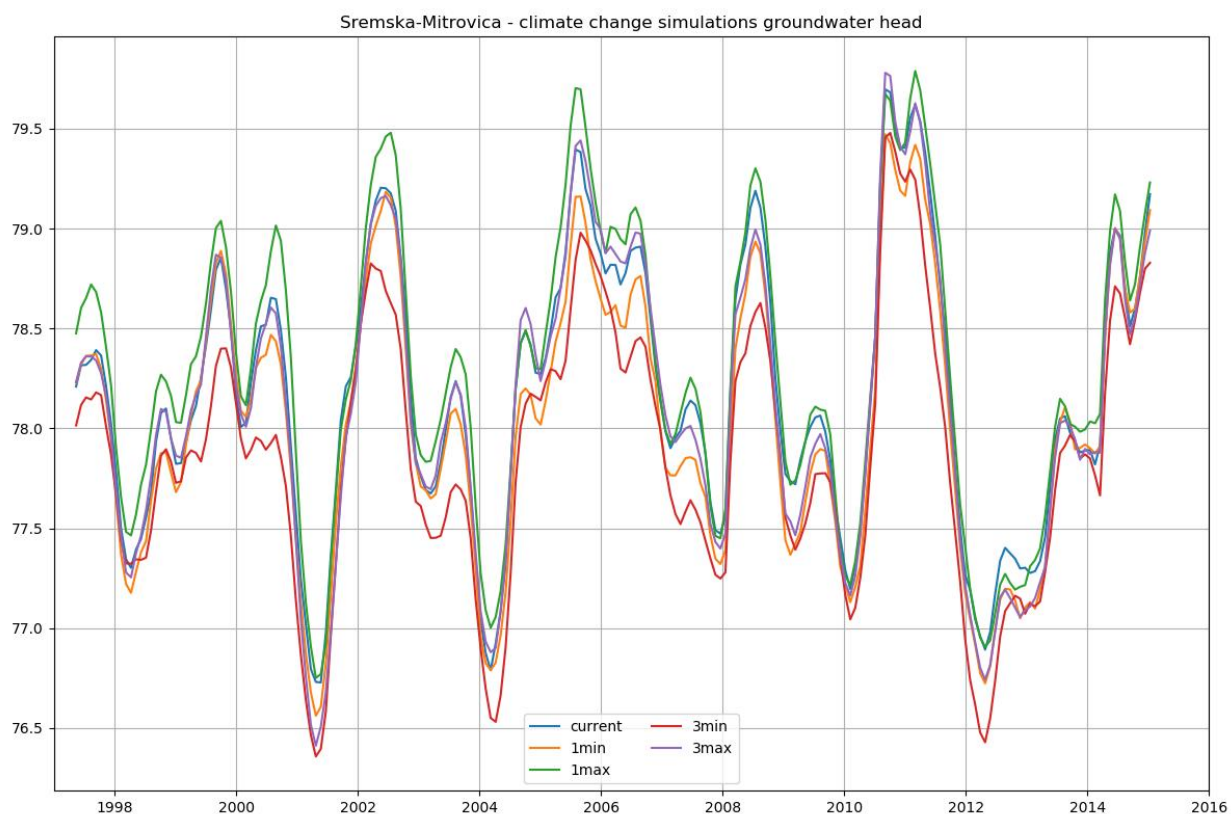


Figure 9. The results of groundwater head time series at Sremska Mitrovica with climate change simulations produced by Metran

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Appendix A: AquiMod methodology

AquiMod is a lumped parameter computer model that has been developed to simulate groundwater level time series at observational boreholes (Mackay et al., 2014a). It is based on hydrological algorithms that simulates the movement of groundwater within the soil zone, the unsaturated zone, and the saturated zone. The lumped models neglect complexities included in distributed groundwater models but maintains some of the fundamental physical principles that can be related to the conceptual understanding of the groundwater system (Mackay et al., 2014b).

While AquiMod was originally designed to capture the behaviour of a groundwater system through the analysis of groundwater level time series, it can produce the infiltration recharge values and groundwater discharges from the aquifer as a by-product. AquiMod is driven by complete time series of forcing data for either historical or predicted future conditions. Running AquiMod in predictive mode can be used to fill in gaps in historical groundwater level time series, or calculate future groundwater levels. In addition to groundwater levels, it also provides predictions of historical and future recharge values and groundwater discharges. In the current application we use calibrated AquiMod models to estimate the recharge values at selected boreholes.

AquiMod consists of three modules (Figure A1). The first is a soil water balance module that calculates the amount of water that infiltrates the soil as well as the soil storage. The second module controls the movement of water in the unsaturated zone, mainly it delays the arrival of infiltrating water to the saturated zone. The third module calculates the variations in groundwater levels and discharges. The model executes the modules separately following the order listed above.

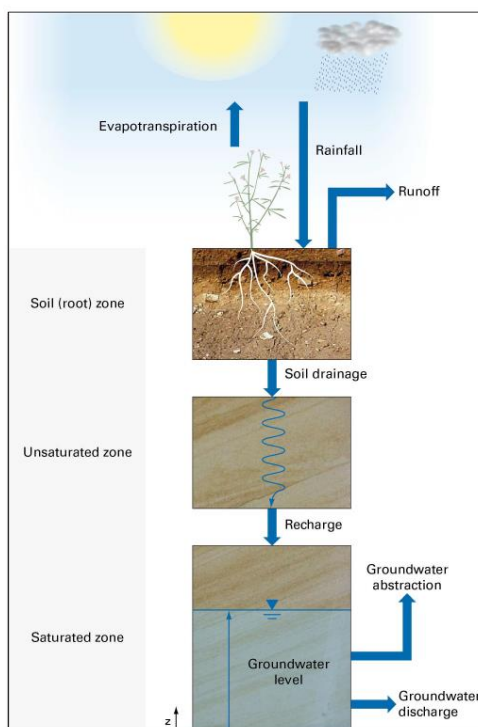


Figure A1 Generalised structure of Aquimod (after Mackay et al., 2014a)

The soil moisture module

There are several methods available in Aquimod that can be used to calculate the rainfall infiltration into the soil zone. In this study we use the FAO Drainage and Irrigation Paper 56 (FAO, 1988) approach. In this method, the capacity of the soil zone, from which plants draw water to evapo-transpire, is calculated first using the plants and soil characteristics. Evapo-transpiration is calculated according to the soil moisture deficit level compared to two parameters: Readily Available Water (RAW) and Total Available Water (TAW). These are a function of the root depth and the depletion factor of the plant in addition to the soil moisture content at field capacity and wilting point as shown in Equations A1 and A2.

$$TAW = Z_r(\theta_{fc} - \theta_{wp}) \quad \text{Equation A1}$$

$$RAW = p \cdot TAW \quad \text{Equation A2}$$

Where Z_r [L] and p [-] are the root depth and depletion factor of a plant respectively, θ_{fc} [L³ L⁻³] and θ_{wp} [L³ L⁻³] are the moisture content at field capacity and wilting point respectively.

The FAO method is simplified by Griffiths et al. (2006) who developed a modified EA-FAO method. In this method the evapotranspiration rates are calculated as a function of the potential evaporation and an intermediate soil moisture deficit as:

$$\begin{aligned} e_s &= e_p \left[\frac{s_s^*}{TAW - RAW} \right]^{0.2} & s_s^* > RAW \\ e_s &= e_p & s_s^* \leq RAW \\ e_s &= 0 & s_s^* \geq TAW \end{aligned} \quad \text{Equation A3}$$

Where e_s [L] is the evapo-transpiration rate, e_p [L] is the potential evaporation rate and s_s^* [L] is the intermediate soil moisture deficit given by

$$s_s^* = s_s^{t-1} - r + e_p \quad \text{Equation A4}$$

Where r [L] is the rainfall at the current time step and s_s^{t-1} [L] is the soil moisture deficit calculated at the previous time step.

The new soil moisture deficit is then calculated from:

$$s_s = s_s^{t-1} - r + e_s \quad \text{Equation A5}$$

Griffiths et al. (2006) proposed that the recharge and overland flow are only generated when the calculated soil moisture deficit becomes zero. The remaining volume of water, the excess water, is then split into recharge and overland flow using a runoff coefficient. In Aquimod a baseflow coefficient is used to reflect the fact that a groundwater discharge is calculated rather than overland water. In this application, the baseflow coefficient is one minus the runoff coefficient.

The unsaturated zone module

The Aquimod version used in this study to simulate the movement of groundwater flow within the unsaturated zone is based on a statistical approach rather than a process-based approach. This method distributes the amount of rainfall recharge over several time steps where the soil drainage for each time step is calculated using a two-parameter Weibull probability density



function. The Weibull function can represent exponentially increasing, exponentially decreasing, and positively and negatively skewed distributions. This can be used to focus the soil drainage over earlier or later time steps or to spread it over a number of time steps after the infiltration occurs. The shape of the Weibull function is controlled by two parameters, k and λ as shown in Equation A6.

$$f(t, k, \lambda) = \begin{cases} \frac{k}{\lambda} \left(\frac{t}{\lambda}\right)^{k-1} e^{-(t/\lambda)^k} & t > 0 \\ 0 & t \leq 0 \end{cases} \quad \text{Equation A6}$$

Where k and λ are two parameters the values of which are calculated during the calibration of the model and t is the time step.

The saturated zone module

AquiMod considers the saturated zone as a rectangular block of porous medium with dimensions L and B as its length and width [L] respectively. This block is divided into a number of layers, each has a defined hydraulic conductivity value, a storage coefficient value, and a discharging feature. The number of layers define the structure of the saturated module used in the study.

The mass balance equation that gives the variation of hydraulic head with time is given by:

$$SLB \frac{dh}{dt} = RLB - Q - A \quad \text{Equation A7}$$

Where:

S is the storage coefficient of the porous medium [-]

h is the groundwater head [L]

t is the time [T]

R is the infiltration recharge [L T⁻¹]

Q is the discharge out of the aquifer [L T⁻¹]

A is the abstraction rate [L T⁻¹]

It must be noted that in a multi-layered groundwater system as shown in Figure A2, we calculate one groundwater head (h) for the whole system. The discharges (Q) from Outlet 1, 2, etc. are calculated using the Darcy law. The total discharges can be summarised using the following equation:

$$Q = \sum_{i=1}^m \frac{T_i B}{0.5 L} \Delta h_i \quad \text{Equation A8}$$

Where:

m is the number of layers in the groundwater system [-]

T_i is the transmissivity of the layer i [L T⁻²]

Δh_i is the difference between the groundwater head h and z_i , the elevation of the base of layer i

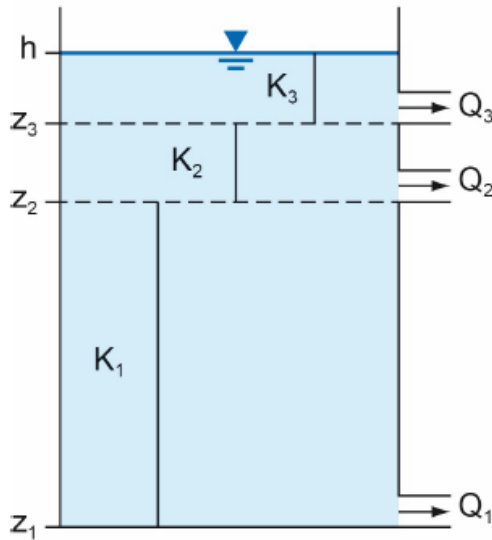


Figure A2 Representation of the saturated zone using a multi-layered groundwater system

Substituting Equation A8 into Equation A7 yields a numerical equation in the form:

$$S \frac{(h-h^*)}{\Delta t} = R - \sum_{i=1}^m \frac{T_i}{0.5 L^2} \Delta h_i - \frac{A}{LB} \quad \text{Equation A9}$$

Equation A9 is an explicit numerical equation that allows the calculation of the groundwater head h [L] at any time and using time steps of Δt [T]. In this equation h^* [L] is the groundwater head calculated at the previous time step and the term Δh_i [L] is calculated as $(h^* - z_i)$.

The terms S , T_i , and L are optimised during the calibration of the model. A groundwater system can be specified with one storage coefficient as shown in the equations above or with different storage coefficient values for the different layers. Several saturated modules are included in AquiMod to provide this flexibility and the model user can select the model structure that represent the conceptual understanding best.

Limitations of the model

AquiMod is a lumped groundwater model that aims at reproducing the behaviour of the observed groundwater levels. It tries to encapsulate the conceptual understanding of a groundwater system in a simple numerical representation. The model results have to be therefore discussed, taking this into consideration. For example, the model represents the groundwater system as a closed homogeneous medium, with no impact from any outer boundary or feature, whether physical or hydrological, such as the presence of rising and falling river stage.

Vertical heterogeneity can be accounted for by using multi-layered groundwater module structure. However, this model setting does not provide any information about the vertical connections between the layers as the discharge from all the layers is calculated using one representative groundwater head value. In other words, it is assumed that all layers are in perfect hydraulic connection.



As mentioned before, the model is designed to simulate the groundwater levels. However, it produces the recharge values and groundwater discharges as by products. In this application we use the calibrated model to calculate recharge. The mass balance equation (Equation A7) shows that recharge is a function of transmissivity and storage coefficient values, which are estimated during the calibration process of the model, i.e. they are not parameters with fixed values provided by the user. The inter-connections between these parameters leads to uncertainties in the estimated recharge values as a high storage coefficient value can produce a high recharge estimate and vice versa. To overcome this problem, it is suggested that the recharge values estimated by Aquimod are always presented as a range of possibilities rather than an absolute value. This can be achieved by estimating the recharge values from all the models that have a performance measure above than a threshold that is deemed acceptable by the user. The recharge estimates can then be presented as an average of all estimates and values corresponding to selected percentiles.

Model input and output

Aquimod includes a number of methods that calculates rainfall recharge as well as a number of model structure from which the user can select what better suits the case study.

Model input consists time series of forcing data including rainfall and potential evaporation, time series of anthropogenic impact mainly groundwater abstraction and time series of groundwater levels that will be used to calibrate the model. These time series must be complete, i.e. a value is available at every time step except the groundwater level time series, which can include missing data. The time step can be one day or multiple of days, and the model automatically calculate the size of the time step based on the input data time series.

The model is run first in calibration mode where a range of parameter values are specified for the different parameters included in the three model modules. A Monte Carlo approach is used to select the best parameter values. The performance of the model is measured by comparing the simulated groundwater levels to the observed ones using the Nash Sutcliff Efficient (NSE) or the Root Mean Squared Error (RMSE) performance measures. The parameter set that produces the best model performance is selected to run the model in evaluation mode.

When the model is run in evaluation mode, it produces output files that give recharge values, groundwater levels and groundwater discharges time series with time as specified in the input file. The number of output files is equal to the number of acceptable models set by the user.

Appendix B: Metran methodology

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 the Figure B1. 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.

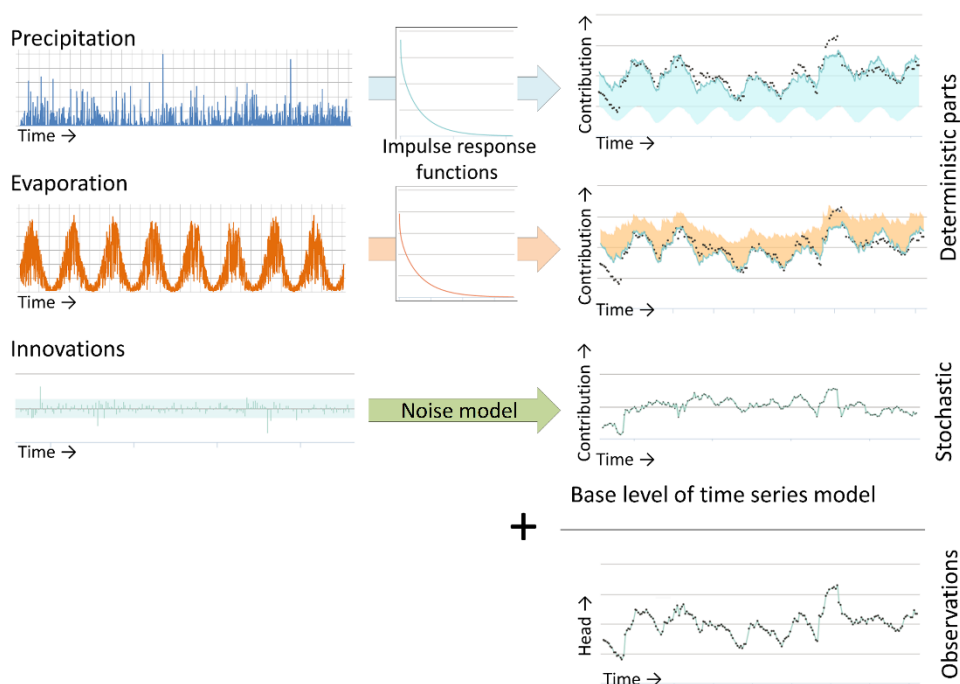


Figure B1 Illustration of METRAN setup

The stochastic part is needed because of the time correlation of the residuals, which does not allow a regular regression to obtain the parameter values of the transfer functions.

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 (f_c). 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. Three parameters regarding 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.



Limitations

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 is not able to find a decent time series model when the response function is not appropriate for the groundwater system. An example of this is a system with a separate fast and slow response as was found for a French piezometer in the Avre region, as is illustrated in Figure B2.

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 an optimal solution.

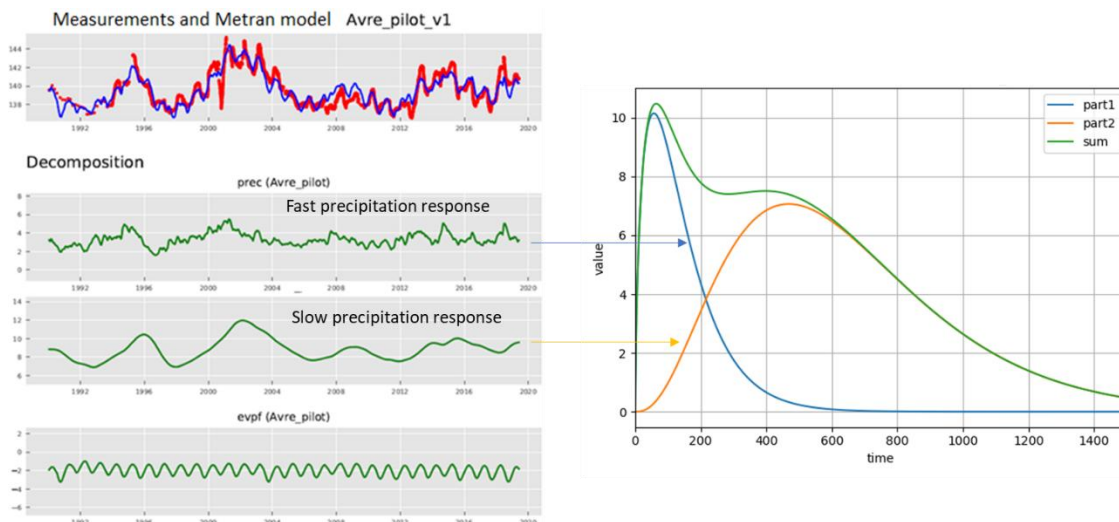


Figure B2. An example where the response function implemented in METRAN is not suitable for the groundwater system

Time step

Metran has been designed to work with explanatory series that have a daily time step. However, it has been adapted so that other time step lengths can be applied; 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.

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

Model output

The evaporation factor f_c gives the importance of evapotranspiration compared to precipitation. The parameter M_0 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 B3 with the impulse response functions and head time series for two models with very different response times for time series of SGU in Sweden.

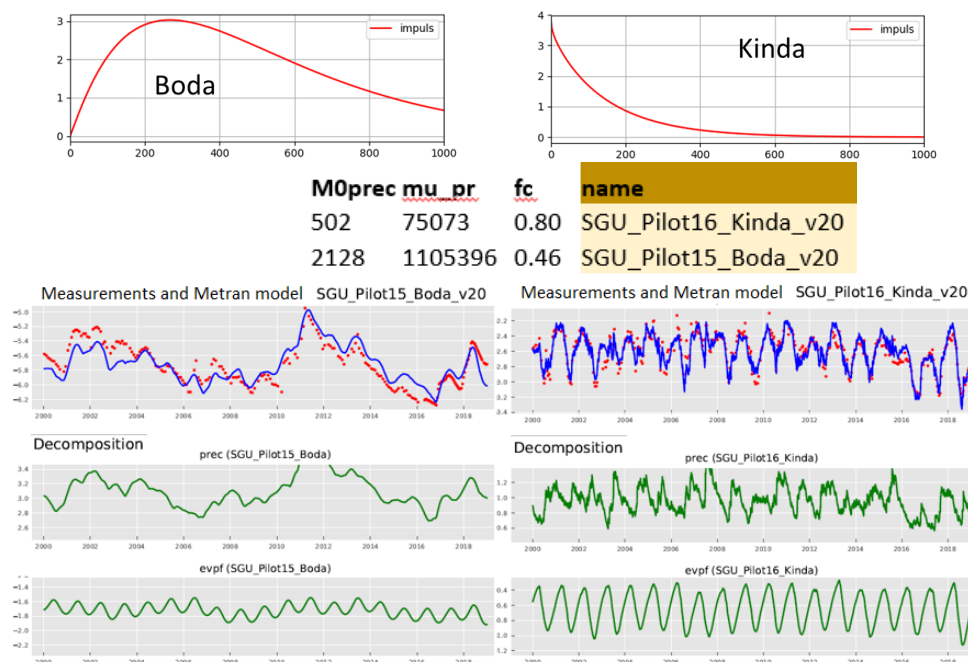


Figure B3 Illustration of Metran output for two case studies in Sweden with different response times.

Model quality

Metran judges a resulting time series model according to a number of criteria and summarizes the quality using two binary parameters Regimeok, Modok (see 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.

Recharge

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

$$R = P - fE$$

Equation B1



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:

$$\begin{aligned} R &= P - fE & f &\leq 1 \\ R &= P/f - E & f &> 1 \end{aligned} \quad \text{Equation B2}$$

These simple formulas can be applied easily for the situations currently modelled in Metran and for the simulations that are driven by future climate data using the delta-change climate factors. However, it is noted that it is a crude estimate using assumptions that are easily violated. Because of this, the equations should be applied only to long term averages using only models of the highest quality.