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Technical note on propagation of climate change projections in integrated models to assess future groundwater conditions

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LIST OF ABBREVIATIONS & ACRONYMS

Abbreviation	**Description**
DLT / Deltares	Dutch institute for applied research in the field of water and subsurface
GCM	General Circulation Model or Global Climate Model used for climate change scenarios
GEUS	Geological Survey of Denmark and Greenland
HGI-CGS	Croatian Geological Survey
IGME	Geological and Mining Institute of Spain
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project https://www.isimip.org
MBFSZ	Mining and Geological Survey of Hungary
RCP	Representative Concentration Pathway (greenhouse gas concentration trajectory used for climate change scenarios)
TNO-GSN	TNO Geological Survey of the Netherlands

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1 INTRODUCTION

Climate change already has widespread and significant impacts in Europe, which is expected to increase in the future. To reduce the damage, detailed assessments, based on a thorough understanding of the hydrological system, are required for the planning of optimal adaptation strategies. Groundwater plays a vital role for the inland freshwater cycle, and have the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taken the hydrogeology into account is therefore essential in the assessment of climate change impacts. The Geological Survey Organisations in Europe acquire the necessary data and knowledge of the groundwater system and some Surveys already have high-end expertise in utilising this in climate change assessments. To streamline the assessments to produce harmonised results at EU scale, and to contribute to a general enhancement of the assessments, the Surveys collaborate in TACTIC on the development of a research infrastructure for the advancement and harmonisation of climate change assessments utilising knowledge and data on the groundwater system, which is tested in pilots covering most climate challenges and hydrogeological conditions in Europe.

Work Package 3 of the TACTIC project focuses on challenges related to groundwater- surface water interaction, which includes 1) changes in shallow groundwater that may lower or raise the groundwater table and cause exacerbate surface flooding, 2) groundwater-dependent ecosystems and, 3) groundwater droughts. To address these complex problems tools/approaches capable of describing both systems and their interaction are required, and the work package focuses on integrated modelling.

Task 3.5 is devoted to examining how climate change scenarios are most adequately propagated in the numerical models. This task investigates changes (climate change, and secondary changes such as land use, urbanisation and others) and their effect on the integrated groundwater-surface water system. This includes reference set-up that can be used across the GSOs, i.e. choice of climate change projection(s) and methods to downscale and propagate scenarios. This technical note further describes modelling aspects related to the propagation of these climate change projections to groundwater.

2 METHOD

For obtaining insight in the effect of climate change on groundwater and groundwater resources, knowledge of the hydrogeology, models, and climate change scenarios are needed.

2.1 Hydrogeological information

The basis of the knowledge of groundwater systems is the geology, which is the primary subject of all geological surveys. Specifically, information on the hydraulic properties of the geological units and geological features like faults is necessary. In addition, data on the external influences on the groundwater are important. The collection of these often lies (at least partly) outside the task of the geological surveys, so cooperation and coordination is necessary.

Precipitation and evaporation usually are the most important external influences. Precipitation is measured routinely, but evaporation is more difficult. Reference evaporation can be determined from standard meteorological quantities, but the difference between the actual evaporation and this reference evaporation can be large. Information on land use, crop type, soil moisture may help to get more accurate evaporation, but this does require additional knowledge of processes and associated parameters.

Information on the presence and properties of surface water and drainage systems is also needed for proper assessment of groundwater systems. Drainage level and drainage capacity are relatively simple types of data, but often not systematically registered and made available. Depending of the geologic and hydrologic settings, it may vary strongly what data on surface water is relevant. This usually includes location, width and depth and the surface water level. Topographic maps can be used for the former two, measurements of the latter may be available. Surface water fluxes, presence of sludge and frequency of dredging are examples on additional data, that may be useful.

The last group of external influences is groundwater extraction and irrigation. Usually, data on large extractions is available, especially when a licence is required. Smaller extractions and irrigation generally are less well known.

The quality and quantity of hydrogeological information used to setup and calibrate integrated models are generally reflected in the uncertainty or the trustworthiness of the model-predictions.

It must be noted that modelling also provides information about the groundwater system, so that data collection benefits from insights obtained from modelling, and modelling can be improved with additional insight from data suggesting a repetitive and cyclic process (e.g. Hill & Tiedeman, 2007; Haitjema, 1995).

2.2 Available models

A model is a system conceptualization together with process parameters and input variables. The included processes as well as the time and space resolution are important aspects of the model and determine the usability of the results together with their reliability.

2.2.1 Recharge from precipitation

The conceptualization of the recharge from precipitation determines largely, how effectively the effects of climate change on the groundwater can be determined. This is illustrated by Figure 1.

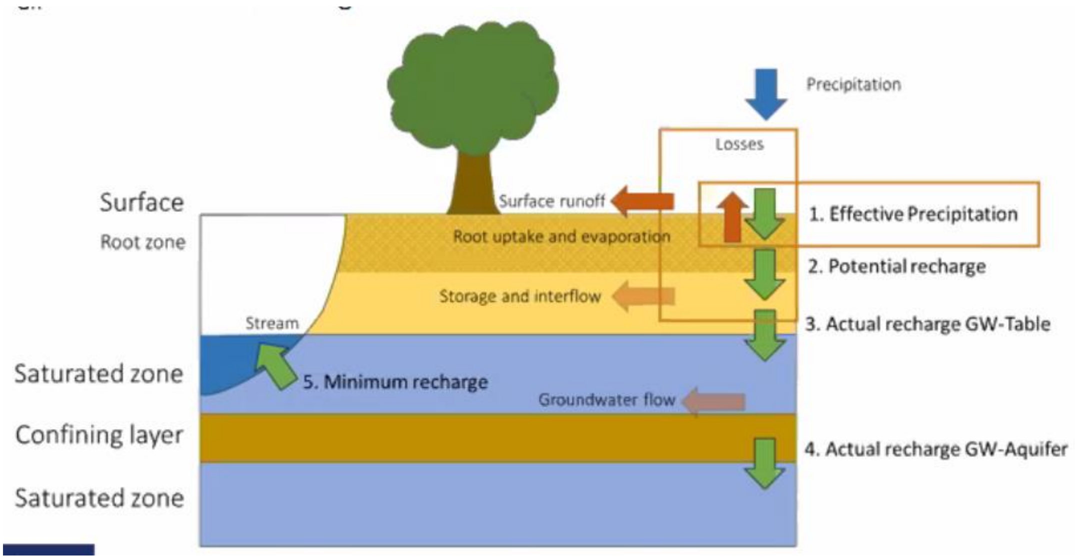


Figure 1 Groundwater recharge

The effective precipitation (1. In Figure 1) is equal to the precipitation minus the actual evapotranspiration, in which more or less elaborate modelling concepts may be used to determine the actual evaporation (from reference evaporation, land use, etc.). If surface runoff is calculated, then potential recharge (2. Figure 1) is obtained which is smaller than the effective precipitation. Also simulating rootzone storage and interflow, leads to yet another value for the actual recharge at the groundwater table (3. in Figure 1). Finally, in a multi-aquifer approach the recharge to deeper aquifers has a different value (4. Figure 1). The minimum recharge to the surface water (5. In Figure 1) is a groundwater discharge to the surface water system (see subsection 2.2.2).

2.2.2 Surface water interaction

From the viewpoint of the groundwater, the interaction with surface water consists of water fluxes generated by head differences. The fluxes are either a groundwater loss feeding the surface water or a groundwater gain fed by surface water.

An undisputable part of these water fluxes is the water exchange through the contact surface between surface water and groundwater. For many practical purposes, it is not useful to consider only the interface with surface water on the one and saturated groundwater on the other side (Figure 2, yellow ellipse). Often, a useful extension is to include the groundwater outflow through seepage faces in river banks above the surface water level and infiltration through lake and river beds that lie above the phreatic groundwater table (Figure 2, orange ellipses). Furthermore, depending on circumstances, surface runoff, interflow, and drainage that ends up in the surface water can be included in the definition of the surface water exchange flux in a groundwater model (Figure 2, red ellipse).

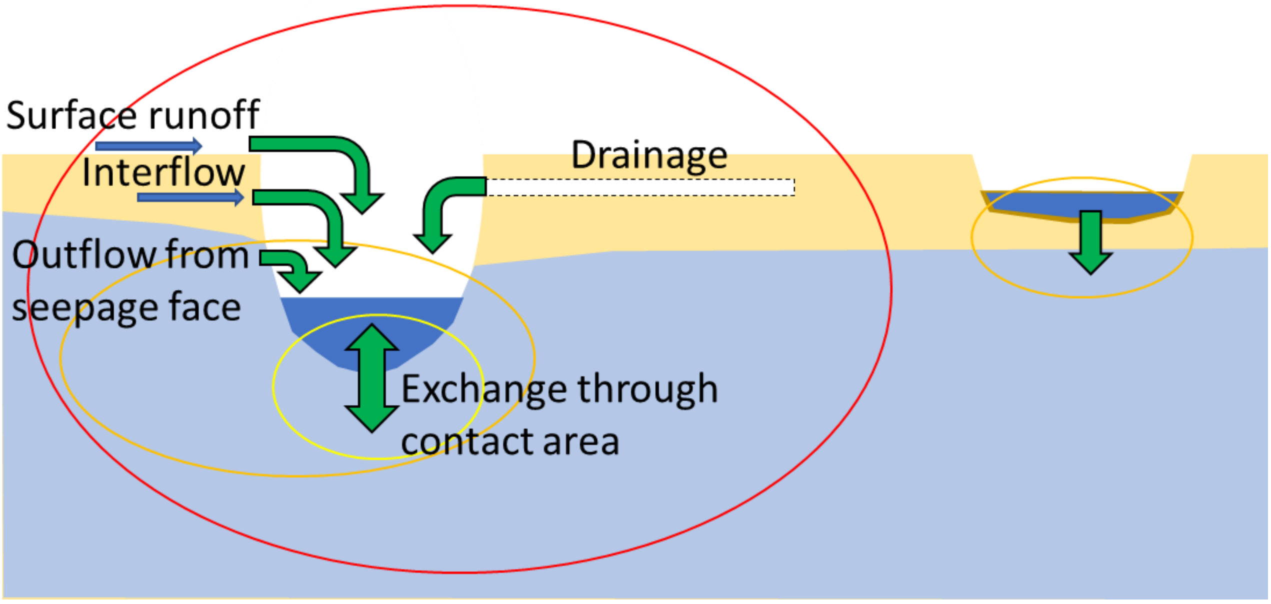


Figure 2 Various scopes in groundwater - surface water exchange (indicated by ellipses of different colour; groundwater is light blue; surface water dark blue)

A special case is hyporheic exchange, which does not result in a net flux but is ecologically important (see e.g. Woessner, 2017). Hyporheic flow is flow in a stream bed of water that originates from the stream and flows back into the stream. For streams with large head gradients and meanders the water may flow back further downstream, while the return flow occurs at a later time after recession of the water level in the stream after a flood. In the streambed and floodplain mixing of the stream water with groundwater may occur.

The influence of surface water may be included in different ways in groundwater flow modelling:

- Implicitly as is done in simulating groundwater head time series with a transfer function noise model; the transfer functions reflect the surface water control together with other properties of the groundwater system;
- Explicitly as the outflow of a groundwater reservoir in lumped modelling;
- Explicitly using spatiotemporal boundary conditions as done in distributed groundwater modelling.

The latter may be formulated as a prescribed head, a prescribed flow or a combination of these two. According to Jazayeri & Werner (2019) the following names apply for the versions of the spatio-temporal boundary conditions:

- Type 1: Dirichlet – specified head;
- Type 2: Neumann – specified flux;
- Type 3: Robin – linear combination of specified head and flux.

The boundary conditions may be non-linear. The most common form is piecewise linearity in which the exchange coefficient has different values for separate ranges of the groundwater head. Examples are the MODFLOW (McDonald & Harbaugh, 1988; Harbaugh & McDonald, 1996); Harbaugh et al., 2000; Harbaugh, 2005) packages DRN and RIV and combinations of these

(Zaadnoordijk, 2009). The GHB package implements a linear combination of head and flux (Robin boundary). Causes of non-linearity are change of the surface water – groundwater contact area and formation of seepage zone depending on the groundwater head (see e.g. Rushton 2007).
In addition to non-linear relations, the parameters of the surface water interactions may change in time. This occurs e.g. when the surface water bottom changes due to dredging, sedimentation, or clogging.
More complex schematisation of the groundwater – surface water interaction can be used in integrated models using e.g. SHE (Abbott et al., 1986), NHI (De Lange et al., 2014) or HydroGeoSphere (Therrien & Sudicky, 1996). The surface water is no longer an external model boundary like it is in a pure groundwater model, but may be an internal boundary to which specific conditions apply. Moreover, it still is necessary to choose a conceptualization in order to extract the groundwater – surface water interaction from the results of such an integrated model. In practice, an integrated model is necessary when the interaction has important influence not only on the groundwater but also on the surface water.
Note that simulation programs like Mike SHE do allow the user to create simple non-integrated groundwater models as well, allowing to start simple and gradually increase the complexity of the model together with the growing understanding of the groundwater system (together with available data of the physical groundwater system).

The goal of the simulations determines which fluxes need to be separated and which detail in time or in space is needed. This will vary strongly for e.g. change of the long term water balance, evaluation of agricultural water supply during the growing season, or impact assessment for riparian ecology of climate change.

2.3 Climate change scenarios

To assess future change in groundwater conditions from a changing climate, estimates of precipitation, temperature and potential evapotranspiration for the chosen future period is needed. This data should be obtained from Global Climate Models (GCM) downscaled to catchment resolution or using an intermediate Regional Climate Model (RCM) applying boundary conditions from the GCM and downscale the results from the RCM to catchment resolution, Figure 3. For the long term application and comparison of the results it is important to properly document the climate change data used in the groundwater application.

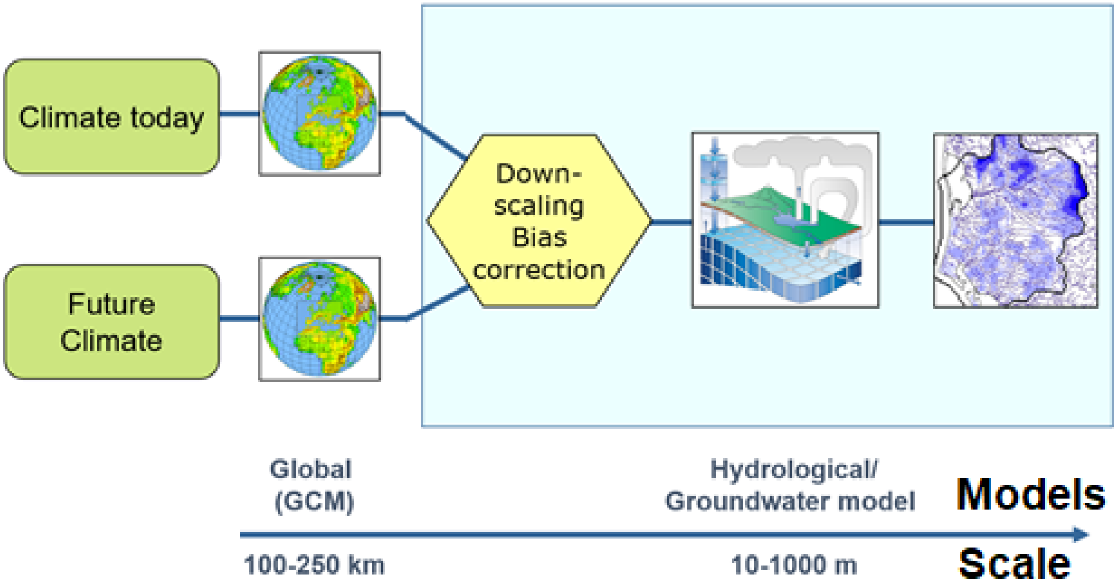


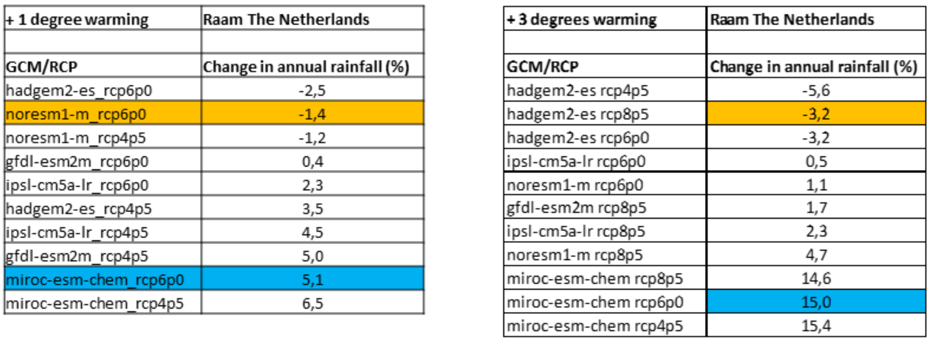
Figure 3 Calculation of climate change effect on groundwater with integrated groundwater and hydrological models. Especially the downscaling and/or bias correction can be done in multiple ways.

In order to arrive at results that are intercomparable for all of Europe a new procedure for selection of climate change scenarios has been developed within TACTIC.

The climate change scenarios have been based on climate data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). These data consist of ensembles of 15 models: three Representative Concentration pathways (RCP) applied to five Global Climate Models. The spatial resolution is 0.5° and the temporal resolution 1 day. Two criteria were used to select an ensemble member (Sperna Weiland et al., 2021):

- a global warming level of +3 degrees and +1 degrees, relative to a reference period (1980-2010);
- the 2nd highest and 2nd lowest scenario are selected, using the following indicators for regional climate change response: European mean temperature change, regional (case specific) precipitation change, regional net precipitation change and regional temperature change.

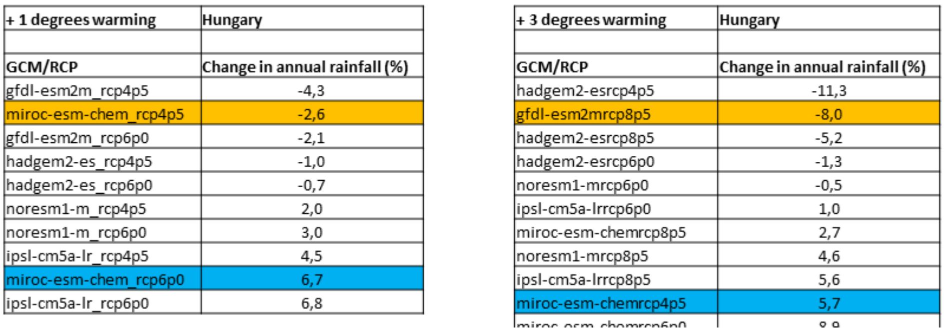
This procedure leads to a different ensemble member for each scenarios (compare Figure 4 and Figure 5).



+ 1 degree warming	Raam The Netherlands
GCM/RCP	**Change in annual rainfall (%)**
hadgem2-es_rcp6p0	-2,5
noresm1-m_rcp6p0	-1,4
noresm1-m_rcp4p5	-1,2
gfdl-esm2m_rcp6p0	0,4
ipsl-cm5a-lr_rcp6p0	2,3
hadgem2-es_rcp4p5	3,5
ipsl-cm5a-lr_rcp4p5	4,5
gfdl-esm2m_rcp4p5	5,0
miroc-esm-chem_rcp6p0	5,1
miroc-esm-chem_rcp4p5	6,5

+ 3 degrees warming	Raam The Netherlands
GCM/RCP	**Change in annual rainfall (%)**
hadgem2-es rcp4p5	-5,6
hadgem2-es rcp8p5	-3,2
hadgem2-es rcp6p0	-3,2
ipsl-cm5a-lr rcp6p0	0,5
noresm1-m rcp6p0	1,1
gfdl-esm2m rcp8p5	1,7
ipsl-cm5a-lr rcp8p5	2,3
noresm1-m rcp8p5	4,7
miroc-esm-chem rcp8p5	14,6
miroc-esm-chem rcp6p0	15,0
miroc-esm-chem rcp4p5	15,4

Figure 4 ISIMIP ensemble members for the Dutch TACTIC pilot "de Raam".



+ 1 degrees warming	Hungary
GCM/RCP	**Change in annual rainfall (%)**
gfdl-esm2m_rcp4p5	-4,3
miroc-esm-chem_rcp4p5	-2,6
gfdl-esm2m_rcp6p0	-2,1
hadgem2-es_rcp4p5	-1,0
hadgem2-es_rcp6p0	-0,7
noresm1-m_rcp4p5	2,0
noresm1-m_rcp6p0	3,0
ipsl-cm5a-lr_rcp4p5	4,5
miroc-esm-chem_rcp6p0	6,7
ipsl-cm5a-lr_rcp6p0	6,8

+ 3 degrees warming	Hungary
GCM/RCP	**Change in annual rainfall (%)**
hadgem2-esrcp4p5	-11,3
gfdl-esm2mrcp8p5	-8,0
hadgem2-esrcp8p5	-5,2
hadgem2-esrcp6p0	-1,3
noresm1-mrcp6p0	-0,5
ipsl-cm5a-lrrcp6p0	1,0
miroc-esm-chemrcp8p5	2,7
noresm1-mrcp8p5	4,6
ipsl-cm5a-lrrcp8p5	5,6
miroc-esm-chemrcp4p5	5,7
miroc-esm-chemrcp6p0	8,9

Figure 5 ISIMIP ensemble members for the Hungarian TACTIC pilot.

In a next step for a selected scenario, monthly change factors are determined for the area to be modelled for the precipitation, temperature, and reference evaporation (Figure 6 gives an example for Hungary).

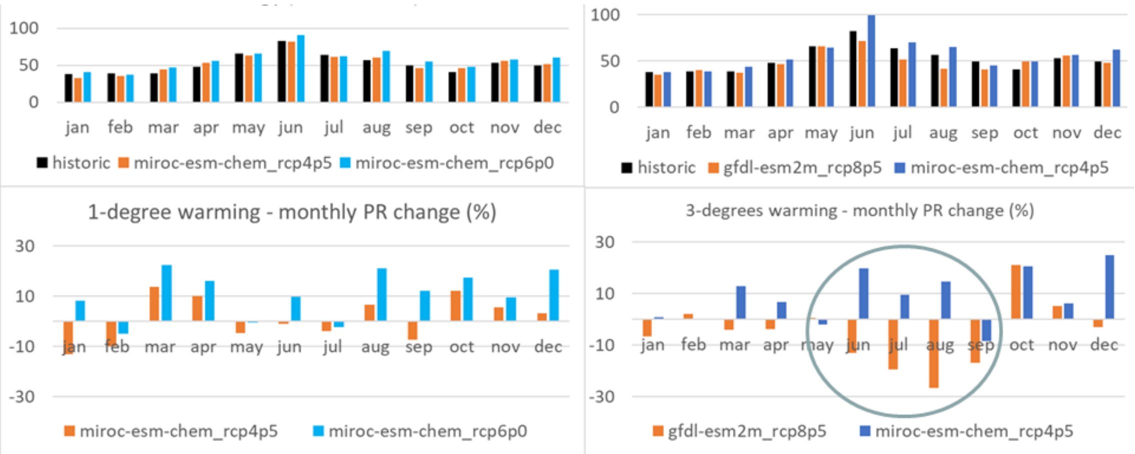


Figure 6 Monthly change factors for precipitation for the Hungarian TACTIC Pilot for 1-degree global warming (left) and 3-degrees (right).

The change factors allow for the transformation of existing meteorological data to time series belonging to the selected scenario for that area. A period with a length of at least 30 years should be used to include sufficient meteorological variation. The correction factors for temperature are additive, the correction factors for evaporation and precipitation are multiplicative to avoid negative future values.

3 RESULTS

Relevant quantities for climate change assessment are:

- Groundwater table (elevation with respect to datum like mean sea level);
- Depth of the groundwater table (previous value subtracted from the surface elevation);
- Groundwater heads (elevation with respect to datum; in deeper layers);
- Various recharge fluxes (length per time = volume per area per time);
- Fluxes between groundwater and surface water (totals or separated into sub-fluxes as described in subsection 2.2.2);
- Depending on additional processes included in the model other specific quantities such as sea water intrusion, water quality changes, subsidence, agricultural yield (losses).

The quantities should be calculated for the reference period and for the climate change scenario(s).

The quantities have both temporal and spatial aspects.

3.1 Temporal aspects

For long term averages, steady state calculations can be appropriate if the system is sufficiently linear. For strongly non-linear models, transient calculations are necessary even for the calculation of long term averages (e.g. Witte et al., 2019). This does not only depend on the physical non-linearity of the system, but also on the understanding of the system and available data.

Transient calculations are necessary to account for variability. In many cases, the seasonal variability will be important with more risk of water shortages in summer and in winter more risk of groundwater flooding. In general, flood risks require a higher temporal resolution (e.g. days) than risk of water shortage during droughts (e.g. weeks). Risks of extreme events and return times require a long period (minimally the 30 years of the climate definition, but preferably 100 years for which then both data for a reference period and a climate projection are needed).

It should be noted that the effective model parameters depend on the temporal schematisation. E.g., because it influences the surface water exchange fluxes that are calculated. This relates mostly to the separate quantification of flux in both directions instead of calculating the net exchange. This may be illustrated by the hyporheic exchange connected to a flood wave in a river: no exchange will be calculated if monthly time steps are used when the infiltration into the ground and subsequent exfiltration takes place within days.

The relevant time resolution is related to the output or analysis time steps. The calculation timesteps in the numerical scheme of the simulation software may be much smaller in order to get an numerically accurate solution. Depending on the output time steps, it may be important to distinguish between instantaneous or time integrated or averaged values. For flooding, peak values are more important while integrated fluxes are needed for water balance assessments.

3.2 Spatial aspects

The spatial resolution has different aspects:

- The amount of detail in the geography (long straight line segments – detailed area of river bed; e.g. for major rivers or large lakes);
- Inclusion of all individual surface water features or representing spatially averaged effect (e.g. for fine drainage network).
- Subgrid processes are not simulated (e.g. only net flow from groundwater to surface water instead of both outflow and inflow).

In the Netherlands, drainage and surface water networks often have a finer resolution than groundwater models. This makes it more efficient to use one effective boundary condition (a so-called 'top system' per point, node, or cell) than to represent the influence of each drain, ditch, and stream individually. Several authors have published analytic solutions which are used to calculate the parameters of a Robin boundary condition for the top system of a regional distributed groundwater model to reflect a dense system of drains or ditches (Ernst, 1978; Bruggeman – see Kovar & Rolf, 1978; de Lange, 1996).

Schematization as a line (or string of model nodes or cells) is appropriate for rivers and canals that are much longer than the model resolution, but have a width that is smaller. In this case longitudinal variations can be included, but the transverse variation is lumped together with an effective width. The model will produce a net value per river section while there may be both exfiltration and infiltration depending on regional flow and local groundwater abstractions. Other models do not use the size of the numerical grid as river minimum width but simulate rivers "between" numerical grid cell as a 1D models (Mike11/Mike Hydro integrated in Mike She). In the 1D model, cross-sections define the widths of the river.

When not only the length but also the width of surface water is larger than the model resolution, details of the variation can be specified in all directions. Benoit et al. (2019) and Ghysels et al. (2019) give an example of a very detailed schematization of an individual river bed. In such a case, the model will produce insight in the local variation in exchange fluxes, which may be important for e.g. groundwater quality issues.

4 DISCUSSION

Confidence or uncertainty assessment is an essential part of (groundwater) modelling (e.g. Hill & Tiedeman, 2007). It feeds the cyclic process that modelling necessarily is, because of the invisibility of the groundwater and the subsurface and the limited data that is available. Usually, the a priori knowledge of model parameters is insufficient and needs to be improved by calibration of model output with independent observations. Also, it is impossible to determine beforehand how accurate results will be for a specific schematisation. So, model output is necessary to determine whether required assessments can be made e.g. if future water shortages under climate change can be determined accurately enough to decide that measures are necessary or to decide on the budget for the design of measures.

For climate projections, it is especially important to include the assessment of the model schematization and the included processes. The more the climate scenarios differ from the reference situation, the more likely it is that more processes need to be included or that different effective values are needed for parameter. An example is the use of a single crop factor evaporation coefficient to determine actual evapotranspiration from data available for reference evaporation (see e.g. Allen et al., 1998). This is reasonable when the actual evapotranspiration is not limited by water shortages. So, crop factors for the reference period cannot be used for a climate change scenario, if water shortage increases strongly in a climate change scenario. A simple solution would be to use different values of the crop factors. However, it may be more appropriate to use a different description for evapotranspiration in the model, that does account for evaporation reduction when crops have water stress.

5 CONCLUSIONS AND RECOMMENDATIONS

Modelling is necessary for the assessment of the impact of climate change on groundwater and groundwater resources.
The choice of model schematisation, temporal and spatial resolution does not only depend on the groundwater system and the goal of the modelling but also on the understanding of the system, the available data and the time and resources available for the assessment.

The developed method for selection of climate change scenarios provides a basis for a uniform assessment of climate change effects throughout Europe.
For assessment of climate change, a period of at least 30 years needs to be considered to capture the meteorological variability associated with the climate.

Evaluation of the model and model output are an essential part of the modelling process. Without it, the value of the output remains unknown and the results cannot be used.

Groundwater modelling is a cyclic process, which makes it important to store and make available model information. This is a task that fits well the role of Geological Surveys.

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