Deltares

Groundwater module SOBEK

A groundwater module for the hydraulic model of the Rhine between Andernach and Lobith in GRADE

Groundwater module SOBEK

A groundwater module for the hydraulic model of the Rhine between Andernach and Lobith in GRADE

Author(s)

Bernhard Becker
Asako Fujisaki

Groundwater module SOBEK

A groundwater module for the hydraulic model of the Rhine between Andernach and Lobith in GRADE

Client	Rijkswaterstaat Water, Verkeer en Leefomgeving
Contact	mevrouw R. Lammersen
Reference	
Keywords	Groundwater Module SOBEK, river-aquifer interaction, GRADE

Document control	
Version	0.3
Date	15-12-2023
Project nr.	11209265-005
Document ID	11209265-005-ZWS-0002
Pages	154
Classification	
Status	final

Author(s)		
	Bernhard Becker Asako Fujisaki	

Summary

A groundwater module SOBEK has been developed as module for the SOBEK 3 model of the Rhine to represent the water exchange between river and aquifer. Several model runs have been carried out and the simulation results were analysed to assess the usage of the groundwater module SOBEK with respect to three aspects:

1 Added value of modelling river-aquifer interaction in hydraulic models
2 Impact of river-aquifer modelling on extreme flood events and flood statistics
3 Practical aspects of modelling river-aquifer interaction

The SOBEK 3 model with groundwater module SOBEK produces good results. This is supported by a comparison with data based on observations, the HyMoG data, for three flood scenarios (1995, 1993, 1988). Comparison runs with the SOBEK-RE model and the GRADE data set show a good match of the SOBEK 3 simulation result, too. Different to earlier approaches for modelling the river-aquifer interaction in SOBEK models, the modelling approach of the Groundwater Module SOBEK uses the leakage-approach, an approach which is well-documented in literature and a widely accepted modelling approach for river-aquifer interaction in computer models.

The SOBEK 3 model has already a good level of calibration without the groundwater module SOBEK. Adding the groundwater module SOBEK in its current state does not necessarily improve the model results at all locations. At the downstream locations however, which are considered as the most important ones, the Groundwater Module SOBEK shows already an improvement in terms of match between simulated and observed data.

A new integrated calibration of the SOBEK 3 model that involves both the hydraulic model component (roughness parameters) and parameters of the groundwater module SOBEK will provide an even better match between simulated data and observed data. The calibration parameter of the hydraulic model, the roughness, mainly allows to tune the water level. The shape of the discharge curve can only be addressed to some extent with the roughness parameter (wave damping). With the Groundwater Module SOBEK it is now possible to model bank storage, which is technically and physically a temporary withdrawal of water. This process has been reported as significant in literature; now it is incorporated in the model this opens a new dimension for the calibration.

Simulation runs of extreme scenarios from GRADE have been carried out with the Groundwater Module SOBEK. The effect of the river-aquifer interaction is also clearly visible for extreme scenarios. The more extreme a scenario, the smaller is the effect of river-aquifer interaction on the model results. This can be explained with the bank storage processes and the effect of inundations that take place under extreme flood conditions on the water level.

Modelling river-aquifer interaction with the Groundwater Module SOBEK will thus have an impact on the flood statistics that are produced with the GRADE instrument. However, for an assessment of good quality, more simulations must be carried out. Correction functions that are currently used to achieve model consistency between SOBEK 3 and SOBEK-RE should be updated after the integrated calibration of the SOBEK 3 model of the Rhine. Ideally, the models are sufficiently consistent such that no correction is needed.

As next steps we recommend an integrated calibration of the SOBEK 3 model, where the parameters of the hydraulic model (roughness parameters) and the parameters of the Groundwater Module SOBEK are adjusted coherently.

Contents

1 Context and objective

The GRADE instrument (**G**eneration of **R**ainfall **a**nd **D**ischarge **E**xtremes) is a combination of a stochastic weather generator, a hydrological model and a hydraulic (hydrodynamic) model for the simulation of extreme discharges in the Rijn at Lobith and the Meuse at Borgharen (Hegnauer et al. 2023; Hegnauer & Becker 2013). One important part of GRADE is the hydraulic model of the German Lower Rhine between Andernach and Lobith (Figure 1, left). When building and calibrating the first hydraulic model of this river branch it appeared to be difficult to obtain good results for discharges and water levels (Barneveld & Meijer 1997). Adding river-aquifer interaction along the German Lower Rhine to the model was considered to be the solution, since it has been reported for the Rhine (RheinEnergie AG 2009; Giebel & Hommes 1988, 1994; Gölz et al. 1991; Ubell 1986, 1987b, 1987a) that there is a contribution from river-aquifer interaction to flood wave modification. There are also a lot of other studies on the effect of river-aquifer interactions on river discharge which can be found in literature (BWK 2022; Sommer et al. 2008; Sommer & Ullrich 2004, 2004; Sächsisches Landesamt für Umwelt und Geologie 2003; Pinder & Sauer 1971; Ubell 1964). This process of river-aquifer interaction is also referred to as bank storage (Pinder & Sauer 1971).

When going on in successive steps of improving the hydraulic model and adapting it to software-changes, the way how the river-aquifer interaction was modelled gradually changed (see Appendix A). In order to reduce computing time and because it seemed to have minor effects on the results in the way it was implemented in the current model version, the groundwater module finally was removed from the model in 2017 (Becker 2020a). Later, however, when using the results from GRADE for flood-statistics, large differences were found compared to the results made with the earlier hydraulic models where river-aquifer interaction was included (SOBEK-RE). To obtain a better match to the earlier results where river-aquifer interaction was accounted for, a correction was applied to the peak discharges that were obtained from the new model (Hegnauer et al. 2023). It is important that both the SOBEK-RE and the SOBEK 3 model produce consistent results because both the old SOBEK-RE model and the new SOBEK 3 model are still used within in GRADE.

Figure 1 shows the total set up of SOBEK-RE and SOBEK 3 model in GRADE. With the river section Maxau-Lobith the SOBEK-RE model covers a larger part of the Rhine (right side of Figure 1) than the SOBEK 3 model, which only covers the river section between Andernach and Lobith (left side of Figure 1).

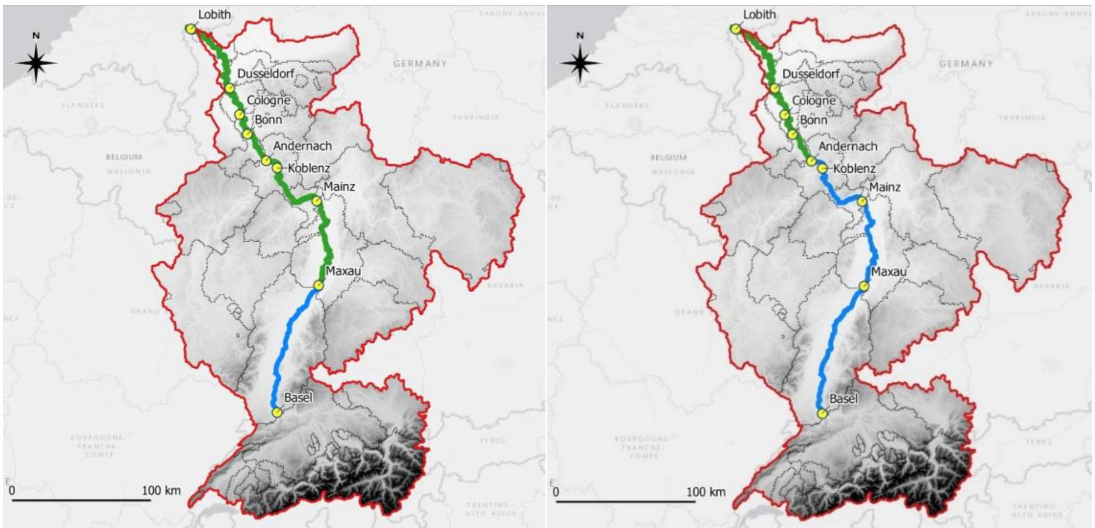

Figure 1 Overview of the hydrological catchment of the Rhine River upstream of Lobith with course of the main river (blue and green). The stretches covered with the SOBEK 3 model (right) and the SOBEK-RE model (left) are shown in green (Hegnauer et al. 2023). Note that the hydraulic models of the Rhine also cover parts of the larger tributaries, these parts of the model are not shown.

The Groundwater Module SOBEK has been developed in the period from 2020 to 2022 as an additional module for the SOBEK 3 model of the German Lower Rhine to represent the water exchange between river and aquifer (Appendix A, Becker & Fujisaki 2022; Becker 2020c, 2020b, 2021). Primary goal is to achieve consistency with the SOBEK-RE model in terms of river-aquifer interaction. Note that the SOBEK-RE model and the SOBEK 3 model will not produce identical results, because the SOBEK 3 model is more up to date in terms of model data than the SOBEK-RE model and because the SOBEK 3 model accounts for inundations with its 1D2D-flow module; SOBEK-RE does not have a feature for two-dimensional inundation modelling, but the SOBEK-RE model of the Rhine contains nodes to account for retention areas.

The objective of this study is to further develop and to pre-calibrate the groundwater module as well as to analyse the effects on river discharges and water levels when using this module in order to support a decision on the usage of the groundwater module SOBEK in general and within GRADE specifically. In particular, this report aims to answer the following questions:

1 Added value of modelling river-aquifer interaction in hydraulic models
   - What is the effect of modelling river-aquifer interaction on the modelled river discharge?
   - How does the river-aquifer interaction modelled in SOBEK compare to the results from SOBEK-RE?
   - Is it possible to calibrate the groundwater module?
   - What is the added value of modelling river-aquifer interaction for GRADE?
2 Impact of river-aquifer modelling on extreme flood events and flood statistics
   - What is the effect of modelled river-aquifer interaction on extreme discharge events?
   - What is the effect on the statistics of floods (“werklijn”, the peak discharge that corresponds to a certain return period)
   - How do the model results compare to the corrections that are currently used to account for river-aquifer interaction?
3 Practical aspects of modelling river-aquifer interaction in the GRADE context
   - How can initial conditions be specified and what is a good simulation period prior to the flood event?
   - How does the model react on the model parameters (sensitivity, relevant for calibration)
   - What are the computational costs?

The following chapters address the questions grouped under items 1 to 3. In each chapter, the approach, results, and conclusions are given. Chapter 7 closes the report with a summary and remarks.

2 Functional principle of the Groundwater Module SOBEK

2.1 Basic equations

The so-called leakage approach is commonly used to model water exchange between river and aquifer. Different leakage approaches can be found in literature (see Becker et al. 2015; Becker 2010). The most common leakage approach follows Darcy's law. This approach is implemented in many groundwater flow simulation software to facilitate river aquifer interaction as third order (Cauchy) boundary condition. Figure 2 shows the functional principle of this approach. The head difference Δh between river stage h_R and groundwater level h_G is computed as

$$\Delta h = h_R - h_G \qquad 1$$

and is multiplied with a leakage parameter

$$c = \frac{k_S}{d} \qquad 2$$

The leakage parameter comprises the hydraulic resistance of an interface layer between river channel and aquifer with hydraulic conductivity k_S and thickness d (Figure 2).

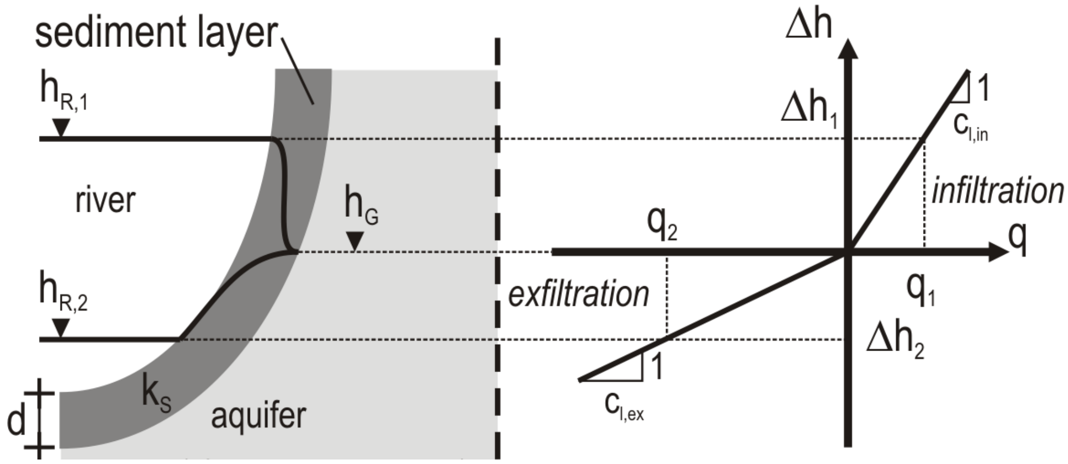

Figure 2 Leakage-approach after Darcy (Becker et al. 2015)

The water exchange Q between river and aquifer then is

$$Q = \Delta h \cdot c \cdot A \qquad 3$$

In this equation, A is the interface area between river channel and aquifer where the exchange of water takes place. It is calculated as the product of wetted perimeter of the river cross section and the length of the river segment. With a constant value for the interface area A the exchange flux Q is related linearly to the head difference Δh.

The river stage and the groundwater level vary in time and influence each other. In the beginning of a flood period the head difference increases. This makes river water flow towards the aquifer, where the groundwater level rises as a consequence. Towards the end of a flood event, the river stage decreases, while the groundwater level still rises, both reducing the head difference.

2.2 Groundwater Module SOBEK

2.2.1 Approach

The basic idea of the modelling approach for the groundwater module SOBEK is to model groundwater storage units lateral to the course of the river, and these groundwater storage units exchange water with the river according to the leakage approach which is described in Section 2.1 (see also Becker 2020b).

The water volume in the groundwater storage unit V changes from one time step t to another with the water exchange flux between river and aquifer Q:

$$V_t = V_{t-1} + Q \cdot \Delta t \quad (4)$$

The size of the groundwater storage unit depends on the length of the river segment and the extent how far the river aquifer interaction reaches laterally to the river. The exchange flux Q is calculated according to Equations 1, 2 and 3 in Section 2.1 and a constant value for the interface area A. The groundwater level in the storage unit h_G is calculated from the groundwater volume V with the help of a linear relation (see Figure 3 for an example). For the normal conditions where the groundwater level is below the top ground surface, the effective porosity of the soil material (typically a value between 0.1 and 0.3) is accounted for in the calculation of the groundwater level. If the water level in the groundwater storage unit is above the top ground surface, the porosity changes to 1.0.

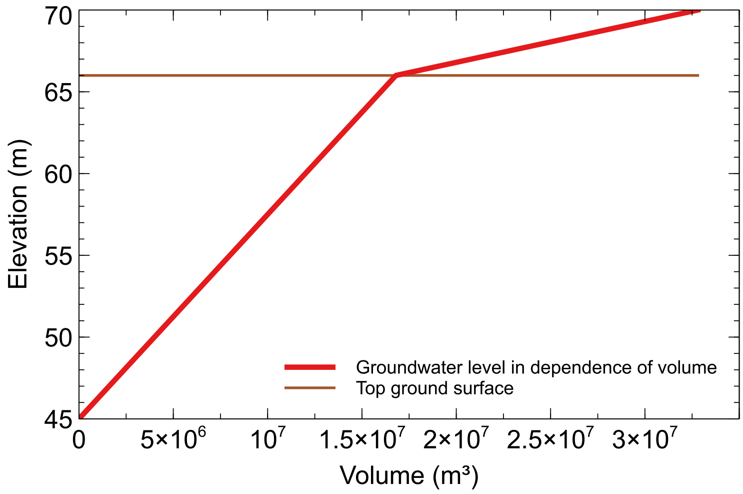

Figure 3 Relation between groundwater level and groundwater volume in a groundwater storage unit; top ground surface is at 66 m

2.2.2 Technical implementation in SOBEK

The modelling concept described in Section 2.2.1 has been implemented into the channel flow simulation software SOBEK with the help of its D-RTC-module. The implementation concept is schematically shown in Figure 4.

The first step is to determine the current groundwater level h_G in the groundwater storage unit. This is done with the help of the relation between groundwater level and groundwater volume (Figure 3), using the volume of water in the groundwater storage unit V_G from the previous time step.

The river water level h_R comes from the hydraulic computation of SOBEK (module D-Flow 1D). Now all information for the calculation of the head difference Δh is available. With the head difference, the exchange flux between river and aquifer Q is calculated. The groundwater volume in the storage unit is updated with the exchange flux, and the exchange flux is also transferred back to the channel flow simulation module as lateral inflow or outflow Q_lat, but with inverted sign. A positive head difference means a leakage flow towards the aquifer.

If the river stage is higher than the groundwater level, the lateral inflow in the open channel flow module is negative, i. e. water is withdrawn from the river to the groundwater storage unit.

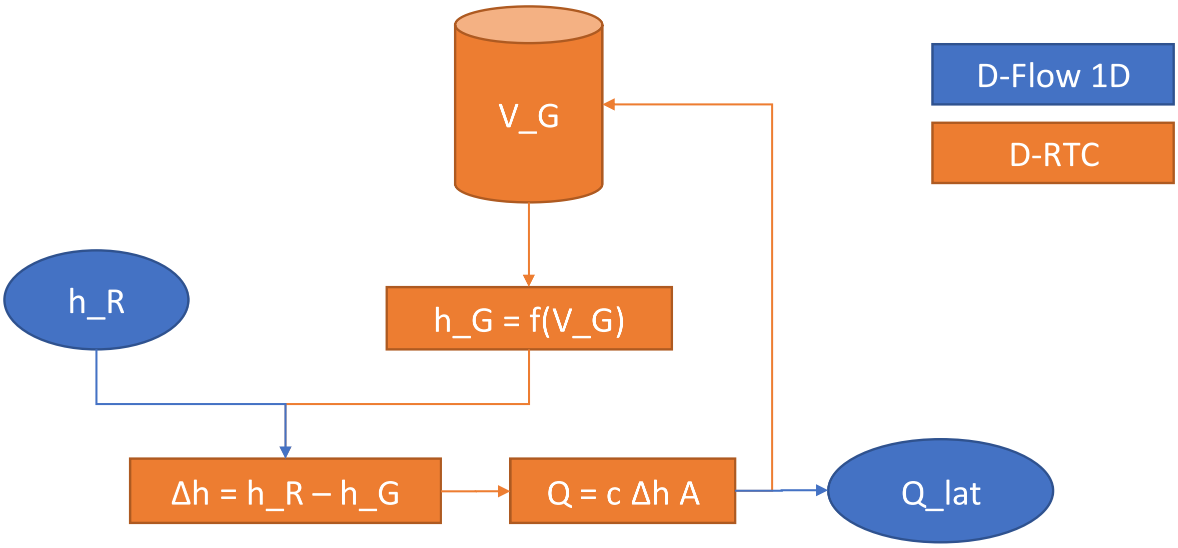

Figure 4 Concept of the groundwater module SOBEK to model river aquifer interaction with the D-RTC module

The coupling with the hydraulic channel flow simulation is explicit (Morita & Yen 2002), this means that groundwater level and river stage are taken from the previous time step when the head difference is calculated. The exchange of water between the two domains river and aquifer comes to bear not before the next time step. No iteration of head difference within one time step is carried out.

Table 1 contains the calculation steps that are carried out per time step and which D-RTC model object (trigger, rule) is used.

The SOBEK 3 model of the Rhine has already a D-RTC model component. In this model component the control of structures is implemented. The Groundwater Module SOBEK has been added to the D-RTC model component by modifying the D-RTC input files. With the Groundwater Module SOBEK the SOBEK 3 model must run within the Deltares Integrated Model Runner (DIMR). It cannot be run from the user interface, because not all elements of the Groundwater Module SOBEK are supported by the user interface. A control file with name “dimr_config.xml” controls the interaction between the channel flow module D-Flow 1D and the D-RTC module. The D-RTC input files from this DIMR export are located in the folder “rtc”, namely

- rtcDataConfig.xml (time series definition)
- rtcToolsConfig.xml (calculation logic according to Table 1)
- state_import.xml (initial groundwater volume).

Table 1 Calculation steps of Groundwater Module SOBEK

Operation	Input	Output	D-RTC feature
Derivation of Groundwater level in the groundwater storage unit from water level-volume relation	Groundwater storage from previous time step	Groundwater level [m]	Trigger: lookup table
Calculation of head difference	Groundwater level, water level from D-Flow 1D	Head difference [m]	Trigger: expression
Choice of leakage parameter for infiltration or exfiltration	Head difference	Leakage parameter [1/s]	Trigger: lookup table
Calculation of leakage flux under consideration of head difference limits	Head difference, leakage parameter	Leakage flux [m/s]	Trigger: standard, Trigger: expression
Calculation of leakage lateral flow rate	Leakage flux, wetted perimeter [m] (fixed)	Leakage lateral flow rate [m²/s]	Trigger: expression
Calculation of leakage lateral flow	Leakage lateral flow rate, length of river section [m] (fixed)	Leakage lateral flow [m³/s]	Trigger: expression
Change leakage lateral flow to opposite sign	Leakage lateral flow	Leakage lateral flow from river perspective	Trigger: expression
Leakage lateral flow volume per time step	Leakage lateral flow, time step length [s]	Leakage lateral flow volume [m³]	Trigger: expression
Add leakage lateral flow volume to groundwater storage for this time step	Groundwater storage [m³], Leakage lateral flow volume	Groundwater storage [m³]	Trigger: expression
Activate rule	n. a.	n. a.	Trigger: rule reference
Rule	Leakage lateral flow from river perspective	Lateral source in D-Flow 1D model	Rule: timeAbsolute

3 Model schematization and calibration

3.1 Model schematization of the Groundwater Module SOBEK

The SOBEK 3 model represents the Rhine from Andernach to Lobith. Process equations for river-aquifer interaction have been configured within the SOBEK D-RTC module (see Becker & Fujisaki 2022; Becker 2020c, 2020b, 2021) for seven groundwater storage units that correspond to the river segments that are separated by gauging stations:

1. Andernach – Bonn
2. Bonn – Köln
3. Köln – Düsseldorf
4. Düsseldorf – Ruhrort
5. Ruhrort – Wesel
6. Wesel – Rees
7. Rees – Lobith.

This model schematization follows Hammer 2003 and Meißner 2008. A groundwater storage unit represents the groundwater storage along a river section of the Rhine (see Figure 5 for a schematic view). The schematized groundwater storage units do not represent hydrogeological groundwater bodies. The volume of groundwater stored in the groundwater storage units is thus not meaningful by itself in a physical sense.

The exchange between river and aquifer is modelled as point exchange for a lateral inflow point between the gauging stations. For the head difference calculation, the river water level is taken from the observation point at 100 m upstream of the lateral inflow point.

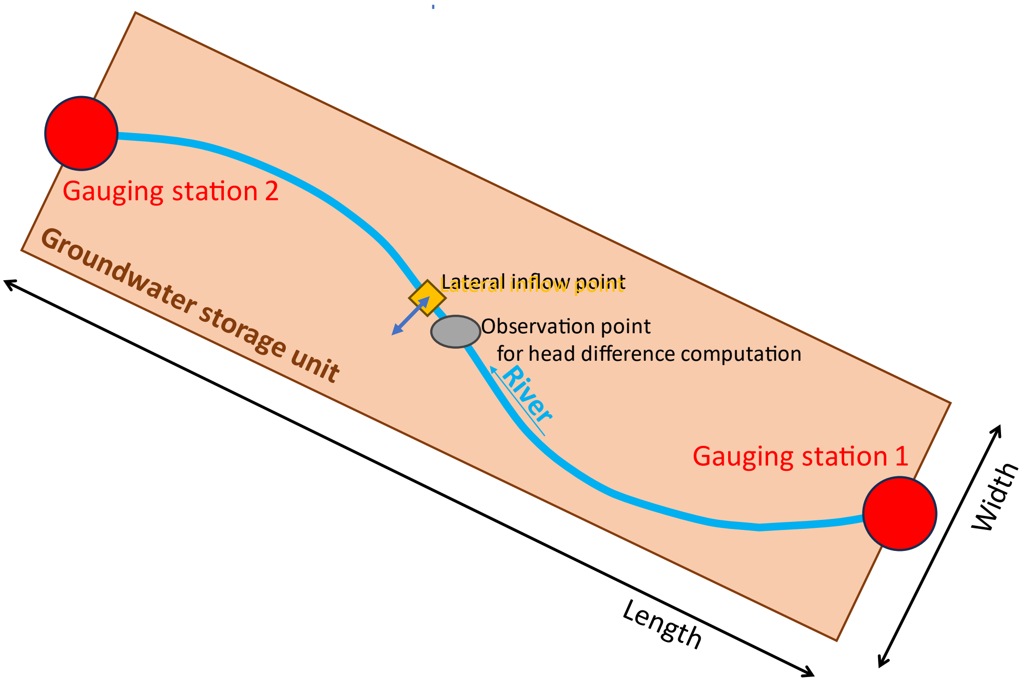

Figure 5 Groundwater storage unit between two gauging stations

With respect to the earlier reported state of the groundwater module SOBEK (Becker & Fujisaki 2022), the model schematization has been modified in such a way that the lateral inflow points, where the river-aquifer interaction is applied to in the D-Flow 1D module of SOBEK, is now located at the middle of the branch between the gauges as shown in Figure 5.

Corresponding model parameters for the groundwater storage units have been modified accordingly:

- elevation of bottom level and surface level of the groundwater storage unit
- initial water volume in the groundwater storage units.

3.2 Calibration of the Groundwater Module SOBEK

The aim of a model calibration is to adjust model parameters such that the model results match observed data. The primary model output of the Groundwater Module SOBEK is the water exchange between river and aquifer. Corresponding observation data of the river-aquifer exchange to calibrate the Groundwater Module SOBEK on is not available, because it is practically not possible to measure leakage flow, in particular not on the river segment scale and during flood events.

Earlier studies (Barneveld & Meijer 1997) have done a sort of calibration by changing parameter values in order to get good results on water level and discharge in the river. The amount of water that is exchanged between river and groundwater over time is, however, not reported. Time series of modelled river-aquifer exchange from the SOBEK model of the Rhine are available from Meißner 2008 who also changed parameter values of his groundwater module to get good results on water level and discharge in the river. Therefore, the objective of the calibration was defined to produce plausible results that match in order of magnitude of river-aquifer exchange the results from Meißner 2008. Note that this calibration data is also obtained from model simulations and not derived from field measurements.

Within the calibration, the size of the groundwater storage unit has been modified by adjusting the width of the groundwater storage unit with respect to Meißner 2008 for the flood event of 1995. For this calibration the data set exported from GRADE (a so-called bc file) was used. The resulting parameter values are given in Table 2, and more calibration results are given in Becker & Fujisaki 2022.

Table 2 Model parameters of the groundwater module SOBEK for the seven river segments

Parameter	Andernach - Bonn	Bonn - Cologne	Cologne - Düsseldorf	Düsseldorf - Ruhrort	Ruhrort - Wesel	Wesel - Rees	Rees - Lobith
Length of the groundwater storage unit (m)	39,529.00	24,622.00	35,588.00	25,179.00	23,880.00	18,768.00	18,581.00
Width of the groundwater storage unit (m)	4,750.00	7,000.00	7,500.00	12,500.00	18,500.00	5,000.00	5,000.00
Adjustment factor (-)	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Adjusted width of the groundwater storage unit (m)	3,325.00	4,900.00	5,250.00	8,750.00	12,950.00	3,500.00	3,500.00
Area of the groundwater storage unit (m^2)	131,433,925.00	120,647,800.00	186,837,000.00	220,316,250.00	309,246,000.00	65,688,000.00	65,033,500.00
Top elevation of the groundwater storage unit (m)	54.50	46.50	37.00	28.00	22.00	18.00	15.50
Nominal groundwater level in groundwater unit (m)	49.00	42.00	31.00	22.00	16.50	11.00	11.00
Elevation of groundwater storage unit base (m)	39.00	32.00	21.00	12.00	6.50	6.00	5.00
Leakage parameter, infiltration to groundwater (m/s)	5.00E-05	5.00E-05	5.00E-05	5.00E-05	5.00E-05	5.00E-05	5.00E-05
Leakage parameter, exfiltration from groundwater (m/s)	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Initial water level in groundwater storage unit (m)	44.00	34.00	23.00	24.00	18.00	13.50	11.50
Initial volume in groundwater storage unit (m^3)	131,433,925.00	48,259,120.00	74,734,800.00	528,759,000.00	711,265,800.00	98,532,000.00	84,543,550.00
Wetted perimeter for river-aquifer exchange (m)	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Height of groundwater storage unit (m)	5.50	4.50	6.00	6.00	5.50	7.00	4.50
Porosity (-)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Volume of groundwater storage unit at nominal height (m^3)	144,577,317.50	108,583,020.00	224,204,400.00	264,379,500.00	340,170,600.00	91,963,200.00	58,530,150.00
Maximum groundwater level of groundwater storage unit (m)	15.50	14.50	16.00	16.00	15.50	12.00	10.50
Maximum volume in groundwater storage unit (m^3)	407,445,167.50	349,878,620.00	597,878,400.00	705,012,000.00	958,662,600.00	157,651,200.00	136,570,350.00

The Groundwater Module SOBEK described in this report shows a much less dynamic exchange of water between river and aquifer than Meißner 2008, because the approach is fundamentally different (Appendix A). Against this background, parameters from Meißner 2008 for the geometry of the groundwater storage units have been taken as a starting point and they were only modified to a small extent in order to reach consistency in terms of the order of magnitude of river-aquifer exchange. The parameters for groundwater hydraulics, i. e. the leakage parameters, porosity, wetted perimeter for river-aquifer exchange are not included in the approach applied by Meißner 2008. The porosity values have been chosen according to literature (Ubell 1987a), leakage parameters and wetted perimeter have been set within the early phase of the calibration before adjusting the width of the groundwater storage units.

The leakage parameter (Section 2.1) incorporates the hydraulic conductivity of a sediment layer interface. The hydraulic conductivity is usually the main calibration parameter in groundwater models.

Consequently, the leakage parameter is the main calibration parameter for further calibration (Chapter 7), it directly affects the water exchange between river and aquifer. A sensitivity analysis has been carried out, too; Section 6.3 provides further insights on how the Groundwater Module SOBEK reacts on changes of different model parameters.

4 Added value of modelling river-aquifer interaction in hydraulic models

4.1 General approach

In order to analyse the added value of modelling river-aquifer interaction in the SOBEK3 model results, 3 general analyses were carried out:

1. Comparison of simulation results of the SOBEK 3 model with groundwater module to data from observations
2. Comparison of simulation results of the SOBEK 3 model with groundwater module to simulation results of the SOBEK 3 model without groundwater module
3. Comparison of simulation results of the SOBEK 3 model with groundwater module to simulation results SOBEK-RE (also with river-aquifer interaction).

This analysis has been done for three historical flood events:

- Flood event 1995
- Flood event 1993
- Flood event 1988; this scenario has two peaks.

4.2 Scenario data

To simulate a flood event with a hydraulic model, consistent boundary conditions must be compiled. A set of boundary conditions is called scenario. For the SOBEK model this means providing a discharge time series for the upstream boundary condition at Andernach and time series of lateral inflow from tributaries and diffusive lateral sources. Diffusive lateral inflow is assigned to inflow from so-called “Zwischeneinzugsgebiete” (German for the part of a river basin between two gauging stations, abbreviated “ZEG” or “ZWE”, Hegnauer & Becker 2013) In addition, time series of discharge and water levels for the gauging stations Bonn, Cologne, Düsseldorf, Ruhrort, Wesel, Rees and Lobith are needed for comparison.

The following data sources are available:

- The HyMoG dataset. The HyMoG dataset is the result of a comprehensive water balance analysis of the Rhine (Steinrücke et al. 2011b, 2011a). Primary goal of HyMoG was to create reliable time series of (measured) discharge and water levels as well as rating curves for various locations of interest in the Rhine and its major tributaries between lake Constance (Bodensee) and Lobith as a basis for hydrological and hydraulic modelling (German: “**hy**drologische **Mo**dell**g**rundlagen”). HyMoG data is available only for the flood events 1993 and 1995, but not for 1988.
- Data (model results) from GRADE. GRADE exports a data file that can be read by SOBEK 3 directly (bc file format). The GRADE data is a composition of multiple model results:
  - The upper boundary condition at Andernach is derived from the hydraulic model SOBEK RE.
  - Some major tributaries to the Rhine are used in the SOBEK3 model as boundary condition (Lippe, Ruhr, Sieg). The inflow time series is generated with the hydrological model HBV.

  - Other major tributaries to the Rhine are modelled as lateral inflow. The inflow time series are generated with the hydrological model HBV, too.
  - Lateral inflow from minor tributaries and diffusive inflow are lumped together, this data also comes from the GRADE hydrological model HBV.
  - Water level and discharge time series for the gauging stations within the model are derived from a hydraulic model, in our case relevant is the SOBEK-RE model of the Rhine.

Both data sets have advantages and drawbacks: With its hydrological model and its hydraulic model, GRADE produces a consistent data set where comparison data for the gauging stations and lateral boundary conditions can be derived from. However, the GRADE data is simulated data, not observed. The HyMoG data set is based on observations but does not contain diffusive lateral inflow to the Rhine nor inflow from minor tributaries.

To make best use of the available data for the scenario analysis, the two data sets were used as follows:

Data set GRADE:

- The data export from GRADE is used without modifications.
- This data set is used to compare results from SOBEK-RE and SOBEK 3 and as boundary conditions for simulations with the new model.

Dataset GRADE-HyMoG:

- The dataset GRADE-HyMoG is used
  - to compare simulation results from SOBEK 3 with the groundwater module SOBEK to observed data.
  - to compare SOBEK 3 model results with groundwater module being activated and not being activated.
- The data set GRADE-HyMoG has been compiled as follows:
  - The simulation results from GRADE are taken as basis.
  - The upper boundary condition is replaced with data from HyMoG.
  - The time series for boundary conditions and lateral inflow are replaced with observed data where available; this is the case for the following tributaries:
    - Sieg
    - Wupper
    - Erft
    - Ruhr
    - Emscher
    - Lippe
  - For diffusive lateral inflow and minor tributaries that are not further specified in HyMoG, the GRADE data remains. This lateral inflow is lumped in the so-called “Zwischeneinzugsgebiete”

For the flood event 1988, only the GRADE data set is available. This event is not covered with the HyMoG data.

Table 3 gives an overview of the data sources for the data sets and different models. The following sections describe the scenario analysis for the three flood events.

Table 3 Configuration of model boundaries and source data sets

Data set		GRADE	GRADE	GRADE-HyMoG
Available for Models		SOBEK-RE	SOBEK 3 (with Groundwater Module SOBEK)	SOBEK 3 (with and without Groundwater Module SOBEK)
Model data and data source				
Upper boundary	Rhine discharge at Andernach	Not applicable; Andernach is not a model boundary	Result from SOBEK-RE model generated within GRADE	HyMoG
Other boundaries	Discharge Sieg (Menden) Discharge Ruhr (Mühlheim) Discharge Lippe (Schermbeck)	HBV	HBV	HyMoG
Lateral inflow	Discharge of major tributaries Wupper, Erft and Emscher	HBV	HBV	HyMoG
	Discharge of minor tributaries (not further specified)	HBV	HBV	HBV
	Diffusive lateral inflow	HBV	HBV	HBV

The initial conditions for the hydraulic models come from GRADE. To reach consistency within the model the boundary condition data foresees a pre-event time with normal inflow conditions before the flood event to give the model room to align itself to the initial conditions.

The initial groundwater level in the groundwater storage units represent normal conditions (see Table 2). Section 6.3.4 deals with the model sensitivity on the initial groundwater level.

4.3 Comparison of SOBEK 3 simulation results with data from observations (GRADE-HyMoG dataset)

4.3.1 Flood event 1995

The following figures show simulation results from the SOBEK 3 model with the Groundwater Module SOBEK for gauging stations Andernach, Köln (Cologne), Rees and Lobith together with comparison data from the HyMoG data set. Results for all stations along the Rhine are shown in Appendix B.1.1. In the first two diagrams of each figure, water level and discharge for the gauging stations are shown, respectively. In these diagrams, the following entries are used for titles and legends:

- SOBEK3 denotes the result from a hydraulic computation with SOBEK 3. The groundwater module SOBEK (GWM) is active.
- GRADE-HyMoG refers to the boundary conditions according to Section 4.1 and Table 3.
- HyMoG represents the water level or discharge from the HyMoG data base. This data is based on observations.

For all gauging stations except Andernach a third diagram shows results from the groundwater module SOBEK. The river-aquifer interchange computed with the groundwater module is calculated for the river section upstream of the gauging station. The groundwater level corresponds to the storage of groundwater in the groundwater storage unit and cannot be directly compared to the water level in the same figure, because the groundwater storage unit is located several kilometres upstream of the gauging station. Note that there is no corresponding object to this groundwater level in the real world.

The leakage flow is the amount of water exchanged within the D-Flow module of SOBEK 3 (the hydraulic modelling component) and the groundwater module SOBEK (the D-RTC model component).

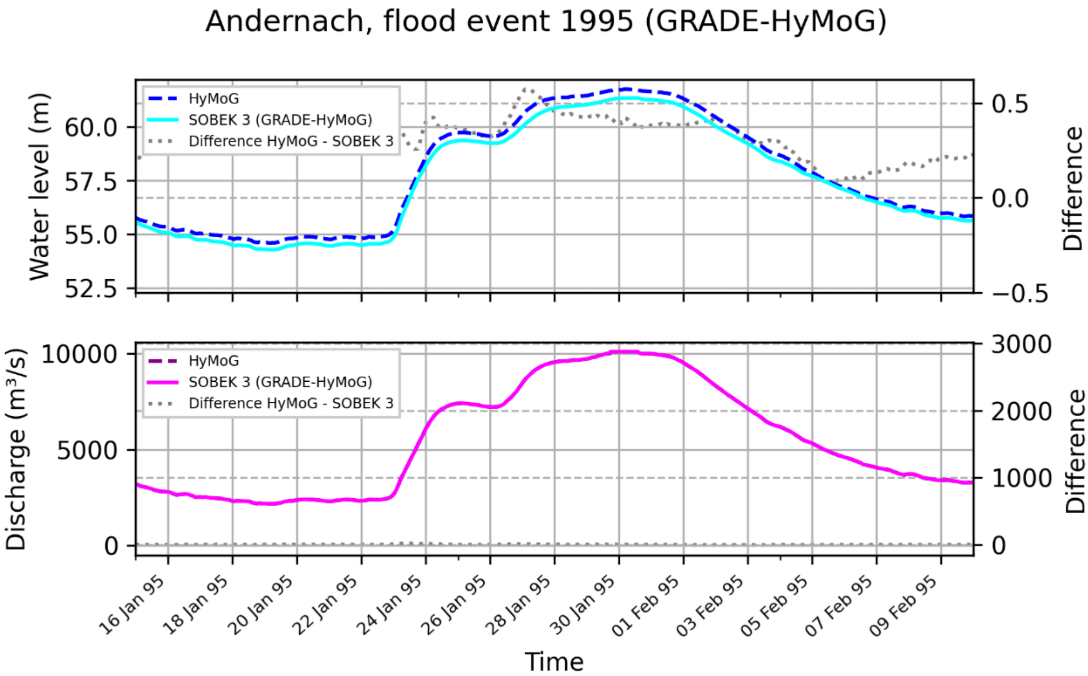

Figure 6 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Andernach, flood event 1995

At Andernach (Figure 6) the discharge curve from HyMoG and SOBEK3 are identical, because the HyMoG data is set as discharge boundary condition here. For the other locations, the SOBEK 3 model follows the corresponding HyMoG data quite well, too. Except for Rees (Figure 8), the discharge computed with SOBEK 3 with groundwater module SOBEK is lower than the HyMoG discharge. Note that the SOBEK 3 model is the result of a migration from an earlier version (Appendix A, Table 19, Line No. 4). After the migration the model has not been calibrated thoroughly again. The groundwater module models river-aquifer interaction and withdraws water from the river, which explains that the groundwater module reduces the discharge. The effect of the Groundwater Module SOBEK on discharge and water level is subject of Section 4.4. In this section model results without the Groundwater Module SOBEK are presented.

Water levels don’t match exactly at Andernach, because the water level is a model result, and the modelled water level is impacted by the situation in the model further downstream under conditions of sub-critical flow so backwater effects can reach the upper model boundary.

The interchange of water between river and aquifer depends on the difference between river stage and groundwater level (Section 2, Becker 2020b). The groundwater level in the groundwater storage unit rises with the flood wave. The exchange rate is different for the river reaches, for Bonn the exchange rate takes values in the order of 100 m³/s. This matches to the quantity that has been reported in other studies (Meißner 2008; Ubell 1987a, see also Becker & Fujisaki 2022). After the flood wave has passed, the groundwater level remains high until the end of the simulation period. The falling river water level reduces the head difference such that the leakage flow becomes small by the end of the simulation period. The groundwater level does not fall within the period shown.

This matches to observations of so-called subsurface flood events (Becker et al. 2022; Becker 2010; Sächsisches Landesamt für Umwelt und Geologie 2003) and has mainly two reasons:

- During flood conditions, erosion processes at bank and riverbed take place. This reduces the hydraulic resistance for water entering the aquifer (Becker et al. 2015; Simpson & Meixner 2012; Blaschke 2002). In the Groundwater Module SOBEK, a smaller leakage parameter has been set for exfiltration than for infiltration.
- During the flood event, the absolute value of the head difference is higher than during normal conditions and low flow conditions. This is because the flood stage is much higher with respect to the normal water level than the river stage during normal or low flow conditions.

Consequently, it can take several months until the groundwater level reaches normal conditions after the flood event.

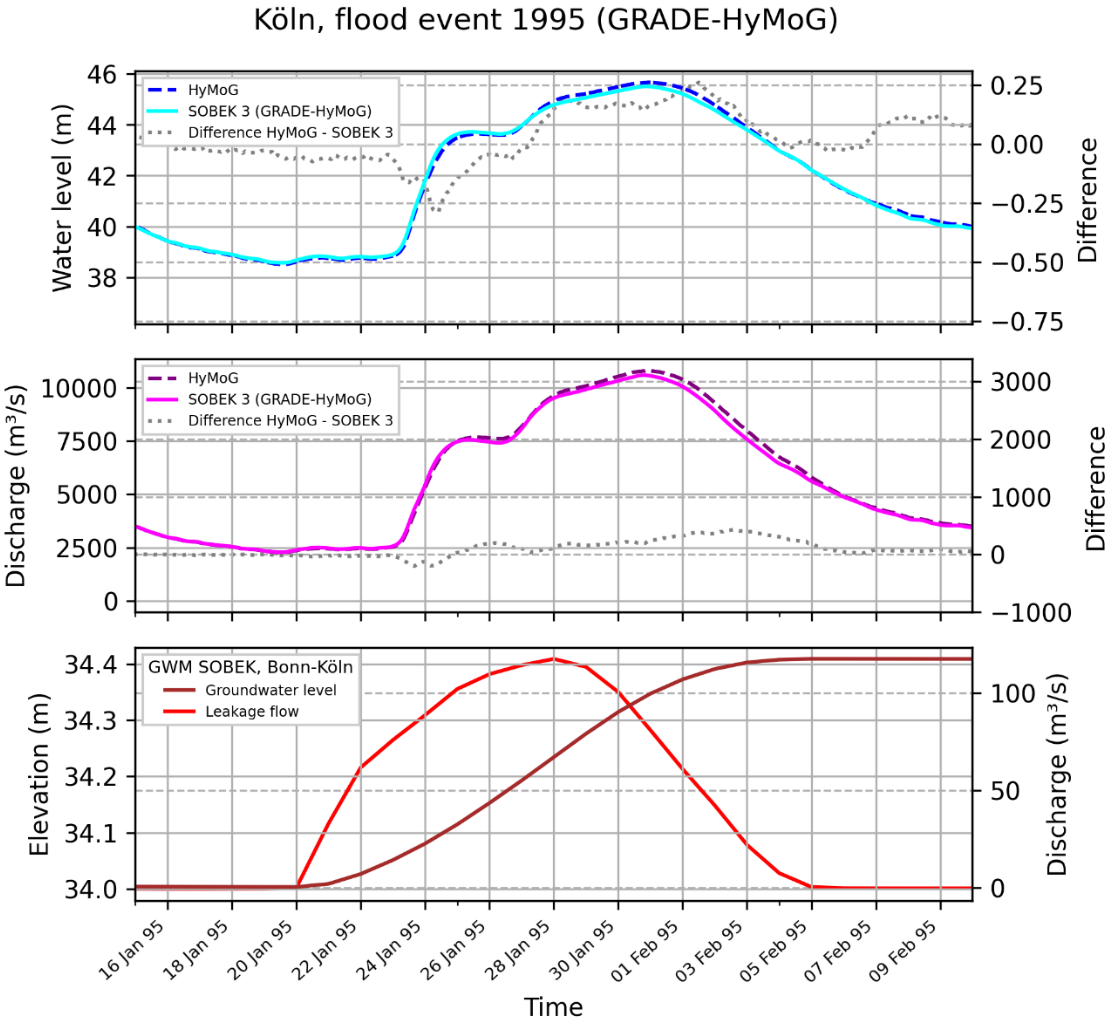

Figure 7 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Köln, flood event 1995

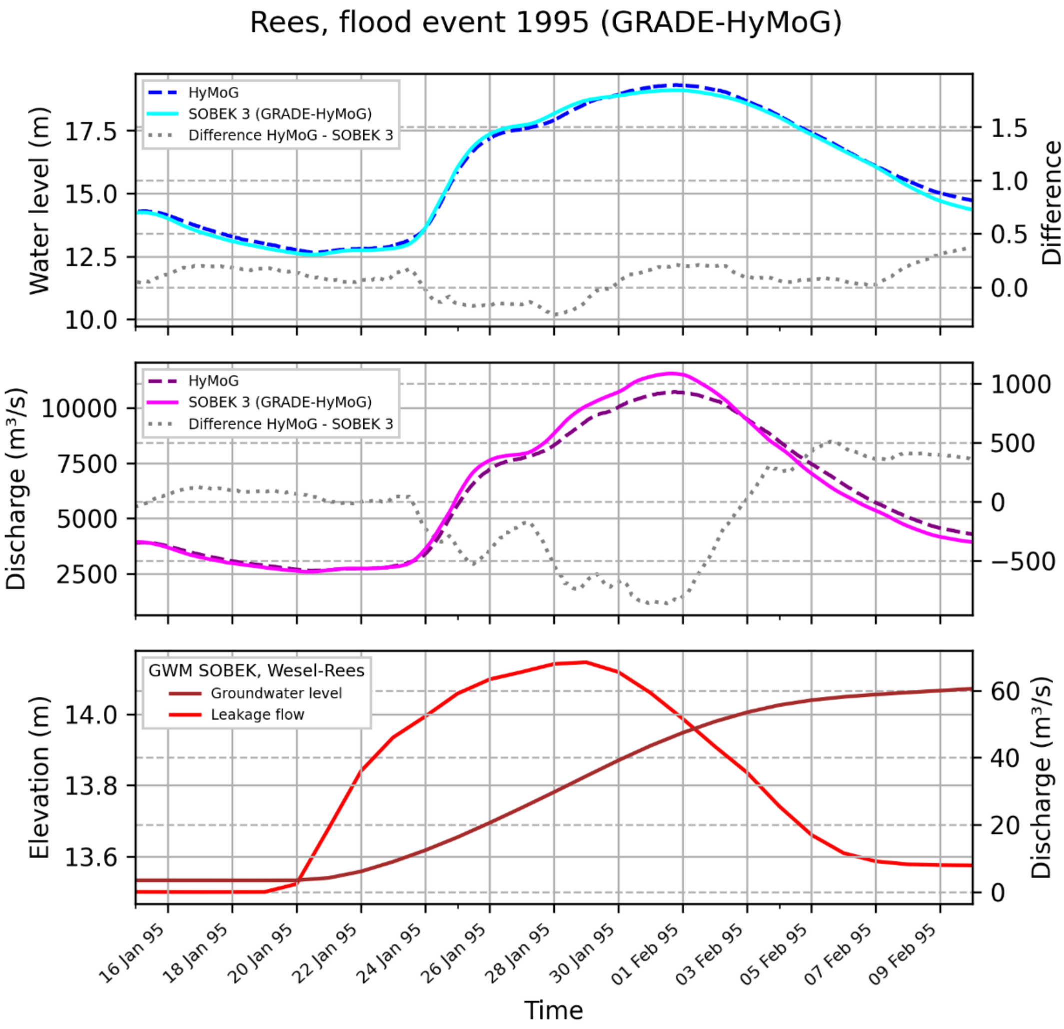

Figure 8 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Rees, flood event 1995

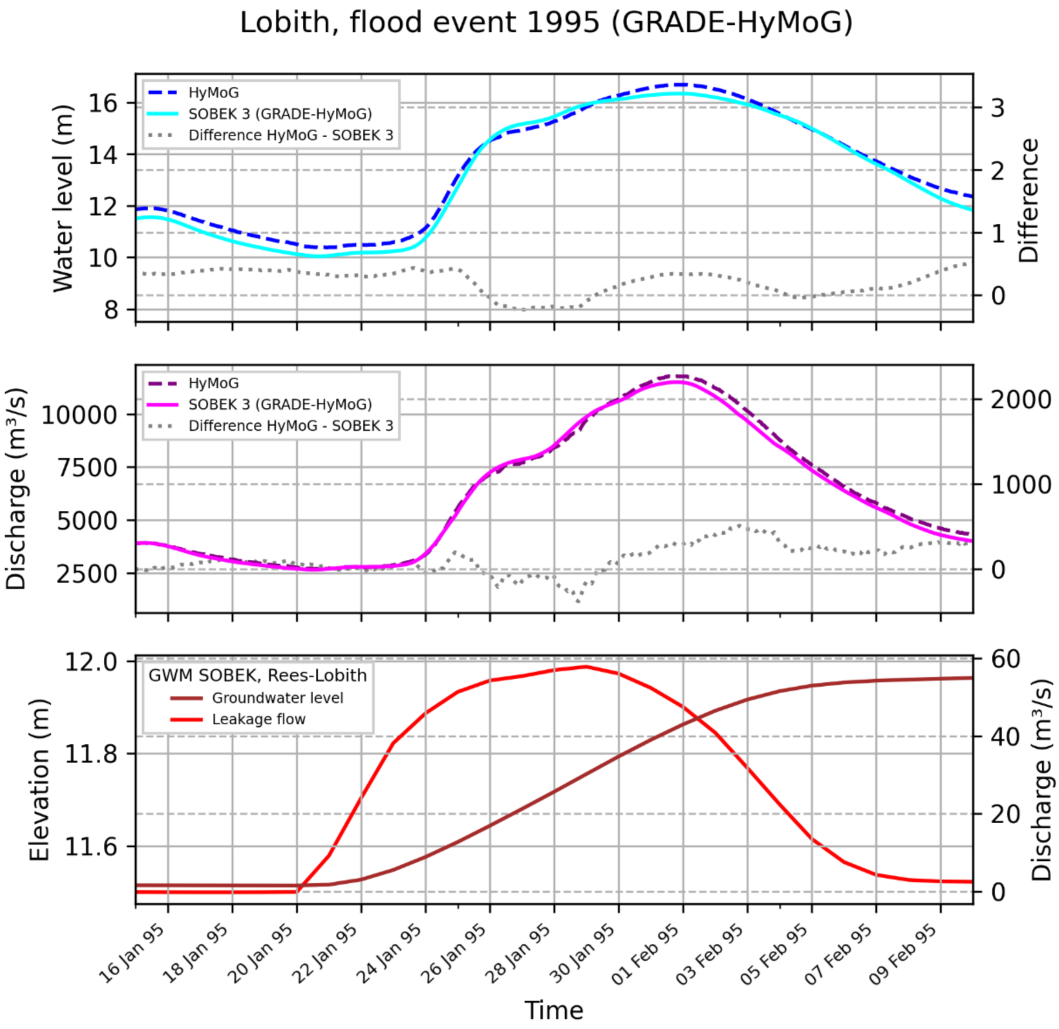

Figure 9 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Lobith, flood event 1995

4.3.2 Flood event 1993

The results from simulations with SOBEK 3 with groundwater module SOBEK and the GRADE-HyMoG dataset as boundary conditions for the flood event 1993 together with the corresponding HyMoG data are given in the following figures for selected gauging stations. Appendix B.1.2 contains the results for all gauging stations. The comparison shows a similar pattern like the flood event 1995 (Section 4.3.1): simulated discharges are lower for all stations except Rees, and location Rees shows a large deviation from observed values. In general, the SOBEK 3 result shows quite a good match to the data that is based on observations (HyMoG). The exchange rate of water between river and aquifer and the groundwater level in the groundwater storage units reflect the two peaks of the flood wave. When the river water level goes down between the two peaks the head difference between river and aquifer follows, consequently the leakage flow decreases, too.

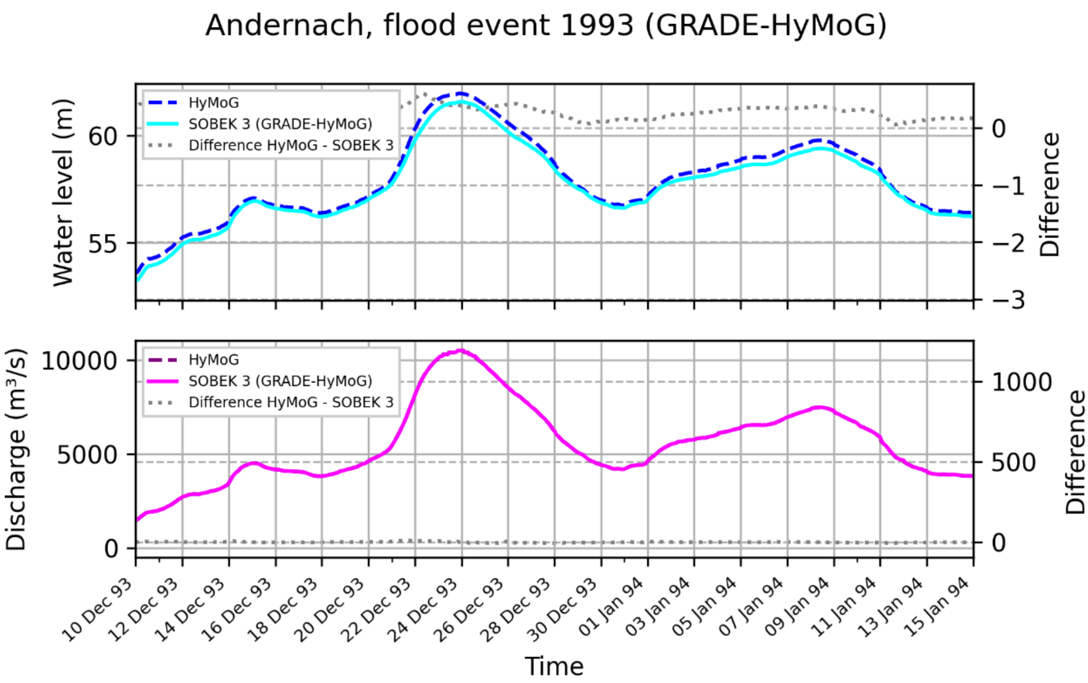

Figure 10 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Andernach, flood event 1993

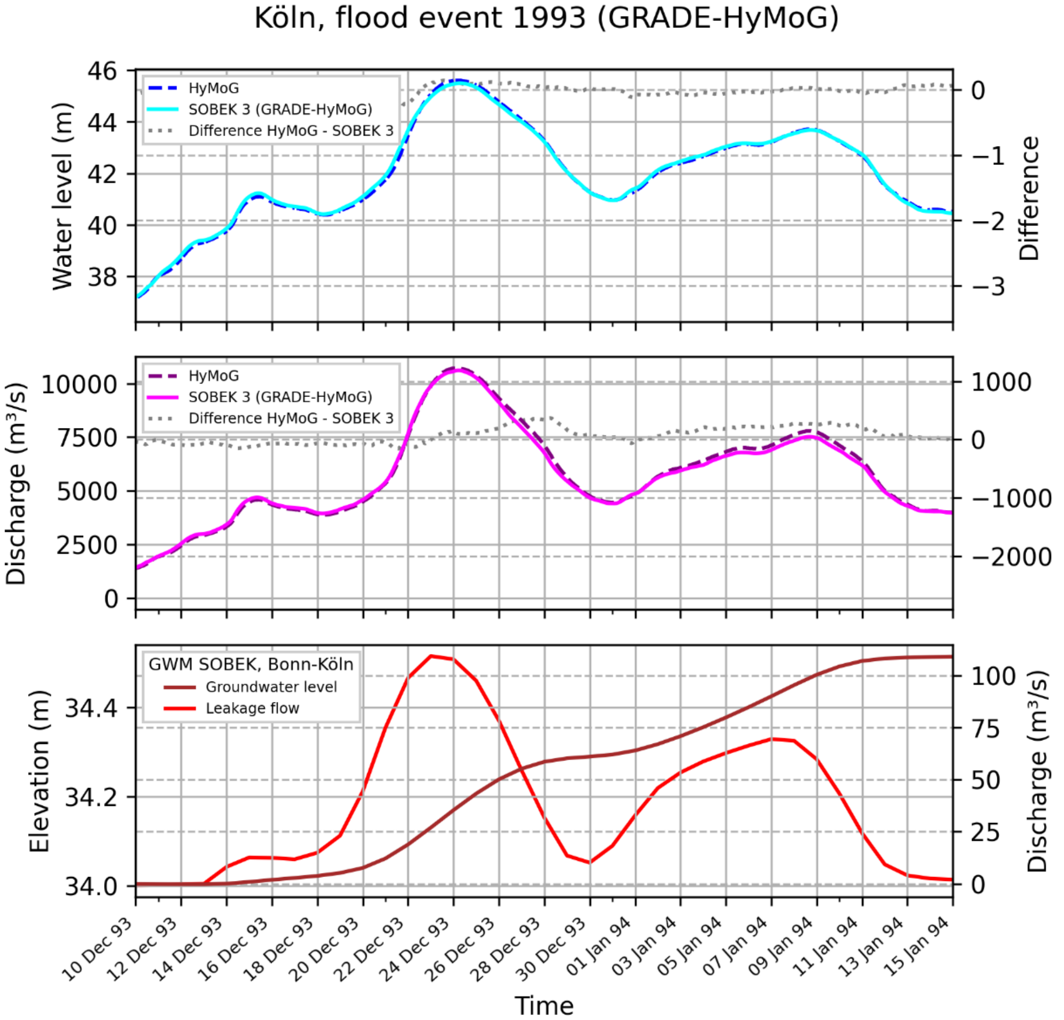

Figure 11 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Köln, flood event 1993

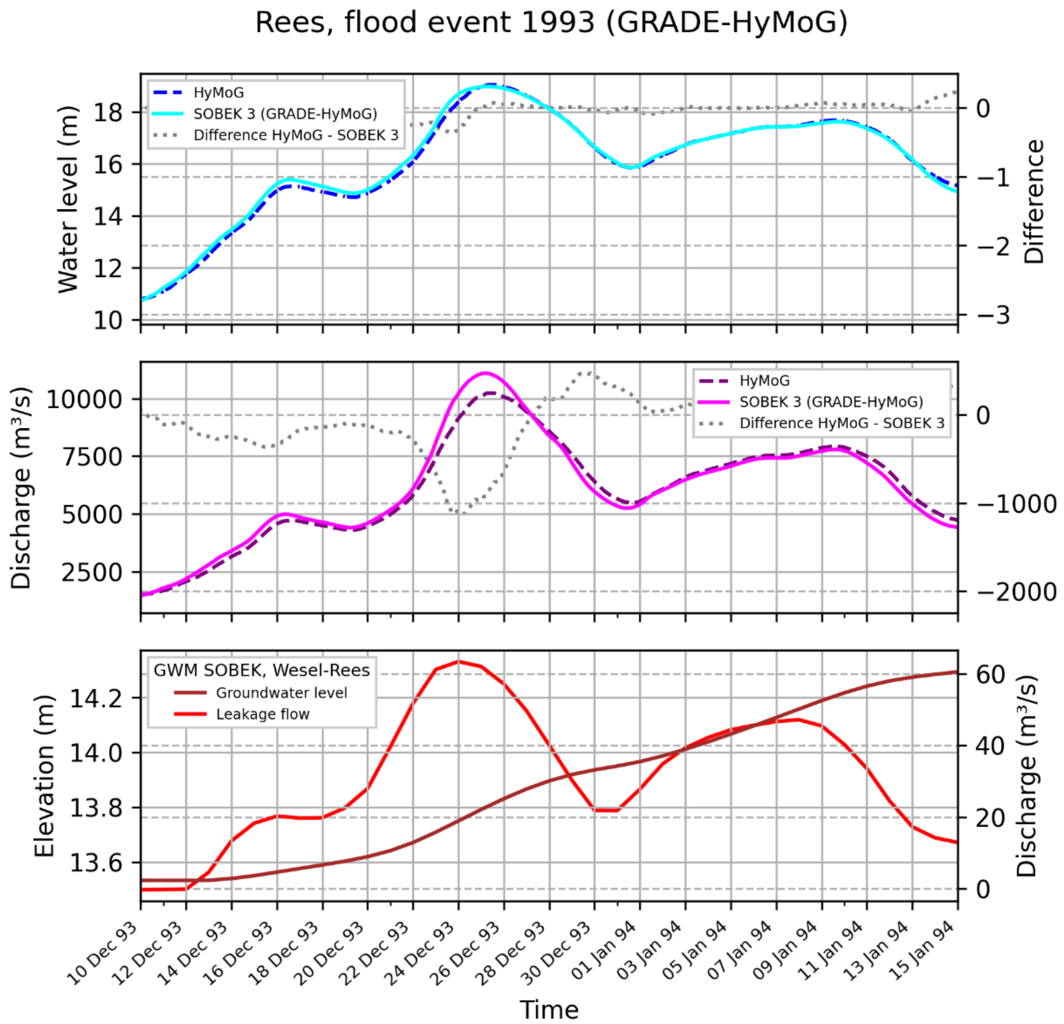

Figure 12 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Rees, flood event 1993

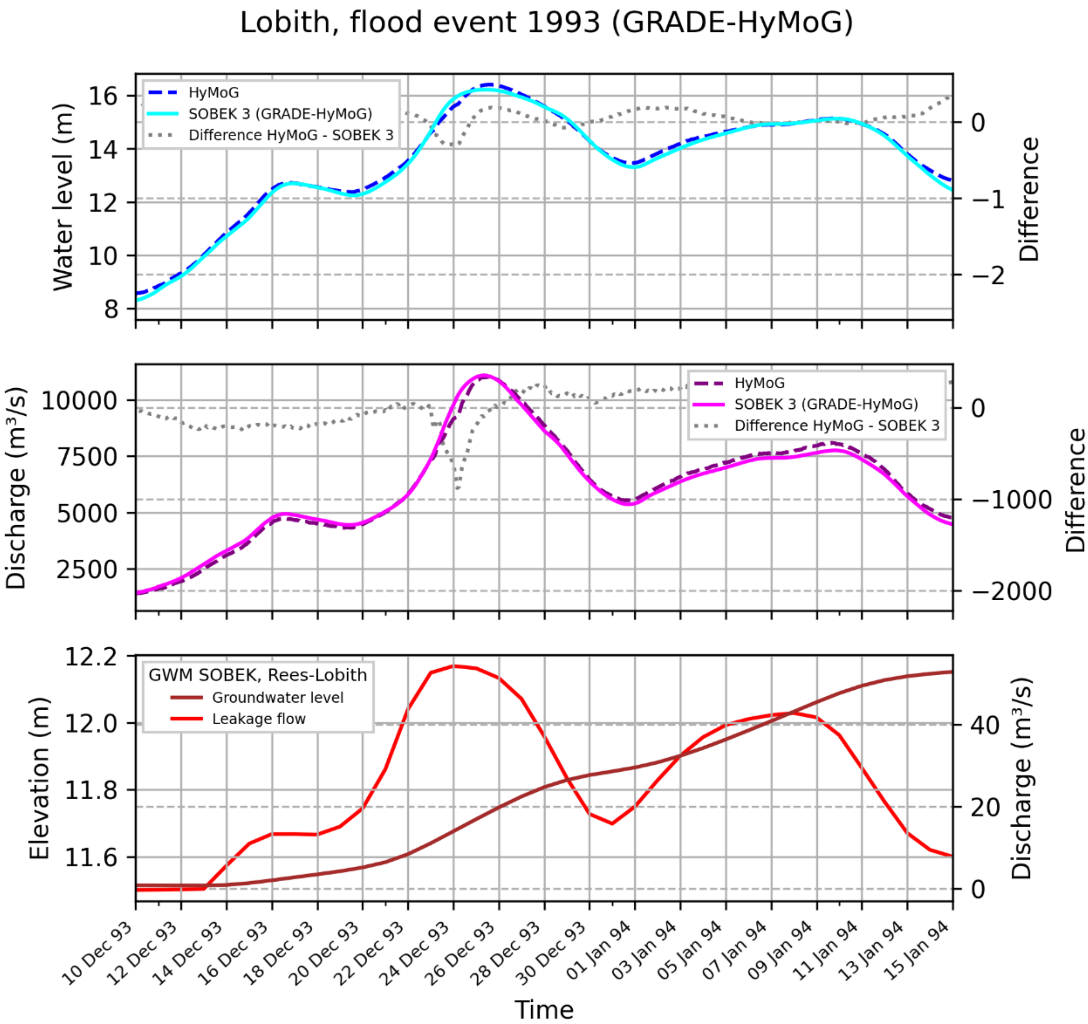

Figure 13 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Lobith, flood event 1993

4.4 Contribution of the river-aquifer interaction to the discharge (GRADE-HyMoG dataset and GRADE data set)

4.4.1 Flood event 1995

While the previous section shows that the results obtained with the groundwater module SOBEK are quantitatively in the expected range with respect to reference data, in this section a comparison of simulation runs with and without the groundwater module SOBEK is carried out to show the impact and the added value of the groundwater module SOBEK.

Figure 14 to Figure 17 show simulation results from SOBEK 3 for the 1995 flood event with the groundwater module SOBEK being active and not active and the corresponding HyMoG data for Andernach, Köln, Rees and Lobith (for all stations see Appendix B.2.1). The figures show that the groundwater module SOBEK reduces the computed river discharge. This is due to the bank storage effect the groundwater module models: the exchange between river water and groundwater has parts of the river water temporarily stored in the lateral groundwater storage units during the flood event. At the most upstream sections this effect is barely visible, because the total amount of exchanged water is small. For Andernach there is no difference at all, because this is the upper boundary of the model and the water exchange modelled in the Section between Andernach and Bonn has no effect here.

The amount of water stored in the groundwater storage unit accumulates with the course of the river: the further downstream the river section is located the larger is the effect of the groundwater storage on the flood wave.

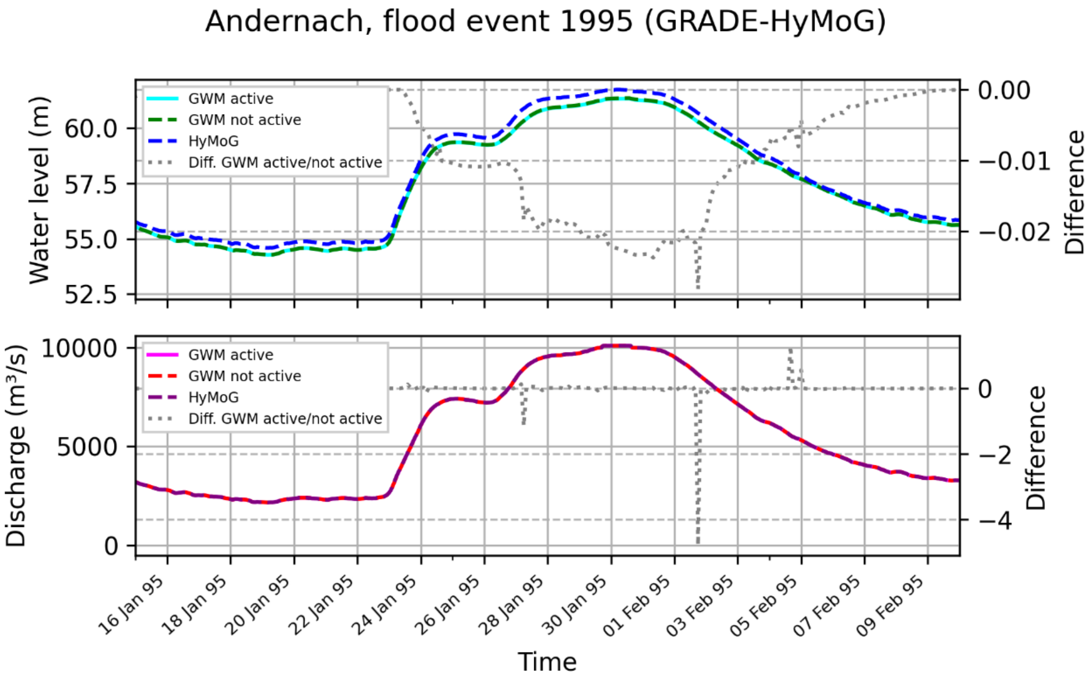

Figure 14 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1995

In terms of matching the HyMoG data, for the downstream stations Rees and Lobith the groundwater module means an improvement for the simulated discharge, while for the other stations the discharge deviates more from the HyMoG data with groundwater module active, but only to a small extent. For the water level, the groundwater module is advantageous for the gauging stations Ruhrort, Wesel, Rees and Lobith. For the other gauging stations, the groundwater module means a slightly larger deviation from the corresponding HyMoG data.

The figures also show the difference between groundwater module active and inactive for water level and discharge. Differences are high during the flood wave, but the largest difference is not necessarily at the flood peak. Water level differences reach 10 to 25 cm for different stations, and the difference in discharge becomes more than 700 m³/s at Lobith.

For some stations, including Lobith, the line of simulated discharge with groundwater module active crosses the corresponding line of HyMoG discharge: close to the discharge peak the simulated discharge with groundwater module active is lower than the simulated discharge with groundwater module not active, this means a larger deviation to the HyMoG discharge. In the rising limb of the discharge curve, however, the simulated discharge with groundwater module active is closer to the HyMoG discharge than the simulated discharge with groundwater module not active.

Table 4 shows the computed discharge peak (maximum discharge) for each gauging station obtained with active and inactive groundwater module SOBEK, the difference between the two, and the difference of the two model results (groundwater module not active and active) compared to the discharge peak of the HyMoG data. Again, at Andernach there is no difference between the two simulation runs with and without groundwater model, because Andernach is the upper boundary and for this location the effect of river-aquifer interaction has not come to bear yet, and the discharge peak value is identical with the HyMoG data, because the HyMoG discharge is set as boundary condition. At Lobith the difference in peak discharge is 533 m³/s. Note that the maximum difference in discharge and water level between the simulation result with groundwater module active and not active is not at the discharge peak, as the figures above show.

Comparing the peak discharge with the HyMoG data set, the results are mixed: for some locations the groundwater module improves the result in terms of absolute values, for others not. For Rees the peak discharge of the SOBEK results with groundwater module active is closer to HyMoG than the result obtained without groundwater module. For Lobith the sign changes, i. e. the discharge peak is smaller than the discharge peak in the HyMoG data set. For Bonn and Köln the groundwater module changes the deviation to the worse.

Table 4 Comparison of peak discharge computed with SOBEK 3 with groundwater module SOBEK not active and active for the flood event of 1995, difference between the two, peak discharge in HyMoG and the difference of the two model results with Groundwater Module SOBEK not active and active to the HyMoG data

Gauging station	Peak discharge in m³/s, Groundwater module not active	Peak discharge in m³/s Groundwater module active	Difference in peak discharge in m³/s, Groundwater module active/not active	Peak discharge HyMoG in m³/s	Difference in peak discharge in m³/s, Groundwater module not active/HyMoG	Difference in peak discharge in m³/s, Groundwater module active/HyMoG
Andernach	10100	10100	0	10100	0	0
Bonn	10175	10072	104	10543	-368	-471
Köln	10819	10605	214	10814	5	-209
Düsseldorf	10913	10582	331	10710	203	-128
Ruhrort	11725	11295	430	11526	200	-230
Wesel	11767	11272	494	11887	-120	-615
Rees	12035	11541	494	10715	1321	827
Lobith	12039	11505	533	11821	218	-316

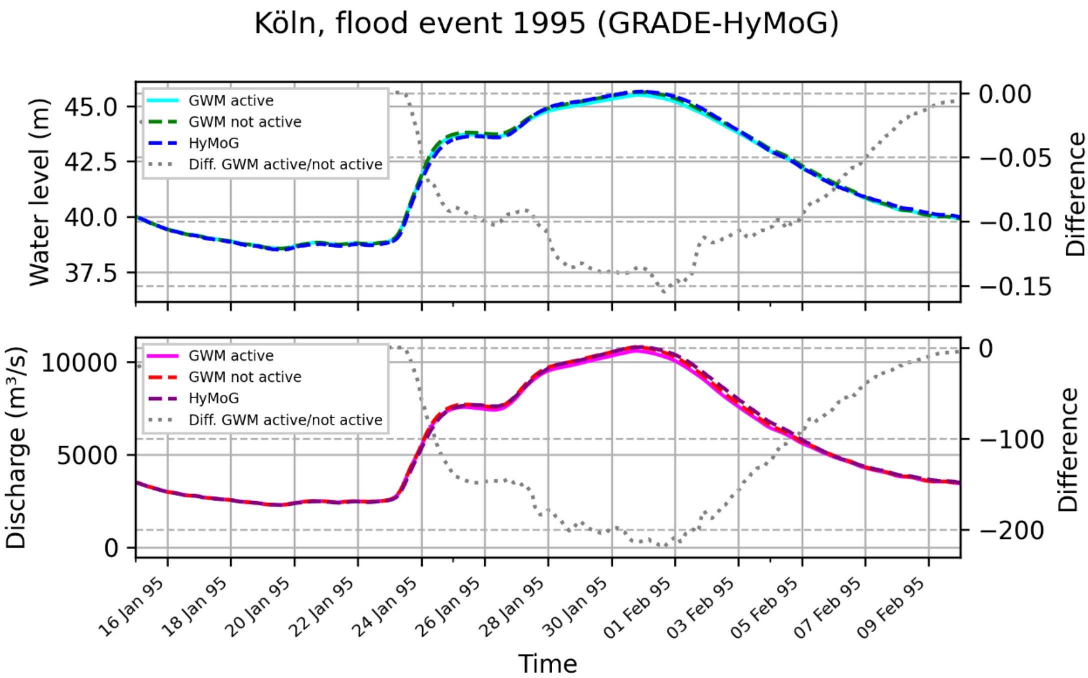

Figure 15 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1995

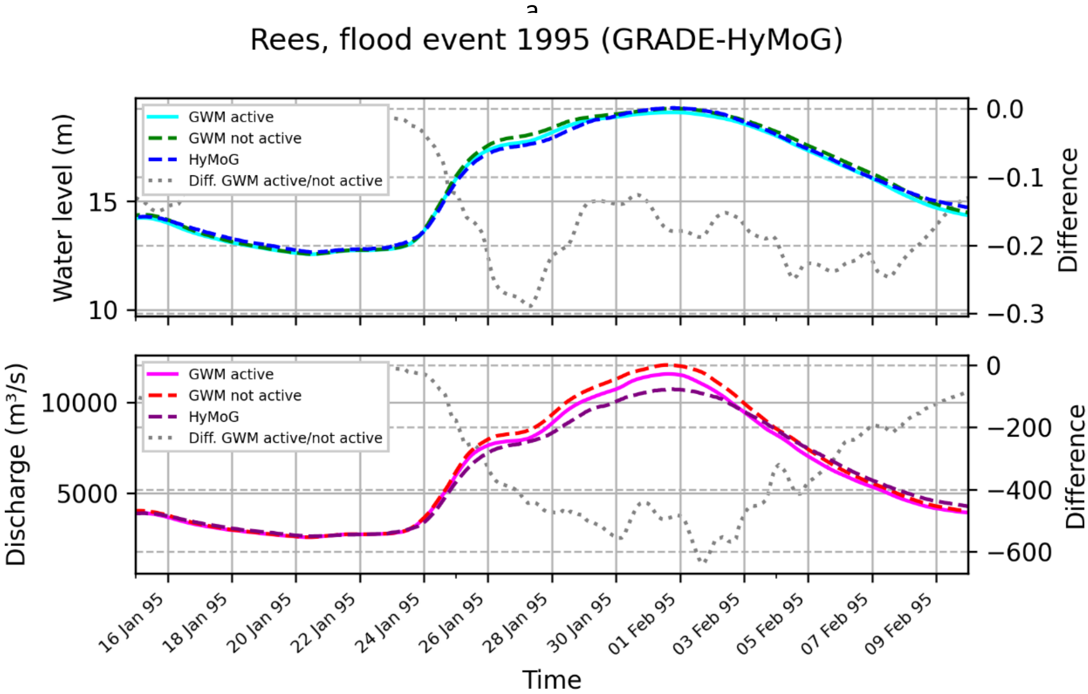

Figure 16 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1995

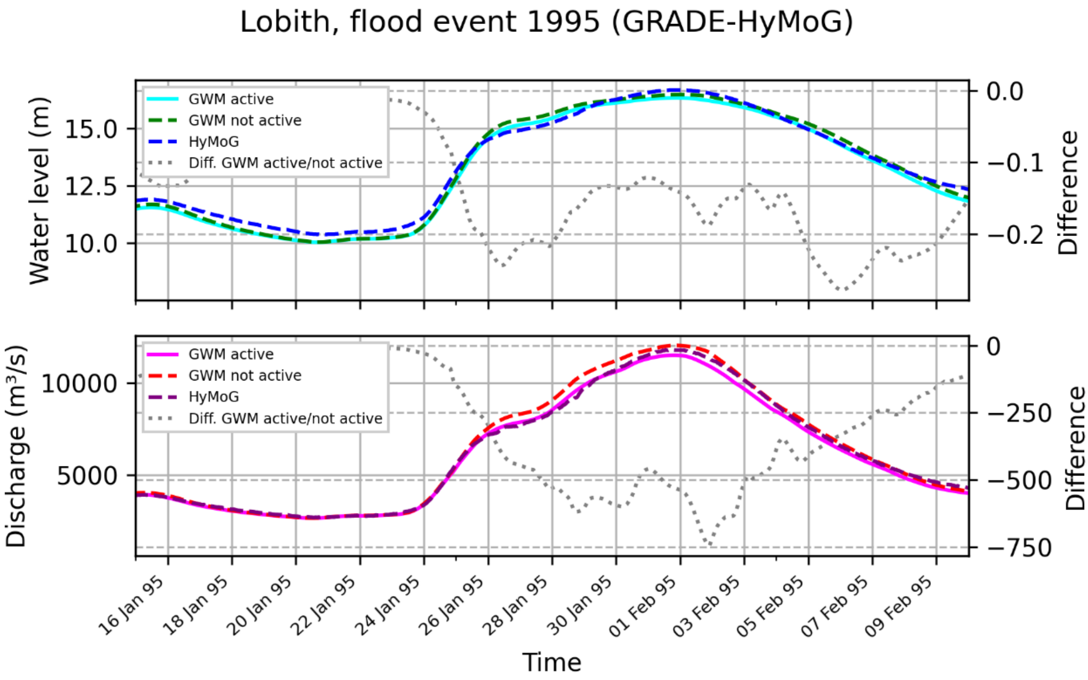

Figure 17 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1995

4.4.2 Flood event 1993

Like for the flood event 1995 (Section 4.3.1), the comparison of a simulation with SOBEK 3 with active and not-active groundwater module shows an improvement in terms of matching HyMoG data for the gauging stations further downstream, but at stations further upstream the simulation results deviate more from HyMoG data with groundwater module active.

The contribution of the groundwater module SOBEK results in a discharge reduction of more than 600 m³/s at Lobith, and the water level reduces up to 10 to 30 cm.

The comparison of peak discharges in Table 5 shows that for most stations the groundwater module provides an improvement for the match between the HyMoG discharge peak in particular for the three downstream locations Rees, Wesel and Lobith. Here, the groundwater module SOBEK reduces the deviation of the SOBEK model result to the HyMoG discharge peak without changing the sign of the difference, i. e. the discharge peak in the SOBEK model result is still above the HyMoG peak when activating the groundwater module. The deviation of discharge between simulation result and HyMoG data remains very high at Rees.

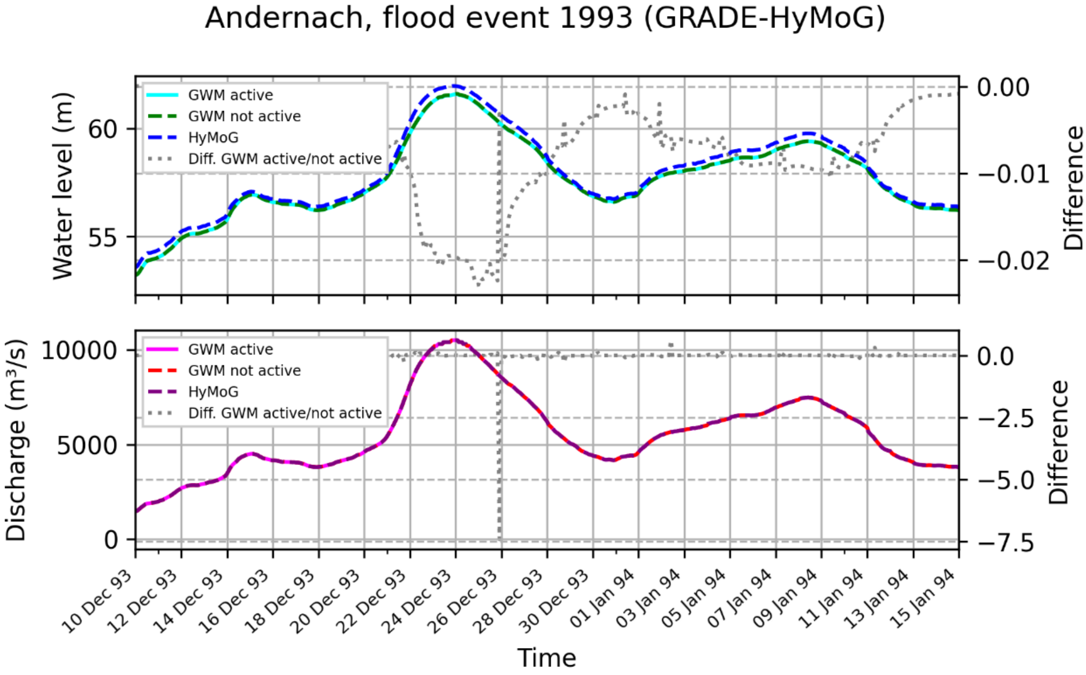

Figure 18 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1993, flood event 1993

Table 5 Comparison of peak discharge computed with SOBEK 3 without and with groundwater module SOBEK for the flood event of 1993

Gauging station	Peak discharge in m³/s, Groundwater module not active	Peak discharge in m³/s Groundwater module active	Difference in peak discharge in m³/s, Groundwater module active/not active	Peak discharge HyMoG in m³/s	Difference in peak discharge in m³/s, Groundwater module not active/HyMoG	Difference in peak discharge in m³/s, Groundwater module active/HyMoG
Andernach	10500	10500	0	10500	0	0
Bonn	10547	10442	105	10668	-121	-226
Köln	10828	10614	214	10712	116	-98
Düsseldorf	10883	10553	330	10585	298	-32
Ruhrort	11314	10922	392	11047	267	-125
Wesel	11387	10918	470	11296	91	-378
Rees	11630	11104	526	10237	1393	867
Lobith	11635	11063	573	11026	609	37

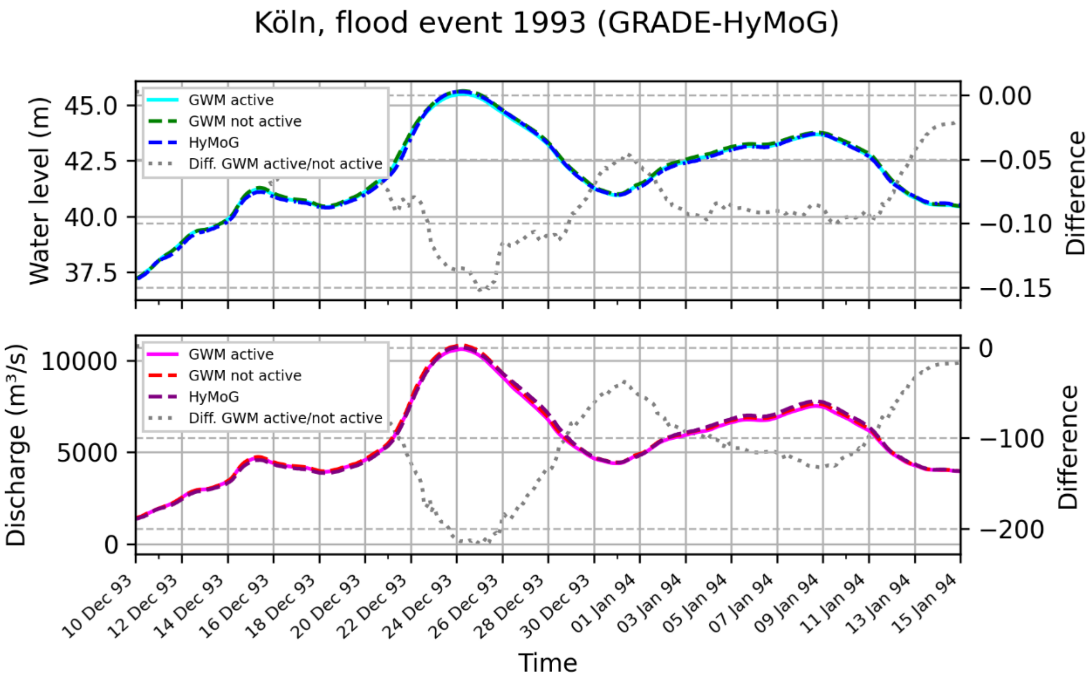

Figure 19 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1993

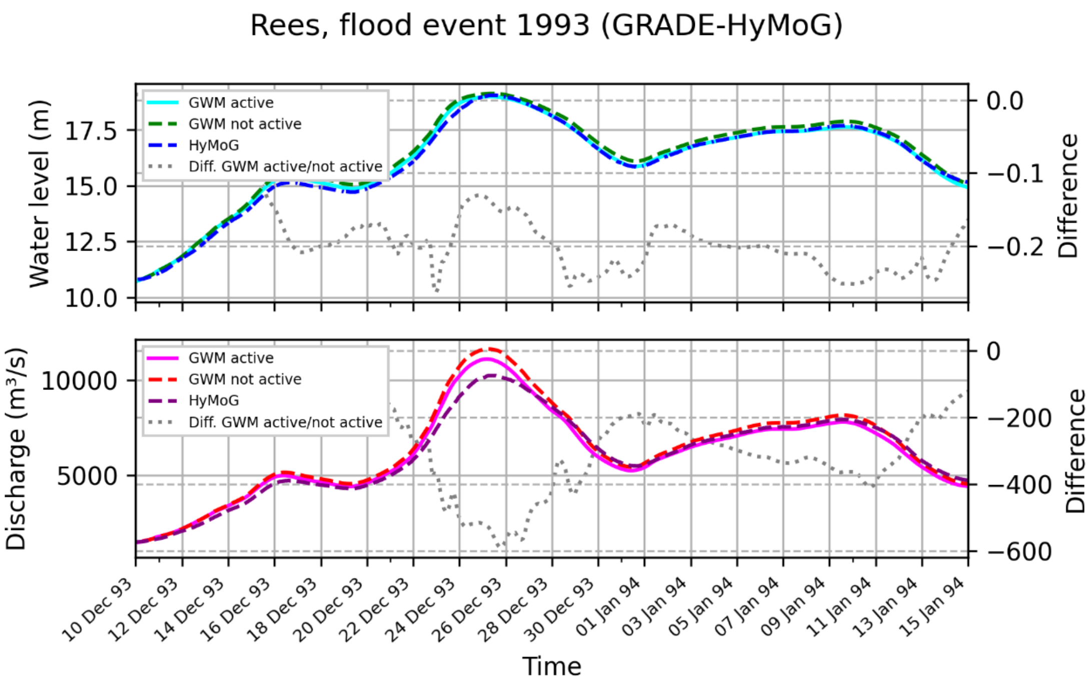

Figure 20 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1993

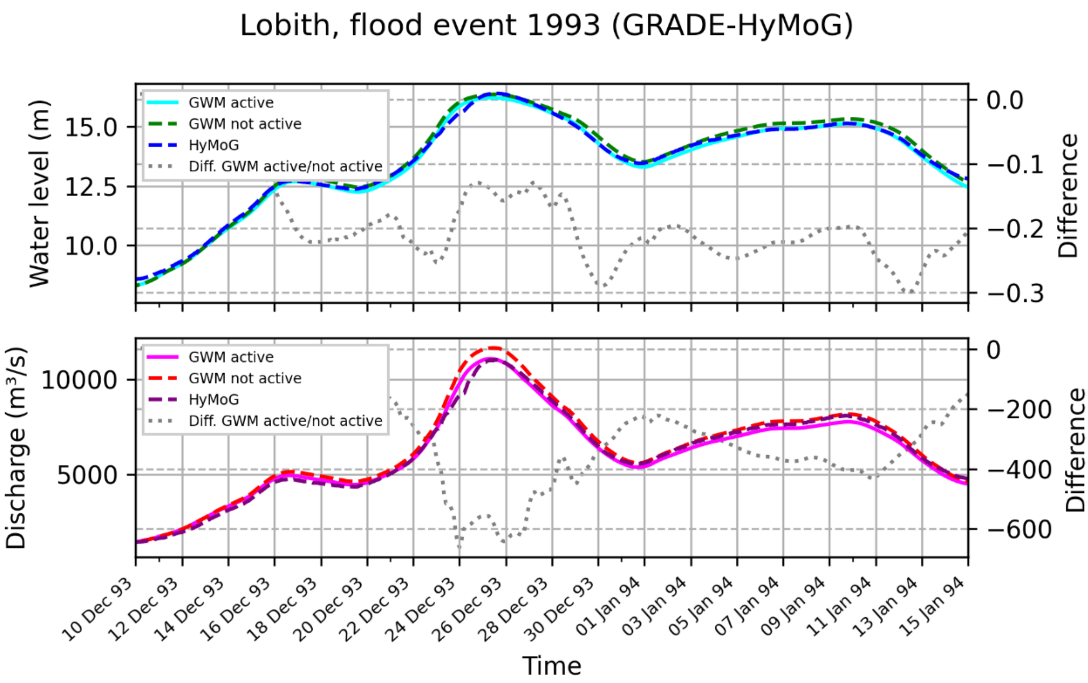

Figure 21 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1993

4.4.3 Flood event 1988

The flood event 1988 is not covered with the HyMoG data set. To assess the contribution of the river-aquifer interaction for this event the GRADE data set has been applied as boundary condition for this reason. The comparison of simulation results from SOBEK 3 with groundwater module active and not active is shown in Figure 22 to Figure 25 for selected gauging stations and in Appendix B.2.3 and Table 6 for all stations.

Like for the flood events 1993 and 1995, for gauging station Lobith the groundwater module SOBEK contributes with a reduction of discharge of ca. 600 m³/s and the water level reduces by up to 30 cm. The reduction of the discharge peak (Table 6) is similar.

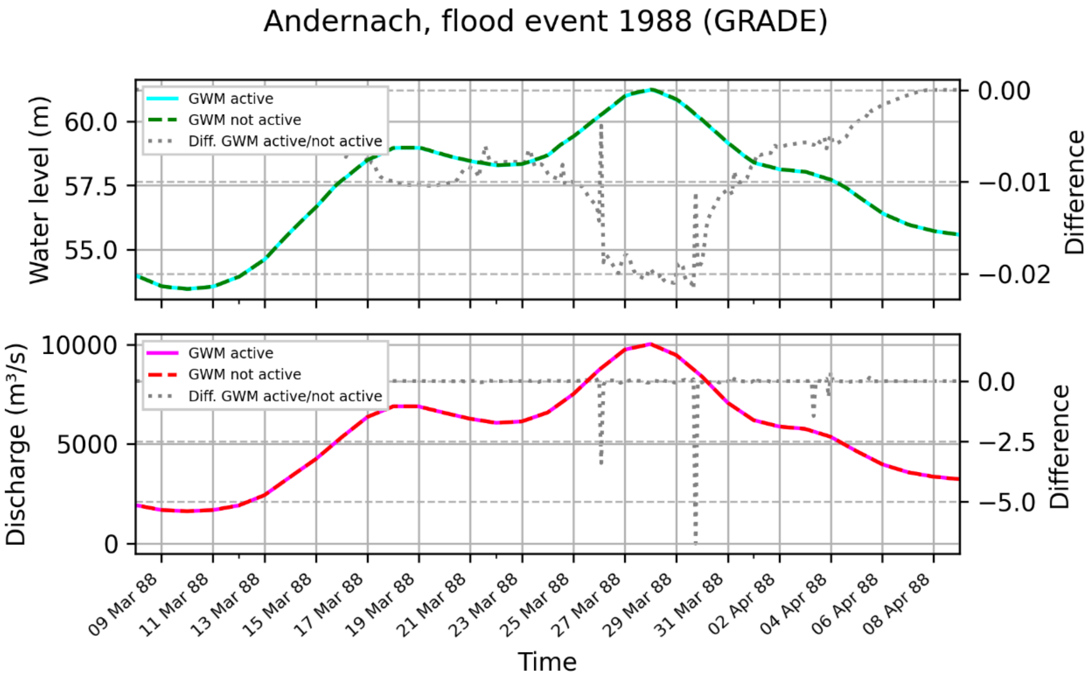

Figure 22 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1988

Table 6 Comparison of peak discharge computed with SOBEK 3 without and with groundwater module SOBEK for the flood event of 1988

Gauging station	Peak discharge in m³/s, Groundwater module not active	Peak discharge in m³/s Groundwater module active	Difference in peak discharge in m³/s, Groundwater module active/not active
Andernach	10019	10019	0
Bonn	10025	9927	98
Köln	10440	10240	200
Düsseldorf	10509	10195	314
Ruhrort	11027	10639	388
Wesel	11094	10626	468
Rees	11347	10818	529
Lobith	11357	10778	579

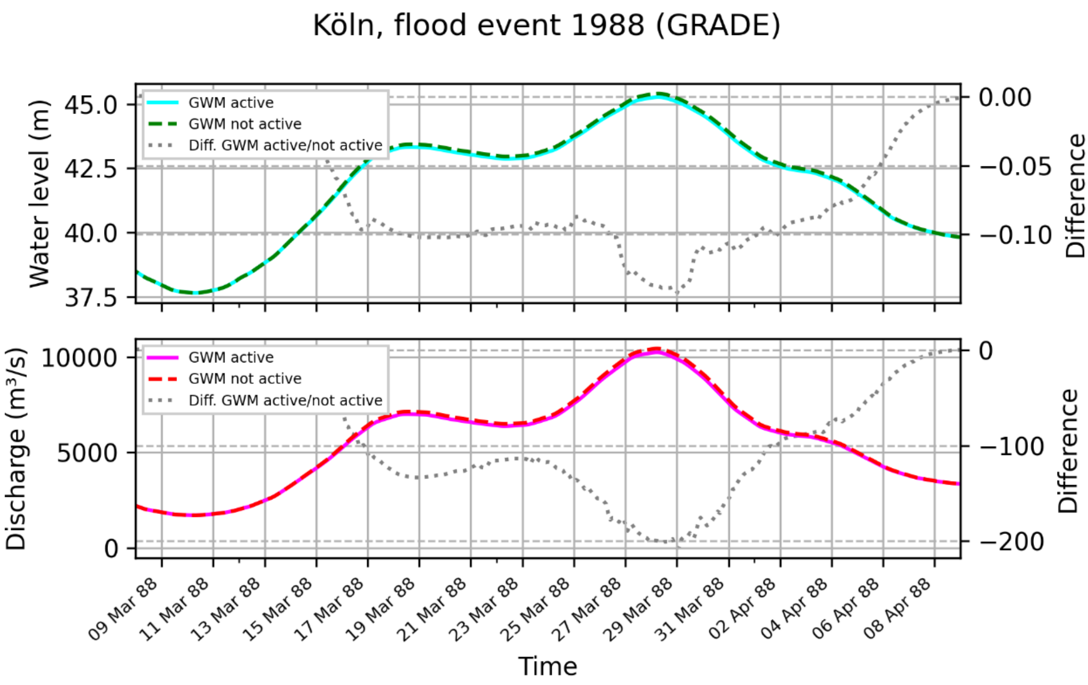

Figure 23 Comparison of water level und discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1988

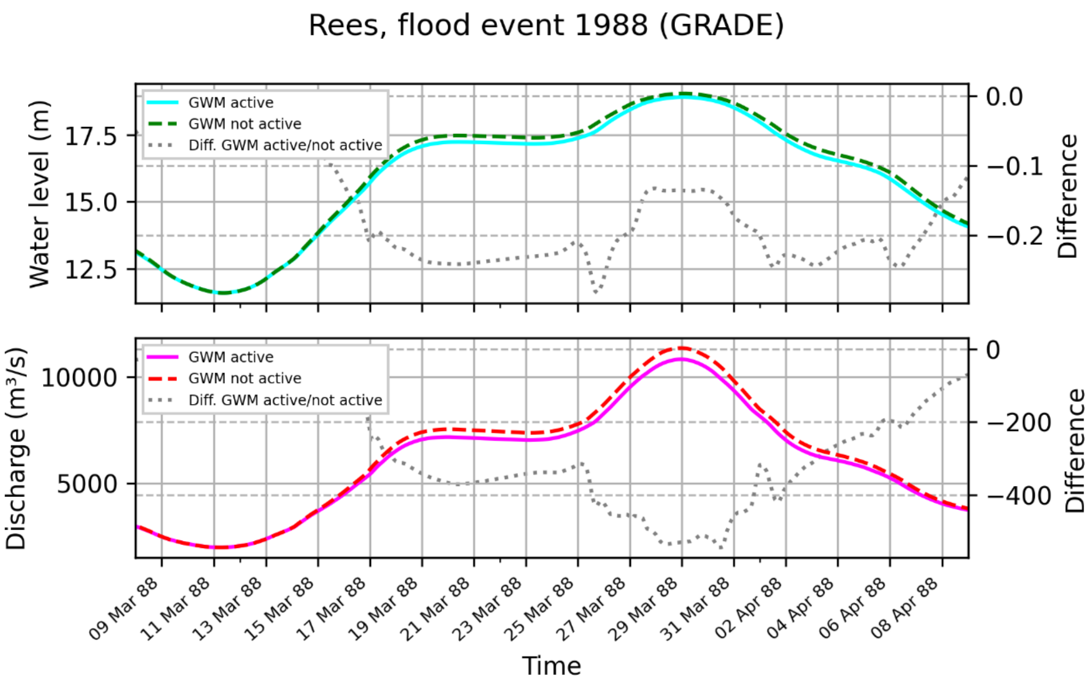

Figure 24 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1988

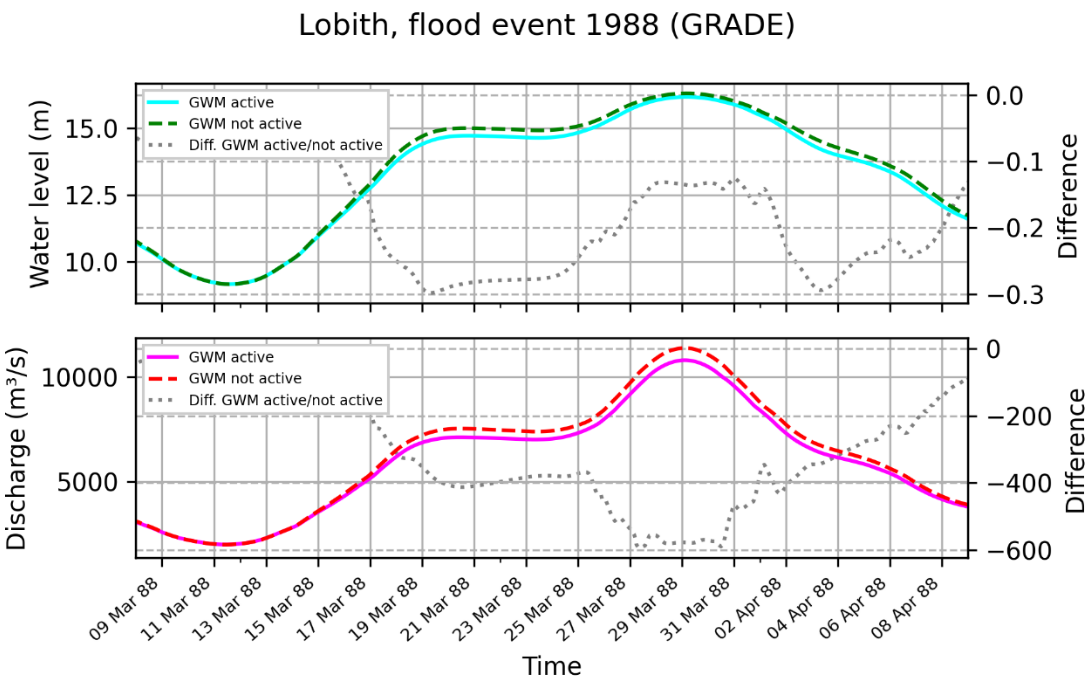

Figure 25 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1988

4.5 Comparison of SOBEK-RE and SOBEK 3 simulations with GRADE dataset

4.5.1 Flood event 1995

The previous sections show a comparison of model results with observation-based data. This section compares simulation results from SOBEK-RE with SOBEK 3 for the GRADE data set for selected gauging stations (see Appendix B.3.1 for all gauging stations and Table 7 for the peak discharges). In both models, groundwater interaction with the river is accounted for. This comparison is important to assess consistency when interpreting results from GRADE, since the SOBEK-RE and the SOBEK3 model are both used in GRADE for deriving flood frequency curves.

Results of the SOBEK-RE model and the SOBEK 3 model are qualitatively similar. Quantitatively, the difference in terms of discharge and water level is different at each of the eight locations. The discharge curves at Andernach should be the same for SOBEK 3 and SOBEK-RE, because the GRADE exports the SOBEK-RE model result as boundary condition (Section 4.1). Small difference in discharge can be seen in Figure 26, though. Analysis of the data set exported from SOBEK-RE has shown that the data is exported with a coarse time resolution and interpolated to the temporal resolution needed for SOBEK 3. At Lobith, the peak discharge differs by 507 m³/s.

The way the river-aquifer interaction is accounted for is different in the two models (see Hegnauer & Becker 2013 and Appendix A, Table 19, Line No. 3). Differences in discharge between SOBEK 3 and SOBEK-RE can thus be explained with the different approaches for handling river-aquifer interaction in both models.

The location of Bonn (Figure 27) shows a significant difference for the water level. Consequently, this difference is not only caused by the Groundwater Module SOBEK but will be related to other aspects. Possible reasons for differences in model results are the following:

- The state of maintenance is different in both models: model updates on cross-sections and roughness have been applied to the SOBEK 3 model that are not present in the SOBEK-RE model.
- SOBEK-RE and SOBEK 3 use different numerical schemes to solve the flow equations. SOBEK-RE uses the Preismann-scheme, and SOBEK 3 solves the flow equations with the staggered-grid approach after Stelling & Duinmeijer 2003.
- There are differences in how some model features are handled in addition to the numerical solution of the flow equations. An example is the interpolation of roughness values along the course of the river.

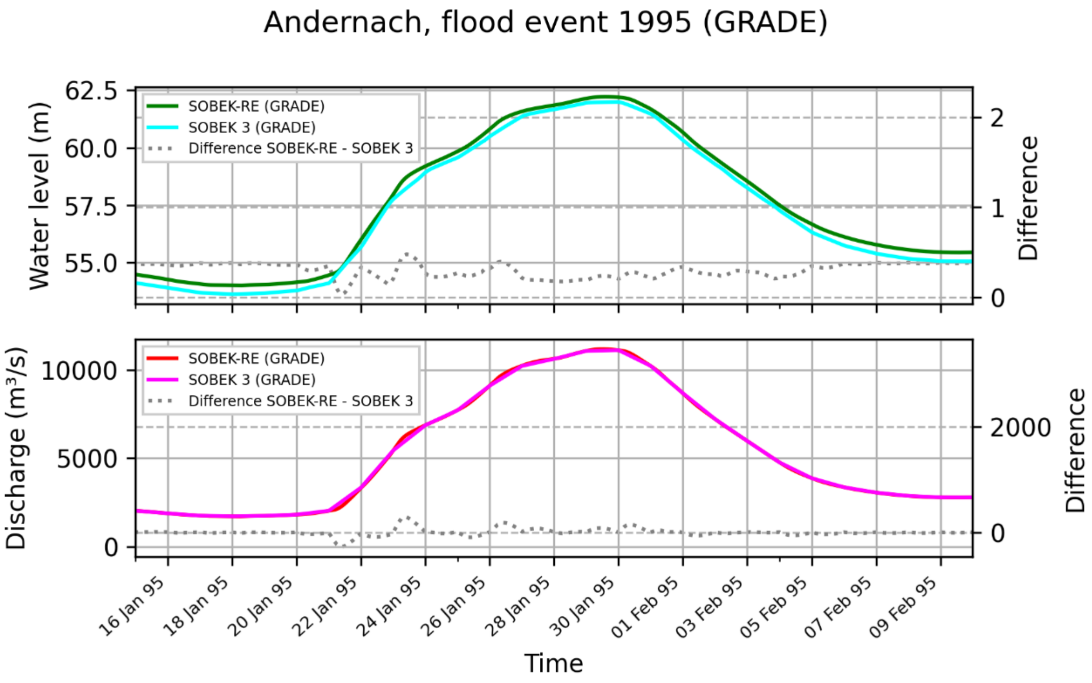

Figure 26 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1995

Table 7 Comparison of peak discharge computed with SOBEK 3 with groundwater module SOBEK active and SOBEK-RE for the flood event of 1995

Gauging station	Peak discharge in m³/s, SOBEK-RE	Peak discharge in m³/s, SOBEK 3	Difference in peak discharge in m³/s, SOBEK 3/SOBEK-RE
Andernach	11186	11127	-59
Bonn	11240	11101	-138
Koeln	11731	11529	-202
Duesseldorf	11797	11504	-292
Ruhrort	12598	12237	-361
Wesel	13085	12274	-810
Rees	13038	12543	-496
Lobith	13015	12508	-507

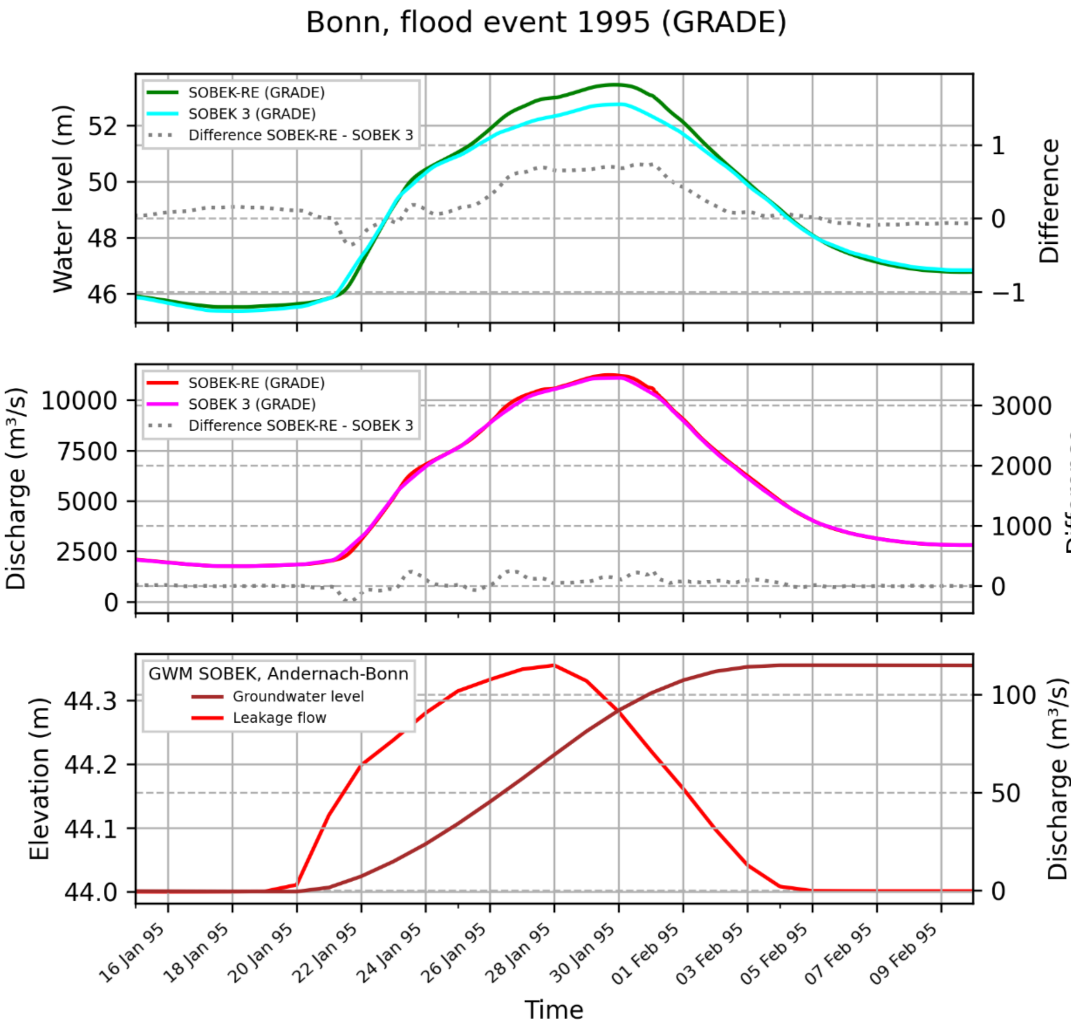

Figure 27 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Bonn, flood event 1995

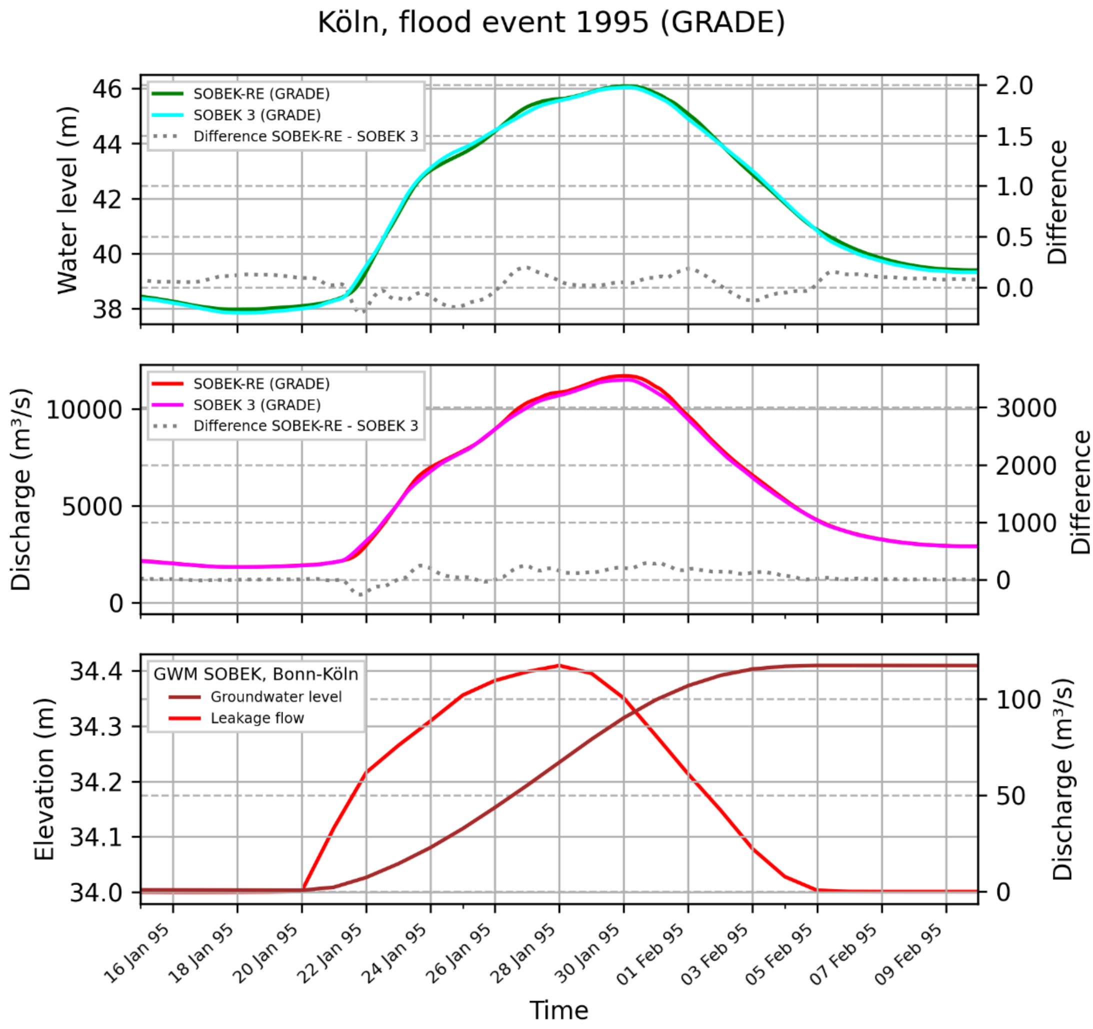

Figure 28 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1995

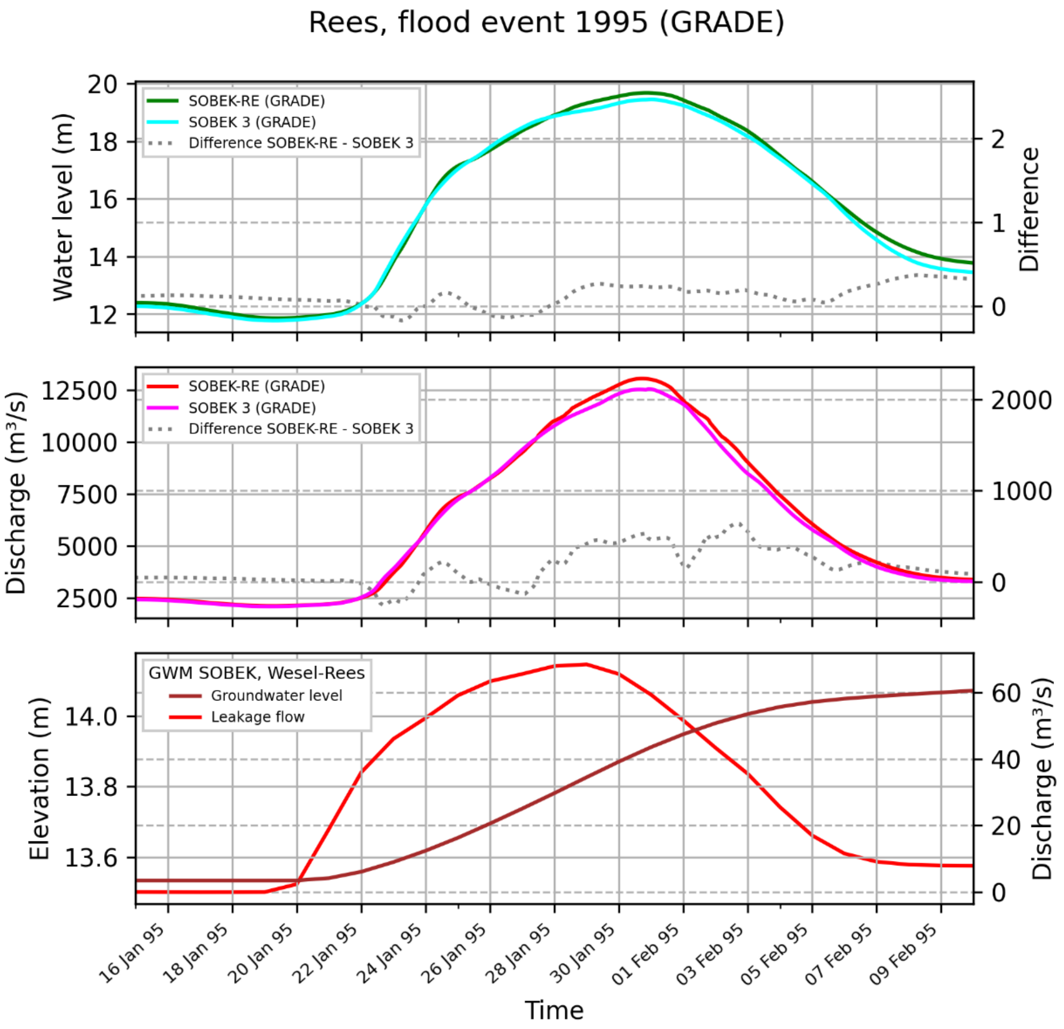

Figure 29 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1995

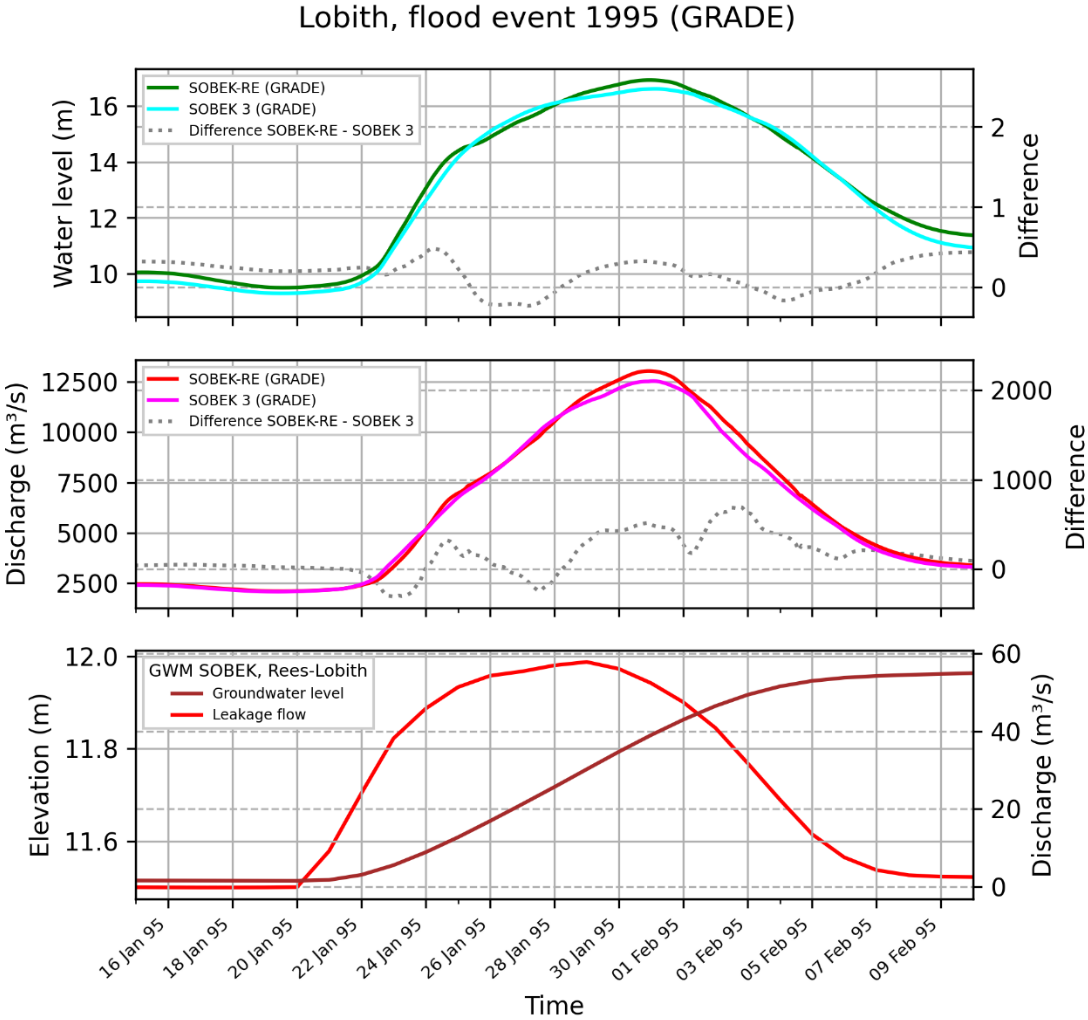

Figure 30 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1995

4.5.2 Flood event 1993

The following figures show a comparison of SOBEK 3 simulations with SOBEK-RE for the flood event 1993 with the GRADE data set. The pattern is similar to the flood event of 1995 (Section 4.5). With 277 m³/s (Table 8) the difference in peak discharge at Lobith is smaller than for the flood event 1995.

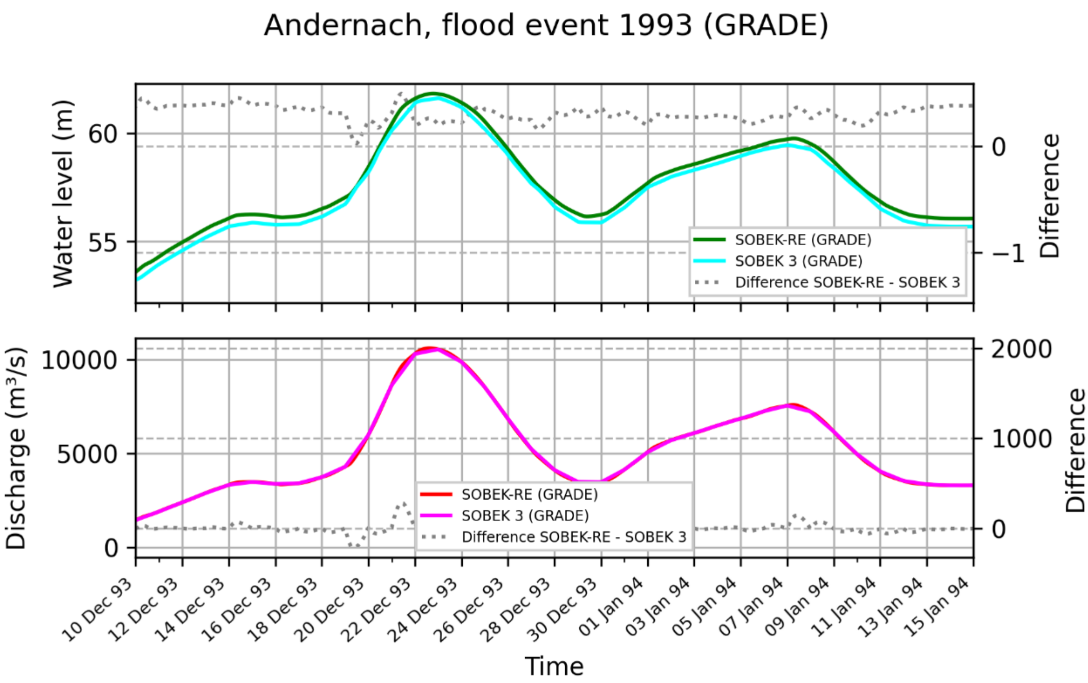

Figure 31 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1993

Table 8 Comparison of peak discharge computed with SOBEK 3 with groundwater module SOBEK active and SOBEK-RE for the flood event of 1993

Gauging station	Peak discharge in m³/s, SOBEK-RE	Peak discharge in m³/s, SOBEK 3	Difference in peak discharge in m³/s, SOBEK 3/SOBEK-RE
Andernach	10610	10546	-64
Bonn	10643	10516	-127
Koeln	10878	10666	-212
Duesseldorf	10922	10615	-308
Ruhrort	11118	10782	-337
Wesel	11308	10772	-536
Rees	11208	10933	-274
Lobith	11177	10900	-277

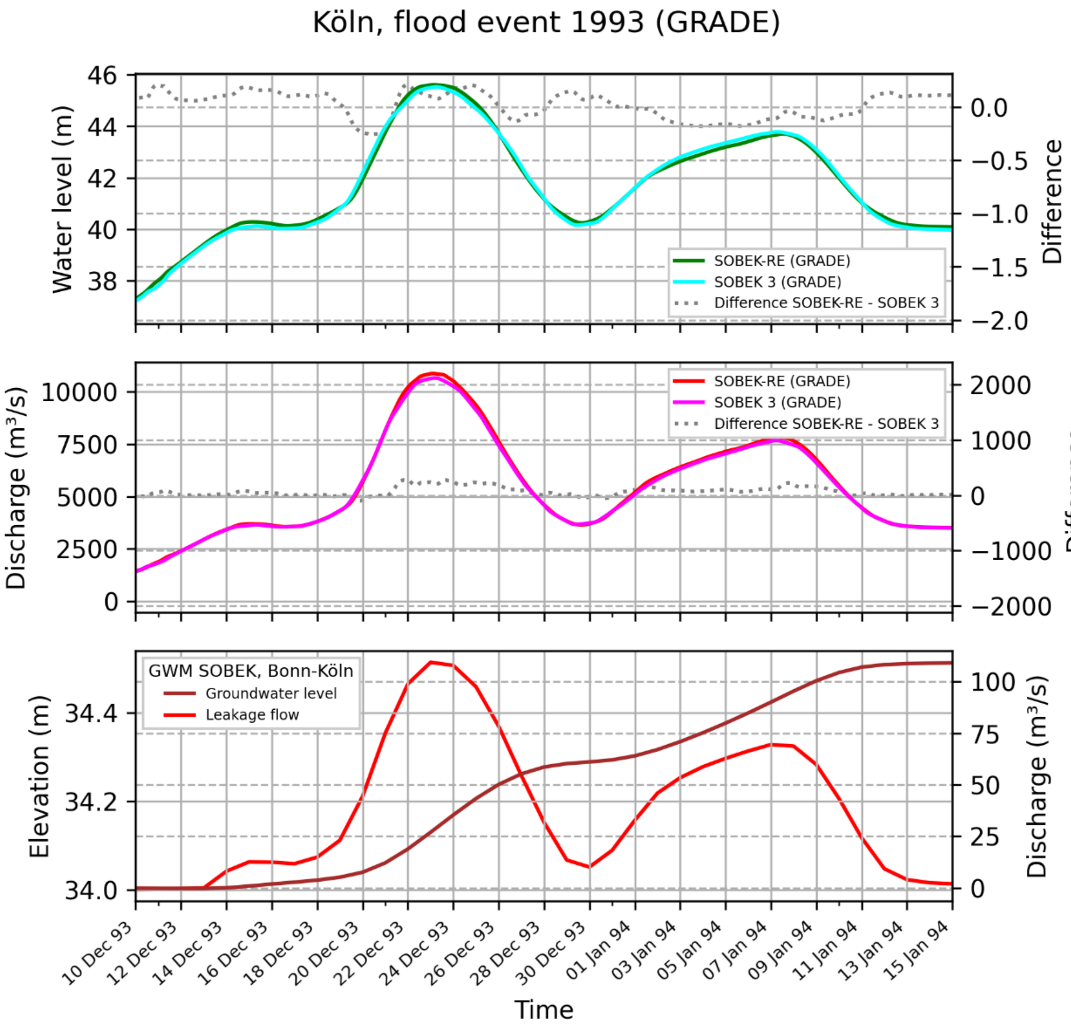

Figure 32 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1993

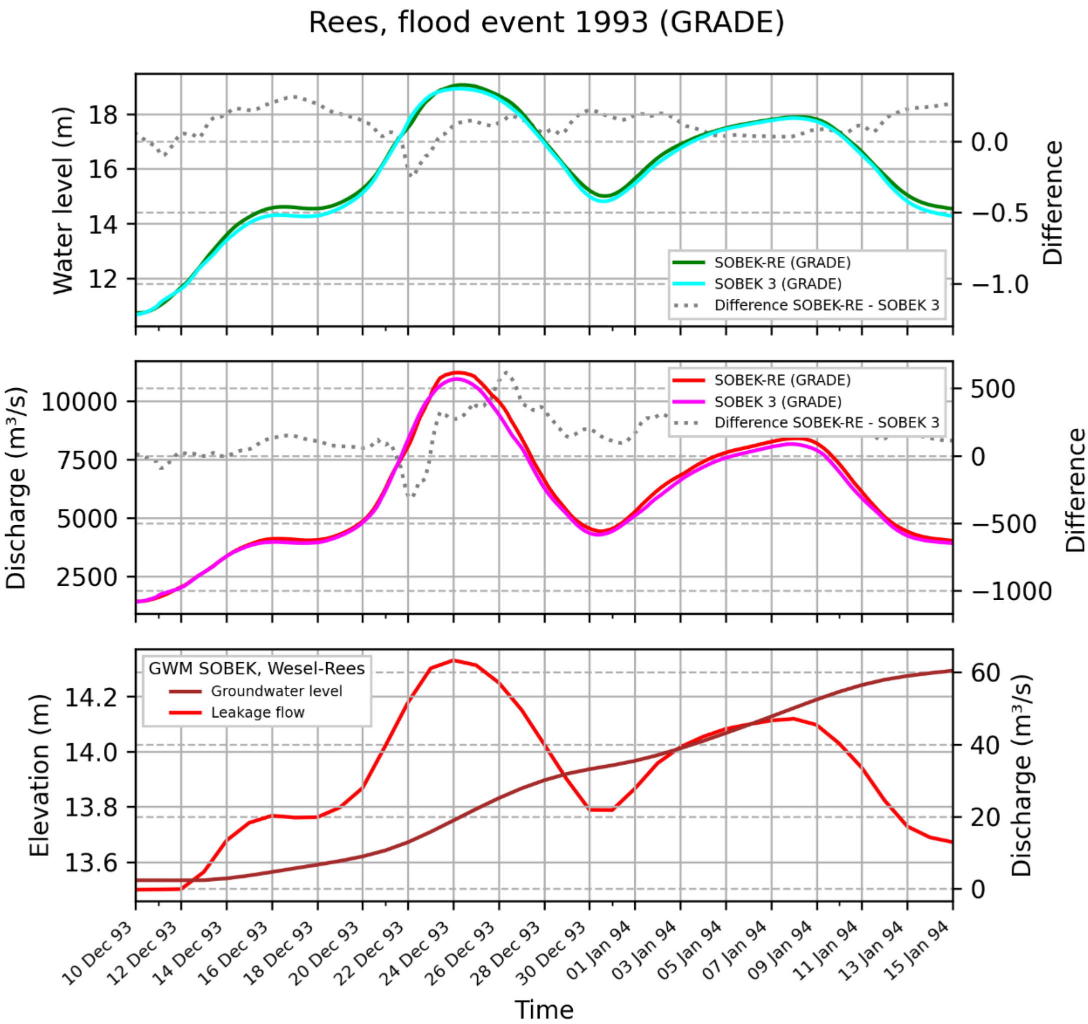

Figure 33 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1993

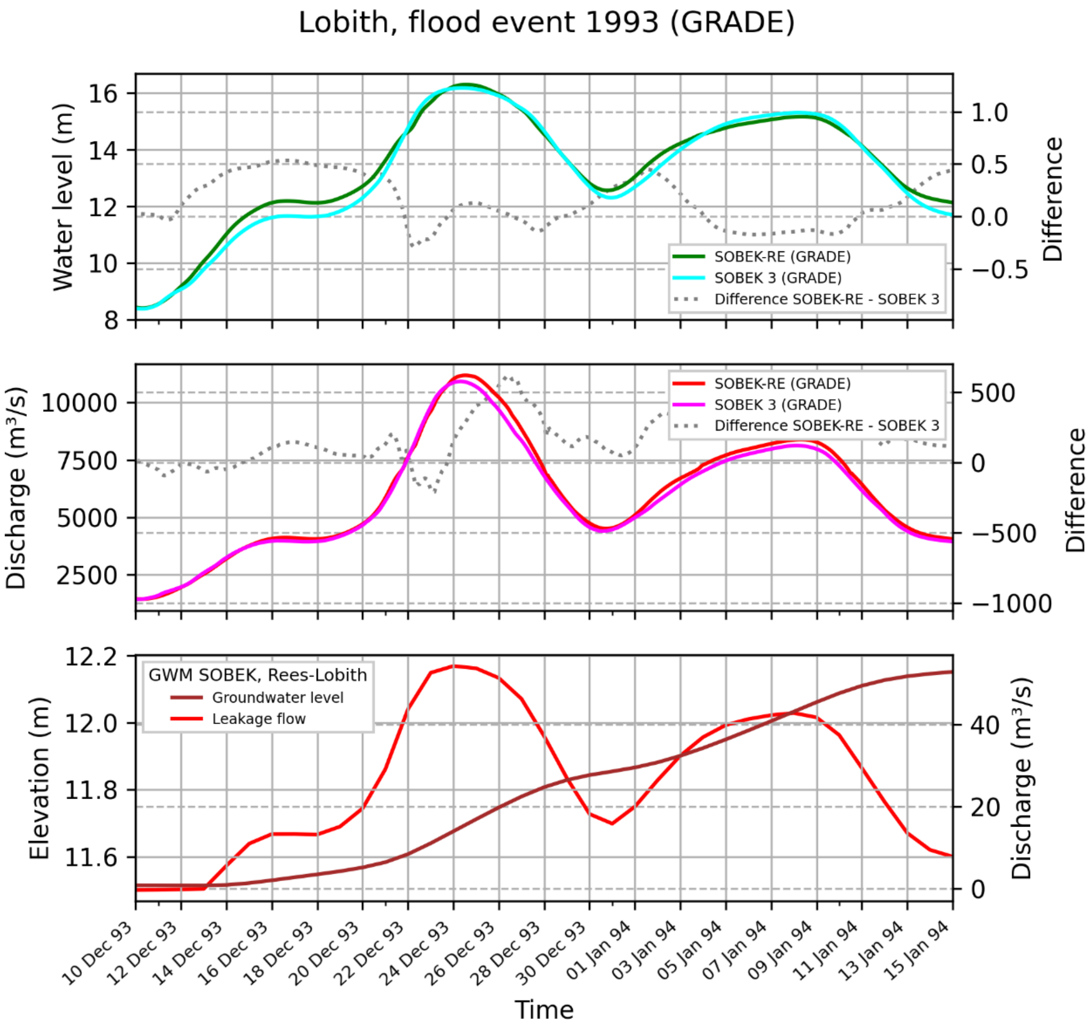

Figure 34 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1993

4.5.3 Flood event 1988

The flood event 1988 has two distinct peaks. The model results of SOBEK 3 and SOBEK RE match well, and the two peaks are well represented in the models. For Lobith the peak discharge differs by 321 m³/s (Table 9).

Deltares

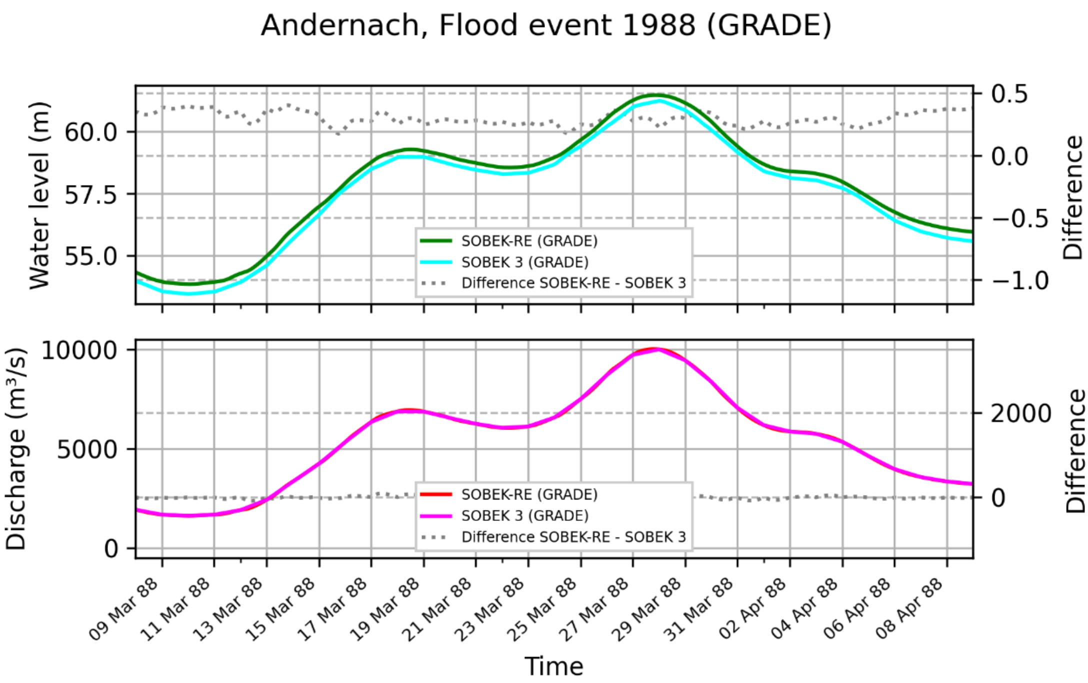

Figure 35 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1988

Table 9 Comparison of peak discharge computed with SOBEK 3 with groundwater module SOBEK active and SOBEK-RE for the flood event of 1988

Gauging station	**Peak discharge in m³/s, SOBEK-RE**	**Peak discharge in m³/s, SOBEK 3**	**Difference in peak discharge in m³/s, SOBEK 3/SOBEK-RE**
Andernach	10034	10019	-15
Bonn	10041	9927	-114
Koeln	10447	10240	-206
Duesseldorf	10474	10195	-279
Ruhrort	10953	10639	-314
Wesel	11174	10626	-548
Rees	11120	10818	-302
Lobith	11099	10778	-321

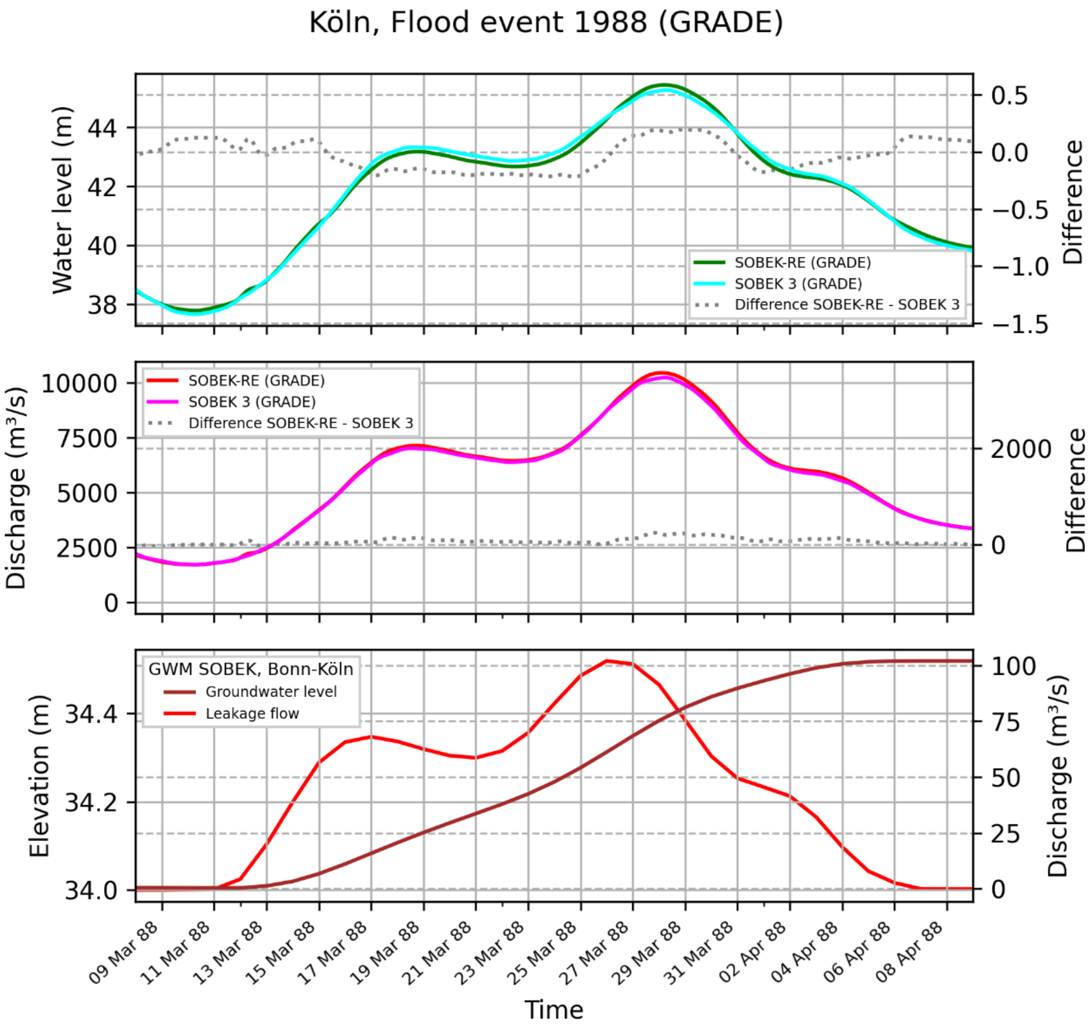

Figure 36   Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1988

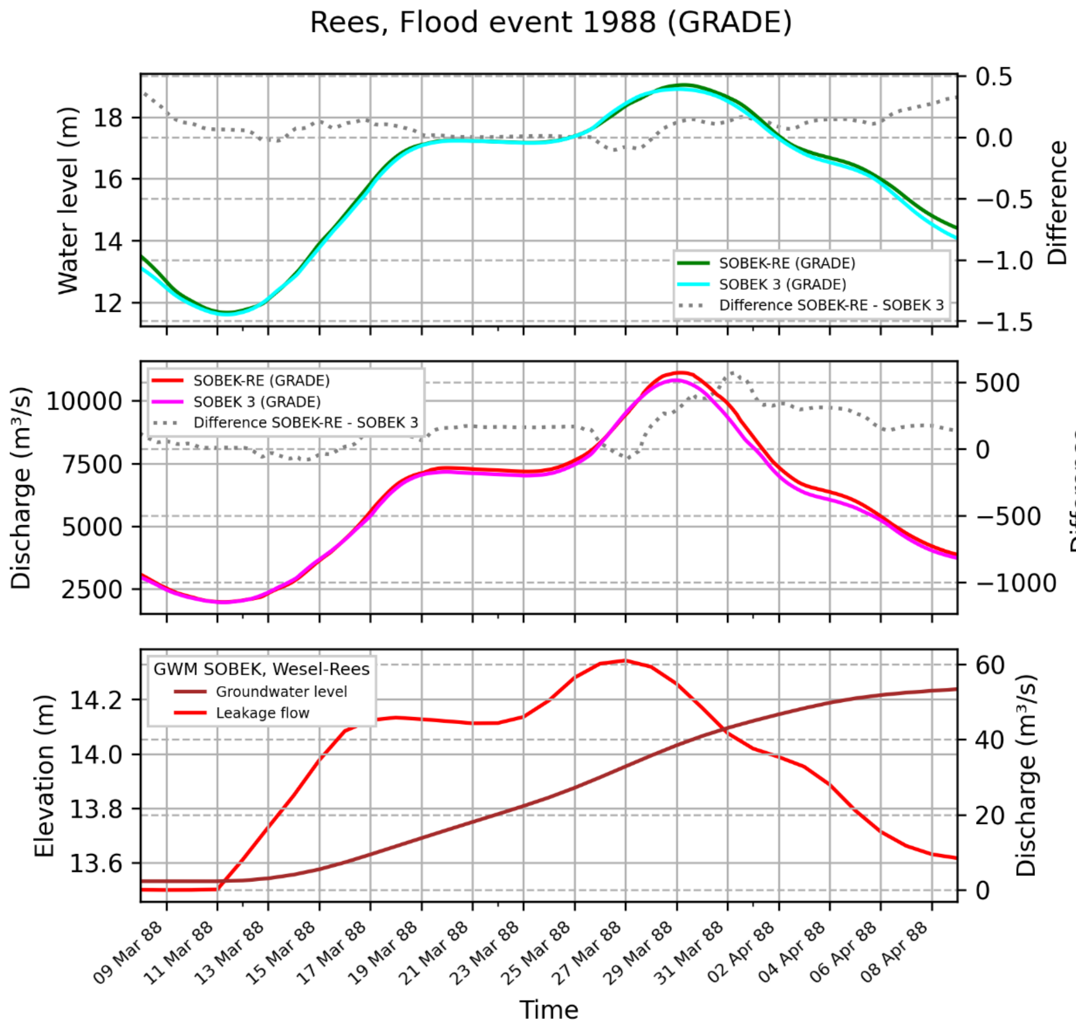

Figure 37 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1988

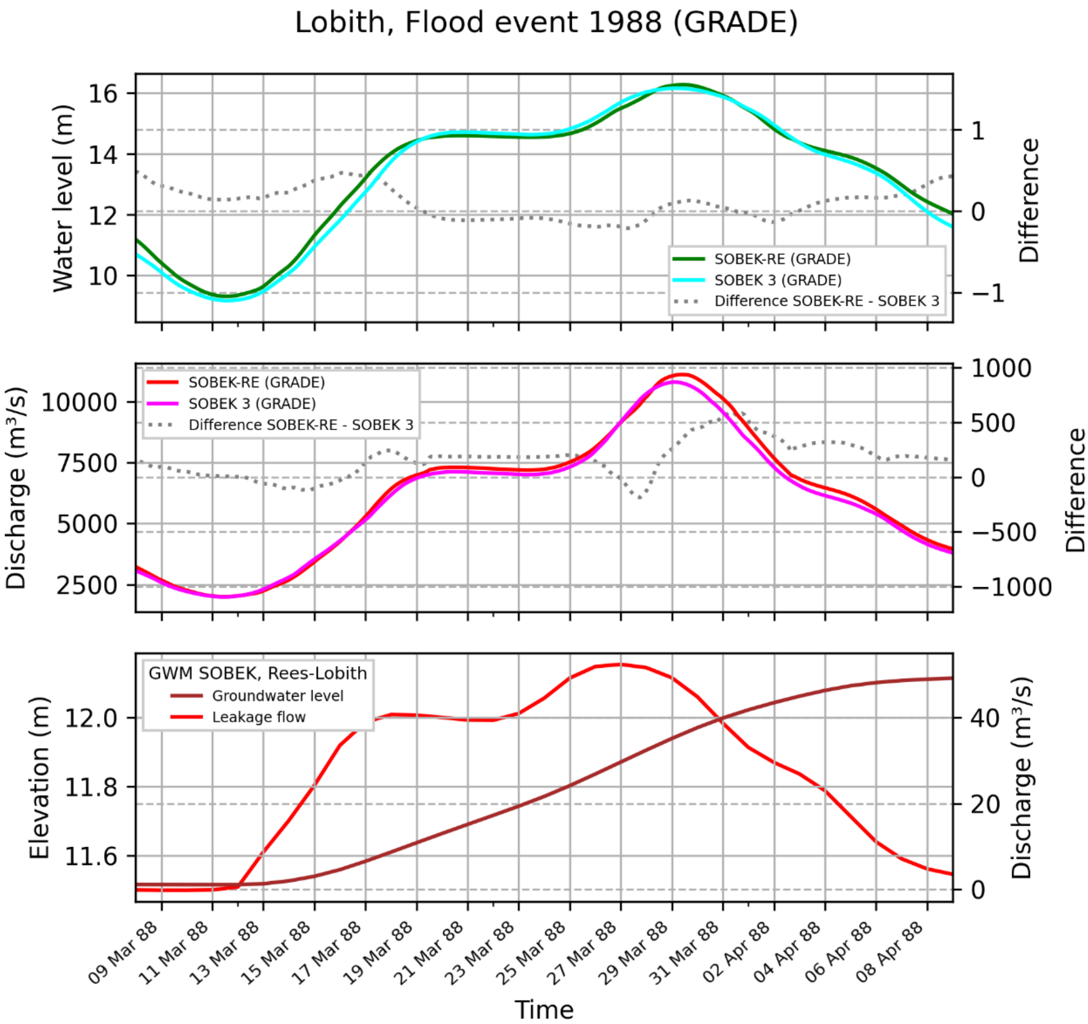

Figure 38 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1988

4.5.4 Conclusions

The comparison of SOBEK 3 fed with the GRADE-HyMoG data set as boundary conditions and the HyMoG data shows that the SOBEK 3 model already produces results that qualitatively match well to the observation-based data without accounting for river-aquifer interaction. The SOBEK 3 model looks well calibrated already.

The groundwater module withdraws water from the river during a flood event. Consequently, the groundwater module reduces the discharge during the flood event, and this again reduces the water level. The effect of the groundwater module comes to bear more at the downstream locations, because the effect of the groundwater storage cumulates with the river chainage. The groundwater module SOBEK improves the modelled discharge in terms of match to HyMoG data for the downstream locations Rees and Lobith. For the upstream locations the groundwater module SOBEK does not improve the result in all cases, but as mentioned above, the difference between discharge computed with and without groundwater module SOBEK is smaller here.

The downstream locations Lobith and Rees are of primary interest. The comparison of simulation results with groundwater module active and not active shows that the groundwater module SOBEK contributes a discharge reduction of several hundreds of cubic metres per second (600 - 700 m³/s) at Lobith, the peak discharge reduces by 530-580 m³/s, which is a reduction of about 5 %.

For the water level, the groundwater module contributes with a difference of up to 25 cm at Lobith. In relation to the total discharge these seem not to be huge, however for use for calculating flood statistics these are significant quantities.

In addition, a comparison between the results of the SOBEK-RE model and results from the SOBEK 3 model was carried out to give an understanding on the consistency of the two models. In both models, boundary conditions from the GRADE data set were used. Qualitatively, both models have a good match, too. At Lobith, the difference in flood peak discharge is between 277 and 507 m^3/s, though. This difference is in the order of magnitude of the correction factor that is used in GRADE to match results from SOBEK-RE to SOBEK 3 without river-aquifer interaction modelling (Figure 52). This must be taken into account when using model results from both models.

In this study the goal of parameter adjustment in the Groundwater Module SOBEK was defined to meet the quantity of river-aquifer interaction (the leakage flow) from another study (Meißner 2008). Note that there is no detailed data for river-aquifer interaction to calibrate the groundwater module against.

The Groundwater Module SOBEK adds the process of river-aquifer interaction to the model. According to literature (see Section 1), river-aquifer interaction is a relevant process for flood wave propagation modelling. Modelling this process allows to further improve the model accuracy of the hydraulic model, because now the bank storage effect, which technically is a withdrawal of water during the flood event, can now be modelled.

The calibration towards a good match for river water level and river discharge between HyMoG data and/or the SOBEK-RE model is a possible next step and should be carried out in an integrated way, because the parameters of the hydraulic model, in particular the roughness of the riverbed, but also the riverbed elevation, impact water level and discharge, too. Now that the Groundwater Module SOBEK is ready, an integrated calibration of the SOBEK 3 model should be carried out.

5 Impact of river aquifer modelling on extreme flood events and flood statistics

Simulation runs with the SOBEK 3 model and the new Groundwater Module SOBEK have been carried out with boundary conditions that represent extreme flood events to understand the effect of the river-aquifer interaction as modelled with the new groundwater module on the model results under extreme discharge conditions. Different to the model runs presented in Chapter 4, the extreme scenarios lead to extensive inundations behind the dikes. To account for inundations behind the dikes (hinterland, Dutch: “binnendijks”) due to dike overtopping along the course of the river, the 2DFLOW flooding module of SOBEK 3 has been set to active.

Again, boundary conditions have been prepared with the help of the GRADE instrument. Simulation runs have been carried out for the following synthetic events:

- GRADE flood wave with discharge peak of 18 000 m³/s at Andernach
- GRADE flood wave with discharge peak of 20 000 m³/s at Andernach
- GRADE flood wave with discharge peak of 30 000 m³/s at Andernach.

5.1 Extreme scenario GRADE with a peak discharge of 18 000 m³/s at Andernach

Figure 39 to Figure 42 show water level and discharge at gauging stations Andernach, Köln, Rees and Lobith (for other gauging stations see Appendix B.4.1) computed with the SOBEK 3 model under the GRADE extreme scenario of 18 000 m³/s with Groundwater Module SOBEK active and not active. The groundwater module has a similar effect like in the simulations of historical flood events (Chapter 4): the effect of the groundwater module is higher in the downstream reaches, because here the effect of bank storage has cumulated over multiple stretches.

Table 10 shows the summary of the differences in water level and discharge calculated as maximum value and for the point in time of the flood peak. With the groundwater module active, the peak water level is 12.7 cm lower in Lobith than without accounting for bank storage, and the maximum difference in water level is 24 cm – the largest difference is not necessarily at the flood peak. Up to Köln, the effect on the discharge and water level cumulates. For locations Düsseldorf, Ruhrort and Wesel, however, the effect on discharge and water level is smaller than it is in Köln. For Rees and Lobith, both further downstream, the effect becomes larger again. Except for the first two reaches, the effect of the bank storage is between 1,5 to 2,3% of the total peak flow.

The difference in discharge at the flood peak of 381 m³/s at Lobith is smaller than for the flood event 1995 (Section 4.4). The extreme scenario lets the groundwater level in the groundwater storage unit rise faster. A high groundwater level is already reached during the rising limb of the flood wave. Due to the inundations that come with this scenario, the river water level does not increase in the same extent as the discharge rises, because the water escapes into the flood plains behind the dikes (hinterland, Dutch: binnendijks). Both the high groundwater level and the effect of the inundation of areas behind the dikes limit the head difference during the flood peak, which means that less water is withdrawn from the river discharge. Note that Table 10 shows differences in discharge for certain time stamps and not the total amount of exchanged water. The maximum leakage flow is higher than in less extreme events, the maximum difference in discharge is higher, too. The total amount of river water that infiltrates into the aquifer also becomes larger the more extreme the event is.

Table 10 Difference in discharge and water level between without groundwater module and with groundwater module

18 000 m³/s	Difference at the peak discharge (m3/s)	Difference at the peak water level (m)	Maximum difference in discharge (m³/s)	Maximum difference in water level (m)
Andernach	0	-0.025	-12	-0.028
Bonn	-119	-0.078	-151	-0.090
Köln	-262	-0.096	-344	-0.126
Düsseldorf	-244	-0.077	-560	-0.224
Ruhrort	-261	-0.084	-527	-0.288
Wesel	-249	-0.116	-566	-0.240
Rees	-320	-0.127	-573	-0.243
Lobith	-381	-0.127	-674	-0.240

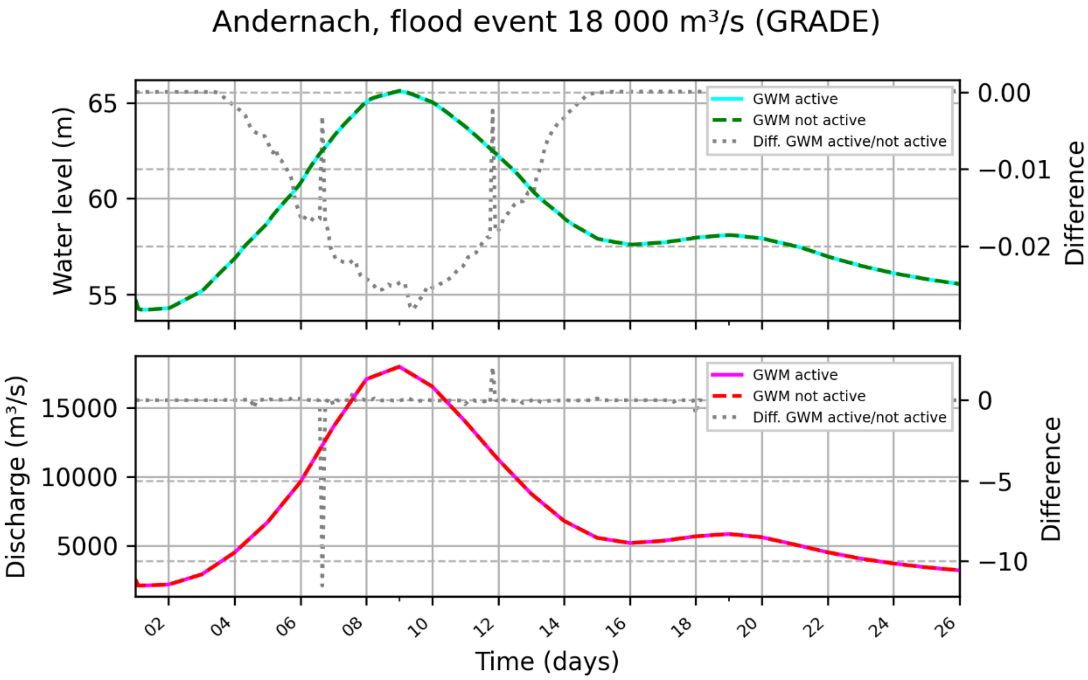

Figure 39 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

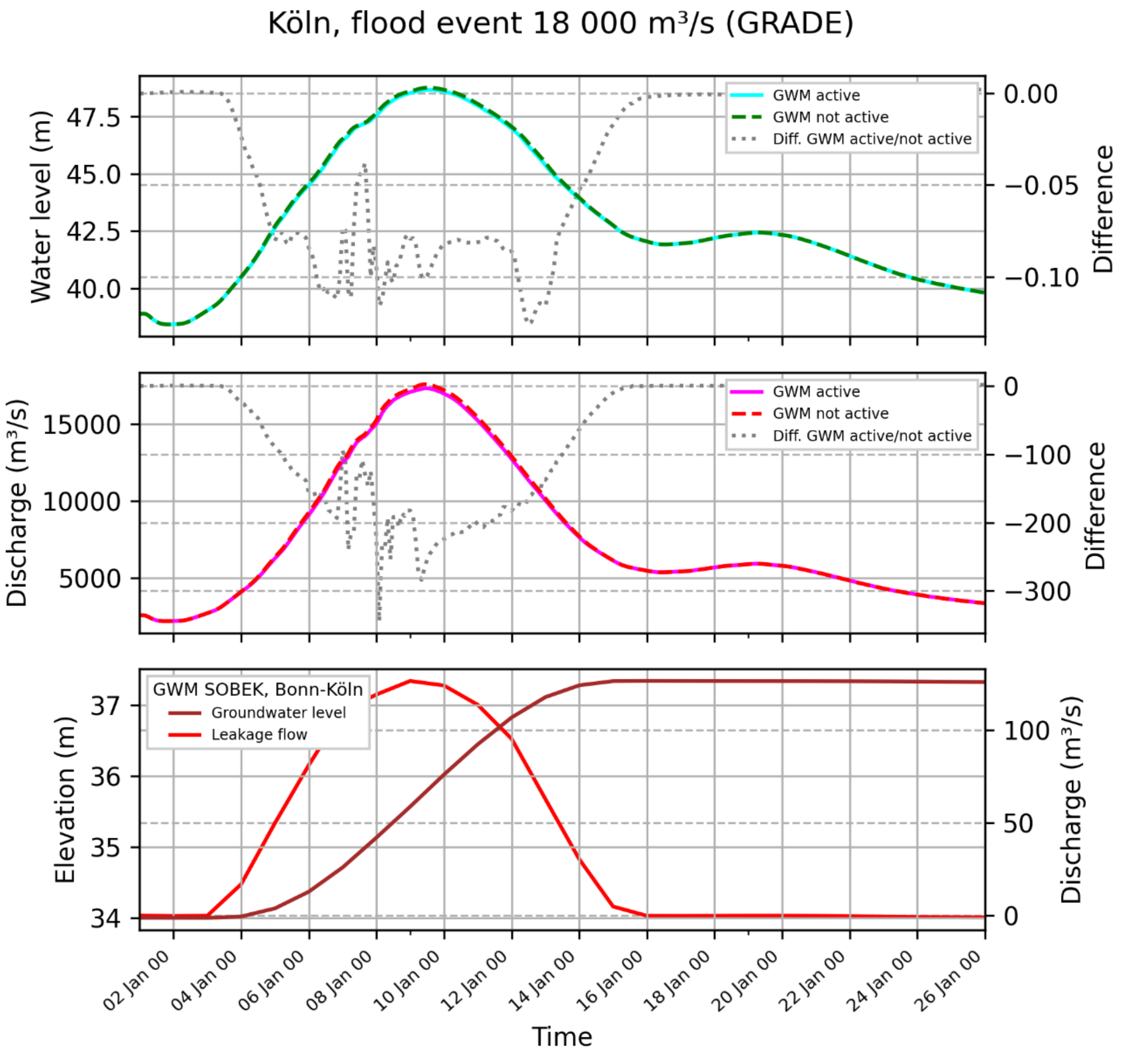

Figure 40 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

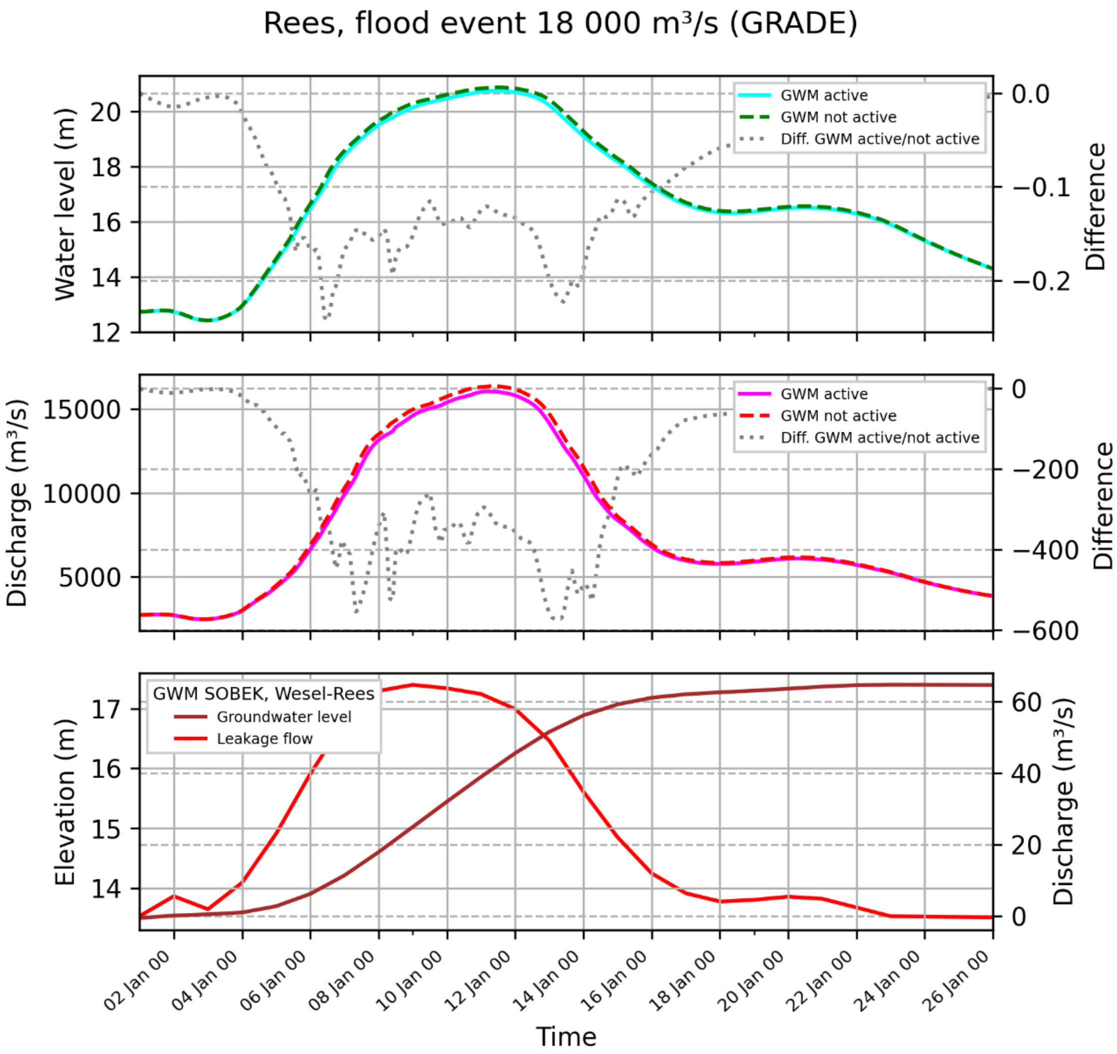

Figure 41 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

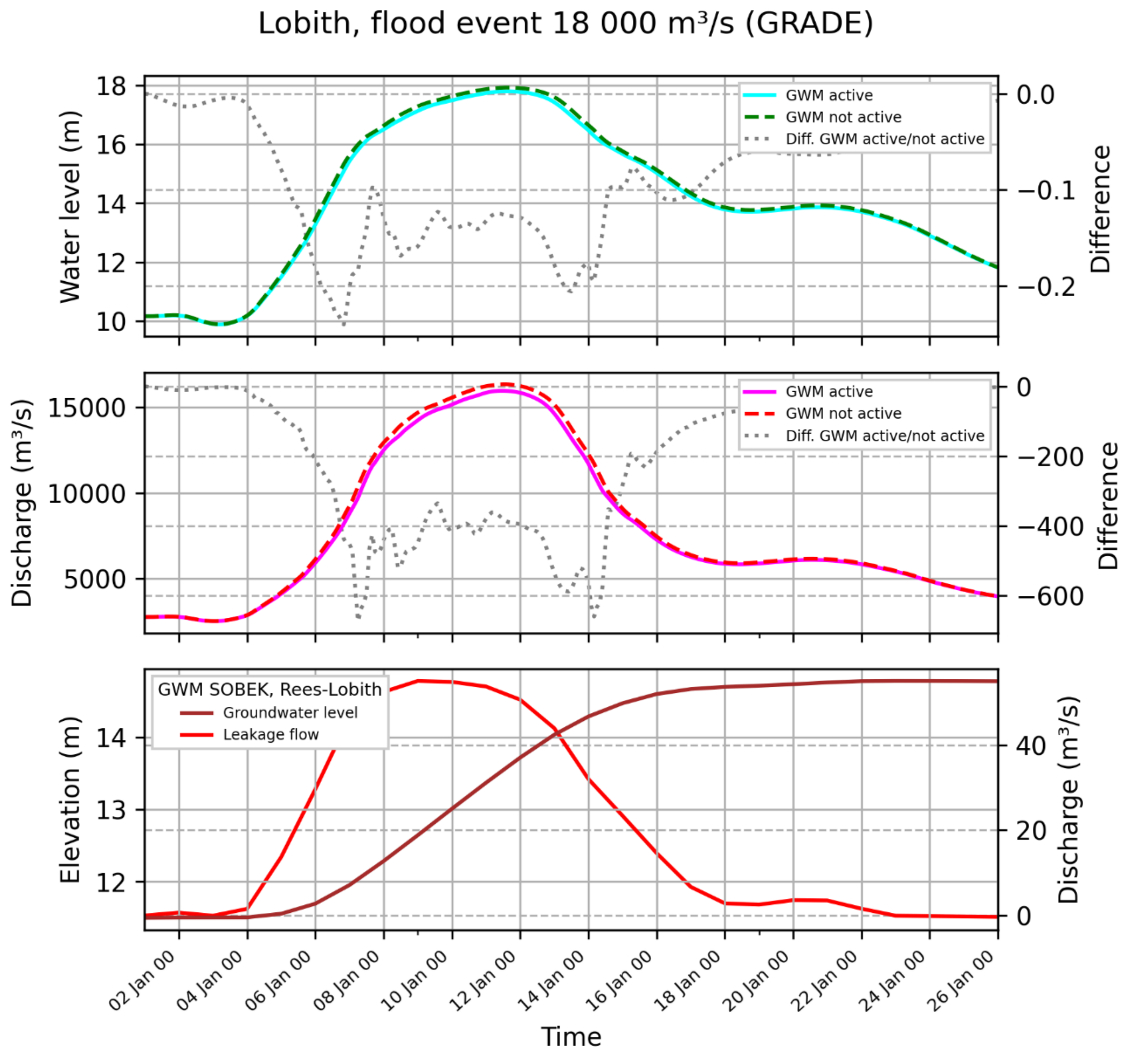

Figure 42 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

5.2 Extreme scenario GRADE with a peak discharge of 20 000 m³/s at Andernach

Simulation results for the GRADE scenario of 20 000 m³/s are given in Figure 43 to Figure 46 and Appendix B.4.2. Table 11 shows the summary of the differences for the different locations. Again, the difference in discharge at the flood peak is not simply accumulative because the groundwater rises faster than in the less extreme historical scenario, and water flows over to the inundation area (see Section 5.1). Outside the peak, however, the maximum difference in discharge exceeds 1000 m³/s at Rees. The effect of the Groundwater Module SOBEK at the peak water level is lower than in the GRADE scenario “18 000 m³/s”, because the groundwater storage is already addressed in an early stage during the flood event. Water levels differ less than 10 cm, at Lobith the difference is about 7 cm, but the maximum water level difference, which is then outside the peak, is considerably greater. With less than 1 % difference in maximum discharge (not necessarily at the flood peak) at most locations the difference as percentage is small, the highest percentage difference is 1.4 % at the two downstream locations Rees and Lobith.

Table 11 Difference in discharge and water level between without groundwater module and with groundwater module

20.000 m³/s	Difference at the peak discharge (m³/s)	Difference at the peak water level (m)	Maximum difference in discharge (m³/s)	Maximum difference in water level (m)
Andernach	0	-0.025	-1	-0.027
Bonn	-139	-0.049	-150	-0.086
Köln	-164	-0.052	-265	-0.102
Düsseldorf	-85	-0.049	-553	-0.186
Ruhrort	-162	-0.043	-416	-0.254
Wesel	-171	-0.068	-456	-0.381
Rees	-197	-0.073	-1024	-0.377
Lobith	-226	-0.067	-996	-0.341

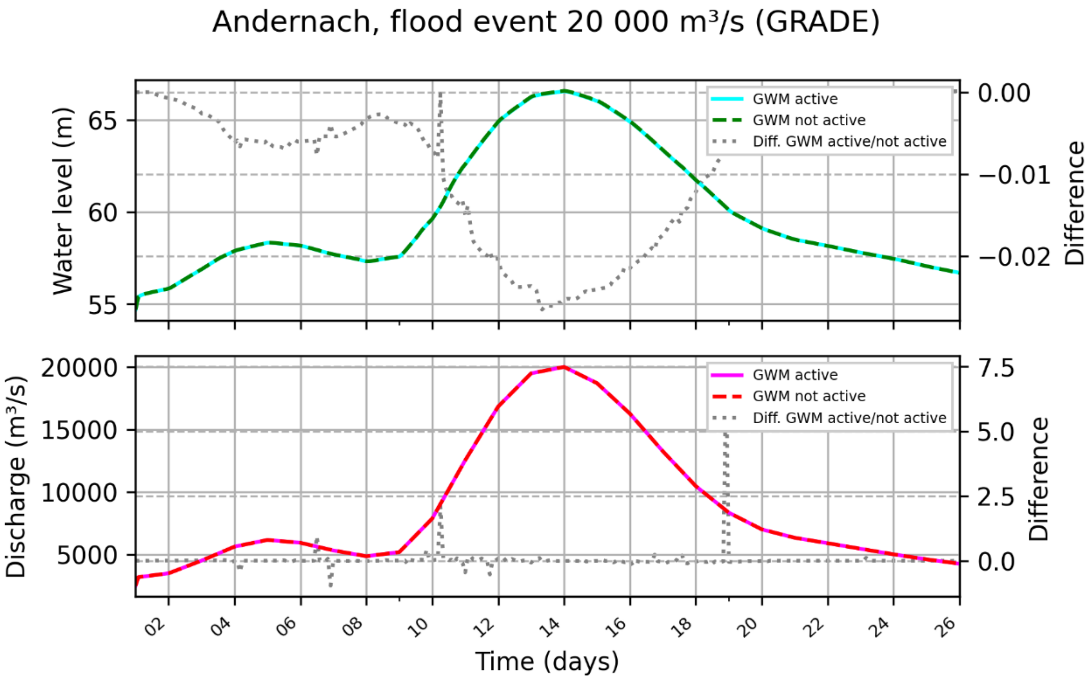

Figure 43 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

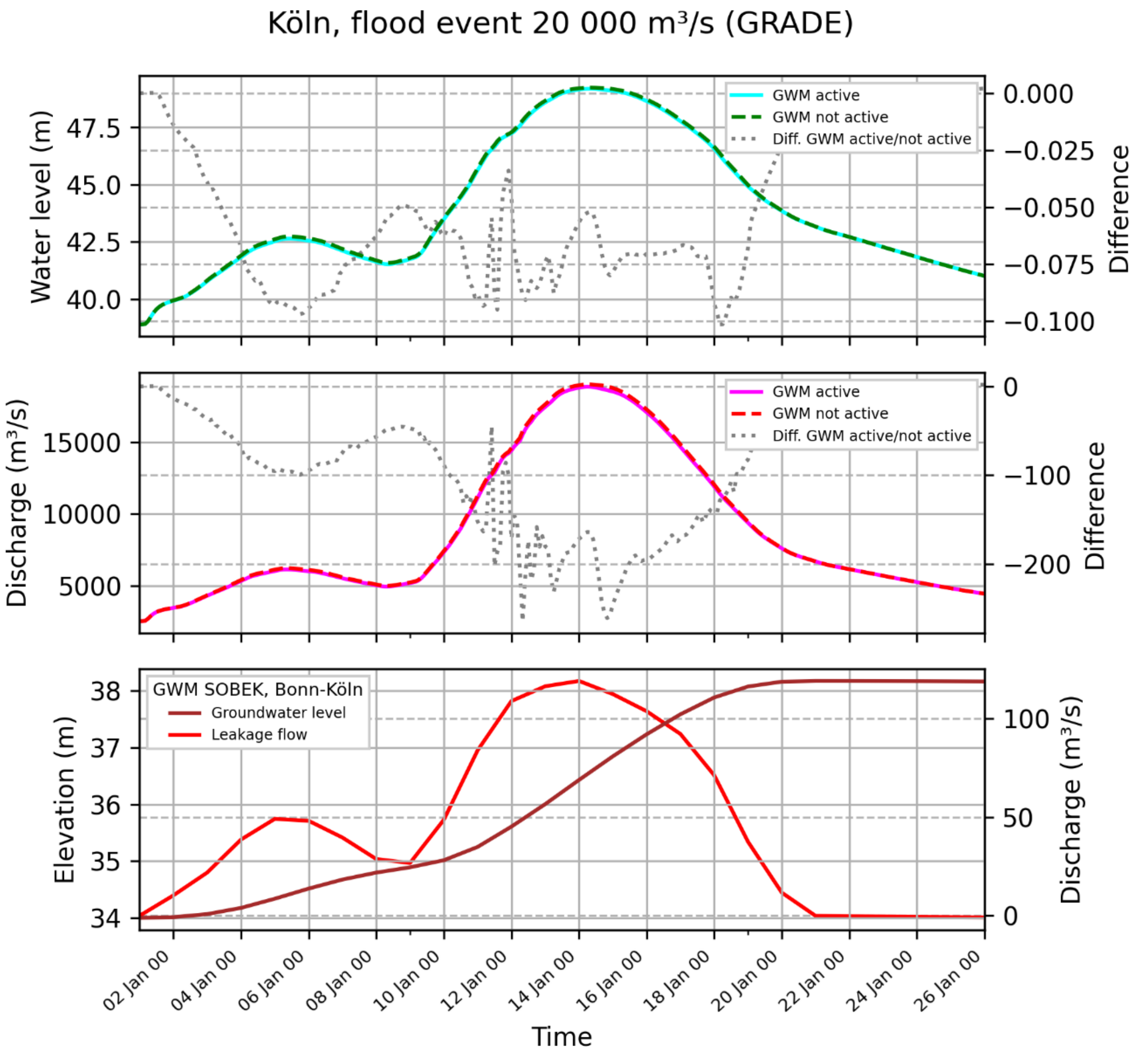

Figure 44 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

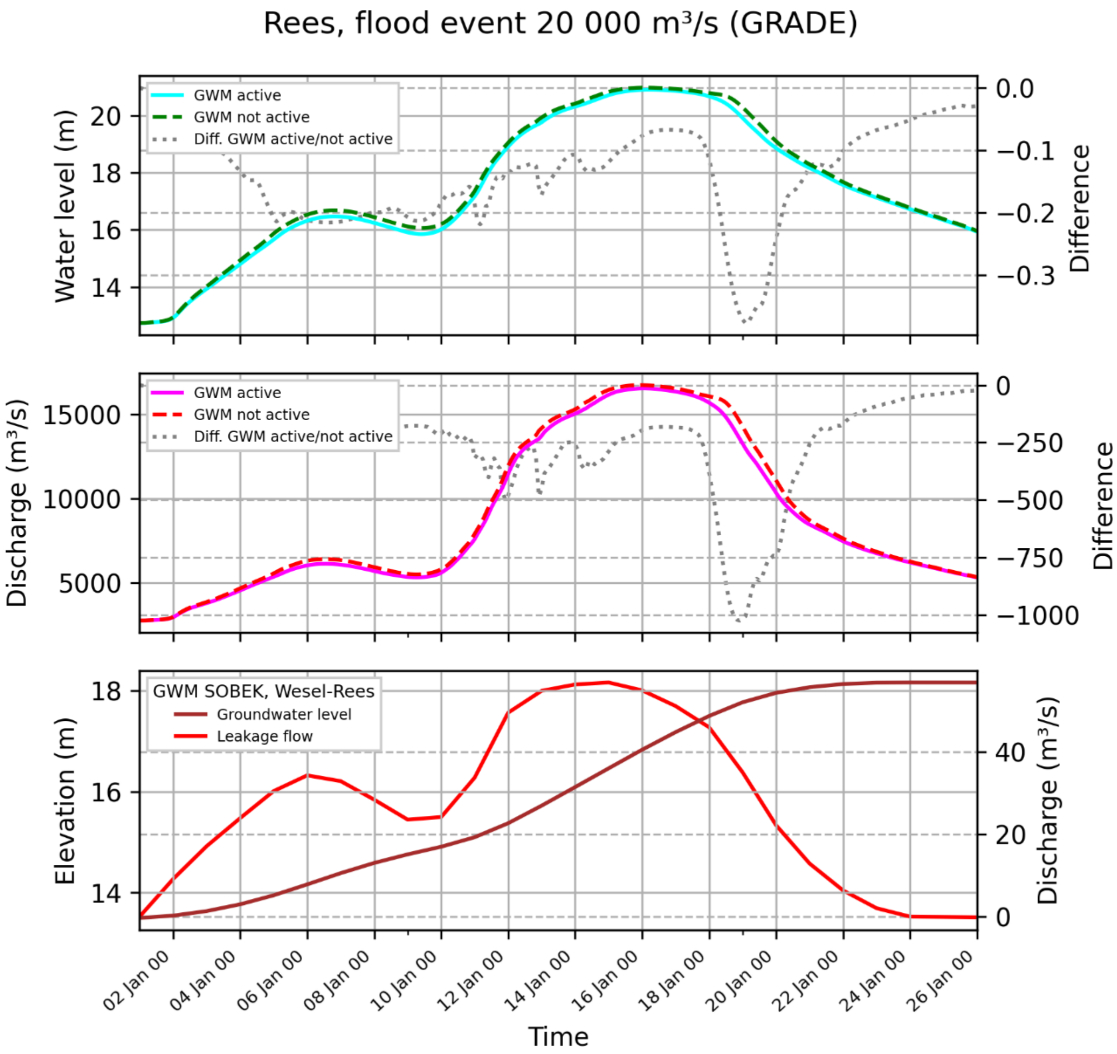

Figure 45 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

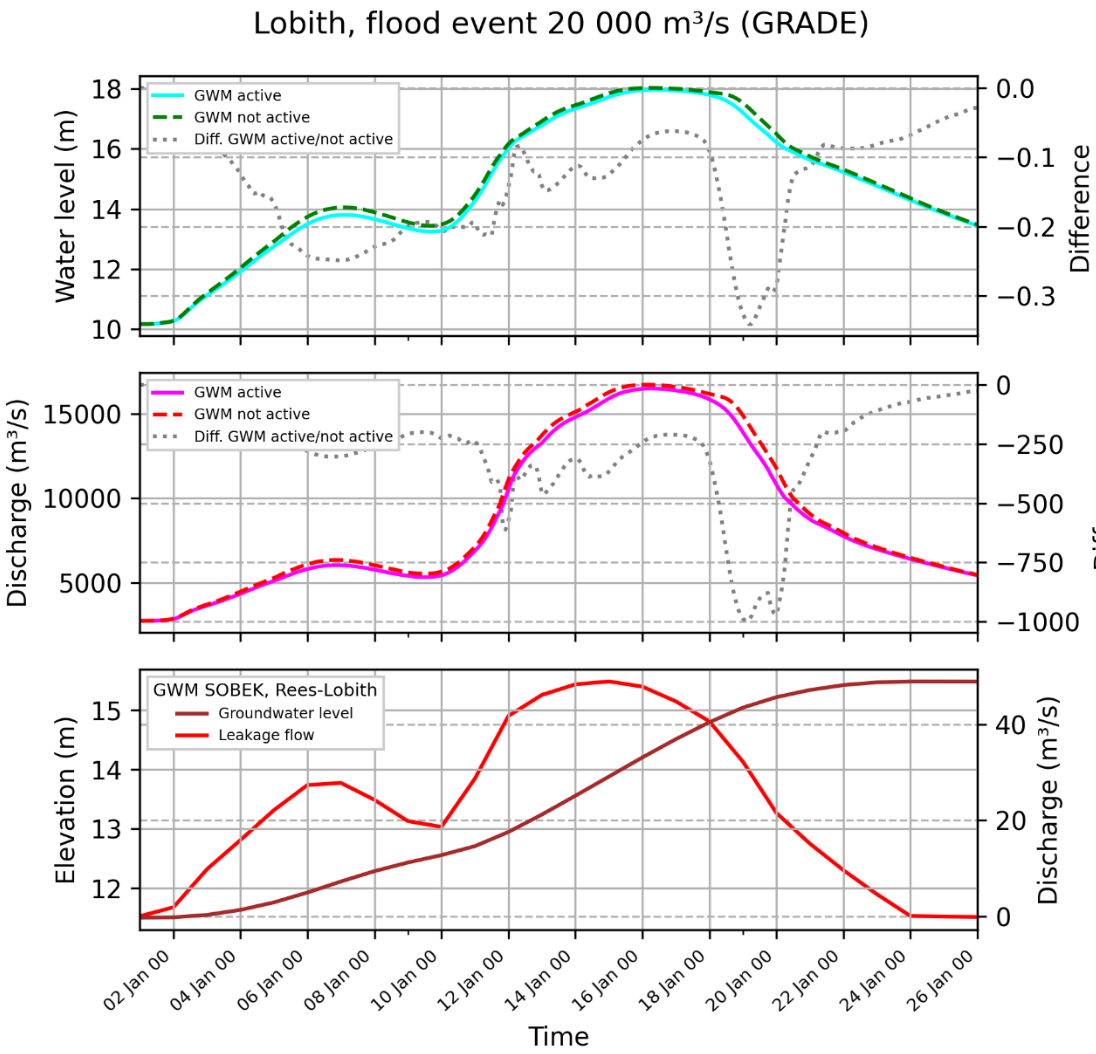

Figure 46 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

5.3 Extreme scenario GRADE with a peak discharge of 30 000 m³/s at Andernach

Figure 47 to Figure 50 and Appendix B.4.3 show the simulation results for the GRADE scenario of 30 000 m³/s. As Table 12 shows, difference in water levels at the peak discharge are significantly lower than for other scenarios, the Groundwater Module SOBEK has less effect on the discharge for this scenario than it has in other scenarios that have been simulated. As percentage, the difference is between 0.1 and 0.2 %. The difference in water level at the flood peak is 5 cm at Lobith.

Table 12 Difference in discharge and water level between without groundwater module and with groundwater module

30.000 m³/s	Difference at the peak discharge (m3/s)	Difference at the peak water level (m)	Maximum difference in discharge (m3/s)	Maximum difference in water level (m)
Andernach	0	-0.023	-17	-0.026
Bonn	-151	-0.030	-181	-0.061
Köln	-133	-0.043	-234	-0.095
Düsseldorf	-14	-0.057	-464	-0.164
Ruhrort	-33	-0.031	-418	-0.211
Wesel	55	-0.043	-437	-0.293
Rees	-39	-0.006	-572	-0.273
Lobith	-19	-0.051	-536	-0.258

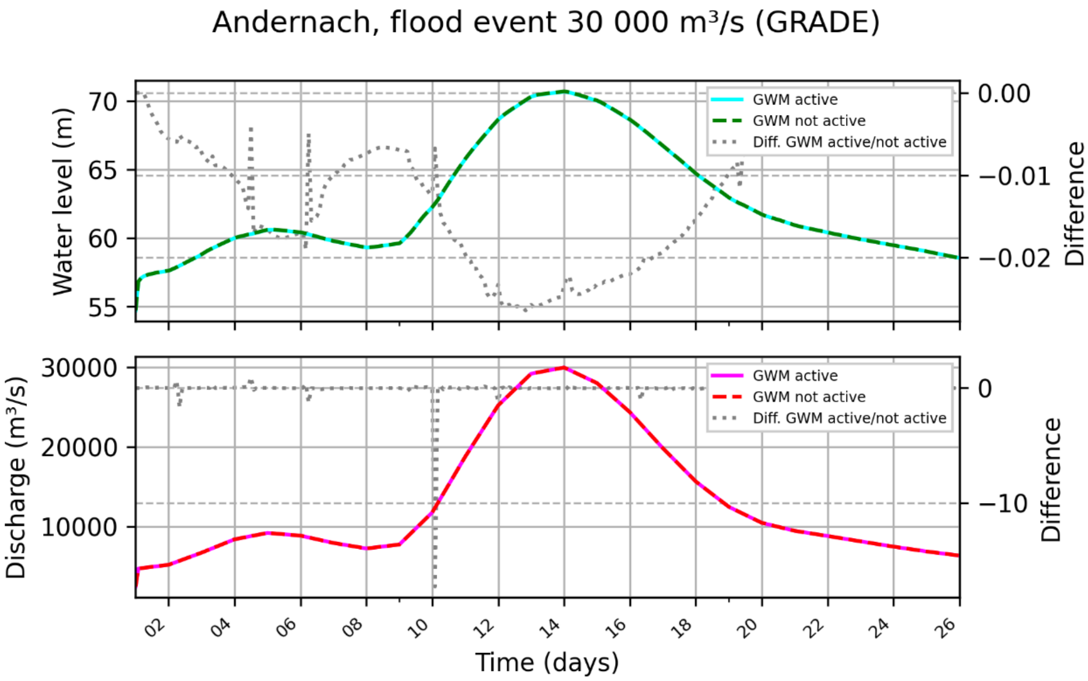

Figure 47 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

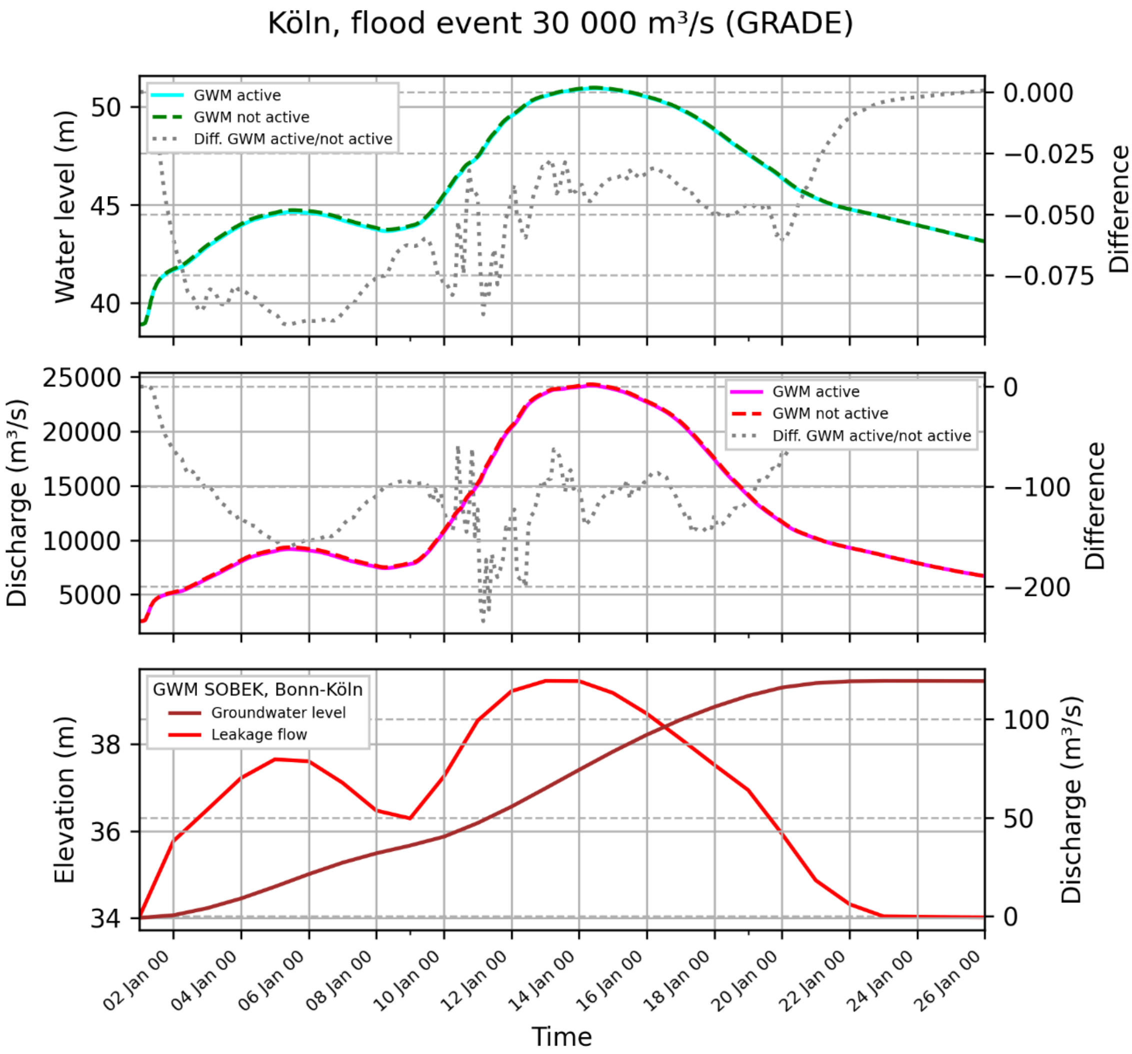

Figure 48 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

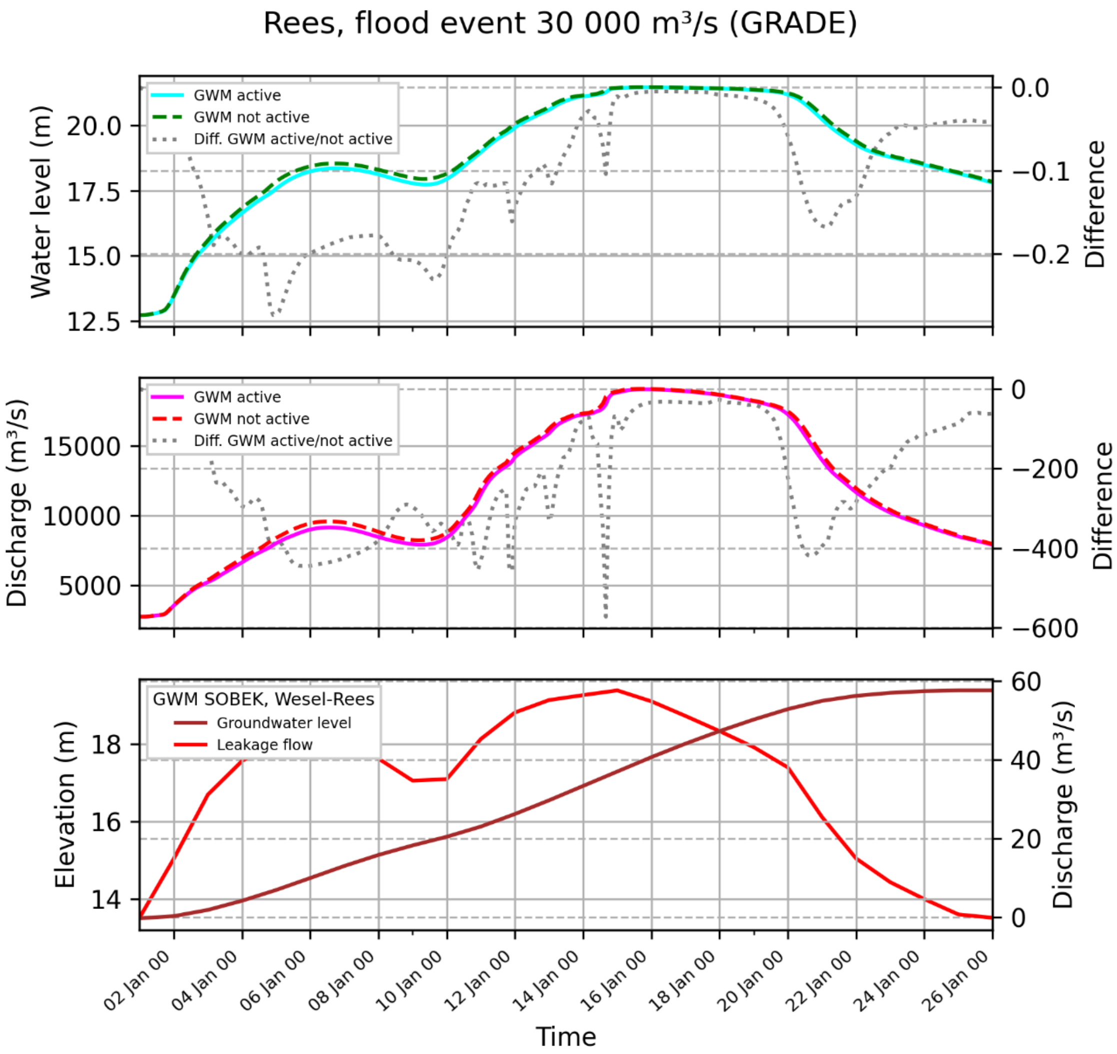

Figure 49 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

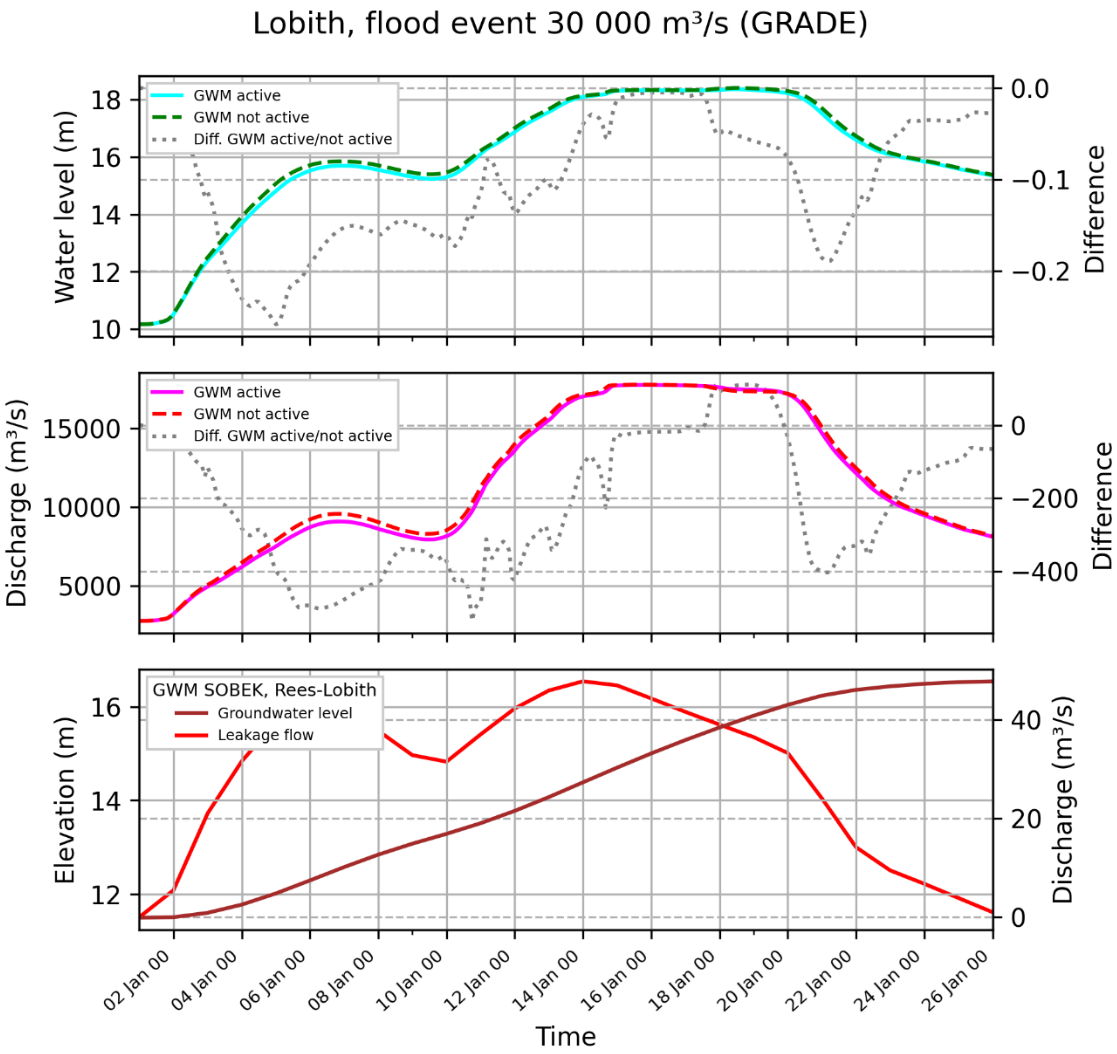

Figure 50 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

5.4 Conclusions

The extreme scenarios are synthetic scenarios generated with GRADE, and with peak discharges of 18 000, 20 000 and 30 000 m³/s at Andernach their peak discharge at all stations is much higher than the peak discharge of the historical scenarios from the years 1995, 1993 and 1998. The flood waves in the extreme scenario let the groundwater level in the groundwater storage units lateral to the river rise faster. A high groundwater level is already reached during the rising limb of the flood wave. Due to the inundations that come with this scenario, the river water level does not increase in the same extent as the discharge rises, because the water escapes into the areas behind the dikes. Both the high groundwater level and the effect of the flooding of the area behind the dikes (hinterland, Dutch: binnendijks) limits the head difference around the peak, which means that less water is withdrawn from the peak discharge in the extreme scenarios compared to the historical scenarios. The consequence is that the effect of the Groundwater Module SOBEK on the peak discharge is smaller compared to the historical scenarios. This does not mean that the total amount of water that is exchanged between river and aquifer is smaller; the exchange between river and aquifer is just more intensive before the peak. The more extreme the scenario is, i.e. the higher the discharge peak of a scenario is, the smaller is the effect on the peak discharge and on the corresponding water level, but the river-aquifer exchange does change the peak discharge also for extreme scenarios.

Modelling river-aquifer interaction with the Groundwater Module SOBEK will thus have an impact on the flood statistics that are produced with the GRADE instrument, but it decreases with the peak discharge.

However, the Groundwater Module SOBEK does not account for vertical infiltration from inundation areas behind the dikes (hinterland, Dutch: binnendijks) into the aquifer. This process of vertical infiltration has been identified as an important process during riverine floods (Becker et al. 2022; Becker 2010; Sommer et al. 2008; Sommer & Ullrich 2004), but is not (yet) being modelled with the Groundwater Module SOBEK. The Groundwater Module SOBEK (module D-RTC) is technically coupled with the D-Flow module that accounts for open channel flow, a coupling with the 2DFLOW module would be necessary to account for the process of vertical infiltration. An inundation of the flood plain extends the interface area A (Section 2.2.1) to a much larger value. This means that the potential inflow of river water into the aquifer becomes much higher (Becker et al. 2022; Becker 2010). On the other hand, the water passes the unsaturated zone when infiltrating vertically from the inundation area into the aquifer. The unsaturated zone has a larger flow resistance than the bank storage process. However, depending on the soil properties, the unsaturated zone above the groundwater table saturates quite fast (Sinaba et al. 2013; Becker 2010). Against this background it is recommended to analyse the effect of vertical infiltration from an inundation area on discharge and water level under extreme flood conditions in the future.

5.5 Impact on the correction that is currently used to account for river-aquifer interaction in the SOBEK 3 model

The Groundwater Module SOBEK, whose development and functioning is documented in this report, has not been available for the latest simulations with GRADE. To account for river-aquifer interaction and to maintain consistency between the SOBEK 3 model and the SOBEK-RE models that both run under GRADE, a correction is carried out in recent use of GRADE (Hegnauer et al. 2023). This correction depends on the river discharge. The corresponding correction function has been determined based on “expert judgement and a visual interpretation of the data from a comparison between SOBEK-RE and SOBEK3-1D2D model results”. Both the correction function and the data base are shown in Figure 51. The correction factor applies to discharge values at gauging station Lobith.

Figure 52 shows the correction suggested by Hegnauer et al. 2023 and the differences in peak discharge from scenarios that were run within this study with the SOBEK 3 model from Andernach to Lobith with Groundwater Module SOBEK not active and active.

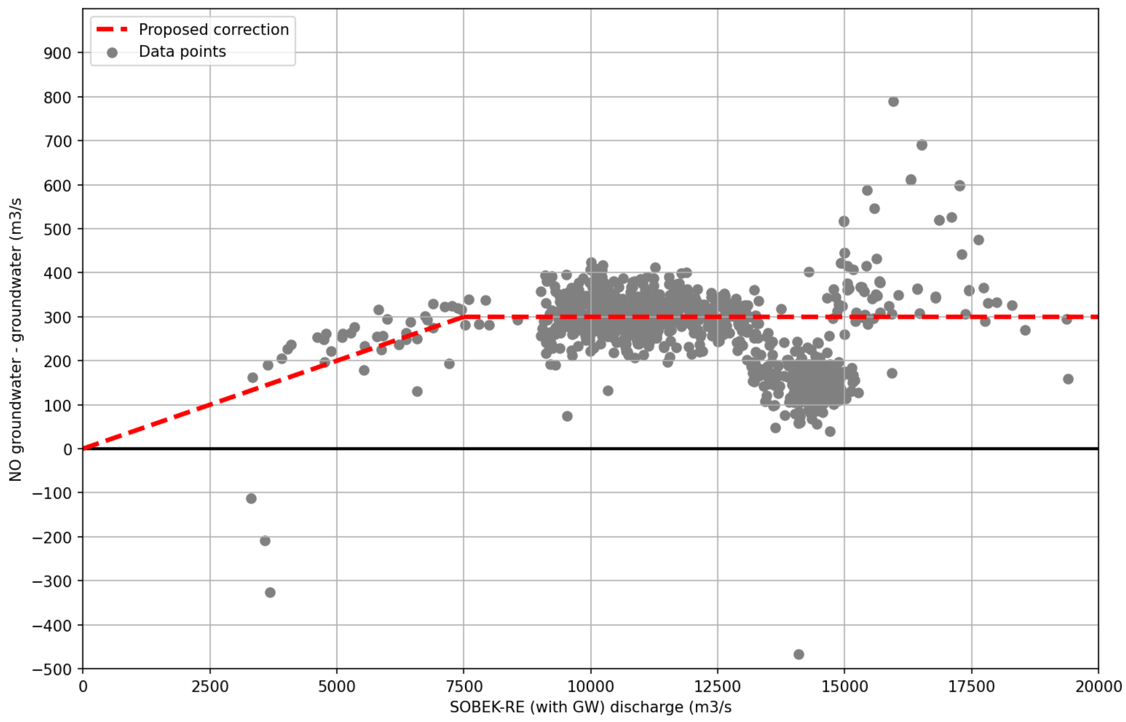

Figure 51 Correction factor for river-aquifer interaction and supporting data points for Lobith from model results from Hegnauer et al. 2023, Appendix C3

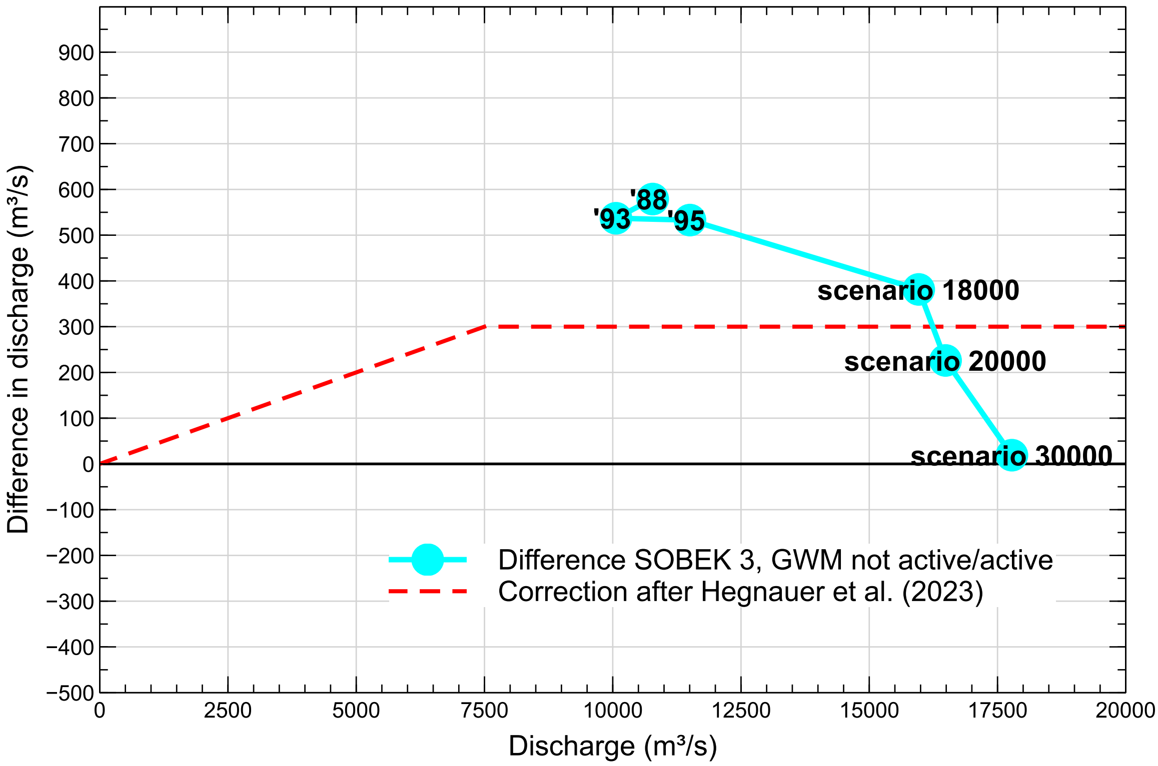

Figure 52 Correction after Hegnauer et al. 2023 and differences in discharge from simulations with SOBEK 3 with Groundwater Module active and not active for Lobith over discharge computed with groundwater module active at Lobith (difference SOBEK 3, GWM active/not active)

For the historical flood events 1988, 1993 and 1995, the river-aquifer interaction modelled with the Groundwater Module SOBEK is larger than the correction suggested by Hegnauer et al. 2023.

As already pointed out in the previous sections, the more extreme synthetic scenarios with a peak discharge of 18 000, 20 000 and 30 000 m^3/s at Andernach, the smaller is the impact of the groundwater module. However, as mentioned above, the Groundwater Module SOBEK does not account for the interaction between the inundated area and the aquifer from vertical infiltration. In reality, the impact will probably be larger.

Hegnauer et al. 2023 have proposed a correction to achieve consistency of SOBEK-RE simulation results with simulation results from SOBEK 3 without modelled river-aquifer interaction with groundwater module SOBEK. The proposed correction function limits the change of peak discharge due to river-aquifer exchange to 300 m^3/s. The results obtained in this study suggest that the impact of river-aquifer interaction on the discharge can be higher for flood events with high peak discharges. To achieve consistency between SOBEK 3 model results with Groundwater Module SOBEK active and SOBEK-RE, it can make sense to aim for a good match between both models after the calibration such that the correction factor can be omitted. Note that the SOBEK 3 model has not yet been fully calibrated towards the good match to observed river water level and discharge (see Section 4.1.5), and within this study only the Groundwater Module SOBEK has been calibrated (Section 3.2). The river-aquifer interaction under flood conditions with inundations should be addressed separately. It can be difficult to quantify the effect with the available models, because the SOBEK-RE model does not account for inundations and both models neglect vertical infiltration from the inundation area into the aquifer; expert judgement will be needed to accompany the findings.

6 Practical aspects of modelling river aquifer interaction

6.1 Introduction

In the following sections we discuss some practical aspects about the usage of the Groundwater Module SOBEK within GRADE with respect to:

- initial conditions for the Groundwater Module SOBEK
- the sensitivity of model results on model parameters
- computing time

and minor issues, which came across and which should be improved.

6.2 Pre-simulation time

Within GRADE, a pre-event period of two years is foreseen for the hydrological model runs to provide stable conditions during the flood event. For the hydraulic models (SOBEK RE and SOBEK 3) a pre-event period of 14 days is used to give the model time to adjust to initial conditions before the discharge reaches flood conditions.

The simulation results of the groundwater module SOBEK don’t show extensive instabilities in the beginning of the simulation period. Figure 53 shows the result from a simulation with the groundwater module SOBEK including the pre-event period before the flood wave arrives at the location. Initial oscillations can be seen in the river water level curve and in the leakage flow the groundwater module computes. The groundwater storage units are very large and have a dampening effect such that this initial adjustment does not propagate into the groundwater module. This means that the usage of the groundwater module SOBEK does not require special attention in terms of pre-event simulation period to ensure stability with respect to initial conditions.

The river water level during normal conditions can be used as initial condition for the groundwater storage unit from the groundwater module. The river water level must be translated into a virtual groundwater level. This is a simple calculation, but this pre-processing step must be accounted for in the automated workflows of GRADE.

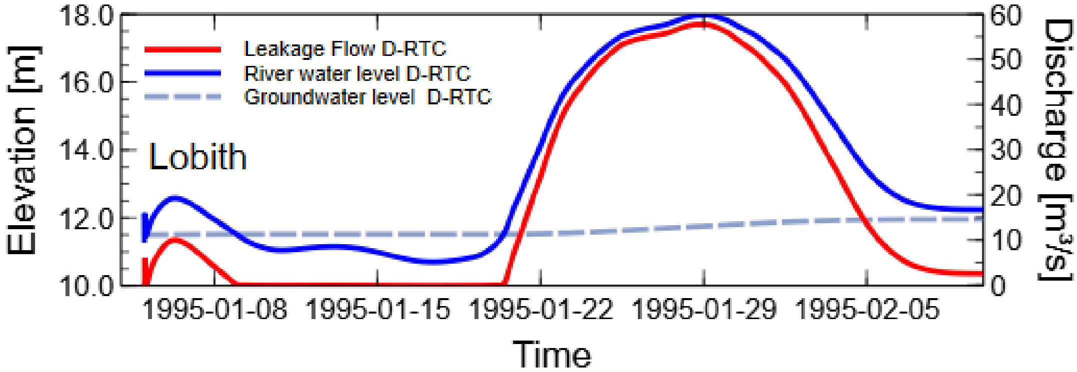

Figure 53 Simulation result of the groundwater module SOBEK (gauging station Lobith, Scenario 1995, HyMoG dataset)

6.3 Sensitivity analysis

6.3.1 Introduction

To understand how the Groundwater Module SOBEK reacts on changes in the model parameters, three model parameters have been varied for the scenario “flood event 1995” (HyMoG data set). The parameters:

- leakage parameter
- porosity
- initial groundwater level

have been changed by ±10 % with respect to the values given in Section 3.2. The accumulative effect at Lobith has been compared to the unchanged result. The change in model result related to the variation of a certain parameter indicates the sensitivity of the model with respect to the changed parameter.

6.3.2 Variation of the leakage parameters

The leakage parameters are the same throughout all the GW intake locations along the River between Andernach and Lobith (Table 2). Table 13 shows the variation of the leakage parameter for the sensitivity analysis.

Table 13 Variation of leakage parameter

	Exfiltration	Infiltration
+10%	1.11e-6	5.55e-5
default	1.00e-6	5.00e-5
-10%	9.00e-7	4.50e-5

The effect of a change in leakage parameter by ±10 % can be seen in Figure 54. The discharge at Lobith differs by about 100 m³/s between increasing and reducing the leakage parameter by 10 %, respectively. The highest difference in discharge occurs around the peak. For the water level, the difference is a bit more than 2 cm, but before and after the peak the difference is more than 4 cm for certain periods. The variation by 10 % has here been applied to the leakage parameter c. As the leakage parameter is multiplied with the interface area A to determine the leakage flow, the model’s sensitivity on the variation of the leakage parameter also reflects the model’s sensitivity on the interface area.

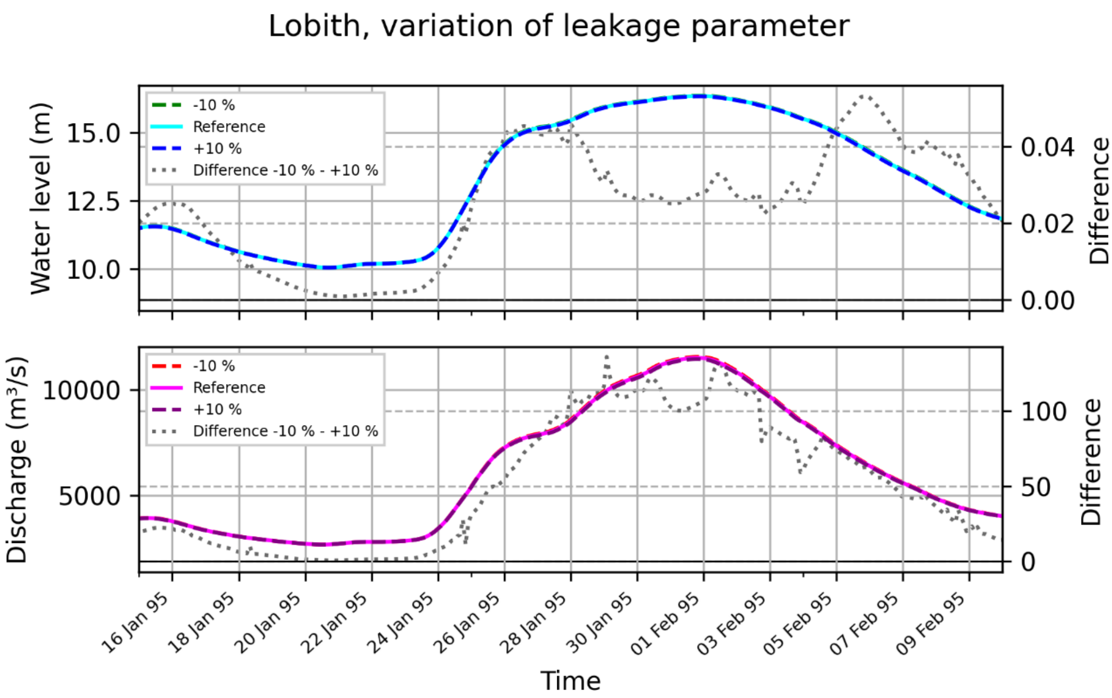

Figure 54 Water level and discharge at Lobith, simulated for the flood event 1995 (HyMoG data set) with different leakage parameters and difference in model result from simulation with a parameter increase/decrease by 10 %

6.3.3 Variation of the porosity

The default value for porosity in all groundwater storage units is 0.2. In the model, the porosity affects the relation between volume and water level and thus the initial groundwater volume. Table 14 and Table 15 show the corresponding volumes for the variation of the porosity by ±10 %.

Table 14 Maximum volume in the groundwater storage unit for different porosity values in m³

	Andernach-Bonn	Bonn-Köln	Köln-Düsseldorf	Düsseldorf-Ruhrort	Ruhrort-Wesel	Wesel -Rees	Rees-Lobith
0.22 (+10%)	448 189 684	384 866 482	657 666 240	775 513 200	1054 528 860	173 416 320	150 227 385
0.2	407 445 168	349 878 620	597 878 400	705 012 000	958 662 600	157 651 200	136 570 350
0.18 (-10%)	366 700 651	314 890 758	538 090 560	634 510 800	862 796 340	141 886 080	122 913 315

Table 15 Initial volume in the groundwater storage unit for different porosity values in m³

	Andernach-Bonn	Bonn-Köln	Köln-Düsseldorf	Düsseldorf-Ruhrort	Ruhrort-Wesel	Wesel -Rees	Rees-Lobith
0.22 (+10%)	144 577 318	53 085 032	82 208 280	581 634 900	782 392 380	108 385 200	92 997 905
0.2	131 433 925	48 259 120	74 734 800	528 759 000	711 265 800	98 532 000	84 543 550
0.18 (-10%)	118 290 533	43 433 208	67 261 320	475 883 100	640 139 220	88 678 800	76 089 195

A change of porosity by ±10 % has a smaller effect on the results for discharge and water level at Lobith than a change in leakage parameter, and the effect comes to bear later in the simulation period, as Figure 55 shows. With a difference in the order of 1 centimetre for water level and 20 m³/s for discharges, the effect is very small. Oscillations in the difference have not further been investigated, but they are probably related to the modelling approach for the river-aquifer interaction.

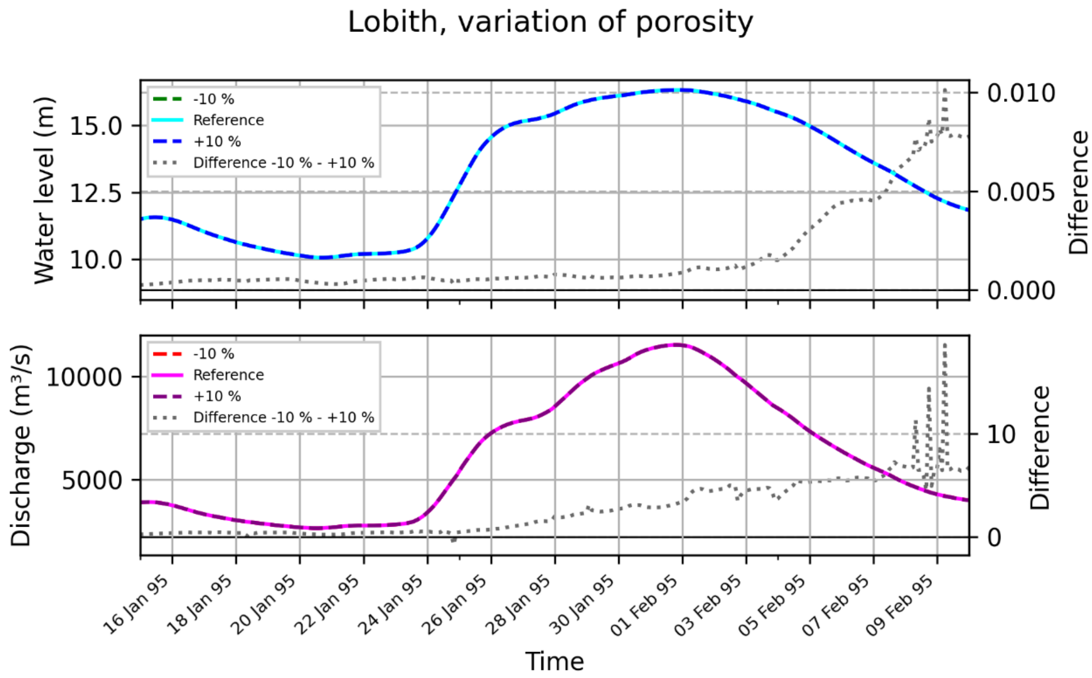

Figure 55 Water level and discharge at Lobith, simulated for the flood event 1995 (HyMoG data set) with different leakage parameters and difference in model result from simulation with a parameter increase/decrease by 10 %

6.3.4 Variation of the initial groundwater level

The variation of the initial groundwater level for each groundwater storage unit is given in Table 16. The corresponding initial volume of the groundwater storage units is given in Table 17. For the groundwater storage units Bonn-Köln and Köln-Düsseldorf the reduction of the initial value by 10 % would lead to an initial groundwater level lower than the base of the groundwater storage unit. In this case, the initial groundwater level has been set 0.5 m higher than the base level of the groundwater storage unit.

With a change of more than 20 cm in water level and more than 400 m³/s in discharge between two simulation runs where the initial groundwater level has been increased by 10 % and decreased by 10 %, respectively (Figure 56), the impact of the initial groundwater level in the groundwater storage unit is much larger than the impact of other parameters that were analysed within the sensitivity analysis.

In Section 6.2 we suggest using the river water level during normal conditions from the pre-simulation period as initial condition. It can make sense to set the initial conditions differently: with a higher initial water level less river water infiltrates into the aquifer which probably produces results that are more on the safe side. This makes sense for a project as GRADE that focusses on extreme floods, because extreme floods are often preceded by long-lasting rainfall.

Table 16 Initial groundwater level which are used in the model

	Andernach-Bonn	**Bonn-Köln**	**Köln-Düsseldorf**	**Düsseldorf-Ruhrort**	**Ruhrort-Wesel**	**Wesel -Rees**	**Rees-Lobith**
+10%	48.4	37.4	25.3	26.4	19.8	14.85	12.65
default	44.0	34.0	23.0	24.0	18.0	13.50	11.50
-10% or *0.5 m above base*	39.6	*32.5*	*21.5*	21.6	16.2	12.15	10.35

Table 17 Initial groundwater volume in m³ that corresponds to the initial level in Table 16.

	Andernach-Bonn	**Bonn-Köln**	**Köln-Düsseldorf**	**Düsseldorf-Ruhrort**	**Ruhrort-Wesel**	**Wesel -Rees**	**Rees-Lobith**
+10%	247095779	130299624	160679820	634510800	822594360	116267760	99501255
default	131433925	48259120	74734800	528759000	711265800	98532000	84543550
-10% or *0.5 m above base*	15772071	*12064780*	*18683700*	423007200	599937240	80796240	69585845

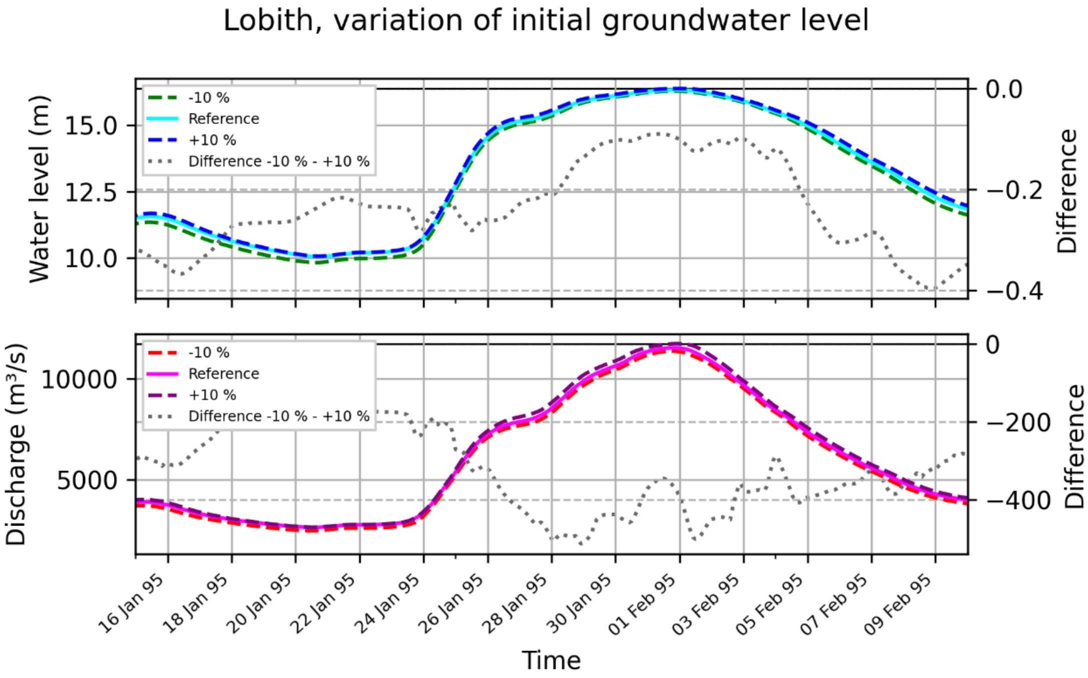

Figure 56 Water level and discharge at Lobith, simulated for the flood event 1995 (HyMoG data set) with different leakage parameters and difference in model result from simulation with a parameter increase/decrease by 10 %

6.4 Computing time

Table 18 shows the computing time from different scenario runs with the SOBEK 3 model and groundwater module active and not active. The computing time does not necessarily increase if the groundwater module is active. This indicates that the impact of the Groundwater Module SOBEK on the computing time of the SOBEK 3 model of the Rhine is small. This is not surprising, because the SOBEK 3 model already comprises a D-RTC model component to account for the control of hydraulic structures, in particular for the control of the weirs. In earlier tests for simulation times, that module has already proven to have very little influence on computation times. The groundwater module SOBEK only adds a couple of extra computations that do not contain any iterations. The model runs have been carried out on a personal laptop with other processes running. The computing time records are thus subject to inaccuracies and must be treated as an indication rather than as exact computing times.

For the more extreme GRADE scenarios where the river leaves the bank and inundations take place, the 1D2D-FLOW module becomes active. A technical test run of a GRADE scenario with extreme discharge has been carried out with and without the 1D2D-FLOW module (Table 18, scenarios “GRADE 24 000 m³/s”). The runtimes are the same. This indicates that the Groundwater Module SOBEK has little impact on computations with the 1D2D-FLOW module, too.

Table 18 Computing time in minutes from different simulation runs carried out on a personal Laptop

Scenario	Groundwater module not active	Groundwater module active
1988	30	26
1993	39	58
1995	39	48
GRADE 24 000 m³/s 1D2D-FLOW module activated	83	71
GRADE 24 000 m³/s 1D2D-FLOW module deactivated	83	71

6.5 Other technical aspects

6.5.1 Export of boundary conditions

During the analysis we found that the export of boundary condition data for SOBEK (the so-called bc file) is on a coarse time resolution with values interpolated in-between (see Section 4.5) and has a time shift. The export feature from GRADE should be checked and corrected accordingly. It is recommended to export boundary condition data with a resolution of at least 1 hour, rather 15 minutes.

6.5.2 Deltares Integrated Model Runner (DIMR)

Section 2.2.2 mentions that the SOBEK 3 model with Groundwater Module SOBEK cannot be run from the user interface and must be run with the DIMR. This has no implications for GRADE, because the SOBEK 3 model runs within GRADE are executed with the DIMR anyway.

6.5.3 Model schematization

The Groundwater Module SOBEK has been implemented into the existing SOBEK 3 model of the Rhine from Andernach to Lobith within this study. The changes applied to the schematization of different modules of SOBEK 3 are summarized here, the model that runs under GRADE must be updated accordingly:

- 1DFLOW
  - Lateral inflow points for the river-aquifer interaction have been added between the gauging stations.
  - Observation points as input for the D-RTC module have been added between the gauging stations (100 m upstream and downstream of the groundwater lateral inflow points).
- D-RTC
  - D-RTC configuration added according to Section 2.2.2
- DIMR configuration file
  - Configuration of exchange items for groundwater interaction needs to be added to the existing configuration.

7 Summary of conclusions and remarks

A groundwater module SOBEK has been developed as module for the SOBEK 3 model of the Rhine to represent the water exchange between river and aquifer. Several model runs have been carried out and the simulation results were analysed to assess the usage of the groundwater module SOBEK with respect to three aspects:

1. Added value of modelling river-aquifer interaction in hydraulic models
2. Impact of river-aquifer modelling on extreme flood events and flood statistics
3. Practical aspects of modelling river-aquifer interaction

With respect to the added value of modelling river-aquifer interaction in hydraulic models, the conclusions of the study are:

- The SOBEK 3 model with groundwater module SOBEK produces good results. This is supported by a comparison with data based on observations, the HyMoG data, for three flood scenarios (1995, 1993, 1988). Comparison runs with the SOBEK-RE model and the GRADE data set shows a good match of the SOBEK 3 simulation result, too.
- Different to earlier approaches for modelling the river-aquifer interaction in SOBEK models, the modelling approach of the Groundwater Module SOBEK uses the leakage-approach, an approach which is well-documented in literature and a widely accepted modelling approach for river-aquifer interaction in computer models.
- The effect of the river-aquifer interaction on the discharge and water level is comparatively small, but significant: the flood peak at Lobith changes in the order of 5 % for historic scenarios. At the downstream model boundary at Lobith, the cumulative groundwater storage reduces the peak discharges by ca. 533 m^3/s for the 1995 flood.
- The SOBEK 3 model has already a good level of calibration without the groundwater module SOBEK, both in comparison with model results from SOBEK-RE, where river-aquifer interchange is incorporated, as well as compared to the HyMoG data set, which is based on observed data. Adding the groundwater module SOBEK in its current state does not necessarily improve the model results at all locations. At the downstream locations however, which are considered as the most important ones, the Groundwater Module SOBEK shows already an improvement in terms of match between simulated and observed data, while at the locations further upstream there is not necessarily an improvement by the groundwater module.
- A new integrated calibration of the SOBEK 3 model that involves both the hydraulic model component (roughness parameters) and parameters of the groundwater module SOBEK will provide an even better match between simulated data and observed data. The calibration parameter of the hydraulic model, the roughness, mainly allows to tune the water level. The shape of the discharge curve can only be addressed to some extent with the roughness parameter (wave damping). With the Groundwater Module SOBEK it is now possible to model bank storage, which is technically and physically a temporary withdrawal of water. This process has been reported as significant in literature; now incorporated in the model opens a new dimension for the calibration of the shape of the discharge wave.
- For the integrated calibration it is important to decide if consistency with the SOBEK-RE model or with observed data (HyMoG dataset) is the primary calibration goal.

With respect to the impact of river aquifer modelling on extreme flood events and flood statisticsImpact of river-aquifer modelling on extreme flood events and flood statistics , the conclusions are summarized as follows:

- Simulation runs of extreme scenarios from GRADE have been carried out with the Groundwater Module SOBEK. The effect of the river-aquifer interaction is also clearly visible for extreme scenarios.
- The more extreme a scenario, the smaller is the effect of river-aquifer interaction on the model results. This can be explained with the bank storage processes and the effect of inundations that take place under extreme flood conditions on the water level.
- The vertical infiltration of water from a flood plain into the groundwater is not accounted for in the Groundwater Module SOBEK. When it comes to inundations, it is possible that river-aquifer interactions have a larger effect on peak discharge and corresponding water level than the model shows.
- Modelling river-aquifer interaction with the Groundwater Module SOBEK will thus have an impact on the flood statistics that are produced with the GRADE instrument. However, for an assessment of good quality, more simulations must be carried out.
- Correction functions to achieve model consistency should be updated after the integrated calibration of the SOBEK 3 model of the Rhine. Ideally, the models are sufficiently consistent such that no correction is needed.

Practical aspects of modelling river-aquifer interaction that are to be considered are:

- The groundwater module SOBEK does not require special attention in terms of pre-event simulation time for model stability.
- The initial condition, i. e. the initial groundwater level in the groundwater storage unit, has the largest impact on the model result. The main calibration parameter, the leakage parameters and the interface area, can be used to adjust the model result in the order of centimetres for water level or tens of cubic metres per second for discharge. The porosity has a small effect which comes to bear late in the simulation period only.
- The impact of the groundwater model on the computing time is small.

As next steps we recommend an integrated calibration of the SOBEK 3 model, where the parameters of the hydraulic model (roughness parameters) and the parameters of the Groundwater Module SOBEK are adjusted coherently. The current model is already in a good state, so we expect the integrated calibration not to be extremely laborious. With the current model we have shown that the Groundwater Module SOBEK is an improvement for some, but not all gauging stations. This should be sufficient support for a usage of the Groundwater Module SOBEK within GRADE, but the full potential of the Groundwater Module SOBEK will come to bear after an integrated calibration.

Furthermore, we have some minor adjustments in the GRADE instrument that should be addressed (Section 6.5), and finally, the SOBEK model with Groundwater Module SOBEK must be implemented into FEWS-GRADE.

8 References

Barneveld, H. J.; Meijer, D. G. (1997): SOBEK-model Andernach-Lobith / Model construction, calibration and verification. HKV LIJN IN WATER, geodan GEODESIE. [on behalf of] Institute for Inland Water Management and Waste Water Treatment (RIZA) Ministry of Transport, Public Works and Water Management (RWS) PR042.

Becker, A. (2020a): 1D2D model of the Lower Rhine and the upper Dutch Rhine branches between Andernach and Nijmegen, Arnhem and Zutphen. Deltares. Draft report 11205237-002-ZWS-0001. URL: https://open.rws.nl/open-overheid/onderzoeksrapporten/@253305/1d2d-model-the-lower-rhine-and-the-upper/ (Checked: 08/11/2023).

Becker, B. (2021): An approach for modelling the river-aquifer interaction for SOBEK models of the Rhine. Deltares. Memo 11205237-003-ZWS-0019_v0.5.

Becker, B. (2020b): Modellierung Grundwasseraustausch in SOBEK-Modellen. Deltares. Memo 11205237-003-ZWS-0011 v0.4.

Becker, B. (2020c): Modelling river-aquifer water exchange in SOBEK. Deltares. Memo 11205237-003-ZWS-0012_v0.2.

Becker, B.; Fujisaki, A. (2022): Groundwater module SOBEK current status. Deltares. Memo 11208037-002-ZWS-0009.

Becker, B. P. J.; Jansen, M.; Sinaba, B. P.; Schüttrumpf, H. (2015): On the Modeling of Bank Storage in a Groundwater Model: The April, 1983, Flood Event in the Neuwieder Becken (Middle Rhine). Water Vol. 7 (2015) No. 3 pp. 1173–1201. DOI: 10.3390/w7031173.

Becker, B. P. J. (2010): Zur Gekoppelten Numerischen Modellierung von unterirdischem Hochwasser. RWTH Aachen University, Dissertation. URL: https://publications.rwth-aachen.de/record/63111/files/3288.pdf (Checked: 02/08/2015).

Becker, B.; Reichel, F.; Bachmann, D.; Schinke, R. (2022): High groundwater levels: Processes, consequences, and management. WIREs Water Vol. 9 (2022) No. 5 pp. e1605. DOI: 10.1002/wat2.1605.

Blaschke, A. P. (2002): Auswirkungen der Selbstdichtung auf das Grundwasser in staugeregelten Flüssen. In: H. Wittenberg, M. Schöniger (Editors): Wechselwirkungen zwischen Grundwasserleitern und Oberflächengewässern : Beiträge zum Tag der Hydrologie 2002 20. bis 22. März 2002 in Suderburg, Lüneburger Heide: / Forum für Hydrologie und Wasserbewirtschaftung. Fachgemeinschaft Hydrologische Wissenschaften in der ATV-DVWK. ISBN 3-936514-22-4.

BWK (2022): Umgang mit hohen Grundwasserständen / Prozesse, Lösungsansätze, Fallbeispiele. BWK-Fachinformationen. Lüneburg: Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau (BWK) e. V. ISBN 978-3-936015-99-7. URL: https://www.verbandonline.org/BWK_Bund/?action=shop_order&kategorie=Fachinformationen.

Giebel, H.; Hommes, A. (1988): Zum Austausch zwischen Fluß- und Grundwasser – Weitergehende Auswertung aus dem Neuwieder Becken. Deutsche Gewässerkundliche Mitteilungen Vol. 32 (1988) No. 1/2 pp. 18–27.

Giebel, H.; Hommes, A. (1994): Zum Austausch zwischen Fluß- und Grundwasser - Fortführung der Auswertungen im Neuwieder Becken -. Deutsche Gewässerkundliche Mitteilungen Vol. 38 (1994) No. 1/2 pp. 2–10.

Gölz, E.; Schubert, J.; Liebich, D. (1991): Sohlenkolmation und Uferfiltration im Bereich des Wasserwerks Flehe (Düsseldorf). gwf-Wasser/Abwasser Vol. 132 (1991) No. 2 pp. 69–76.

Hammer, M. (2003): Untersuchung des Internen Grundwasserbausteins in SOBEK-RE. Bundesanstalt für Gewässerkunde. Bericht.

Hegnauer, M.; Becker, A. (2013): Technical Documentation GRADE part II: models Rhine. Deltares. Deltares report 1207771–003. URL: https://open.rws.nl/open-overheid/onderzoeksrapporten/@253530/technical-documentation-grade-3-0-part-0/ (Checked: 08/11/2023).

Hegnauer, M.; Beersma, J.; van den Brink, H.; Leander, R. (2023): Generator of Rainfall and Discharge Extremes for the Rhine / Final report of GRADE-Rhine version 3.0. Deltares and Koninklijk Nederlands Meteorologisch Instituut (KNMI). Deltares report 1205237-003-ZWS-0016. URL: https://open.rws.nl/open-overheid/onderzoeksrapporten/@253518/generator-rainfall-and-discharge-extreme/ (Checked: 08/11/2023).

HKV Hydrokontor (2014): Erstellung eines SOBEK-River Modells für den Rhein von Iffezheim bis Pannerdense Kop als Weiterentwicklung bestehender SOBEK-RE Modelle. HKV Hydrokontor. Projektbericht PR2278.10.

de Jong, J. (2015): Totstandkoming van het model van de Duitse Rijn in SOBEK 3. Deltares. Memo 1220065-000-ZWS-0017.

Kroekenstoel, D. F. (2003): Calibratie interne Grondwatermodule SOBEK-model Andernach - Lobith. Ministerie van Verkeer en Waterstaat Directoraat-Generaal Rijkswaterstaat Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling/RIZA. Memo WSR 2003-027 (MEMO SOBEK-GWmodule.doc).

Kroekenstoel, D.; van der Veen, R. (n.d.): Grondwater intern SOBEK voor Andernach Lobith. Word-document Grondwater intern SOBEK voor Andernach Lobith.doc.

Meißner, D. (2008): Erstellung, Kalibrierung und Validierung des SOBEK-modells für die Rheinstrecke zwischen Pegel Andernach und Lobith. Bundesanstalt für Gewässerkunde. BfG-Bericht 1593.

Morita, M.; Yen, B. C. (2002): Modeling of Conjunctive Two-Dimensional Sufrace-Three-Dimensional Subsurface Flows. Journal of Hydraulic Engineering Vol. 128 (2002) No. 2 pp. 184–200. DOI: 10.1061/(ASCE)0733-9429(2002)128:2(184).

Pinder, G. F.; Sauer, S. P. (1971): Numerical Simulation of Flood Wave Modification Due to Bank Storage Effects. Water Resources Research Vol. 7 (1971) No. 1 pp. 63–70.

RheinEnergie AG (2009): Instationäre Grundwassermodellrechnung eines 200- jährigen Bemessungshochwassers unter besonderer Berücksichtigung der Auswirkungen auf die Kölner Stadtbahnanlagen / Berechnung der maximalen Grundwasserstände für die linksrheinischen Kölner Stadtbahnanlagen der Kölner Verkehrsbetriebe KVB. Stadt Köln, Amt für Brücken und Stadtbahnbau. Erläuterungsbericht.

Simpson, S. C.; Meixner, T. (2012): Modeling effects of floods on streambed hydraulic conductivity and groundwater-surface water interactions. Water Resources Research Vol. 48 (2012) No. 2. DOI: 10.1029/2011WR011022.

Sinaba, B.; Becker, B.; Klauder, W.; Salazar, I.; Schüttrumpf, H. (2013): On the proceeding of a saturation front under ponded conditions. Obras y Proyectos Vol. 13 (2013) pp. 31–39.

Sommer, T.; Ettrich, N.; Eulitz, K.; Haase, D.; Karpf, C.; Peetz, J.-V.; Steckel, B.; Weichel, T. (2008): Entwicklung eines 3-Zonen-Modells für Grundwasser- und Infrastrukturmanagement nach extremen Hochwasserereignissen in urbanen Räumen (3ZM-GRIMEX). Dresdner Grundwasserforschungszentrum e.\,V. (DGFZ); Fraunhofer Institut für Algorithmen und Wissenschaftliches Rechnen (SCAI); Fraunhofer Institut für Techno- und Wirtschaftsmathematik (ITWM); Technische Universität Dresden, Institut für Siedlungs- und Industriewasserwirtschaft (ISI); Helmholtz-Zentrum für Umfeltforschung GmbH - UFZ, Department Angewandte Landschaftsökologie. Abschlussbericht / BMBF-Verbund-Projekt / FKZ: 02WH0557. URL: http://edok01.tib.uni-hannover.de/edoks/e01fb09/594029457.pdf.

Sommer, T.; Ullrich, K. (2004): Das unsichtbare Hochwasser - Auswirkungen des August-Hochwassers 2002 auf das Grundwasser im Stadtgebiet von Dresden. In: J. Köngeter (Editor): 34. IWASA, Internationales Wasserbau-Symposium Aachen 2004 : Hochwasserschutz - eindeichen oder ausweichen? / Mitteilungen des Institutes für Wasserbau und Wasserwirtschaft der RWTH Aachen. Aachen: Shaker. ISBN 3-8322-3592-2.

Steinrücke, J.; Fröhlings, B.; Weißhaupt, R. (2011a): HYMOG / Hydrologische Modellierungsgrundlagen im Rheingebiet. ProAqua Ingenieurgesellschaft für Wasser und Umwelttechnik mbH. Dokumentation für die Bundesanstalt für Gewässerkunde [Hauptbericht].

Steinrücke, J.; Fröhlings, B.; Weißhaupt, R. (2011b): HYMOG / Hydrologische Modellierungsgrundlagen im Rheingebiet. ProAqua Ingenieurgesellschaft für Wasser und Umwelttechnik mbH. Dokumentation für die Bundesanstalt für Gewässerkunde Anlage 2: Bilanzanalysen und Anpassungen.

Stelling, G. S.; Duinmeijer, S. P. A. (2003): A staggered conservative scheme for every Froude number in rapidly varied shallow water flows. International Journal for Numerical Methods in Fluids Vol. 43 (2003) No. 12 pp. 1329–1354.

Ubell, K. (1987a): Austauschvorgänge zwischen Fluß und Grundwasser – Teil I. Deutsche Gewässerkundliche Mitteilungen Vol. 31 (1987) No. 4 pp. 119–125.

Ubell, K. (1987b): Austauschvorgänge zwischen Fluß und Grundwasser - Teil II. Deutsche Gewässerkundliche Mitteilungen Vol. 31 (1987) No. 5 pp. 142–148.

Ubell, K. (1986): Wechselbeziehung zwischen Rheinwasser und Grundwasser am Beispiel des Neuwieder Beckens. Bundesanstalt für Gewässerkunde. Bericht BfG-0322.

Ubell, K. (1964): Surface- and groundwater relationships along the Hungarian reach of the Danube river. In: Symposium surface waters hold at the occasion of general assembly of Berkeley of I.U.G.G. 19.-31.8.1093: / Publication de l’association internationale d’hydrologie scientifique. URL: http://www.iahs.info/.

Sächsisches Landesamt für Umwelt und Geologie (ed.) (2003): Einfluss des August Hochwassers 2002 auf das Grundwasser. Materialien zur Wasserwirtschaft. .

A Model history

A history of river-aquifer modelling in the hydraulic model of the Rhine between Andernach and Lobith with GRADE models (SOBEK-RE and SOBEK 3) is given in the following table.

Table 19 History of SOBEK models for the Rhine between Andernach and Lobith

No.	Year	Model and reference	Approach for river-aquifer interaction
1	1996	First SOBEK-RE model with external groundwater module (Barneveld & Meijer 1997)	External groundwater model computes river-aquifer exchange as pre-processor.
2	2003	SOBEK-RE model with internal groundwater module (Kroekenstoel & van der Veen n.d.; Hammer 2003; Kroekenstoel 2003)	River-aquifer interaction modelled within an internal groundwater module.
3	2005-2008	Update of SOBEK-RE-Modell (Meißner 2008)	River-aquifer interaction modelled with the help of laterals inflow and retention nodes; exchange between river and aquifer modelled as weir flow (gated weir).
4	2014	Update and migration to SOBEK 2 (HKV Hydrokontor 2014)	River-aquifer interaction with retention node and weir formula (fixed weir, closed weir profile) on separate branch.
5	2015	Migration to SOBEK 3 for flood forecasting purpose in the Netherlands (de Jong 2015)	River-aquifer interaction with retention node and weir formula (fixed weir, open weir profile) on separate branch.
6	2017	Adaptation of SOBEK 3 model for GRADE (Becker 2020a)	Model objects representing river-aquifer interactions removed. The additional branches account for a significant computing time because they show up in the equation system of the numerical scheme. Correction factors have been developed to correct the peak discharges (Appendix C.3 in Hegnauer et al. 2023)
7	2022-2023	Groundwater Module SOBEK in D-RTC of SOBEK 3 (this report, Becker & Fujisaki 2022; Becker 2020b, 2020c, 2021)	Groundwater storage units exchange water with the river via the so-called leakage approach. This leakage approach is a widely accepted representation of the interchange mechanism. It shows less dynamics than previous approaches (weir formula and retention basin), which is closer to reality. The D-RTC module exchanges data with the channel flow module on a time step basis, this means that the groundwater module is not part of the channel flow computation.

B Simulation results

B.1 Comparison of SOBEK 3 simulation results with data from observations (GRADE-HyMoG dataset)

B.1.1 Flood event 1995

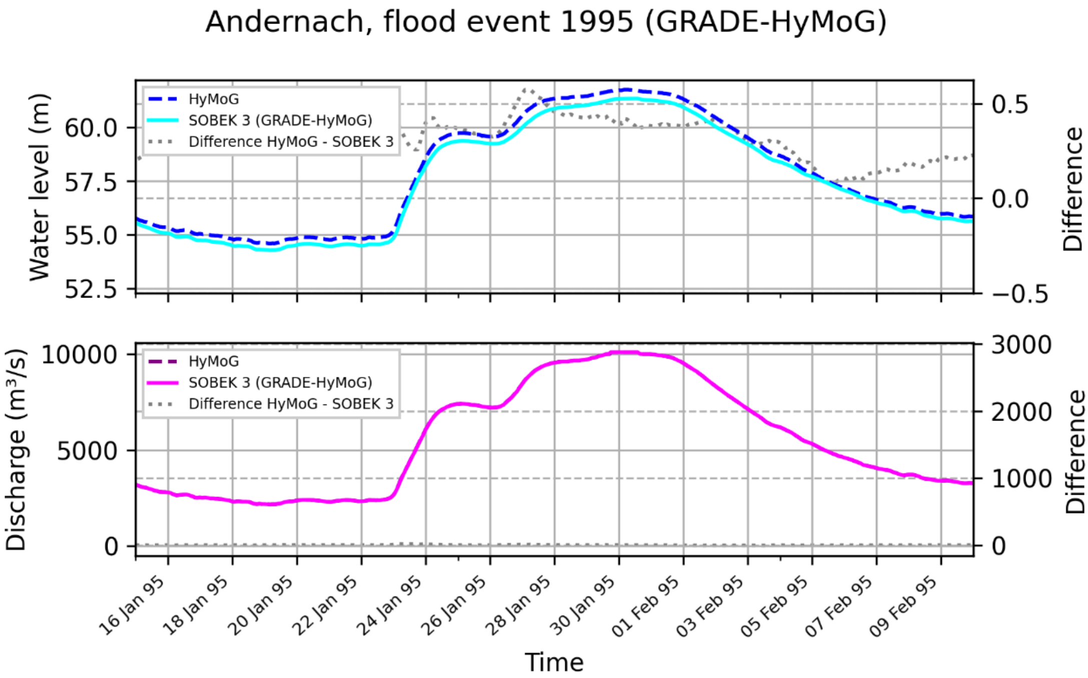

Figure 57 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Andernach, flood event 1995

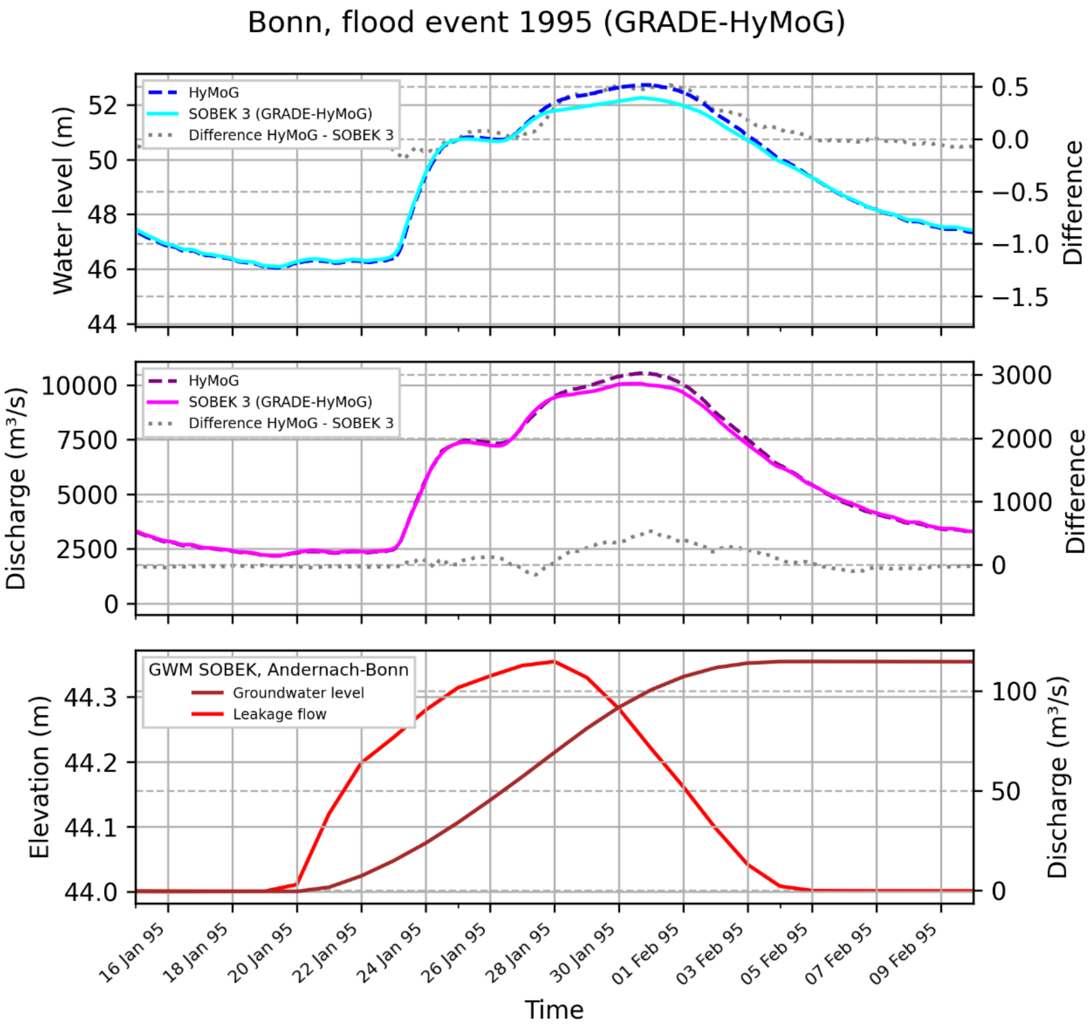

Figure 58 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Bonn, flood event 1995

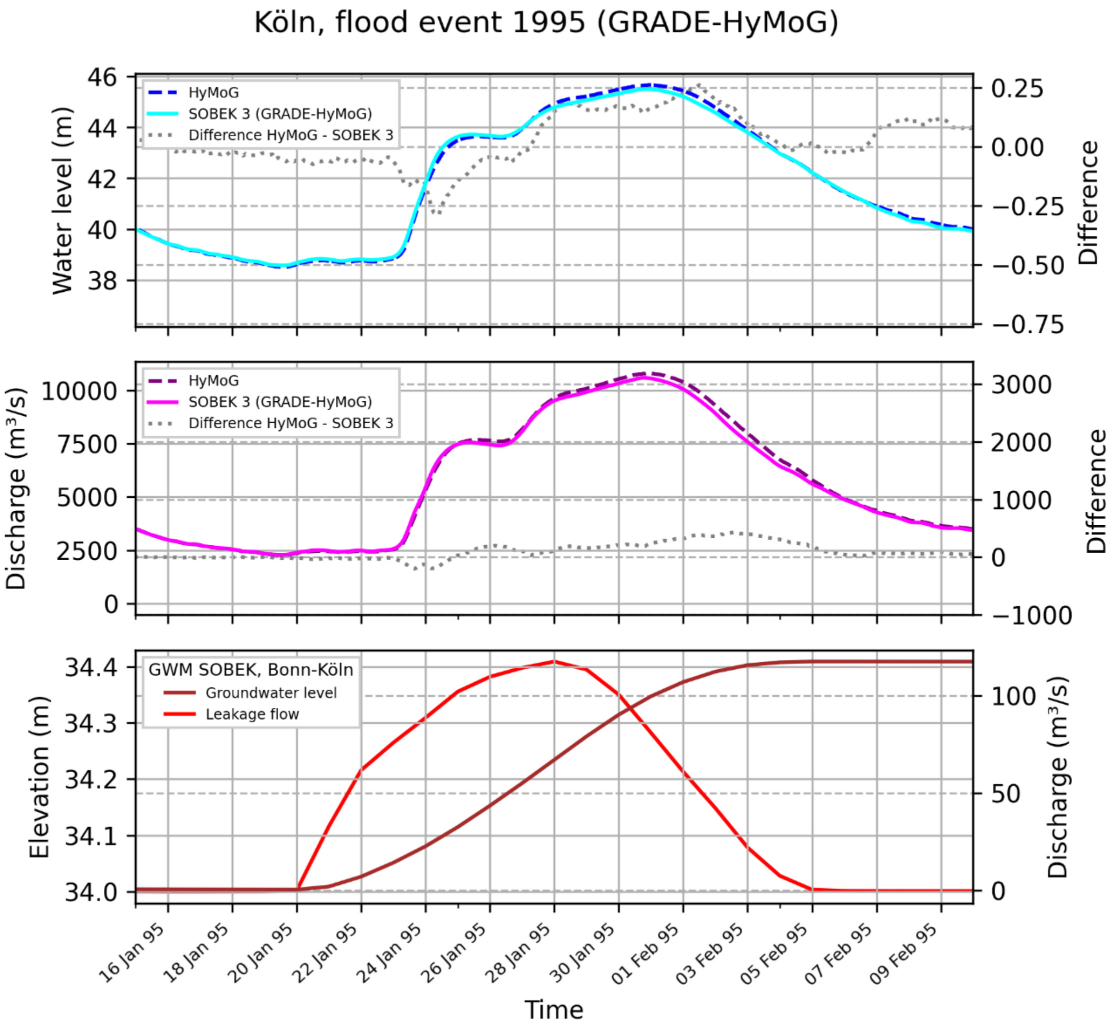

Figure 59 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Köln, flood event 1995

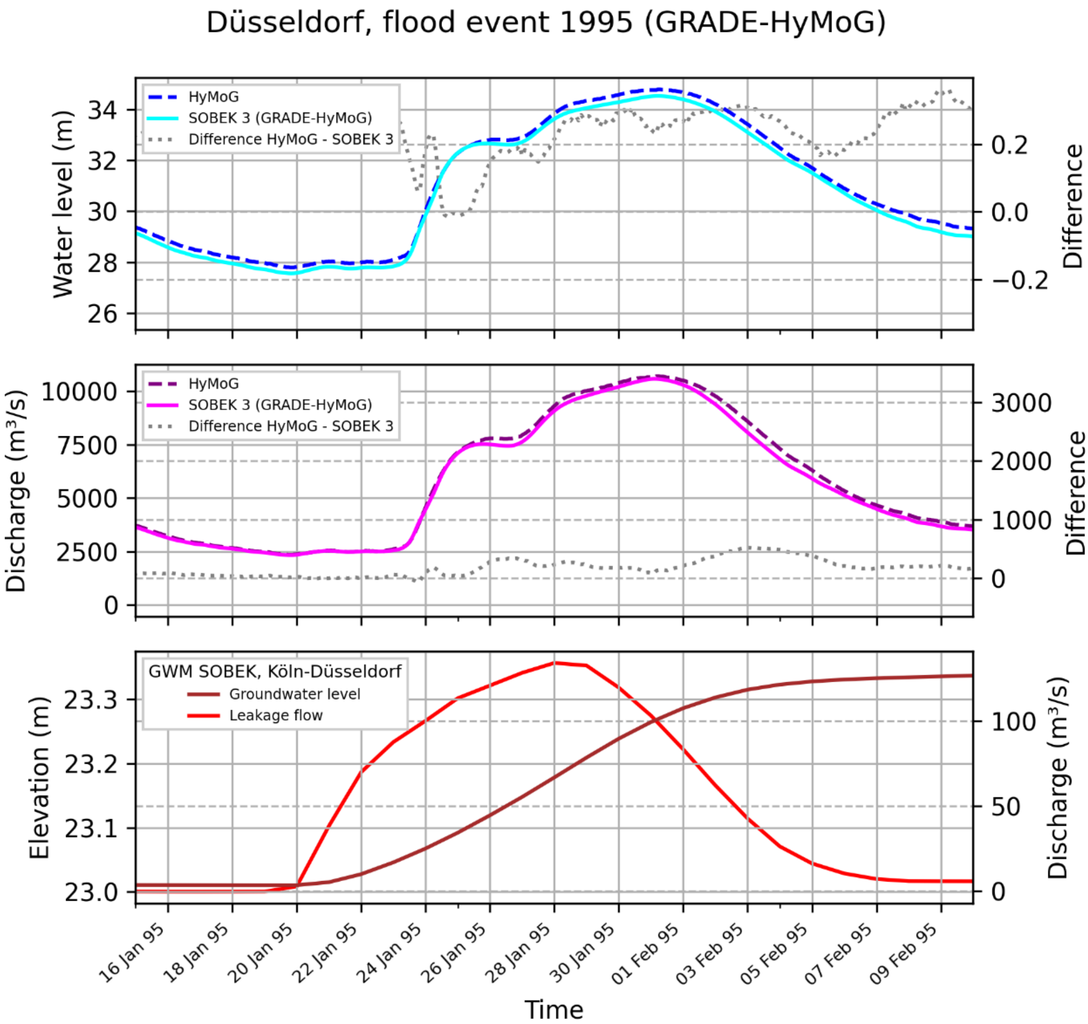

Figure 60 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Düsseldorf, flood event 1995

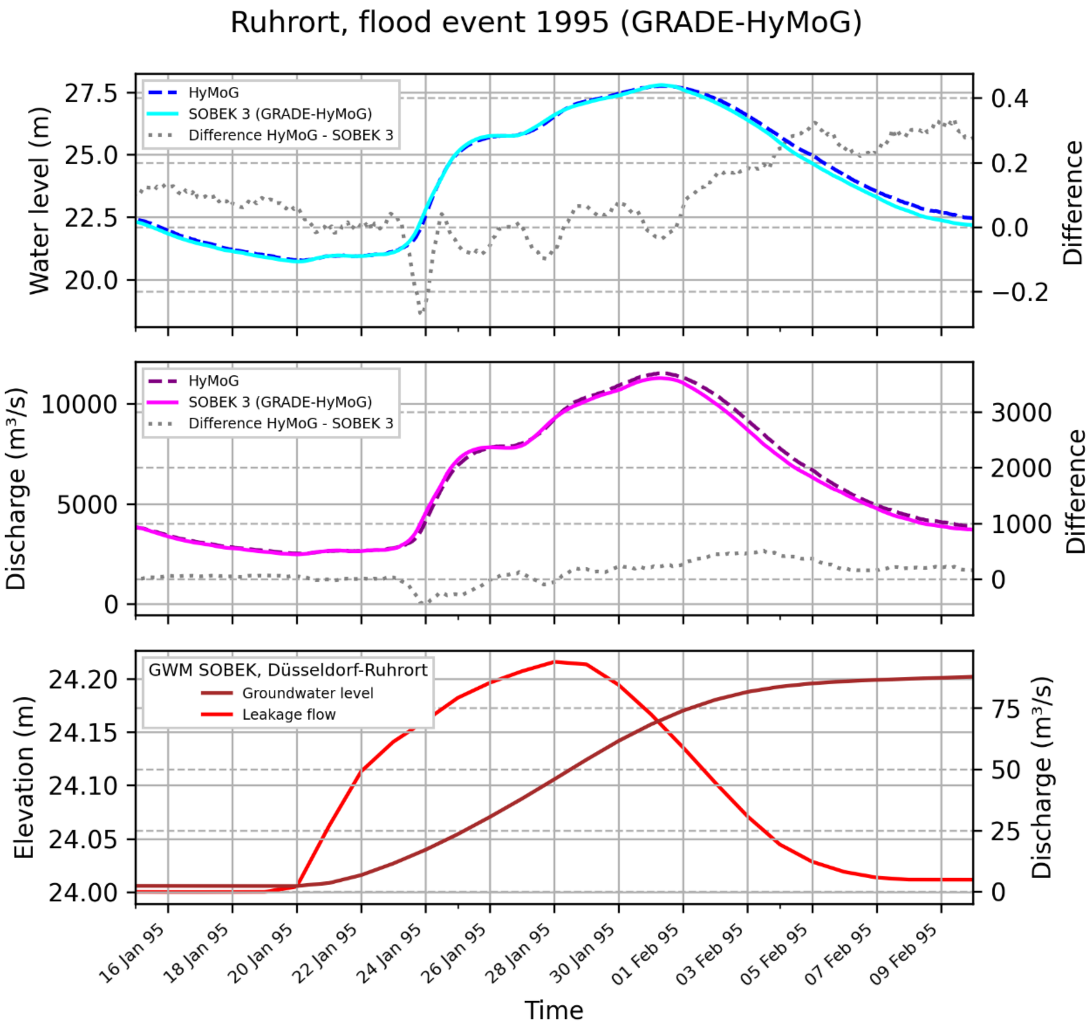

Figure 61 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Ruhrort, flood event 1995

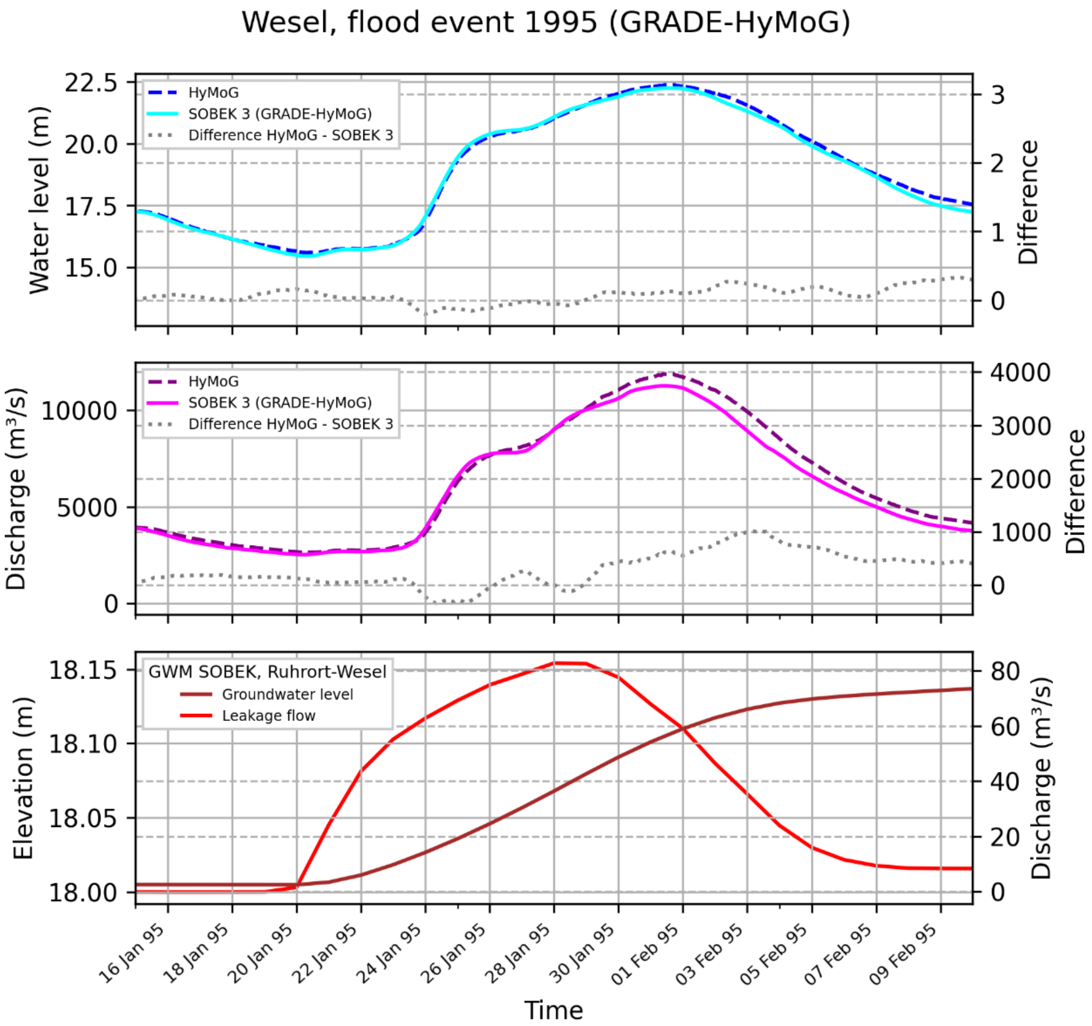

Figure 62 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Wesel, flood event 1995

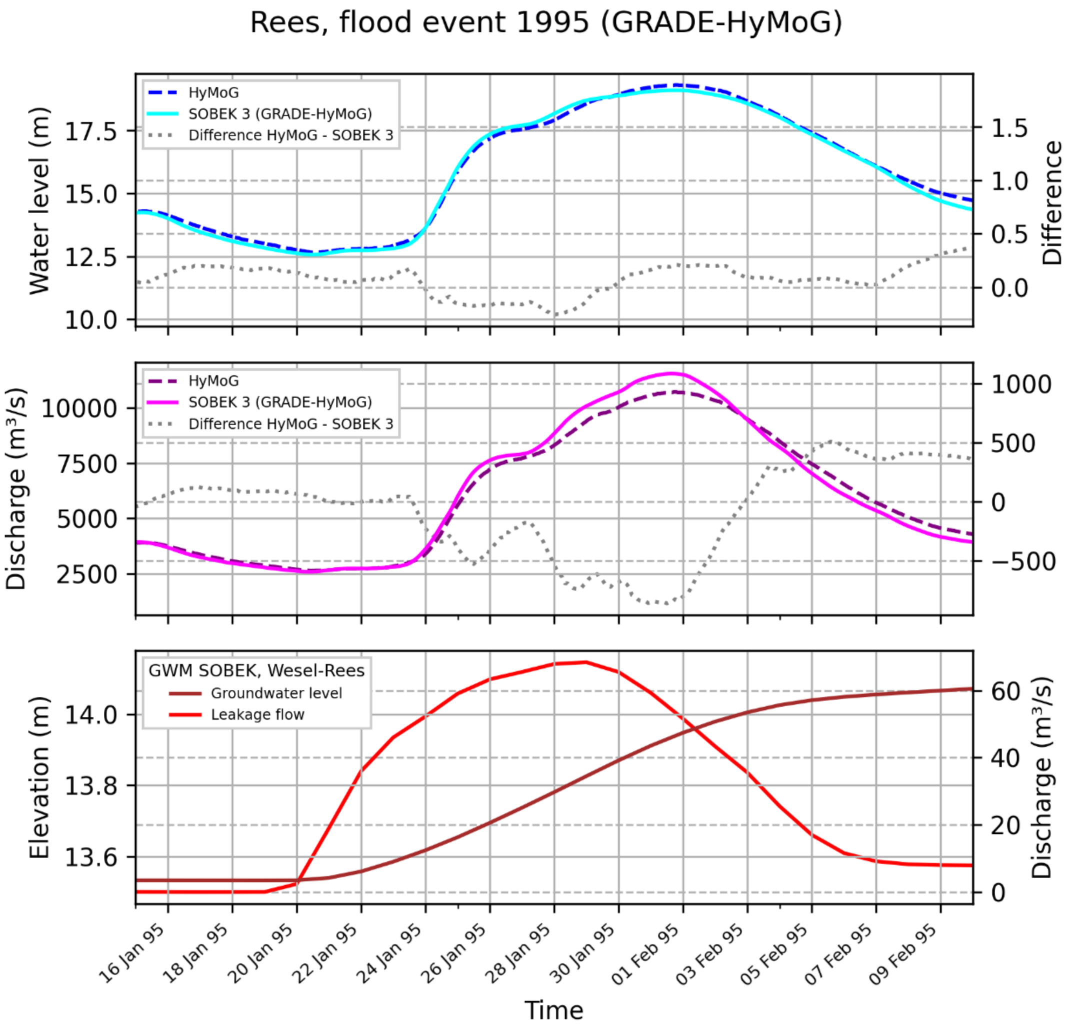

Figure 63 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Rees, flood event 1995

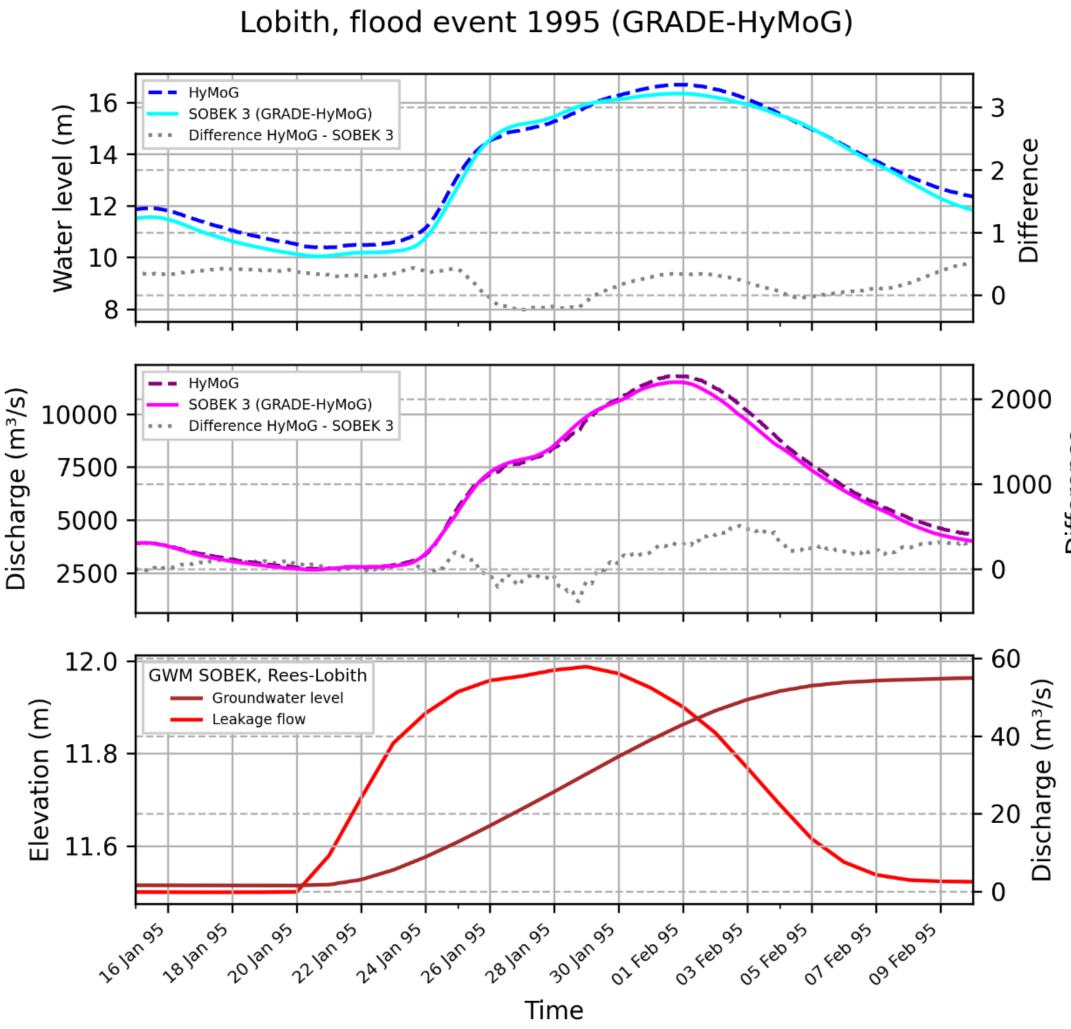

Figure 64 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Lobith, flood event 1995

B.1.2 Flood event 1993

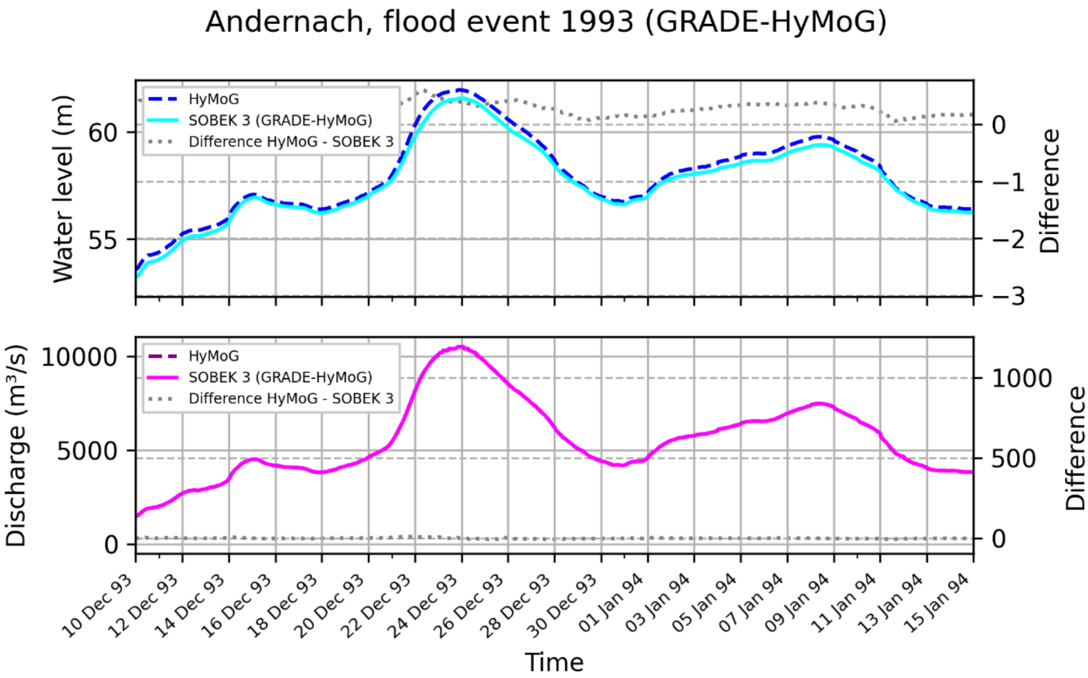

Figure 65 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Andernach, flood event 1993

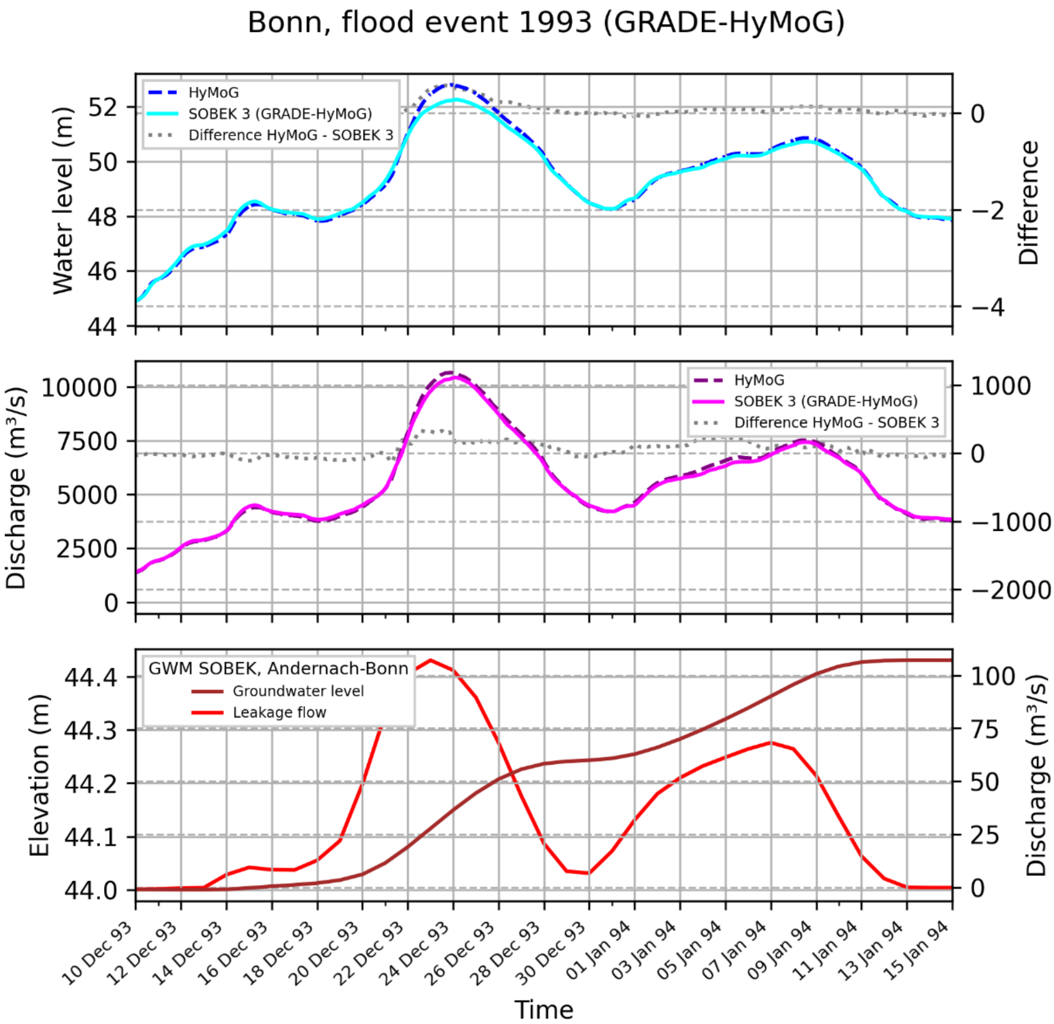

Figure 66 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Bonn, flood event 1993

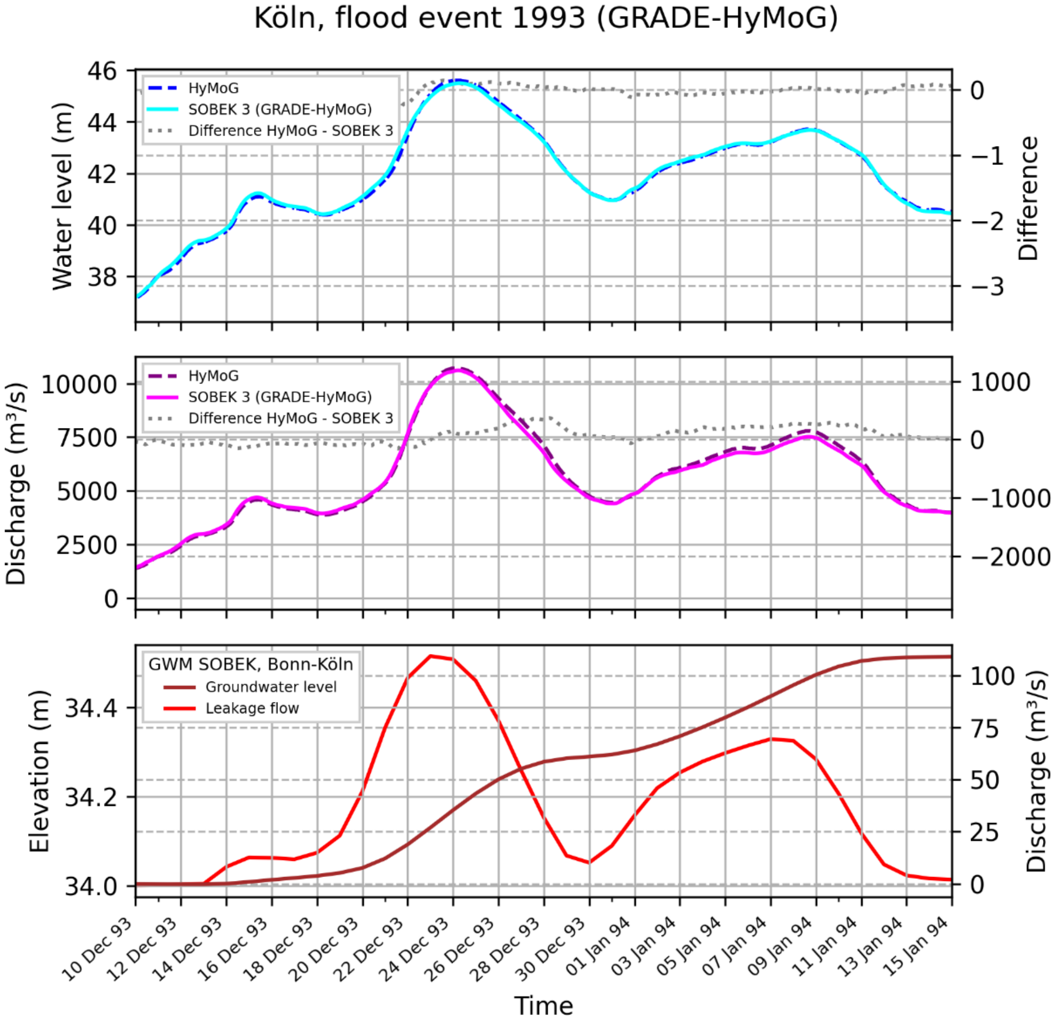

Figure 67 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Köln, flood event 1993

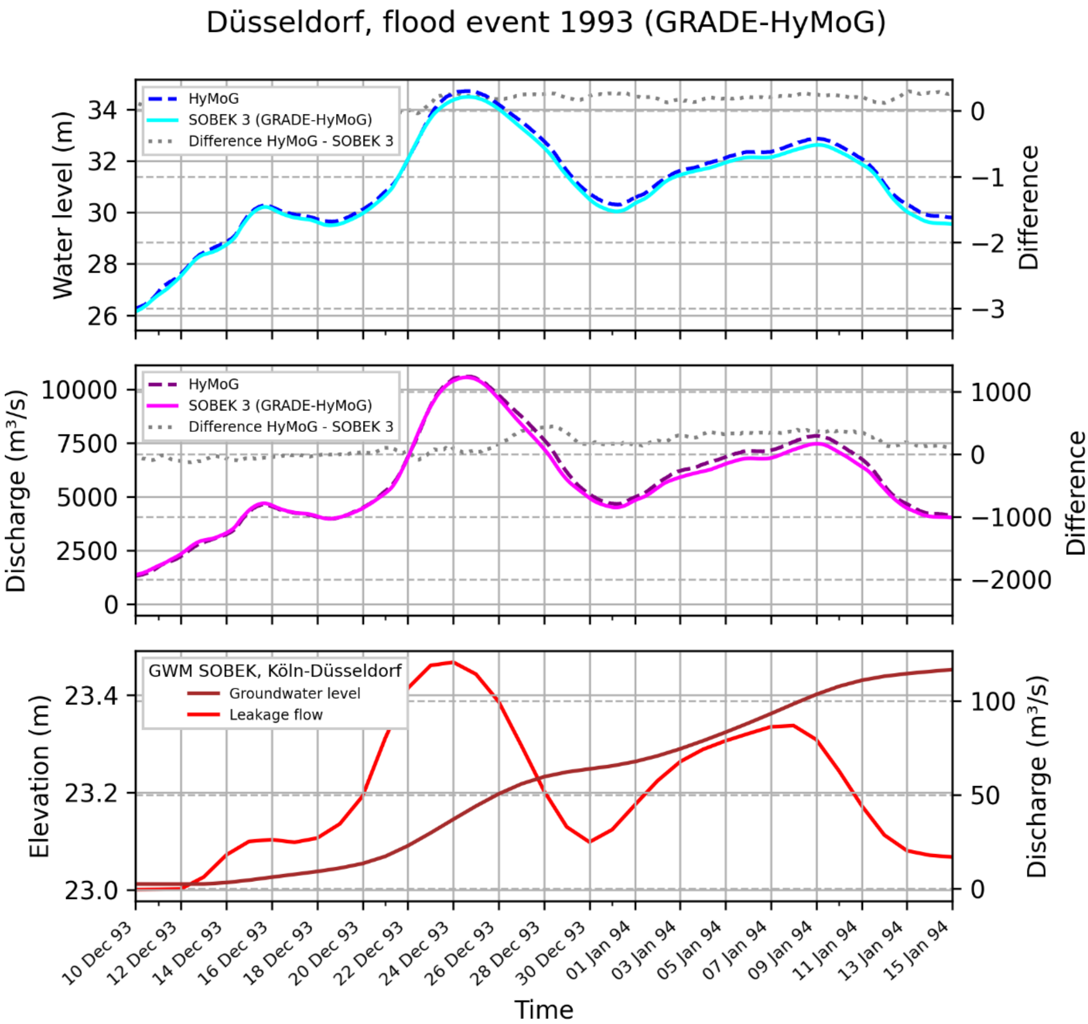

Figure 68 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Düsseldorf, flood event 1993

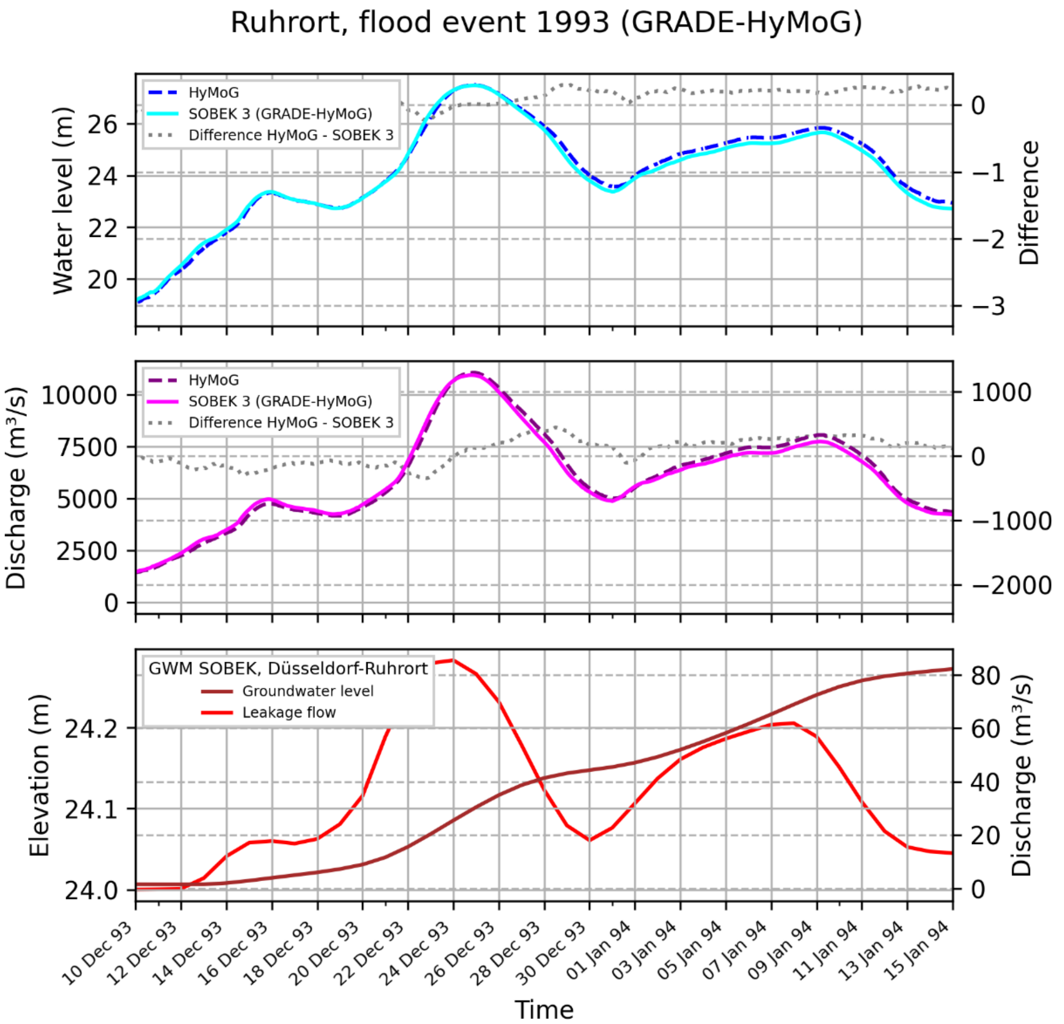

Figure 69 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Ruhrort, flood event 1993

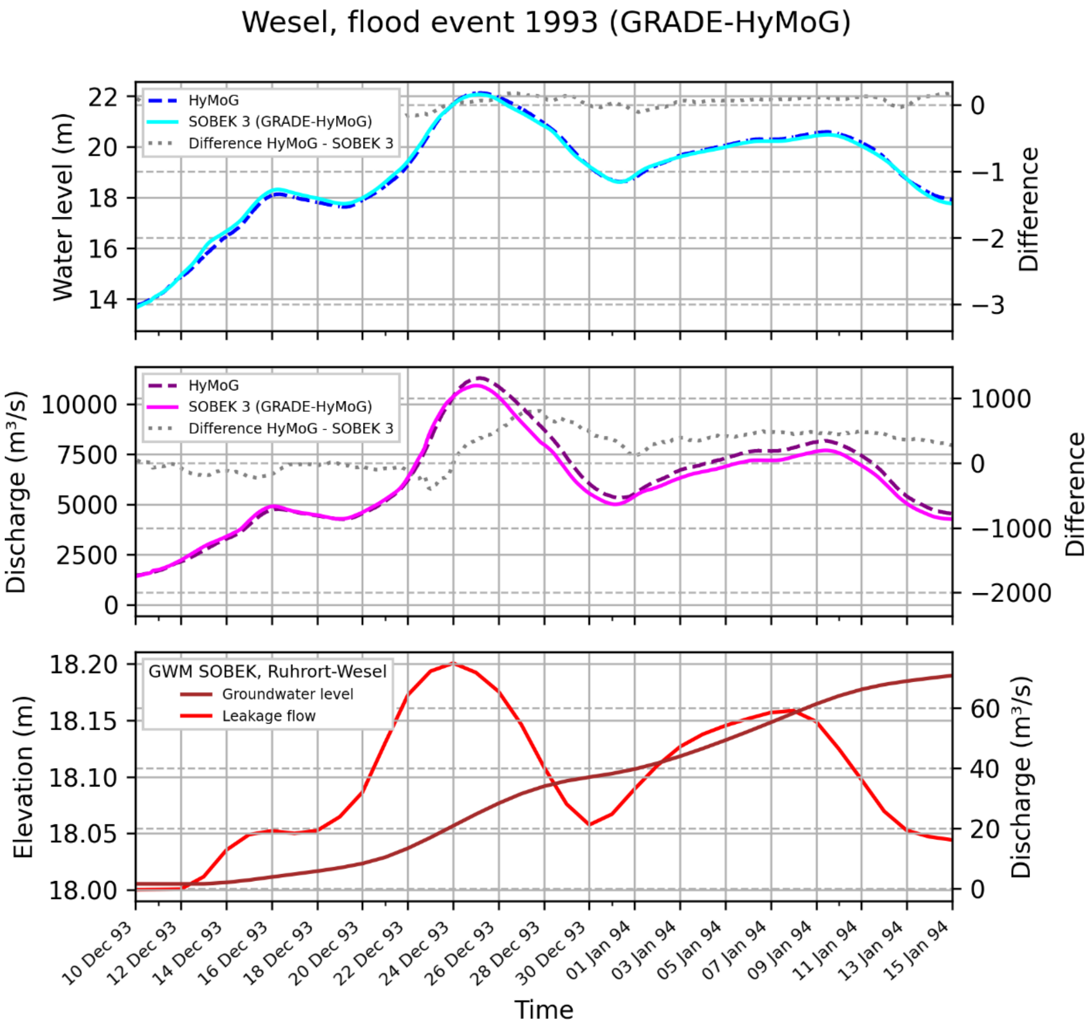

Figure 70   Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Wesel, flood event 1993

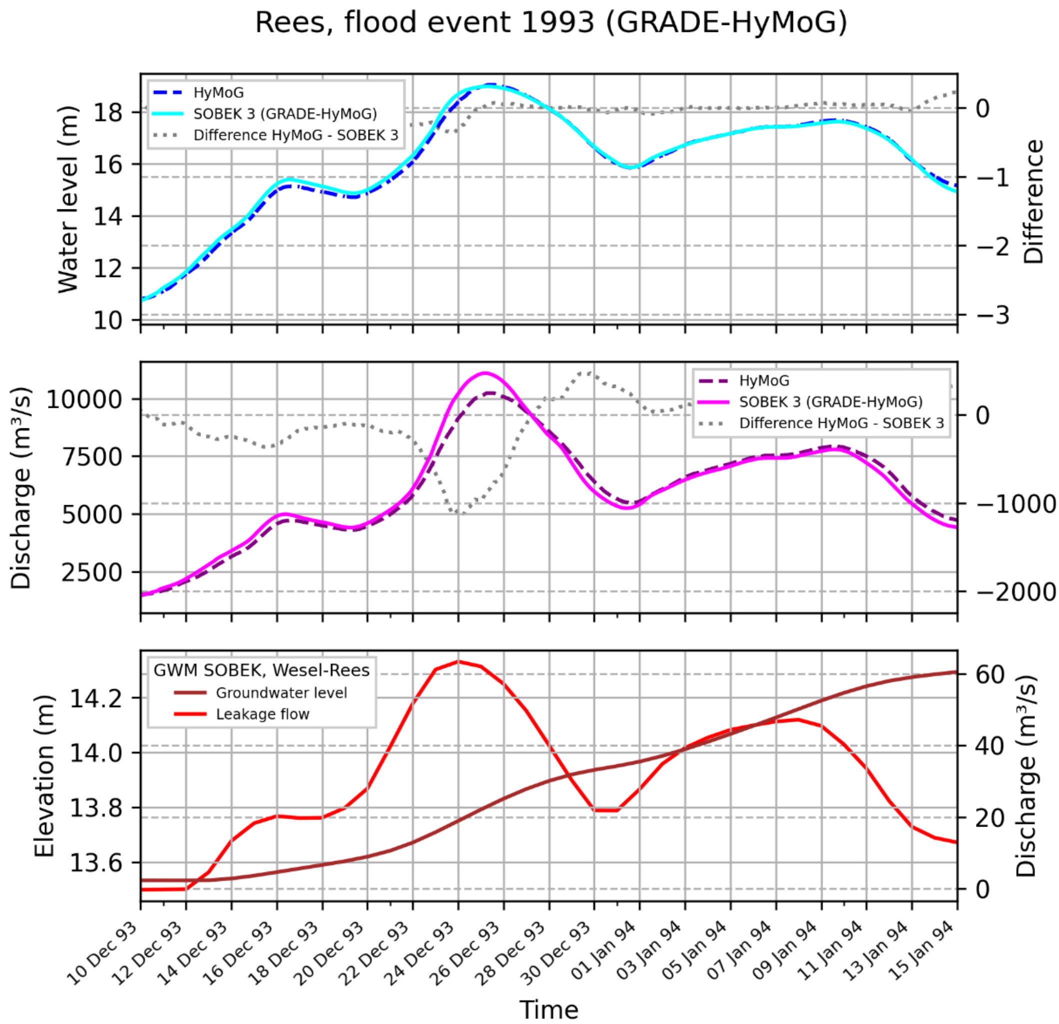

Figure 71 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Rees, flood event 1993

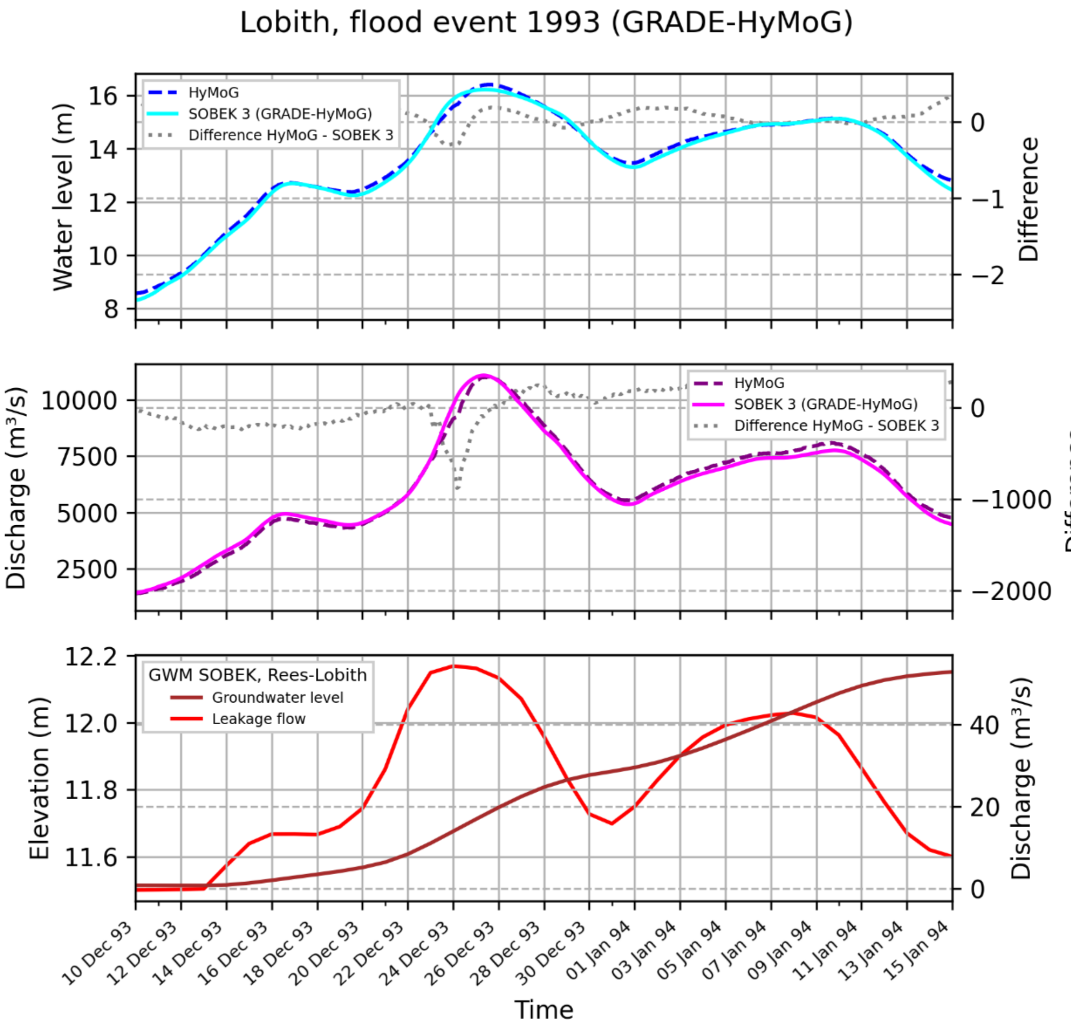

Figure 72 Simulation results obtained with the groundwater module SOBEK and comparison data for the gauging station Lobith, flood event 1993

B.2 Contribution of the river-aquifer interaction to the discharge (GRADE-HyMoG dataset and GRADE data set)

B.2.1 Flood event 1995

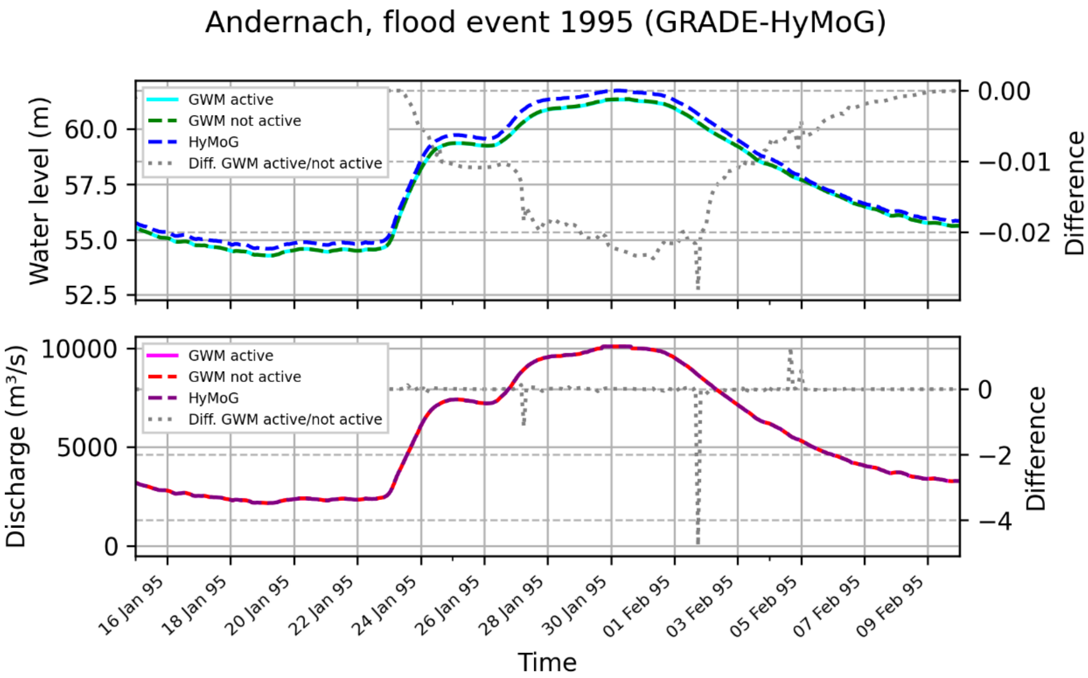

Figure 73 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1995

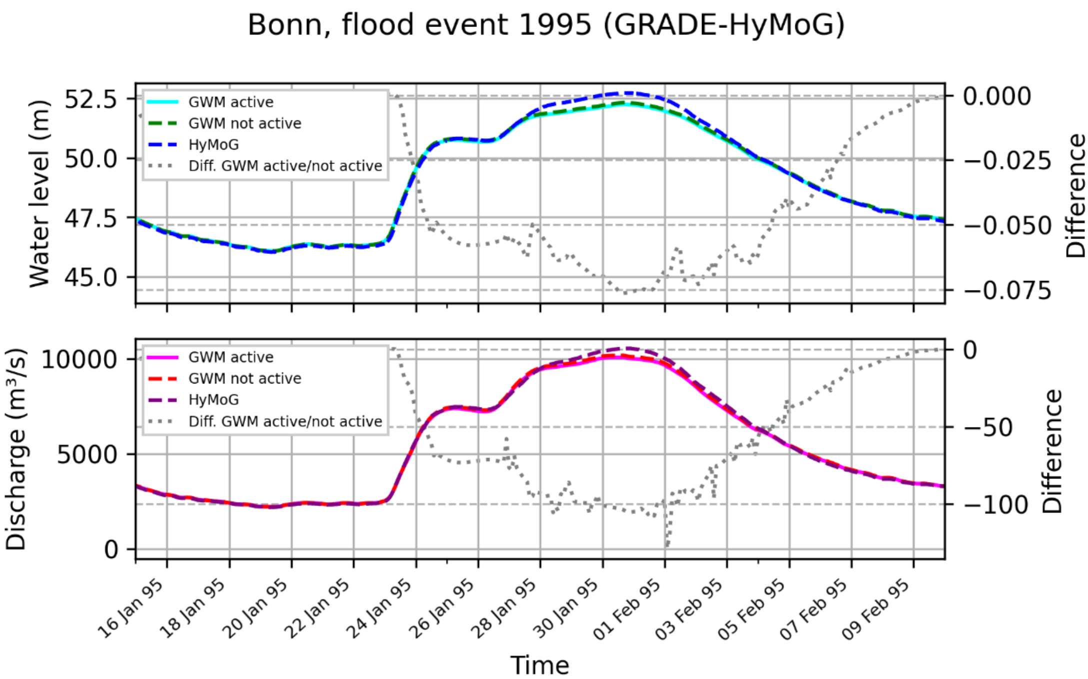

Figure 74 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, flood event 1995

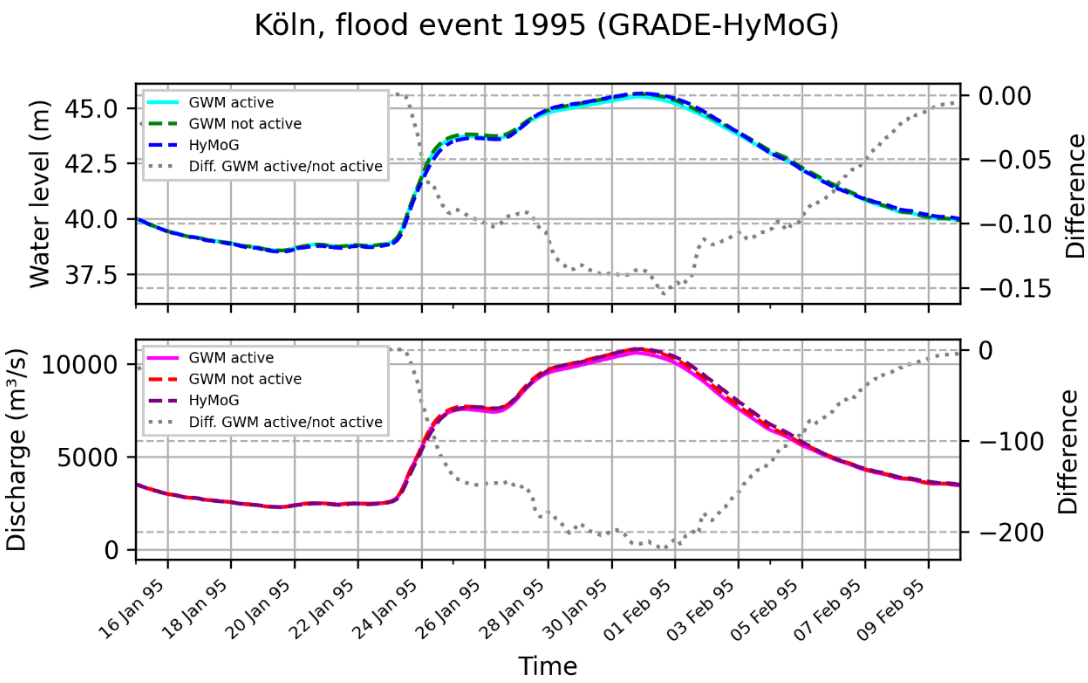

Figure 75 Comparison of water level und discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1995

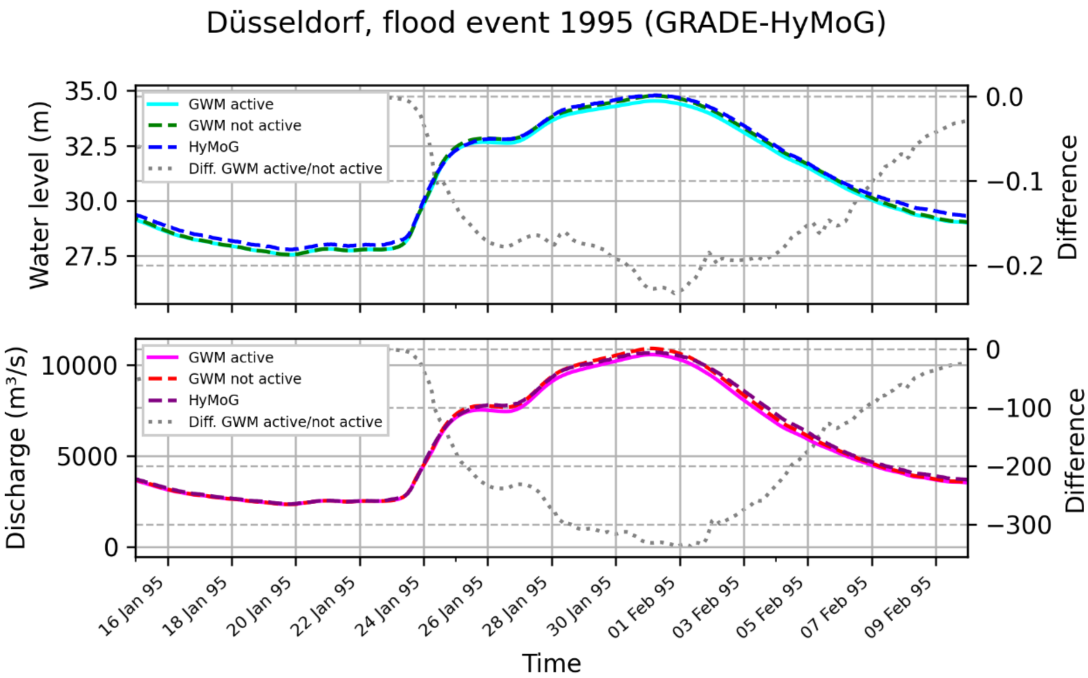

Figure 76 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, flood event 1995

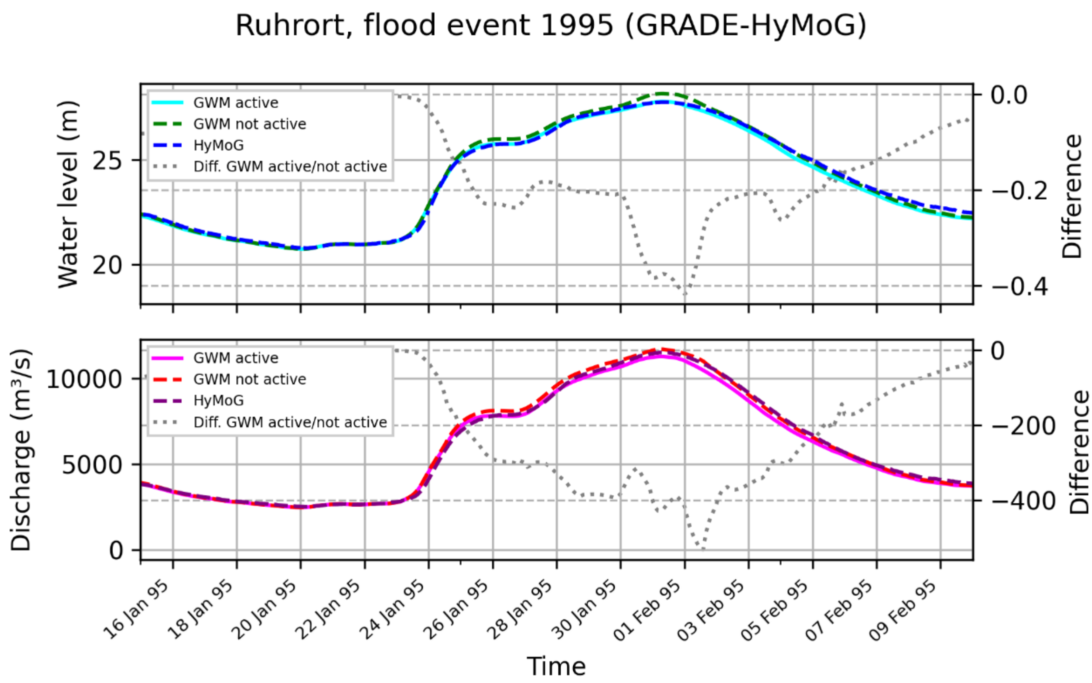

Figure 77 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, flood event 1995

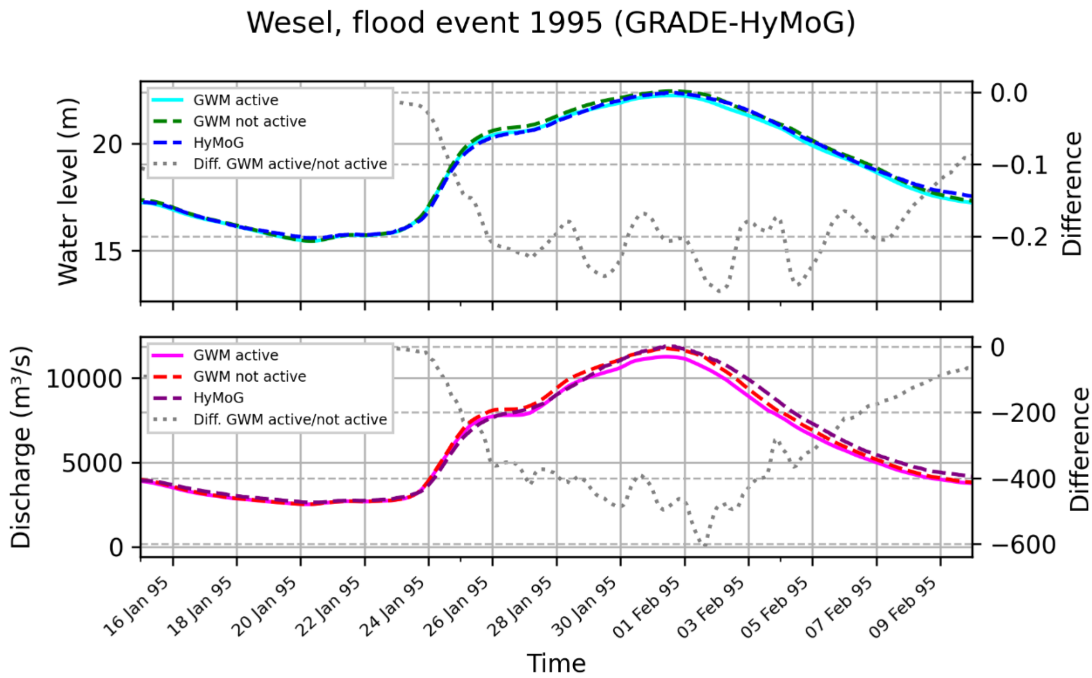

Figure 78 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, flood event 1995

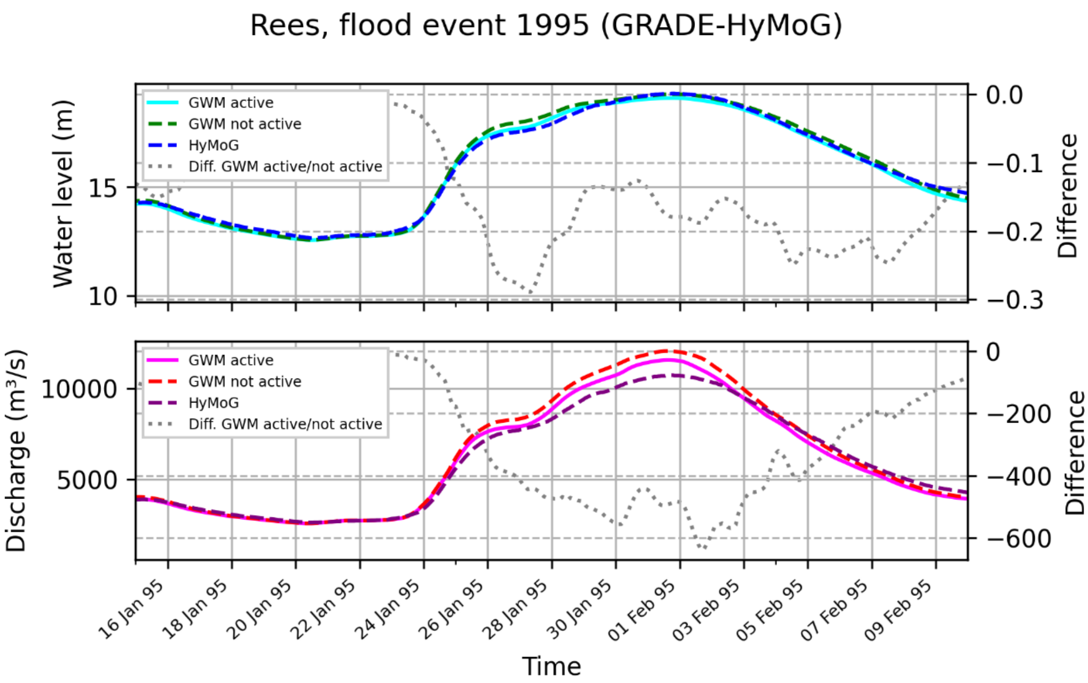

Figure 79 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1995

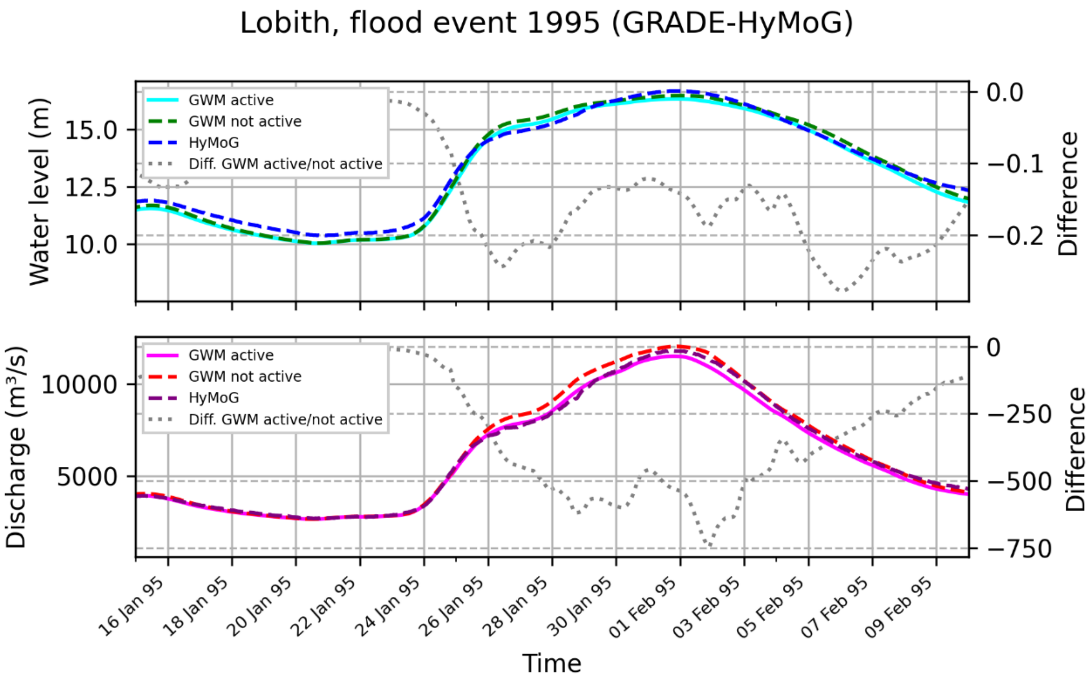

Figure 80 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1995

B.2.2 Flood event 1993

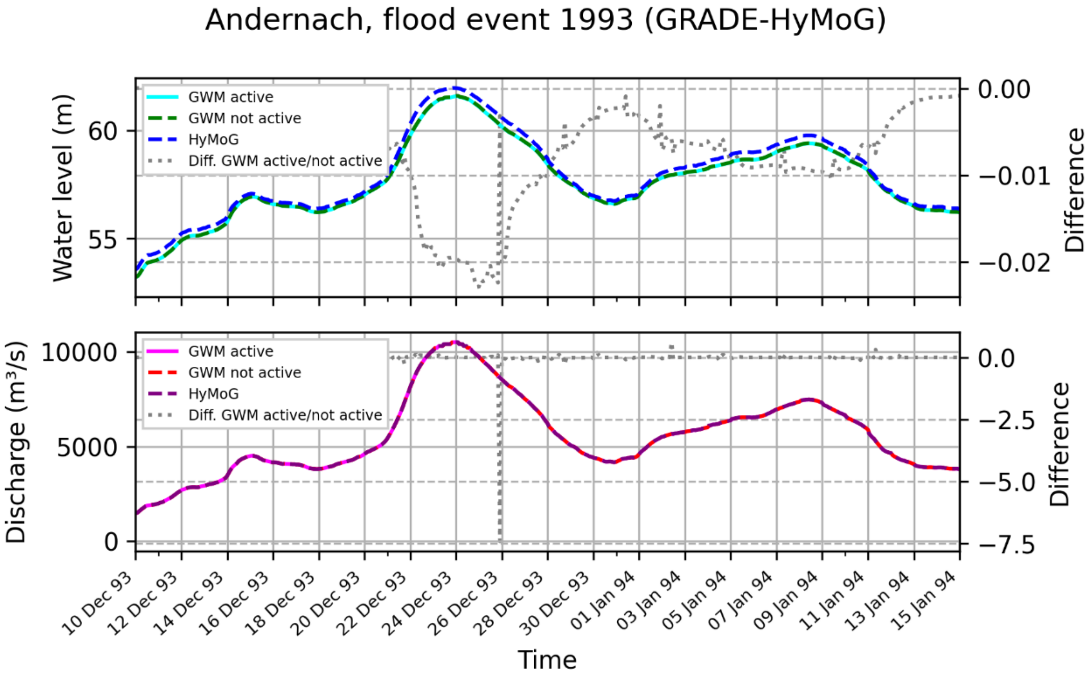

Figure 81 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1993, flood event 1993

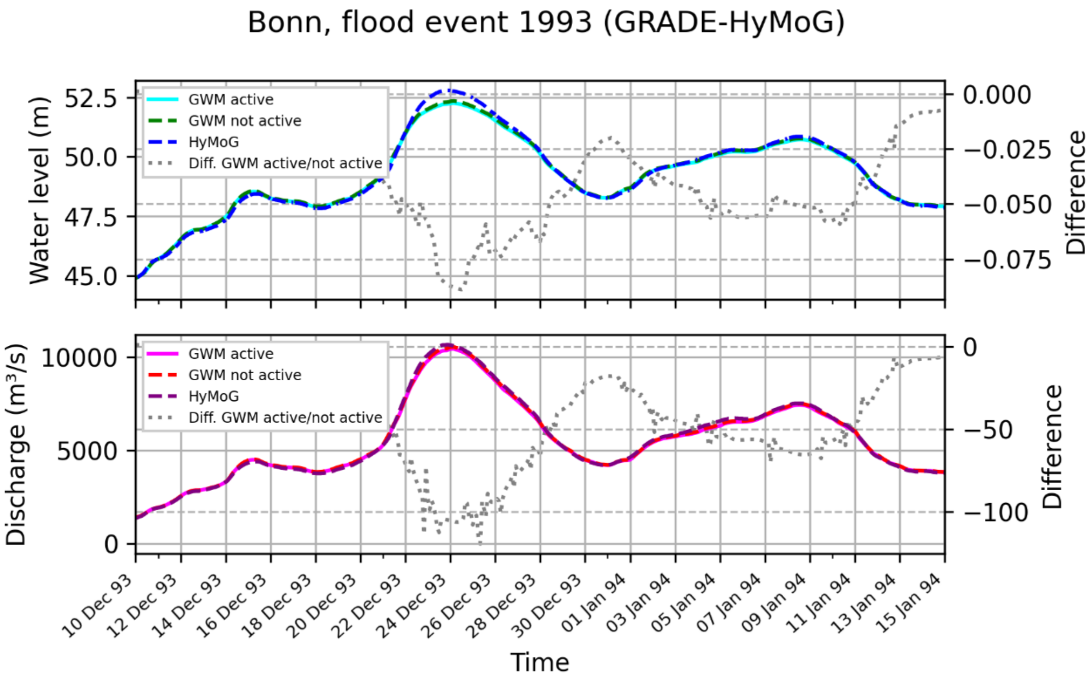

Figure 82 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, flood event 1993

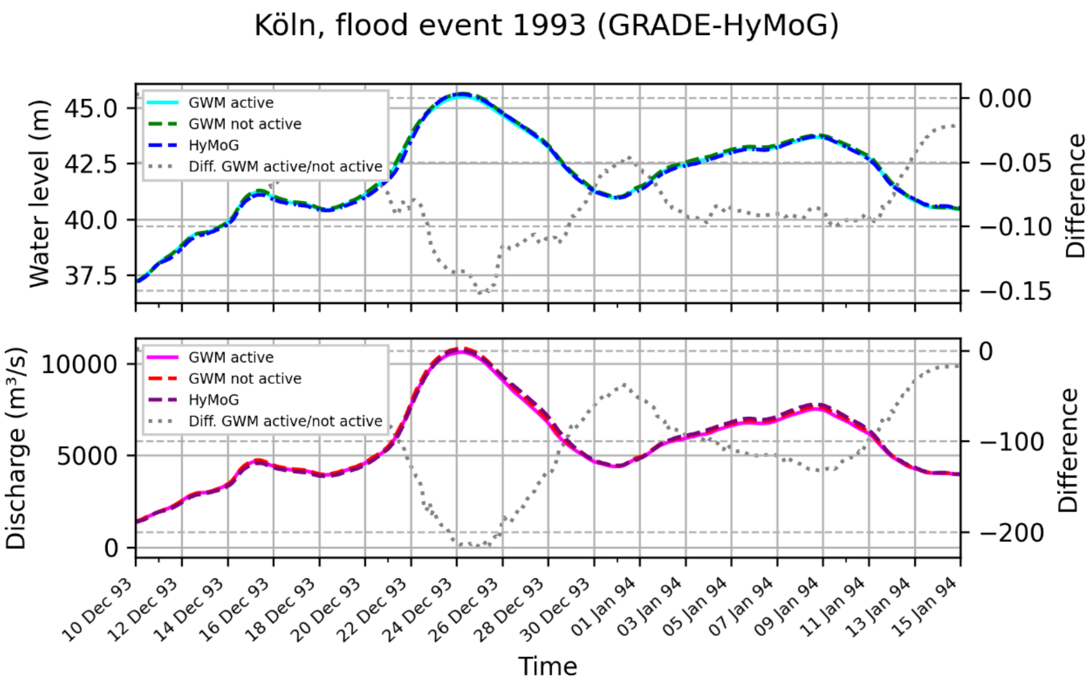

Figure 83 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1993

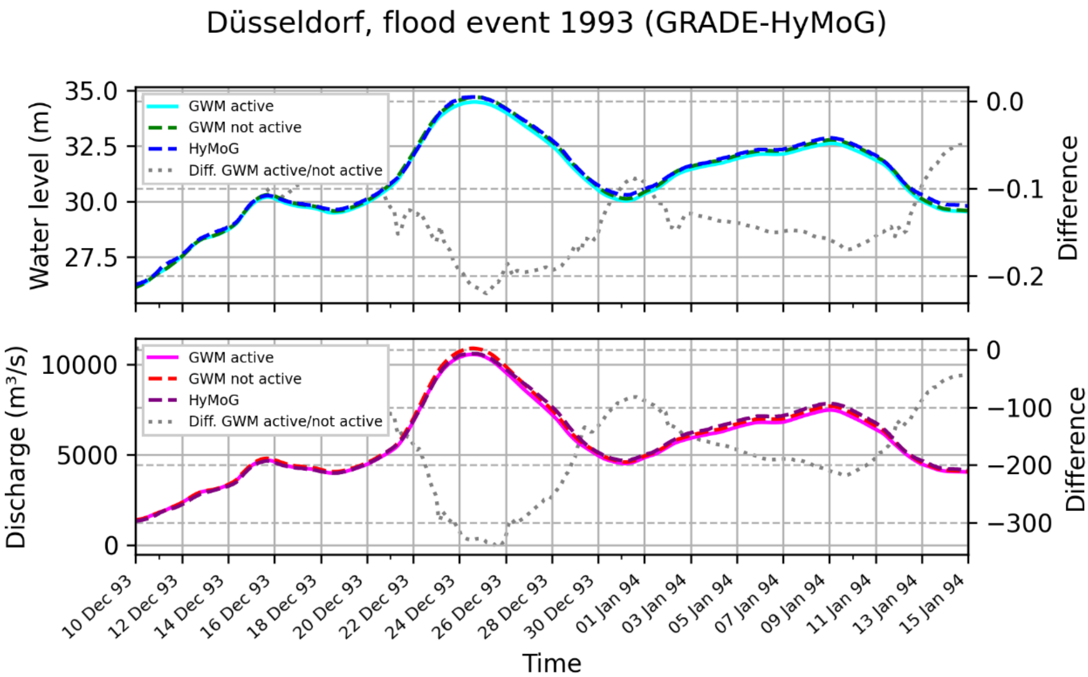

Figure 84 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, flood event 1993

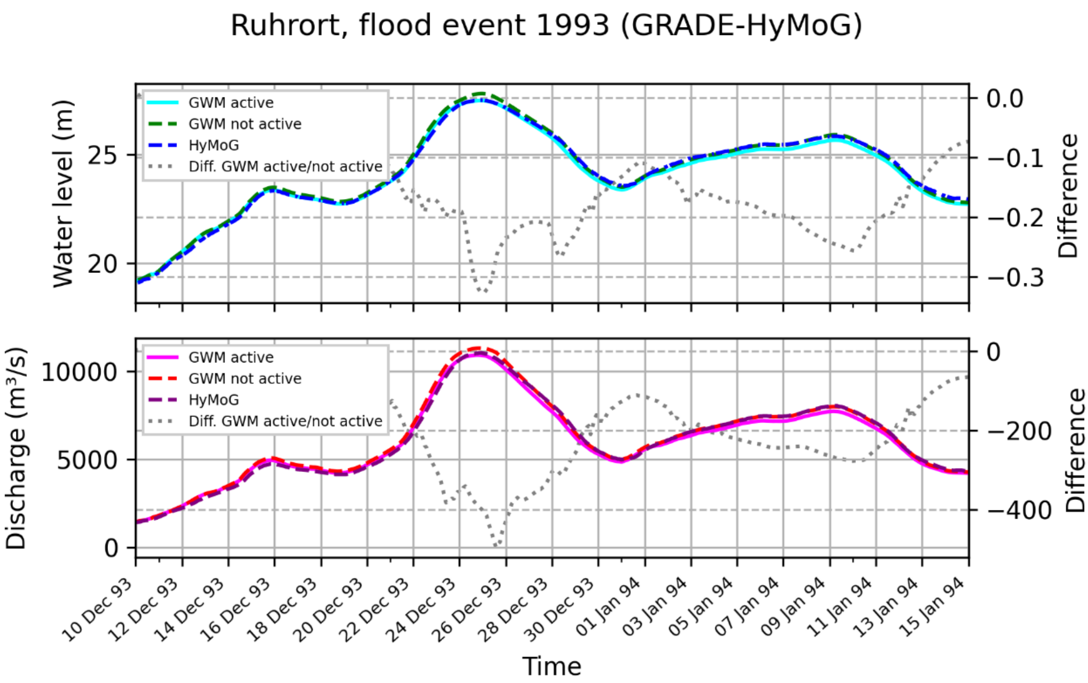

Figure 85 *Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, flood event 1993*

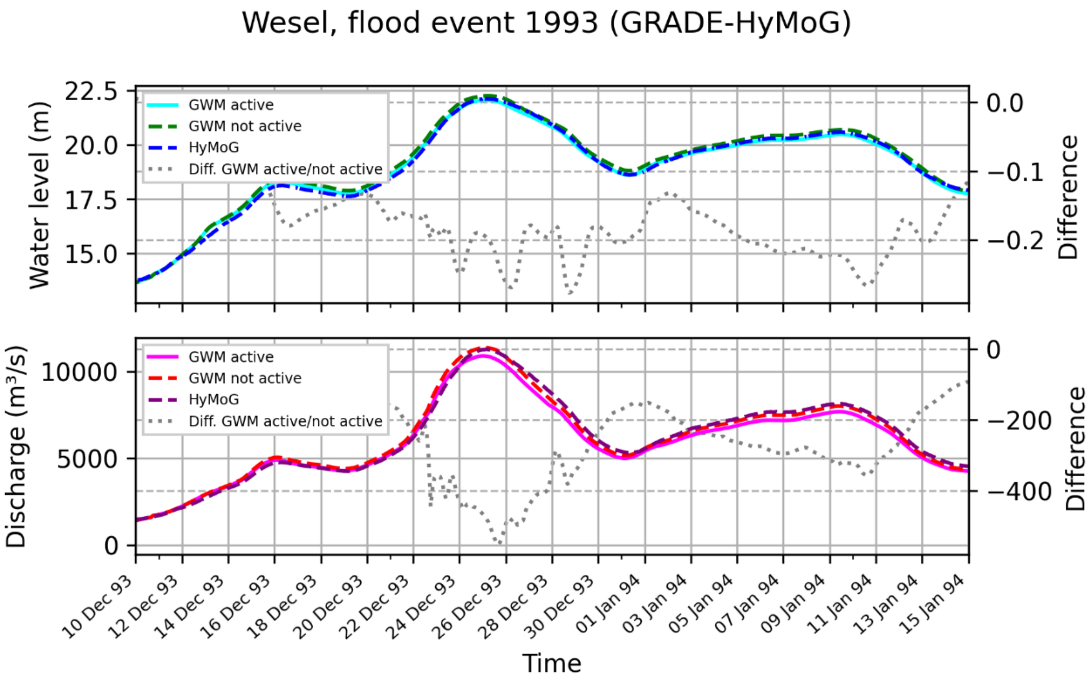

Figure 86 *Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, flood event 1993*

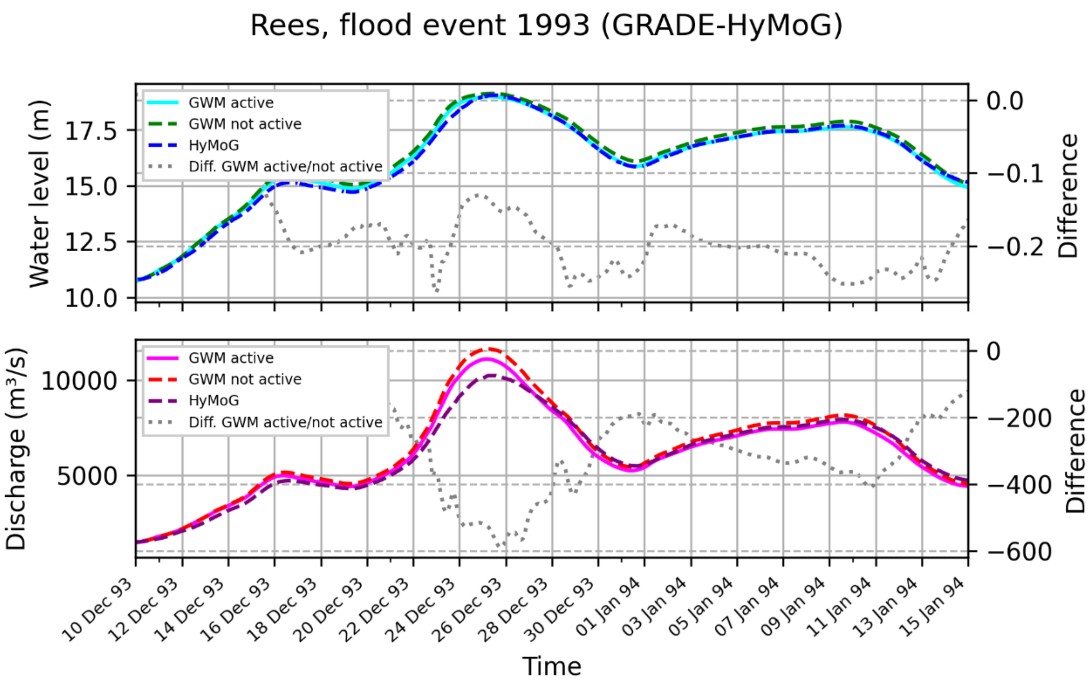

Figure 87 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1993

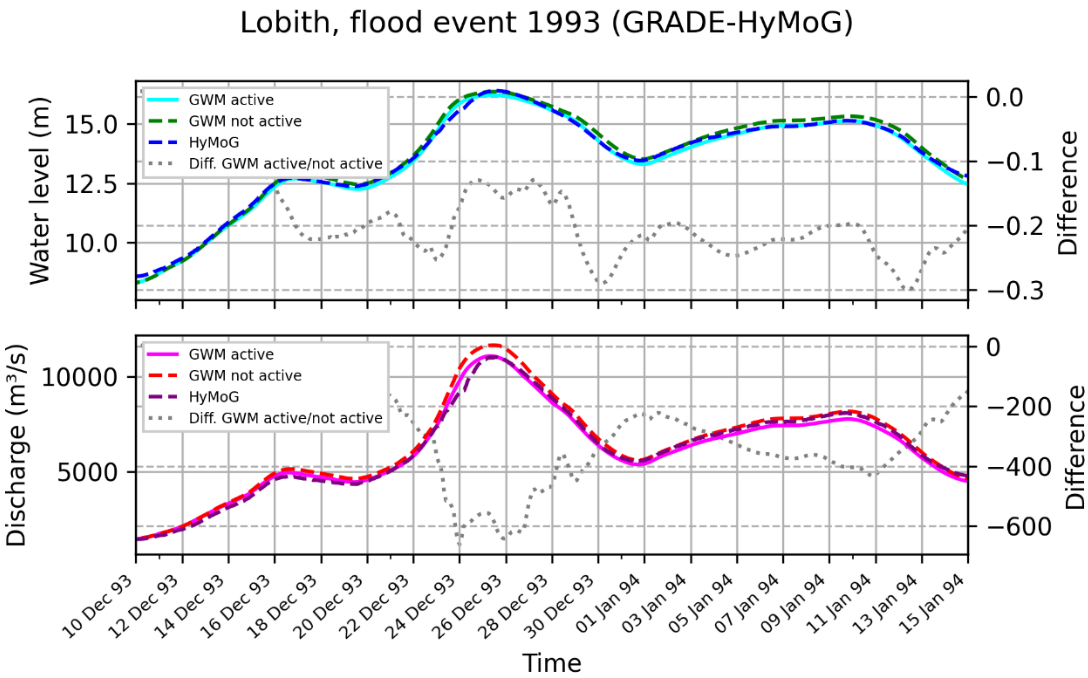

Figure 88 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1993

B.2.3 Flood event 1988

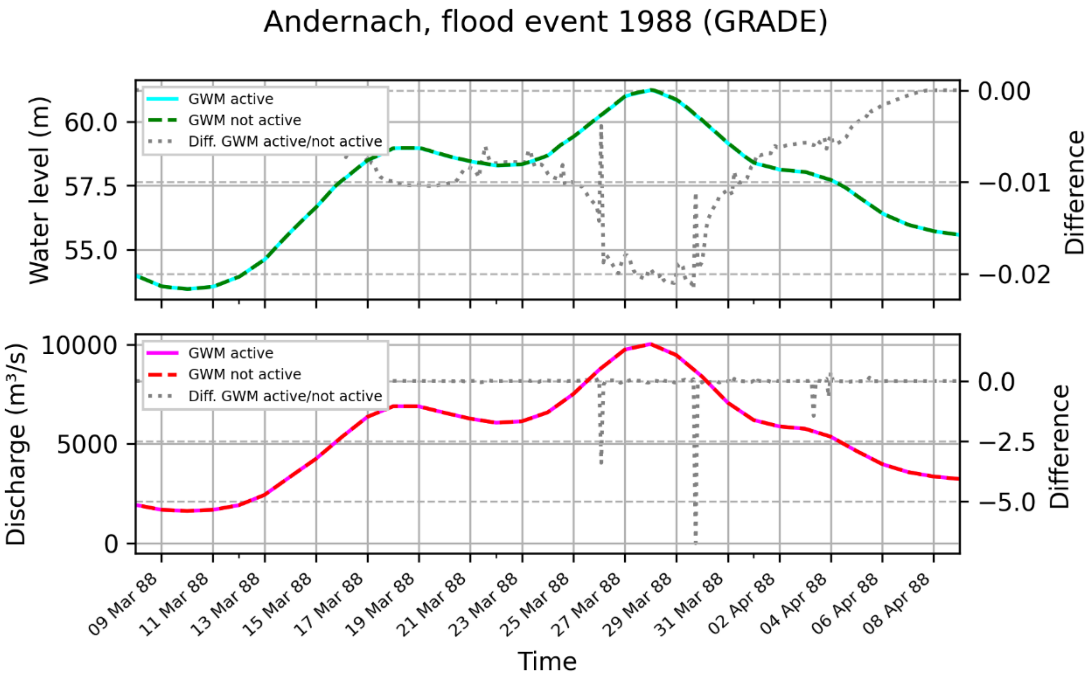

Figure 89 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, flood event 1988

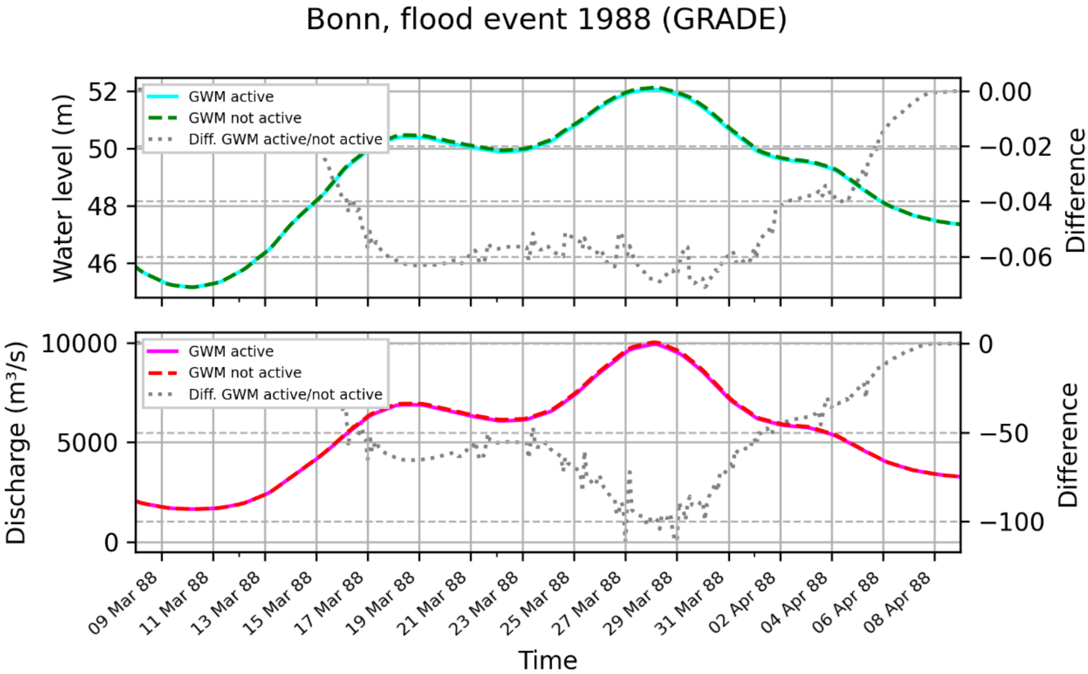

Figure 90 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, flood event 1988

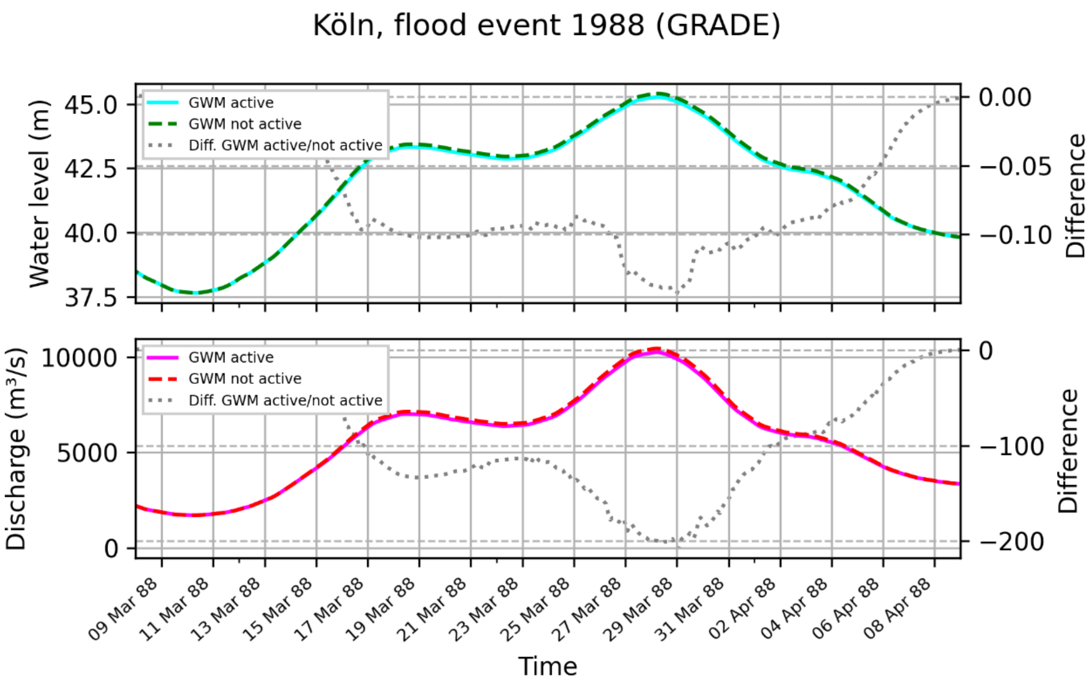

Figure 91 Comparison of water level und discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, flood event 1988

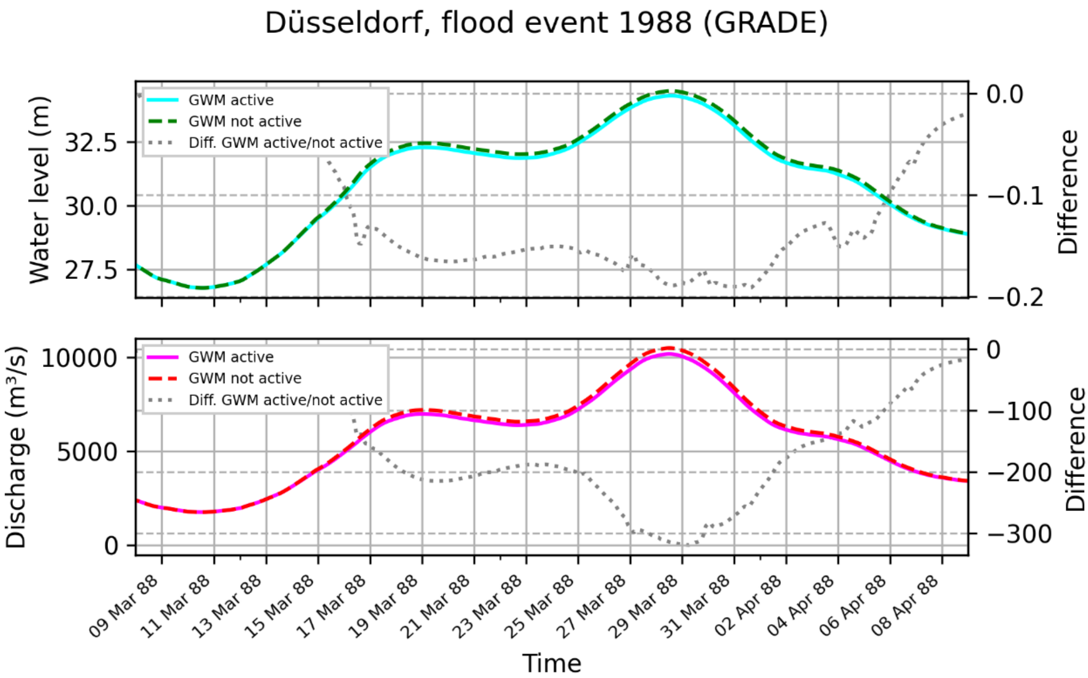

Figure 92 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, flood event 1988

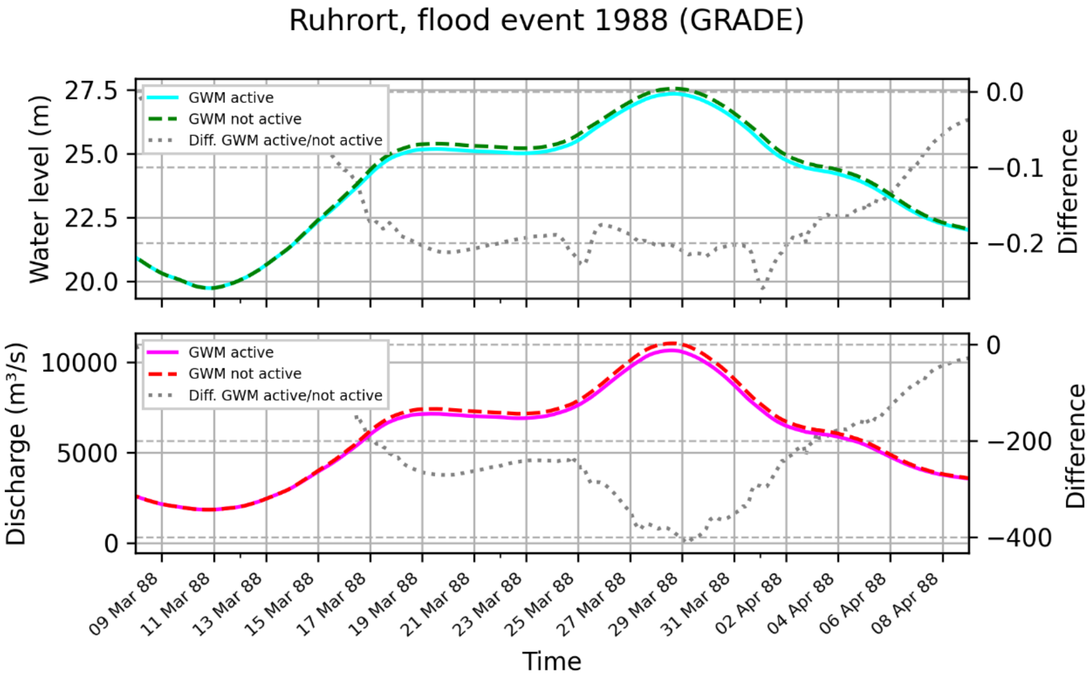

Figure 93 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, flood event 1988

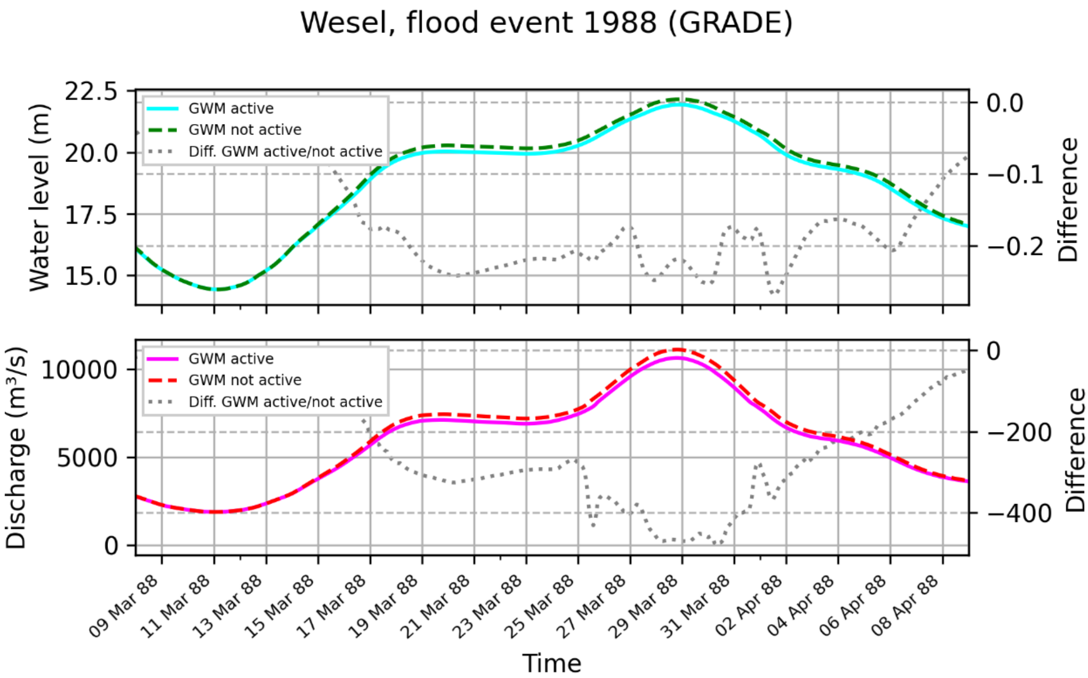

Figure 94 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, flood event 1988

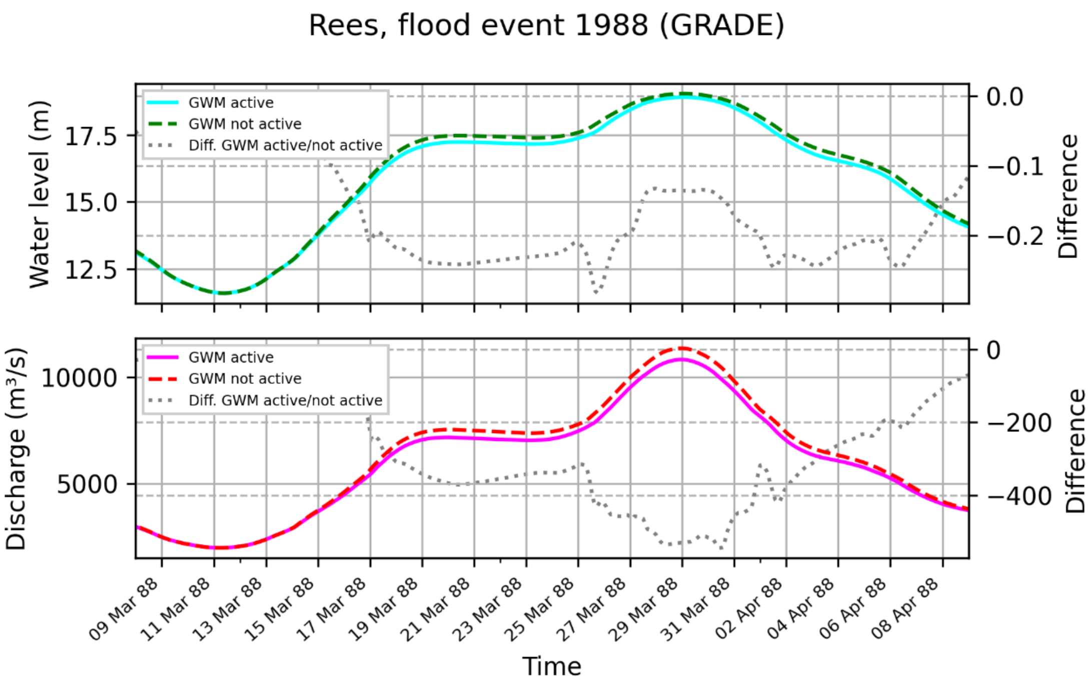

Figure 95 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, flood event 1988

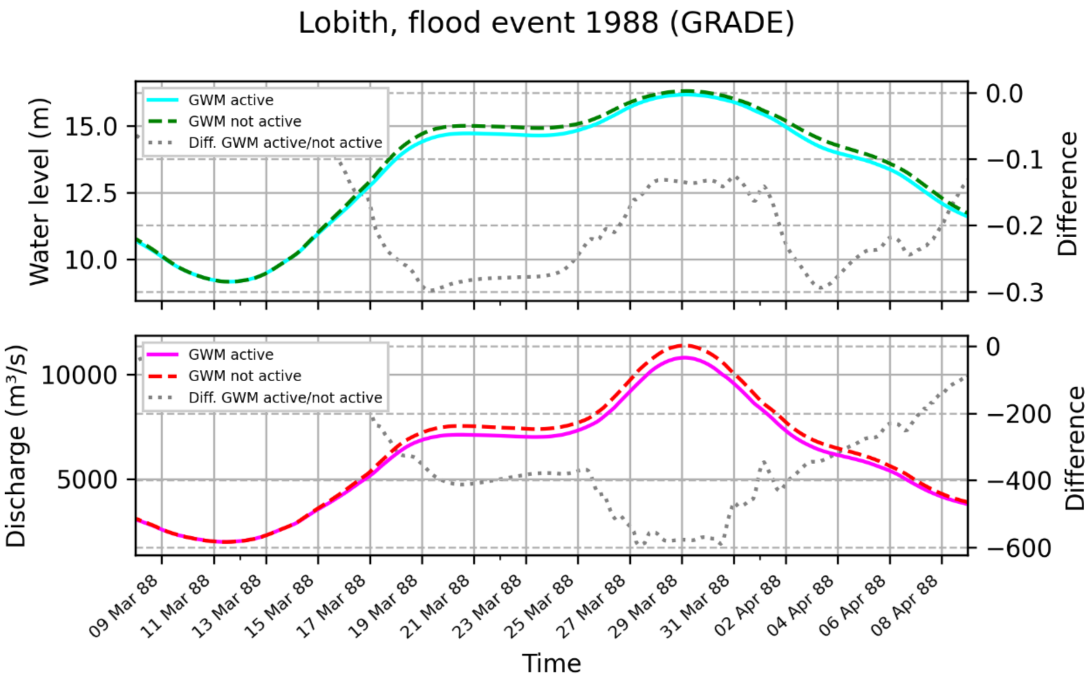

Figure 96 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, flood event 1988

B.3 Comparison of SOBEK-RE and SOBEK 3 simulations with GRADE dataset

B.3.1 Flood event 1995

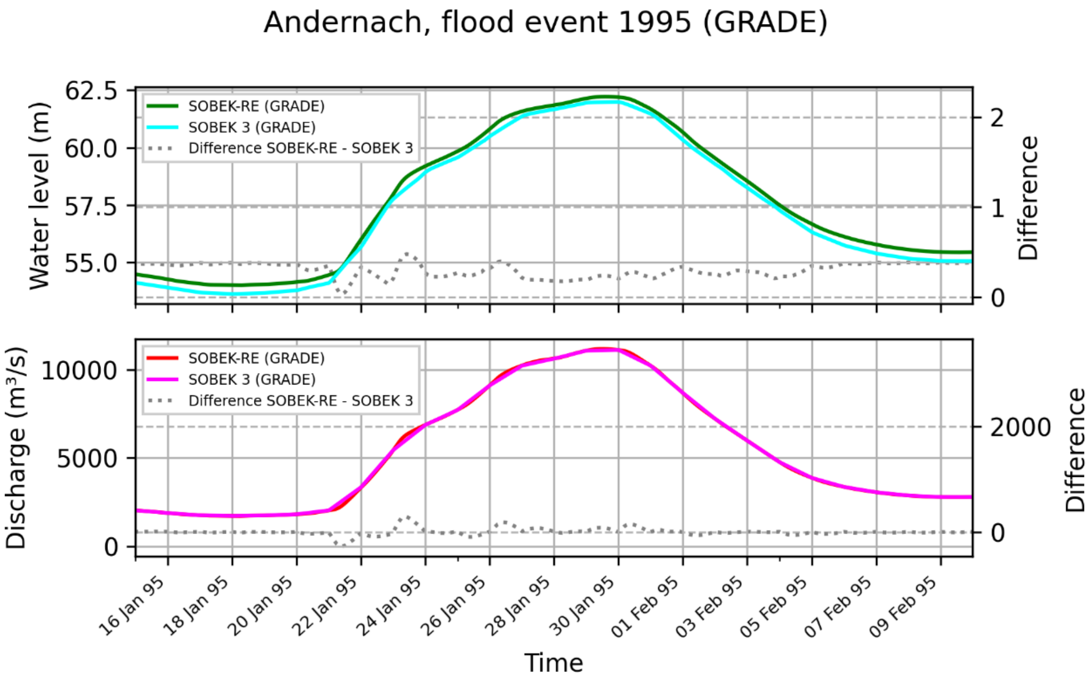

Figure 97 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1995

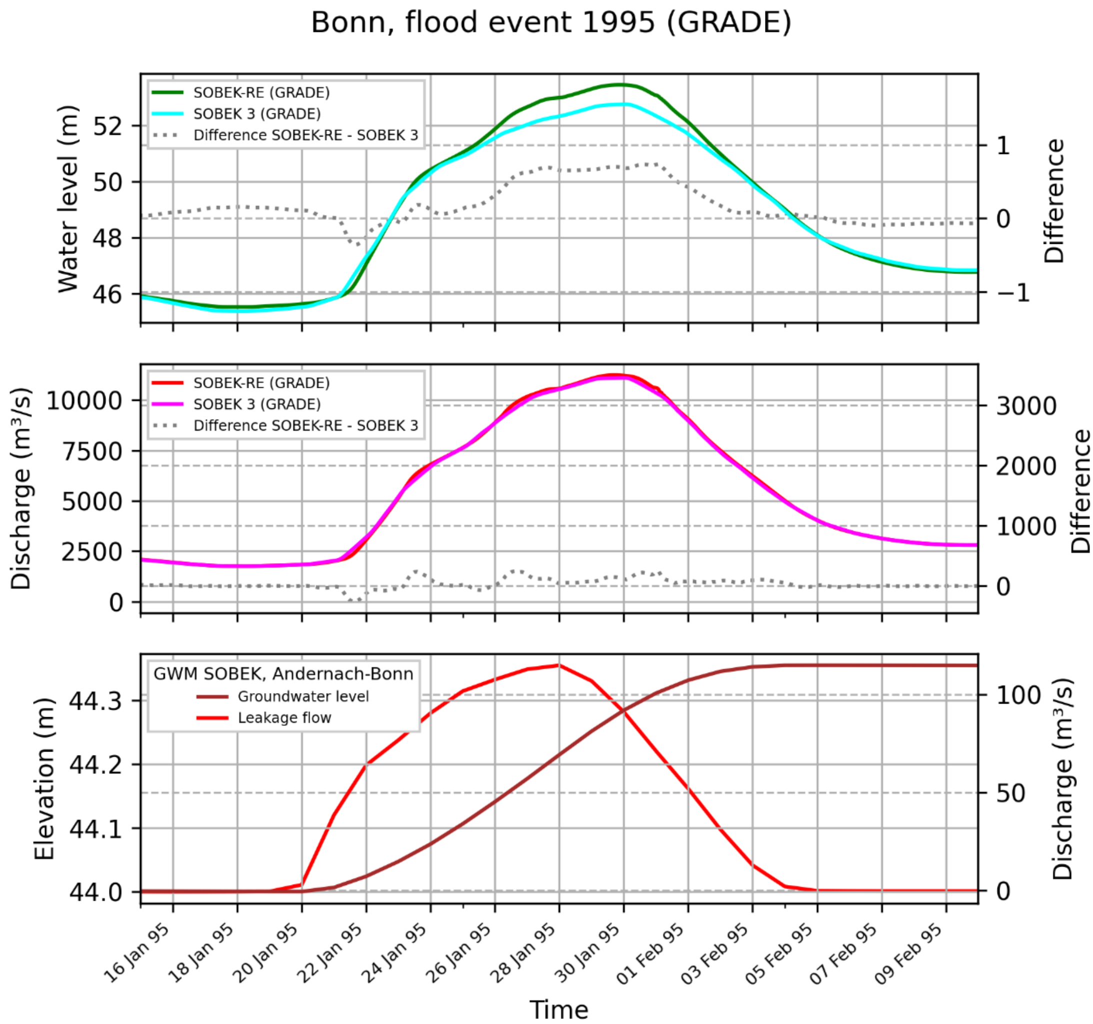

Figure 98 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Bonn, flood event 1995

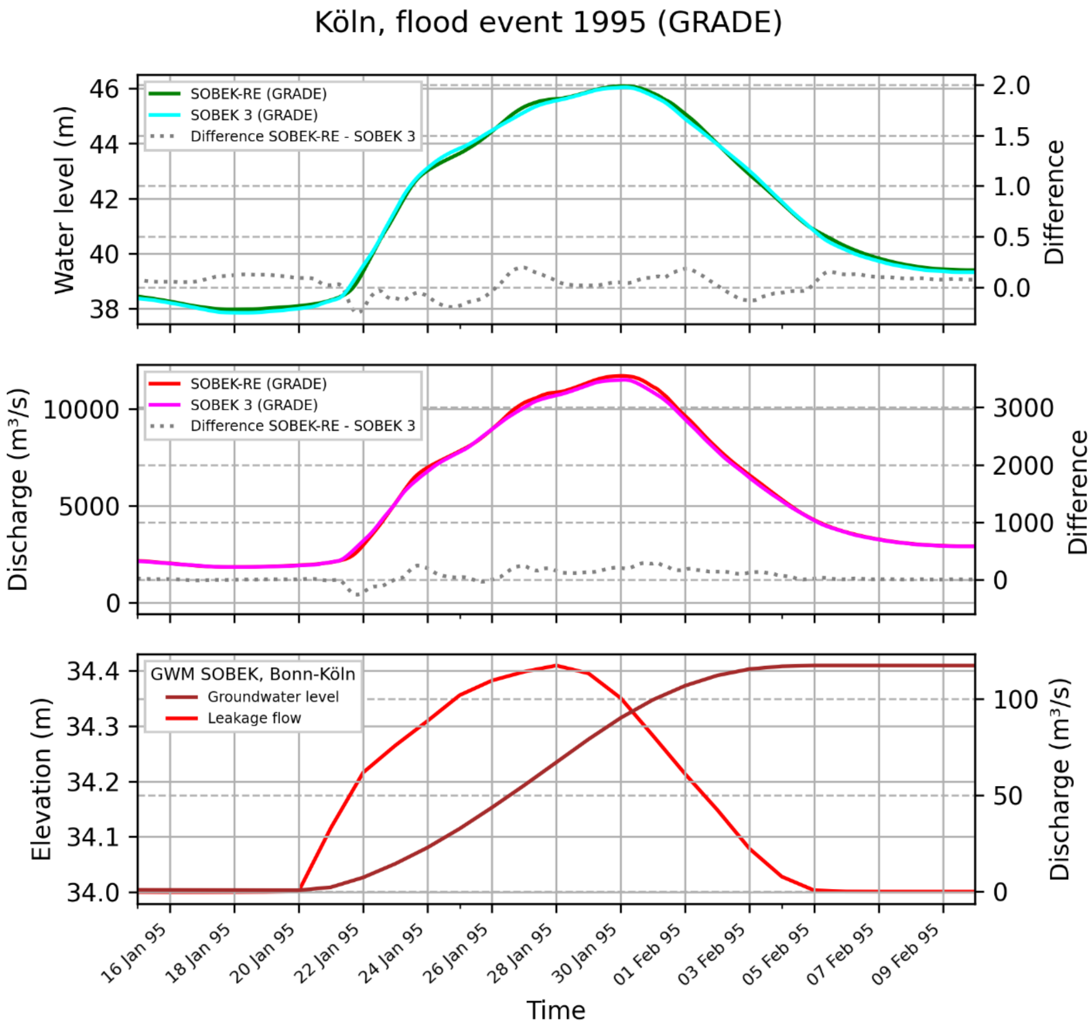

Figure 99 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1995

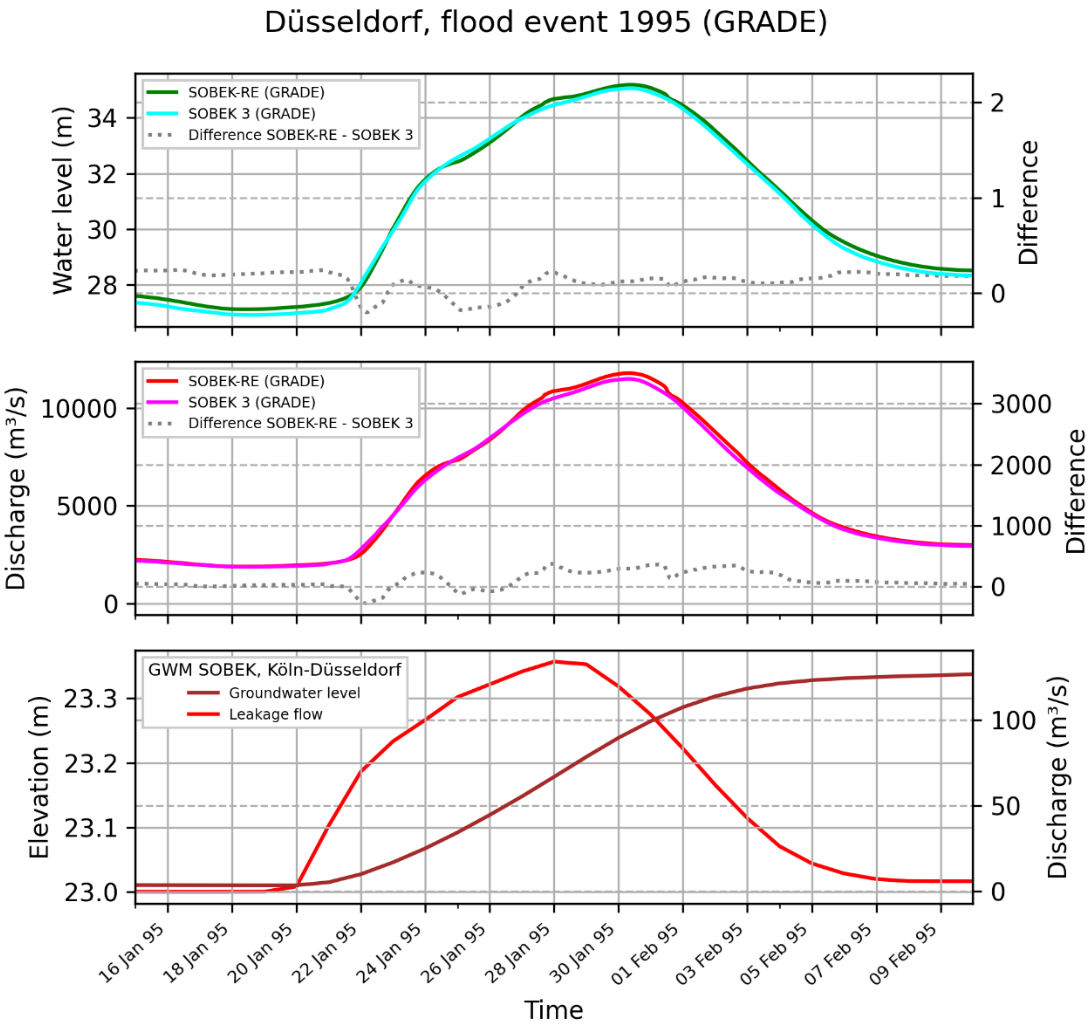

Figure 100 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Düsseldorf, flood event 1995

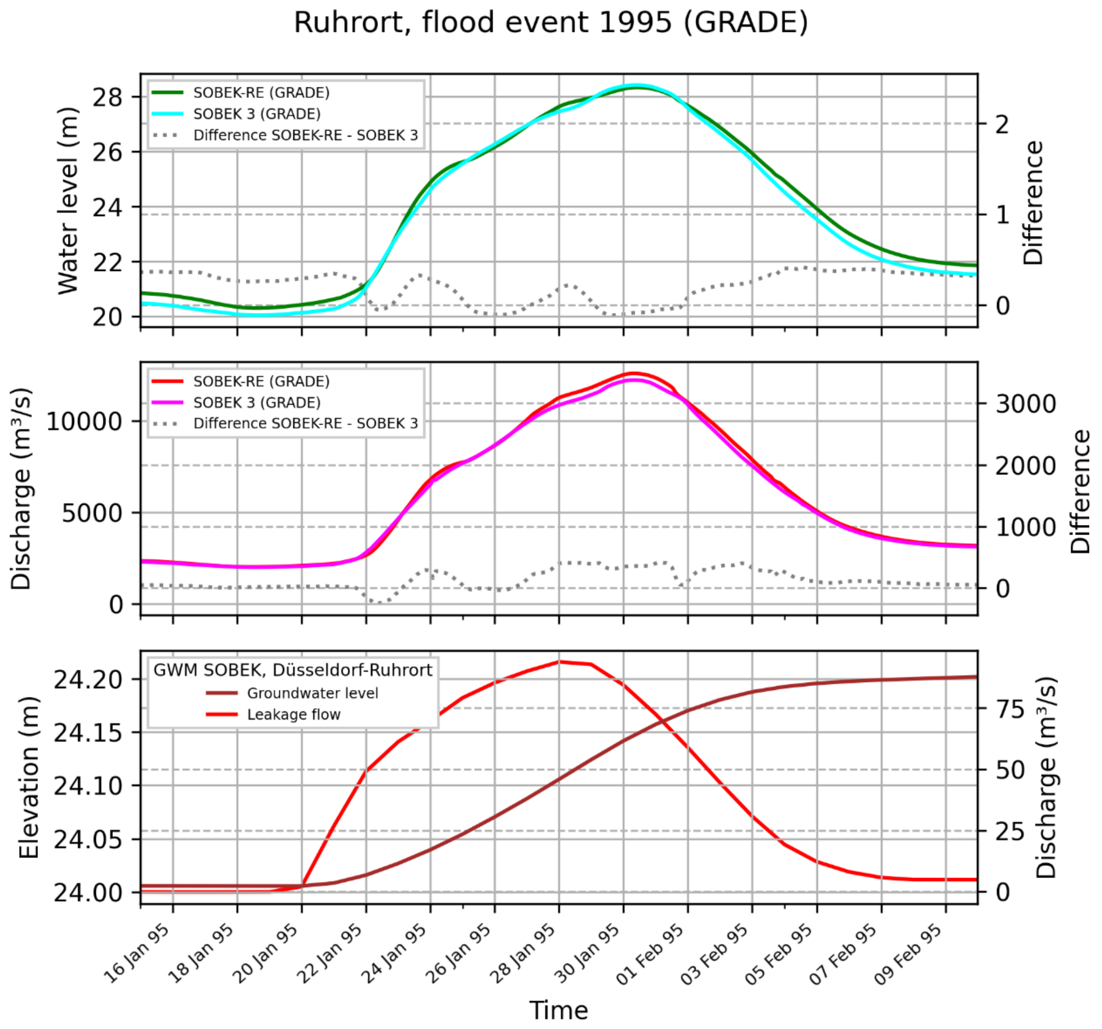

Figure 101 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Ruhrort, flood event 1995

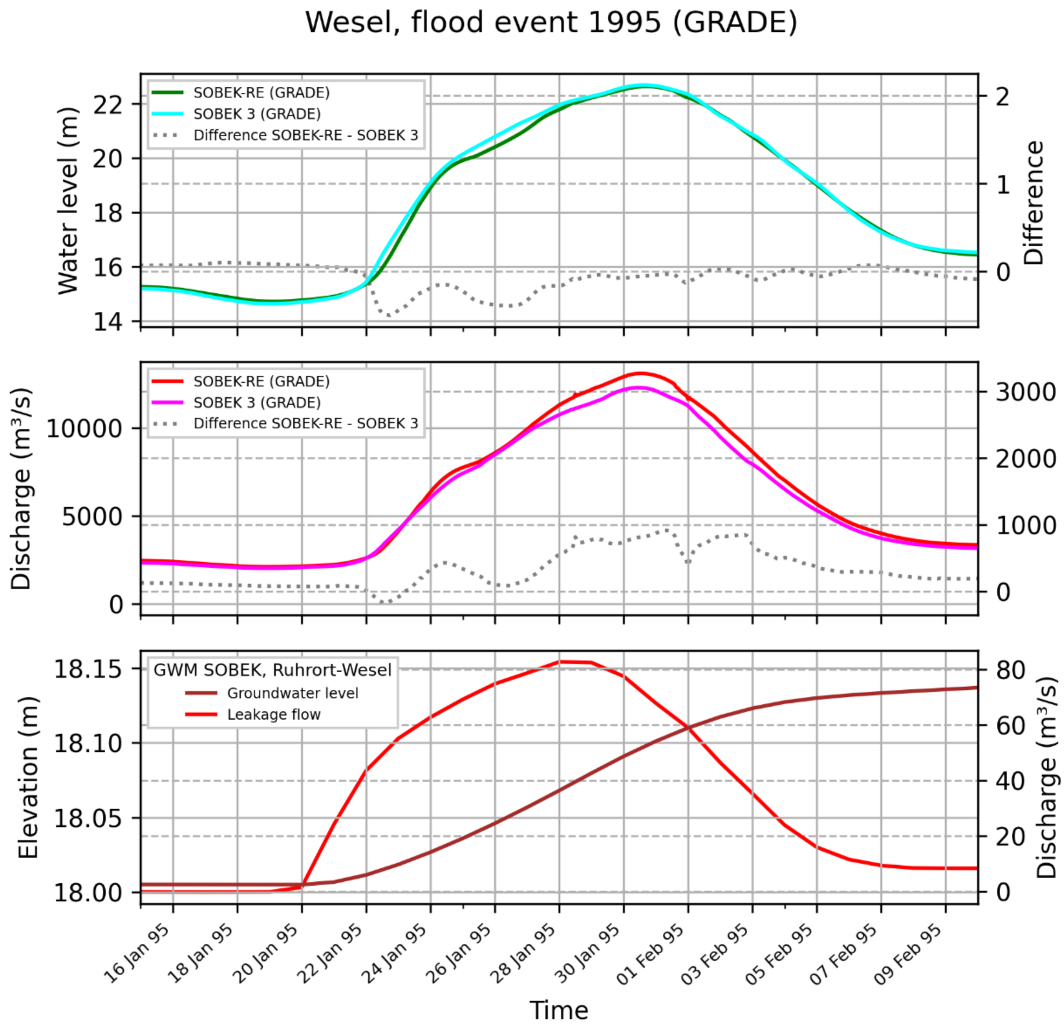

Figure 102 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Wesel, flood event 1995

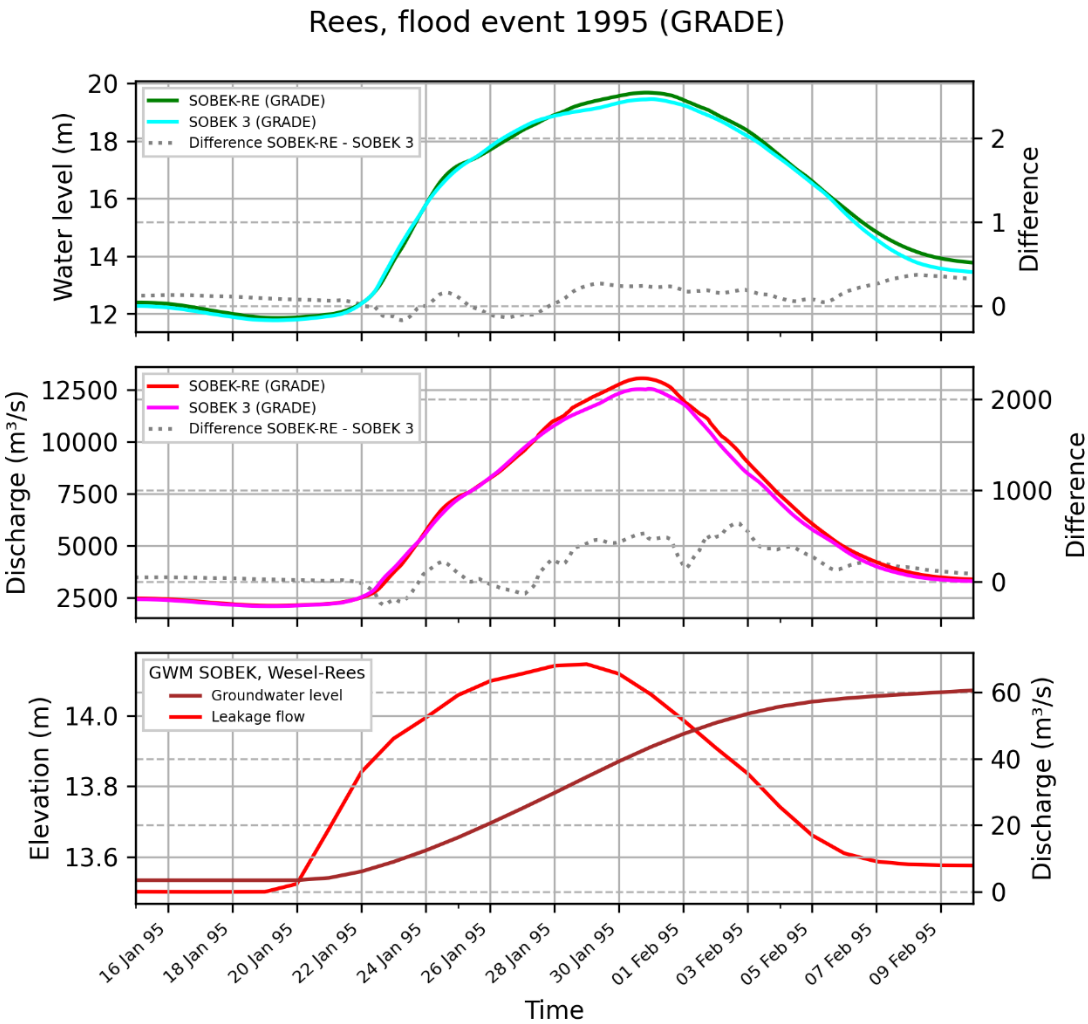

Figure 103 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1995

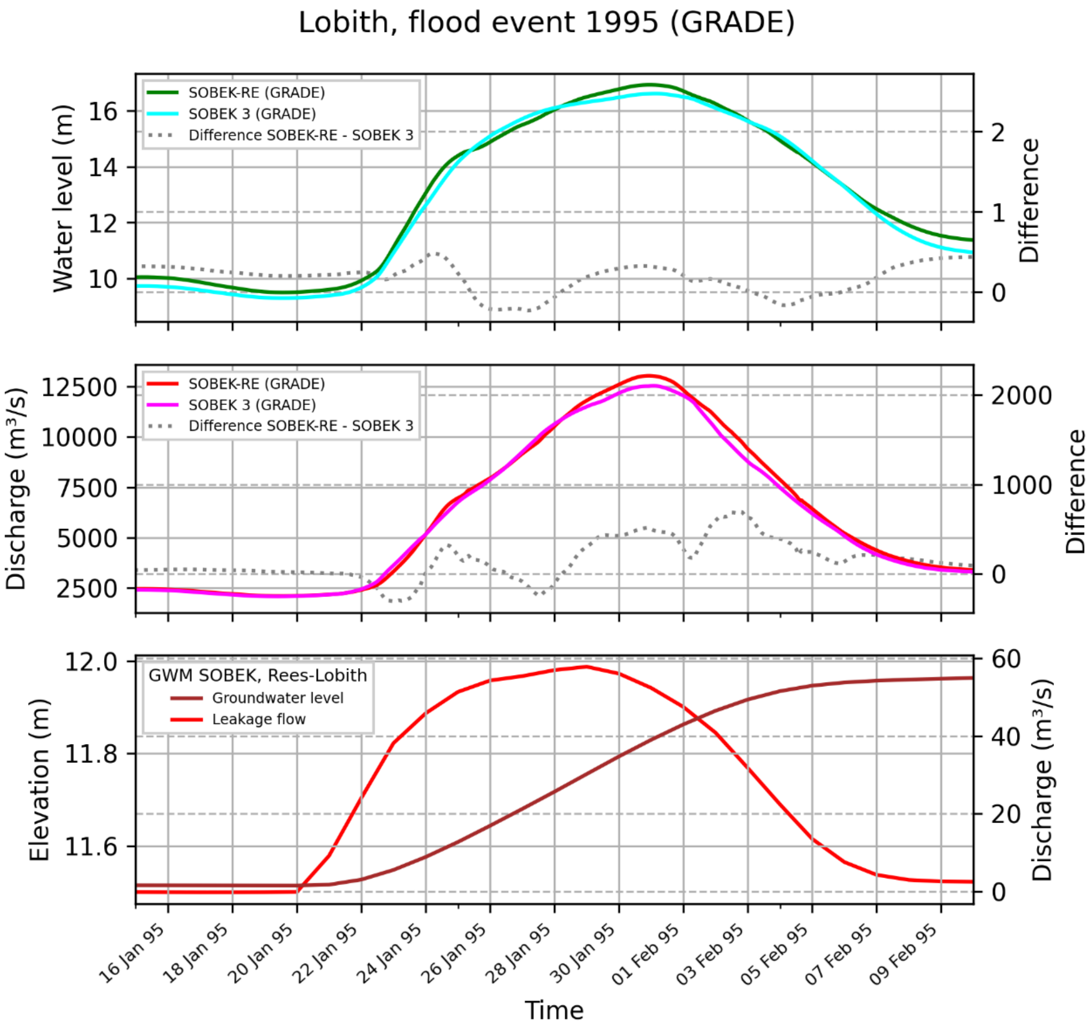

Figure 104 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1995

B.3.2 Flood event 1993

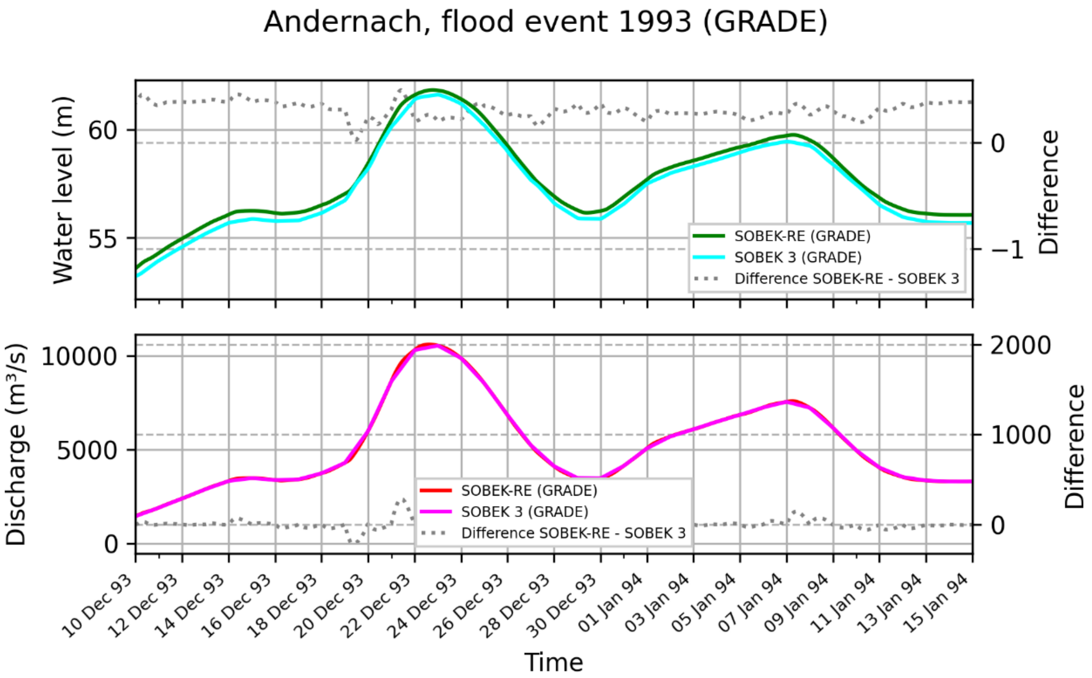

Figure 105 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1993

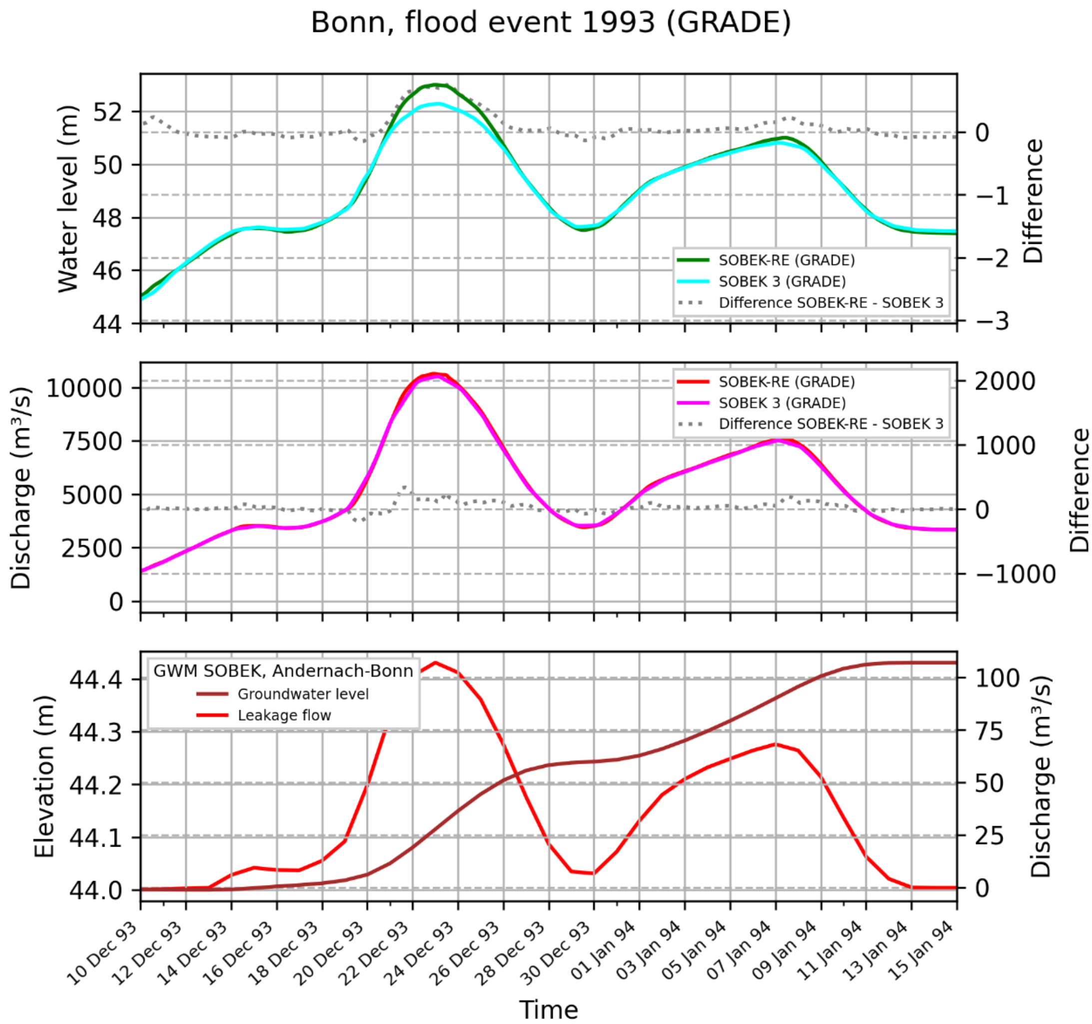

Figure 106 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Bonn, flood event 1993

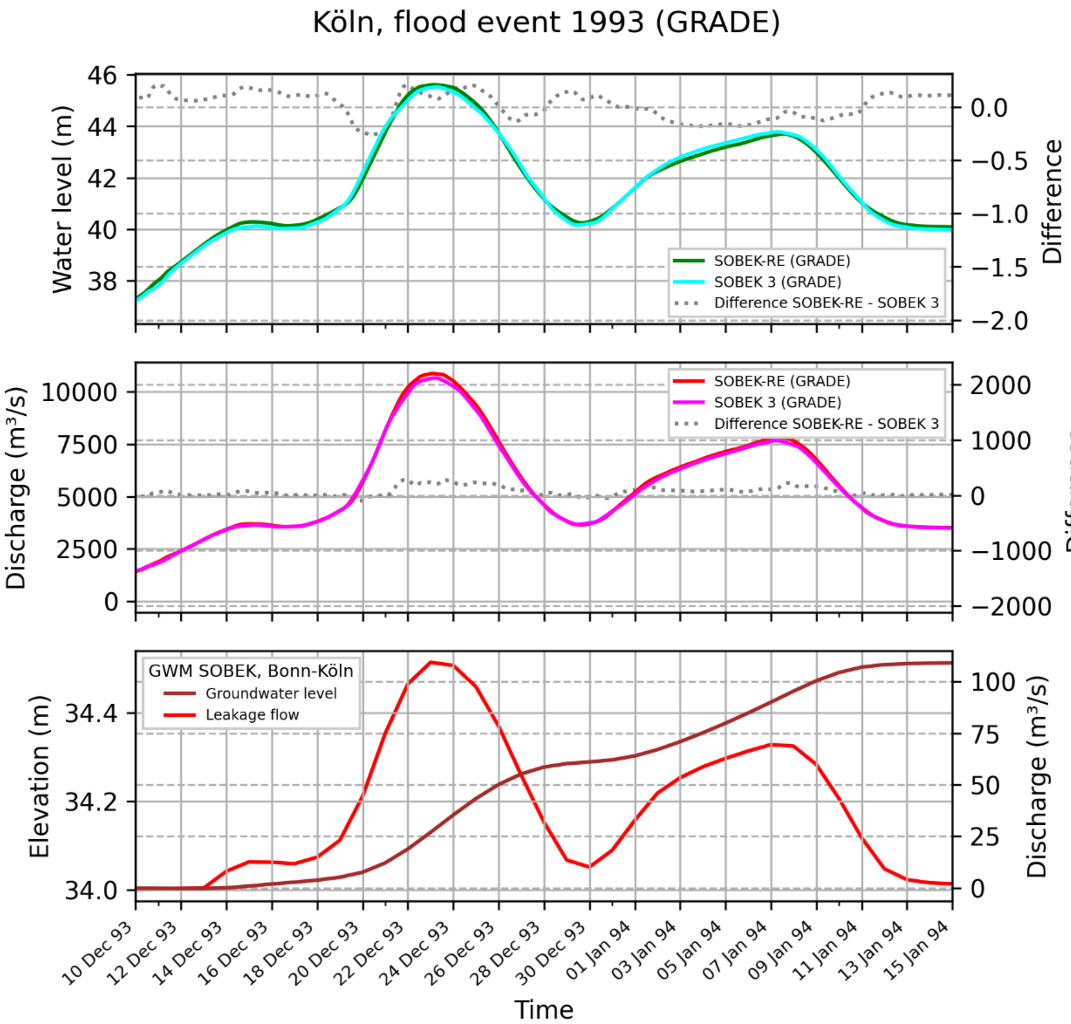

Figure 107 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1993

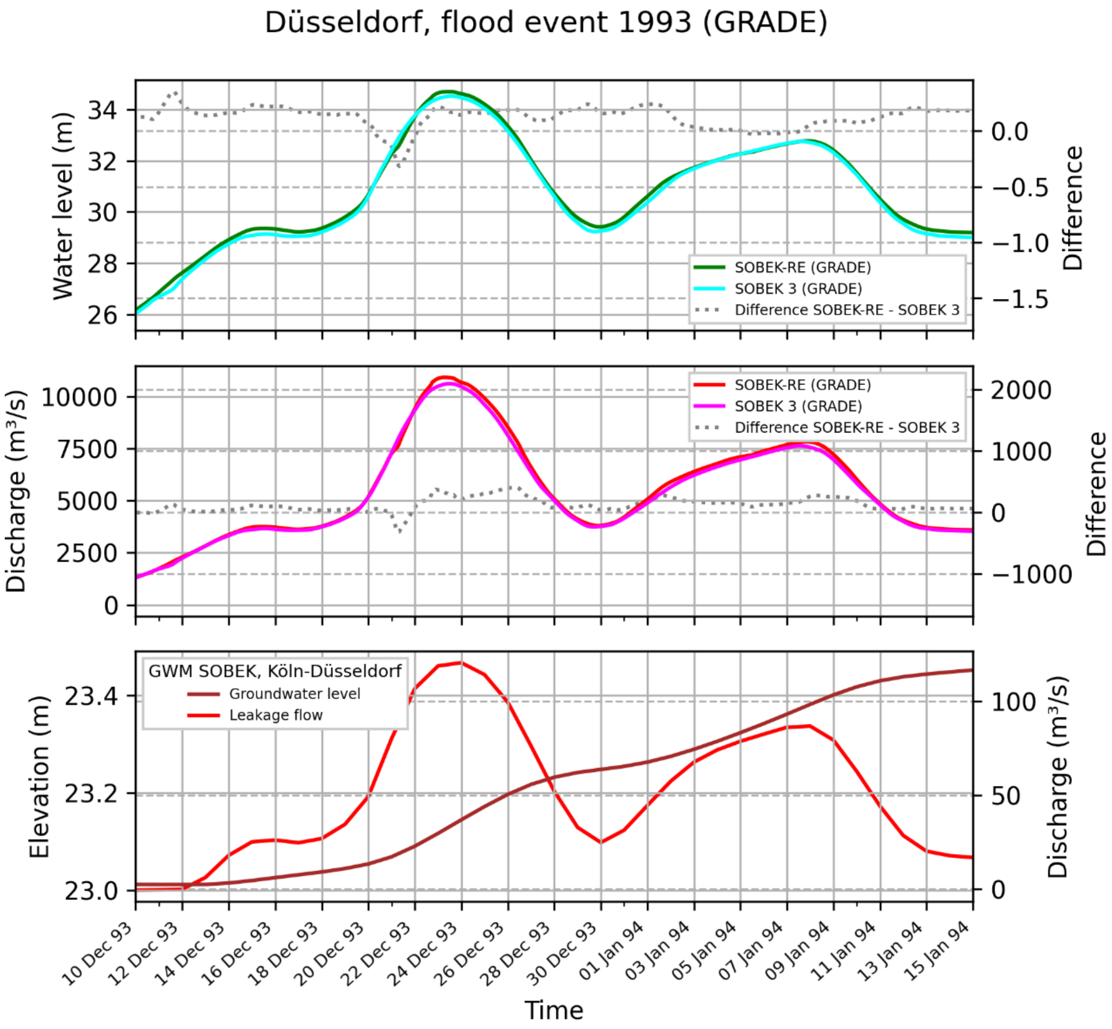

Figure 108 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Düsseldorf, flood event 1993

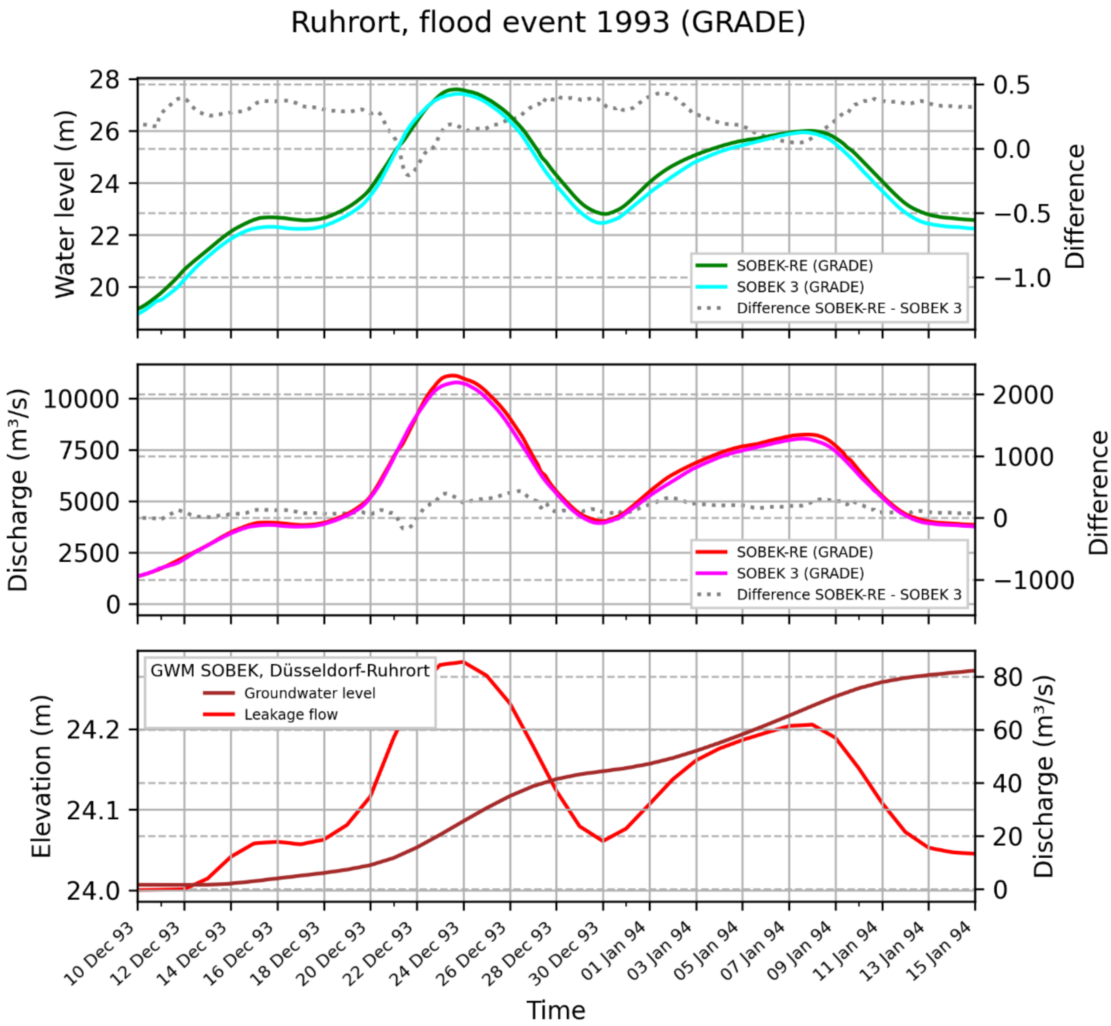

Figure 109 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE and comparison data for the gauging station Ruhrort, flood event 1993

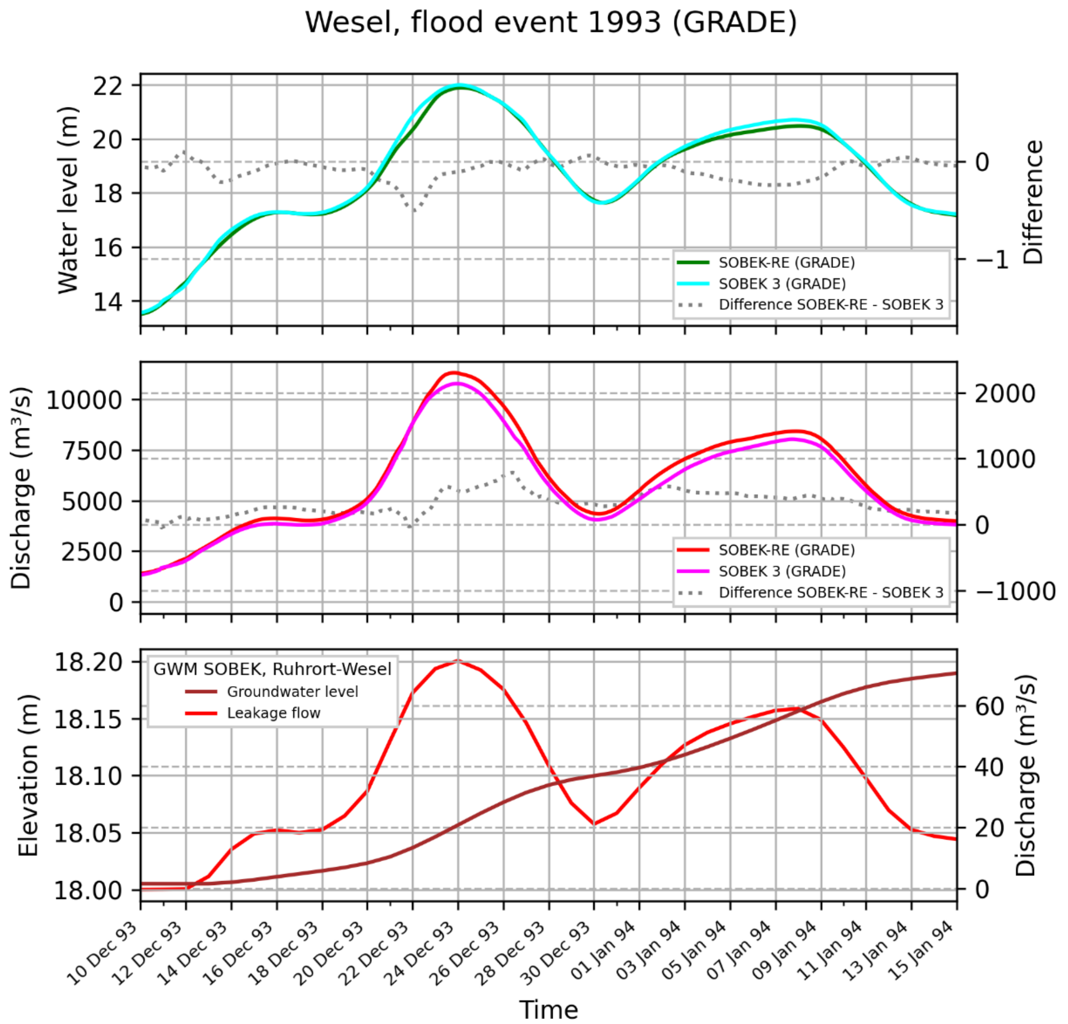

Figure 110 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Wesel, flood event 1993

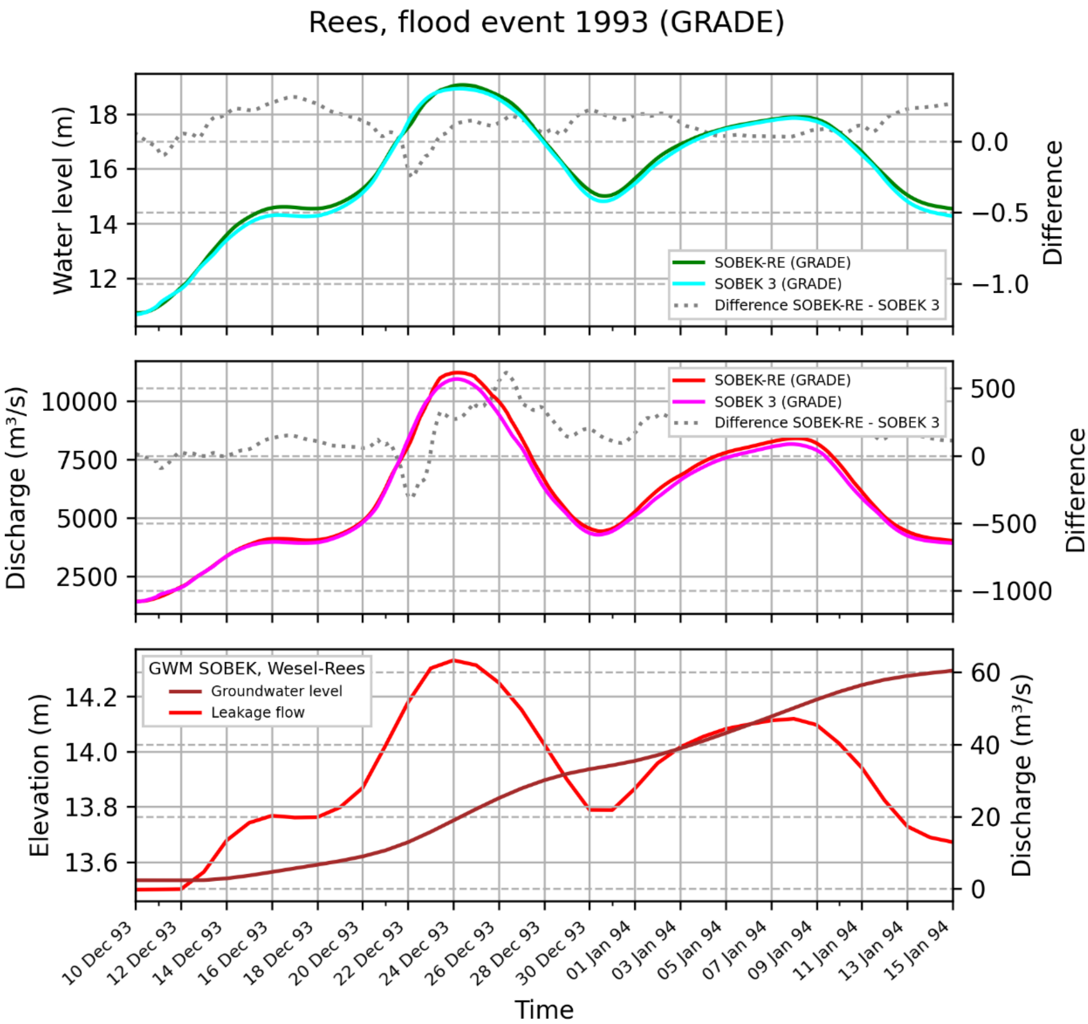

Figure 111 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1993

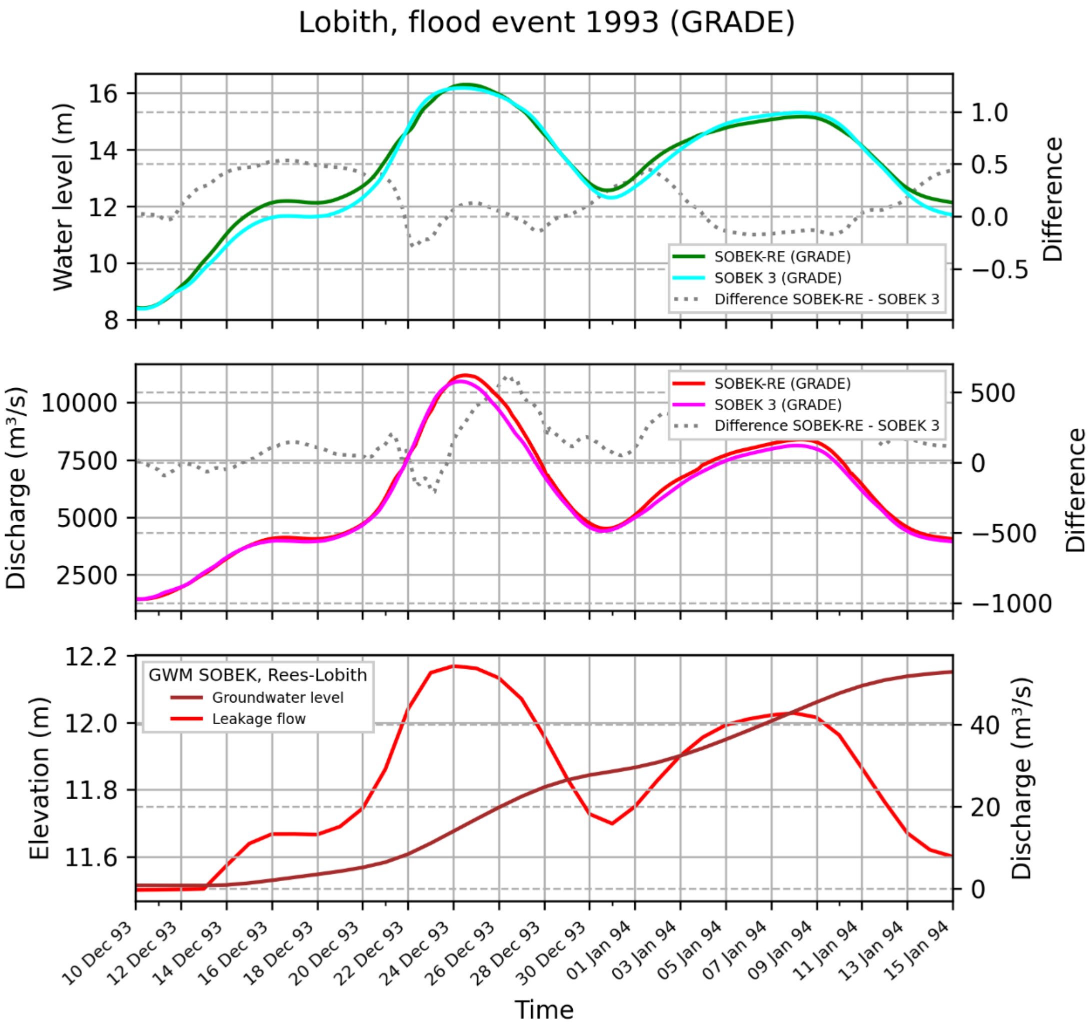

Figure 112 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1993

B.3.3 Flood event 1998

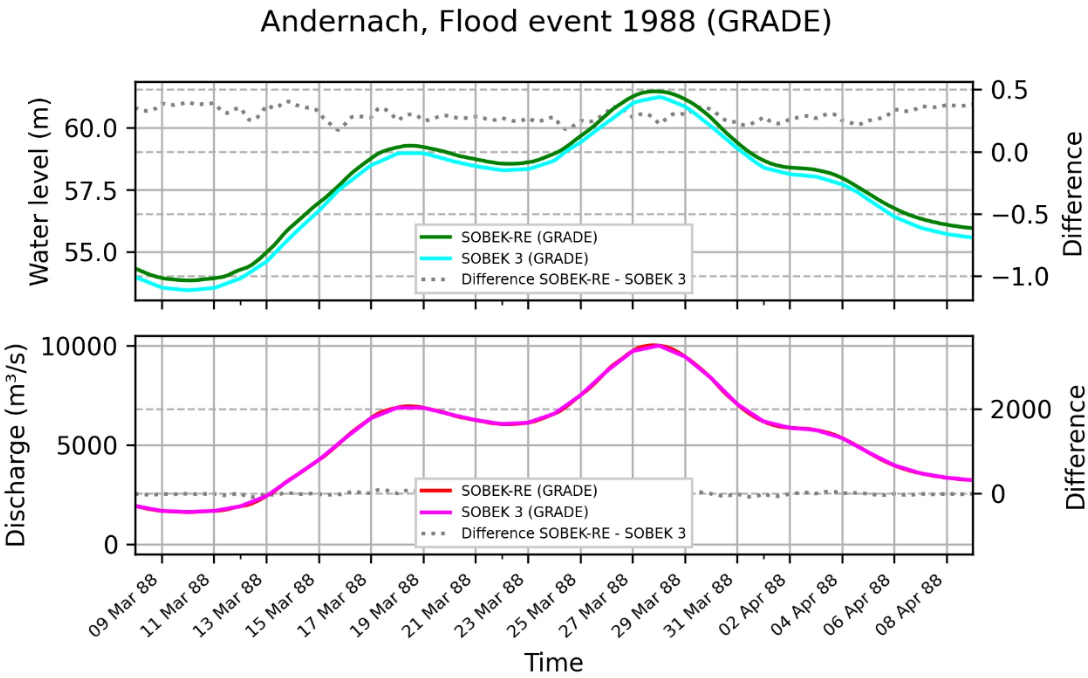

Figure 113 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Andernach, flood event 1988

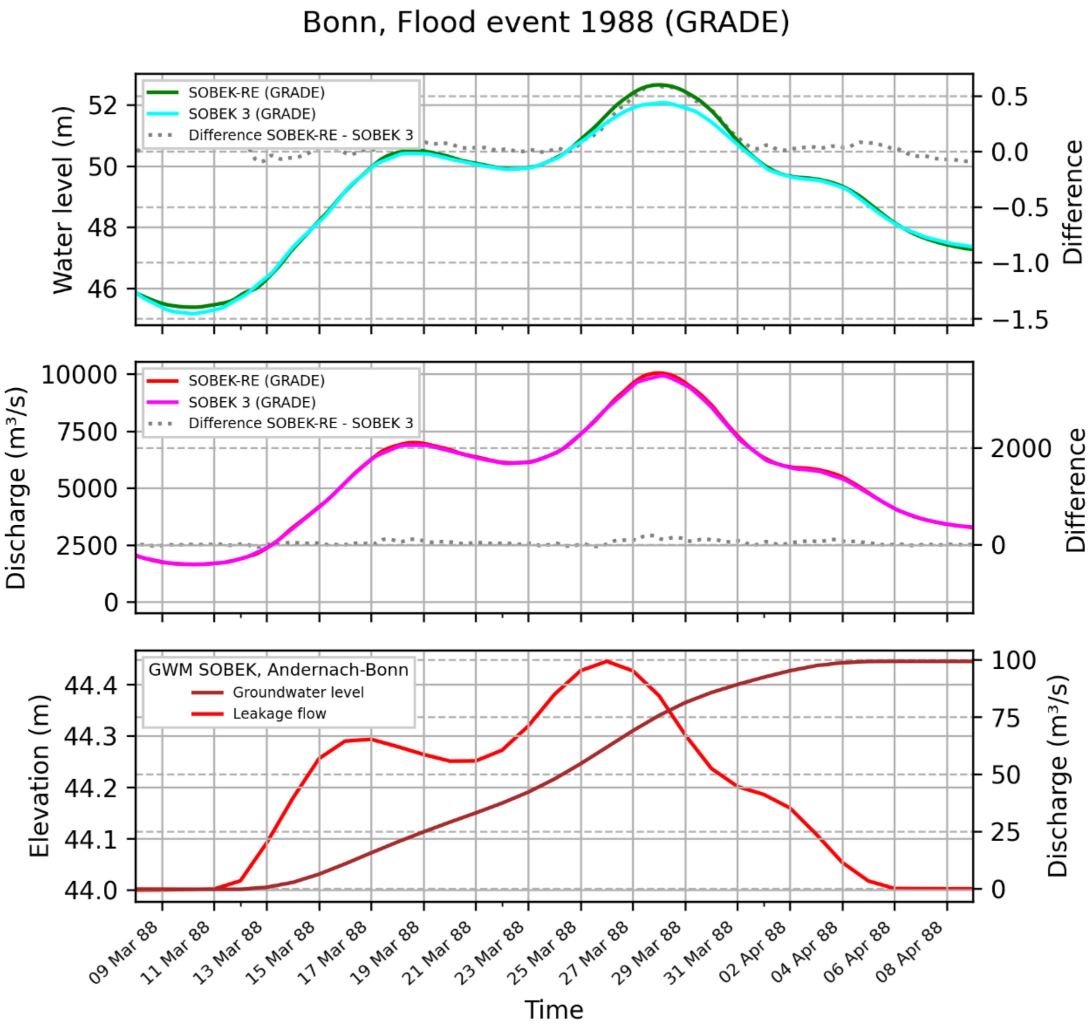

Figure 114 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Bonn, flood event 1988

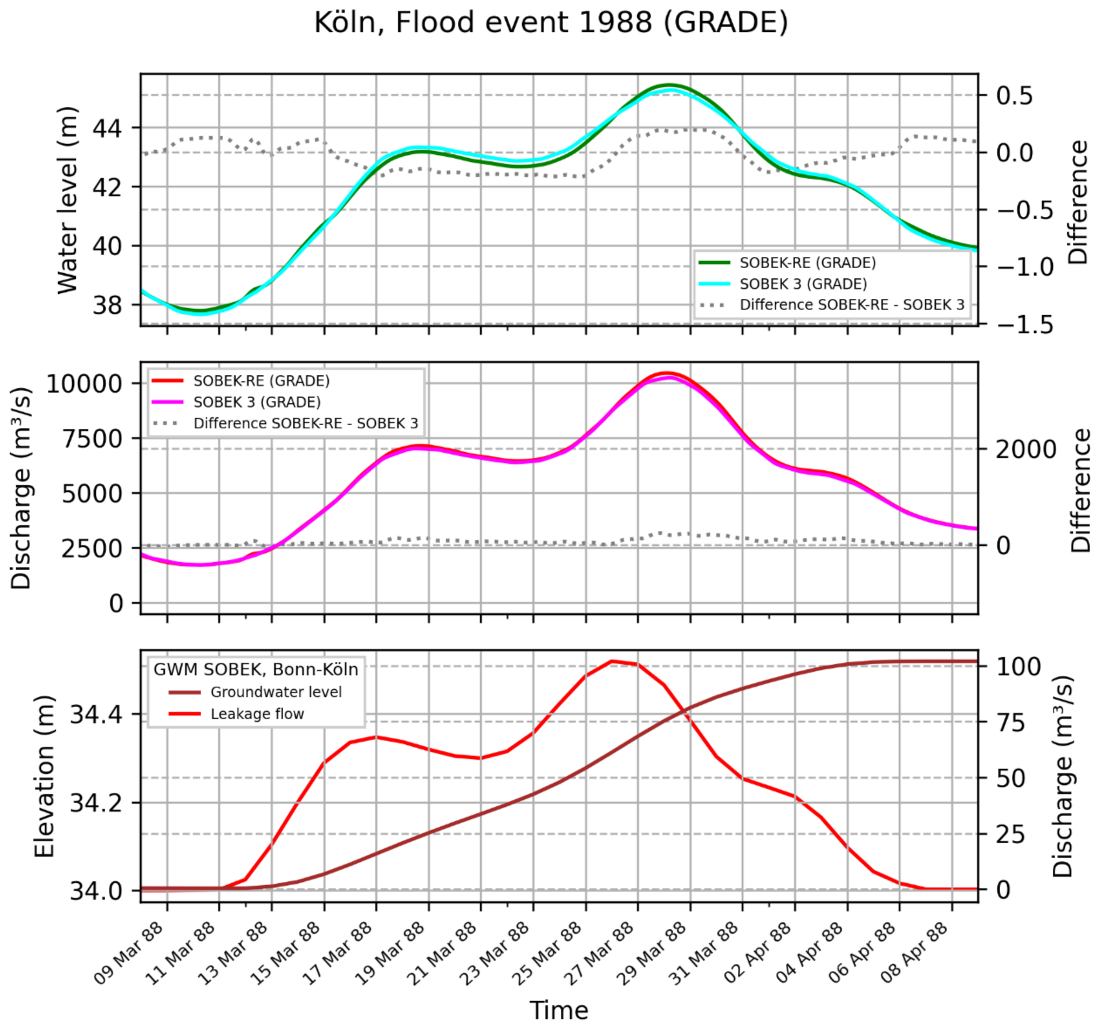

Figure 115 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Köln, flood event 1988

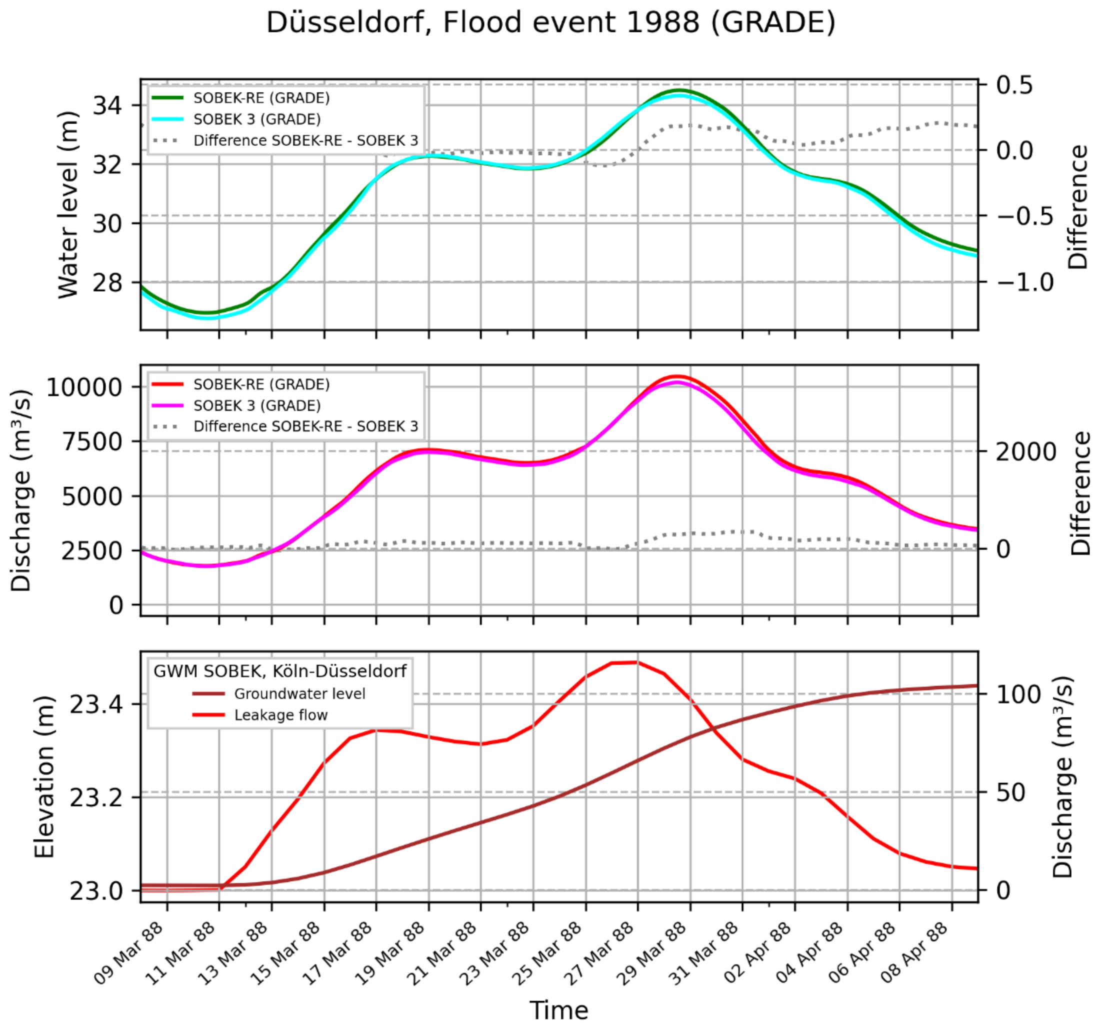

Figure 116 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Düsseldorf, flood event 1988

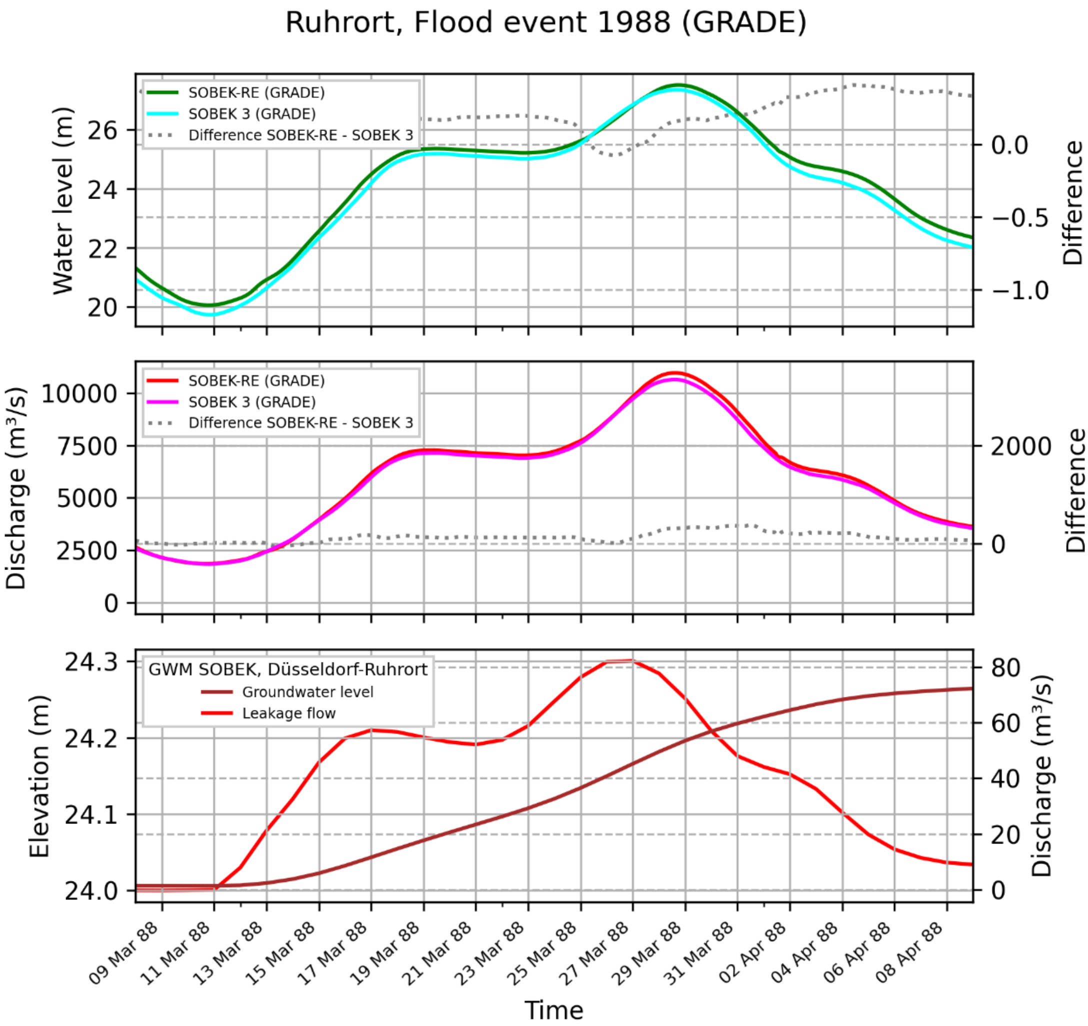

Figure 117 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Ruhrort, flood event 1988

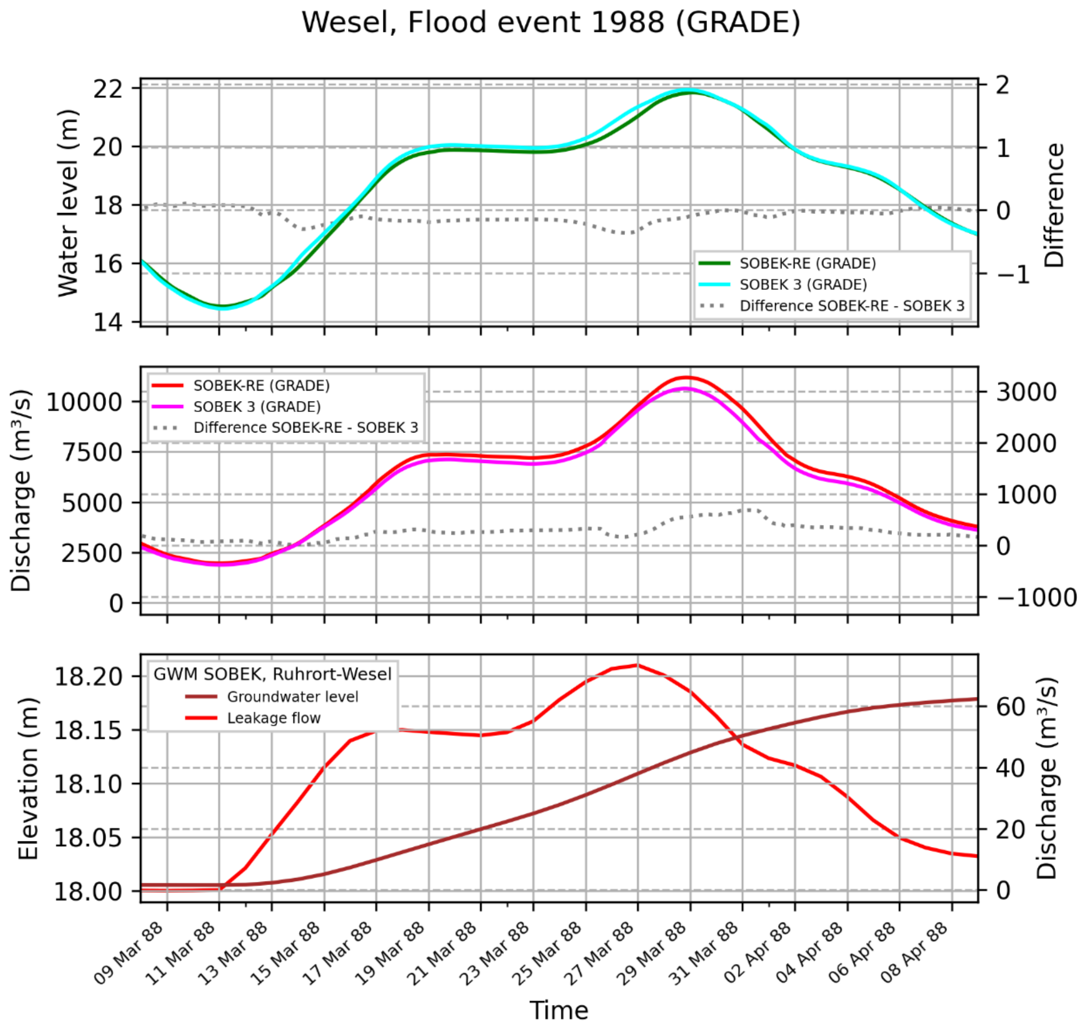

Figure 118 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Wesel, flood event 1988

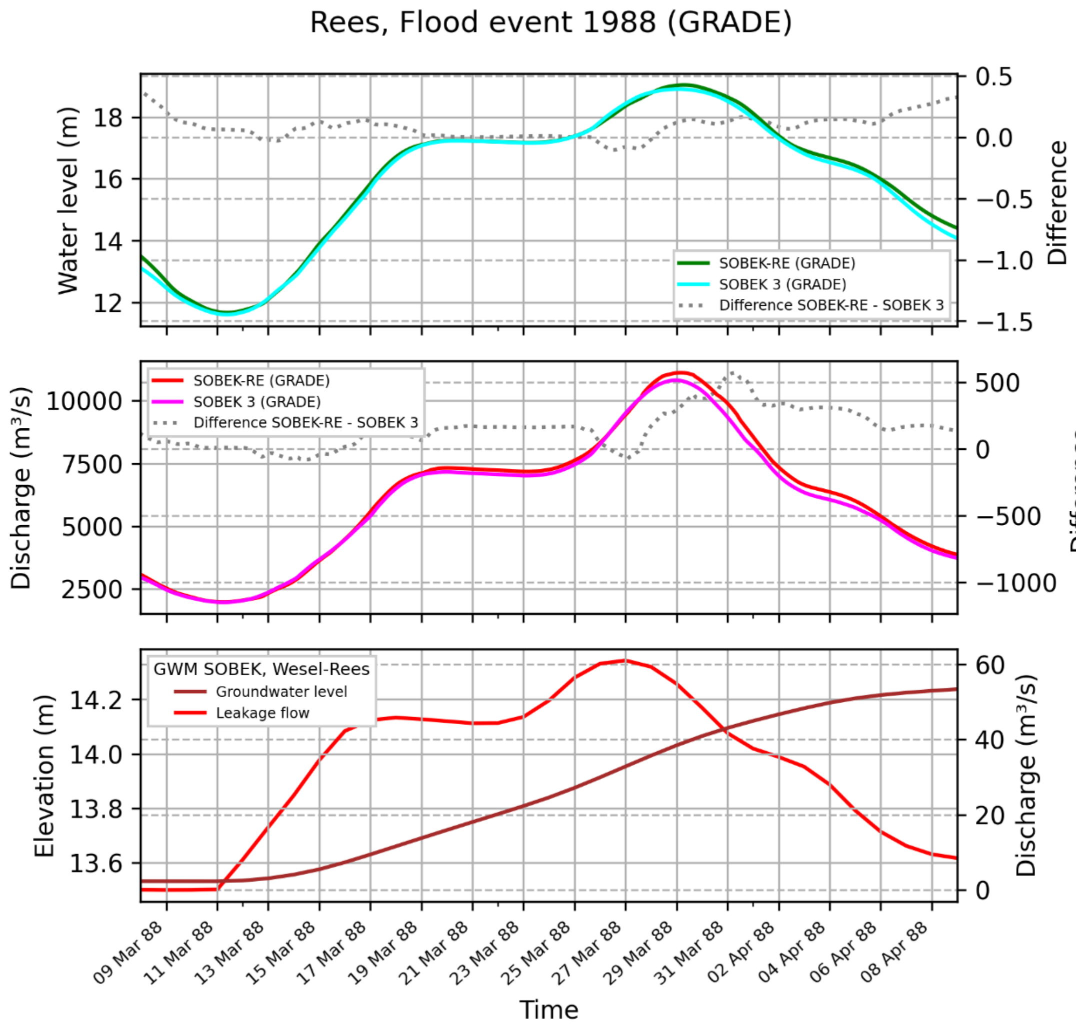

Figure 119 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Rees, flood event 1988

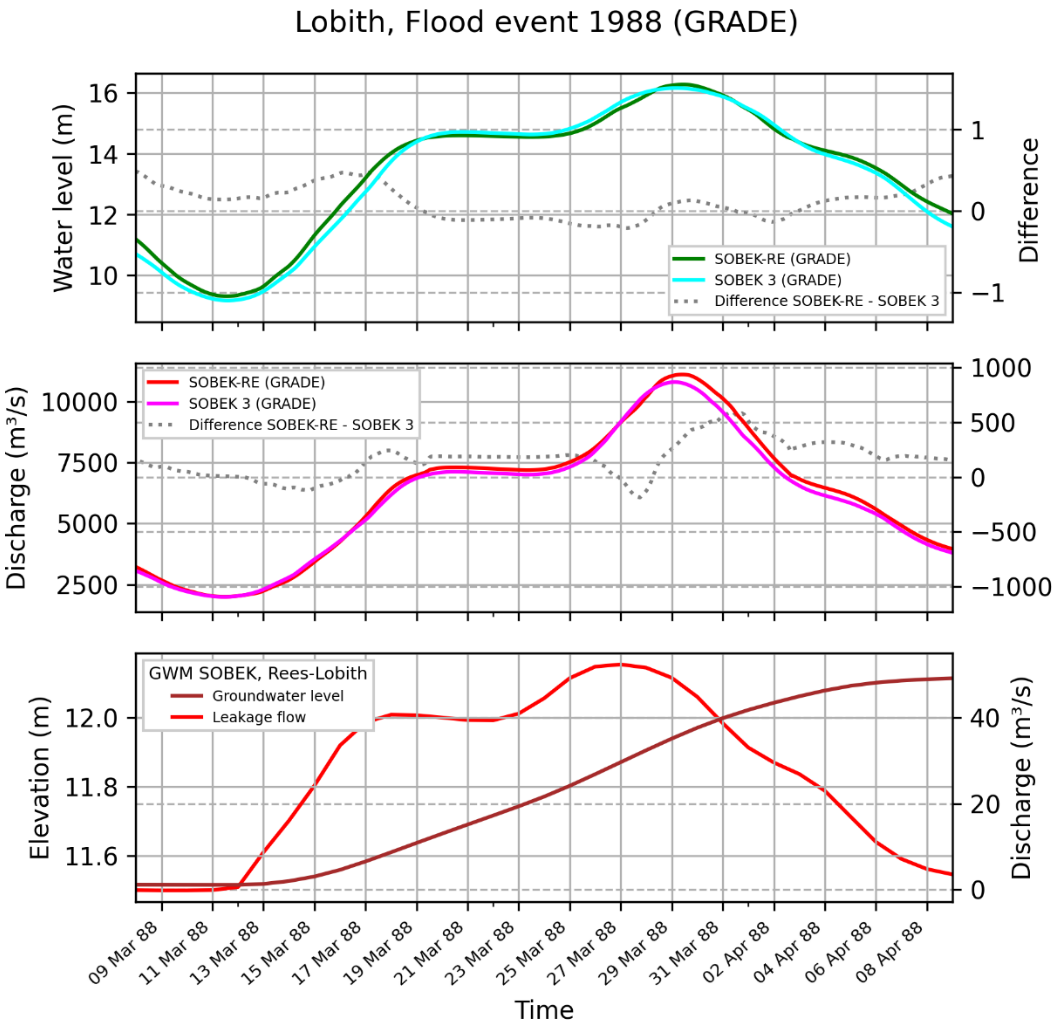

Figure 120 Simulation results obtained with the groundwater module SOBEK in SOBEK 3 and with SOBEK-RE for the gauging station Lobith, flood event 1988

B.4 Extreme scenarios GRADE

B.4.1 Peak discharge of 18 000 m³/s at Andernach

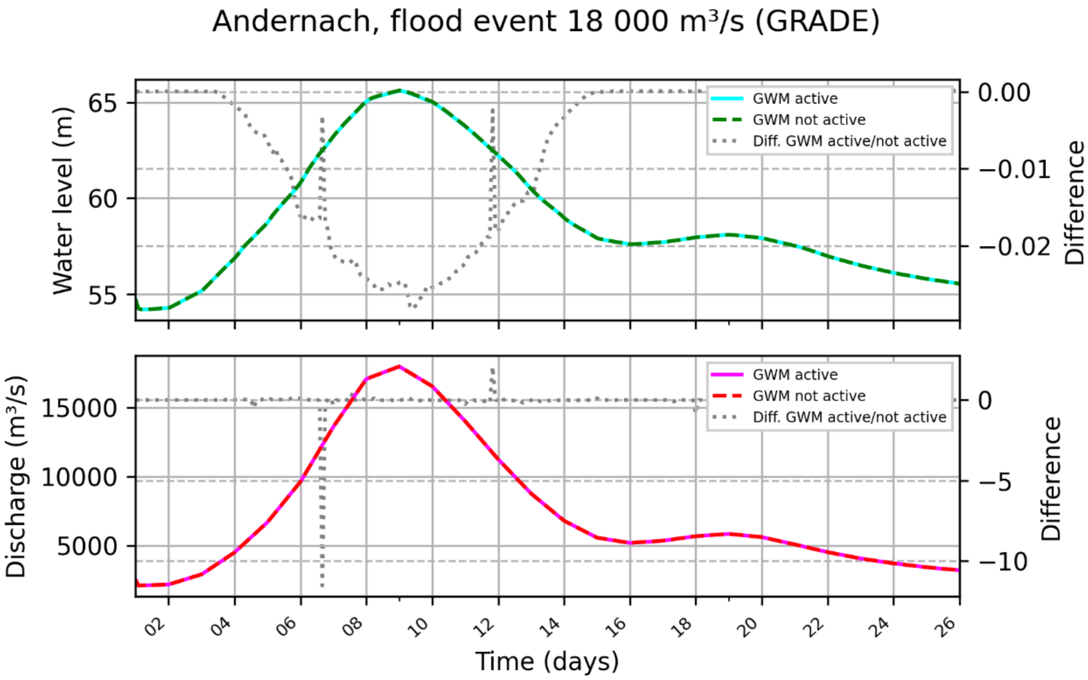

Figure 121 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

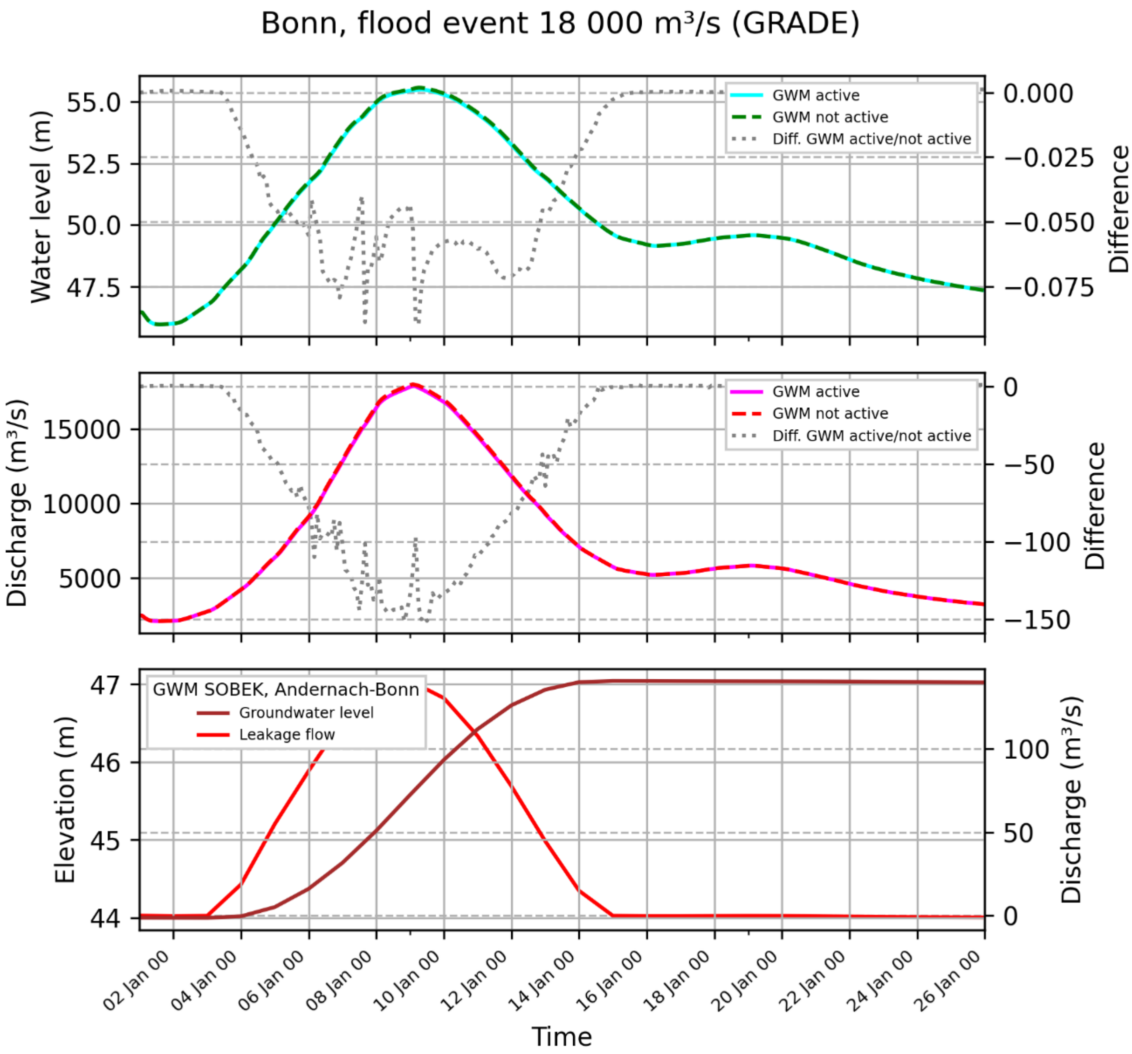

Figure 122 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

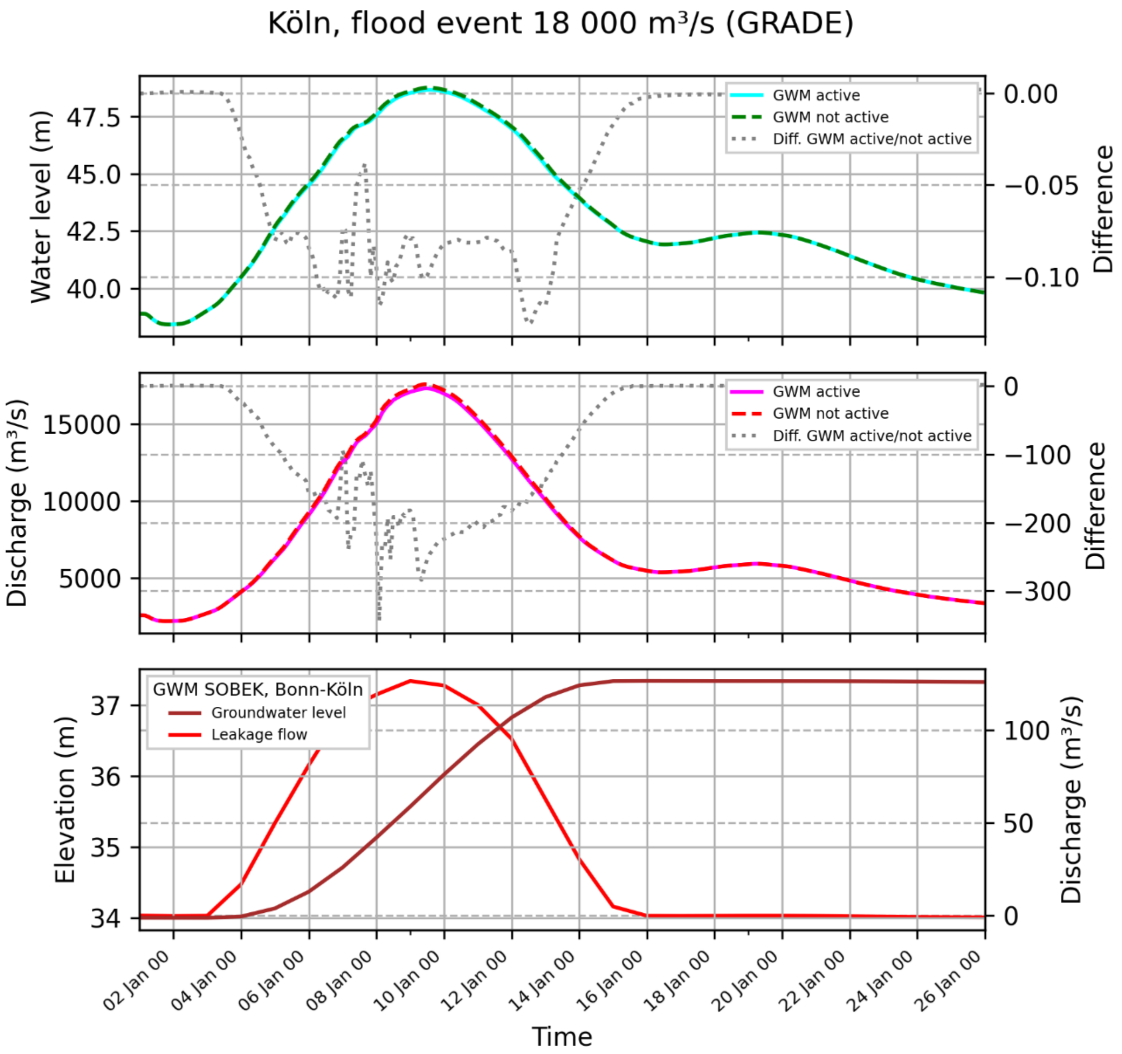

Figure 123 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

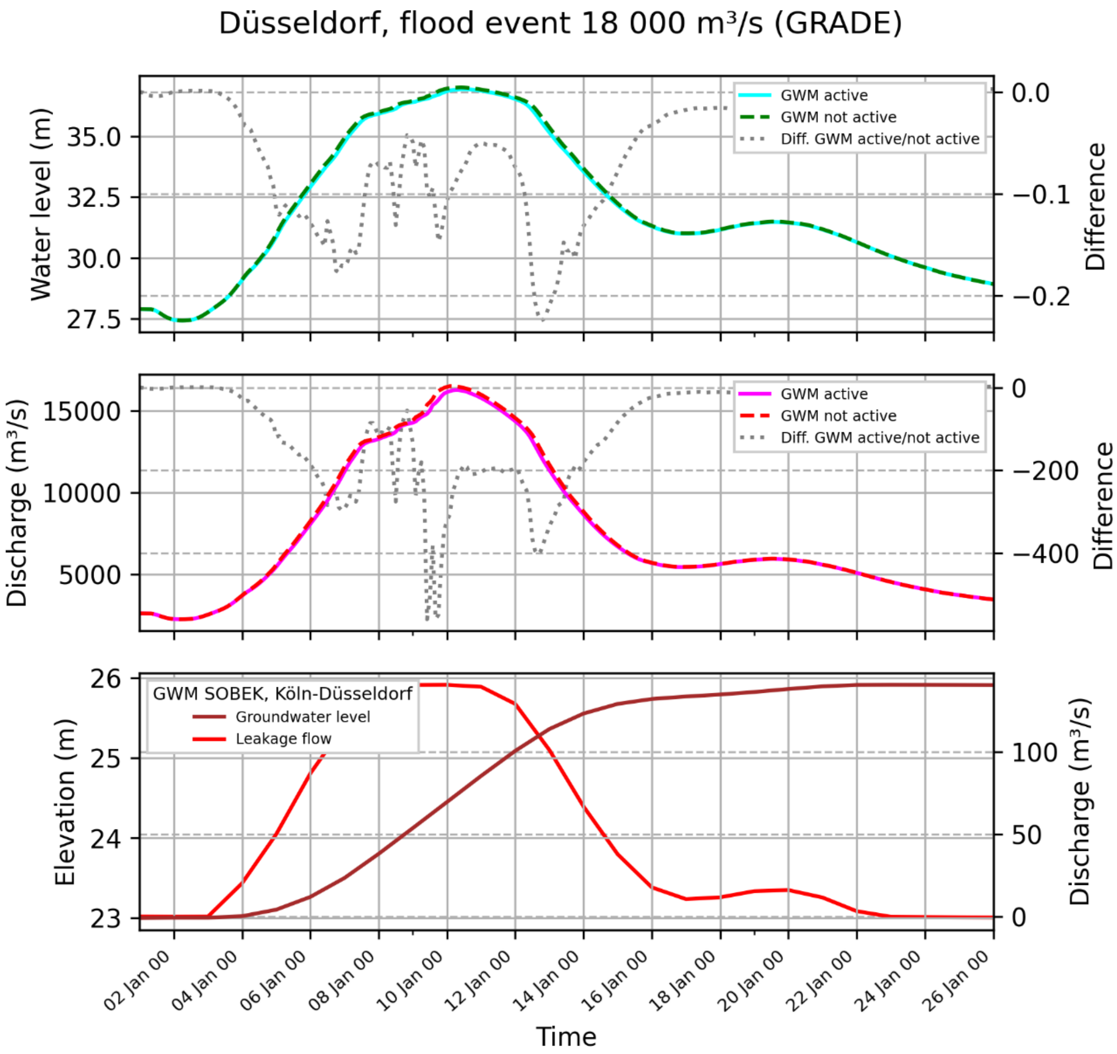

Figure 124 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

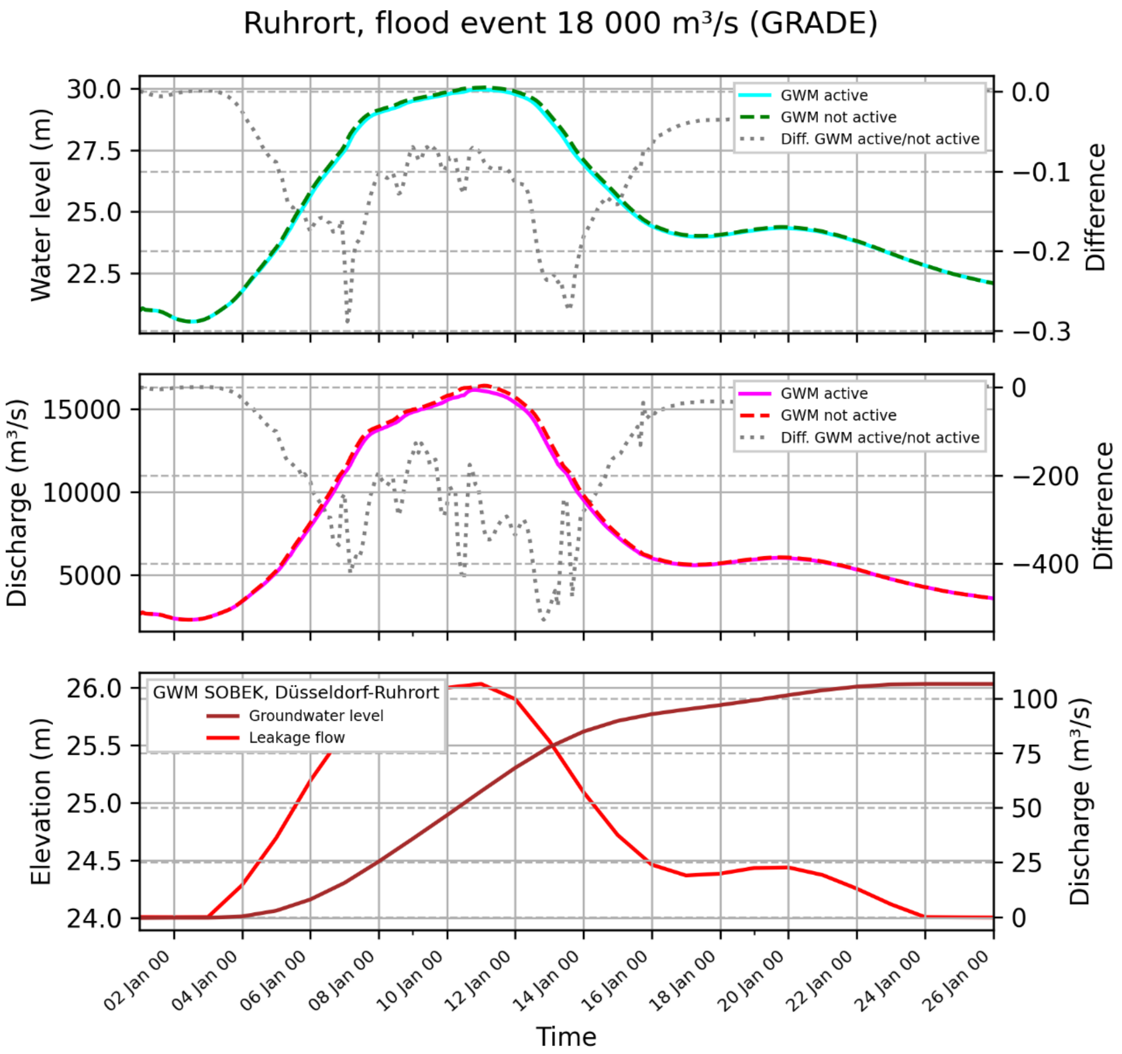

Figure 125 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

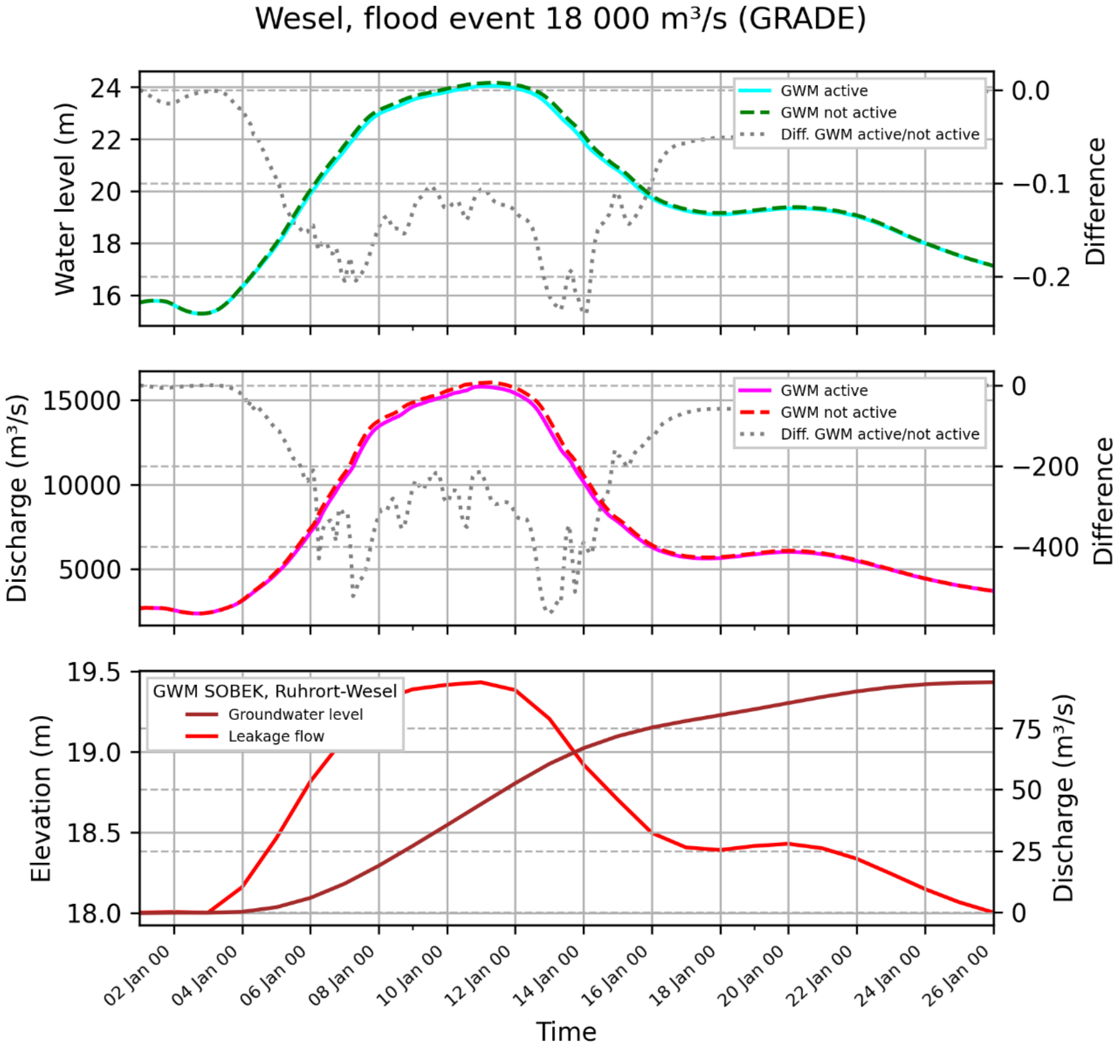

Figure 126 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

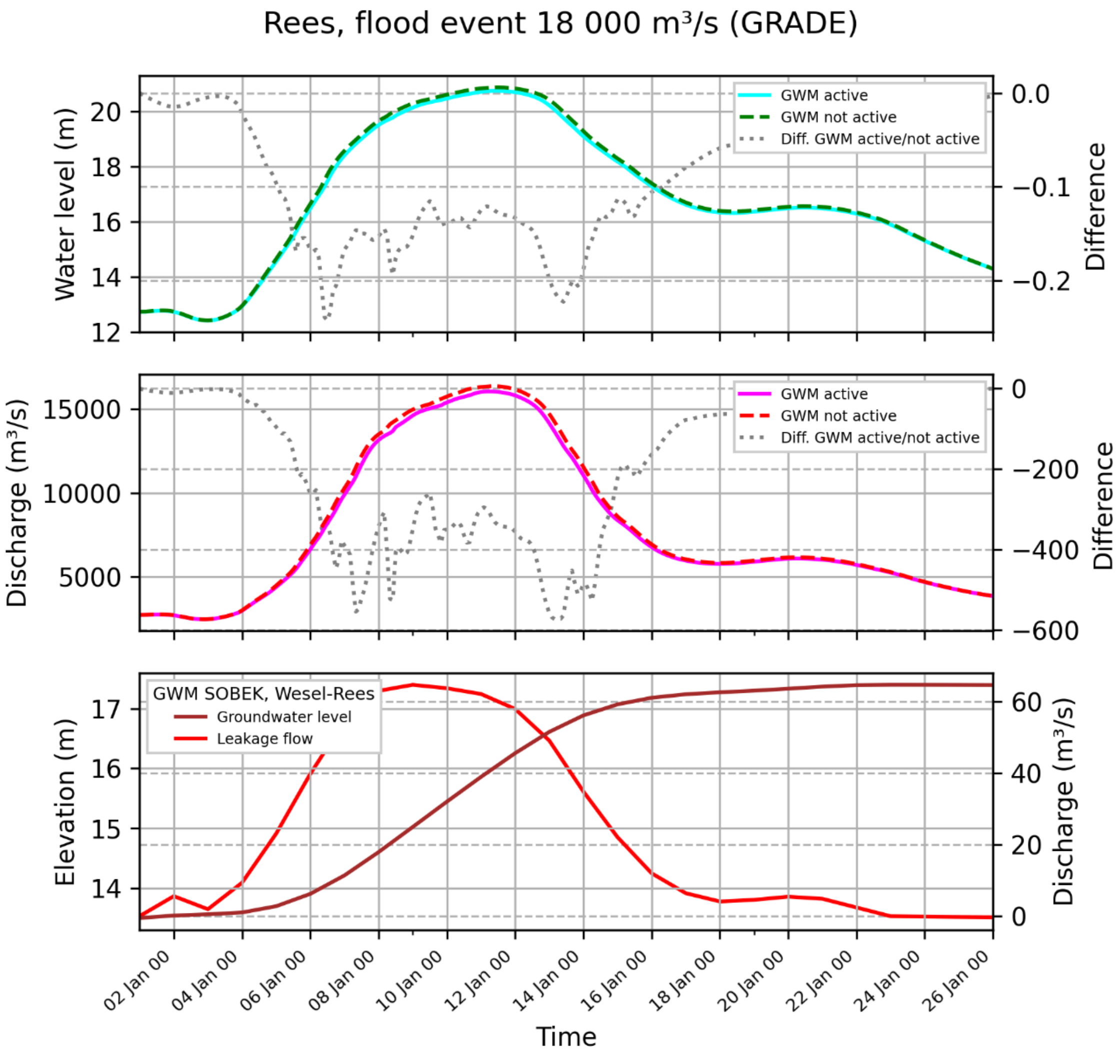

Figure 127 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

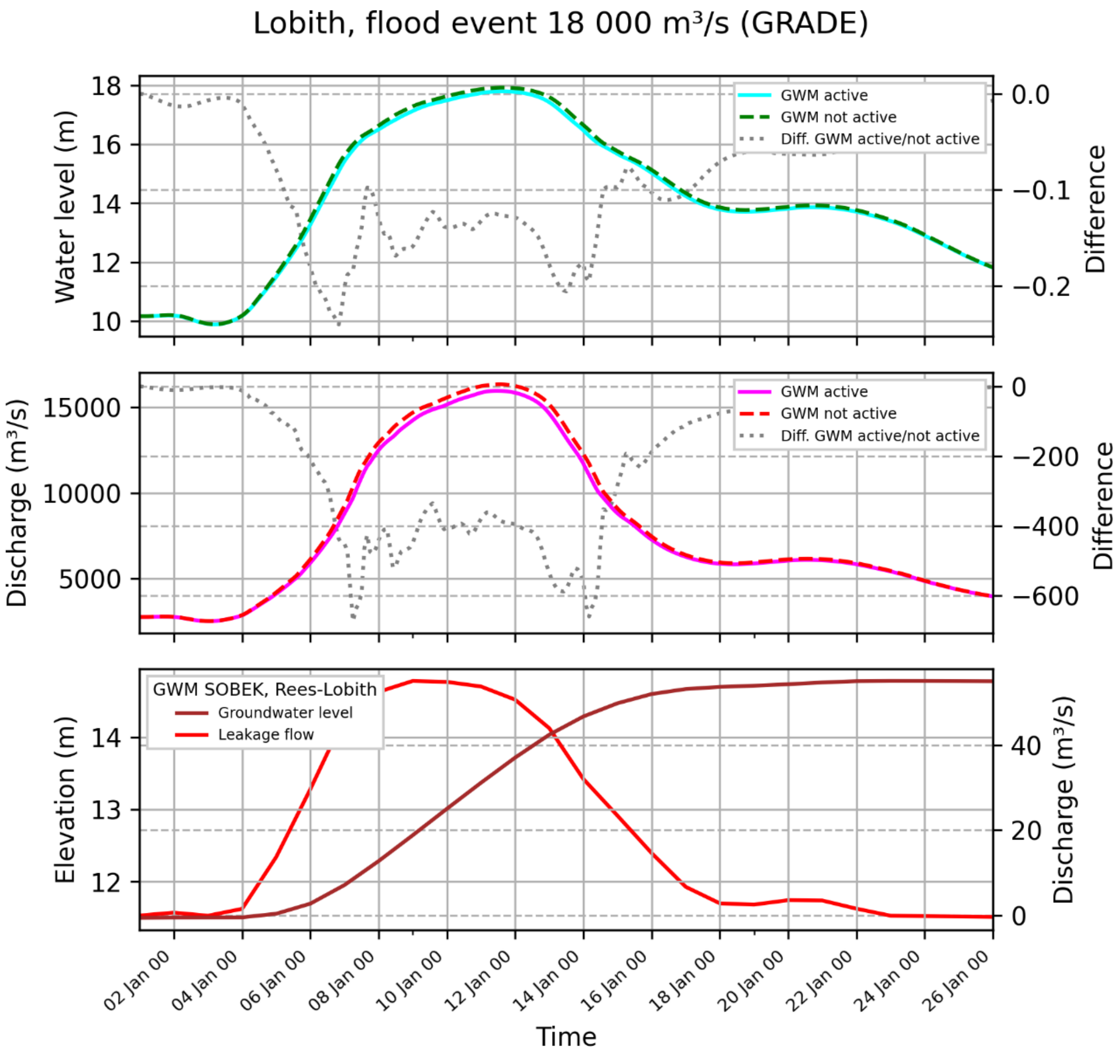

Figure 128 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 18 000 m³/s peak discharge at Andernach

B.4.2 Peak discharge of 20 000 m³/s at Andernach

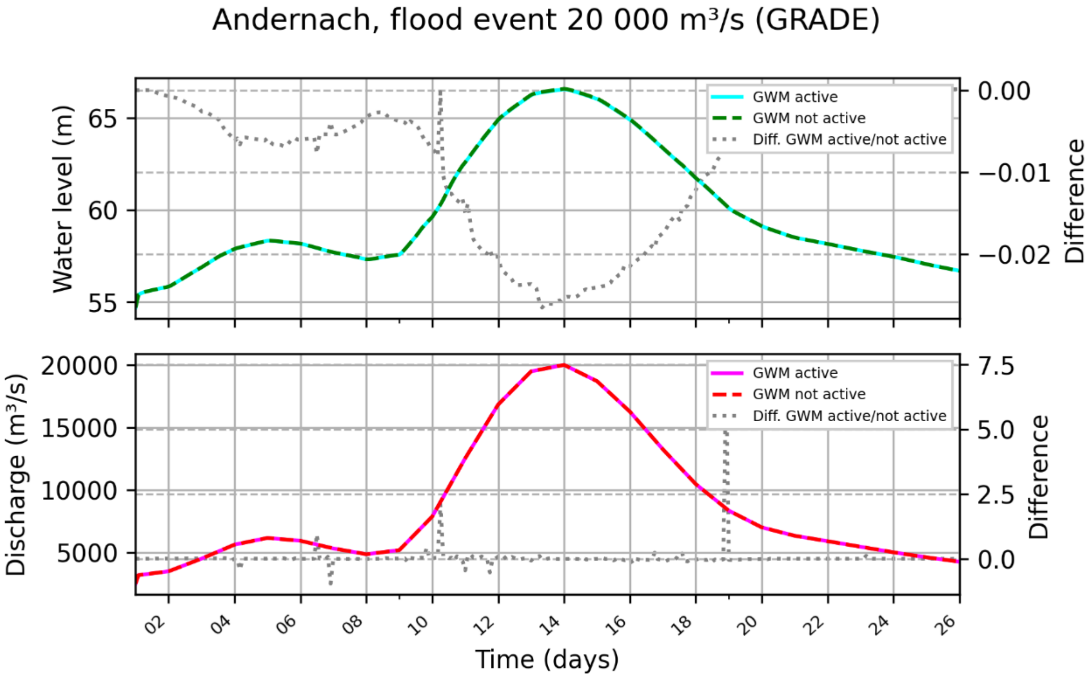

Figure 129 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

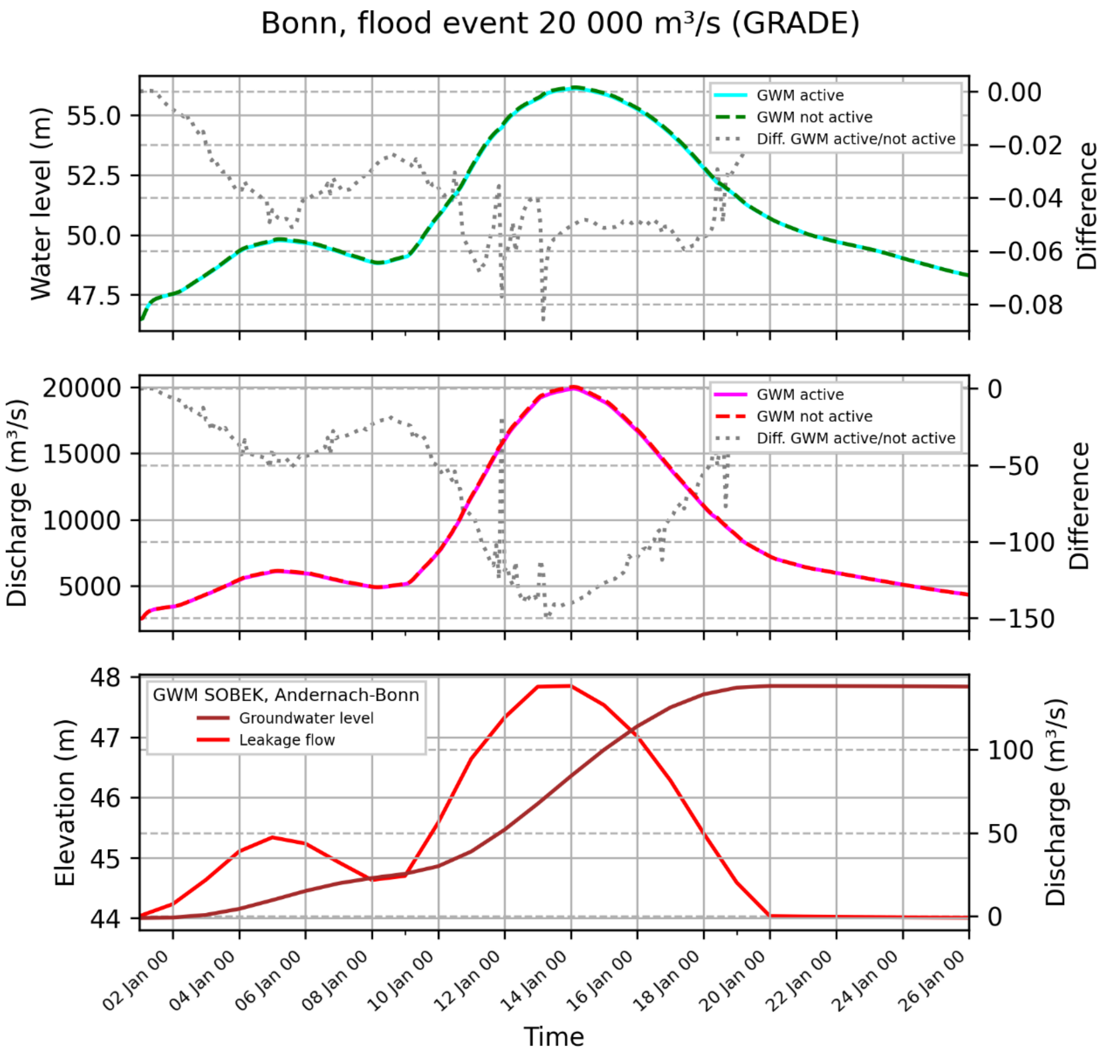

Figure 130 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

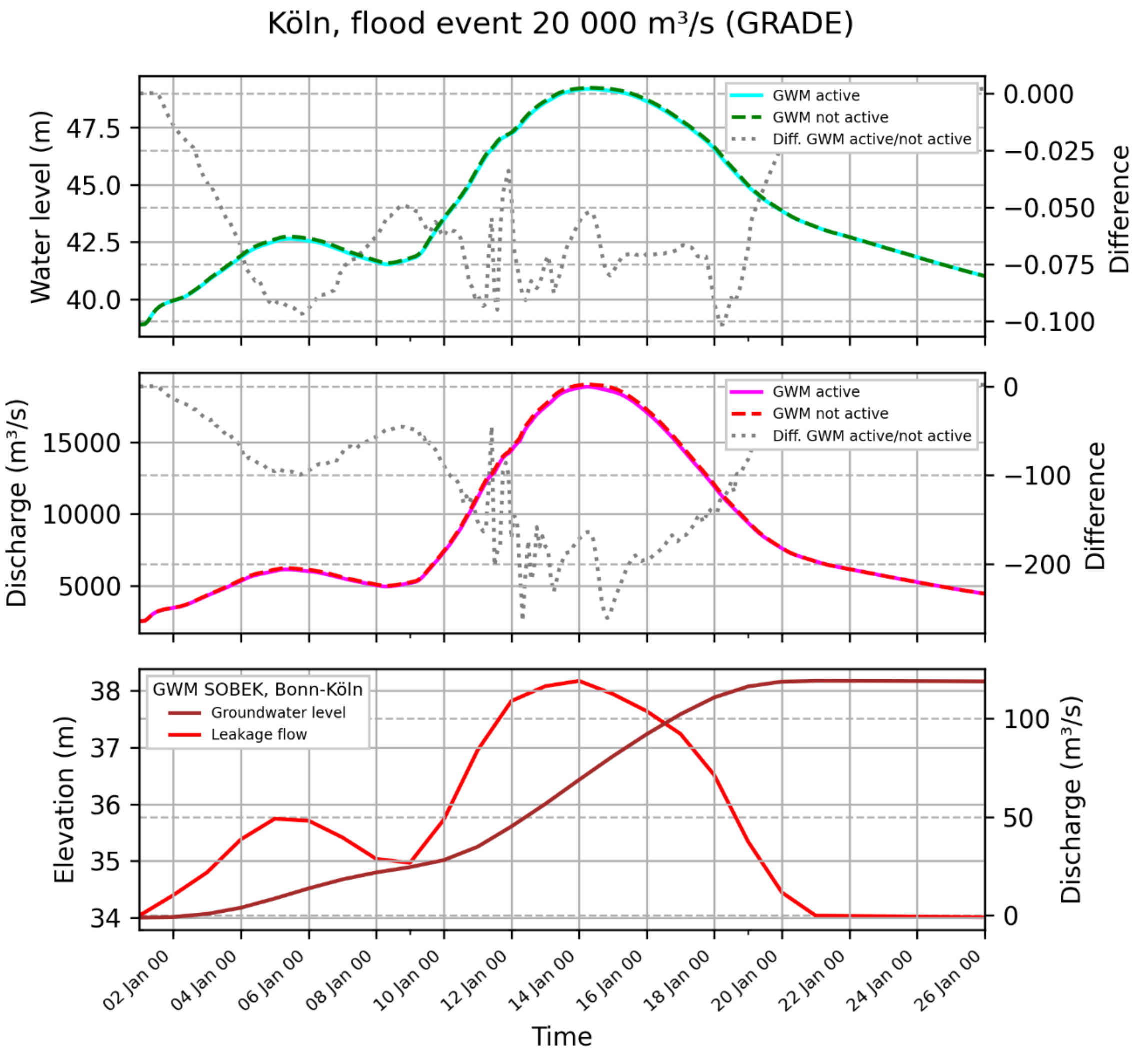

Figure 131 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

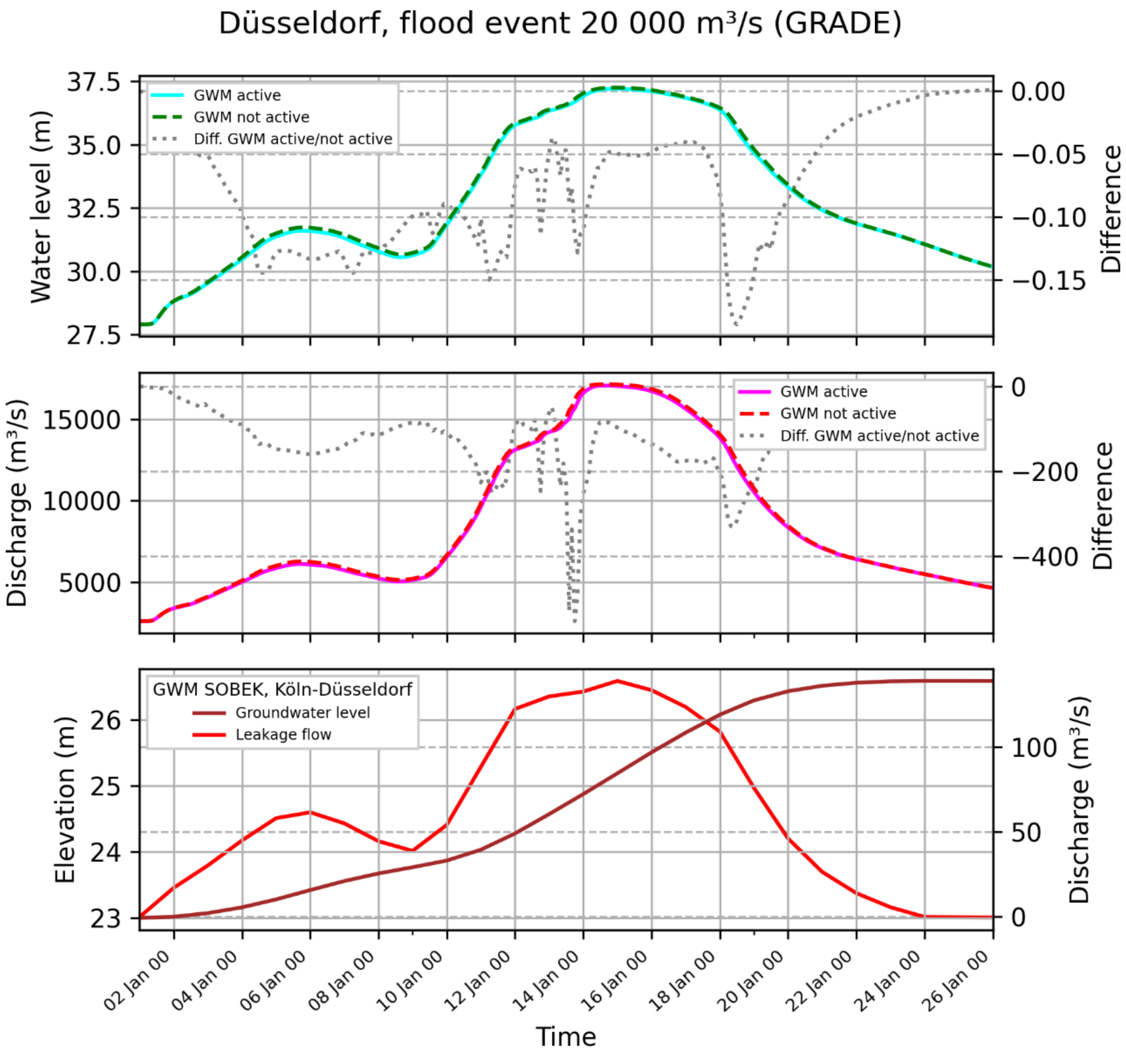

Figure 132 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

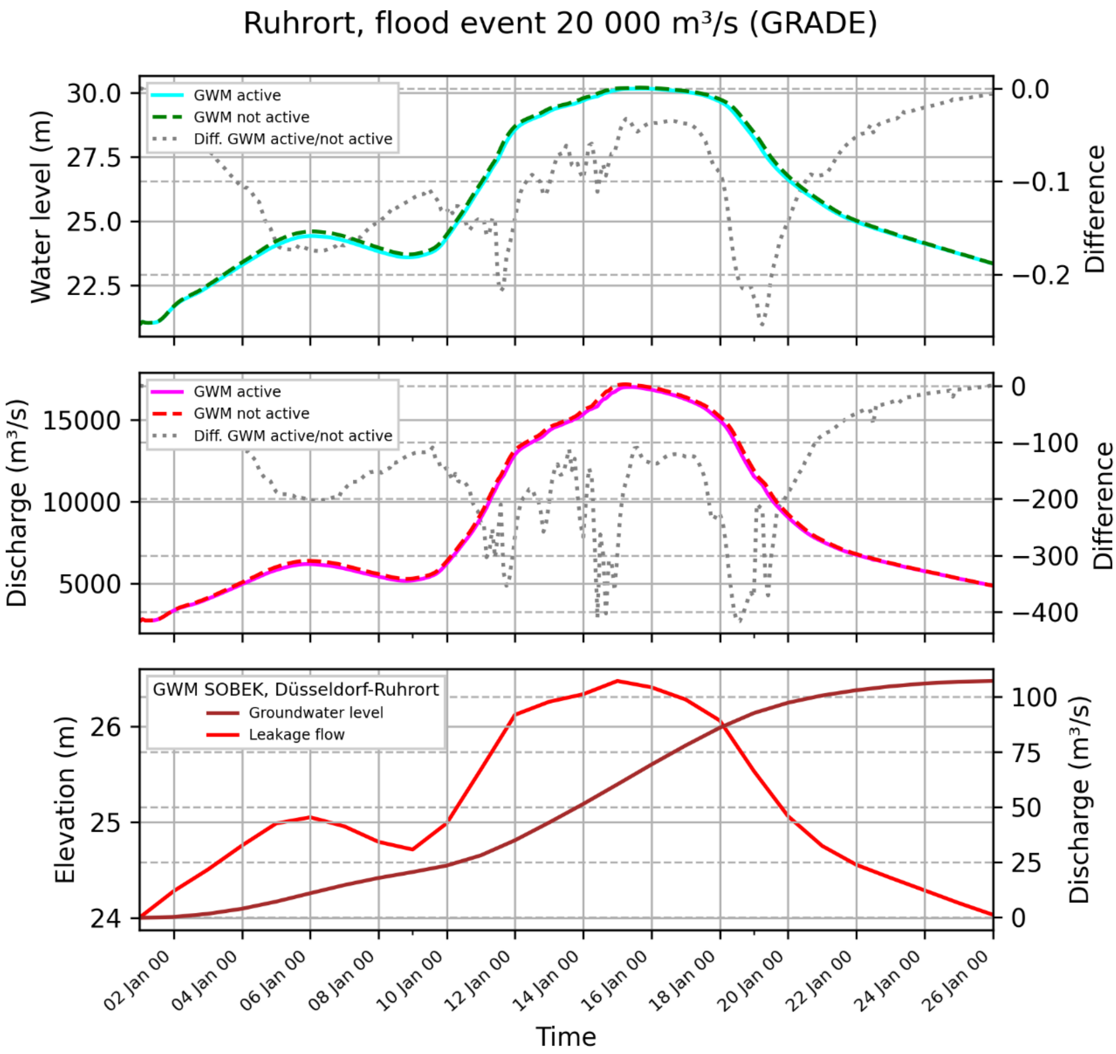

Figure 133 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

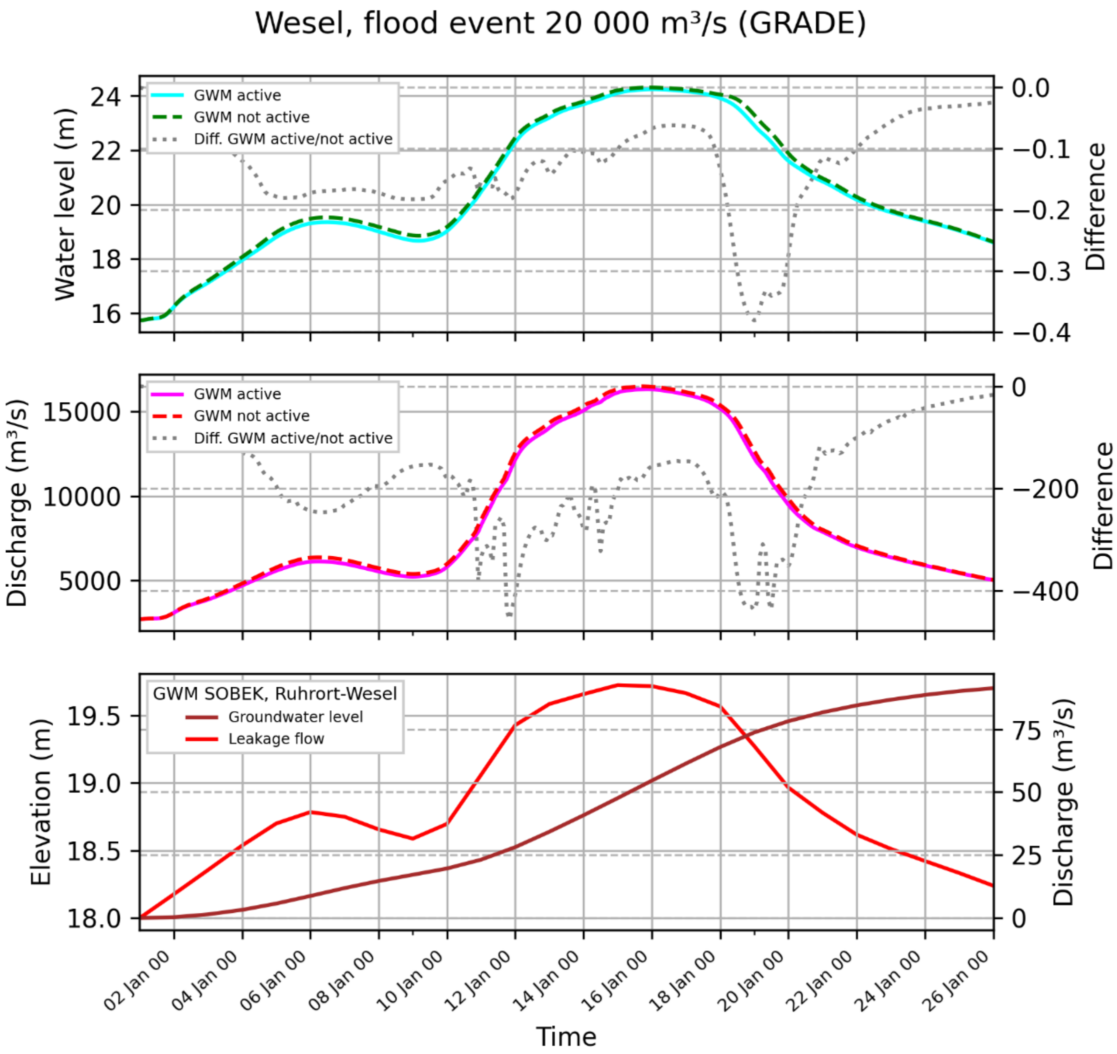

Figure 134 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

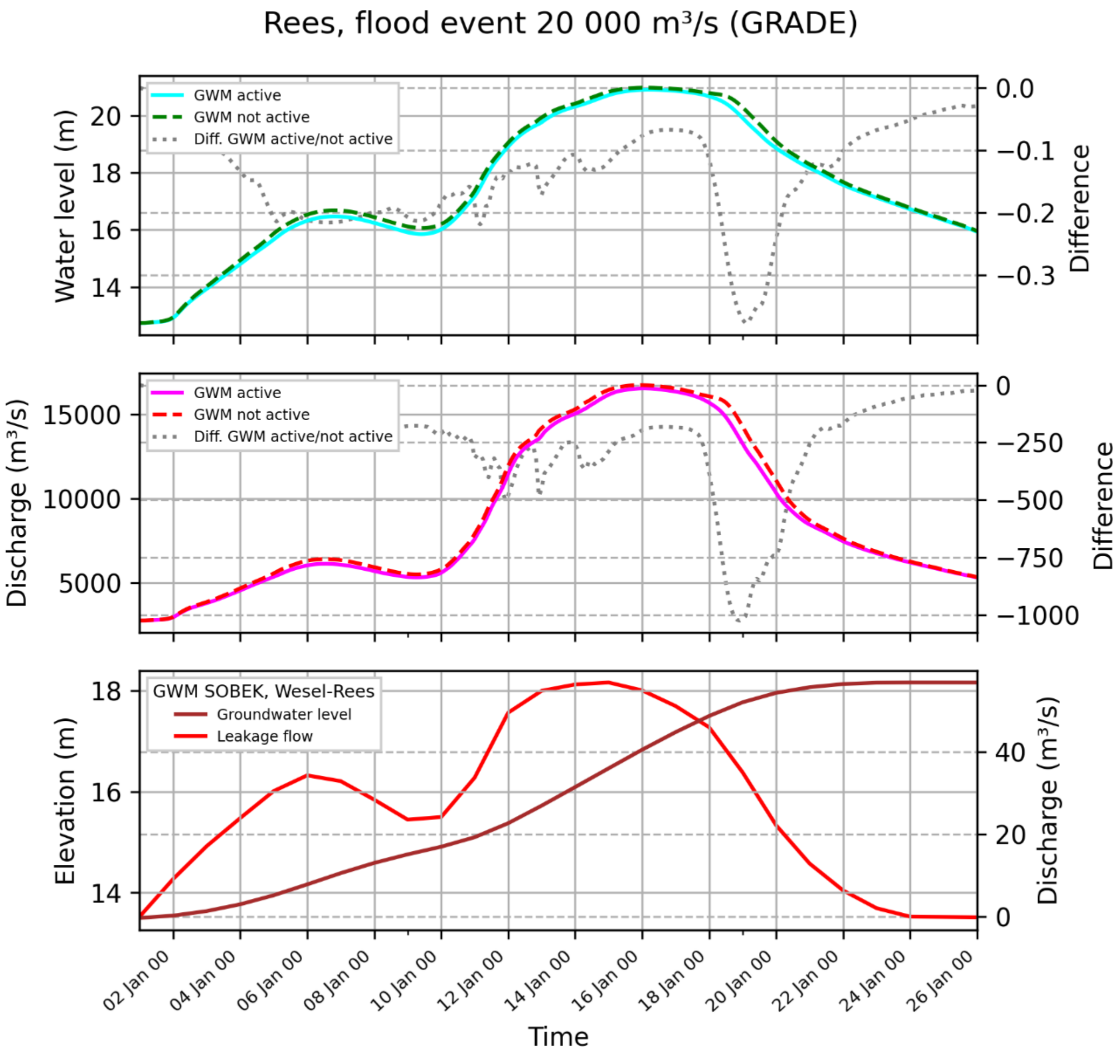

Figure 135 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

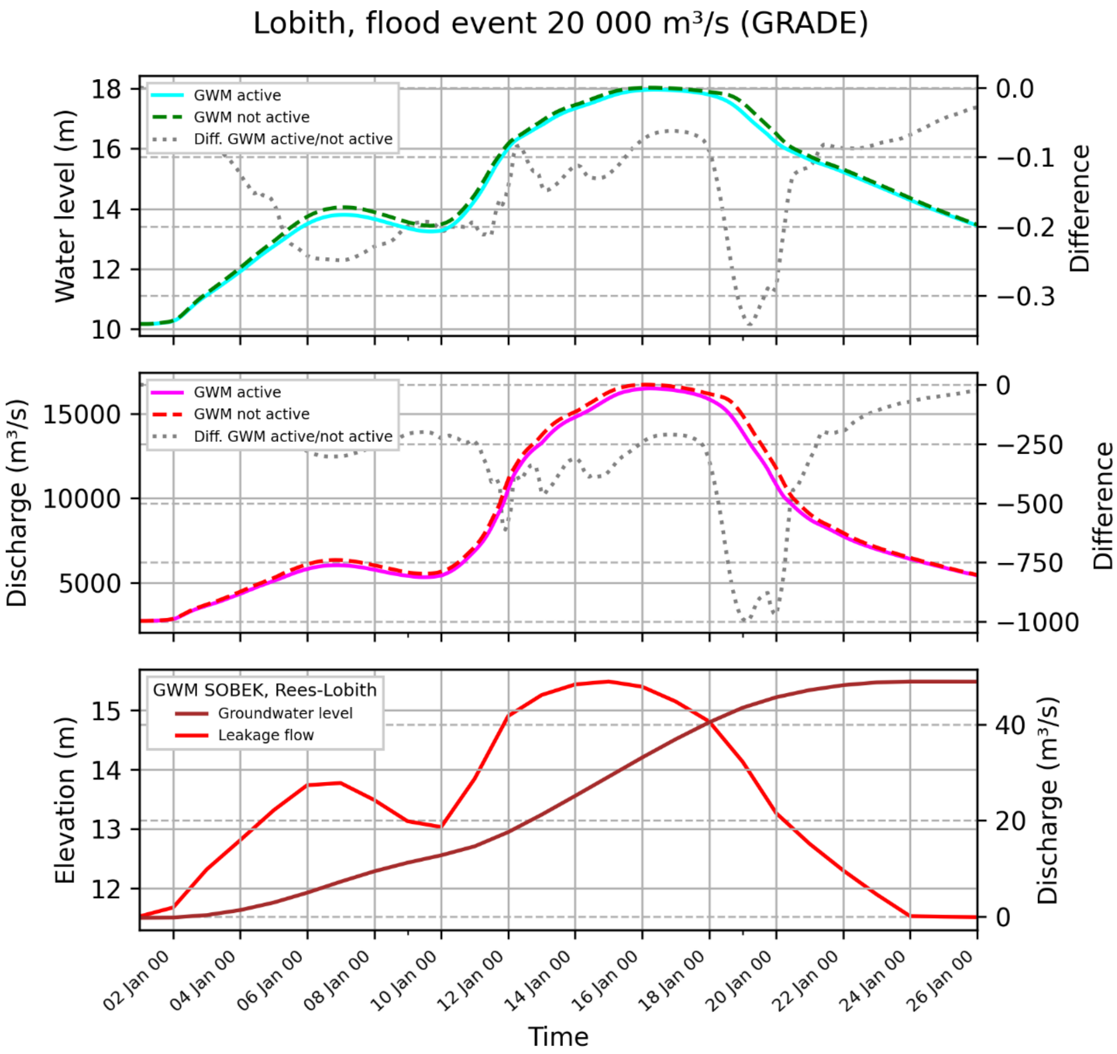

Figure 136 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 20 000 m³/s peak discharge at Andernach

B.4.3 Peak discharge of 30 000 m³/s at Andernach

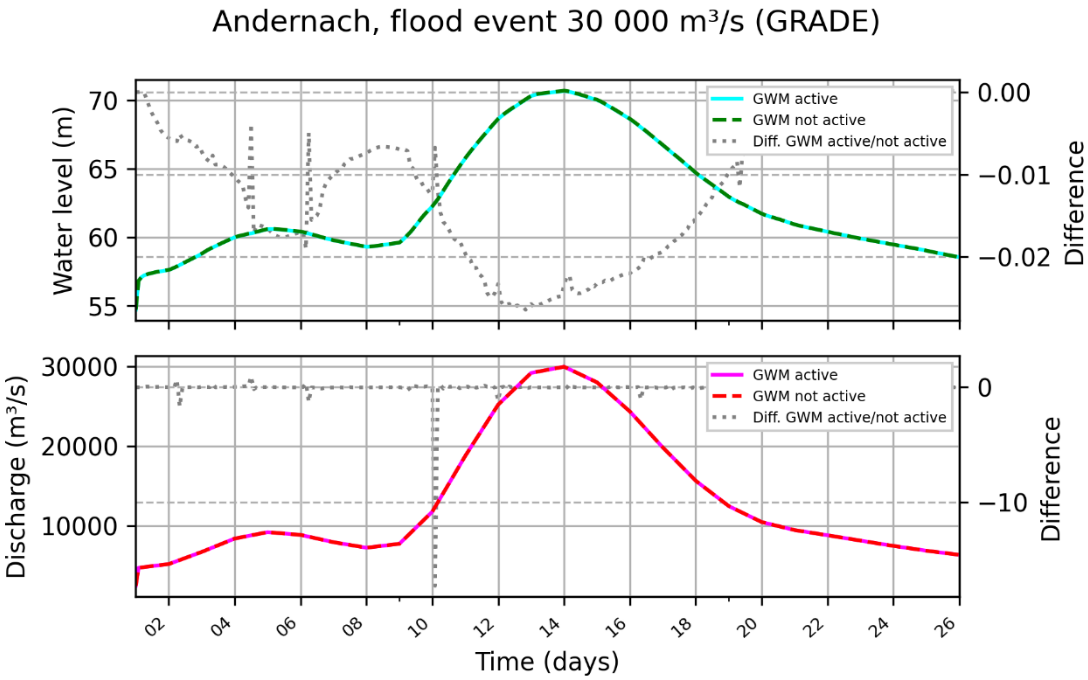

Figure 137 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Andernach, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

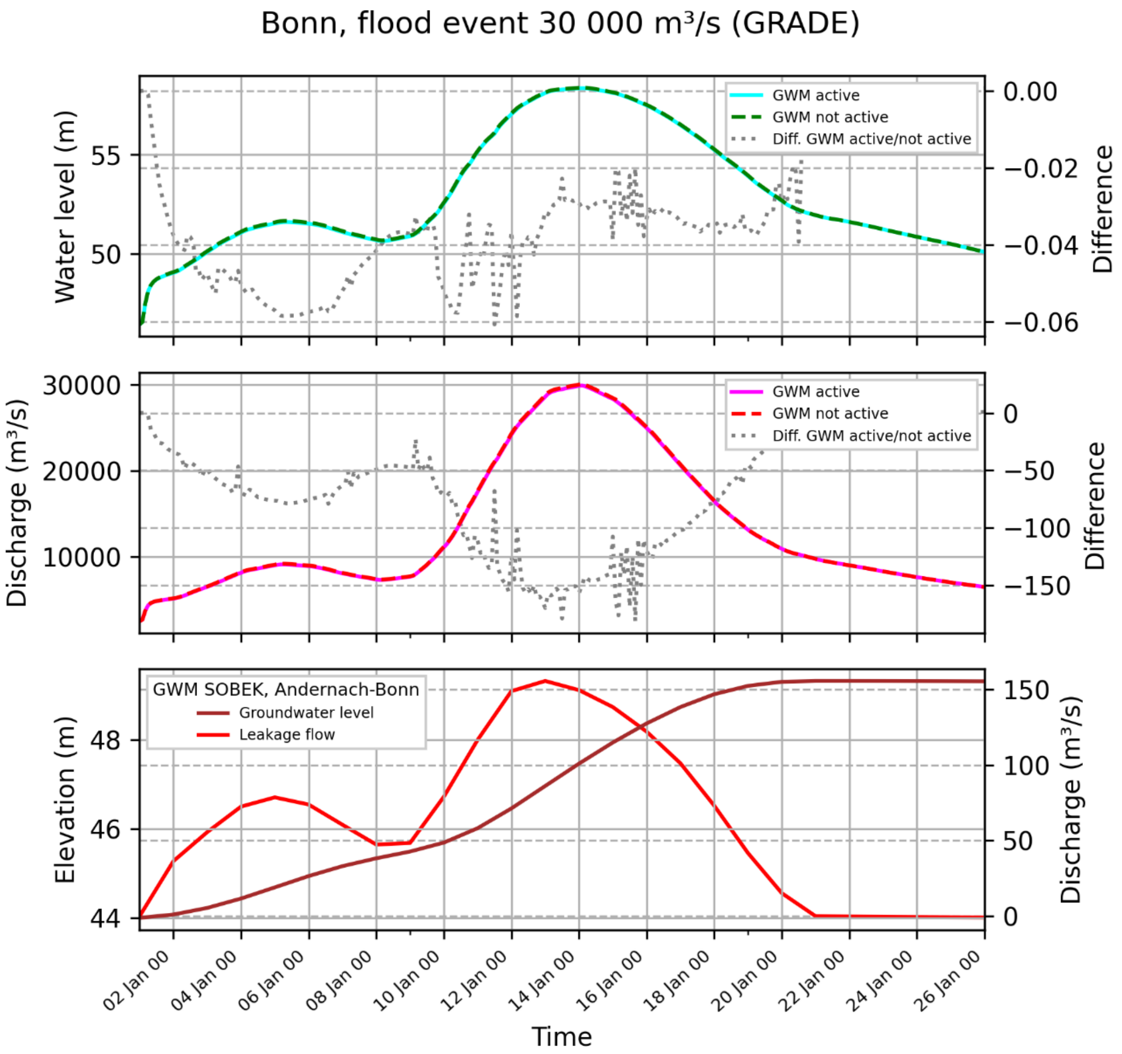

Figure 138 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Bonn, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

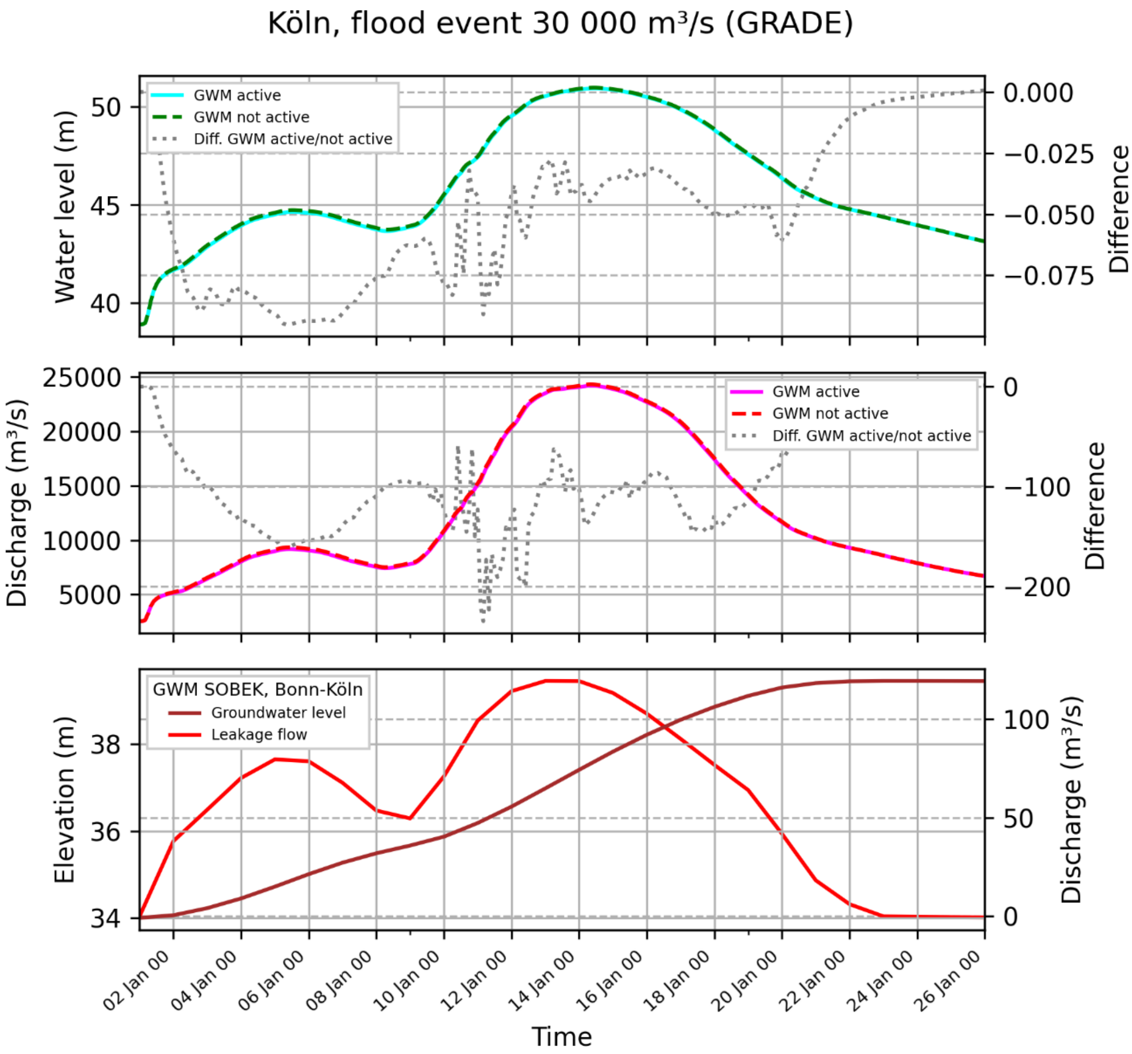

Figure 139 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Köln, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

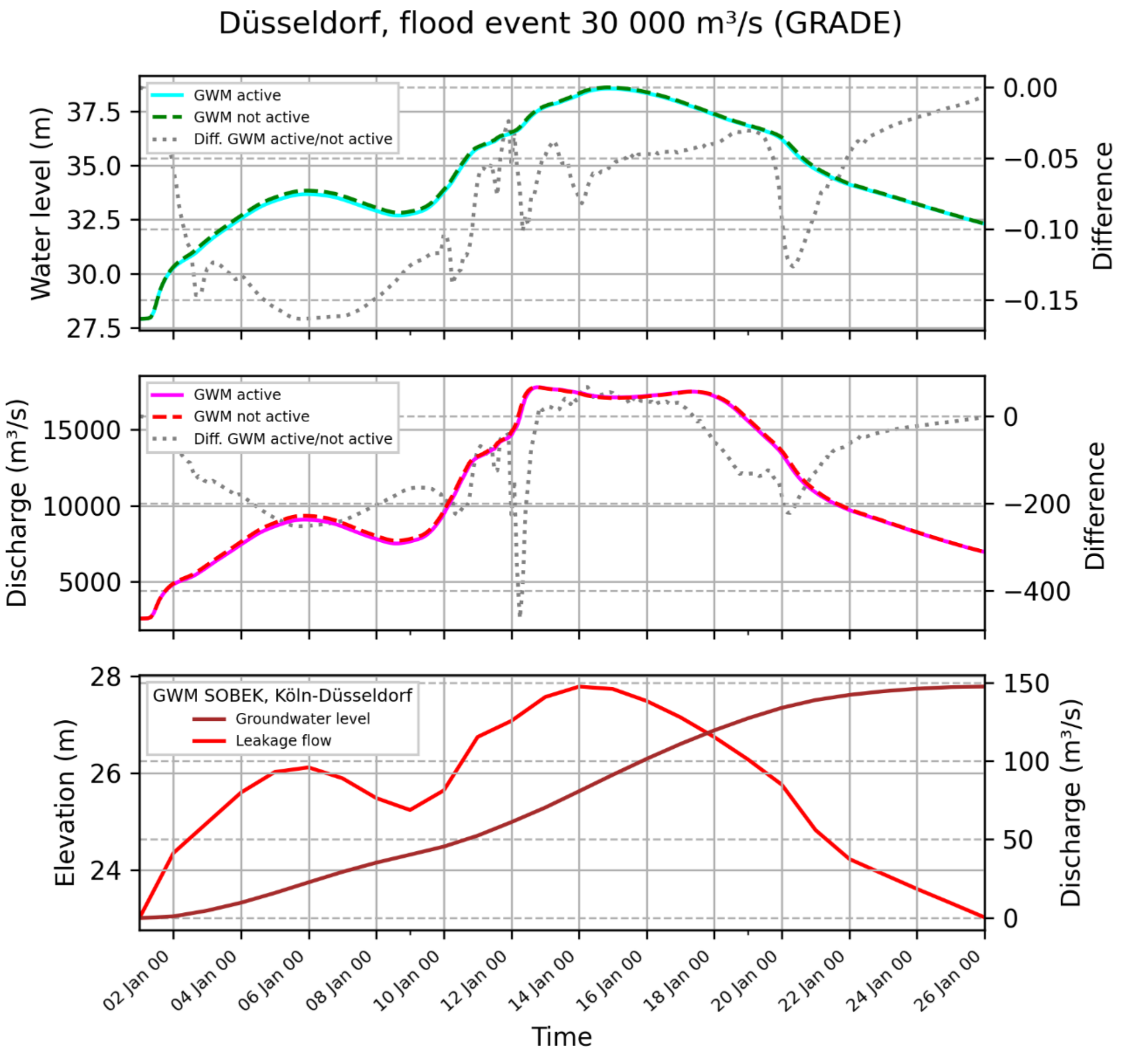

Figure 140 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Düsseldorf, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

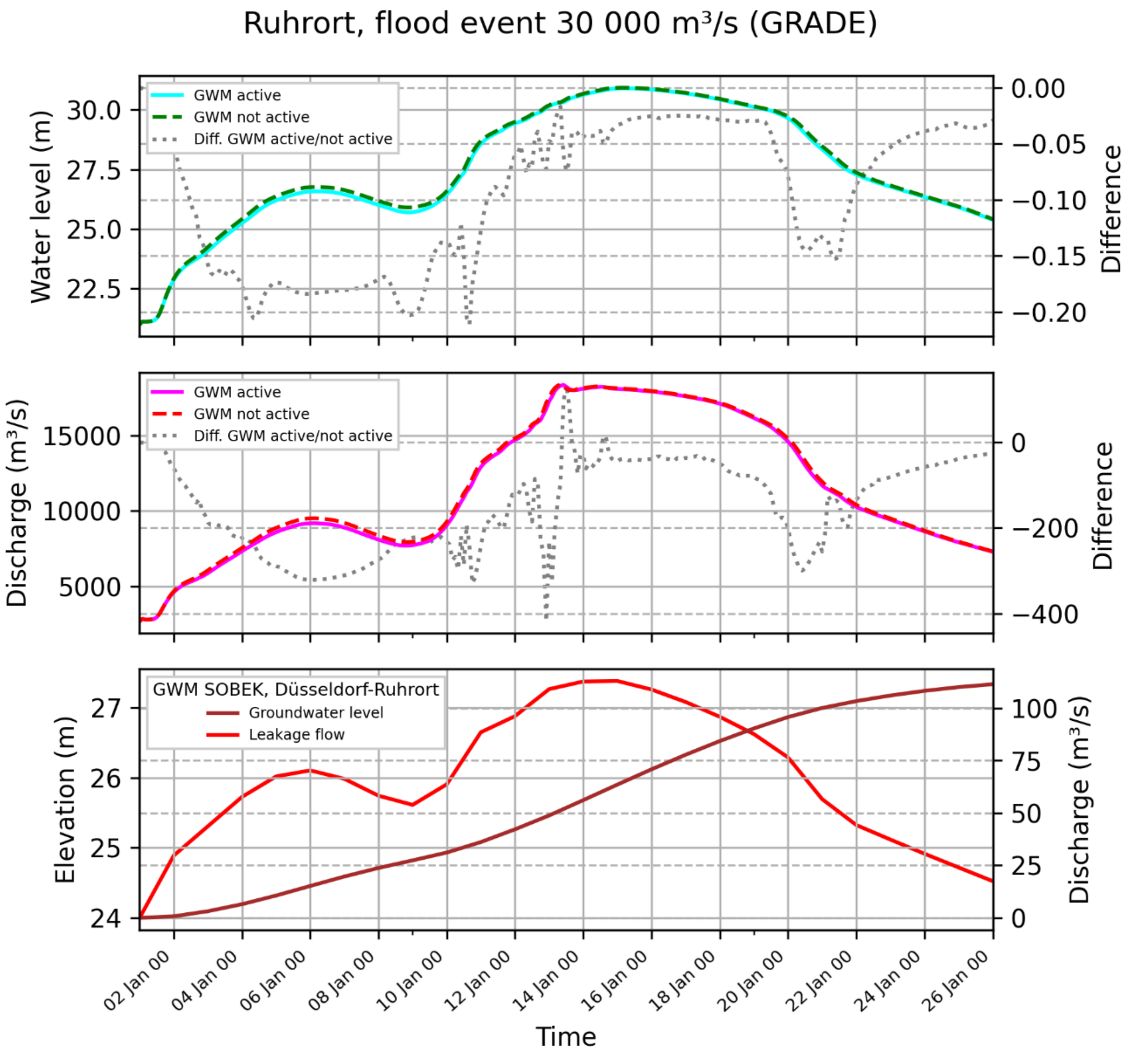

Figure 141 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Ruhrort, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

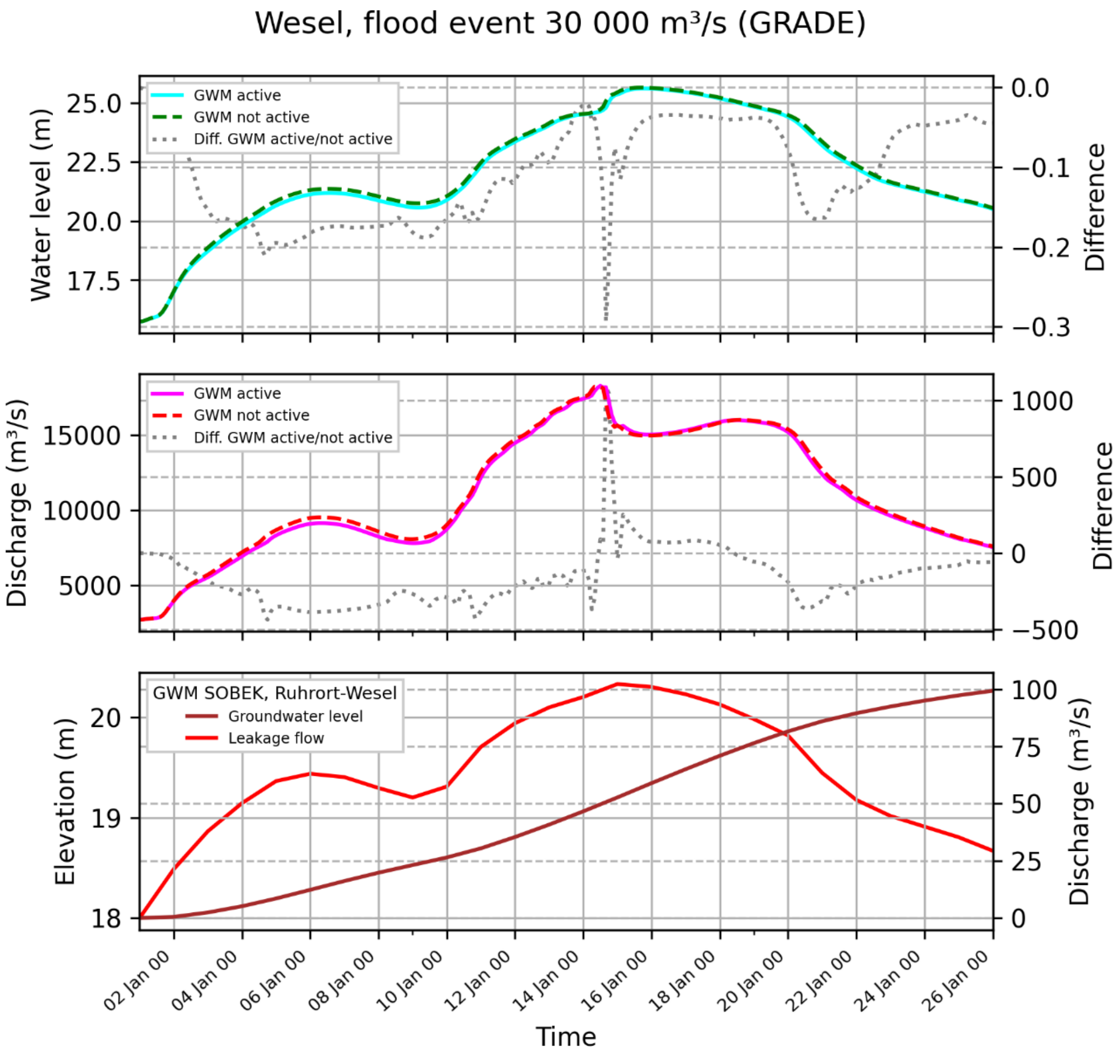

Figure 142 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Wesel, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

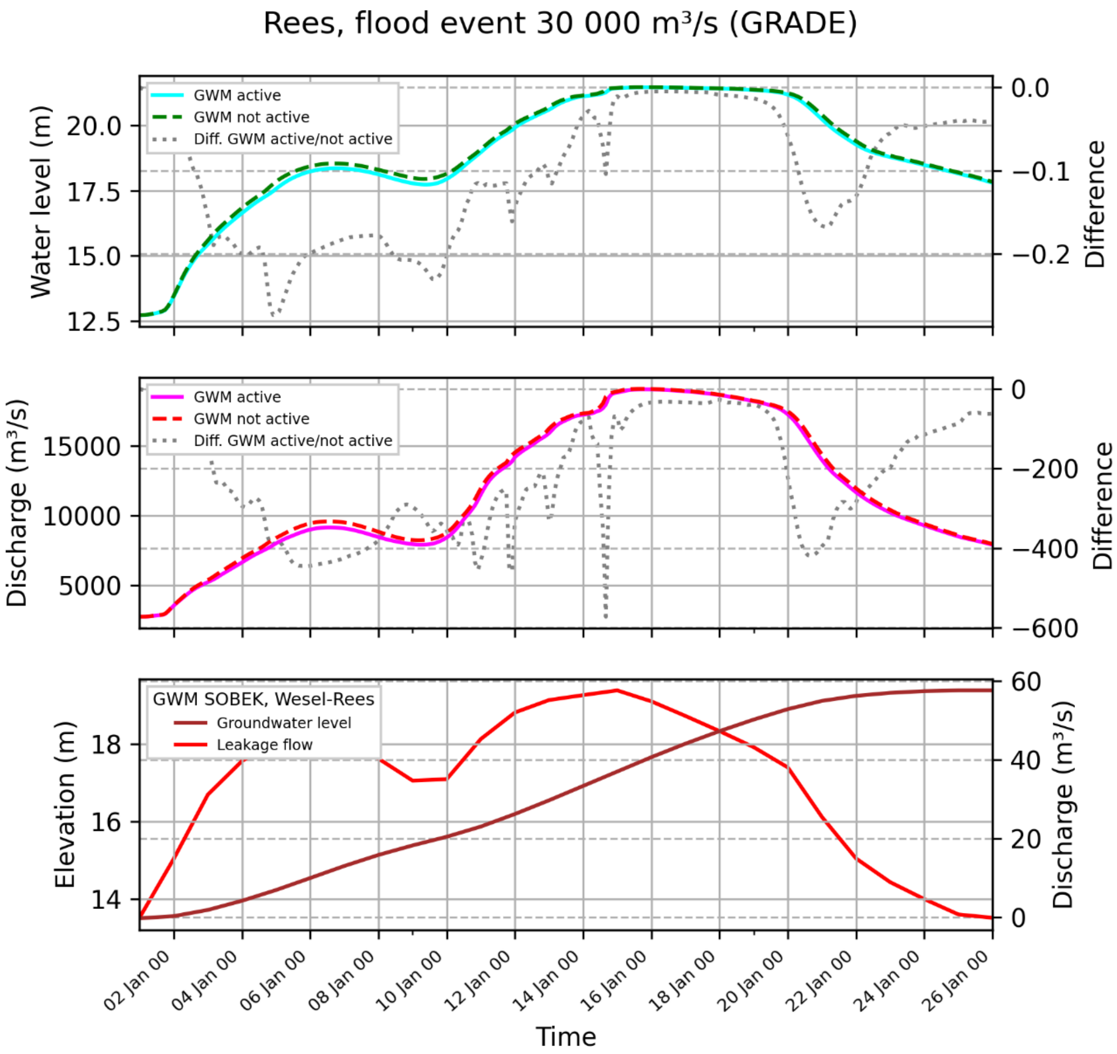

Figure 143 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Rees, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

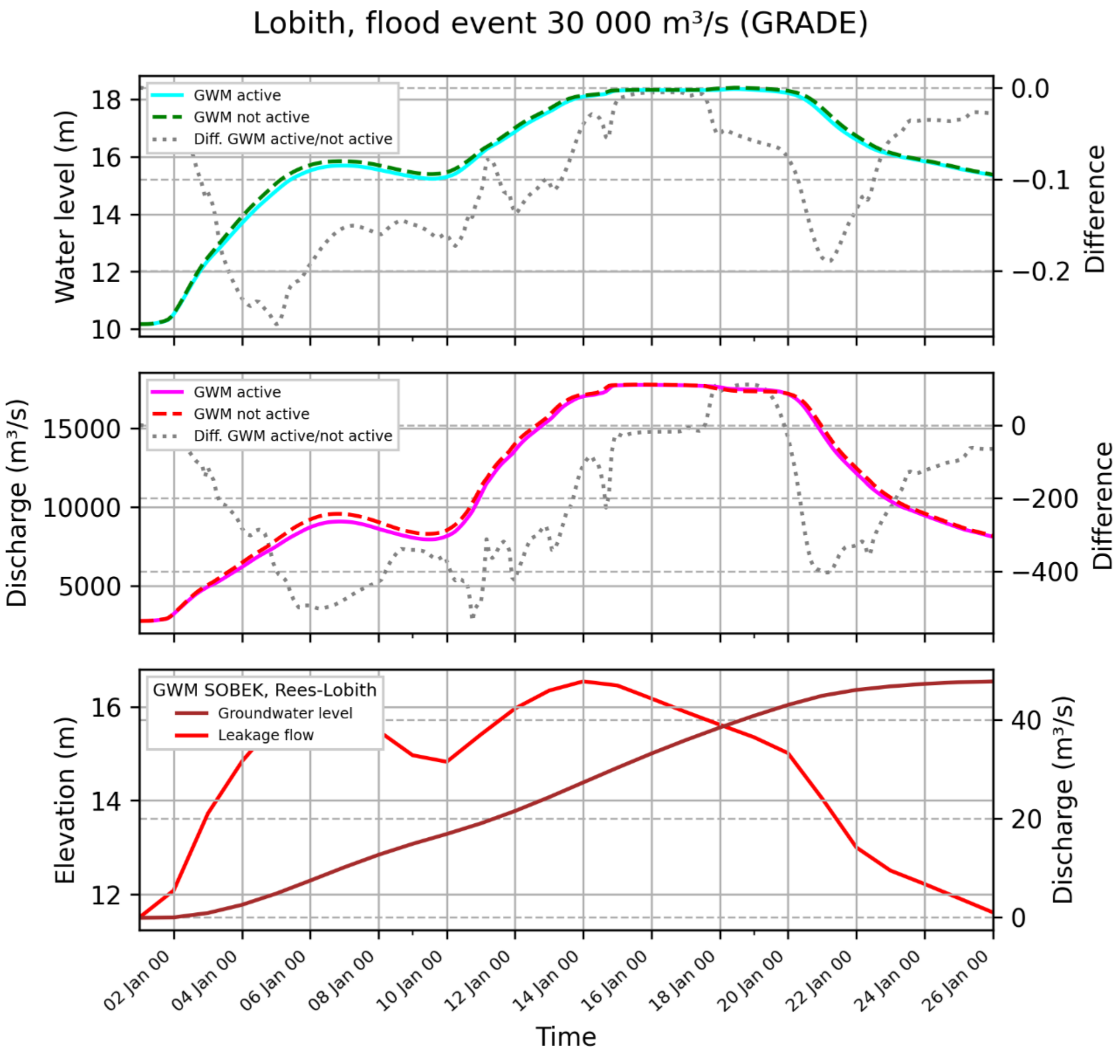

Figure 144 Comparison of water level and discharge from a simulation with and without groundwater module SOBEK for the gauging station Lobith, GRADE extreme event with 30 000 m³/s peak discharge at Andernach

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares

www.deltares.nl