



Deliverable x.2

PILOT DESCRIPTION AND ASSESSMENT

Kinda and Böda, Sweden

Authors and affiliation:

**Emil Fagerström, Johan Öhman,
Mattias Gustafsson, Ellen Walger**

Geological survey of Sweden

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



Deliverable Data	
Deliverable number	D2.4
Dissemination level	Public
Deliverable name	<i>Pilot description and assessment report for recharge and groundwater vulnerability</i>
Work package	WP4
Lead WP/Deliverable beneficiary	BRGM, BGS
Deliverable status	
Version	<i>Version 2</i>
Date	28/02/21

[This page has intentionally been left blank]

LIST OF ABBREVIATIONS & ACRONYMS

CC	Climate Change
GSOs	Geological Survey Organisations
TACTIC	Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies
HYPE	Hydrological Predictions for the Environment
SGU	The Geological Survey of Sweden
ET	evapotranspiration
NSE	Nash Sutcliffe Efficiency coefficient
ISIMIP	Inter Sectoral Impact Model Intercomparison Project
RCPs	Representative Concentration Pathways (development in greenhouse gas concentrations)
GCMs	Global Circulation Models
SMHI	the Swedish Meteorological and Hydrological Institute
TNO	Netherlands Organisation for Applied Scientific Research

TABLE OF CONTENTS

LIST OF ABBREVIATIONS & ACRONYMS	5
1 EXECUTIVE SUMMARY	5
2 INTRODUCTION	8
2.1 Background on TACTIC	8
2.2 Introduction to the pilot areas	9
3 PILOT AREAS	11
3.1 Site description and data for pilot Kinda	12
3.2 Site description and data for pilot Böda	13
3.3 Climate change challenge	16
4 METHODOLOGY	19
4.1 Methodology and climate data	19
4.1.1 HYPE	19
4.1.2 AquiMod	20
4.1.3 Metran	21
4.1.4 Climate data	22
4.2 Model set-up	25
4.2.1 Observation data	25
4.3 Model calibration	27
4.4 Uncertainty	29
5 RESULTS AND CONCLUSIONS	30
5.1 Historical recharge	30
5.2 Climate projections on recharge	32
6 REFERENCES	36
7 APPENDICES	38
Appendix A: AquiMod methodology	38
The soil moisture module	39
The unsaturated zone module	40
The saturated zone module	40
Limitations of the model	42
Model input and output	42
Appendix B: Metran methodology	43
Limitations	44
Time step	44
Model output	45
Model quality	45
Recharge	46

1 EXECUTIVE SUMMARY

As a partner of TACTIC WP4, the Geological Survey of Sweden (SGU) has studied groundwater-related effects from climate change in two pilot areas, Kinda and Böda (Table 1 and Table 2). The primary challenge regarding the future groundwater situation in these areas is the supply of drinking water. A specific challenge for Böda concerns peak consumption, related to tourism, which coincides with minimum groundwater storage at the end of the drought period. As such, model results were analysed from a drinking-water supply context, focusing on the delicate balance between recharge and drought periods that essentially determines if the groundwater, stored during winter recharge, is sufficient to last during the subsequent drought period.

Typically, groundwater resources in Sweden are found in the overburden regolith (soil thickness in the pilot areas: 0 to 10 m). Swedish groundwater resources are, depending on geology, divided into two groups: major and minor resources (Figure 1). Here the pilot Böda represents a major resource, while Kinda is taken to represent a minor resource. Effectively, the groundwater regime at Kinda exhibits strong seasonality, with snowmelt as a key component in recharge, compared to Böda, where, owing to its larger storage capacity, the regime is dominated by interannual variation.

Table 1. Summarized description of the Kinda pilot area

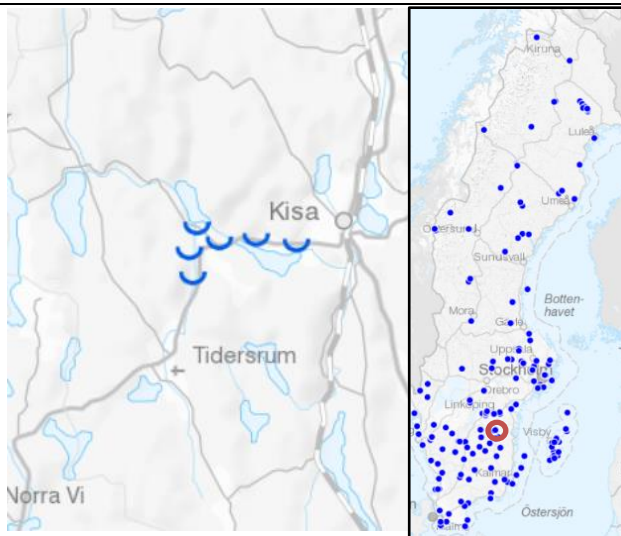
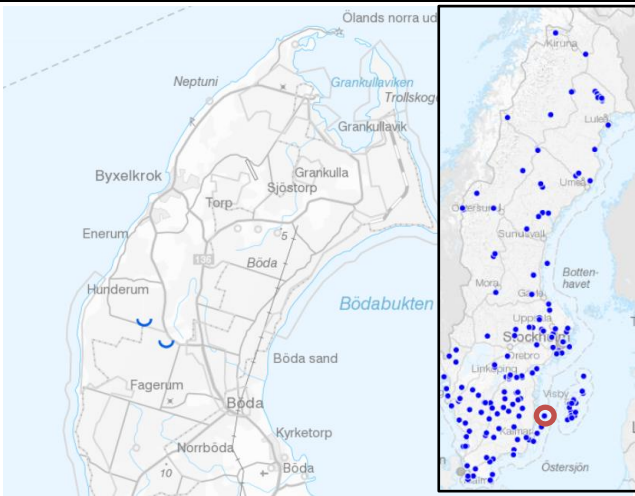
Pilot name	Kinda	
Country	Sweden	
EU-region	Northern europe	
Area (km ²)	2/40 km ² (area of groundwater body/catchment)	
Aquifer geology and type classification	Glacial sand and gravel deposits and till, Porous	
Primary water usage	Drinking water	
Main climate change issues	Future challenges with precipitation in the form of rain during winter (less snow) and longer summer periods with less recharge	
Models and methods used	Lumped-catchment modelling of time series (HYPE, Aquimod, Metran)	
Key stakeholders	SGU, municipality of Kisa, Region of Östergötland	
Contact person	Mattias Gustafsson, SGU, Mattias.gustafsson@sgu.se	

Table 2. Summarized description of the Böda pilot area

Pilot name	Böda	
Country	Sweden	
EU-region	Central and Eastern Europe	
Area (km ²)	26 km ²	
Aquifer geology and type classification	Glacial sand and gravel deposits, Porous	
Primary water usage	Drinking water	
Main climate change issues	Future challenges with more precipitation in winter (less snow) and longer summer periods with less recharge. The island of Öland has busy tourism during summertime, and the precipitation is low.	
Models and methods used	Lumped-catchment modelling of time series (HYPE, Aquimod, Metran)	
Key stakeholders	SGU, municipality of Borgholm, Region of Kalmar	
Contact person	Mattias Gustafsson, SGU, Mattias.gustafsson@sgu.se	

Three lumped precipitation-runoff models, HYPE, Aquimod, and Metran, were used to evaluate groundwater recharge in the two pilot areas. The models were first calibrated for a historic period, 1980 to 2010. Next, a selection of future climate scenarios (i.e., forcing data subject to climate change: P, T, and PET) was applied for the calibrated models, to project expected climate-change effects on the groundwater regime for the two pilot areas.

The TACTIC project employs four standard climate scenarios based on the Inter Sectoral Impact Model Inter-comparison Project (ISIMIP) that represent two stages of global annual mean warming (+1°C and +3°C), combined with two cases to cover the range of likely precipitation: Wet and Dry cases.

Although all three models could be reasonably well calibrated to the historic time period, Aquimod and Metran were suspected to fit for the wrong reasons (as they lack snow storage), and hence their climate-change projections were considered to be less reliable. Confidence in HYPE was, on the other hand, well-supported by field data, not only by standard performance measures as NSE, but also by: 1) a close resemblance in seasonal patterns and 2) an ongoing, climate-related, transition in groundwater regime (a widespread phenomenon in SGU's monitoring programme). Hence, the HYPE simulations are considered sufficiently reliable for assessing the current recharge situation, as well as future changes in groundwater regime, which is associated to stress for the drinking-water supply.



For the present-day situation, the simulated recharge agrees reasonably well with earlier estimates for both pilot areas. For climate-change projections, simulations re-produce a concerning pattern (consistent with both observed trends in field data and in earlier modelling), where the groundwater regime is shifting towards: 1) increased winter recharge, 2) retreating snowmelt, resulting in 3) an earlier and prolonged drought period. In turn, the prolonged drought period increases the stress on water resources, particularly during late summer when consumption peaks due to tourism.

Taken as an average of the Dry and Wet cases, the reduction in recharge is estimated to -15% for Kinda and -30% for Böda (results apply to both +1°C and +3°C warming). This study is consistent with earlier work and underpins the current understanding of future challenges for drinking-water supply, particularly along the south-eastern coast of Sweden (here exemplified by the Böda pilot area on Öland).

2 INTRODUCTION

2.1 Background on TACTIC

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>).

The following TACTIC activities have been defined to focus on specific 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).

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).

2.2 Introduction to the pilot areas

This report describes the work undertaken by the Swedish Geological Survey (SGU) as a part of TACTIC WP4 to calculate groundwater recharge at two locations, Kinda and Böda. The two pilots have been selected to represent two different types groundwater resources, which are typical for the supply of drinking water in Sweden. Sweden is dominated by crystalline bedrock where the porosity is considerably lower than it is in sedimentary rock. As the bedrock does not serve as drinking water aquifers (at least, in general), the groundwater resources are mainly found the regolith (overlying loose soil deposits). These groundwater resources are divided into two main types (Figure 1):

- **Major groundwater resources (Böda pilot area):** found in glaciofluvial eskers, typically abstracted via groundwater wells to supply municipal water works. The groundwater dynamics is dominated by interannual variation, with periodicity ranging from years to decades.
- **Minor groundwater resources (Kinda pilot area):** typically thin (few meters) till layer, typically abstracted via bedrock boreholes to supply private households in rural areas. The groundwater dynamics is dominated by flashy, intra-annual variation (strong seasonal pattern).

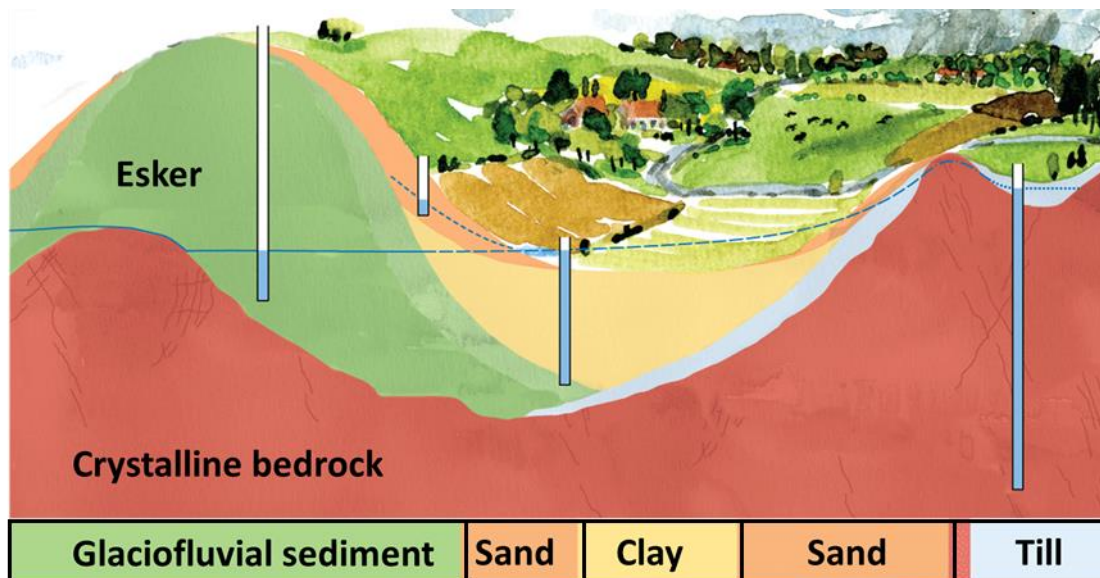


Figure 1. Conceptual figure illustrating the classification of Swedish groundwater resources: Major resources, illustrated by well in glaciofluvial esker (left, here represented by pilot Böda) and Minor resources, illustrated by drilled borehole dewatering thin layers of overlying till, sand or silt (right, here represented by pilot Kinda).

The work presented here is related to Task 4.3 with the aim to estimate of recharge under current and future climates. This is undertaken using multiple tools selected from the TACTIC toolbox (developed under WP2 of TACTIC). The toolbox is a collection of hydrogeological models, scripts, spreadsheets that serves all the activities identified in TACTIC workpackages.

Here, we use three lumped groundwater models: HYPE (Lindström et al., 2010), AquiMod (Mackay et al., 2014a and Mackay et al., 2014b), and the Transfer Function-Noise Model Metran (Zaadnoordijk et al., 2019). The modelling is undertaken in two steps. In the first step, the models are calibrated to reproduce the behaviour of the observed groundwater level time series, during the period 1980-2010. In the second step, the calibrated models are used to study future recharge by means of a simplified sensitivity analysis.

3 PILOT AREAS

Two pilot areas have been selected for the WP4 TACTIC project: Kinda and Böda. These pilot areas were selected to cover two aspects, which are considered key to understanding recharge under present and future climate conditions. The pilots are to represent:

- both the Swedish groundwater-resource types (Figure 1)
- the most critical climate challenges (Figure 8); as categorised by the Northern Europe and the Central-and-eastern Europe regions.

Furthermore, the pilot areas were also selected on the basis of modelling data quality and previous modelling experience on groundwater dynamics at the sites (using several lumped-catchment precipitation-runoff models, including Coup, HBV and HYPE).

Here, the Kinda pilot area is taken to represent a *minor groundwater resource* in the *Northern Europe region* (the dominant type of recharge area in Sweden, both under present and future conditions). It should be noted that, strictly speaking, the selected observation well at Kinda, ID 66_5, is classified as an *intermediate* groundwater resource; however, in comparison to the other Swedish pilot, Böda, it may well be taken to represent a minor groundwater resource.

The Böda pilot area is – on the other hand – taken to represent a contrasting situation: a *major groundwater resource* of the *Central-and-eastern Europe region* (the most important groundwater-resource type for municipal waterworks in Sweden, being stressed under present conditions). The area has busy tourism during summer, when the recharge is at its minimum.

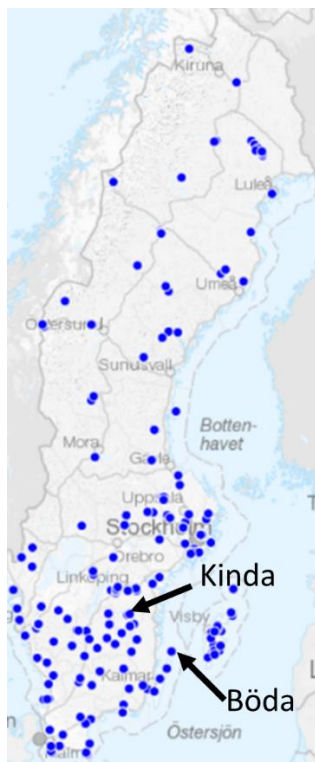


Figure 2. The location of the pilot areas Kinda and Böda in Sweden (blue dots marking SGU monitoring wells).



3.1 Site description and data for pilot Kinda

The Kinda pilot is an inland area located in the south of Sweden (Figure 2). The basin has an approximate area of 40 km² (Figure 3, left). There are several lakes and creeks in the area and they are surrounded with small soft surging hills and ridges of about 100 meters height. The area is located approx. 5 km west of a small town called Kisa, regional centre in the Municipality of Kinda, and the land use of the area is mainly forest and agricultural (Figure 3, right).

The groundwater resources for private wells in the area are formed by a patchwork of soil deposits (Figure 4; left), ranging from thin till layers to thicker glaciofluvial sand- and gravel deposits. The soil coverage (Figure 4; left) is characterised by a mosaic pattern, which is dominated by uncovered bedrock (red) and scattered areas of thin till layers (blue), which are interlaced with thicker esker-type sand and gravel deposits (green). The underlying bedrock (Figure 4; right) is of crystalline origin with limited storage capacity, which is why the overburden soil has such a prominent role for drinking-water supply.

The climate of the Kinda pilot area is of Boreal Northern European type, with a precipitation of approximately 700 mm/year and a potential evapotranspiration of 560 mm/year (P-PET = 140 mm/year). The groundwater recharge is largely limited by storage capacity in the soil deposits and has been estimated to 260 mm/year (Rodhe et al., 2006; Figure 7). The recharge is limited by low storage capacity in areas of uncovered bedrock and thin soil coverage (generally 0-5 m). The main water storages are found in sand and gravel deposits where the soil depth is up to about 20 m.

Precipitation and temperature data are available on daily basis since 1961-01-01 (provided via the Swedish Meteorological and Hydrological Institute, SMHI's PTHBV-raster at a resolution of 4 km). Forcing data for modelling can be downloaded from SMHI's webpage (<https://www.smhi.se/data/meteorologi/>). Potential evapotranspiration, PET, is calculated from temperature, based on an empirical relationship (Rodhe et al., 2006).

The groundwater level in the area is monitored in six wells, of which two are located in sand and gravel deposits and the remaining four are located in till. In this study, groundwater well 66_5 was used for modelling historic and future change in groundwater recharge. This particular well is located in a 4.5 m thick sand deposit, which is classified as an *intermediate* groundwater resource (i.e., falling between the two end points illustrated in Figure 1). The groundwater level has been measured manually twice a month since 1975-08-28, and daily since the installation of an automatic logger system in 2017-12-12. The groundwater time series can be downloaded from SGU's web page (<https://www.sgu.se/grundvatten/grundvattennivaer/matstationer/>).

There are no streamflow data available for the pilot area.

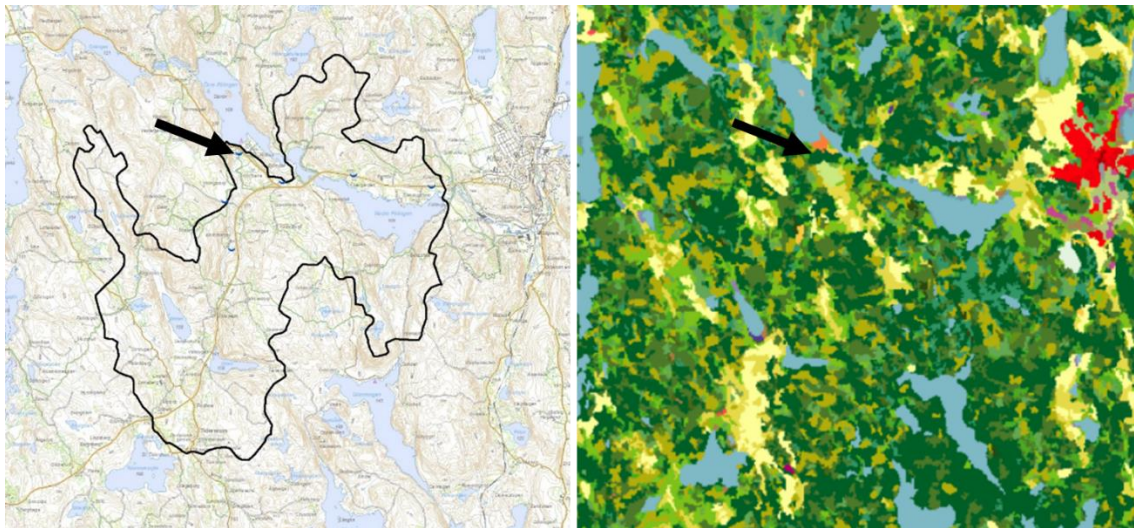


Figure 3. Catchment of the Kinda pilot area and land use (mainly forest and agricultural). Arrow marks the location of well 66_5.

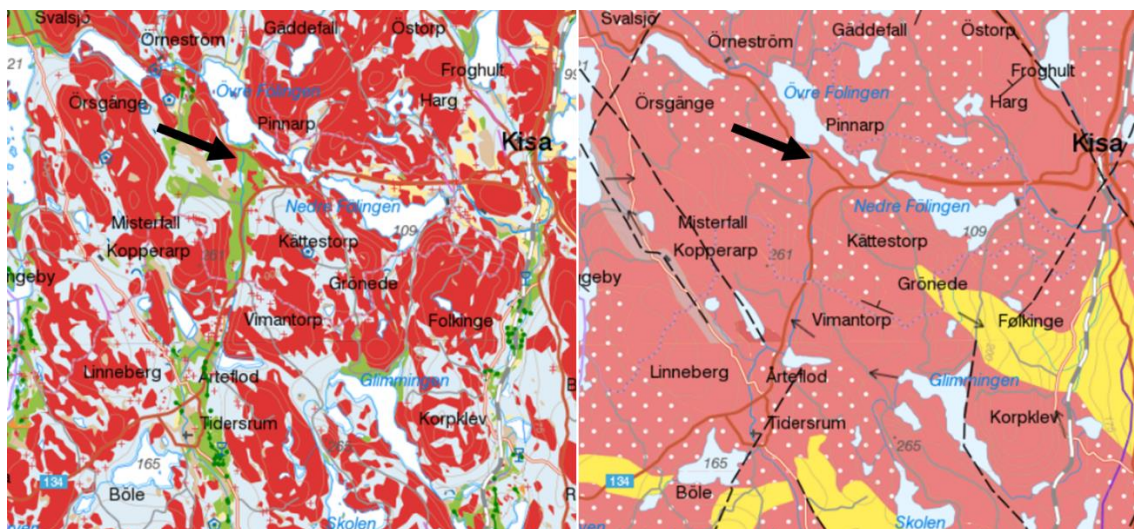


Figure 4. The soil coverage in the Kinda area (left) is a mosaic pattern of: till (blue), sand and gravel deposits (green), and clay (yellow), but soil layers are thin and the area is dominated by uncovered bedrock (red). The underlying bedrock (right) is dominated by granite (pink) and rhyolite (yellow).

3.2 Site description and data for pilot Böda

The Böda pilot is located on the island of Öland in the Baltic Sea, about 10 km east of the mainland of south-eastern Sweden (Figure 2). The climate is of Baltic-island Central and Eastern European type. The island extends c. 140 km in the north-south and 15 km in the east-western direction. The catchment area (coast to coast) is 26 km² and is characterised by a very flat topography, ranging from zero to about 20 meters above sea level, and a few small creeks. The pilot area is mainly covered by forest, with visible drainage trenches (Figure 5, left), but also some areas are also agricultural (Figure 5, right).



The soil coverage in the area is up to 10 m and is dominated by sand and gravel deposits (Figure 6, left), including a few isolated patches of till. The underlying bedrock is Ordovician limestone (Figure 6, right), and has been investigated with a large-scale geophysical airborne survey (SKY-TEM; Dahlqvist et al., 2018). As such, the constraining factor for recharge at Böda is quite different from that of Kinda; the recharge at Böda is not limited by the storage capacity of soil (as is the case for Kinda; Figure 7), but instead by its significantly lower precipitation (i.e., $PET > P$).

The precipitation is approximately 500 mm/year and the potential evapotranspiration is c. 600 mm/year. The groundwater recharge is approximately 150 mm/year (Rodhe et al., 2006; Figure 7). Precipitation is low during summer resulting in negligible recharge during the vegetation period. Moreover, the water balance is stressed during summer by the water consumption from tourism, which peaks during the dry period. Precipitation and temperature data are available on daily basis since 1961-01-01 (provided via the Swedish Meteorological and Hydrological Institute, SMHI's PTHBV-raster at a resolution of 4 km). Forcing data for modelling can be downloaded from SMHI's webpage (<https://www.smhi.se/data/meteorologi/>). Potential evapotranspiration, PET, is calculated from temperature, based on an empirical relationship established by Rodhe et al. (2006).

The groundwater level in the area is monitored in two active wells located in sand and gravel deposits (there are 14 more groundwater wells with data from 1968 to 1980). In this study, groundwater well 7_9 was used for modelling historic and future change in groundwater recharge. This particular well is located in a 10 m thick sand deposit, which is classified as a *major* groundwater resource (Figure 1). The groundwater level has been measured manually twice a month from 1968-05-28, and daily since the installation of an automatic logger system in 2016-04-26. The groundwater time series can be downloaded from SGU's web page (<https://www.sgu.se/grundvatten/grundvattennivaer/matstationer/>).

There are no streamflow data available for the pilot area.

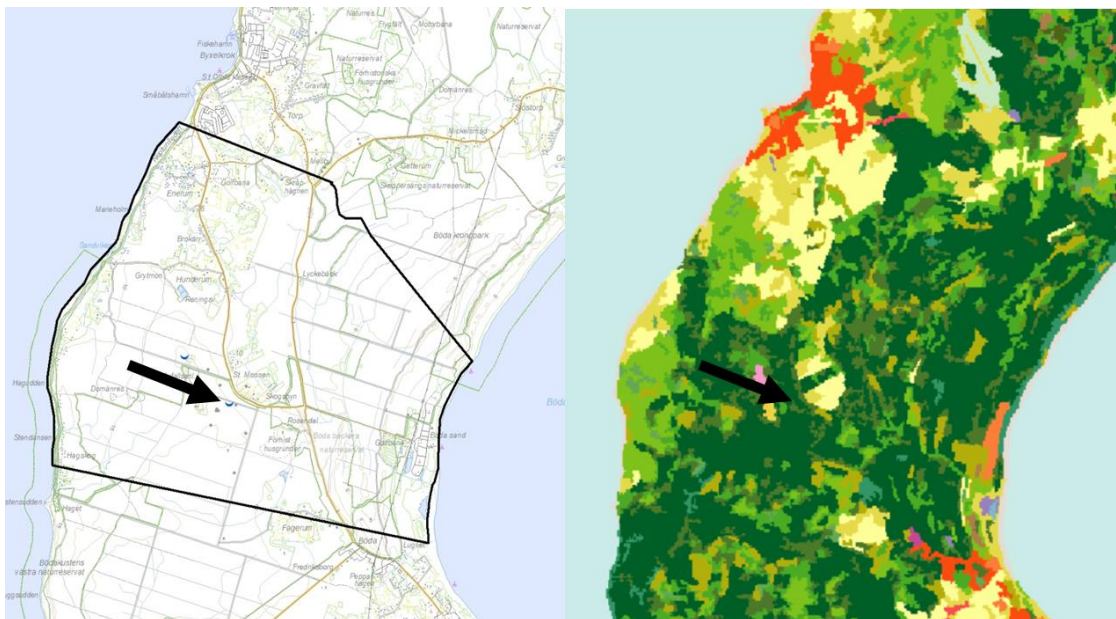


Figure 5. Catchment of the Boda pilot area, c. 6 km wide coast to coast (left), and land use (right), mainly forest (dark green), but also agricultural (yellow). Arrow marks the location of well 7_9.

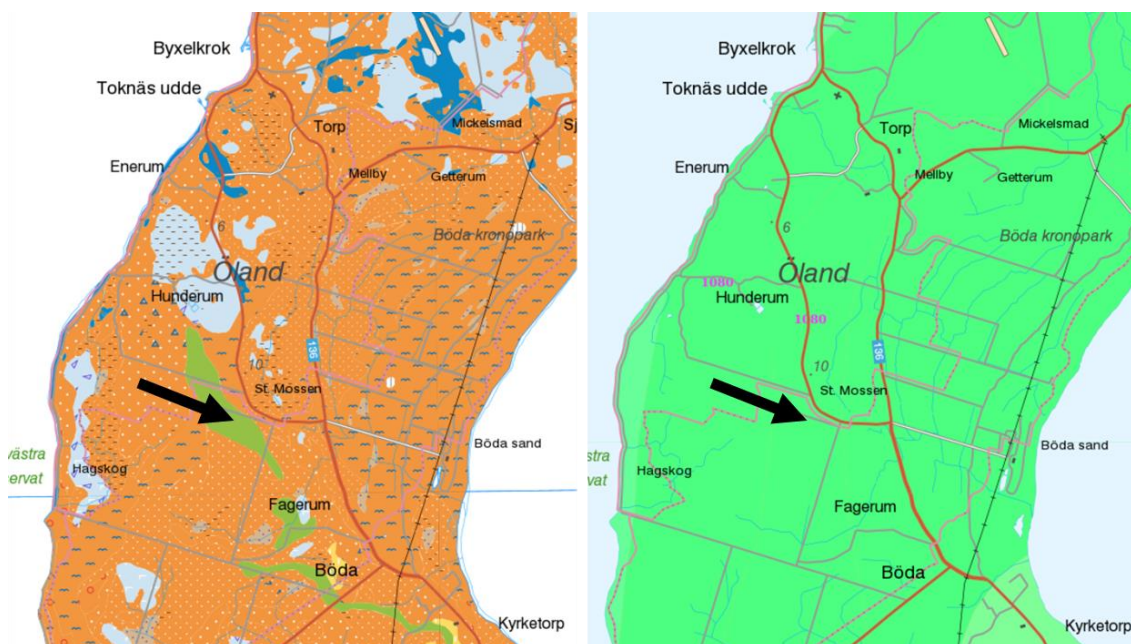


Figure 6. The dominant soil type in the Boda area (left) is sand (orange) with streaks of glacial sand- and gravel deposits (green), and patches of till (light blue). The underlying bedrock (right) is Ordovician limestone (green). Arrow marks the location of well 7_9.

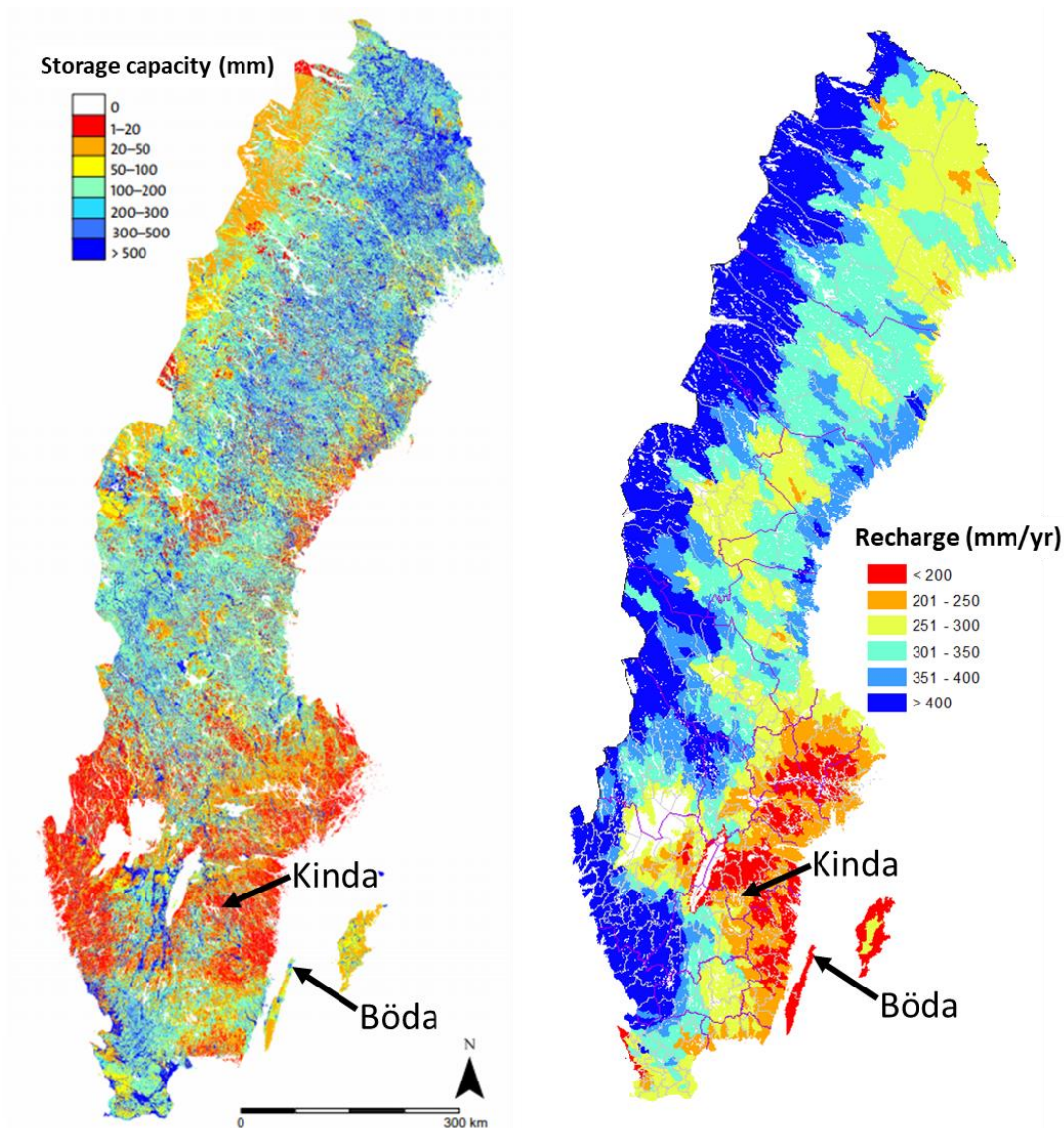


Figure 7. National maps of storage capacity (left) and recharge (right) available for Sweden. The glaciﬂuvial deposits at Böda has high storage capacity (c. 400 mm) compared to the thin soil cover at Kinda (c. 20 – 100 mm).

3.3 Climate change challenge

The expected consequences that climate change (CC) has on society depends, among other factors, on geographical location. The geographical diversity in expected CC challenges is illustrated in a generalised map over EU (Figure 8). The two Swedish pilot areas fall into different regions, indicating that somewhat different CC challenges are to be expected in future; Kinda belongs to the Northern-Europe region, while Böda belongs to the Central and eastern Europe region (Figure 8).



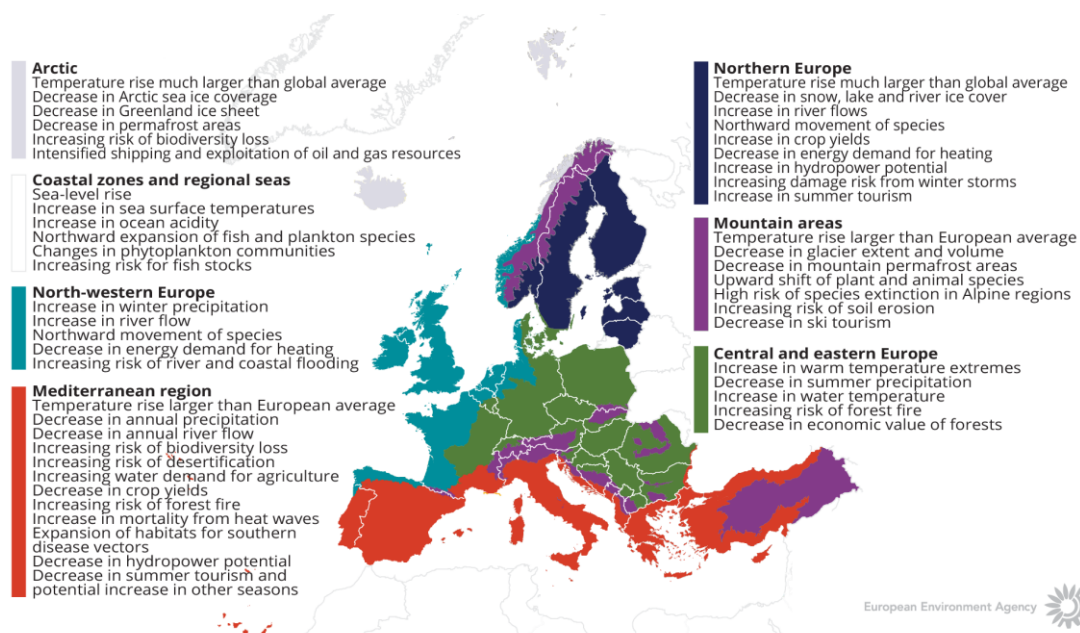


Figure 8. General expected climate challenges in different EU-regions.

As such, the main future CC changes, relevant to drinking-water supply, are:

- **Warmer winters:** precipitation falling as rain (less snow storage, causing less groundwater recharge during spring, and in turn less significance of maximum infiltration rate during snowmelt)
- **Longer summer period** (or vegetation period, during which recharge is negligible): longer drought, or at least longer groundwater recession period, with additional stress on storage capacity to last longer period.
- **Less summer precipitation:** may increase the need of irrigation, additionally stressing storage capacity during summer
- **Increased tourism:** increased water consumption, additionally stressing storage capacity during summer

In particular for Böda, groundwater resources are already under strain during the summer, due to limited recharge and storage capacity combined with peaking consumption (tourism). Expected consequences are longer periods of shortage in water supply, resulting in salt-water intrusion into drinking-water wells from the Baltic Sea.

The recharge for pilot areas Böda and Kinda is expected to follow the typical pattern for south-eastern Sweden. In effect, the recharge is expected to decline c. -10% to -15% at Böda and Kinda, respectively (Figure 9), which might cause shortage of drinking water and saltwater intrusion (i.e., at least for borehole wells).

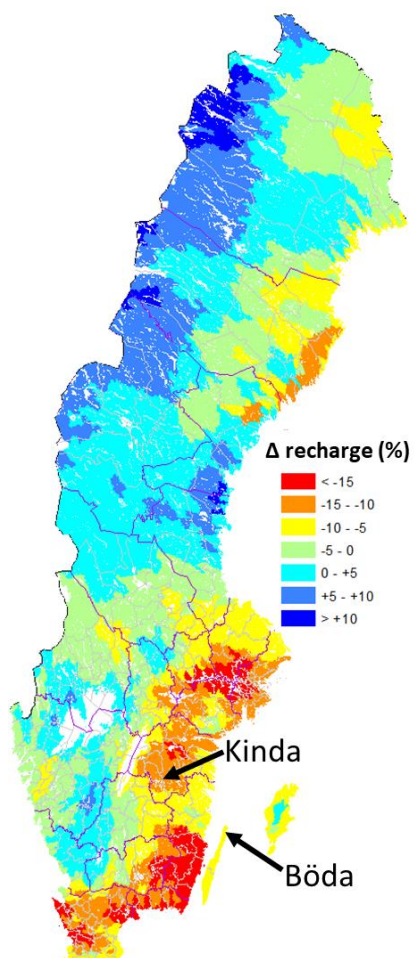


Figure 9. Existing modelling indicates decreasing groundwater recharge at Kinda and Böda, ranging from -5% to -15% (scenario SRES A1b, corresponding to RCP4.5; modified from Rodhe et al., 2009).

4 METHODOLOGY

Climate change impacts on recharge is assessed for the two Swedish pilot areas, based on the TACTIC standard climate change scenarios and two lumped models: HYPE and AQUIMOD. The transfer noise model, METRAN, is also calibrated to measured groundwater data for the two pilots.

4.1 Methodology and climate data

4.1.1 HYPE

In essence, the Hydrological Predictions for the Environment model (HYPE) originates from the lumped-model concept, describing precipitation and runoff at catchment scale, e.g., the classical HBV model (Bergström et al., 1976). However, one of the many strengths of HYPE is its wide flexibility in setup, offering complex semi-distributed setups; for example, national-scale simulation of surface water flow and nutrient fluxes, from precipitation and via various storage compartments on its way towards the sea (Lindström et al., 2010). The model code is open source and offers a range of descriptions to hydrological processes in interconnected sub-basins. An implication of the lumped concept is that its algorithms are not strictly based on physical laws but are instead formulated on a more conceptual basis. The model can be set up in a multi-basin manner to simulate flow paths in the landscape at a high spatial resolution. Moreover, the model can be calibrated or evaluated against various types of measurements, e.g., river flow or groundwater levels. The model was initiated in 2003, applied on national scale for Sweden in 2008, and finally for the entire globe (e.g., Arheimer et al., 2019).

This study employs HYPE in its most basic setup (details at: <http://www.smhi.net/hype/wiki/>), namely groundwater level modelling as a standalone point-observation. In terms of modelled groundwater levels, the Böda model is representative of the glaciofluvial deposits in the area, whereas the Kinda model representativeness is limited to the immediate surroundings of the observation well. The modelled CC effects, on the other hand, are assumed to be representative of Major and Minor groundwater resources at wider geographical area (as expressed in relative terms of change). The model uses precipitation, P mm/day, and temperature, T °C, as forcing data and is run at a daily time step. Potential evapotranspiration, PET mm/day, is not treated as forcing data (i.e., not used as model input), but is instead calculated from temperature and season (based on a set of pre-determined model parameters that have been calibrated on national scale for the water balance for > 100 large catchments).

The many model options offered combined with the open-source code, leads to branching of purpose-specific HYPE versions; the version in this study was developed by SGU to address specific processes relevant to groundwater modelling (such as delayed percolation, capillary rise, and recharge calculation). Like most precipitation-runoff models the soil horizon in HYPE is typically divided into three conceptual soil boxes holding and exchanging soil water. Depending on seasonal variation in water content, the groundwater table is allowed to vary freely between these three boxes (however, underlying soil boxes must be fully saturated). Recharge is calculated as percolation (mm/day) reaching the soil box that currently holds the groundwater table (i.e., percolating soil water that adds to the groundwater table).



Two main differences against Aquimod can be noted: 1) HYPE allows snow-cover storage during wintertime and 2) HYPE allows the groundwater level to reach ground surface (i.e., does not assume an unsaturated zone, for example during snow melt). HYPE offers a range of calibration methods and performance measures; in this study we calibrated the model to observed groundwater data in a Monte Carlo approach to maximise the Nash Sutcliffe Efficiency (NSE) performance measure.

4.1.2 *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, P mm/day, and potential evapotranspiration, PET mm/day, as forcing data. In this study, PET was precalculated based on the empirical relationship defined for HYPE. 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.



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 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, 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°x0.5°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 occur varies between the scenarios.
4. To represent conditions of low/high precipitation (referred to as Dry and Wet), 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 (Table 3). 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 ($\times\Delta P$ and $\times\Delta PET$) or by an additive factor ($+\Delta T$).
6. Delta change factors were applied to local climate data by which the local particularities are reflected also for future conditions.

Table 3. RCP-GCM combinations to assess future climate in the Kinda and Böda pilot areas

Scenario		RCP	GCM
+1 °C	“Dry”	noresm1-m	rcp4p5
	“Wet”	gfdl-esm2m	rcp4p5
+3 °C	“Dry”	hadgem2-es	rcp6p0
	“Wet”	miroc-esm-chem	rcp8p5

The “Dry” and “Wet” cases are selected to cover the likely span of precipitation on annual basis; thus, no consideration is taken to if the precipitation falls under typical recharge seasons, or



not). In fact, the largest differences between the Wet and Dry cases occur during summer months (Figure 10), a period during which most precipitation is lost as evapotranspiration without contribution to groundwater recharge. This implies that precipitation range spanned by Dry and Wet cases, *defined on annual basis*, does not necessarily cover the full uncertainty range for recharge. In particular, it can be noted that the precipitation in the “+1 °C Wet” scenario falls below its current value (i.e., $\times\Delta P < 1$) during three “typical recharge months”: March, September and October (Table 4). Note also that, for individual months, the relation between Dry and Wet cases may in fact be reversed; for example, the October precipitation in the “+1 °C, Dry” case exceeds the “Wet” case by some +15%. Note also that the “Dry” cases have only 3% lower precipitation, while the “Wet” cases have 9% and 21% higher precipitation for the +1°C and +3°C cases, respectively.

The provided correction factor for PET was not used in modelling of the Swedish pilots. The reason for this is that the temperature increase in CC scenarios (+ ΔT) reduces the number of days below freezing in wintertime (i.e., when PET = 0), which is not well-represented by a multiplication factor for PET. Instead, PET was re-calculated based on the future temperature (+ ΔT) and the established empirical Swedish relationship between T and PET. This way, increasing evaporation wintertime, during periods which are currently below freezing, could be accounted for (Figure 10). Moreover, the cases +1 °C Wet and +3 °C Wet have average temperature increases of 2.5°C and 3.4°C during winter, which is expected to have a drastic impact on the groundwater regime (snowmelt-induced recharge).

Table 4. Temperature and precipitation* correction factors in CC scenarios for Kinda and Böda

scenario	Temperature additive factor + ΔT				Precipitation multiplication factor $\times\Delta P$			
	+1 °C		+3 °C		+1 °C		+3 °C	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Jan	0.56	3.44	2.38	3.35	1	1.18	1.25	1.31
Feb	1.01	2.13	2.02	3.77	1	1.07	0.98	1.33
Mar	1.41	1.6	2.01	3.09	0.87	0.92	1.03	1.04
Apr	1.5	1.39	2.94	3.38	0.98	1.15	0.99	0.92
May	1.53	1.29	3.14	3.2	0.98	1.14	0.7	1
Jun	1.06	0.97	3.35	3.24	0.98	1.1	0.79	1.08
Jul	1.77	1.06	2.73	3	0.87	1.12	0.96	1.45
Aug	1.11	1.28	2.86	3.07	0.81	1.18	0.75	1.33
Sep	1.2	1.12	2.79	2.97	1.01	0.98	0.86	1.27
Oct	0.54	1.42	3.07	2.37	1.14	0.99	0.98	1.3
Nov	0.6	1.73	1.73	3.2	1.02	1.08	1.2	1.25
Dec	1.17	1.99	2.75	3.03	0.99	1.11	1.17	1.22

* Precipitation change pronounced by colouring: blue indicates lower than the current situation and red indicates future increase.

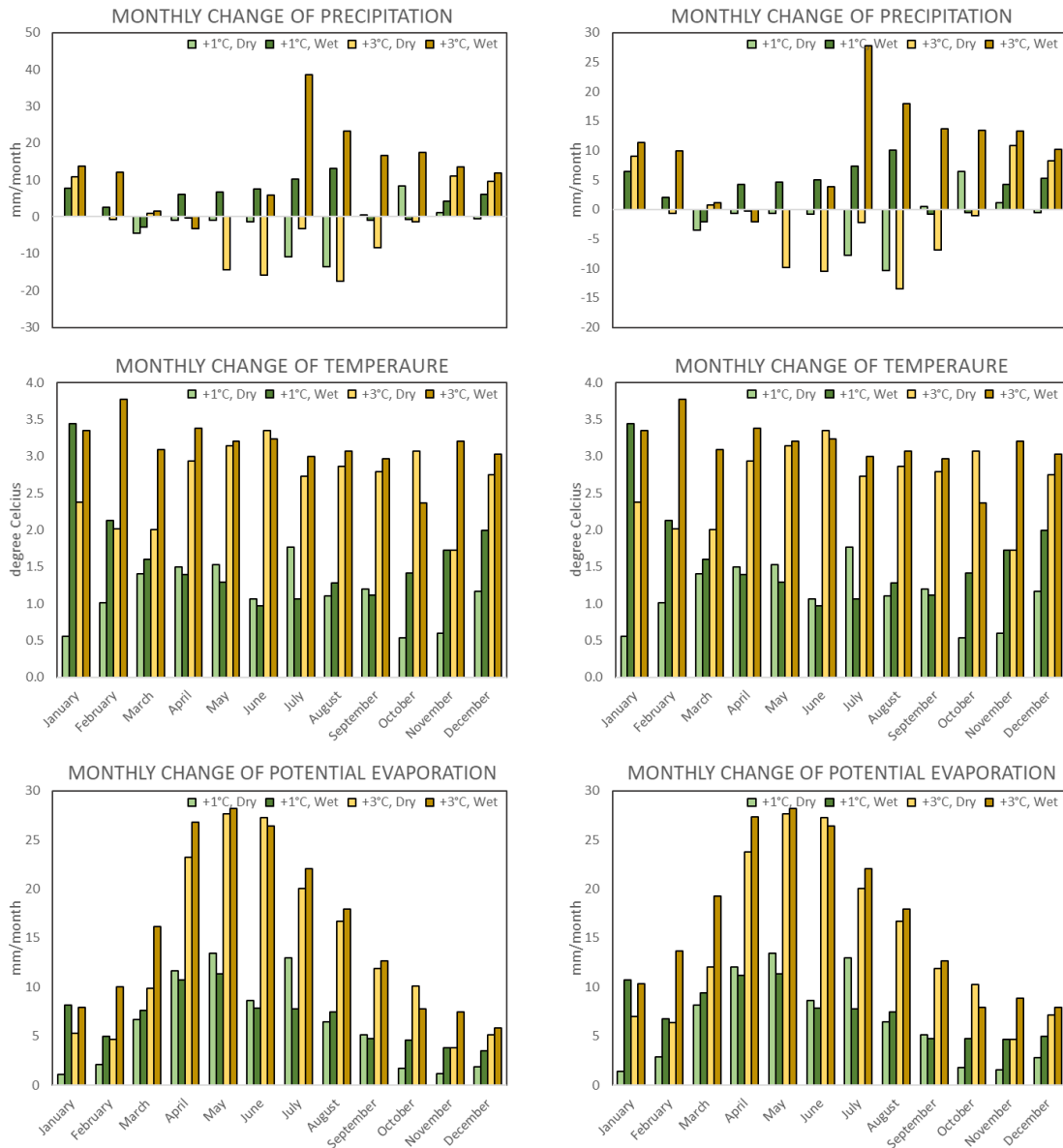


Figure 10. Climate effect on forcing data for TACTIC standard scenarios. Kinda (left) and Böda (right). Note that monthly change in PET does not reflect the provided multiplication factor ($\times \Delta \text{PET}$), but re-calculated values using the established empirical relationship for $(T + \Delta T)$. Note that, although the CC effects on P and PET differ somewhat between the pilots, the change in T is identical.

4.2 Model set-up

The three models HYPE, Aquimod, and Metran were setup as independent point models for the wells 66_5, at Kinda, and 7_9, at Böda (i.e., without claiming to represent the entire pilot area). The Metran modelling was undertaken by the Dutch TACTIC partner TNO, and hence not described here.

HYPE and Aquimod were calibrated in a Monte-Carlo approach to find the best set of parameters that can reproduce groundwater observations based on local time series of forcing data at a daily time step (i.e., precipitation, temperature, and/or potential evapotranspiration). Due to the lack of streamflow data for the two pilots, the model calibration is constrained by groundwater-level data, alone. This implies that water balance at catchment scale is neglected, and in turn, that the magnitude in simulated recharge is unconstrained. However, this difficulty is partly circumvented by relying on an established empirical relationship for calculating PET based on T (determined by Rodhe et al., 2006). The authors established this relationship in a national-scale calibration, involving the water balance for a large number of catchments (several hundreds). Thus, the use of the empirical relationship is assumed to compensate the lack of site-specific constraining streamflow data and to provide realistic magnitudes of recharge.

HYPE allows several inbuilt model options for the calculation of PET, of which one possibility is the aforementioned empirical PET relationship. Both Aquimod and Metran use PET as forcing data (PET is not available as measured observations); thus, to enhance consistent input data between the models, PET for Aquimod and Metran was calculated as daily forcing data using the same empirical relationship as used in HYPE (Rodhe et al., 2006).

4.2.1 Observation data

The forcing data (precipitation and potential evapotranspiration) and calibration targets (groundwater levels) are presented in Figure 11 and Figure 12, for Kinda and Böda, respectively.

The models were run from the starting point of forcing data, 1961-01-01 (i.e., allowing 20 years of warm up period). The calibration applied the full period of available groundwater data, 1975-2018 and 1968-2018, respectively (Sections 3.1 and 3.2); however, for consistency in the TACTIC project, model performance is presented only for the period 1980 – 2010 (e.g., Table 5). To avoid calibration bias to periods of high data measurement frequency (i.e., overwhelming amounts of conditional data during the period of logger recording), the excessive data during the logger-measuring period was reduced for application in Aquimod (to compensate for inbuilt feature in HYPE).

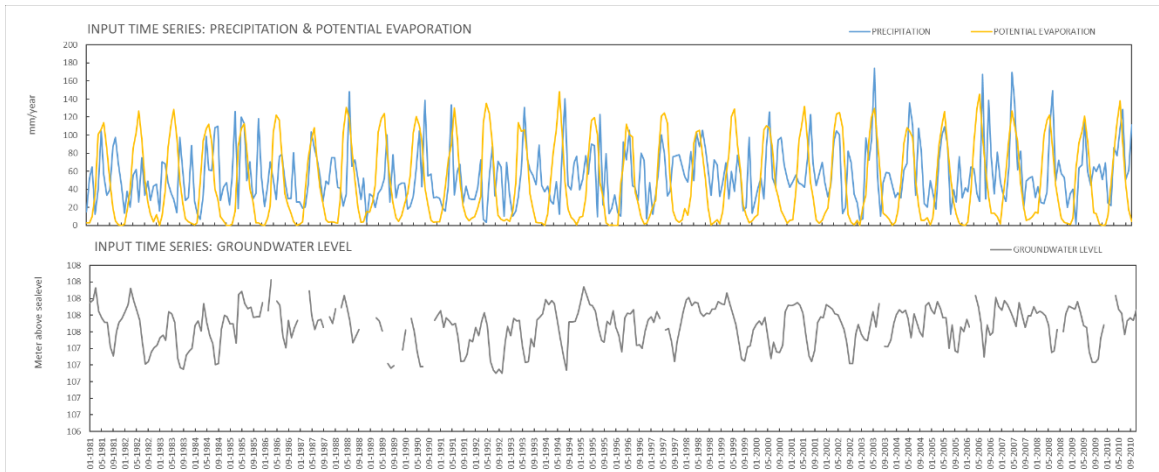


Figure 11. Daily time series of forcing data, P and PET (mm/year), as well as the calibration target groundwater table fluctuation at Kinda (time period 1980 to 2010).

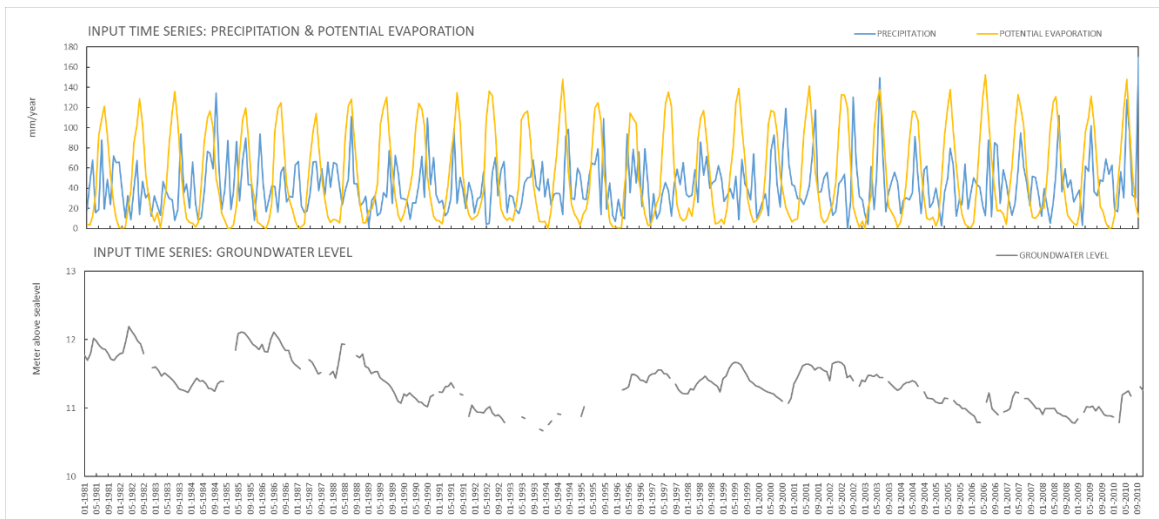


Figure 12. Daily time series of forcing data, P and PET (mm/year), as well as the calibration target groundwater table fluctuation at Böda (time period 1980 to 2010).

For both pilots, the key recharge periods occur in spring and autumn, when temperature is sufficiently low to hamper evapotranspiration, but still above freezing, to allow percolation from rain or melting snow. The two recharge periods can be described as (Figure 13):

- March/April: snowmelt with low evapotranspiration (just before the vegetation period)
- September/October: falling evapotranspiration, precipitation still in form of rain (just after the vegetation period)

As described earlier, the snow-melt induced recharge at Kinda is limited by storage capacity and infiltration rate, whereas the recharge at Böda is more limited by the low net precipitation. Aquimod does not feature snow-cover storage, and hence does not reproduce the recharge peak associated to snowmelt; this is a limitation in describing recharge for Swedish conditions.



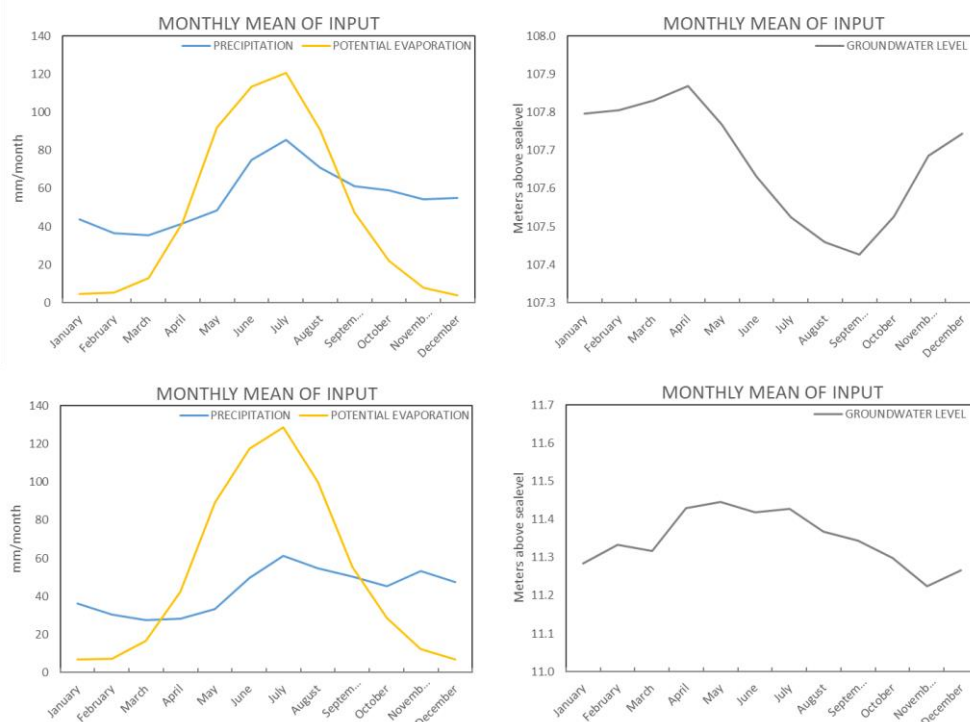


Figure 13. Seasonal patterns in forcing data, P and PET, as well as groundwater regime (time period 1980 to 2010). Kinda (above) has a strong seasonal pattern, with groundwater levels peaking at snowmelt, whereas the seasonality pattern is weak at Böda (below), whereas long-term periodicity spans over decades (Figure 12).

4.3 Model calibration

All three models are reasonably well calibrated to the groundwater data (Table 5). As the exception, Aquimod provides a notably poorer calibration for Kinda, NSE = 0.59. This poorer fit is associated to the significant role that snowmelt has for the seasonal patterns at Kinda (Figure 15, left), as the snowmelt phenomenon is not featured in Aquimod. The snowmelt peak is less pronounced at Böda, and consequently, all three models perform more or less equally well. In fact, HYPE even overestimates the recharge somewhat during the snowmelt period; however, it is unclear if this implies overestimation of the snowmelt phenomenon, or if the percolation delay is underestimated (Figure 15, right). Moreover, parts of the long-term periodicity at Böda can be captured, whereas the period 1996-2000 is poorly captured by both models (Figure 14). This period could be fitted in Metran, but at the expense of a poor fit during the 1980's. This signifies that a component of this long-term periodicity cannot be captured by our lumped model concepts or the forcing data used. For example, it may reflect some type of external disturbance, such as change in land use (clearcutting a forest, maintenance restoration of drainage trenches) or periods of groundwater abstraction.



Table 5. Model performances for the historic period 1980-2010

		Kinda			Böda		
		HYPE	Aquimod	Metran	HYPE	Aquimod	Metran
Nash Sutcliffe efficiency	NSE	0.81	0.59	0.83	0.67	0.61	0.62
Root mean square error	RMSE	0.1	0.16	0.1	0.19	0.21	0.2
Mean error	ME	0.04	0.02		0.10	0.09	

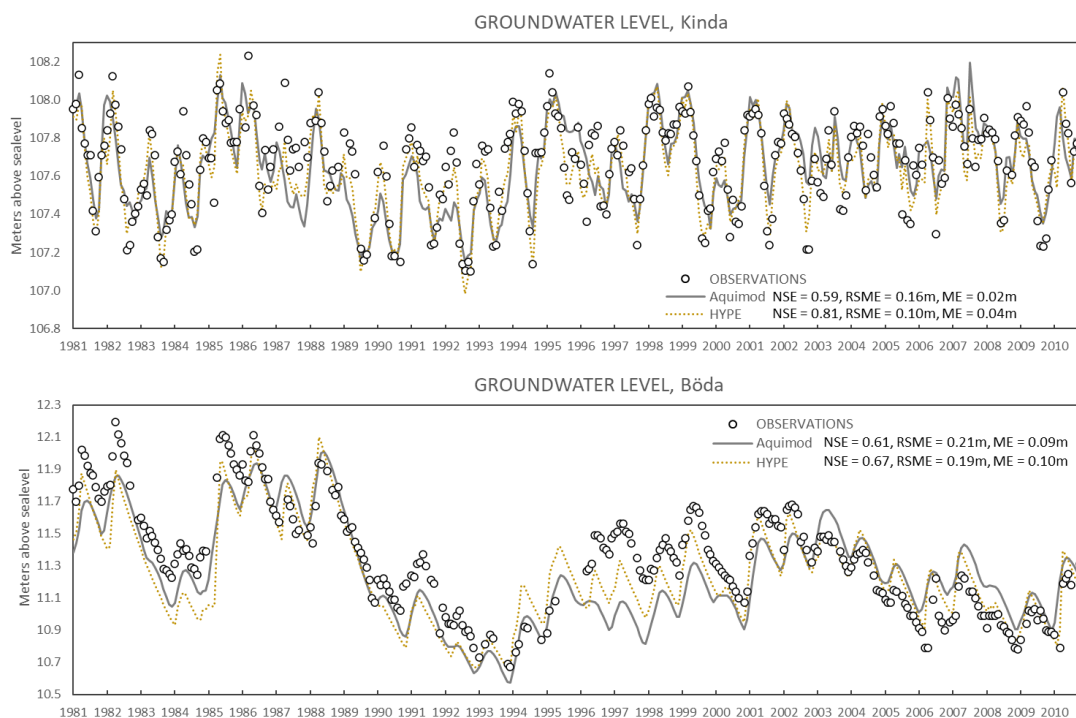


Figure 14. Model calibration for the historical time period 1980 to 2010; Kinda (upper) and Böda (lower). Aquimod (solid lines) compared to HYPE (dashed lines).

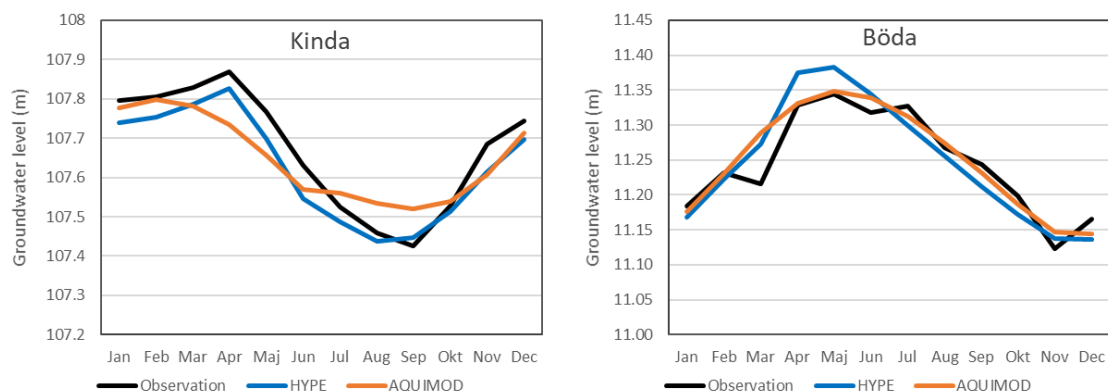


Figure 15. Simulated groundwater seasonality during historical time period, 1980 to 2010.

4.4 Uncertainty

The dominating uncertainty in the calibrated models is the lacking constraint on water balance on catchment scale (Section 4.2). At least for Böda, a substantial amount of discharge may also occur as underground groundwater flow into the Baltic sea.

A typical problem in lumped models is that of equifinality due to linearly dependent parameters. The impact of uncertainty in model parameterisation in predictive modelling can be quantified in a stochastic onset (e.g., evaluating the range of predictions arising from an ensemble of equally likely parameterisation combinations). Both HYPE and Aquimod offers the possibility to quantify the uncertainty in model parameterisation in simulations. That is: during the calibration phase, all parameterisation combinations that reproduce the calibration target (groundwater time series) sufficiently well (meet a defined by e.g., NSE-criterion), are stored to define the span of parameterisation uncertainty. In the second phase, all the members in the ensemble of equally likely parameter combinations are used in predictive simulation, to evaluate the effect that model uncertainty has in simulated results. A drawback of this stochastic approach is that it requires management of results from multiple realisations, which may complicate the sensitivity analysis of CC projections. It was therefore decided not to evaluate this model uncertainty, and instead focus on the best-fitted model in CC projections.

5 RESULTS AND CONCLUSIONS

5.1 Historical recharge

The recharge, as estimated with the three models, is compared against the established national estimates for Sweden (Figure 7, right). The HYPE results agree well with the existing estimates by Rodhe et al., 2006 (Table 6 and Figure 16); however, this agreement partly rests on circular evidence, as both values are intimately related to the established PET relationship (Rodhe et al., 2006). Bearing in mind Aquimod's lower NSE for Kinda, which has been associated to its lack of snowmelt model (Table 5), its discrepancy in simulated recharge is to be expected (Table 6). It can also be noted that the simulated recharge for Kinda (and consequently also runoff) is systematically higher in Aquimod (Figure 18). This suggests a higher percolation in Aquimod, with a lesser fraction of the PET (provided as forcing data) actually lost as ET from the root zone, compared to HYPE. Again, this highlights that the assumed water balance, associated to the empirical PET relationship, is probably more valid for HYPE, than it is for Aquimod. It is somewhat surprising that Metran provides the lowest estimate for Kinda, as the reported value refers to potential recharge (i.e., an upper estimate for actual recharge).

HYPE and Aquimod provides fairly similar recharge estimates for Böda, which are somewhat below the existing estimate, whereas Metran stands out with a significantly higher estimate. A clear difference can be observed between the simulated recharge patterns at Böda, with spiky peaks in HYPE compared to the dampened pulses in Aquimod (Figure 17).

The concern, whether this suggests an overestimation of the snowmelt phenomenon at Böda, or if its percolation delay is underestimated in HYPE was raised in Section 4.3 (Figure 15, right). It should be noted that this type of delayed percolation pulses can also be simulated with HYPE, although such a model parameterisation was not optimised in the Monte Carlo simulations. This suggests linear dependency in parameters, which may cause optimization to be trapped in local performance maxima. There are numerical schemes to escape such local optima (e.g., simulated annealing), or the optimization can simply be manually restarted with other initial settings.

In hindsight, this demonstrates the benefit of addressing model uncertainty by means of a stochastic onset in model parameterisation (Section 4.4).

Table 6. Estimated recharge (mm/year), period 1980-2010 (compared to Rodhe et al., 2006)

Kinda				Böda			
Existing estimate ²⁾	HYPE ²⁾	Aquimod ³⁾	Metran ¹⁾	Existing estimate ²⁾	HYPE ²⁾	Aquimod ³⁾	Metran ¹⁾
260	239	344	217	150	119	105	237

1) Potential recharge: Water that leaves the root zone

2) Actual recharge GWT: Water reaching the phreatic groundwater table

3) Actual recharge GWA: Water reaching a groundwater aquifer (non-phreatic)



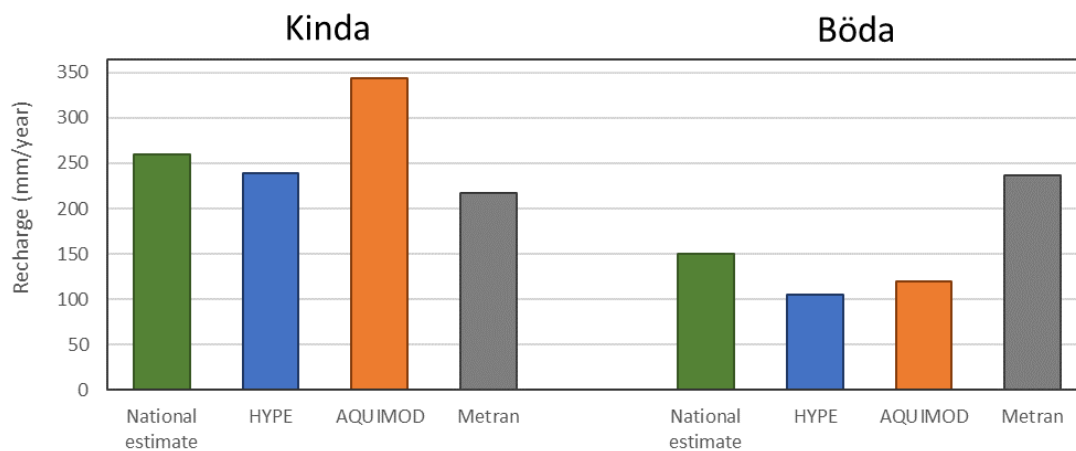


Figure 16. Simulated recharge during historical time period, 1980 to 2010, compared to existing estimates by Rodhe et al. (2006; Figure 7).

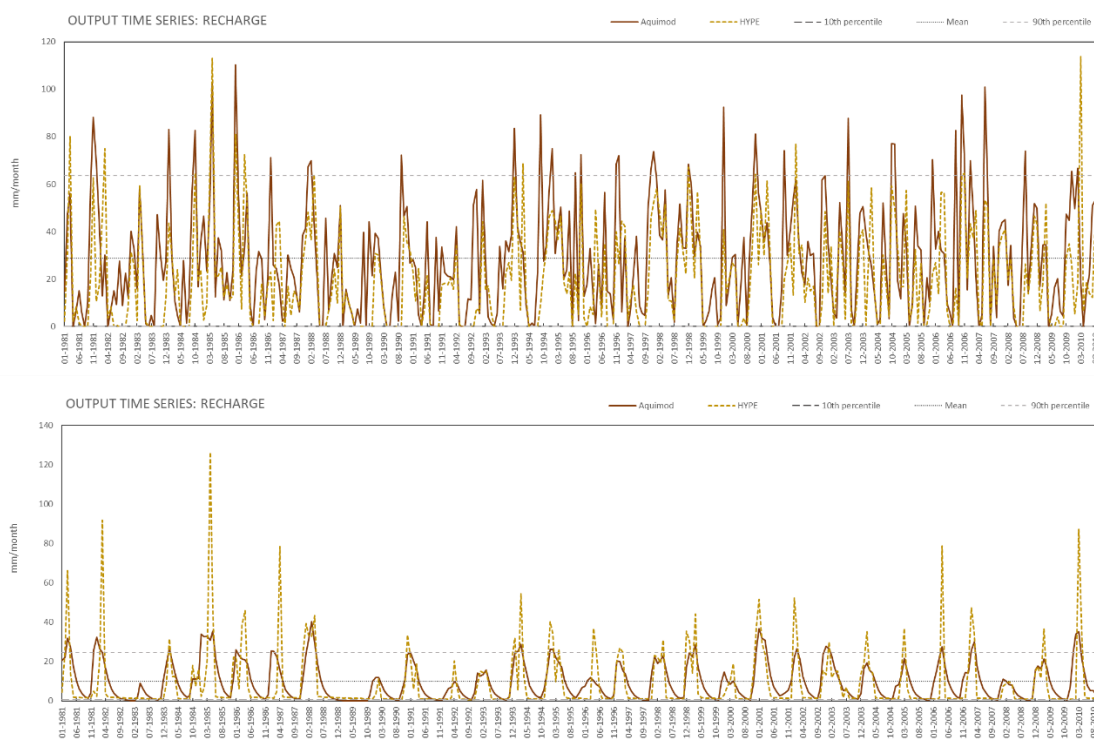


Figure 17. Simulated recharge during historical time period, 1980 to 2010, for Kinda (upper) and Böda (lower). Aquimod (solid lines) compared to HYPE (dashed lines).

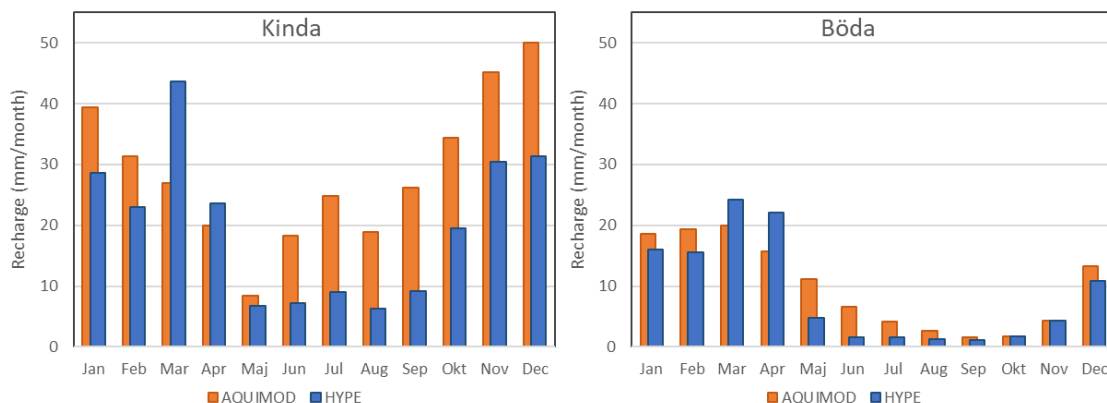


Figure 18. Seasonal patterns in simulated recharge during historical time period, 1980 to 2010.

5.2 Climate projections on recharge

The climate-change effects on groundwater regimes at Kinda and Böda are projected as a sensitivity analysis of modified forcing data (Table 4); here, the analysed cases are temperature scenarios +1°C and +3°C, combined with Dry and Wet cases (i.e., minimum/maximum precipitation, as explained in Section 4.1.4). The modelled CC projections are analysed separately for the pilots Kinda and Böda, based on the outcome of both HYPE and Aquimod.

The main climate-change effect projected for Kinda is associated to the gradual retreat of snowmelt (Figure 19). The projected outcome is in accordance with expectations (Section 3.3): mild winters imply an increasing number of winter days with temperature above freezing, which allows percolation, either from precipitation in the form of rain, or from temporarily melting snow cover. This increasing recharge during winter months occurs at the expense of less snow accumulation, and in turn less snowmelt-induced recharge in spring. In effect, mild winters shifts the seasonal pattern in recharge from a spring peak to a gradual increase wintertime.

Now, the role of snowmelt for the groundwater regime at Kinda pinpoints the need to capture the dominant system processes for obtaining realistic future projections (i.e., here: snow accumulation). In this situation, HYPE is evidently the better-suited tool. In visual comparison between the two models (Figure 19), HYPE clearly provides a more coherent outcome of the analysed cases. The impact of warmer winters on the groundwater regime (i.e., seasonal pattern) is systematic and independent of change in precipitation, ΔP (i.e., both Dry and Wet cases demonstrate the same change).

The projected change in groundwater regime, with more winter recharge (November through February) followed by less spring/summer recharge (March to June), implies an earlier onset of the drought period (period of falling groundwater levels), which – in effect – prolongs the duration of the drought period and hence resulting in deeper groundwater levels during summer/autumn. This model result is consistent both with field observations and previously modelling of altered groundwater regimes (Vikberg et al., 2015).

Albeit a bit more erratic in appearance, the Aquimod simulations do support the observations made for the HYPE climate-change projections: the projected recharge is clearly lower in the



spring/summer period (March to May), which advances the onset of the drought period to an earlier date. However, in Aquimod simulations the prolonged drought period does not automatically lead to deeper groundwater levels (i.e., within the precipitation uncertainty spanned by the Wet and Dry cases). The reason for this is that the summer recharge is notably higher in Aquimod, which can be disregarded as less realistic.

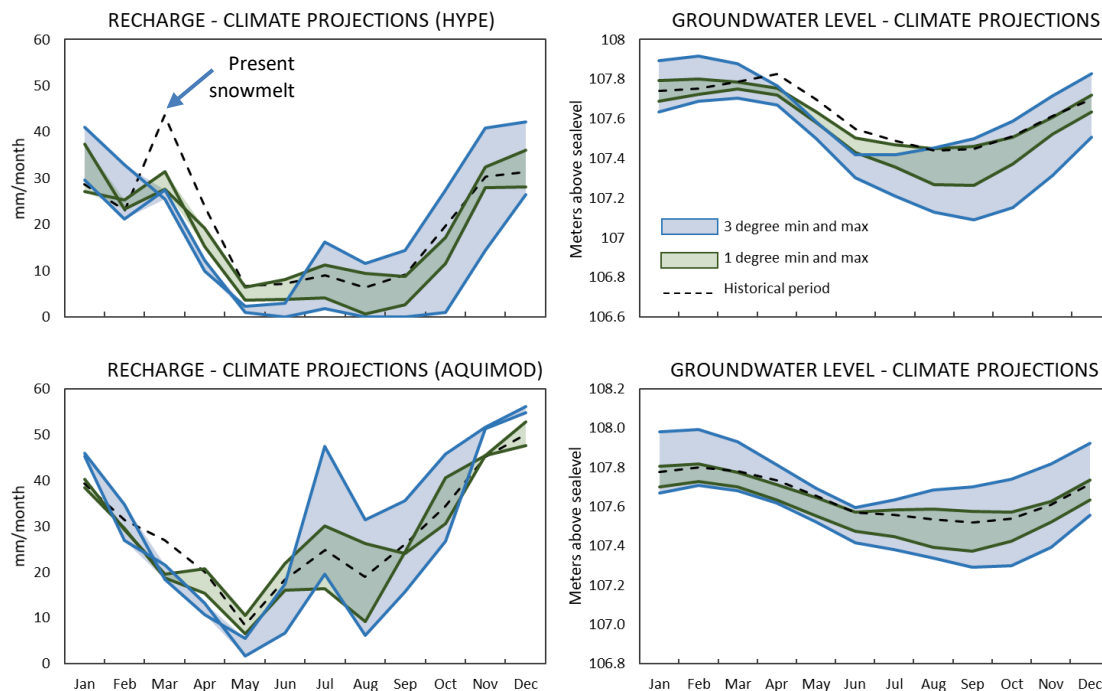


Figure 19. Climate projections on recharge and groundwater levels for Kinda, as simulated with HYPE (upper) and Aquimod (lower).

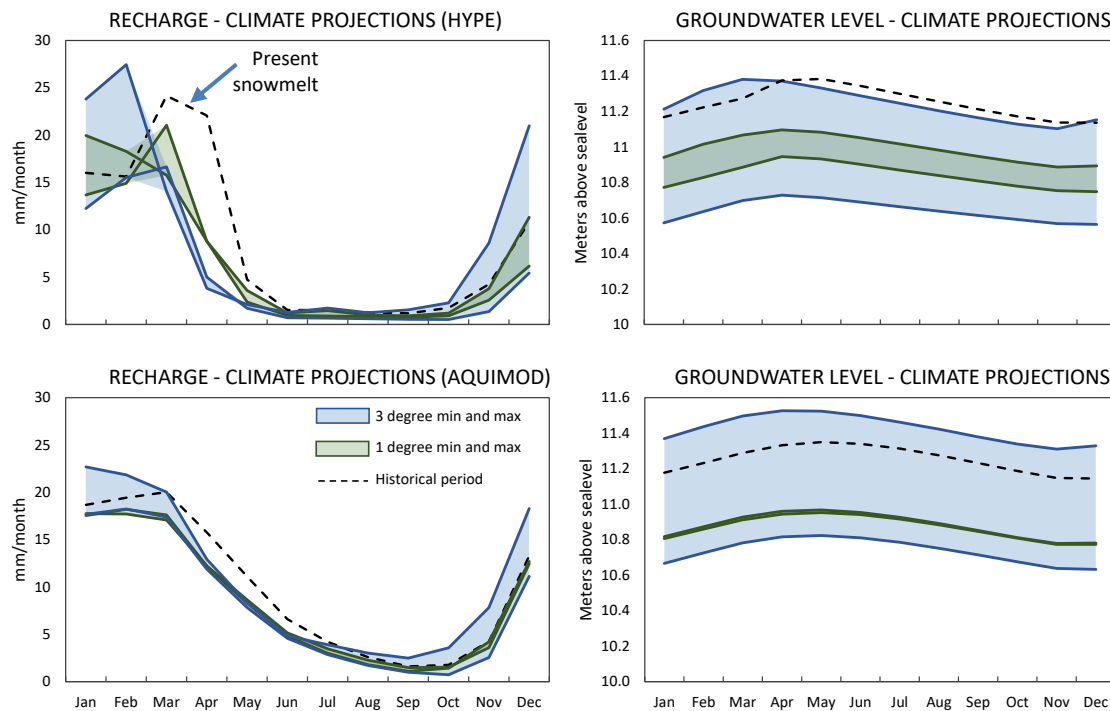


Figure 20. Climate projections on recharge and groundwater levels for Böda, as simulated with HYPE (upper) and Aquimod (lower).

The HYPE simulations provide very similar findings for Böda; also here, the retreating snowmelt is the dominant driver for future changes to the groundwater regime (Figure 20). The results again demonstrate falling spring recharge that goes hand-in-hand with boosted winter recharge, resulting in an earlier start of the drought period (virtually no recharge May to October), and the net effect of the prolonged drought is lower groundwater levels (again, more or less independent of precipitation case Dry/Wet).

Although the results of Aquimod cannot be inferred in terms of changing snowmelt, its outcome is in line with those from HYPE (Figure 20). Also the Aquimod results indicate an overall drop in recharge, particularly during spring, leading to falling groundwater levels, of similar magnitude as that modelled in HYPE. Only the +3°C Wet scenario (maximum precipitation) leads to somewhat higher projected groundwater levels.

In summary, HYPE CC projections re-produce a concerning pattern that has been observed both in trends of measured groundwater levels (Lagergren, 2015) and in earlier modelling (Vikberg et al., 2015), where the groundwater regime is shifting towards: 1) boosted winter recharge, 2) retreating snowmelt, resulting in 3) an earlier and prolonged drought period. The prolonged drought period in turn increases the stress on resources, particularly during late summer when consumption peaks due to tourism. Taken as an average of the Dry and Wet cases the reduction in recharge is estimated to be by -15% for Kinda (for both +1°C and +3°C) and -30% for Böda (Figure 21).



This study is consistent with earlier work and supports the prevailing understanding of future challenges for drinking-water supply, particularly along the south-eastern coast of Sweden (here exemplified by the Böda pilot area on Öland).

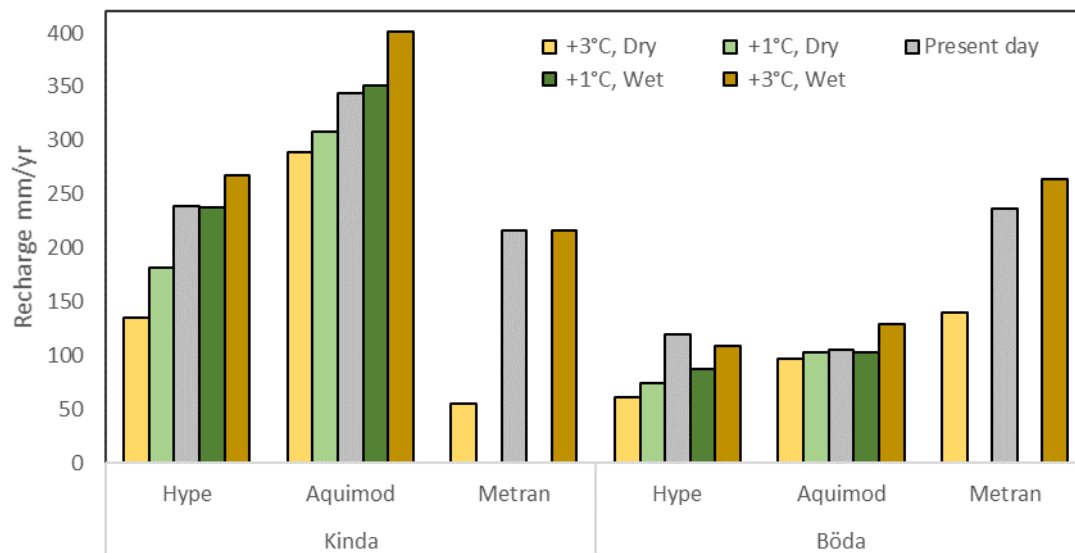


Figure 21. Climate projections on annual recharge.

6 REFERENCES

- Arheimer, B., Pimentel, R., Isberg, K., Crochemore, L., Andersson, J. C. M., Hasan, A., and Pineda, L. (accepted). Global catchment modelling using World-Wide HYPE (WWH), open data and stepwise parameter estimation, Hydrol. Earth Syst. Sci, <https://doi.org/10.5194/hess-2019-111>, 2019.
- Bergström, S. (1976). Development and application of a conceptual runoff model for Scandinavian catchments. SMHI, Reports RHO, No. 7, Norrköping.
- Besbes, M. & de Marsily, G. (1984) From infiltration to recharge: use of a parametric transfer function. Journal of Hydrology, 74, p. 271-293.
- Dahlqvist, P., Bastani, M., Triumf, C-A., Erlström, M., Gustafsson, M., Persson, L. 2018: SkyTEM-undersökningar på Öland – Geologiska tolkningar och hydrogeologisk tillämpning. SGU Rapporter och Meddelanden 145.
- Lagergren H, 2015, Grundvattennivåns tidsmässiga variationer i morän och jämförelser med klimatscenarier. SGU-rapport 2015:20.
- Lindström, G., Pers, C., Rosberg, J., Strömqvist, J. & Arheimer, B. (2010). Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. Hydrology Research 41.3–4, 295-319.
- Mackay, J. D., Jackson, C. R., Wang, L. 2014a. A lumped conceptual model to simulate groundwater level time-series. Environmental Modelling and Software, 61. 229-245. <https://doi.org/10.1016/j.envsoft.2014.06.003>.
- Mackay, J. D., Jackson, C. R., Wang, L. 2014b. Aquimod user manual (v1.0). Nottingham, UK, British Geological Survey, 34pp. (OR/14/007) (Unpublished)
- Obergfell, C., Bakker, M., & Maas, K. (2019). Estimation of average diffuse aquifer recharge using time series modeling of groundwater heads. Water Resources Research, 55. <https://doi.org/10.1029/2018WR024235>
- Rodhe, A., Lindström, G., Rosberg, J. & Pers, C., 2006: Grundvattenbildning i svenska typjordar – översiktlig beräkning med en vattenbalansmodell. Uppsala universitet, Institutionen för geovetenskaper, Report Series A No. 66, 20 s.
- Rodhe, A., Lindström, G. & Dahné, J., 2009: Grundvattennivåer i ett förändrat klimat. Slutrapport från SGU-projektet "Grundvattenbildning i ett förändrat klimat", SGUs diarienummer 60-1642/2007. Institutionen för Geovetenskaper, Uppsala universitet och Sveriges meteorologiska och hydrologiska institut. 44s.
- Vikberg, E., Thunholm, B., Thorsbrink M., Dahné J. 2015: Grundvattennivåer i ett förändrat klimat – nya klimatscenarier. SGU-rapport 2015:19



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

7 APPENDICES

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.

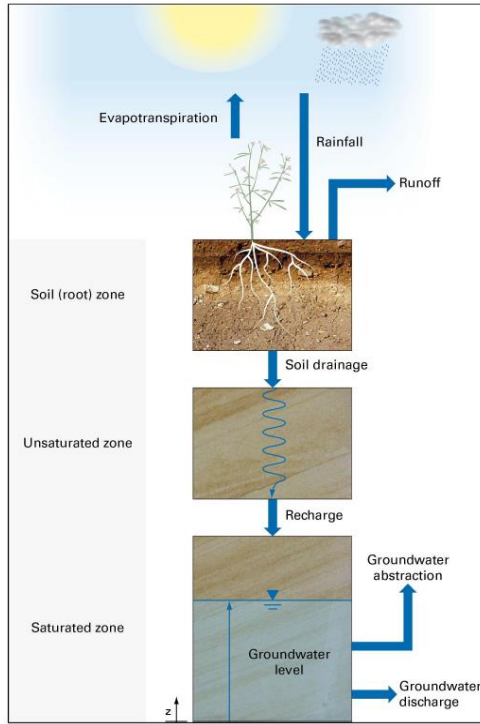


Figure A1 Generalised structure of Aquimod (after Mackay et al., 2014a)

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 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.

$$TAW = Z_r(\theta_{fc} - \theta_{wp})$$

Equation A1

$$RAW = p \cdot TAW$$

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:

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

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

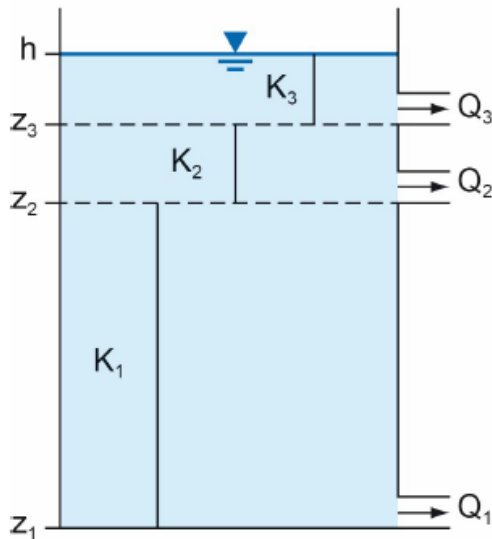


Figure A2 Representation of the saturated zone using a multi-layered groundwater system

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 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.

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.

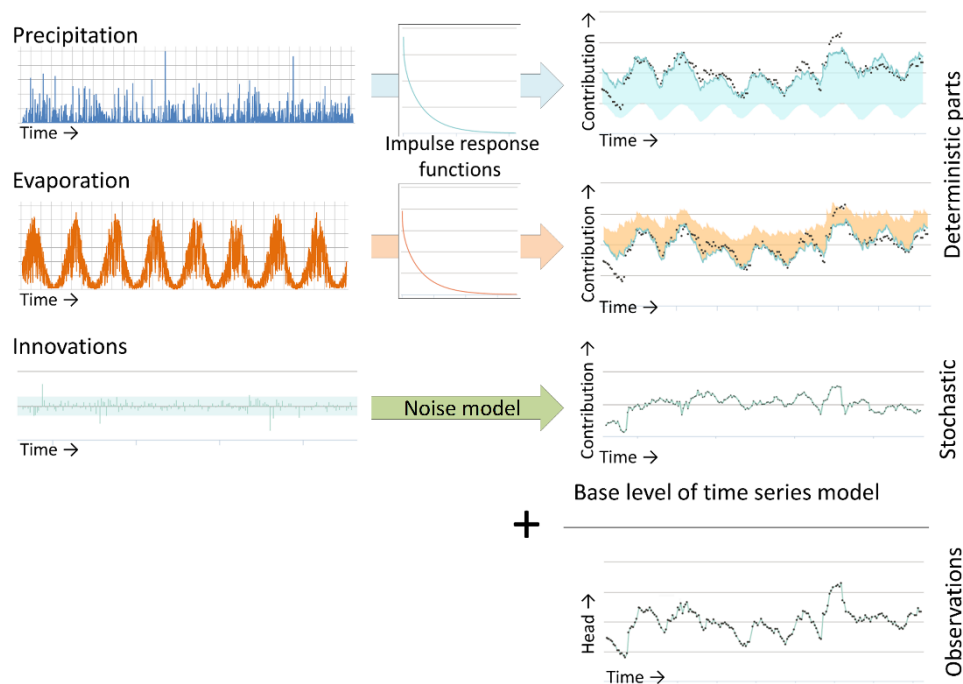


Figure B1 Illustration of METRAN setup

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 unimodal 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.

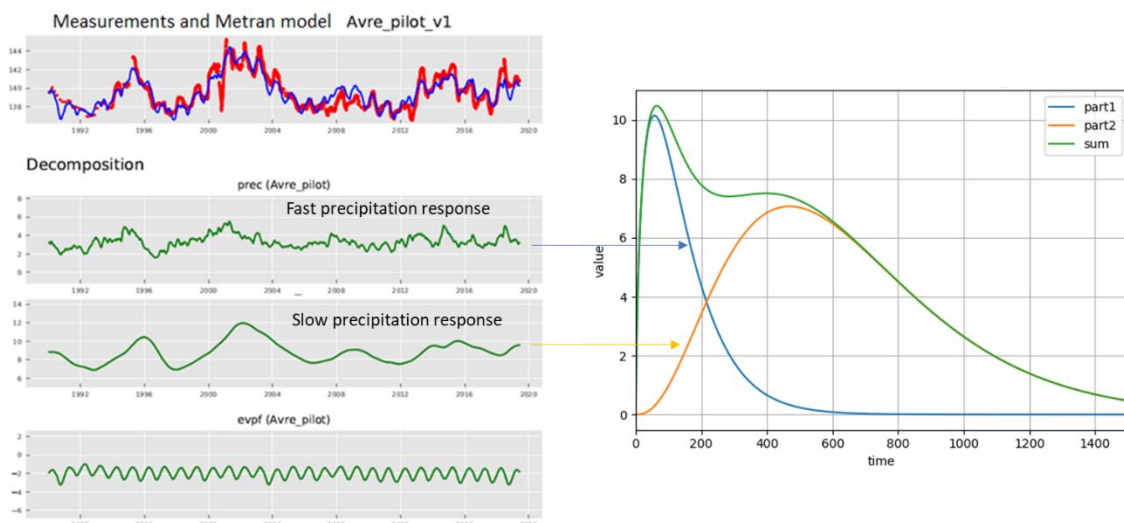


Figure B2. An example where the response function implemented in METRAN is not suitable for the groundwater system

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 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 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.

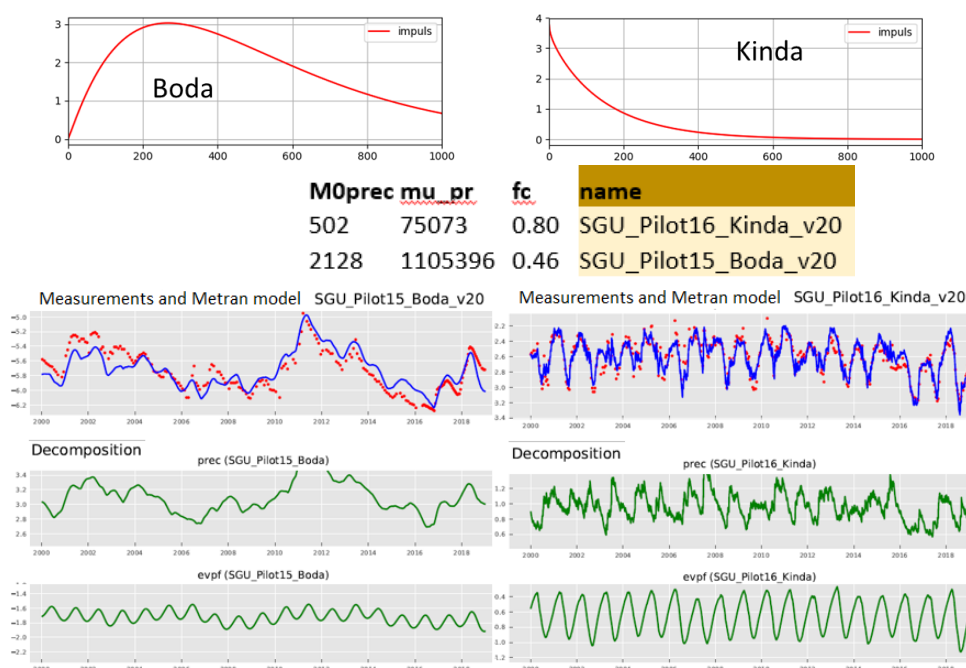


Figure B3 Illustration of Metran output for two case studies in Sweden with different response times.

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, R^2 , 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

$$R = P - fE \quad \text{Equation B1}$$

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.