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PILOT DESCRIPTION AND ASSESSMENT

**North East Po Plain
(Veneto Plain)
Italy**

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LIST OF ABBREVIATIONS & ACRONYMS

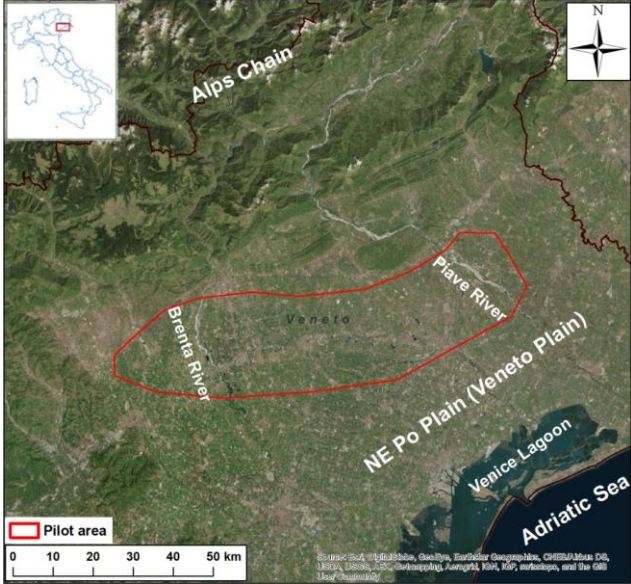
ARPAV	Agenzia Regionale per la Protezione Ambientale del Veneto (Veneto Regional Environment Protection Agency)
CC	Climate Change
EU	European Union
FAO	Food and Agriculture Organization
GCM	Global Circulation Models
GSO	Geological Survey Organization
ISIMIP	Inter Sectoral Impact Model Intercomparison Project
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale (Italian Environment Protection and Research Institute)
NSE	Nash-Sutcliffe Efficiency
PET	Potential EvapoTranspiration
R	Regression coefficient error
RCP	Representative Concentration Pathways
WP	Work Package

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1 EXECUTIVE SUMMARY

Pilot name	North East Po Plain (Veneto Plain)	
Country	Italy	
EU-region	Mediterranean region	
Area (km ²)	1150 km ² (only pilot area)	
Aquifer geology and type classification	Fluvial deposits of major streams. Porous unconfined aquifer	
Primary water usage	Irrigation, drinking water, industry	
Main climate change issues	Due to climate change impacts, in the last years, sustainable water supply has been a major issue for the area	
Models and methods used	Integrated Hydrogeological models: (i) lumped groundwater model AquiMOD; (ii) lumped groundwater model Gardènia; (iii) transfer function-noise model Metran	
Key stakeholders	Veneto Region. Water supply and utility companies. Regional Environmental Protection Agencies. ISPRA – Geological Survey of Italy	
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The selected Italian pilot area is within the North East Po Plain (Veneto Plain; elevation 20÷80 m a.s.l.). This area consists of fluvial deposits of major streams (mixed clay-silt-sand-gravel alluvial sediments; Pleistocene-Holocene). The porous, monolayered and unconfined local aquifer has a depth to top of 10÷15 m below ground surface and a thickness of some hundreds meter. A number of springs occurring along the *Line of Resurgence* crop out in the area.

The collected meteorological data consist of time series of rainfall, air temperature and groundwater heads. The Castelfranco Veneto and the Cittadella boreholes were selected within the pilot area. The local complex hydrogeological situation caused difficulties for AquiMod model to produce an acceptable simulation using the whole 1997-2018 data. In any case, a successful calibration was produced using the period 2011-2018 (NSE value over 0.7). Comparison of the obtained models at the two selected boreholes by a second method (Gardènia) produced similar calibration results. These simulations were used for the evaluation stage by both AquiMod and Gardènia models. A similar recharge estimation of about 0.5÷0.6 mm/day was obtained by both models.

Evaluation of recharge at selected boreholes using climate change scenario data was also performed by AquiMod. It was evidenced, as expected in comparison with the historical



scenario, a reduction (by 17%) in recharge when both the 1°C Min and 3°C Min data are used and, on the contrary, an increasing (by 9%) for both the values of 1°C Max and 3°C Max.

2 INTRODUCTION

Climate change (CC) already has 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>).

The specific TACTIC activities focus on the following research questions:

- What are the challenges related to groundwater- surface water interaction under future climate projections (TACTIC WP3).
- Estimation of renewable resources (groundwater recharge) and the assessment of their vulnerability to future climate variations (TACTIC WP4).
- Study the impact of overexploitation of the groundwater resources and the risks of saline intrusion under current and future climates (TACTIC WP5).
- Analyse the effectiveness of selected adaptation strategies to mitigate the impacts of climate change (TACTIC WP6).

This report describes the work undertaken by the ISPRA – Geological Survey of Italy as a part of TACTIC WP4 to calculate groundwater recharge at two selected boreholes within the NE Po Plain (Veneto Plain) aquifer.

WP4 is divided into seven tasks that cover the following activities: Review of tools and methods and identification of data requirements (Task 4.1), identification of principal aquifers and their characteristics aided by satellite data (Task 4.2), recharge estimation and its evolution under climate change scenarios in the principal aquifers (Task 4.3), analysis of long-term piezometric time series to evaluate aquifer vulnerability to climate change (Task 4.4), assessment of subsidence in aquifer systems using DInSAR satellite data (Task 4.5),



development of a satellite based net precipitation and recharge map at the pan-European scale (Task 4.6), and tool descriptions and guidelines (Task 4.7).

The work presented here is related to Task 4.3 and Task 4.4 that aim at the estimation of recharge under current and future climates. This is undertaken using multiple tools selected from the TACTIC toolbox that is developed under WP2 of the TACTIC project. The toolbox is a collection of hydrogeological models, scripts, spreadsheets that serves all the activities identified in TACTIC workpackages. Here we use the lumped groundwater model *AquiMod* (Mackay et al., 2014a and 2014b), *Gardénia* (Thiéry, 2013, 2014 and 2015) and the Transfer Function-Noise Model *Metran* (Zaadnoordijk et al., 2019) with main challenge to calibrate these models to reproduce the behaviour of the observed groundwater level time series. The calibrated models are then used to calculate historical and future recharge values.

3 PILOT AREA

3.1 Site description and data

The North East part of the Po plain (Veneto Plain) is characterized by a high exploitation rate for several water uses; due to climate change impacts, in the last years water supply has been a major issue for the area. The aim of our research is to assess the capability of the groundwater body to sustain water demand assessing recharge processes of the aquifer.

3.1.1 Location of pilot area

Location of pilot area is shown in Figure 1. The area is situated in the middle plain of the NE Po Plain (Veneto Plain), interposed between the Adriatic Sea basin and the Alps Chain. The WGS84 coordinates of centroid of pilot area are 45°43'30"N 12°07'30"E.

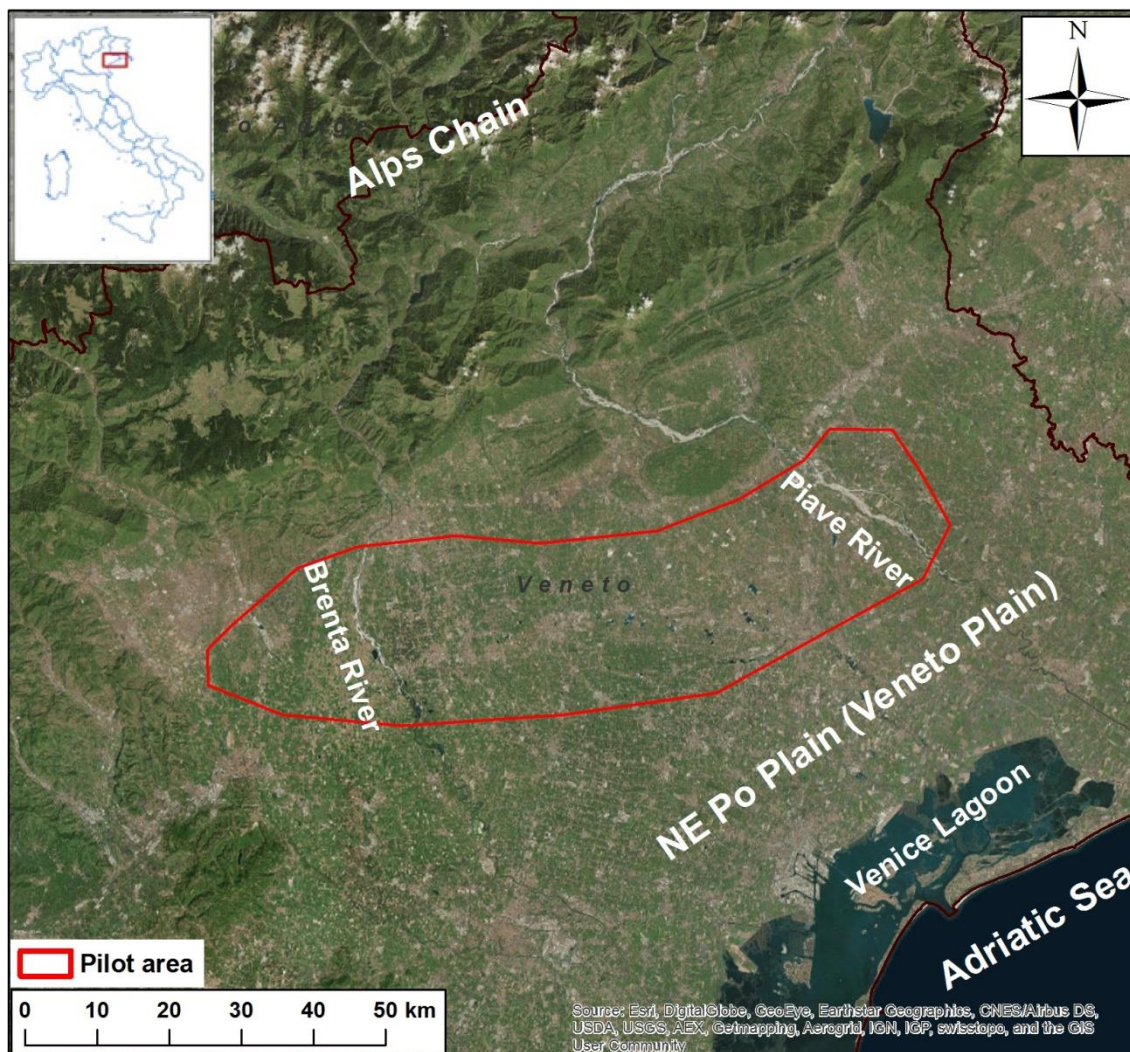


Figure 1: Location of pilot area.

3.1.2 Topography

The pilot area is featured by plain morphology and is comprised in an elevation range from about 20 to 80 m a.s.l. The Brenta and Piave river courses are partially included and cross approximately from NW to SE the pilot area (at the W and E borders, respectively).

3.1.3 Land use and Climate

The widespread land use in the pilot area is related to the diffuse presence of arable land (mainly corn and soy) (ARPAV and Regione del Veneto, 2015).

The climate type of the pilot area is sub-continental, with a mitigating effect of the Adriatic Sea that, along with the contrasting effect of the Alps Chain in the backside, leads to a general temperate climate, with relatively cold and wet winters and hot and sweltering summers.

Average precipitation is about 1200-1300 mm/year. Average potential evapotranspiration is about within the same value range. Furthermore, average real evapotranspiration is about 450-550 mm/year (meteo-climatic data provided by Veneto Environmental Protection Agency and calculated by ISPRA with Turc method). Precipitation is distributed between spring and autumn. Annual mean air temperature is 13-14 °C. The number of days below freezing point is 4-5 days/year on average.

Available meteoroclimatic data collected by Veneto Region Environmental Protection Agency consist of time series of daily rainfall and air temperature (> 30 years worth of data for both) with recorded gaps infrequent and random.

3.1.4 Soil types

The pilot area consists of fine-grained deposits in asset of sandy bumps, plains and troughs (Pleistocene-Holocene). Soil differentiation is from moderate (Cambisols) to high (Calcisols) (ARPAV and Regione del Veneto, 2015).

3.1.5 Geology/Aquifer type

Fluvatile deposits of major streams occur in the pilot area. From a lithological point of view, these deposits consist in mixed clay-silt-sand-gravel alluvial sediments, sporadically associated to calcareous and volcanic rocks (limestone and mafic lavas) and rarely to calcareous-arenaceous sediments (Amanti et al., 2007). The geological framework of the pilot area is shown in Figure 2.

Accordingly, groundwater resources in the pilot area are hosted within unconfined porous aquifers. The transmissivity and storage coefficient values are estimated to be in the range between 10^{-2} - 10^{-4} m²/s and 10^{-2} - 10^{-1} , respectively.

The aquifer recharge in the whole Veneto Plain is mainly due to dispersion from rivers (e.g. Piave and Brenta) in their high valley courses (over 20-30 m³/s) and rainfall infiltration (about 600 mm/year). The outflow occurs in a number of resurgence spring and towards a confined aquifer system in the middle-low plain (Zangheri, 2000). The pilot area including the selected

boreholes is on the contrary 10-15 km far from major streams (minor streams with moderate surface runoff are 200 to 300 m away from the boreholes).

Figure 2 also shows the distribution of the observation boreholes and the location of the selected boreholes across the pilot area, while Table 1 reports the main features of these latter. Lumped groundwater models are built to estimate the recharge values.

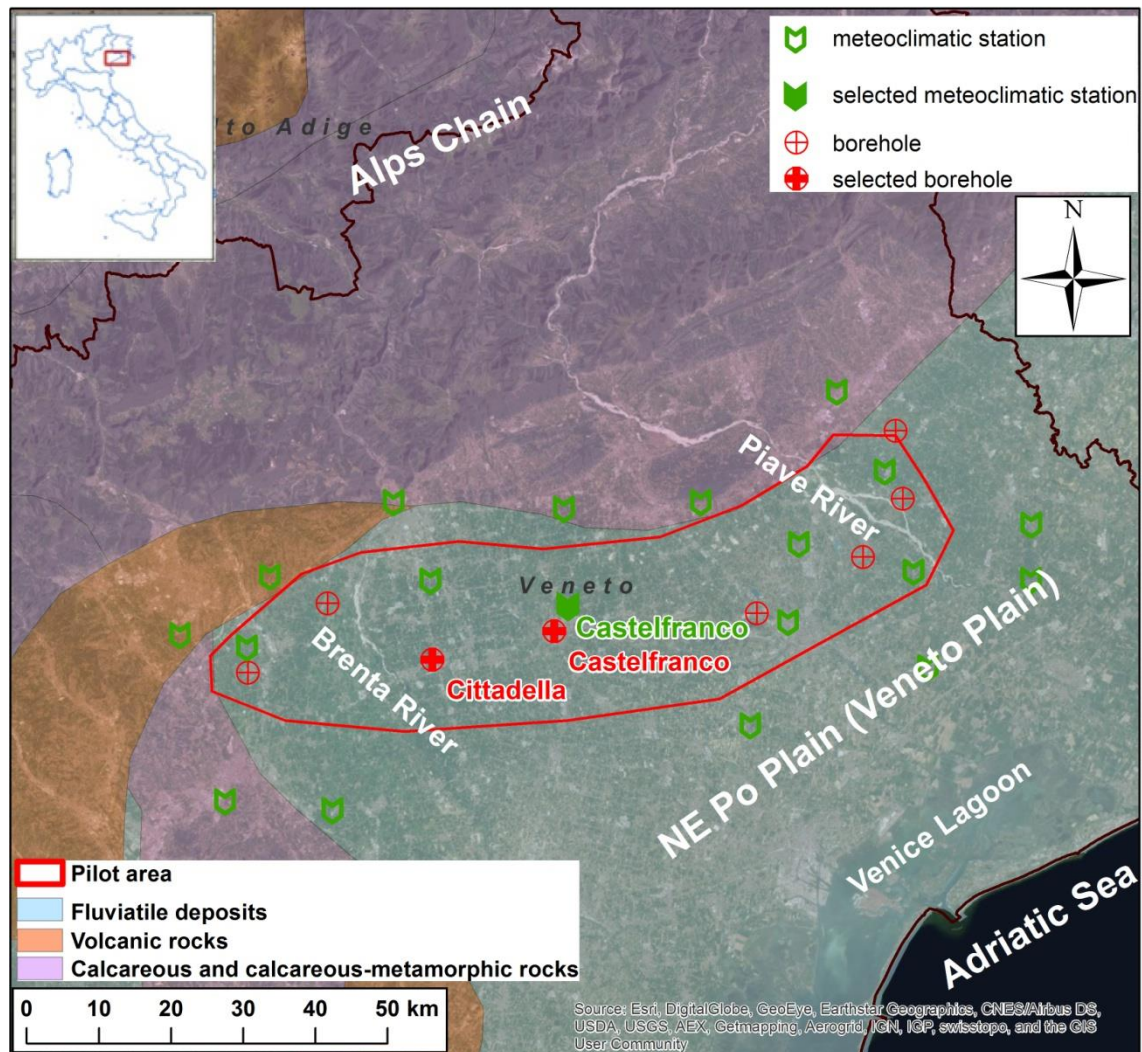


Figure 2: Geological framework of the pilot area (modified from Amanti et al., 2007) and borehole locations.

Table 1: Description of selected observation boreholes.

Borehole name	Elevation (m a.s.l.)	GWs record	Data time step
Castelfranco Veneto	42	1997-current	twice-weekly
Cittadella	47	1997-current	twice-weekly

3.1.6 Surface water bodies

The multilayer aquifer system of the NE Po Plain (Veneto Plain) includes a complex aquifer system consisting of different unconfined or semi-confined aquifers that are hydraulically connected to some different degrees. Their depth is about 90 m from the ground surface.

In any case, the depth to top of aquifer within the pilot area including the selected boreholes is 10-15 m below terrain surface and locally represents a monolayered aquifer characterized by some hundreds meter depth.

3.1.7 Abstractions/irrigation

The groundwater abstractions by wells from the pilot area are mainly related to irrigation (about 35%), industry and productive activity (about 20%), drinking water (15%) and domestic (25%) purposes. In any case, the groundwater resource of the study area did not suffer from major exploitation actions in the recent years, due to the progressive abandoning of intensive agricultural and industrial activities. This has led to the reactivation of a large number of springs along the *Line of Resurgences* occurring in the area.

A number of observation boreholes in alluvial plain geological settings are available (time series of groundwater head data > 15 years; mostly twice-weekly data). They are managed by Veneto Region Environmental Protection Agency (ARPAV).

3.2 Climate change challenge

3.2.1 Expected climate changes

The expected climate changes in the pilot area but also at a larger regional scale included in the Mediterranean region (Figure 3), regard the temperature rise, which is occurring from the last years, and the precipitation distribution with time, characterized during the last years by high (flood) and low (drought) rain events, often having also a spatially random distribution.

3.2.2 Challenges

Due to the previously described climate change impacts, in the last years, sustainable management and supply of (ground)water resources have been major issues for the pilot area and the host district.

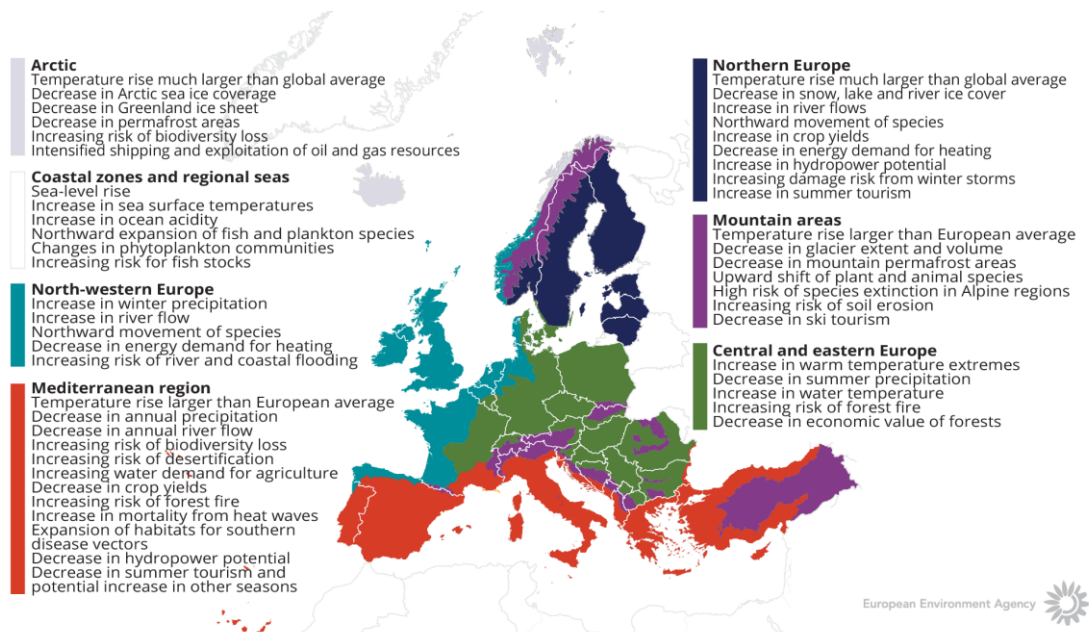


Figure 3: How climate is expected to change in Europe. The European Environment Agency map.

4 METHODOLOGY

The assessment of climate change impacts on recharge in the Italian pilot area of NE Po Plain (Veneto Plain) is performed using the TACTIC standard climate change scenarios and the lumped models AQUIMOD and GARDÉNIA, and the transfer noise model METRAN.

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 for AquiMod are those that reach the aquifer system and drive the groundwater levels. Thus, it is assumed that these are the actual recharge values as defined for TACTIC Project.

4.1.2 *Gardènia*

Gardenia is a lumped hydrological model for the simulation of relationships between series of stream or spring flow data at the outlet of a watershed, and/or groundwater level data at an observation well situated in the underlying aquifer and the rainfall received over the

corresponding watershed. Withdrawals by pumping groundwater can be considered if necessary. Further information about the model is given in Appendix C.

Gardenia estimates the different components of the hydrological balance for a given basin including: actual evapotranspiration, runoff, infiltration, and recharge. The hydrological balance can be used for the evaluation of the renewable resources mainly the groundwater recharge of aquifers. GARDENIA produces time series of river flows, groundwater levels or recharge data over a long period for which precipitation and potential evaporation data are known. These river flows and/or groundwater level time series can then be used to:

- forecast river flows or groundwater levels for civil engineering applications
- study particular events such as groundwater flooding or the occurrence of droughts
- quantify the water balance components of a catchment at a pre-defined time-step (varying from one day to one month) for water resource evaluation or as input for a distributed groundwater model
- study the impact of climate change.

The climate data required for the model are:

- a continuous series of rainfall data,
- a continuous series of potential evapotranspiration data (PET). PET values can be either calculated from information related to sunshine duration, air temperature and relative humidity data, or it can be obtained directly from Meteorological offices.

One or two series of observations can be considered: river flows at the basin outlet and/or representative groundwater levels at an observation borehole located in the basin. The model can take into account impact of groundwater or river abstraction.

These different series of data must be at a regular time step: daily, 5 days, 10 days, or monthly. All the series should refer to the same period. The time step of each series is not necessarily identical (e.g. daily rainfall and monthly PET).

The modelling of the relationships between rainfall and river flows and/or rainfall and groundwater levels includes a minimum of 4 to 6 lumped parameters (soil capacity, recession times, etc.) representative for a basin or a homogeneous unit within the basin.

The software is executed in calibration phase first where model parameters are optimized automatically. The user has to select an objective function to evaluate model efficiency. This is usually dependent on the type of the investigated problem.

4.1.3 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 Figure 15.

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, this 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.

4.1.4 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 $0.5^\circ \times 0.5^\circ \text{C}$ 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 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 RCP-GCM combinations shown in the next table were employed.

Table 2: Combinations of RCPs-GCMs used to assess future climate.

		RCP	GCM
1-degree	"Dry"	rcp6p0	noresm1-m
	"Wet"	rcp4p5	miroc-esm-chem
3-degree	"Dry"	rcp4p5	hadgem2-es
	"Wet"	rcp8p5	miroc-esm-chem

4.2 Model set-up

The two selected boreholes within the NE PO Plain (Veneto Plain) pilot area addressed in this study are listed in paragraph 3.1.5. These two boreholes (Castelfranco Veneto and Cittadella) were preferred since they have available and continuous groundwater level time series (1997-2018).

Enough information on rainfall and air temperature in the same time span was also available for allowing recharge calculation. Potential evapotranspiration was calculated from air temperature.

Stream discharge and abstraction were not included since they are not significant in the boreholes area.

The complex hydrogeological situation (e.g. wideness of recharge area, thickness of unsaturated zone) and the variation of hydraulic conditions of some local elements (e.g. hydraulic contribution from adjacent areas, presence of many active ponds and canals and of diffuse resurgence areas) likely contribute to cause the relatively low NSE values during simulation model processing.

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. The boreholes studied here not include 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 daily basis, and this forces AquiMod to run using a time step length of one day. Figure 4 shows daily time series of rainfall and potential evaporation values (mm/month) as well as the fluctuations of water table at the two selected boreholes.

All AquiMod models built for the boreholes in Table 1 use the FAO Drainage and Irrigation Paper 56 (Allen et al., 1998) 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). However, 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 is selected to undertake the recharge calculations. The structure selected for the two selected boreholes is of one layer layered systems.

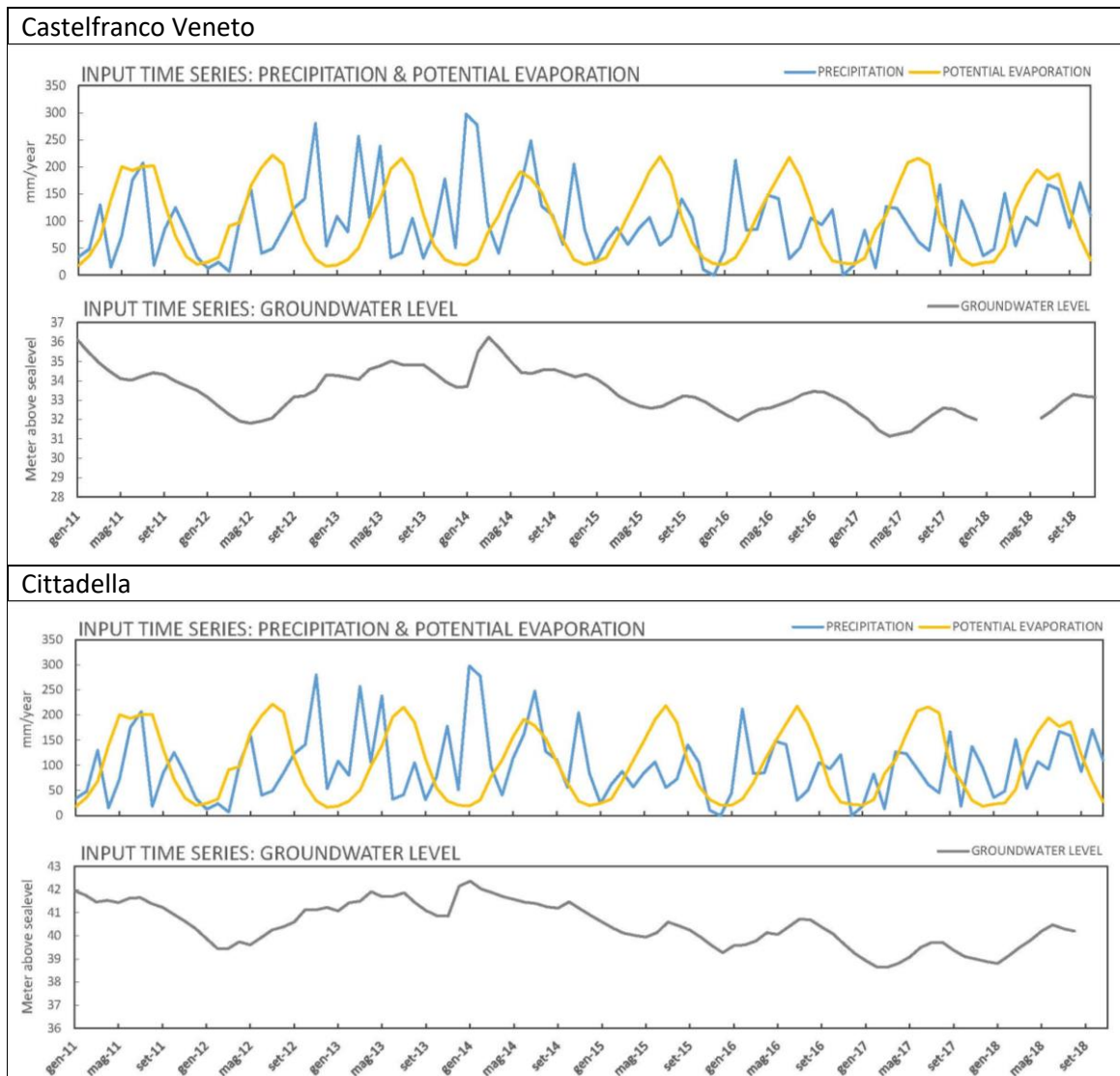


Figure 4: Time series of daily rainfall and potential evaporation values (mm/month) and fluctuations of water table at the two selected boreholes.

4.2.2 Gardènia

Gardènia model setup relies on separated files for different parameter time series. In the present modelling study, we define groundwater levels, precipitation and potential evapotranspiration time series. However, it is also possible to include files for water abstraction and river discharge data. These are not included here because in the last decades intensive groundwater exploitation activities were abandoned and the major river are quite far from the selected boreholes. Furthermore, the Gardènia model was mainly applied in order to get a confirmation of the results from Aquimod, which were obtained without inclusion of pumping and river data. The data provided to the model, like those applied for Aquimod model, are on a daily basis.

The module types and model structure are directly defined within the Gardènia application by input parameter control windows. Gardènia is consequently executed first under a calibration mode followed by an evaluation mode to select the parameter values that yield best model performance.

Gardènia models built for the boreholes in Table 1 were performed with the same one layer with one discharge hydrostratigraphical feature and input data used for AquiMod (Figure 4), to allow for a direct comparison between the two model results.

4.2.3 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 5. 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 daily information of precipitation, potential evaporation and groundwater levels is prepared for each borehole in Table 1. Plots of these data are shown in Figure 4. It must be noted that, while the groundwater levels used in AquiMod and Gardènia shown in Figure 4 have missing values, these have to be provided as complete time series to Metran. To achieve this, a linear interpolation procedure is used to fill in the missing values in the groundwater level time series. Once executed, it calculates the characteristics of the impulse functions and the corresponding parameters automatically.

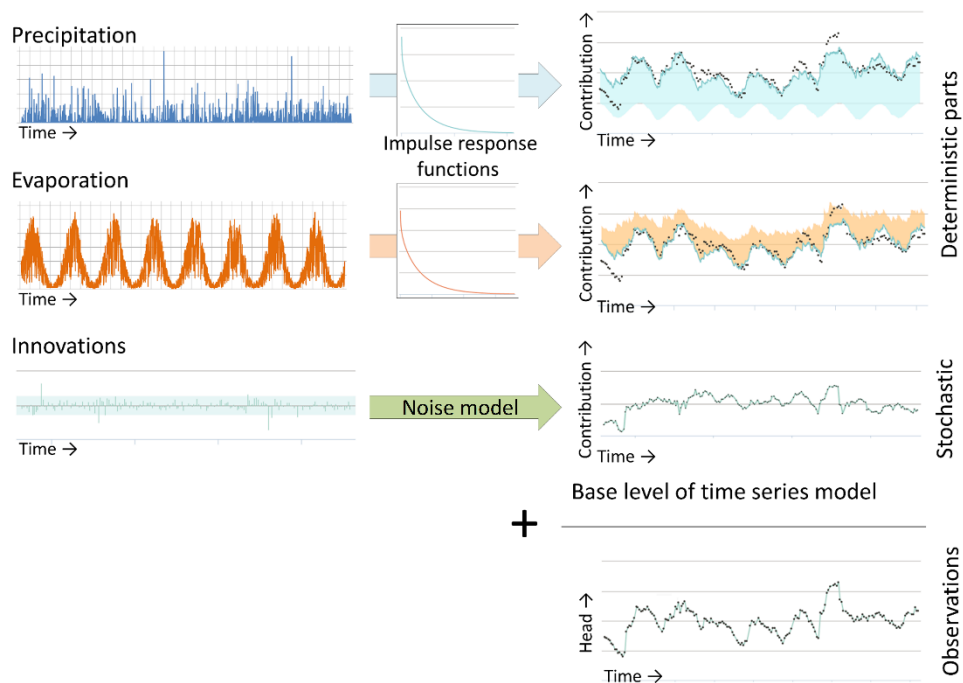


Figure 5: Illustration of METRAN setup.

4.3 Model calibration

Many attempts have been undertaken to calibrate the Aquimod model. However, it was not possible to produce a simulation with an acceptable performance measure, using the rainfall, potential evapotranspiration and groundwater level time series from 1997 to recent time at the selected boreholes (maximum Nash-Sutcliffe Efficiency value produced was approximately 0.3).

The complex hydrogeological situation (e.g. wideness of recharge area, thickness of unsaturated zone) and the variation of hydraulic conditions of some local elements (e.g. hydraulic contribution from adjacent areas, presence of many active ponds and canals and of diffuse resurgence areas) likely contribute to the relatively low NSE values during simulation model processing.

The analysis of time series using the Metran model with the help of TNO (model owner) identified three different periods of the used time series that are having diverse, but internally homogeneous suitable trend features (1998-2002; 2003-2010, 2011-2018). The use of the most recent period to calibrate the Aquimod model yielded a simulation with an NSE value over 0.7. This simulation was selected with the evaluation stage by Aquimod model.

The factors that may have induced different trends in the three former periods are not still clear. Among the major possibilities there are: (i) the thickness of the unsaturated zone (10-15 m); (ii) the non-linearity features within the groundwater system; (iii) the temporal variation in ratio between actual and potential evapotranspiration (some runs gave a precipitation response that explains a reasonable part of the head variation but no contribution of potential evapotranspiration); (iv) the occurring of land use changes (actually with no real evidence in the area).

At the end, the two (out of eight) selected boreholes were successfully improved and calibrated ($NSE > 0.7$) by Aquimod on 8 years span data (2011-2018). On the contrary, the other two former periods (1998-2002; 2003-2010) provided not suitable calibration results. Comparison of the obtained models at the two selected boreholes by a second method (Gardenia model by BRGM) with the same input data produced similar calibration results.

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. The storage coefficients bounds 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. All the models that achieve an NSE higher than 0.6 are included in the analysis but a maximum number of 1000 runs are used if the number of acceptable models is greater than 1000.

Next table shows the best NSE values obtained for the models calibrated at the two selected boreholes listed in Table 1. It is evident that a relatively low but sufficient match was achieved only for the 2011-2018 period between the simulated and observed groundwater levels, as illustrated in the plots shown in Figure 6. This happened since the whole time series 1997-2018 displayed different trends among the 1997-2002, 2002-2009, 2009-2011 and 2011-2018 periods and only the last one reached the sufficient NSE values reported in the nex table. The distinction among the different periods was confirmed by the values of the “residuals” featured by Metran model.

Table 3: Nash-Sutcliff Error at the two selected observation boreholes obtained by AquiMod.

Borehole name	NSE
Castelfranco Veneto	0.72
Cittadella	0.73

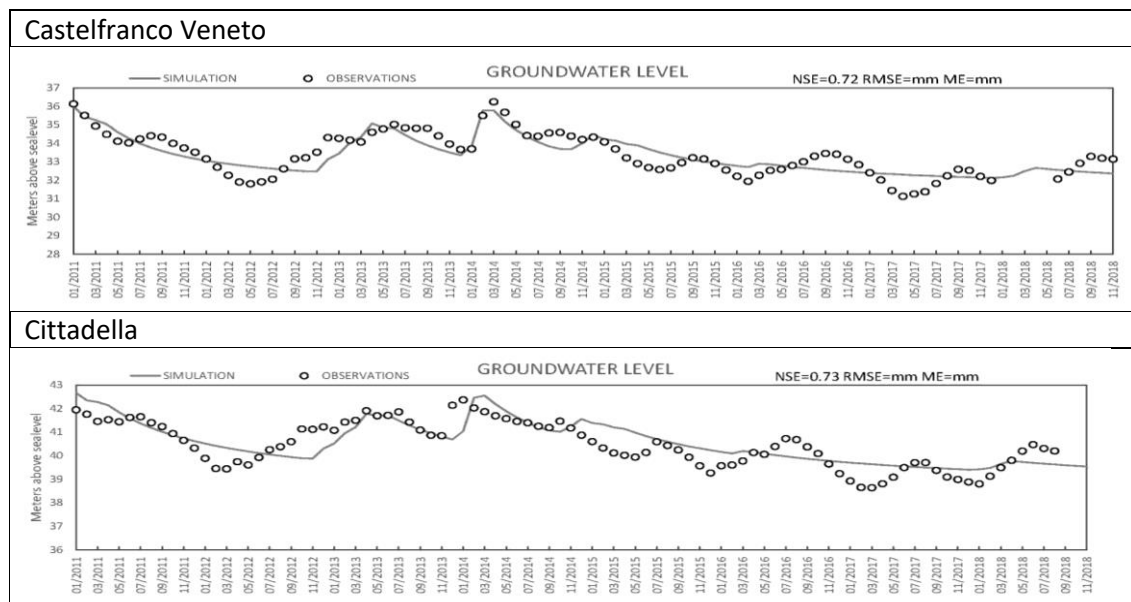


Figure 6: Comparison between the simulated and observed groundwater levels obtained by Aquimod at the two selected observation boreholes.

4.3.2 Calibration of Gardènia models

The data used for Gardènia model calibration at the two selected boreholes are: (i) model "input" continuous series of rainfall and evapotranspiration; (ii) model "output" observed series (levels) not necessarily continuous, but covering a concomitant period with the input series. Calibration was done in a semi-automatic way on the initial set of observed groundwater levels, also indicating which other involved parameters should be optimised.

The model uses a non-linear optimisation algorithm, makes the chosen parameters vary (within a range of values defined by the user) and searches for a set which gives the best fit between observed and simulated series has been found.

The model produces: (i) for each time-step a water balance of the different components of the hydrological cycle (runoff, actual evaporation, groundwater flow, etc.); (ii) a graphical representation of observed and simulated values for a visual evaluation of the calibration; (iii) numerical criteria for the evaluation of the quality of calibration.

Taking into account this information, the user then estimates whether to attempt a new optimization from another set of parameters. When both the numerical fitting criteria and the graphs for visual comparison are satisfactory, the user may consider if the obtained values are realistic.

Next table shows the best NSE and R coefficient values obtained for the models calibrated at the two selected boreholes listed in Table 1. It is evident that the calibration results of Aquimod have been substantially confirmed. The comparison between the simulated and observed groundwater levels are illustrated in the plots shown in Figure 7.

Table 4: NSE and R coefficients at the two selected observation boreholes obtained by Gardènia.

Borehole name	NSE	R
Castelfranco Veneto	0.69	0.83
Cittadella	0.65	0.81

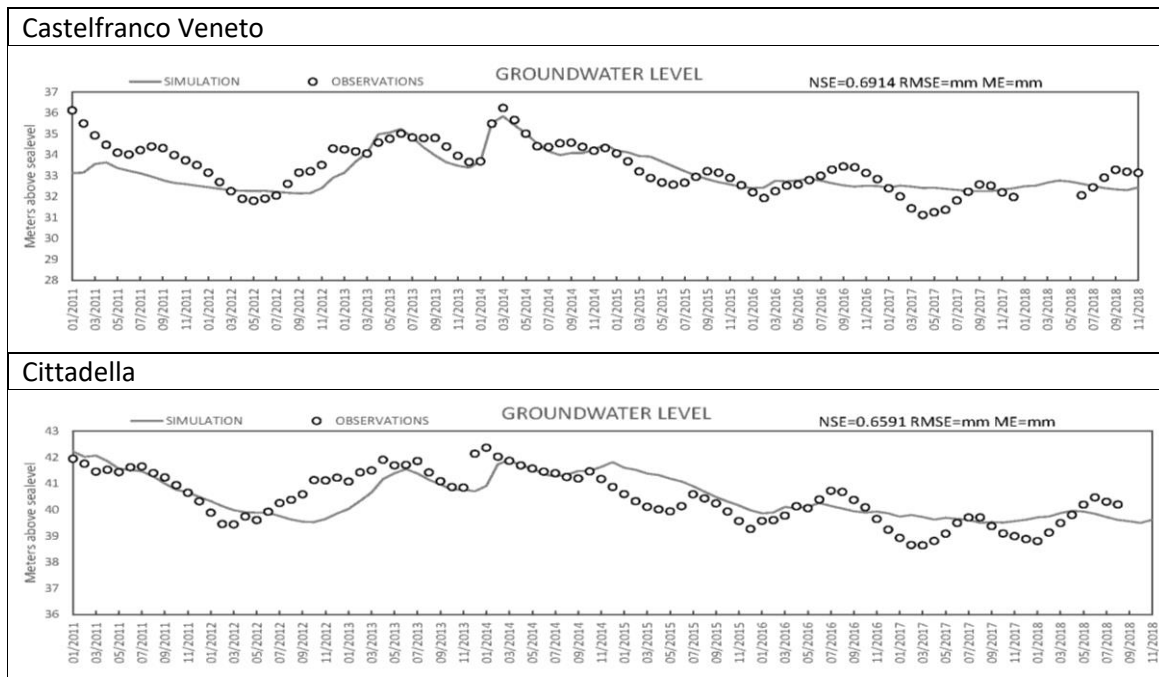


Figure 7: Comparison between the simulated and observed groundwater levels obtained by Gardènia at the two selected observation boreholes.

4.3.3 Calibration of Metran models

For the standard setup with precipitation and evaporation, there are five parameters that have to be determined: three 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 pumping. 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.

Next table shows the performance of Metran for the Castelfranco Veneto selected borehole. It is clear that according to criteria set above, Metran succeeds to produce an acceptable model at Castelfranco borehole with the model output showing a 0.69 value of R^2 . The reasons that may have induced the not reaching of a highest quality acceptance of the model are still not clear.

Table 5: Performance of Metran across the Castelfranco Veneto selected borehole.

Borehole name	Metran performance parameter Regimeok	Metran performance parameter Modok	Overall quality	R ²	RMSE
Castelfranco Veneto	1	0	Acceptable	0.69	0.67

5 RESULTS AND CONCLUSIONS

As shown in Section 1.4, two simulations with NSE greater than 0.7 were produced at the two selected boreholes using rainfall and precipitation data recorded from 2011 to 2018. Using the parameter values of these two simulations and running the model in evaluation mode, AquiMod produced an estimation of recharge (about 0.5-0.6 mm/day). AquiMod results have been compared with those produced by Gardènia to investigate the uncertainty in the estimated recharge values associated to model methodology.

Evaluation of recharge at selected boreholes using climate change scenario data was also performed.

5.1 Historical recharge values

Figure 8 shows the time series of the historical recharge values calculated using the AquiMod model at the two selected boreholes of the NE Po Plain (Veneto Plain) pilot area. The plots in this table also show the 10th percentile, the mean, and the 90th percentile of recharge values calculated from the time series. The 10th percentile values are not visible in the histograms since they are approximately equal to zero.

As mentioned in Appendix B, the formulas used by Metran are based on assumptions that it is better to use only models of the highest quality to calculate long-term average values of recharge with the long-term average values of rainfall and potential evaporation. Therefore, since the performance of Metran for the Castelfranco Veneto selected borehole was acceptable but not of highest quality, it was not possible to produce suitable time series of recharge values using Metran.

One of the benefits of running AquiMod in Monte Carlo mode is the possibility of producing many models with acceptable performance. Consequently, the recharge values estimated from these models are all equally likely. This provides us with a range of recharge values at each borehole that reflects the uncertainty of the optimised hydraulic parameter values. In the current study, the long-term average recharge values are calculated from up to 1000 acceptable models if they exist at each borehole; otherwise, all the acceptable models are used. The mean, 10th and 90th percentiles are then calculated from these long-term recharge values and displayed in Figure 9. It is clear that the differences between the 10th and 90th percentile values are quite significant at the selected boreholes indicating a high degree of uncertainty associated with these values. It is noteworthy that AquiMod calculates actual recharge.

Figure 10 shows historical time series of recharge calculated using Gardènia model at these boreholes. The pattern of the recharge values calculated using Gardènia match that of the recharge values calculated by the other model at the two selected observation boreholes. While the agreement between these two models increases the confidence in the calculated recharge values, it should be noted that the large differences between the 90th and 10th percentiles shown by both models are a clear indication about the high uncertainty associated with the estimated recharge values.

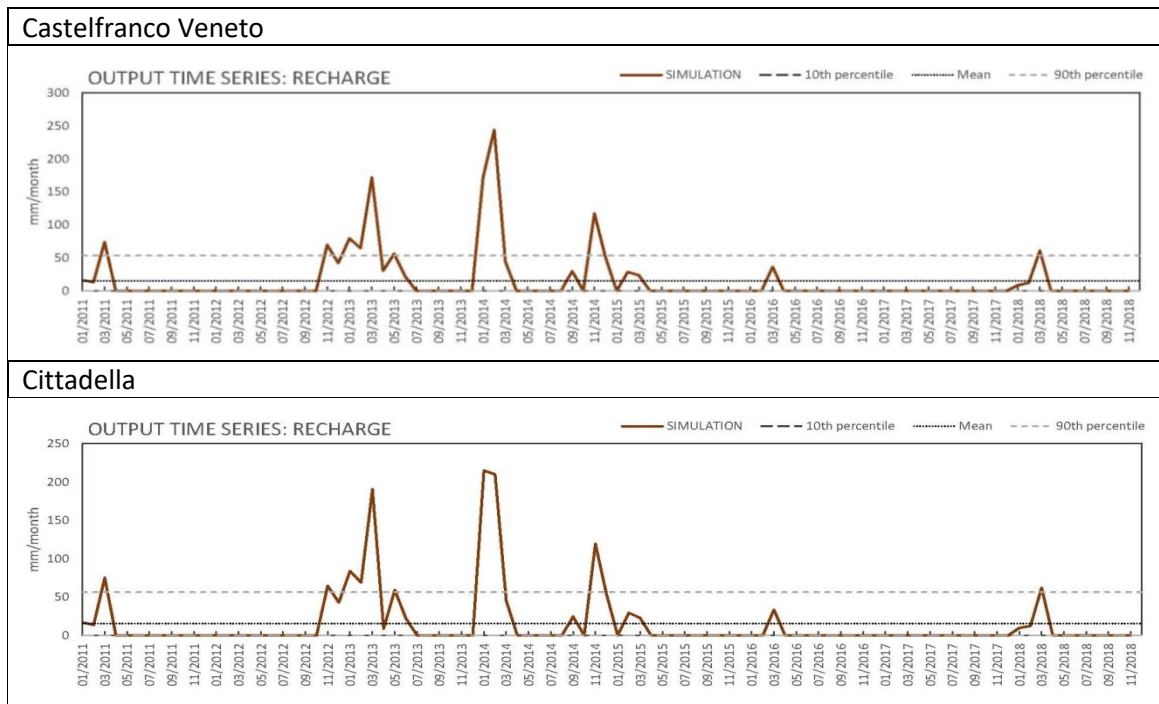


Figure 8: Time series of recharge values obtained from the best performing AquiMod models at the two selected observation boreholes.

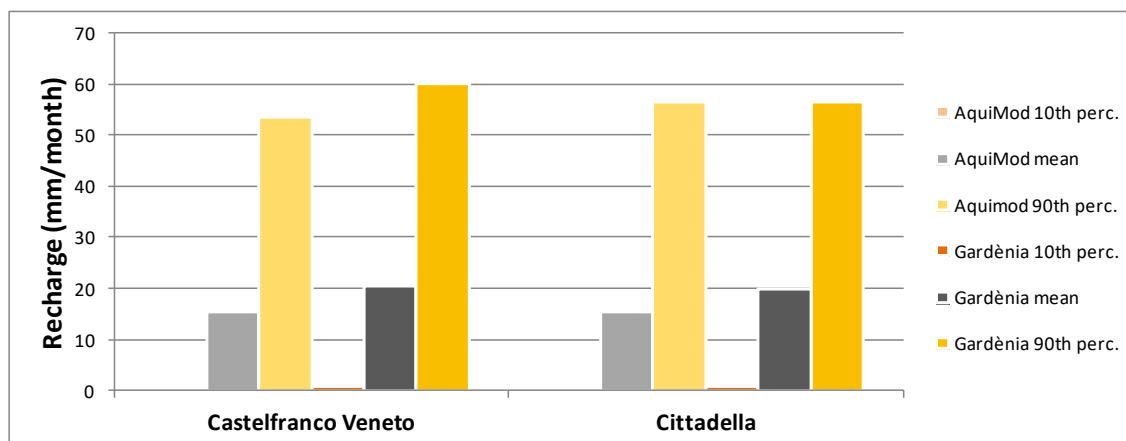


Figure 9: Historical recharge values calculated by AquiMod and Gardènia models at the two selected boreholes. The 10th percentile values are not visible since they are approximatively equal to zero.

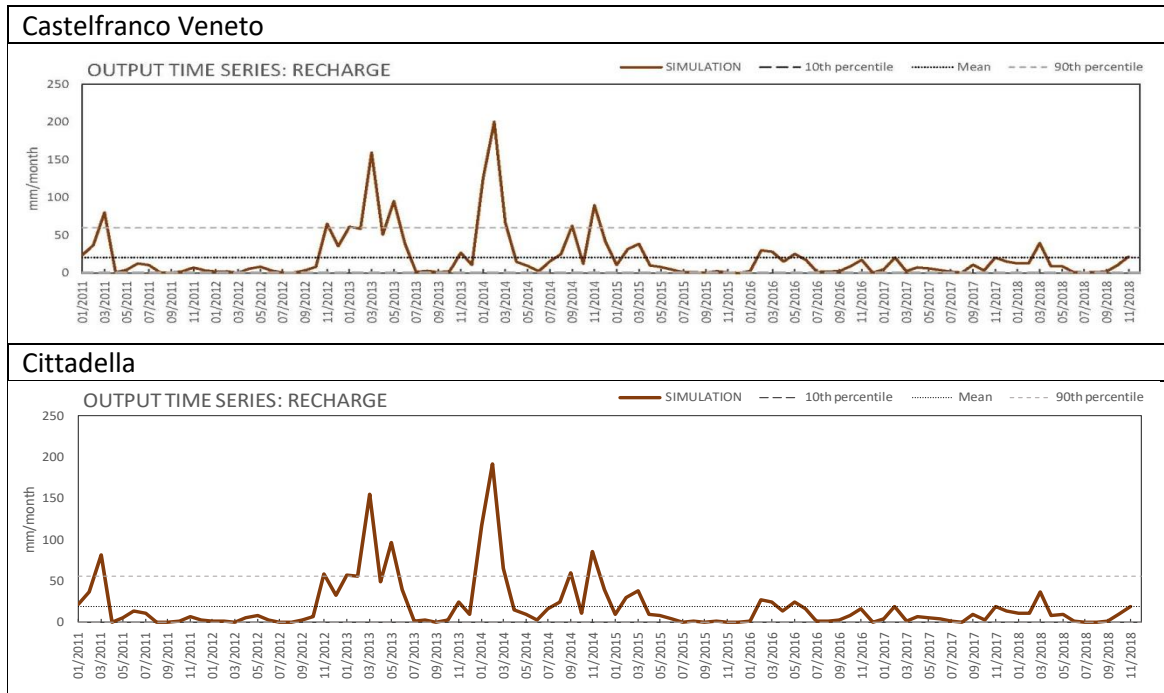


Figure 10: Time series of recharge values obtained from the best performing Gardènia models at the two selected observation boreholes.

5.2 Projected recharge values

The forcing data, rainfall and potential evaporation, are altered using the change factors of the climate models (see Section 4.1.4). For the NE Po Plain (Veneto Plain) area, the set of monthly change factors used with the data driving Aquimod are shown in Table 6: Monthly change factors as multipliers used for the two selected borehole data.. These change factors are used as multipliers to both the historical rainfall and potential evaporation values.

For the application involving Aquimod, these factors are used to alter the time series of historical rainfall and potential evaporation values used to drive the model.

According to the ISIMIP (Inter Sectoral Impact Model Intercomparison Project), these change factors have been used to modify the historical gridded rainfall and potential evaporation data before using them as input to calculate the recharge. In this case, and for any simulation date, the rainfall and potential evaporation change factors for the month corresponding to the date, are used to modify all the spatially distributed historical rainfall and potential evaporation values, respectively.

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

	Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	1°C Min	0.790	0.978	0.983	1.081	1.039	1.015	0.997	0.976	0.956	1.064	0.850	0.987
	1°C Max	1.099	0.979	1.100	1.069	1.025	1.002	1.117	0.961	1.091	1.091	1.097	1.023
	3°C Min	1.093	1.062	1.031	1.294	1.005	0.860	0.659	0.634	0.783	0.896	0.895	0.976
	3°C Max	1.250	1.089	1.177	1.052	1.268	0.781	0.986	0.956	0.989	1.085	1.063	1.214
PE	1°C Min	1.079	1.010	1.005	1.013	1.016	1.016	1.022	1.032	1.030	1.029	1.007	0.994
	1°C Max	1.140	1.127	1.065	1.069	1.078	1.080	1.074	1.075	1.082	1.083	1.083	1.100
	3°C Min	1.173	1.152	1.082	1.065	1.053	1.080	1.133	1.118	1.116	1.105	1.044	1.191
	3°C Max	1.171	1.145	1.084	1.098	1.051	1.066	1.073	1.079	1.097	1.094	1.085	1.109

Figure 11 shows the historical and future long-term average recharge values calculated using the best performing AquiMod model. The results between the two selected boreholes are very similar. It is clear that the highest reduction in recharge values are observed when the 3°C Min rainfall and evaporation data are used (even if they are very similar to 1°C Min values), while the highest increase in recharge values are observed when the 3° Max rainfall and potential evaporation data are used.

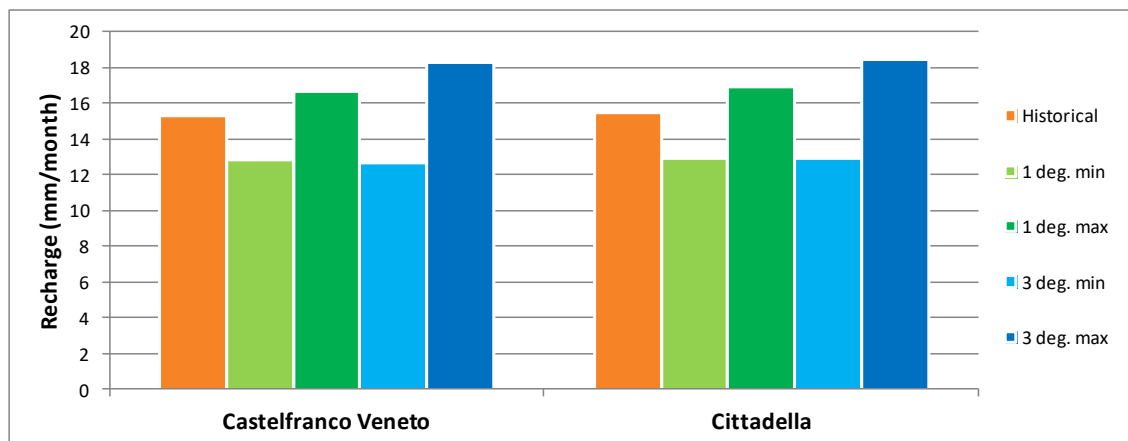


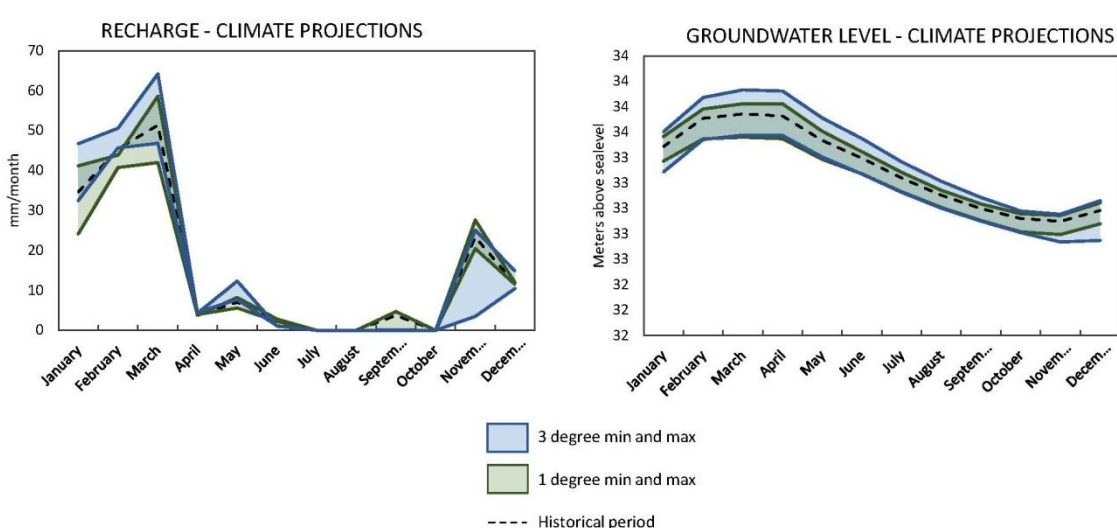
Figure 11: Historical (orange) and future average recharge values (blue and green) as produced by the best performing AquiMod model.

Next table shows, as mean values (mm/day) of the two selected boreholes, the average and maximum estimate of the climate projection recharge data (Figure 12; mm/month). Looking at both the average and maximum recharge values, it is clear that there is a similar reduction (about 17%) in recharge when the 1°C Min and 3°C Min data are used compared to the historical scenario, as expected. On the contrary, the average and maximum recharge values for 1°C Max and 3°C Max projections are higher (about 9%) than those from the historical scenario, as also expected.

Table 7: Statistical information of the climate projection recharge data shown in Figure 12, as mean values of the two selected boreholes.

Recharge scenario	Average recharge (mm/day)	Maximum recharge (mm/day)
Historical scenario	0.513	1.712
CC scenario: 1 degree min	0.429	1.399
CC scenario: 1 degree max	0.559	1.954
CC scenario: 3 degrees min	0.426	1.561
CC scenario: 3 degrees max	0.612	2.139

Castelfranco Veneto



Cittadella

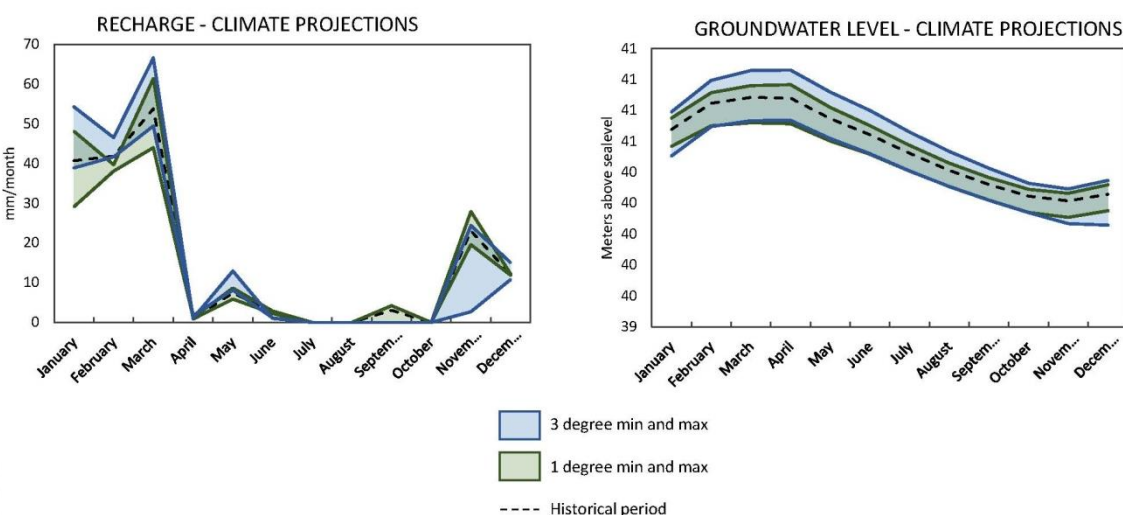


Figure 12: Monthly recharge and groundwater level values estimated by Aquimod using the historical and the projected forcing data.

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7 APPENDICES

7.1 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 13). 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.

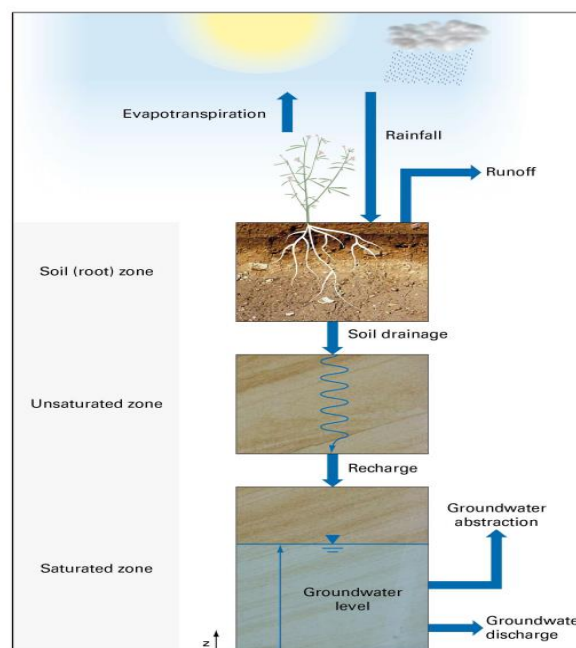


Figure 13: Generalised structure of AquiMod (after Mackay et al., 2014a).



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 (Allen et al., 1998) approach. In this method, the capacity of the soil zone, from which plants draw water to evapotranspire, is calculated first using the plants and soil characteristics. Evapotranspiration 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 evpo-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 14, 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

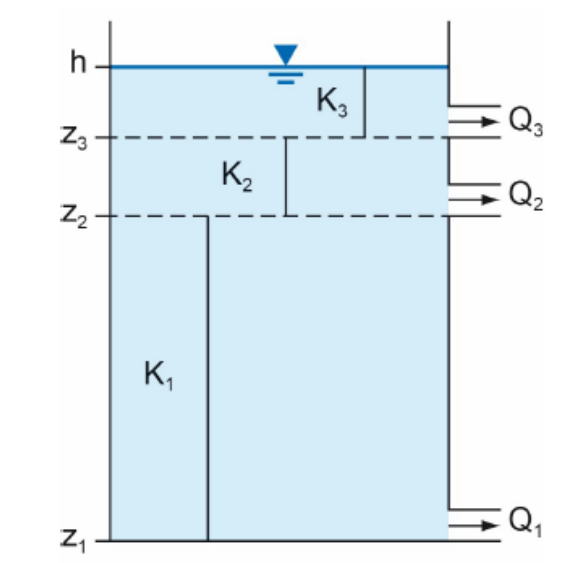


Figure 14: Representation of the saturated zone using a multi-layered groundwater system).

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 Sutcliffe 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.

7.2 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 15. 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.

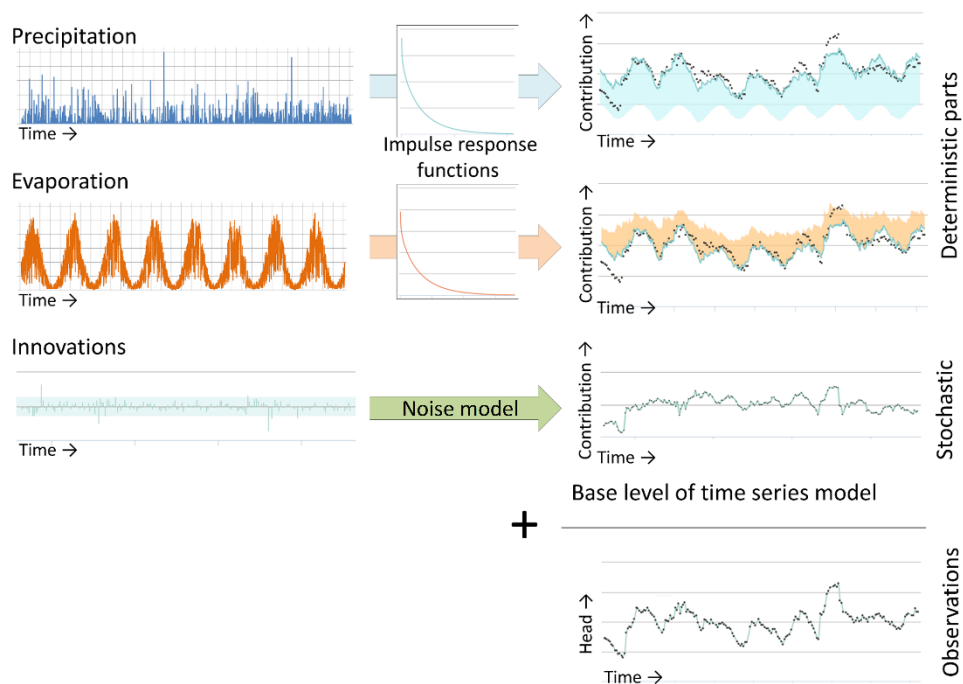


Figure 15: Illustration of METRAN setup

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 16.

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.

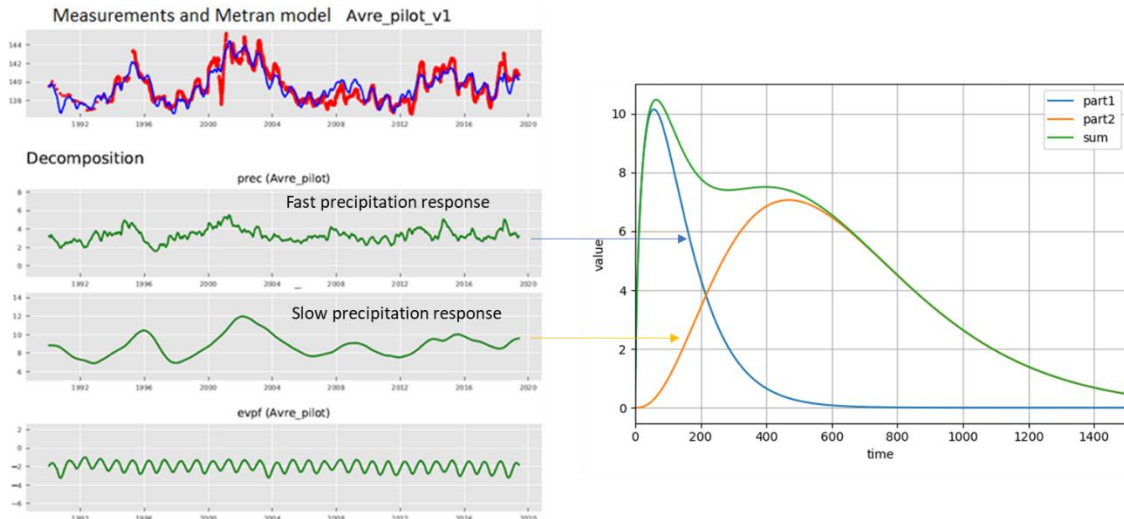


Figure 16: An example where the response function implemented in METRAN is not suitable for the groundwater system

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 fc 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 17 with the impulse response functions and head time series for two models with very different response times for time series of SGU in Sweden.

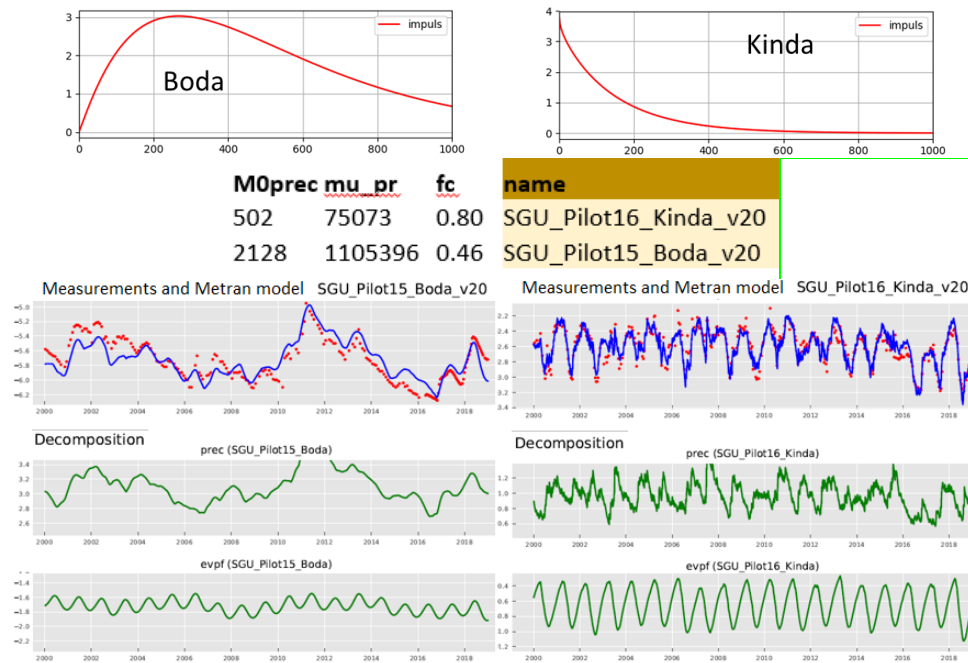


Figure 17: Illustration of Metran output for two case studies in Sweden with different response times.

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.

7.3 Appendix C: Gardènia methodology

Introduction

The computer code GARDÉNIA (modèle Global A Réservoirs pour la simulation des Débits et des Niveaux Aquifères) is a lumped hydrological model for watersheds. It uses time series of meteorological data (rainfall, potential evapo-transpiration) recorded or calculated at a catchment to calculate:

- the river flows at the outlet of a river (or source) basin;
and / or
- the groundwater levels at a borehole drilled in the underlying aquifer.

The effects of pumping or of a pumping group all located in the watershed can be taken into account.

Calculations can be performed at a daily time step, decadal (ten days) or monthly. It is possible to take into account the snow melting process.

The modelling of the relationships between the rainfall and river flows and/or rainfall and groundwater levels includes 4 to 6 lumped parameters (soil capacity, recession times, etc...) representative for a basin or a homogeneous unit within the basin. These parameters are optimized using rainfall and river flow (and/or groundwater level) data over same observation period. The software under control of the user does this calibration phase of the model automatically.

After completion of the calibration, GARDENIA enables:

- The calculation of a hydrological water balance for the basin including actual evapotranspiration, runoff, infiltration, recharge (some terms can be used as input data in a discretized groundwater model). The hydrological water balance can be used for the evaluation of the renewable groundwater resources, mainly the groundwater recharge, of aquifers;
- the prediction of river flows, groundwater levels or recharge estimates over a historical or a future period for which precipitation and potential evaporation data are



known. These projected river flow and/or groundwater level series can then be used for:

- the forecasting of river flows or groundwater levels for the design of structures;
- the study of particular events such as the rise of groundwater levels (flooding) or the occurrence of droughts;
- the study of the impact of climate change.

In addition to the possibility of estimating the different elements of the hydrological cycle (infiltration, evapotranspiration, runoff), GARDENIA allows the characterization of the hydraulic characteristics of the catchment through the calculation of the different runoff components (fast, slow and very slow components).

Methodology

The GARDENIA model represents the water cycle in a basin from rainfall received by the soil surface till the river flow at the outlet, and/or the aquifer level at a given point. GARDÉNIA is a lumped model because it considers a lumped input (rainfall and potential evaporation representative for the basin) averaged over a catchment area and a single output (river flow at the outlet and/or groundwater level in the aquifer).

A lumped hydrological model simulates, through a series of reservoirs, the main mechanisms of the water cycle in a catchment (rainfall, evapotranspiration, infiltration, and runoff). Indeed, the exponential form of the recession of river flows or aquifer levels looks like the emptying of a reservoir (or tank). Therefore, the behavior of an aquifer system can be represented by a series of inter-connected tanks. Non-linear transfer functions improve the capability of this schematic representation to simulate a complex system.

GARDÉNIA simulates the water cycle through a series of 3 or 4 connected tanks that represent respectively (Figure 18):

- the few decimeters of the soil that are subjected to the influence of evapotranspiration (root zone of the present vegetation);
- an intermediate zone generating rapid flow;
- one or two aquifer zones generating delayed slow flow.

The outflow from one reservoir to another is controlled by simple laws, specific to each reservoir; these laws are governed by the model parameters (active storage, duration of outflow, overflow threshold, etc.).

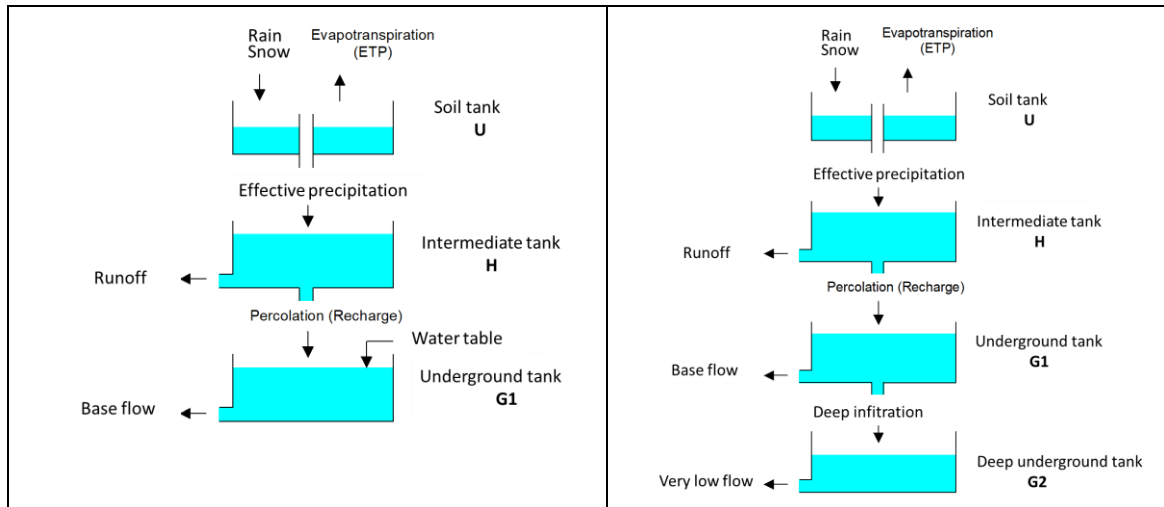


Figure 18: Schematic representation of GARDÉNIA with one underground reservoir (left) or two underground reservoirs (right).

"Production" function and "transfer" function

The calculation consists of two parts, traditionally called: "production" function and "transfer" function.

The "production" function determines the amount of water reaching the system, and the amount that will evaporate or that will infiltrate into the lower horizons to emerge "later". The "transfer" function determines at what time the water, which has not evaporated, leaves the outlet of the basin or will reach the aquifer below. The transfer is represented as the passing of water through the 2 or 3 lower reservoirs of the model.

Due to the lumped nature of the model and the complexity of the hydrological system in reality, the different parameters of the tanks cannot be determined *a priori* from the local physiographical characteristics of the catchment (geology, vegetation cover, etc.).

Model data and parameters

The required data are:

- a continuous time series of rainfall data,
- a continuous time series of potential evapotranspiration data (PET). PET values can be either calculated from sunshine duration, air temperature and relative humidity data, or can be obtained directly at Meteorological offices;
- one or two series of observations, which may include gaps, of:
 - o river flows at the basin outlet; and / or representative groundwater levels at an observation well located in the basin.
- possibly a series of water withdrawals (pumping)

These different series of data must at a regular time step: daily, 5 days, 10 days, or monthly. It is also possible to use any regular time step (5 minutes, 1 hour, 60 days etc.).

All the series should refer to the same period. The time step of each series is not necessarily identical (e.g. daily rainfall and monthly PET).



Hydro(geo)logical parameters

In general a number of 4 to 6 parameters (maximum 8 parameters) is required by the model (15 parameters in case precipitation in form of snowfall are to be taken into account). The dimensional parameters characteristics of the different reservoirs are:

- RUMAX (mm): capacity of reservoir RU, or the storage available for evapotranspiration
- THG (months): time of half-filling of reservoir G
- RUIPER (mm): level in reservoir H for which there is an equal distribution between fast runoff and percolation.
- TG1 (months): time of half-recession of reservoir G1
- TG12 (*) (months): time of half-filling or reservoir G2 (time of half-transfer from G1 to G2)
- TG2 (months): time of half-recession of reservoir G2 (time of half- slow recession)

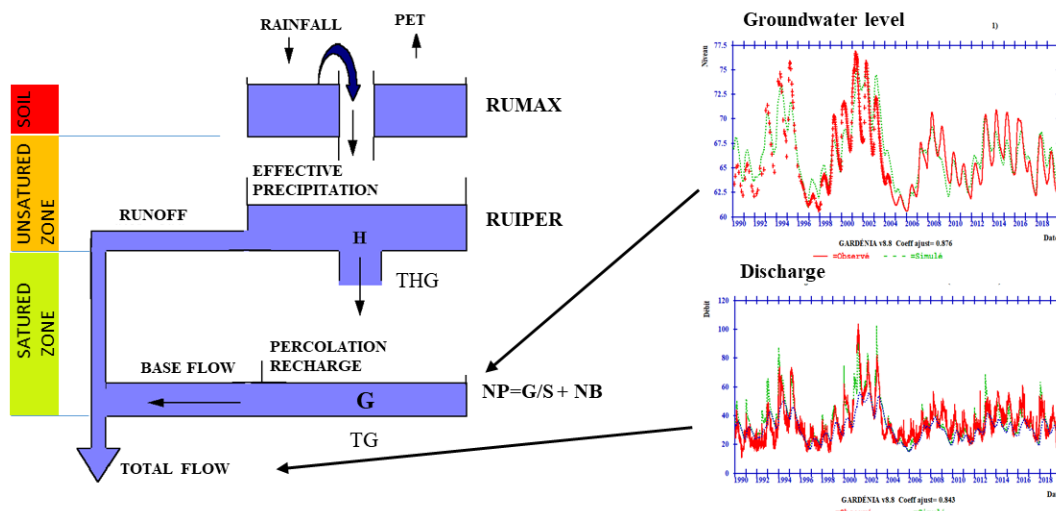


Figure 19: Principle of GARDÉNIA global hydrological model for simulating the flow of a watercourse and/or a groundwater level.

Initialization

It is evident that due to the sometimes considerable hydrological inertia of the system, the calculation of the first values depends a lot on the conditions of the previous years.

To avoid the difficulties that could result from the above, the possibility has been introduced in the model to take into consideration a few years, prior to the first hydrological observations.

However, since it often takes very long for the flow regime to establish, the model is placed in hydrological equilibrium at the beginning of calculations, this means that the out coming flow (or piezometric level) corresponds to incoming effective rainfall.

Model calibration

Model calibration consists of adjusting model parameters, within given limits, with the aim of producing simulated river flows and/or groundwater level series that match the observed ones as precisely as possible.

The data required for calibration are:

- model "input" continuous series: rainfall and evapotranspiration (and air temperature if snowmelt is taken into consideration);
- model "output" observed series (flows or levels) not necessarily continuous. but covering a concomitant period with the input series.

Calibration is done in a semi-automatic way. The user provides an initial set of parameters and indicates which parameters should be optimised. The model uses a non-linear optimisation algorithm adopted from the Rosenbrock method. The model makes the chosen parameters vary (within a range of values defined by the user) and searches for a set which gives the best fit between observed and simulated series has been found.

The model produces the following results:

- for each time-step a water balance of the different components of the hydrological cycle (runoff, actual evaporation, groundwater flow, ...) ;
- a graphical representation of observed and simulated values for a visual evaluation of the calibration ;
- numerical criteria for the evaluation of the quality of calibration.

Taking into account this information, the user then estimates whether to attempt a new optimization from another set of parameters. When both the numerical fitting criteria and the graphs for visual comparison are satisfactory, the user may consider which set of parameters are representative of the catchment as far as the obtained values are realistic. He may then test different values of the parameters around this solution, in order to determine the family of parameter values that are representative, i.e. acceptable from his point of view, of the water cycle (sensitivity study).

Limitation and specific difficulties in the simulation of piezometric levels

The model GARDENIA has been developed to simulate flows as well as piezometric levels indifferently: in fact, the hydrological scheme is the same; the level in the underground reservoir can be thought of as being linked to the piezometric level by a linear relationship irrespective of the type of the aquifer considered.

The storage coefficient then plays the role of an amplitude factor, like the surface area of the catchment in the case of the calculation of flows. Nevertheless, the simulations of levels involve very specific problems.

The storage coefficient is not known, not even in order of magnitude, whereas the surface area of catchment is generally known. In fact, it represents a coefficient of global influence of the fluctuations of a reserve on a particular piezometric level.

This coefficient of influence will only be equal to the average storage coefficient of the aquifer if the point of observation is located far away from any watercourse.

This coefficient cannot be linked easily to interpretations of pumping tests (whose validity remains local) and which are often carried out over short periods and can give a confined aquifer storage coefficient. The storage coefficient in GARDENIA corresponds more to level variations over periods that are much longer and the type of storage coefficient to be taken into consideration is that of an unconfined aquifer. Moreover, the storage coefficient in its traditional meaning is most frequently defined only with a precision far below 20 %, while deviations of 20 percent in the balance equation are difficult to accept.

In case of simulations of levels, the balance established should be interpreted as an analysis of the flux only with extreme care. Although this method of analysis may be a bit dangerous for



effective input estimations, it is often the only method available and it should thus not be rejected in advance.