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RIBASIM River basin simulation model of the Rhine – Volume 1 Main Report

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Summary

The possible impact of water consumption of various socio-economic sectors on low flows in the Rhine basin is already for several years one of the focus points for the International Commission for the Hydrology of the Rhine Basin (CHR). Since 2017 the CHR started to analyze the possible effects of socio-economic scenarios on the discharge of the Rhine, in the so-called Socio-Economic Scenarios for the Rhine (SES-Rhine) project. As part of this SES-Rhine project, in 2020 a water resources model of the Rhine river basin was developed. Th is planning tool allows for scenario analysis of future developments in the Rhine basin, combining water availability, water use and water distribution aspects. A first version has become available now with a base case of the present situation with the intention to improve it in the coming years.

The model development was triggered by the results of the previous study "*Integrated overview on the effects of socio-economic scenarios on the discharge of the Rhine river*" which was executed in 2019. The outcome of the study indicated that there is a large uncertainty in the impact of the actual and possible future water consumption by agriculture (irrigation) and energy production (cooling water) on the river regime (Ruijgh, 2019). In addition, it was recognized in this study that changes in reservoir management could significantly influence the distribution in time of the discharge of the Rhine river. In the 84th CHR-meeting in Dornbirn, October 2019, it was agreed to execute a follow up project, in which these topics are addressed.

The original plan for the project in 2020 was to conduct 4 workshops with experts in the river basin, but for several reasons, a.o. lack of capacity of experts in CHR countries due to Covid-19 situation and absence of significant new data and information, it was agreed to postpone the workshops and instead start to build a planning tool for scenario exploration. The activity was preceded by a literature research study by the end of 2019 (Passchier & Sperna Weiland, 2019).

The planning tool can be used to simulate the behavior of the Rhine Basin under various scenarios (climate, economic developments, interventions, etc.). In similar projects, the scenarios are commonly developed in consultation with the stakeholders in the policy domain and water system experts in the basin. The integration of provided data by the riparian countries, model simulation and scenario analysis will deliver new insights and increase our joint integrated knowledge about the Rhine Basin. The reliability of the model will grow each time more local knowledge and expertise will be transferred into the tool.

In 2020 two river basin simulation models have been setup for the Rhine River basin powered by the RIBASIM river basin modelling software. RIBASIM is a generic model package for simulating the behaviour of river basins under various hydrological conditions. The two Rhine models are:

1. The **Rhine001 model** was set up using the originally developed in Excel application of the SES Rhine project (Socio-Economic Scenarios) as a basis. The model covers the Rhine River basin from its source in Swiss till the border between Germany and the Netherlands and simulates 1 year in monthly time steps. No water storage is considered. The simulation cases reflect the reference case and 3 scenarios. The main purpose of this model was to faithfully reproduce the results of the Excel application and be able to compare the results with future more advanced applications;

2. The **Rhine002 model** has been developed as a detailed water demand and allocation model of the Rhine River basin starting off from open global datasets. All existing and potential water users and major water storage infrastructure like dams, reservoirs and natural lakes are considered. The hydrological boundaries (runoff, rainfall, evaporation) are generated by a rainfall-runoff model (wflow, which is a detailed model for the whole Rhine river basin from its source in Swiss till the North Sea including the Netherlands), but in principle this model can be replaced by any other hydrological timeseries or simulation results of other models.
   The Rhine 002 model simulates multiple year time series with decade time step. A first version has become available now with a base case of the present situation with the intention to improve it in the coming years.

A comparison has been made between the original (Excel spreadsheet / Rhine001) model and the new Rhine 002 model. A first scenario analysis has been carried out to illustrate the potential use of the application. Follow-up activities will first focus on further data collection, using the model as a guideline, and calibration of the model with the aid of local experts.

It is recommended to develop these models further next year based on the guiding principles of participative approach, integration and exchange of data and co-creation of knowledge.

This report has been divided into two parts. The Volume 1 (Main Report) gives a general overview of the model and its application. More details on the model layout and the detailed water demand assessment is given in Volume 2 (Annexes).

Contents

1 CHR's umbrella course on Socio-Economic Scenarios for the Rhine River Basin

1.1 Background

The possible impact of water consumption of various socio-economic sectors on low flows in the Rhine basin is already for several years one of the focus points for the International Commission for the Hydrology of the Rhine Basin (CHR). In March 26 and 27, 2014 a first Seminar was organized by CHR in Bregenz on the socio-economic influences on the discharge of the Rhine river. As a follow-up, an expert workshop was organized in Koblenz on March 30 and 31, 2017 on socio-economic scenarios, with focus on land-use, agriculture, public water supply and industry. A year later (March 2018) a similar expert workshop was organized in Koblenz focusing on the water use and consumption in the energy sector (lignite mining and reservoir management). In addition, CHR organized a seminar on Low flows in the Rhine catchment in Basel, on September 20 and 21, 2017.

Based on the results of the workshops and seminars, Deltares in close cooperation with BfG prepared for CHR an "*Integrated Overview of the effects of various Socio-Economic sectors and Scenarios on the discharge of the Rhine*": the SES-Rhine in project 2018-2019. The (draft) report of this project was discussed during the 83rd CHR-meeting in Nürnburg, March 2019. Figure 1-1 shows the estimated water consumption in the Rhine river basin for several scenarios.

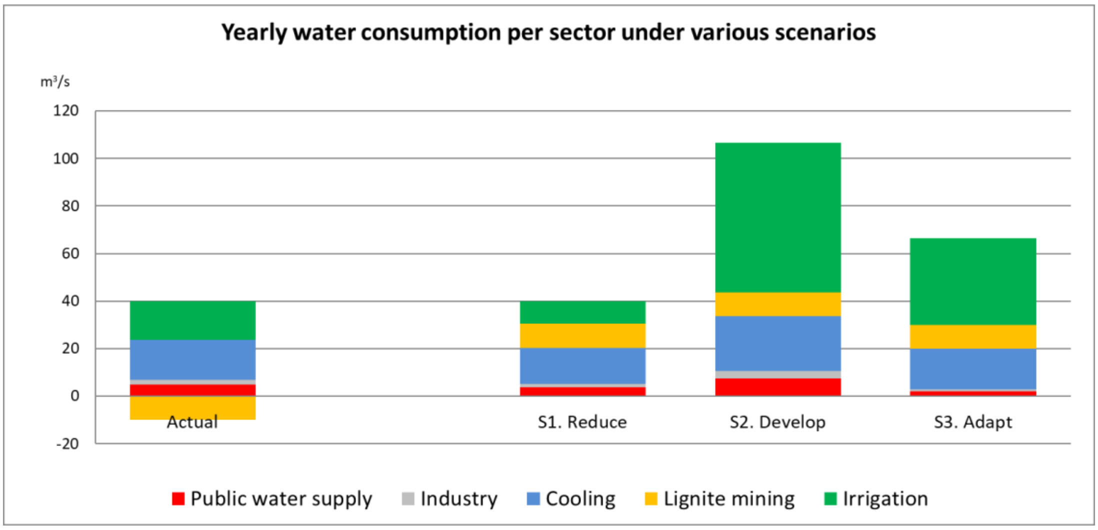

Figure 1-1 Estimated yearly consumption per sector in the Rhine river basin under various scenarios (Ruijgh, 2019)

In addition to the activities of CHR, ongoing national projects in the CHR-member states focus on the water use and consumption by the various socio-economic sectors in relation to low-flows. For instance, in Germany at BfG the "*WaWi2050*" project is being followed-up by "*Sozio-Hydrologie 2050*" project (*Extended modelling approaches for determining anthropologic and quasi-natural changes of water availability in catchments of major rivers in Germany*). In Switzerland the Hydra-CH2018 project (focusing on climate change) provides additional information to NRP61 Sustainable Water management (from 2016). In addition, Switzerland started recently a project to develop socio-economic scenarios for the future for the country. In Austria the TU-Wien is implementing a research project on socio-hydrology, and in the Netherlands the water demands and water allocation are studied in the Deltaprogram on Fresh Water Supply.

1.2 This CHR SES project in 2019-2020

The results of the "*Integrated Overview on the effects of socio-economic scenarios on the discharge of the Rhine river*" (SES-Rhine project in 2018-2019) indicate that our present knowledge on the actual and possible future water consumption by agriculture (irrigation) and energy production (cooling water) presents the largest uncertainty (Ruijgh, 2019) in the assessment of the impact on the low flows. In addition, it is recognized in the study that changes in reservoir management could significantly influence the distribution in time of the discharge of the Rhine river. As part of the SES-Rhine project, an Excel water balance model was developed of the Rhine basin that allowed for simple simulations of scenarios.

During the 84th CHR-meeting in Dornbirn, October 2019, it was agreed to implement a follow up project in the KHR/CHR - *Umbrella course on Socio-economic scenarios*, focusing specifically on these knowledge gaps:

- water consumption by agriculture (irrigation);
- water consumption by energy production (cooling water), as well as;
- (re)distribution in time of discharge due to changes in reservoir management.

The new activity originally distinguished the following three phases in 2019-2020:

- Literature study – as a preparation for the workshops;
- 3 Workshops with experts on the above-mentioned topics, with the aim to collect results of the identified ongoing research groups (see section 1.1) within the various CHR-member states that are currently working on these subjects;
- 1 Workshop for integration and updating of the Integrated Overview;
- Reporting on the activities.

However, in an early stage, after submission of the literature study report (Passchier & Sperna Weiland, 2019) and after data inquiries by email to the CHR representatives, it became apparent that an adjustment was necessary to the original work plan of the project.

The reason was that although the project team (Deltares & BfG) has received valuable information by email from contact persons from various member states, it was felt by both the project team and the CHR project coordinator that countries struggle to allocate capacity and bring significant new data and information forward to the project that has not been shared yet. Besides, due to Covid-19 situation, travelling to workshops was suspended for the time being. This issue was also discussed in the Steering Group meeting in October 2020.

New: Introducing the Planning tool for Scenario Analysis

In consultation with the CHR secretariat it was agreed to adjust the approach for the SES project in 2020 and substitute the workshops by an activity that would both streamline the collection of new data and bring forward an instrument that would support the scenario analyses, viz. to set up of a planning tool for the Rhine basin. The project team started the development of a planning tool for the entire Rhine basin using the *RIver BAsin SIMulation (RIBASIM*) water demand and water resources modelling software, assuming that it will make the data collection much more focused and structured, and enable a much stronger interaction with the various organizations, as soon as a preliminary version of the model (showcase) has become available. Also, CHR representatives suggested that modelling would be the way forward to quantify the influence of irrigation and reservoir operation on the river flow, since this cannot be done by literature research alone. At last, this step was also envisioned later in the SES project but implemented earlier now (see Section 1.4 and Figure 1-2).

1.3 Output of the CHR SES project in 2019-2020

The Chapters 2 to 6 of this report present the set-up of the first version of the planning tool, the initial analysis conducted with the tool and insights gathered this year. The tool, powered by RIBASIM, can compute the changed river discharge for various climate change scenarios and scenarios on water demand, energy production, infrastructure development (e.g. reservoirs) and operation, and basin management. The river runoff time series computed by hydrological models (such as LARSIM, wflow, etc.) are input to the RIBASIM model. Various demand groups, such as public water supply, industry, cooling water and irrigated agriculture, will put a constraint on the water availability. The introduction of this tool is a step up from the spreadsheet (Excel) approach that was followed in the previous stage of the SES-course (in 2018/2019).

In addition, at the end of 2019, a literature study report was submitted to the CHR (Passchier & Sperna Weiland, 2019). The literature study together with the previous Excel model spreadsheet were the starting point for the model development.

During this stage of the project, two river basin simulation models have been setup for the Rhine River basin using the RIBASIM software. The two Rhine models developed are:

1. The **Rhine001 model**, which aims at mimicking the originally developed model in Excel in the previous phase of the SES course. The model covers the Rhine River basin from its source in Swiss till the border between Germany and the Netherlands and simulates 1 year in monthly time steps. No water storage is considered. The simulation case includes four scenarios: the current situation and three development scenarios (Reduce case, Develop case and Adapt case);
2. The **Rhine002 model,** an entirely new model which has been developed making use of mainly open global datasets. The hydrological boundaries (runoff, rainfall, evaporation) are generated in a rainfall-runoff model based on the Wflow software, but this software is not part of the model and the hydrology can be generated by any other hydrological model of the basin, like e.g. Larsim. The Rhine 002 model is a detailed model for the whole Rhine river basin from its source in Swiss till the North Sea including the Netherlands. The model is able to simulate multiple year time series with a decade time step and an internal computational time step of 1 day. All existing and potential water users and major water storage infrastructure like dams, reservoirs and natural lakes are included in the model schematization. Keeping the three knowledge gaps in mind (see Section 1.2) focus was on drinking and industrial water use (including cooling water), irrigated agricultural water use and reservoir management. This first version of a more detailed water demand and allocation model of the Rhine River basin has been setup with the intention to improve it in the coming years. The present base case has been setup and a scenario analysis has been carried out to illustrate the potential use.

1.4 Outlook Planning tool for scenario analysis

The planning tool can be used to simulate the behavior of the Rhine Basin under various scenarios (climate, economic developments, interventions, etc.). In similar projects, the scenarios are commonly developed in consultation with the stakeholders in the policy domain and water system experts in the basin. The integration of provided data by the riparian countries, model simulation and scenario analysis can deliver new insights and increase our joint integrated knowledge about the Rhine Basin. Guiding principles for this will be: participative approach, integration and exchange of data and co-create knowledge.

It is the ambition of the project team and the CHR secretariat to share this first draft version of the tool, including the base case situation, produced in this project, including the RIBASIM software, with all country representatives. Upon request, we can provide an online demonstration and/or training in its application in a next phase of the SES project, so countries can explore and play with the tool themselves.

All Rhine Basin countries are encouraged to connect to the tool e.g. with their own hydrological model output (e.g. Larsim, wflow, HBV-96, etc) in case they have such models, or with better estimates of water demand, land use, crop type etc. when those become available in the future (in Austria and Switzerland institutions are working on socio-economic aspects in 2020 and 2021) and underlying datasets that can be incorporated in the model to stimulate (re-)use of the same national to local datasets. The project team is open to discuss this and make the connection or integration.

Concrete next steps could be:

- Presenting and discussing the output of this activity in the Steering Group in online meeting in January 2021. This is the formal closure of the current project;
- Deltares could provide a Video Conference training on the development and application of the models to stakeholders and end-users to share knowledge about the planning tool. This would also allow for an exchange of ideas on the application and improvements of the model. After the meeting we can hand over the tool, software, licenses etc. If Covid-19 situation permits, this could also be a 'live' workshop with experts in e.g. Koblenz;
- Make a detailed overview of the update of the RIBASIM models: review the data that is in the current model, which data is needed, who to involve, time schedule, etc. Improve the present model by shifting from purely open global datasets to a combination with national and local datasets, based modelling by engaging national expert representatives;
- Discuss the possibilities to use alternative hydrological inflow series from existing calibrated hydrological models of the Rhine basin, such as the Larsim model;
- Initial scenarios and model analysis, by defining a number of future cases that will be run with the model and will be analyzed. The scenarios could relate to climate change and/or economic development, incl. planned new infrastructure. Aim of these runs are to show the potential of this model to the CHR and others and discuss meaning full decision indicators, water state indicators, scenarios. More in-depth scenarios should be modelled in an extensive participatory process (see also next bullet);
- Explore the scientific based development of scenarios for water use in the river basin and develop a project plan for this;
- Make the connection with the course of Rhein Blick II and ASG II (see also Figure 1-2);
- Draft initial dashboard for communicating results; what are meaningful indicators in reference to the policy making and decision-making process.

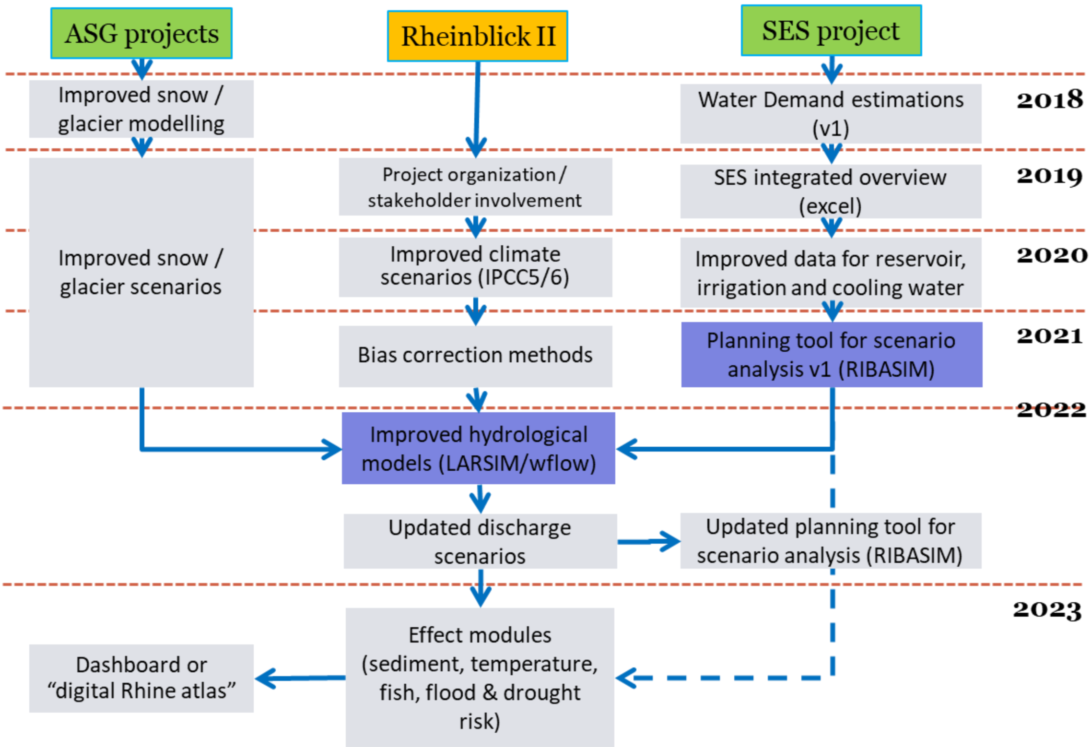

Figure 1-2 The three courses of the CHR

2 Introduction Rhine River Basin modelling

2.1 Model Simulation for the Rhine River Basin

For the setup of the Rhine river basin planning tool, use is made of the RIBASIM software. RIBASIM is a generic modelling software package simulating the water demand and allocation, the flow composition and the water quality in river basins under various hydrological conditions. The model package is a flexible tool linking surface and groundwater sources at various locations with the water user demands like for irrigation, domestic, municipality, industry, environment, aquaculture, navigation, inter-basin transfer and hydro-power, while accounting for infrastructure operation rules, water management options and water allocation priorities. RIBASIM enables the evaluation of hydrological, climate change, socio-economic and agriculture scenarios and combination of measures (strategies) related to physical infrastructure, water demands, surface and groundwater supply, and operational water management. The results are presented on maps, charts and reports and consists of the supply reliability for the various water users, energy production and consumption, water balances on various spatial (from field to basin) and temporal levels (simulation time step, annual, whole simulation period), reservoir behaviour over time, crop yield and crop production costs, water quality parameters, etc.

2.2 Model applications Rhine 001 and Rhine 002

Two river basin simulation models have been setup for the Rhine River basin powered by the RIBASIM modelling software, see Figure 2-1. The two Rhine models are:

1. The **Rhine001 model** which was originally developed in Excel in the SES Rhine project (Socio-Economic Scenarios) and has been converted to RIBASIM. Instead of an Excel spreadsheet interface it has the RIBASIM interface consisting of a user-friendly, graphical map-based interface, simulation case management and analysis tools. This model was developed with the sole purpose of checking whether the RIBASIM application produces the same results as the original spreadsheet;
2. The **Rhine002.model,** which has been developed based on open global datasets and in which the combination of the rainfall-runoff Wflow and the RIBASIM model is used for the whole Rhine river basin, including the Netherlands.

The differences between the Rhine001 and Rhine002 model are summarized in Table 2-1 .

Table 2-1 Differences between Rhine001 and Rhine002 models

Rhine001 model	Rhine002 model
Based on original Excel application	Newly developed
Excel spreadsheet user interface	RIBASIM interface consisting of a user-friendly, graphical map-based interface, simulation case management and analysis tools
Covers the whole Rhine River basin including the Netherlands in more detail	Covers the whole Rhine River basin, including the Netherlands, in more detail
Does not consider water storage infrastructure	Includes all major natural lakes, dams and reservoirs
Model is difficult to extend	Model is easily extendable
Simulates on monthly time step	Simulates on decade (10 daily) timestep with an internal computational time step of 1 day
Simulates only 1 year	Simulates multiple year time series

Rhine001 model	Rhine002 model
Irrigation demand is explicitly specified per month	Irrigation demand is computed in DelftAGRI (component of RIBASIM) based on meteorological data, crop and soil characteristics, crop plan, agricultural and irrigation practise
Runoff, snow melt and glacier melt annual time series are specified explicitly	The runoff, rainfall and evaporation time series are generated and prepared with the external rainfall-runoff model Wflow

This report starts with a short description of the RIBASIM modelling software (Chapter 3). Next the Rhine001 and Rhine002 models are described (Chapters 4 and 5). Technical details on the applications are provided in the Volume 2 (Annexes).

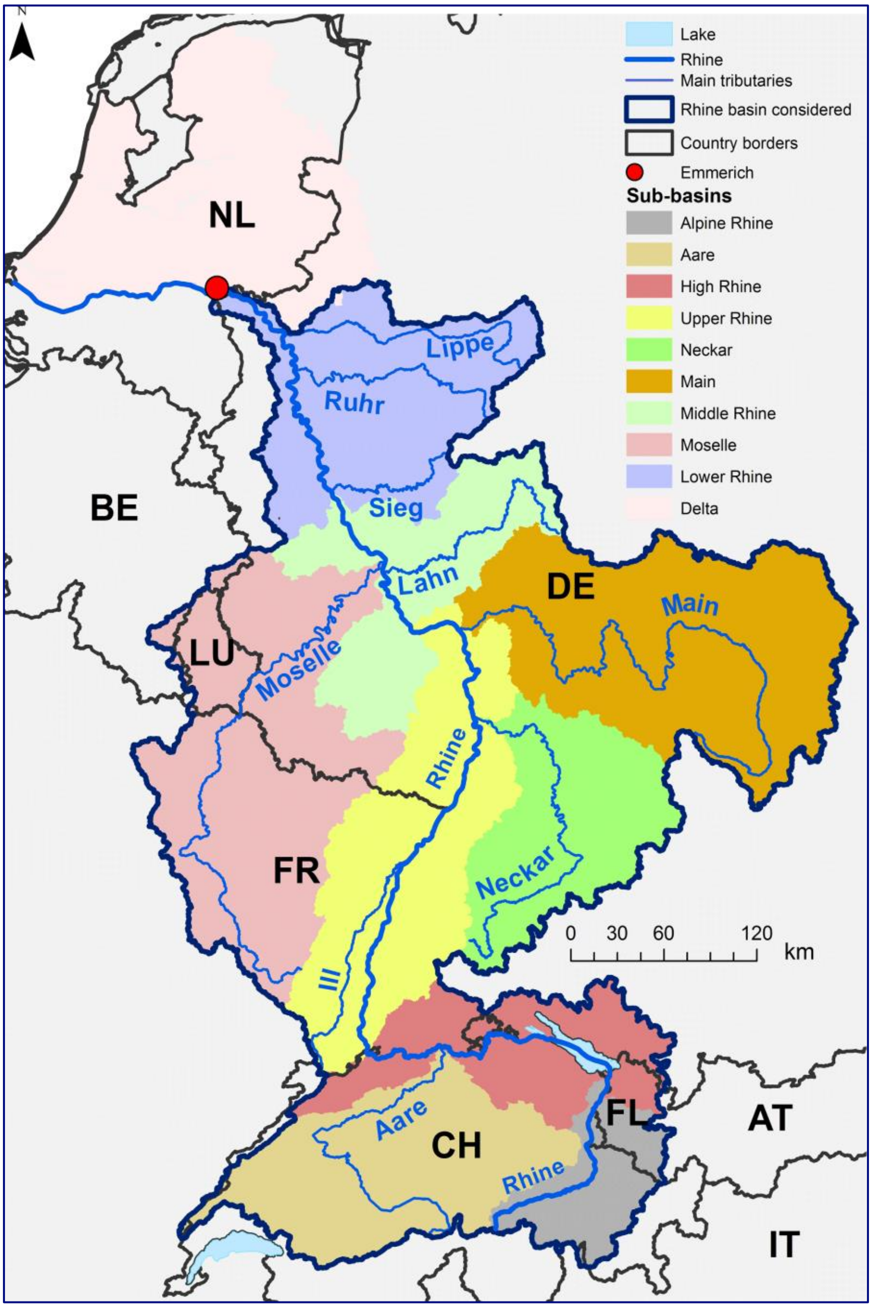

Figure 2-1 The Rhine river basin and its sub-basins

3 River Basin Simulation Model RIBASIM

3.1 Introduction

An integrated approach to the water system and its surroundings is the basis for long-term, sustainable management of environment. Multi sector planning to allocate scarce resources at the river basin level is increasingly needed in the water sector, as water users and governmental agencies become more aware of the trade-offs occurring between quantity, quality, costs and reliability. The RIBASIM (RIver BAsin SIMulation) model package provides an effective tool to support the process of planning and resource analysis. Since 1985 RIBASIM has been applied in more than 30 countries world-wide and is used by a wide range of national and regional agencies (see example of Afghanistan in Figure 3-1). More info can be found on the website *www.deltares.nl/en/software/ribasim*.

RIBASIM is a generic model package for simulating the behaviour of river basins under various hydrological conditions. The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management and to see the results in terms of water quantity, water quality and flow composition. RIBASIM can also generate flow patterns which provide a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs.

RIBASIM is a WINDOWS-based software package and includes a range of Delft Decision Support Systems Tools.

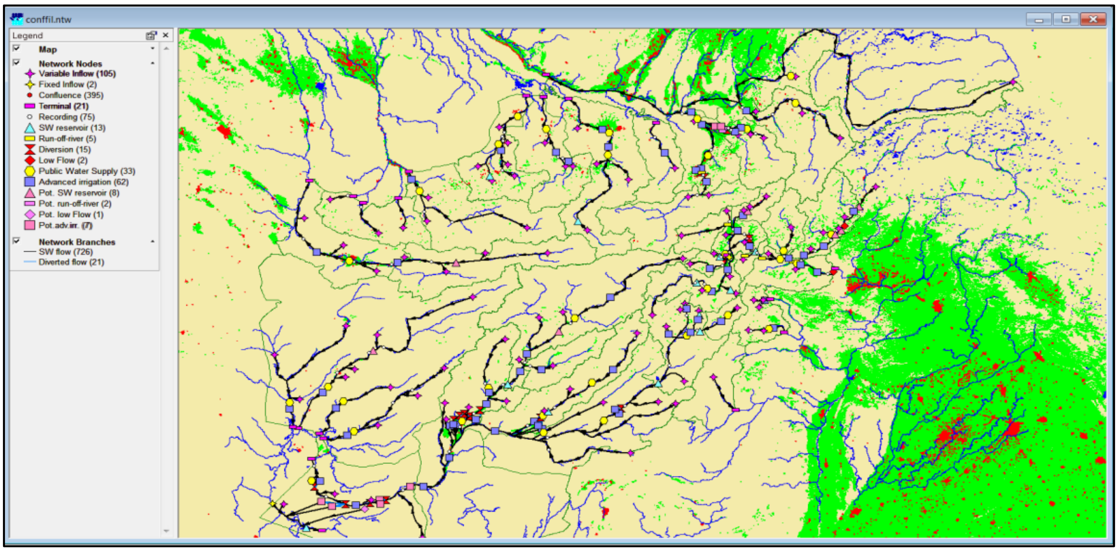

Figure 3-1 RIBASIM network schematization of all river basins in Afghanistan

3.2 Structure of the analysis

The main RIBASIM user interface is presented as a flow diagram of blocks representing the tasks to be carried-out, and their order, to complete the simulation process. The interface guides the user through the analysis from data entry to the evaluation of results. The blocks change colour on the computer screen to show the user which tasks have already been finished, which are in progress, and which still have to be done. The results of various simulation cases can be analysed together. The user does not need to work with the underlying file and directory structures nor with file management. The DELFT tools provide an environment which organises these user functions. These tools have an open structure which makes it possible to add or remove blocks from the flow diagram and to adapt the interface to project requirements.

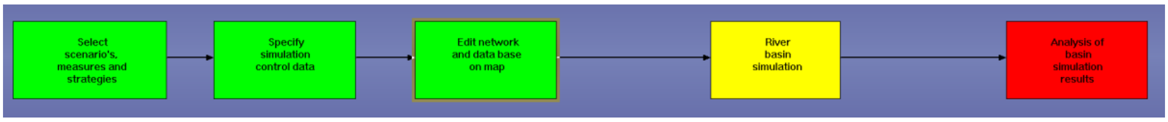

Figure 3-2   The user interface of RIBASIM presented by block flow diagram

3.3 Principles of river basin schematization

To perform simulations with RIBASIM, a model network schematization of the basin has to be made, in which all the necessary features of the basin are represented by nodes connected by links. Such a model schematization is a translation - and a simplification - of the "real world" into a format, which allows the actual simulation. Roughly speaking there are four main groups of elements to be schematized:

1. Infrastructure (surface and groundwater reservoirs, rivers, lakes, canals, pumping stations, pipelines), both natural and man-made;
2. Water users (public water supply, industry, cooling water, agriculture, hydropower, aquaculture, navigation, nature, recreation), or in more general terms: water related activities;
3. Management of the water resources system (reservoir operation rules, allocation methods);
4. Hydrology (river flows, runoff, precipitation, evaporation) and geo-hydrology (groundwater flows, seepage).

These groups are each schematized in their own way. The result of the schematization is a *network of nodes and links* which reflects the *spatial relationships* between the elements of the basin, and the data characterizing those nodes and links. Details on the various types of nodes and links can be found in Volume 2 (Annexes), Chapter 1.

3.4 Interactive schematization of the river basin

RIBASIM enables a schematization of the river basin to be prepared interactively from a map. This schematization consists of a network of nodes connected by branches. The nodes represent reservoirs, dams, weirs, pumps, hydro-power stations, water users, inflows, man-made and natural bifurcations, intake structures, natural lakes, swamps, wetlands, etc. The branches transport water between the different nodes. Such a network represents all of the basin’s features which are significant for its water balance and it can be adjusted to provide the exact level of detail required. The river basin is presented as a map over which the network schematization is superimposed as a separate map layer. The background map can be produced by any Geographical Information System. The attribute data of the network elements are entered interactively and linked to the map of the river basin and its network schematization. Data consistency tests are an integral part of this.

3.5 Scenarios, measures and strategies

RIBASIM is setup by a model data base of the river basin network schematization and a hydrological data base of time series, see Figure 3-3. The model data base contains the data describing the network schematization of all existing and potential (inactive) infrastructure and water users, the node and link characteristics, the source priority list and the water allocation priorities. The hydrological data base contains historical and alternative hydrological time series of runoff, flow, groundwater exfiltration, rainfall and evaporation stored in one or more hydrological scenarios.

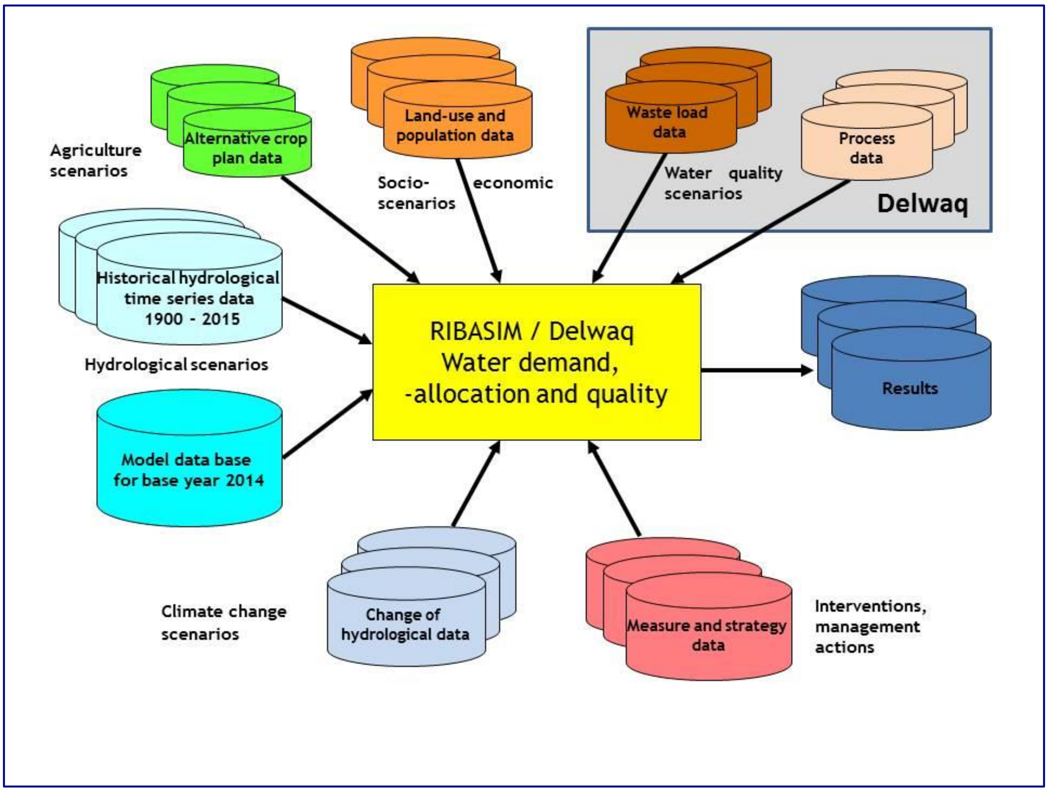

Figure 3-3 Input- and output structure of the RIBASIM with Delwaq model

Various future and potential situations and system configurations can be modeled by defining scenarios and management actions (strategies, interventions). The following options are available:

1. Hydrological scenarios. This scenario type covers multiple years and annual time series of runoff, flow, rainfall, groundwater exfiltration and evaporation;
2. Climate change scenarios. This scenario type contains the percentage change of the hydrological variables defined in the hydrological scenarios due to climate changes;
3. Land-use and population scenarios. This socio-economic scenario type contains the percentage change in irrigated area, population numbers and industrial demand per catchment of base year (stored in the model data base) for future demand years;
4. Agriculture scenarios. This scenario type contains the alternative future crop plans per catchment;
5. Water quality scenarios. Depending on the run mode one of the following scenarios are used:
   a. Basic water quality scenario. This scenario type is used in the run mode without Delwaq and contains the definition of substances and associated waste load lookup tables;

b Delwaq water quality scenario. This scenario type is used in the run mode with Delwaq and contains the waste load related data like emission factors and treatment efficiency, and chemical and biological process data. The data is used by the waste load estimation model to compute the industrial, domestic and agriculture waste loads;

6 Measure and strategies. One or more management actions (strategies, interventions) can be defined. Each management action consists of a combination of defined potential measures. A large variety of measures are valid. Measures can also be labelled with a time stamp to specify when the measure must become active or can be site specific then the measure becomes active when a certain site condition occurs.

3.6 River basin simulation

Simulations are usually made over long (multiple years) time series to include the occurrence of dry and wet periods. The simulation time steps used are variable and are defined by the user. Within each time step, the water demand is determined, resulting in targets for water releases from reservoirs, aquifers, lakes, weirs and pumping stations. Then, the water is allocated to the users according to the release targets, water availability, operation rules and water allocation priorities.

Water allocation to users can be done in several ways: at its simplest, water is allocated on a "first come, first served" basis along the natural flow direction. This allocation can be amended by rules which, for example, allocate priority to particular users, or which result in an allocation proportional to demand.

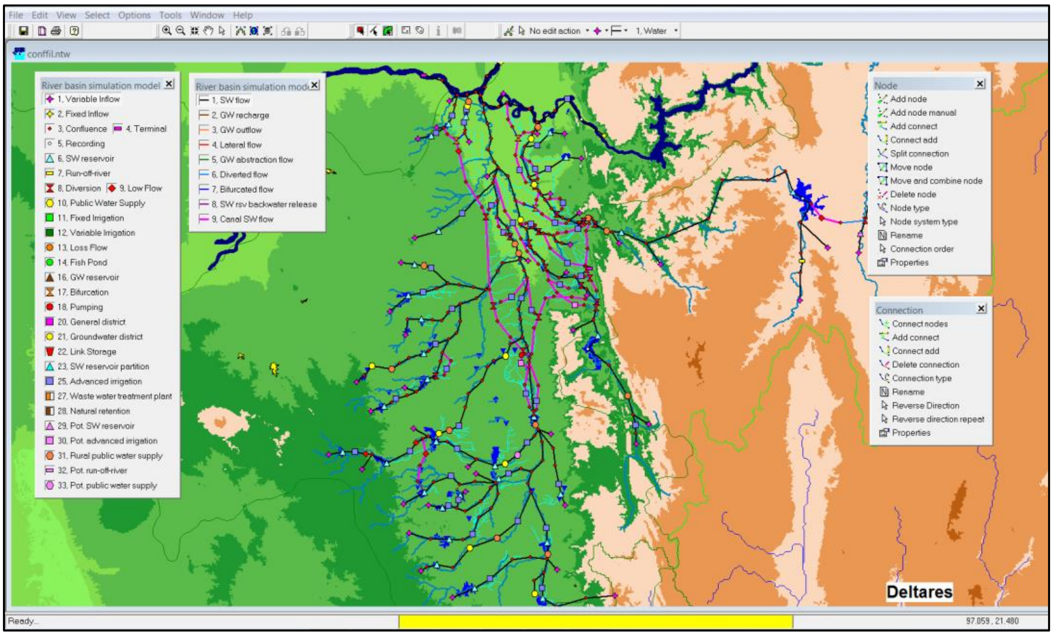

Figure 3-4 Interactive design of river basin network schematization for Samon River basin - Dry Zone, Myanmar

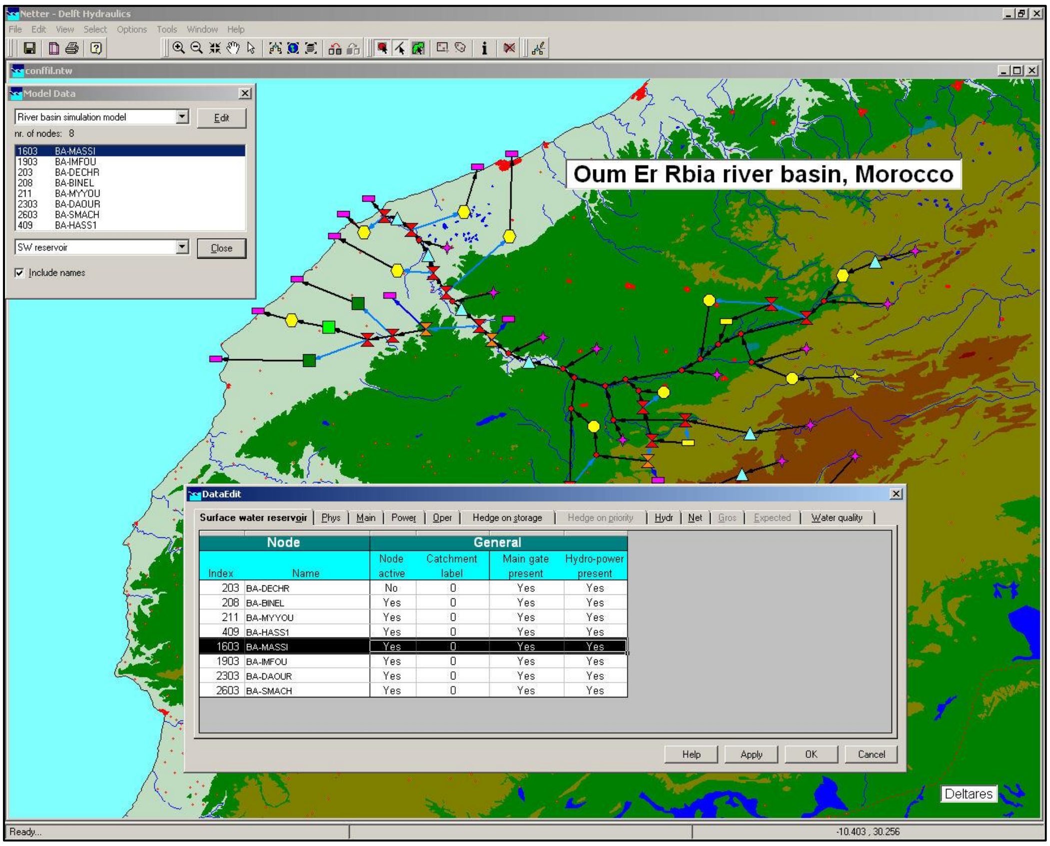

Figure 3-5 Spreadsheet based interactive entry of reservoir node model data

3.7 Evaluation of results

Using a set of simulations, usually made for a range of alternative development or management strategies, the performance of the basin is evaluated in terms of water allocation, water shortages, firm and secondary hydropower production, overall river basin water balance, flow composition, crop production, flood control, water supply reliability, groundwater use, etc.

The user can select how the output data will be shown and in which format: graphs, thematic maps, tables or spreadsheet. A wide range of functions are available to provide insight into the behaviour of large and complex river basins. For instance, it is possible to make an animation of the basin in which flow is indicated with arrows and the size of the flow is shown in different colours and/or line thickness. In a similar way, other output parameters, can be shown. By clicking the item on the map and then selecting the desired output parameter, time diagrams can be presented. Moreover, all output data can be simply exported into other formats.

3.8 Additional features

RIBASIM has a number of additional features that can be very useful for the advanced use of the software, and the analysis of the behaviour of a river basin. Such features include:

3.8.1 Fraction computation

RIBASIM supports a default and user-defined source analysis (*fraction computation*) that gives insight in the water's origin and residence time at any location of the basin and at any time within the simulation period. As an example, in Figure 3-6 the change in composition of the water is shown for a surface water reservoir over a number of years, expressed in fractions (0,0 – 1,0), allowing also for the assessment of the residence time (indicated by red arrow, time needed for the original water content of the reservoir to be entirely renewed).

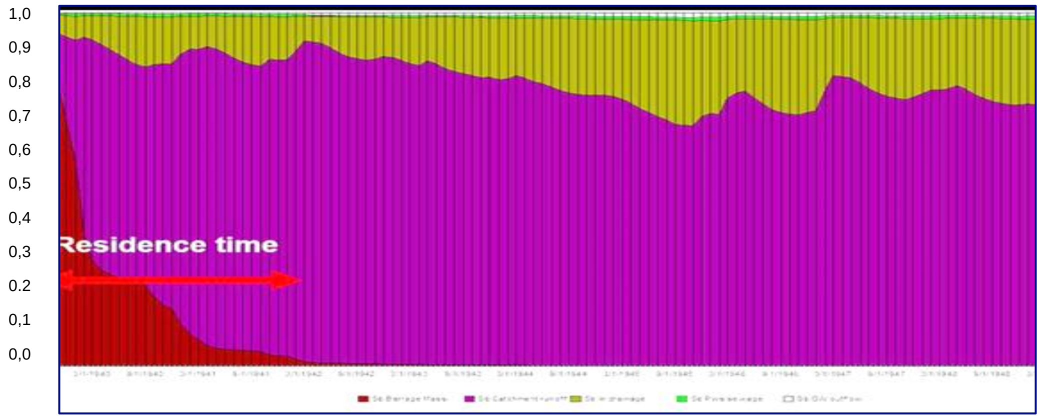

Figure 3-6 Flow composition of water in Massira reservoir from 1940-1949 (Oum Er Rbia River basin, Morocco)

Evidently, this option allows for the 'tracking' of the water from different sources and makes it possible to follow the changes in the source of the water in time, e.g. the percentage of water coming from glacier melt in Switzerland or from certain tributaries in different seasons and in wet / dry years. An example of such a tracking activity is shown in Figure 3-7, where the inflow from a tributary, and the return flow from irrigation and waste water, slowly takes over the original uniform composition (red colour from top source). This is a very strong tool for analysis of the system behaviour of a river basin and can be used in the future to show the change in behaviour due to development scenarios and climate change.

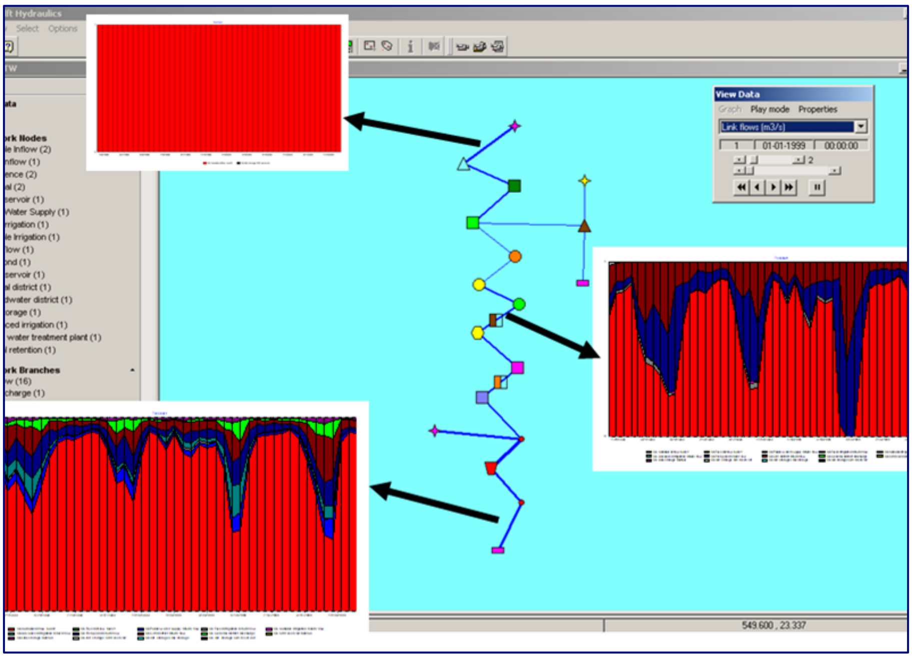

Figure 3-7   Change in flow composition in downstream direction over several years of simulation (wet / dry cycle visible)

3.8.2 Advanced irrigation simulation

RIBASIM has an integrated agriculture water demand, water allocation, crop yield and production costs model based on crop and soil characteristics, crop plan, irrigation and agriculture practise, expected and actual rainfall, reference evapotranspiration, seepage, actual field water balance, potential crop yield and production costs.

RIBASIM has a fully graphical user interface for designing the river basin network but also for crop cultivation planning, see Figure 3-8.

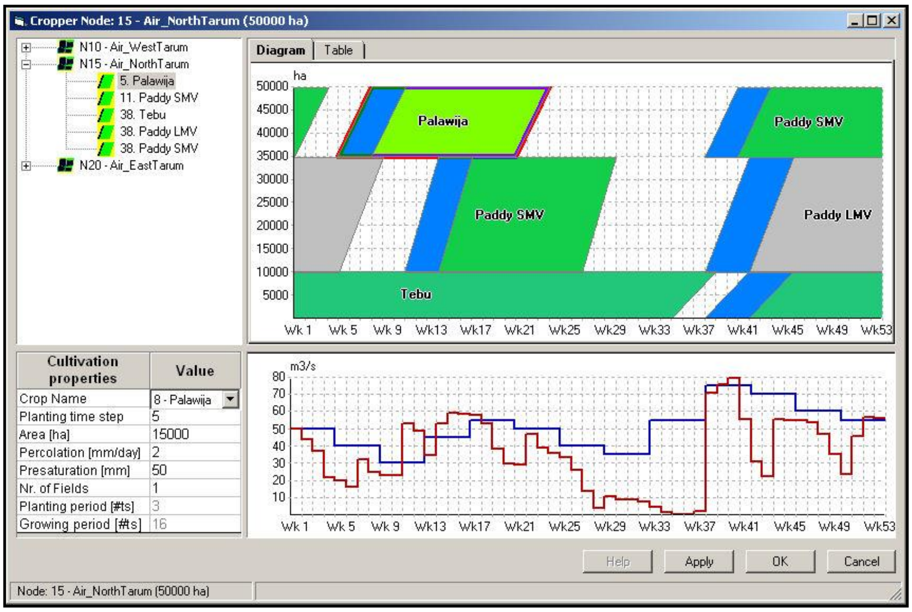

Figure 3-8   Interactive graphical design tool of a crop plan for the North Citarum irrigation area (Indonesia)

In the Rhine002 model, this advanced irrigation option has been used as it allows for a sophisticated assessment of the water demand for irrigated agriculture.

3.8.3 Source priority list

The source priority list is an important input data item for the water allocation in the model. The network schematization contains the following demand node: Fixed irrigation, General district, Public water supply, Industrial use and Cooling water. For each of those nodes a list must be prepared containing all nodes which are a (potential) source for the supply of water. This list is the source priority list. Those potential sources can be:

- Inflow / runoff: Variable inflow, Snow melt and Glacier melt
- Drainage / return flow: Public water supply, Industrial use and Cooling water
- Drainage: Fixed irrigation
- Discharge: General district

The order of the source nodes in the list is the order in which the nodes are chosen by the model to fulfil the water demand. So, the order of the nodes in the list is important. The model initially generates a default source priority list when the network was designed and setup on the map. The order in which the different node types are included in the default list is defined in the fixed data of RIBASIM. In the Rhine001 model only Variable inflow node types are used. The generated list is in most of the situations correct and no additional checking and updating is needed. However, it can be overruled by the user, using the source priority list editor, e.g. in case the user decides that a certain source should be avoided.

3.8.4 Water allocation priority

The water allocation priority outlines the order in which the various water users or water demands get the available water from the various sources specified in the source priority list. Table 3-1 lists all node types for which a water allocation priority was specified. All priorities are value 1.

Table 3-1 Water allocation priorities

Node type	Priority	Description
Public water supply	1	Domestic water uses
Fixed irrigation	1	Irrigation demand
Industrial use	1	Industrial water use
Cooling water	1	Cooling water at (nuclear) power plants
General district	1	Lignite mining water use

By default, the RIBASIM model allocates water in downstream direction, which is called '*first come, first serve'*. There are, however, situations that this leads to undesirable consequences, e.g. in case a city is located downstream from an irrigation area. In order to force the model to give priority to the city, despite its location, the standard order of allocation can be overruled by changing the priority settings and e.g. give a higher priority to public water supply. For this option, it is possible to use priority settings from 1 (highest) to 99 (lowest) priority. It is also possible to assign different priorities to a percentage of a water demand in a demand node, e.g. giving a higher priority to the first 50% of the demand of a public water supply, and a much lower priority to the remaining 50% of that demand.

3.8.5 Additional features

- RIBASIM includes a basic water quality component which allows for the simulation of the concentration of any number of user-specified substances. Waste loads are connected at various user- and boundary nodes. Natural and artificial retention of substances are introduced at any location in the network schematization. Substances are routed thru the network based on the simulated water distribution assuming complete mixture;
- For most basin planning purposes, the RIBASIM basic water quality modelling is enough. If detailed simulation of chemical and biological processes is required, then RIBASIM can be linked with the water quality process model DELWAQ;
- Groundwater can be modelled as separate source for various users with its own characteristics and water management;
- Extreme long simulation periods for example of synthetically generated time series of 5000 or more years can be simulated;
- RIBASIM offers various flow routing procedures like Manning, 2-layered multi-segmented Muskingum, time-delayed Puls method, Laurenson non-linear "lag and route" method, etc.

For more information on RIBASIM see the User and Technical reference manual (van der Krogt, 2008, 2013, 2015).

4 The Rhine001 model

4.1 Introduction

The Rhine001 model is based on the original Excel spreadsheet model stored in file "SES-Rhine version 1.0.xlsx" and described in report "*11201722-000-ZWS-0005 v1.1 - Integrated Overview of the effects of socio-economic scenarios on the discharge of the Rhine*". The Excel spreadsheet model has been converted into a RIBASIM node-link network model, including 4 hydrological scenarios, 4 climate change scenarios and 4 combination of measures (strategies, management actions, interventions). The model does not consider storage capacity at reservoirs in the Rhine River basin and simulates only 1 year on a monthly simulation time step.

The four simulation cases have the same name as defined in the original SES Rhine hydrology Excel "SES-Rhine version 1.0.xlsx":

1 Actual case
2 S1. Reduce case
3 S2. Develop case
4 S3. Adapt case

4.2 Catchment schematization

The Rhine001 model covers the Rhine River basin from the source till the North Sea. The catchment has been divided into the following 9 sub-basins, see Figure 4-1:

1 Bodensee/AlpenRhein
2 Hoch Rhein
3 Ober Rhein
4 Neckar
5 Main
6 Mosel/Saar
7 Mittel Rhein
8 Nieder Rhein
9 Delta Rhein

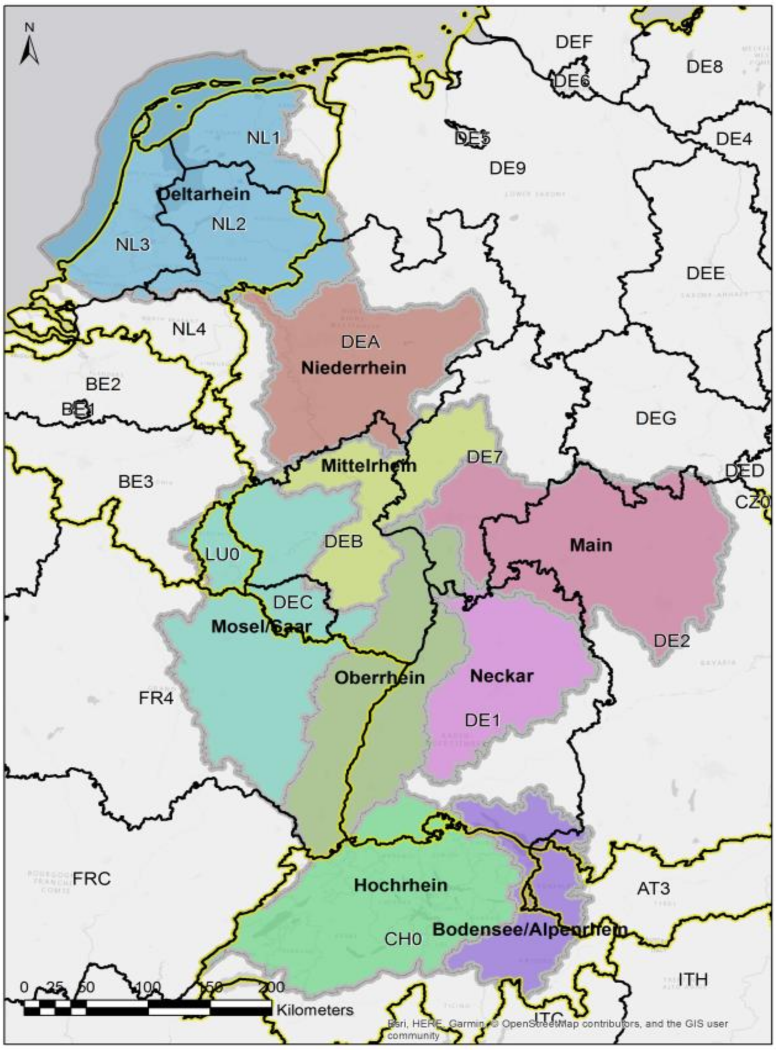

Figure 4-1 Rhine 001 catchment schematization: geographical delineation (Ruijgh, 2019)

4.2.1 Network

The network schematization of the Rhine001 model is presented in Figure 4-2. More details are provided in the figures in Volume 2 (Annexes).

The schematization contains 87 nodes and 86 links. Table 4-1 outlines the number of nodes and links per type. Details on all the nodes in the schematization are also given in Volume 2 (Annexes).

Deltares

Table 4-1 Overview of dimensions of the Rhine001 network schematization

Number of	Total
nodes	87
links	86
variable inflow nodes	19
confluence nodes	25
recording nodes	5
terminal nodes	1
public water supply nodes	27
fixed irrigation nodes	9
general district nodes	1

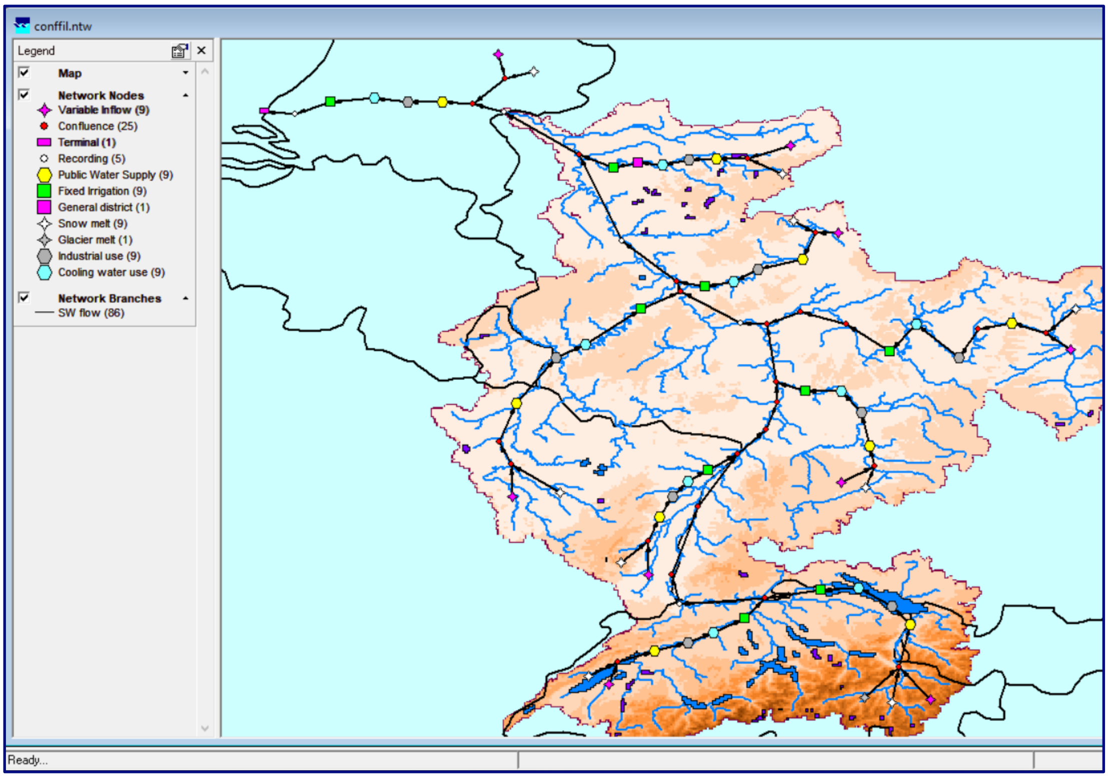

Figure 4-2 The Rhine001 network schematization with map

4.3 Hydrological boundary conditions

The hydrological boundary conditions consist of the inflow time series:

- Glacier Alpine Rhein
- Snow Alpine Rhein, Hoch Rhein, Ober Rhein, Neckar, Main, Mosel/Saar, Mittel Rhein, Nieder Rhein, Delta Rhein
- Runoff Alpine Rhein, Hoch Rhein, Ober Rhein, Neckar, Main, Mosel/Saar, Mittel Rhein, Nieder Rhein, Delta Rhein

Another hydrological input is the flow time series which relate to the 5 recording nodes in the hydrological scenario. The time series are the natural flow (Glacier + Snow + Runoff) for locations Basel, Bingen, Bonn, Lobith and Hoek van Holland.

4.4 Model use

The simulation cases as implemented in the original SES Rhine hydrology Excel "SES-Rhine version 1.0.xlsx" has been implemented in the Rhine001 model as well. A simulation case consists of a combination of hydrological scenario and management action (strategy, intervention, combination of measures). The simulation cases are:

- 2020.05.08 Rhine Actual case
- 2020.05.08 Rhine S1. Reduce case
- 2020.05.08 Rhine S2. Develop case
- 2020.05.08 Rhine S3. Adapt case

Four hydrological scenarios have been created:

- Actual situation
- S1. Reduce
- S2. Develop
- S3. Adapt

The defined measures for each node type are listed in Table 4-2. The measures are combined to three strategies: S1 Reduce, S2 Develop and S3 Adapt.

Further, 3 climate change scenarios have been implemented for illustration. At each scenario the percentage of change (+ or -) of the hydrological parameters is specified. Here only the change of runoff is relevant. The percentage can be specified per series and per timestep.

Table 4-2 Overview of defined measures

Related node type	Measure file name
Cooling water use	Col001_S1Reduce.Mes Col002_S2Develop.Mes Col003_S3Adapt.Mes
Domestic water use	Dom001_S1Reduce.Mes Dom002_S2Develop.Mes Dom003_S3Adapt.Mes
Industrial water use	Ind001_S1Reduce.Mes Ind002_S2Develop.Mes Ind003_S3Adapt.Mes
Irrigation	Irr001_S1Reduce.Mes Irr002_S2Develop.Mes Irr003_S3Adapt.Mes

4.5 Comparison between spreadsheet model and RIBASIM Rhine001 application

Although the content of the original spreadsheet has been implemented unchanged into the RIBASIM Rhine001 model application, it is useful to make a comparison between the two to check whether the modelling results are the same. For this purpose a comparison is made between a number of items:

- Water demand from the various sectors
- River flow in a selection of links.

Although the comparison can be made for the four different cases implemented in the model, we only compared the results of the “Actual situation” in order to check on the reliability of the model.

4.5.1 Water demand of the various demand sectors

First a comparison was made between the demand values, which were found to be identical between the original spreadsheet and the Rhine01 model.

4.5.2 River flow in a selection of links

For model verification the natural flow of simulated and “recording” time series at the recording nodes are compared. Although only one year was simulated in this model, it is useful to show the comparison between the simulated and measured flow at a number of key gauging stations. The input to the variable inflow nodes of the Rhine001 model were taken from the spreadsheet, so in the upstream branches the flow will be identical. A comparison of some key stations that are a result of the model simulation, such as Bonn, Lobith and the final point of the simulation at Hoek van Holland are shown in Figure 4-3.

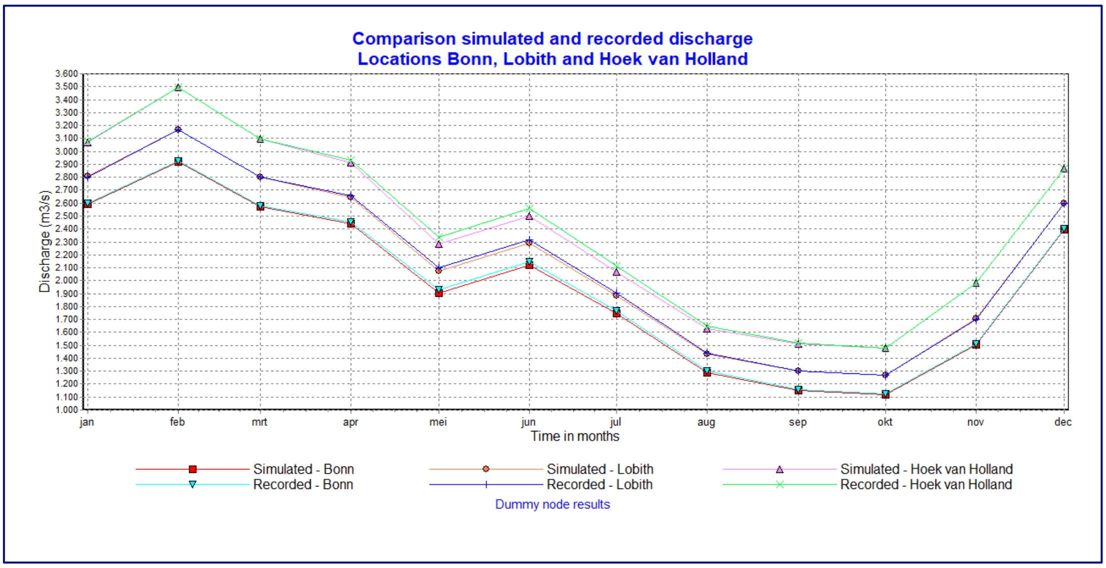

Figure 4-3 Comparison simulated and recorded flow in the Rhine001 model

As the recorded flows are taken from the spreadsheet model, this shows that the results of the Rhine001 model are nearly identical to those from the spreadsheet model. This shows that the functioning of the two models, spreadsheet and RIBASIM, are virtually identical.

The conclusion that both the spreadsheet and the RIBASIM Rhine001 model give identical results implies that all the results presented from the spreadsheet model can faithfully be reproduced by the Rhine001 model.

5 The Rhine002 model

5.1 Introduction

As a further step in the development of a planning tool of the Rhine river with the RIBASIM software, a completely new model was set up, starting off from the Rhine01 model, but using entirely new components and data sources. This resulted in the Rhine002 model.

The Rhine002 model consists of two model components:

1. Wflow Rainfall-runoff model, which covers the entire Rhine river basin up till Lobith;
2. RIBASIM water demand, allocation, flow composition and optional (later) water quality model, which covers the whole Rhine river basin from the Swiss Alps natural lakes till Hoek van Holland.

The Rhine002 model includes all major storage capacity at reservoirs and natural lakes in the Rhine River basin. The demands are lumped into a demand per water user type per sub-basin, similar to those implemented in the Rhine001 model. The storage infrastructure and demands of the Netherlands have been added. The aim is to improve and extend the modelling of the infrastructure and the demands in new versions of the model. The model simulates for multiple year time series, limited by the length of the available time series (presently 1980 – 2018).

The development of the Rhine002 model was carried out in 2 steps, see Figure 5-1. The first step is the design of a catchment schematization of Rhine River basin based on the location of dams, irrigation area intakes, towns/cities, flow monitoring stations and specific desired boundaries. This schematization forms the basis for the input simulated by the hydrological model WFLOW, which computes daily runoff series for each catchment, as well as rainfall and evaporation/evapotranspiration. These time series are input of RIBASIM. The second step is the design of a node - link network schematization, as outlined in Chapter 3.3.

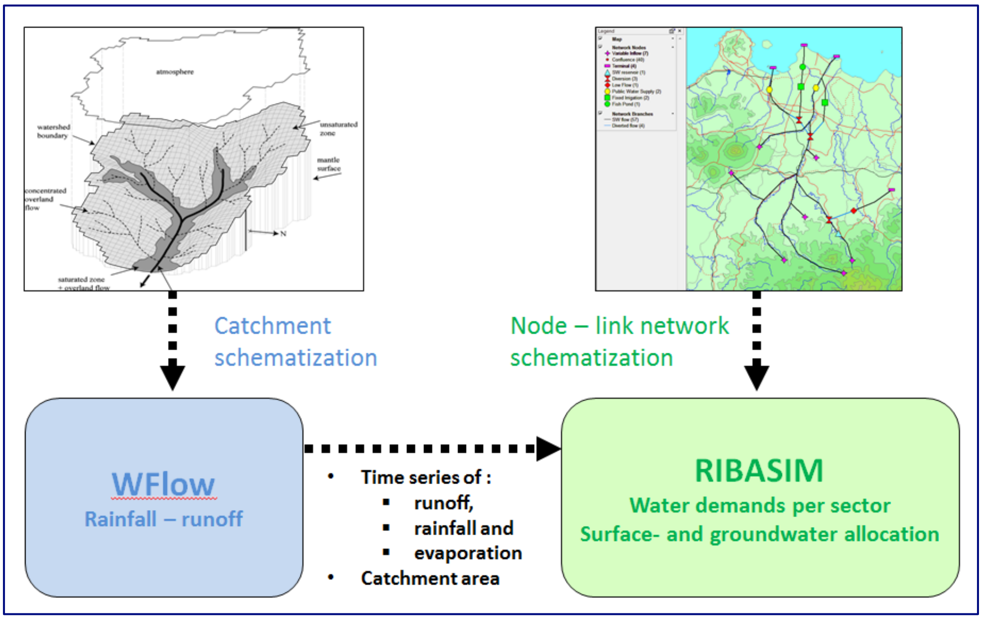

Figure 5-1 Link between Wflow and RIBASIM

The Wflow rainfall-runoff model computes with a daily timestep. RIBASIM simulates with a decade simulation time step and an internal daily computational time step. Decade means that each month is split into 3 timesteps, which makes total 36 timesteps per year.

The maximum simulation time period is 39 years of historical time series from January 1980 till December 2018. This can be extended in the future when additional years of measurement become available.

The Wflow model can also be replaced by the national rainfall-runoff model from the Rhine River riparian countries.

5.2 The Rhine002 Wflow hydrological model

5.2.1 General description

The water availability in the Rhine River basin has been estimated with the Wflow hydrological model. The Wflow model is a completely distributed (gridded), rainfall-runoff model that calculates the runoff at any given point in the model at a given time step, based on physical parameters and meteorological input data. For a more technical description of the model, see Schellekens (2014), Imhoff, et al. (2020).

In order to set up the model, both static and dynamic data are needed. Static data define the structure and parameters of the model. The static data include:

- a digital elevation model (DEM)
- a river network
- a land-use map
- a soil map
- a set of physical parameters defining the properties of different soil types, land-use types and sub-basins

The dynamic data are in the form of time series and include: discharge data (for calibration and validation) and meteorological data (precipitation, temperature, evapotranspiration – for forcing). Sources for these data are both local measurements and global gridded products.

5.2.2 Static and dynamic data

The schematization is based on three main static datasets, the digital elevation model, the land use data and the soil data:

- **Digital Elevation Model (DEM)**
  The DEM used to setup the model is based on Merit-HYDRO (Yamazaki et al., 2019). All hydrography data, like the slope and river network are derived using state-of-the-art upscaling methods (Eilander et al., 2020);
- **Land use data**
  The land use data is based on the CORINE landcover map (EEA, 2018). The landcover data is used to set parameters values linked to land use type, such as the Manning roughness coefficient (N) and the rooting depth;
- **Soil data**
  For the soil data use is made of the SoilGrids250m dataset (Hengl et al., 2017). The soil data is used to derive soil parameters.

The methods for setting up the model and parameterization of the soil parameters is based on the work of Imhoff et al. (2020). The parameters are estimated using Pseudo Transfer Functions that translate the information contained in the SoilGrids250m dataset into model parameters of the Wflow model directly.

The forcing data in the simulation is based on ERA5 re-analysis data developed by the European Center for Medium-range Weather Forecasting (ECMWF). The data, precipitation, temperature and potential evaporation, is available for the period from 1980 – 2018. The temperature data are downscaled using the detailed elevation model for lapse rate correction.

5.2.3 Initial model results

The calibration of the Wflow model has been done in various steps and is still ongoing. As described in the previous section, the model parameters are derived using PTFs linking soil and land use properties to model parameters. One change to the model, compared to the base model, is the increase of the horizontal hydraulic connectivity of the soil (KSatHorFrac). The results of this simulation for Lobith is shown in Figure 5-2. Comparison of the Wflow results are made with measurements, but also with the HBV-96 model that is available for the Rhine basin.

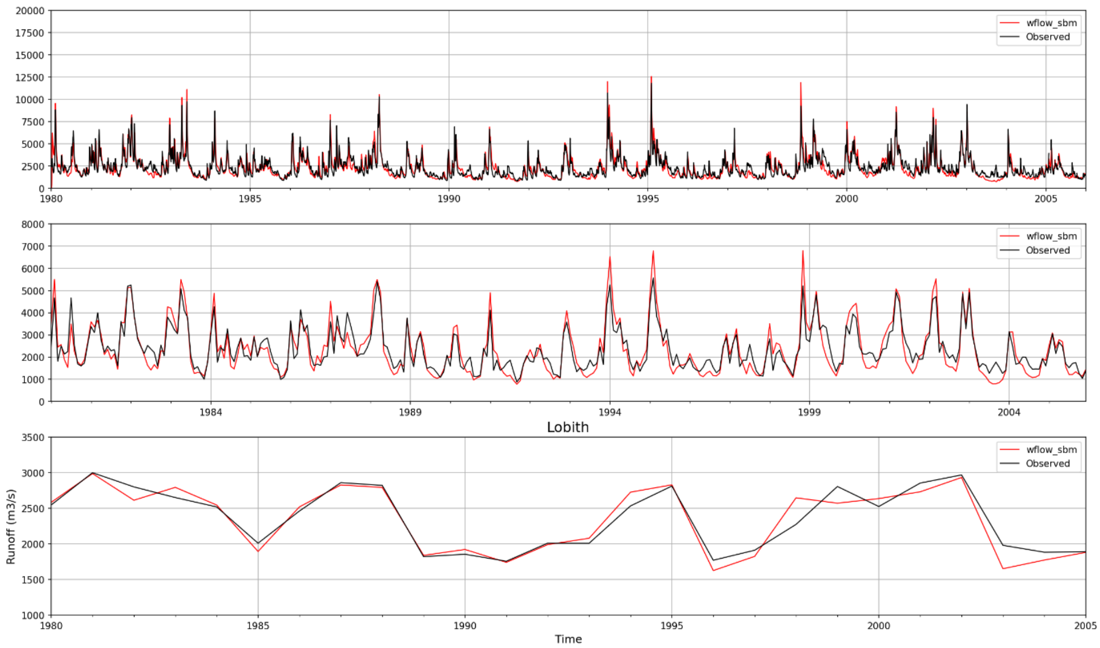

Figure 5-2 Overview of the results of the wflow model (red) at Lobith, compared to observations (black) and the HBV'96 model (blue)

In the meanwhile, some further analysis has been done on the performance of the Wflow model. At the outlet at Lobith, the performance is almost the same. Going into more detail of the sub-catchments, it can be seen that the new Wflow model results improve, especially further upstream near Basel.

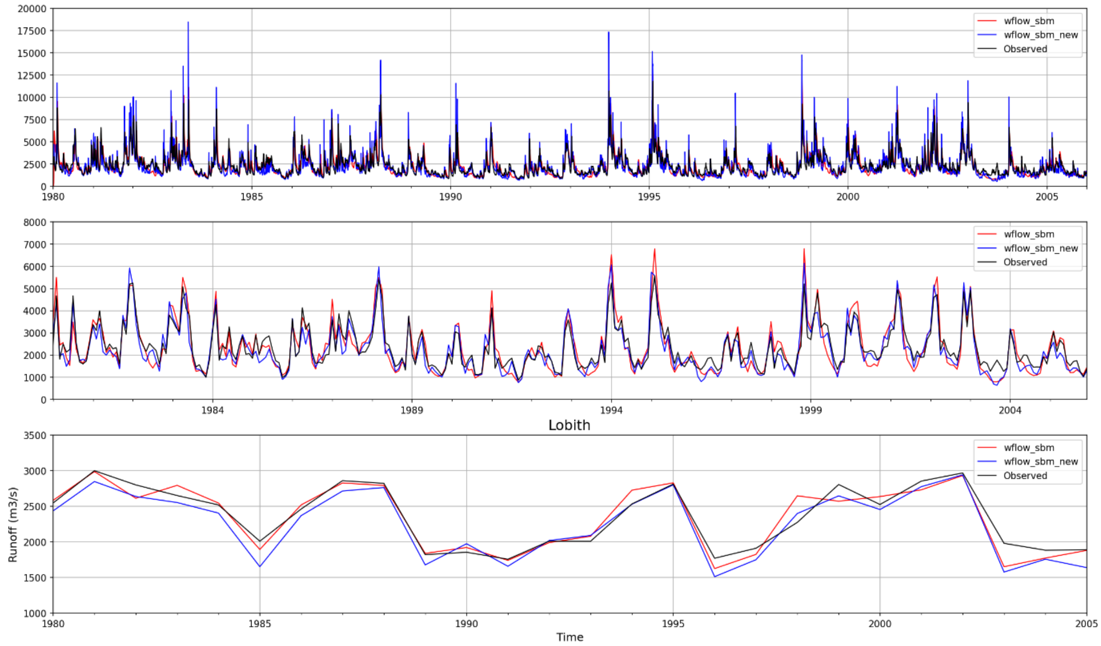

Figure 5-3 Overview of the results of the currently used wflow model (red) at Lobith, compared to observations (black) and latest wflow model results (blue)

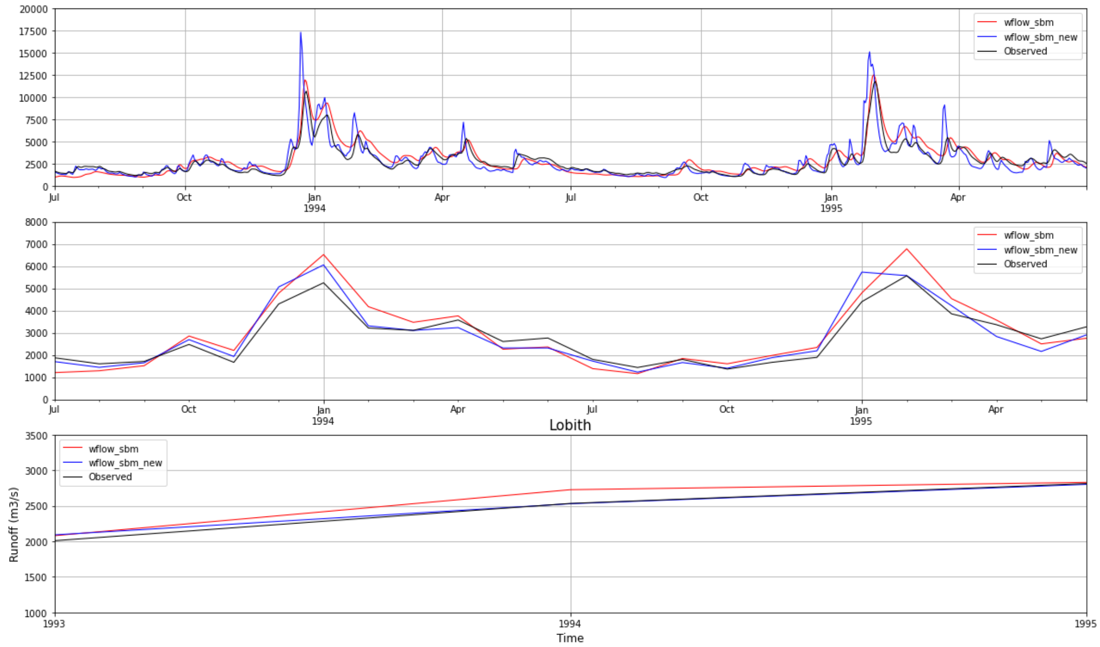

Figure 5-4 Overview of the results of the currently used wflow model (red) at Lobith, compared to observations (black) and latest wflow model results (blue), zoomed in to the period of 1993-95

5.3 The Rhine002 RIBASIM model

RIBASIM component of the Rhine002 model covers the water demand, allocation, flow composition and optional (later) water quality of the whole Rhine River basin from the Swiss Alps natural lakes till Hoek van Holland.

5.3.1 Catchment schematization

Rhine River basin is split into 93 sub-basins based on the location of reservoirs (dams), natural lakes, flow monitoring stations and river mouth. Each sub-basin is related to a runoff timeseries, except 2 sub-basins in the Netherlands. The timeseries of the 91 sub-basins upstream of Lobith are generated by Wflow and the 2 sub-basins in the Netherlands have been added. Figure 5-5 shows the sub-basins modelled in Wflow.

The original schematization in the spreadsheet model "*130311_HWS_v1.6.1 - uitvoer naar Regiotool IJM.xlsm*" has been used as basis for the catchment schematization downstream Lobith in the Netherlands. The 7 regions in the Rhine catchment of the Netherlands (see Figure 5-6) are lumped into 4 sub-basins. Table 5-1 shows the sub-basins, the lumped HWS regions and the source of water.

Each sub-basin, for which a timeseries is prepared, is represented in the RIBASIM network schematization by a variable inflow node. A list of all variable inflow nodes and size of the sub-basin area (km^2) is given in Volume 2 (Annexes). The total area of all sub-basins is 185,000 km^2.

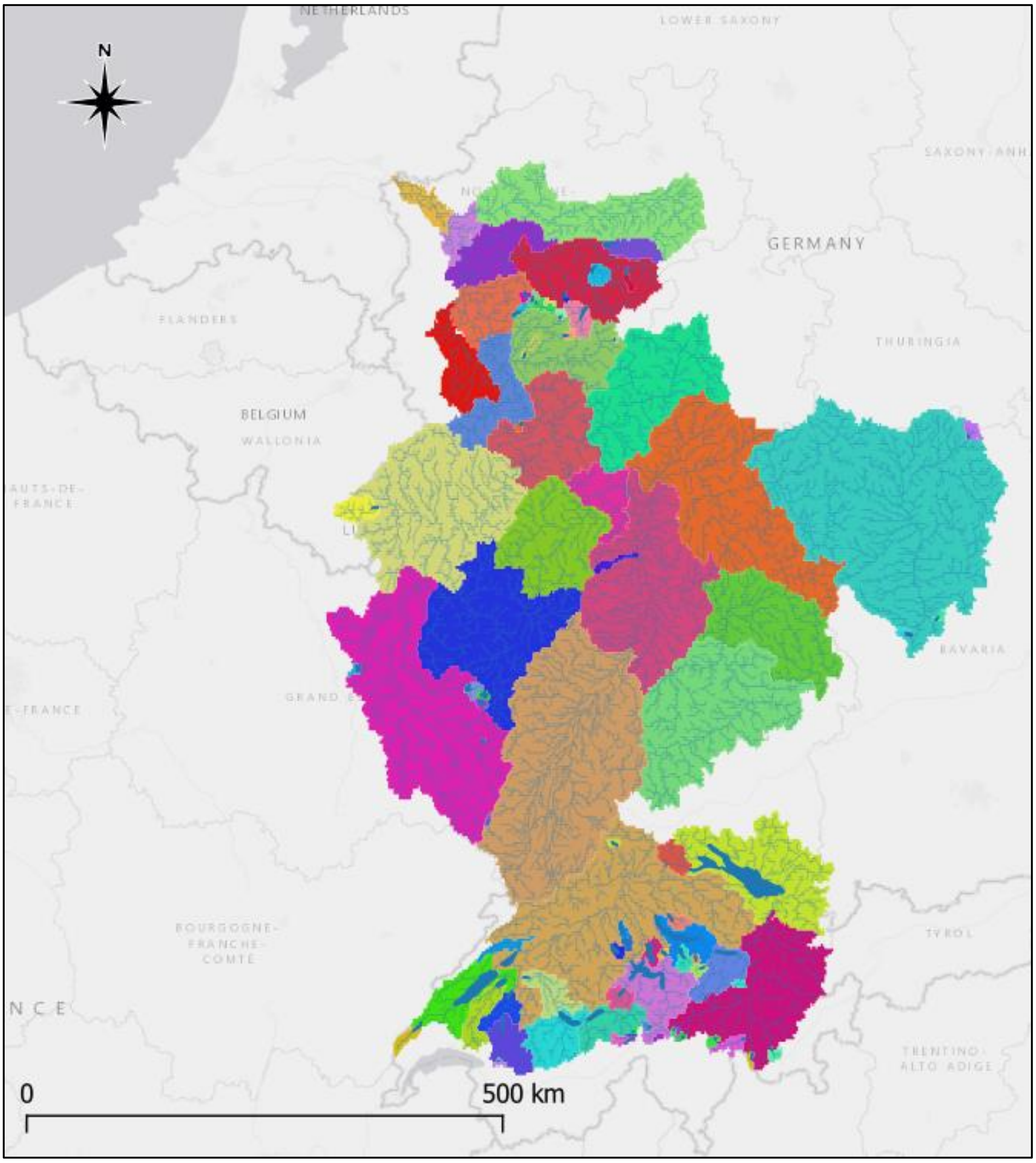

Figure 5-5 Catchment schematization of Rhine River basin split into 93 sub-basins

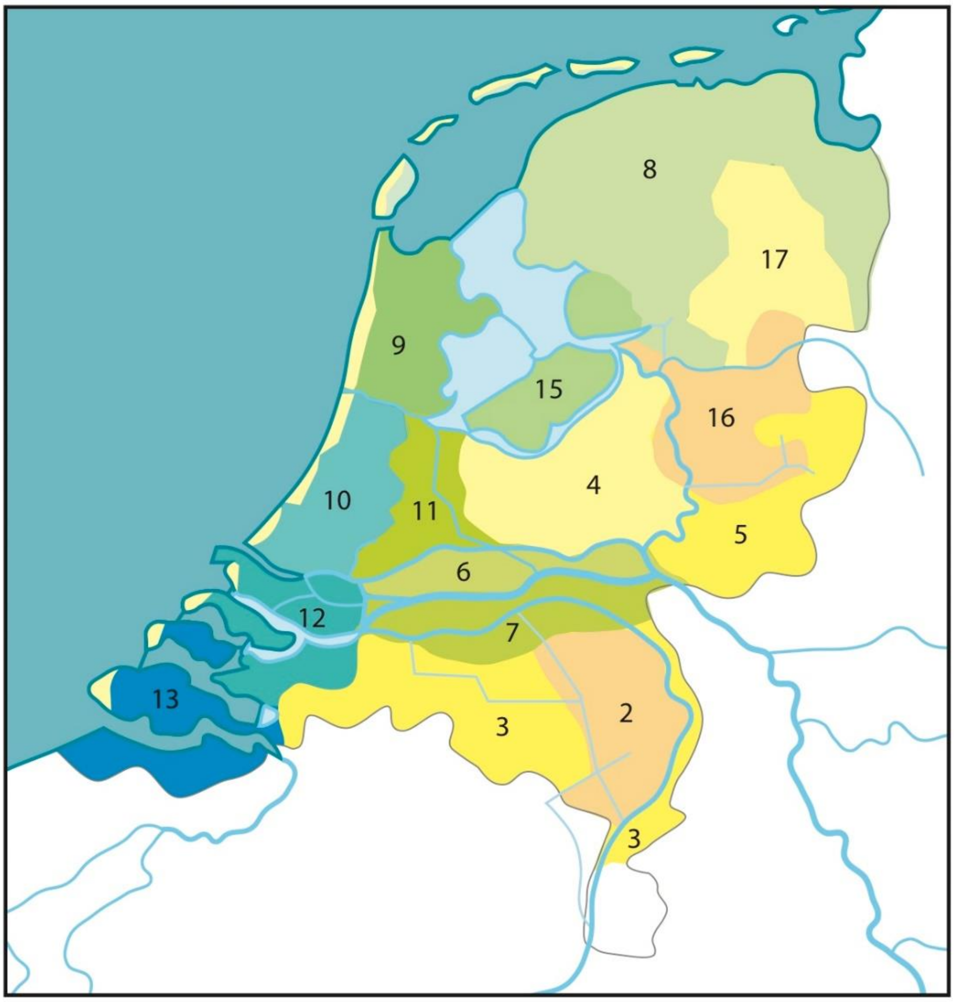

Figure 5-6 Regions in the Netherlands

Table 5-1 Overview of the RIBASIM sub-basins and the clustered HWS regions

Sub-basin name	Nr	Region name	Source
Region 8-9-15	8	Fries Gronings kustgebied	Ijssel lake
	9	Noord Holland	
	15	IJsselmeerpolders	
Region 16	16	IJssel-Vecht	Ijssel river
Region 6-11	6	Rivierengebied - noord	Nederrijn / Lek
	11	Midden West Nederland - niet extern verzilt	
Region 10	10	Midden West Nederland - extern verzilt	Benedenrivieren

5.3.2 Network schematization

The network schematization of the Rhine002 model is presented in Figure 5-7 till Figure 5-10. The schematization covers the rivers: Rhine, Aare, Mosel/Saar, Neckar, Main, Ruhr, Waal / Bovenrijn and IJssel, and consists of 481 nodes and 483 links. Table 5-2 outlines the number of nodes and links per type, with a distinction in active and inactive nodes in the model.

Table 5-2 Overview of dimensions of the Rhine002 network schematization

Type of nodes	Active nodes	Inactive nodes	Total
Total nr. of nodes	452	29	481
Total nr. of links	-	-	483
variable inflow nodes	93	0	93
fixed inflow nodes	2	0	2
confluence nodes	212	0	212
recording nodes	27	0	27
terminal nodes	7	0	7
surface water reservoir nodes	46	20	66
diversion nodes	4	0	4
low flow nodes	21	0	21
public water supply nodes	24	8	32
loss flow nodes	3	0	3
bifurcation nodes	2	0	2
general district nodes	1	0	1
advanced irrigation nodes	10	1	11

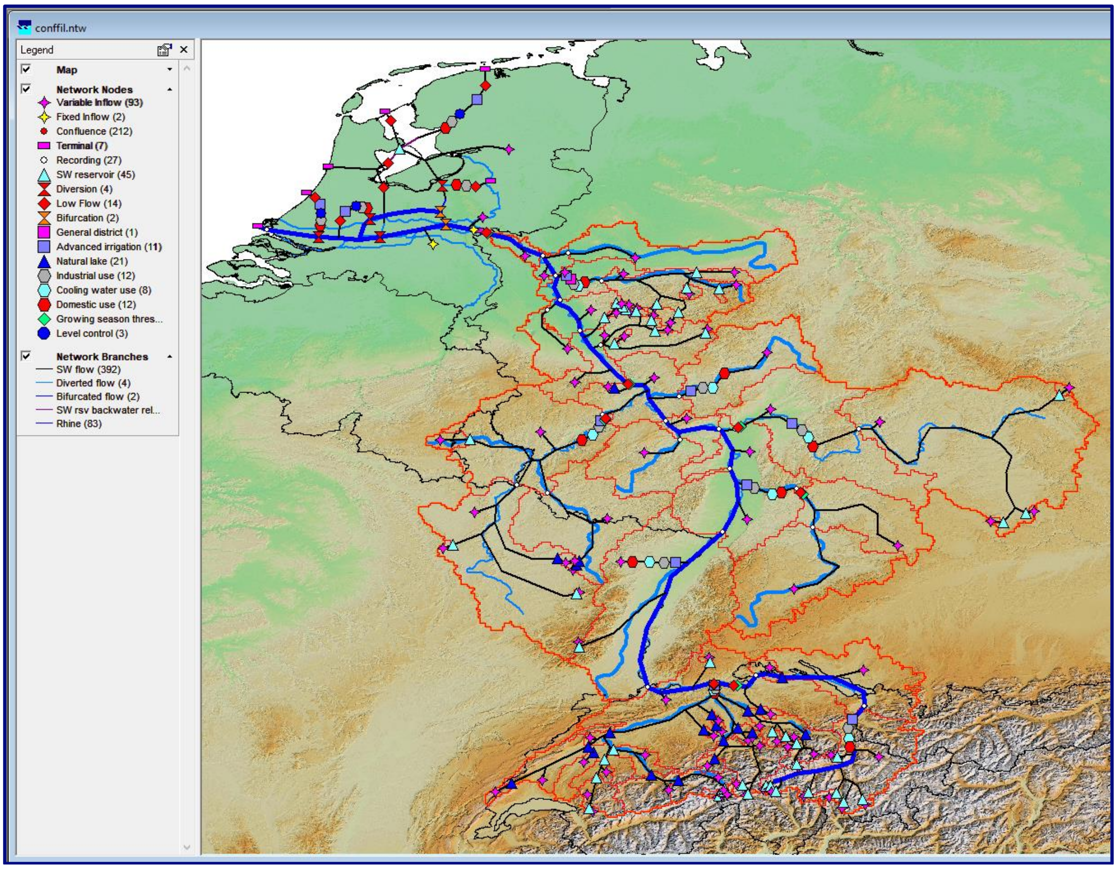

Figure 5-7 The Rhine002 network schematization with map

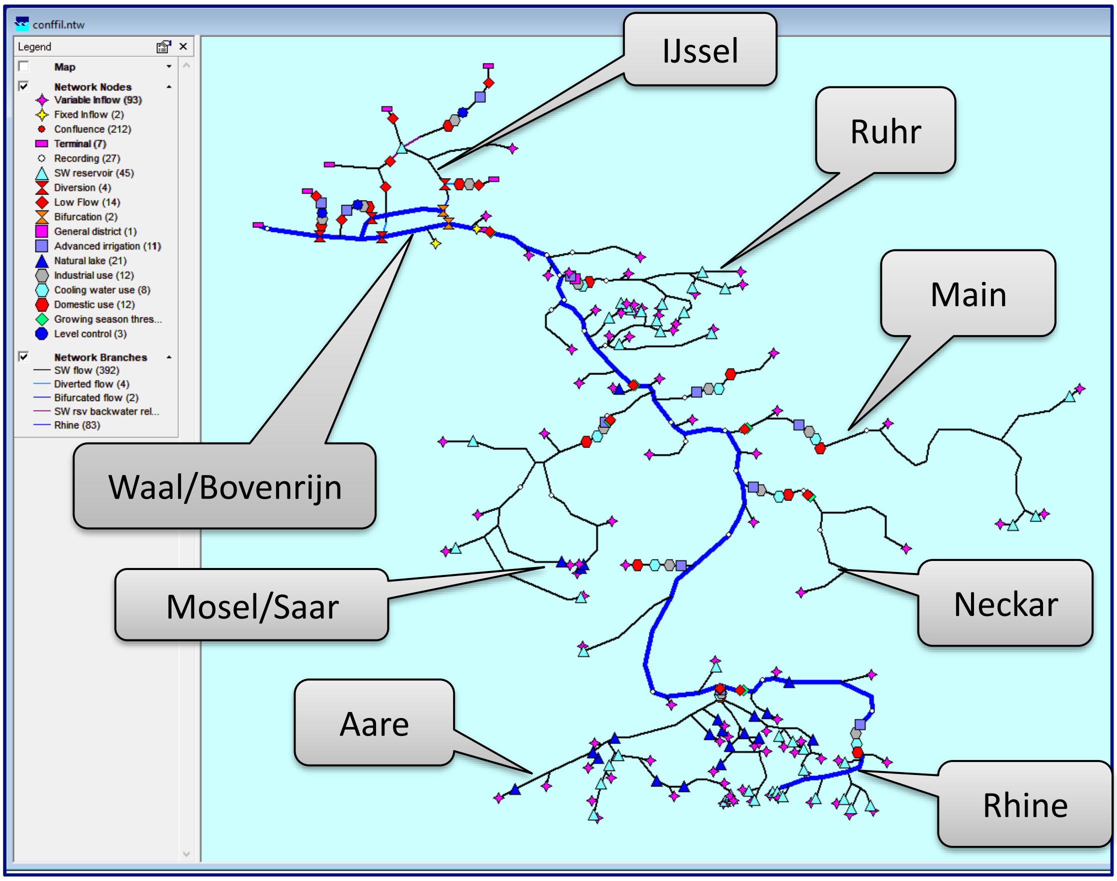

Figure 5-8 The Rhine002 network schematization without map

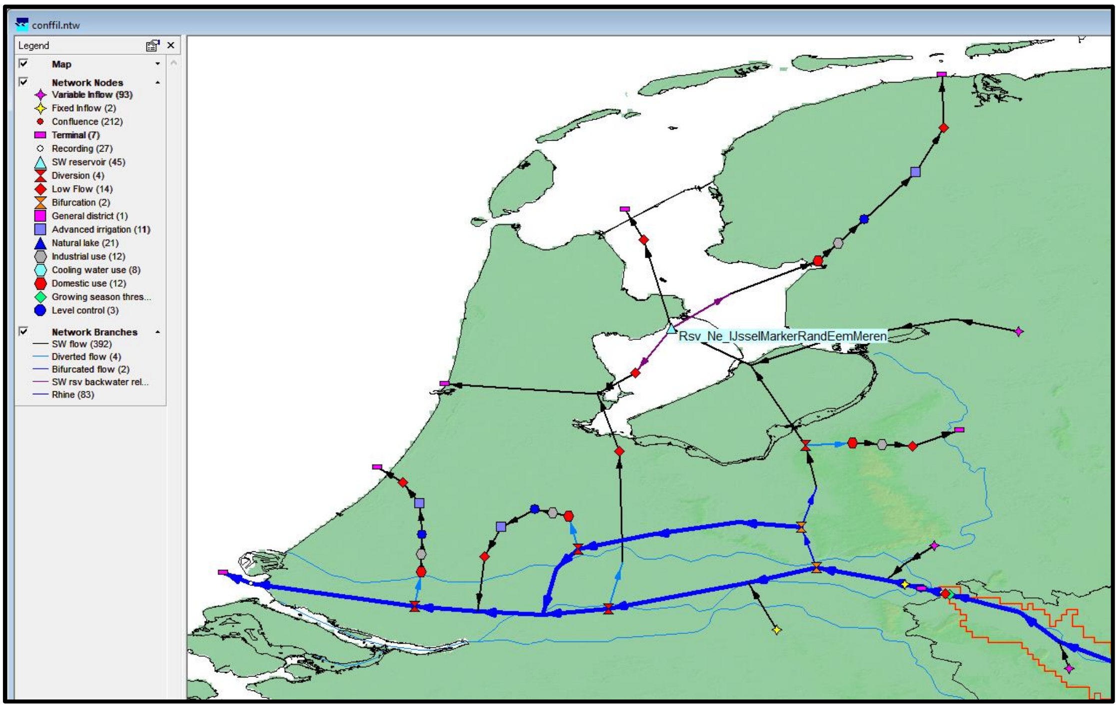

Figure 5-9 The Rhine002 RIBASIM schematization of the Netherlands

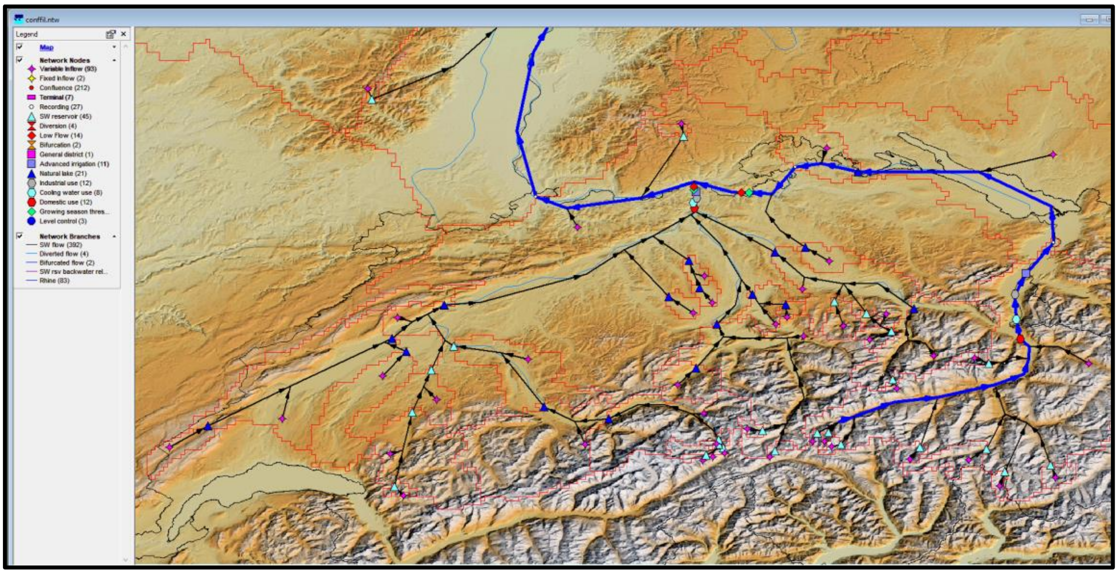

Figure 5-10 The Rhine002 RIBASIM schematization of Swiss

5.3.3 User defined node and link types

The user defined node and link types, specifically defined for the Rhine002 model, are shown in Table 5-3.

Table 5-3 Overview of the user defined node and link types

Node / link type name	Parent node / link type	Representation
Natural lake	Surface water reservoir node	Natural lake
Industrial use	Public water supply node	Industrial water use including cooling water
Cooling water use	Public water supply node	Cooling water use
Domestic use	Public water supply node	Domestic water use: drinking water
Growing season threshold	Low flow node	Minimum flow requirement during growing season*
Level control	Loss flow node	Level control in polders in the Netherlands ("peilbeheer")
Rhine	Surface water flow link	Rhine river branches

* *Maintaining a minimum river discharge at Lobith is extremely relevant for agricultural production, salt management and navigation in the Netherlands*.

5.3.4 Modelling features

5.3.4.1 Modelling natural lakes and reservoirs

The natural lakes are schematized as a surface water reservoir node and modelled as a "continuous spilling reservoir". The full reservoir level (FRL, spillway level) is specified and the relation between the outflow and the net-head (level above the FRL). Separate rainfall and open water evaporation time series is connected to the node.

The dams and reservoirs are schematized as a surface water reservoir node and modelled using the various options that RIBASIM offers. Figure 5-11 shows a general lay-out of a reservoir and its in-and outflows:

- Inflow from the upstream river branch.
- Main dam with primary outlets: main gate, turbine gate, spillway at FRL.
- Secondary outlet(s): backwater outlet, head sluice, direct abstractions by pumping.
- Open water evaporation, rainfall and seepage.

Figure 5-12 shows the annual reservoir operation rules in which the purpose of the reservoir is reflected: flood control, maximum average hydro-power production (target curve), firm storage and hedging of downstream target release for various water users like irrigation, domestic, industrial, minimum flow requirements, firm energy (). The actual reservoir release depends on the function of the reservoir. If the function of a reservoir is the supply of water to downstream irrigation area(s) then the demand of the irrigation area(s) determines the target release. But if the function of a reservoir is the production of hydro-power than the target release will be determined by the monthly firm energy requirements. With the target curve for maximum average hydro-power extra water can be released for additional secondary energy production (fine tuning). If no specific information is known about the reservoir operation then the operation rules are specified such that the target release will always be released if the water is available in the reservoir (no hedging of the release).

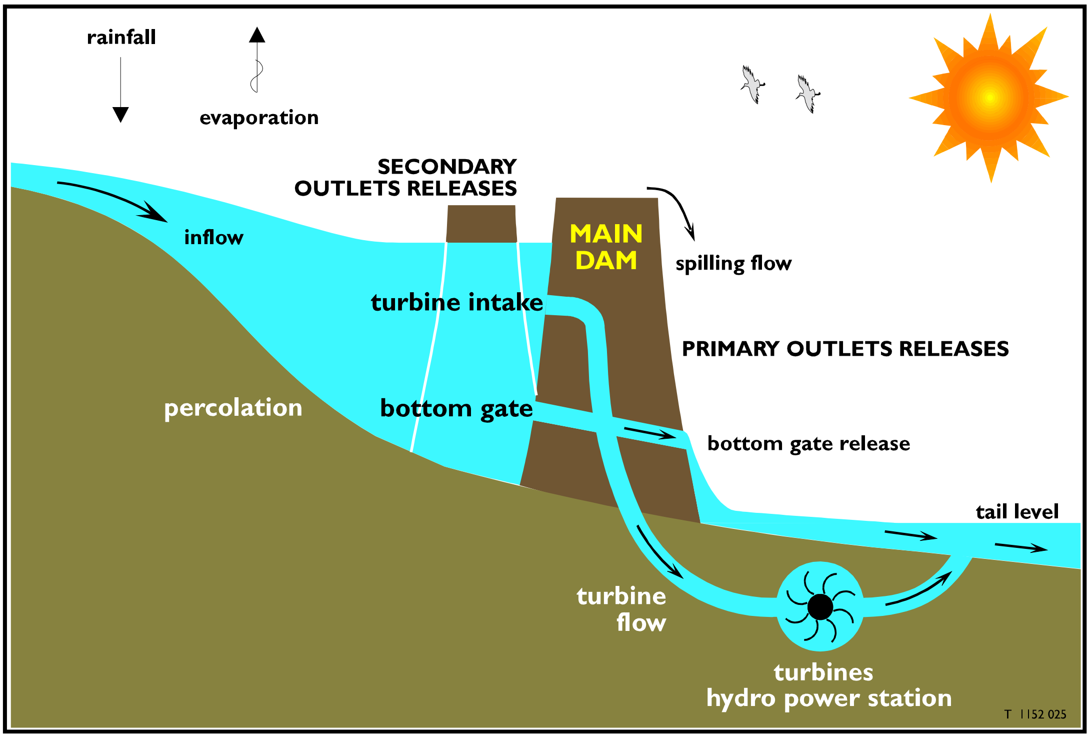

Figure 5-11 General representation of a reservoir in RIBASIM

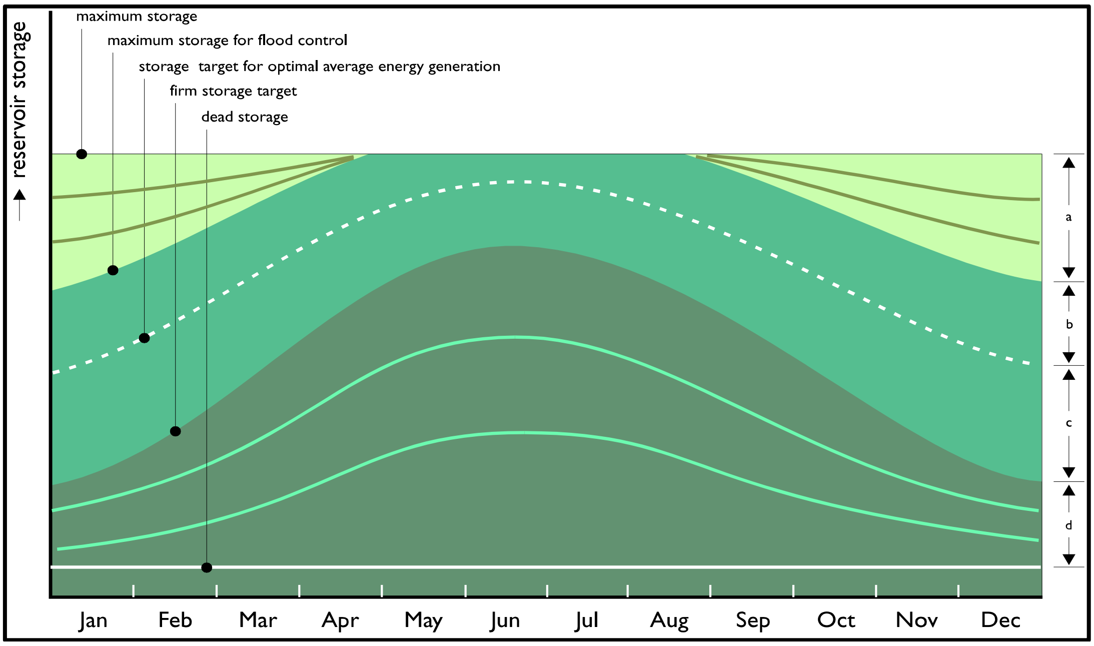

Figure 5-12 Reservoir operation rules in RIBASIM

5.3.4.2 Modelling irrigation water demand and supply

All irrigation areas are modelled as advanced irrigation node which means that the demand is computed based on a specified annual crop plan. An annual crop plan outlines the crops which are cultivated, the start time of land-preparation and some other characteristics. The defined crops are listed in Table 5-4. Different crop plans are defined for the various irrigation area. Figure 5-13 shows graphically the annual crop plan for Regio 10 in a crop-time diagram and the water demand over time. Data are obtained from the Aqua21 database, for details see Volume 2 (Annexes).

Table 5-4 List of defined crops

ID	Crop name
1	Potatoes
2	Sugar beet
3	Maize
4	Oats
5	Carrots and turnips

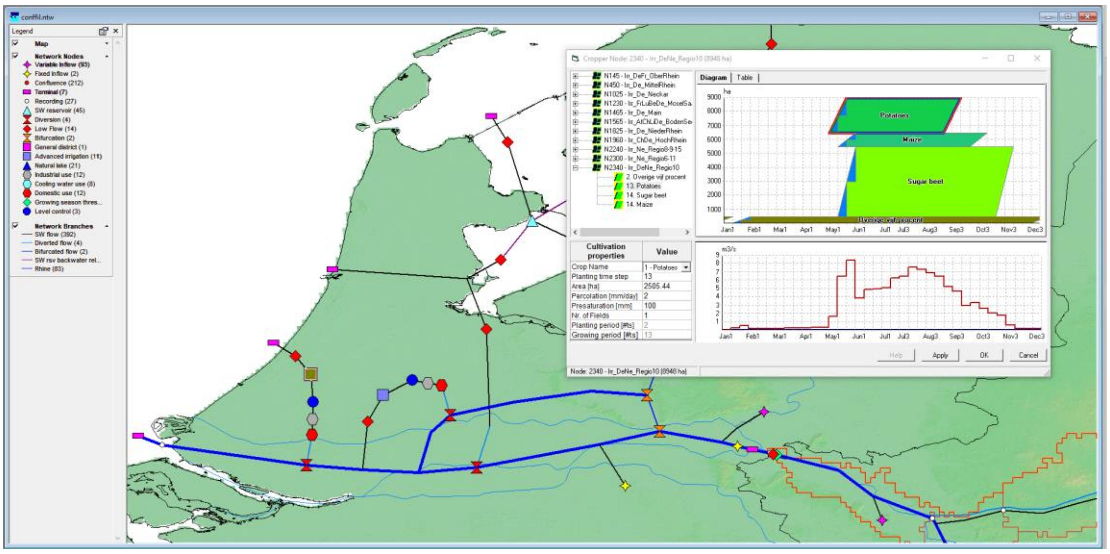

Figure 5-13 Irrigation demand based on annual crop plan for node Regio 10 in the Netherlands

5.3.5 Hydrological boundary conditions

The hydrological boundary parameters consist of:

1. The runoff for each sub-basin
2. The actual rainfall
3. The open water evaporation
4. The reference crop evapotranspiration
5. The 80% dependable rainfall
6. The recording flow

5.3.6 Infrastructure

The network contains 45 reservoirs and 21 natural lakes with a volume of 10 Mcm or more. Their distribution over the various riparian countries is listed in Table 5-5. Further details on the reservoirs and lakes in the model are provided in Volume 2 (Annexes).

Table 5-5 Distribution of reservoirs and natural lakes with storage bigger than 10 Mcm in the model

Country	# of reservoirs	# of natural lakes
Swiss	22	17
Germany	18	1
France	3	3
Luxembourg	1	
Netherlands	1	

5.3.7

5.3.8 Water users

The location of the various nodes in the schematization representing the water users and sectors are shown in Figure 5-14 till Figure 5-19. Those are:

- Domestic (drinking water) use
- Industrial use
- Cooling water
- Lignite mining
- Irrigated agriculture
- Navigation flow threshold
- Growing season flow threshold
- Region flushing (the Netherlands)
- Level control (the Netherlands)

The network schematization contains separate nodes for the cooling water. Those are not used yet as the cooling water demand is included in industrial water use.

The domestic and industrial water demand including cooling water was derived following the method of Wada et al. (2011). Deltares and Utrecht university updated and improved the water demand maps with the latest data from:

- EUROSTAT for water use and demand per country
- World Bank for population statistics and GDP
- Satellite derived Corine land cover data for mapping the industrial areas.

More details on the water demand calculations used in the model are given in Volume 2 (Annexes), Chapter 4.

The lignite mining is represented with a general district node for which a multiple year demand and discharge timeseries is specified in the files Disdemnd.tms and Disdisch.tms. Presently the demand is set on 0.0 m^3/s and the discharge on 10 m^3/s (Ruijgh, 2019).

Growing season flow threshold: Maintaining a minimum river discharge at Lobith is extremely relevant for agricultural production, salt management and navigation in the Netherlands. The "*Landelijke Coordinatiecommissue Waterverdeling*" (LCW) in the Netherlands formulated discharge thresholds that trigger action once discharge of the Rhine falls below this value (Ruijgh, 2019).

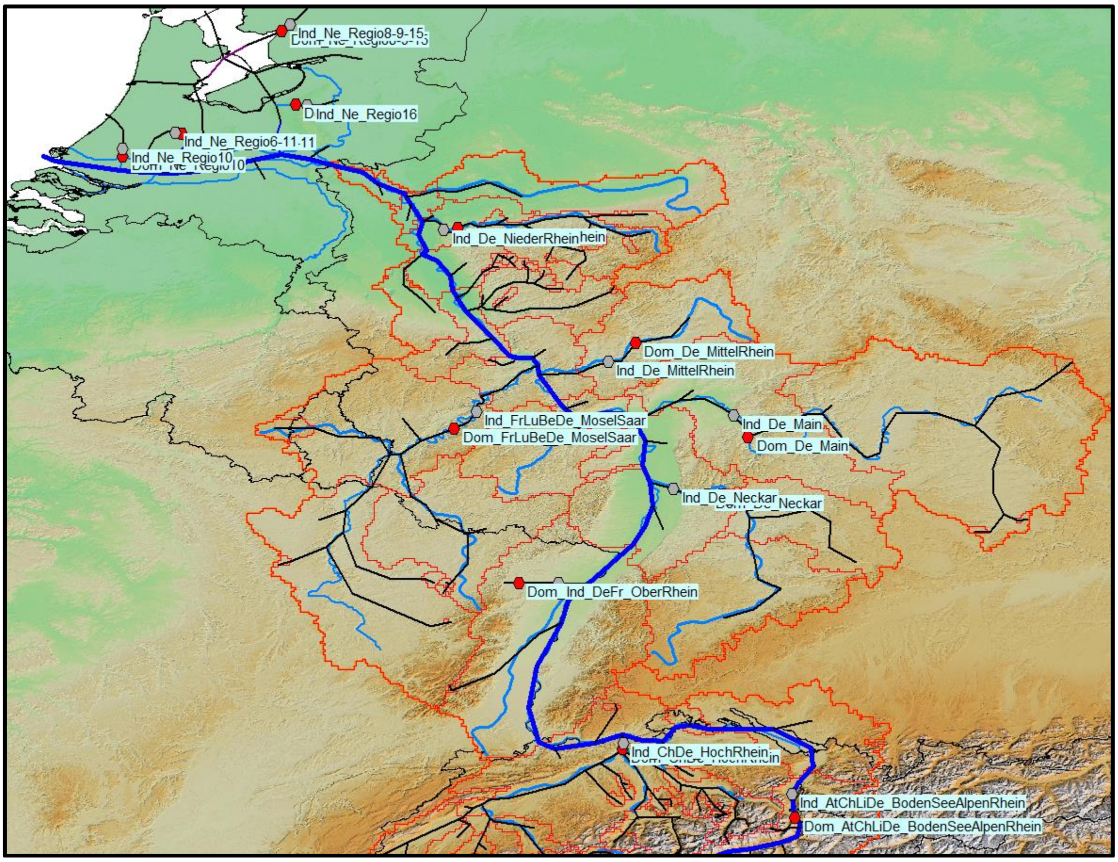

Figure 5-14 Overview of the domestic and industrial demand nodes

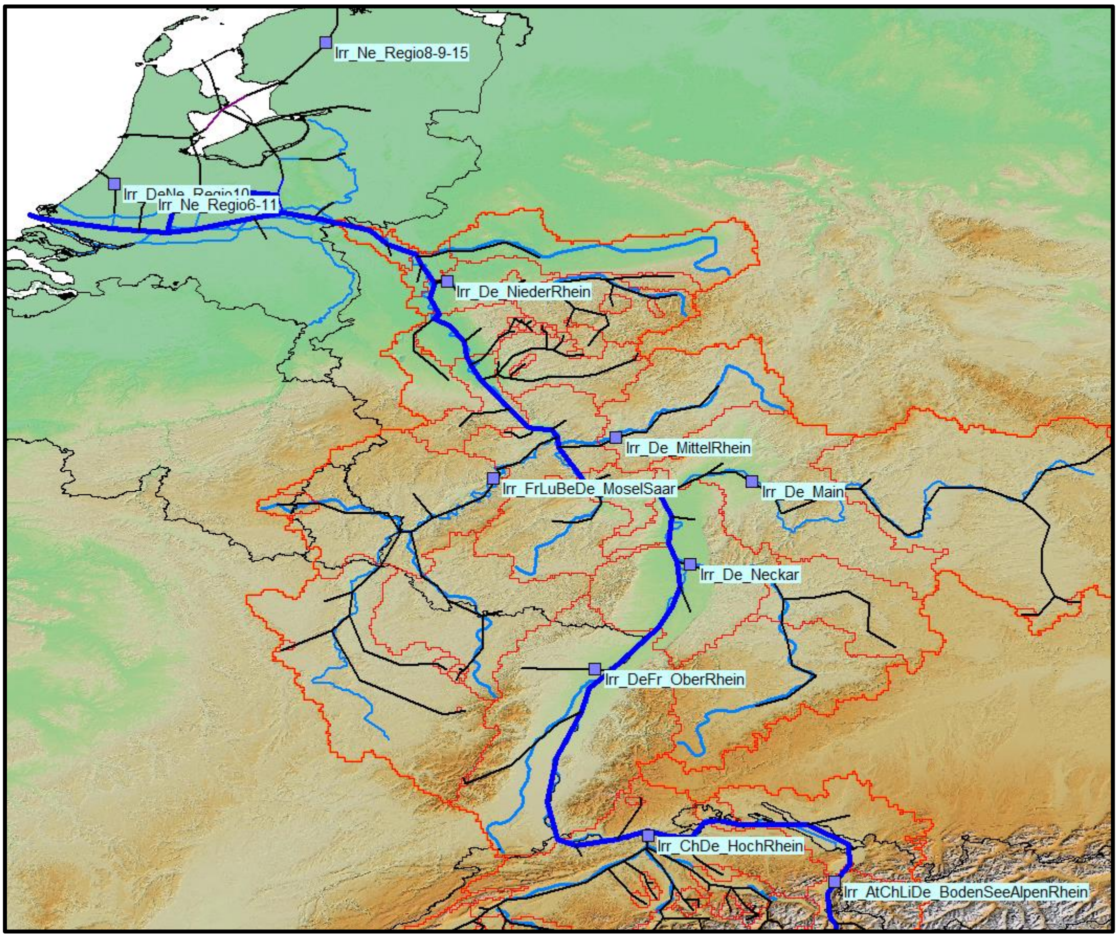

Figure 5-15 Overview of the irrigation nodes

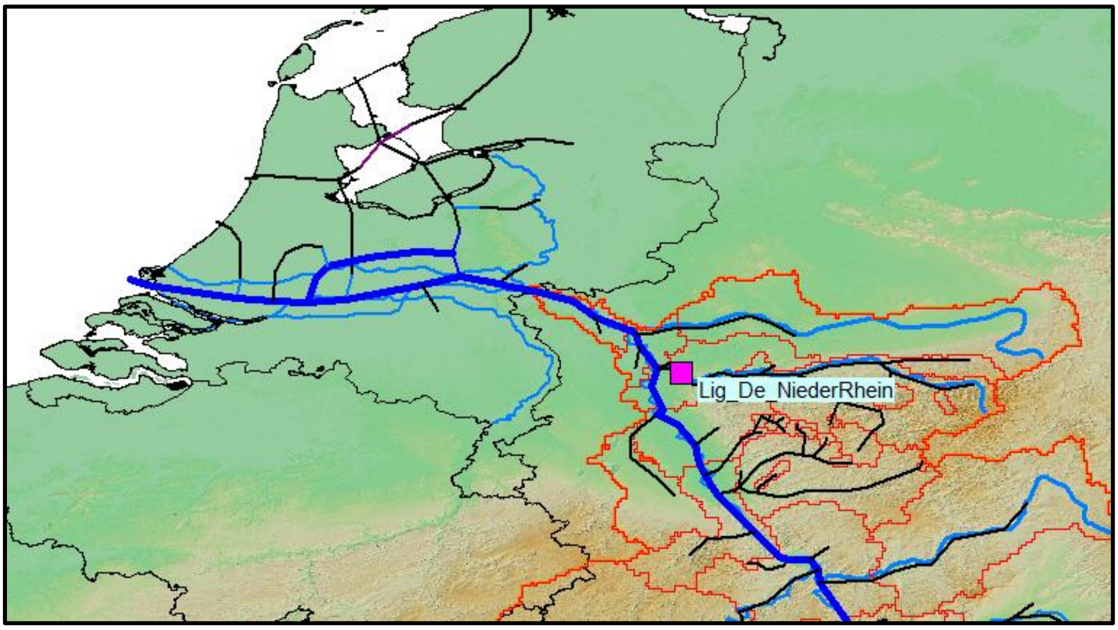

Figure 5-16 Overview of lignite mining node

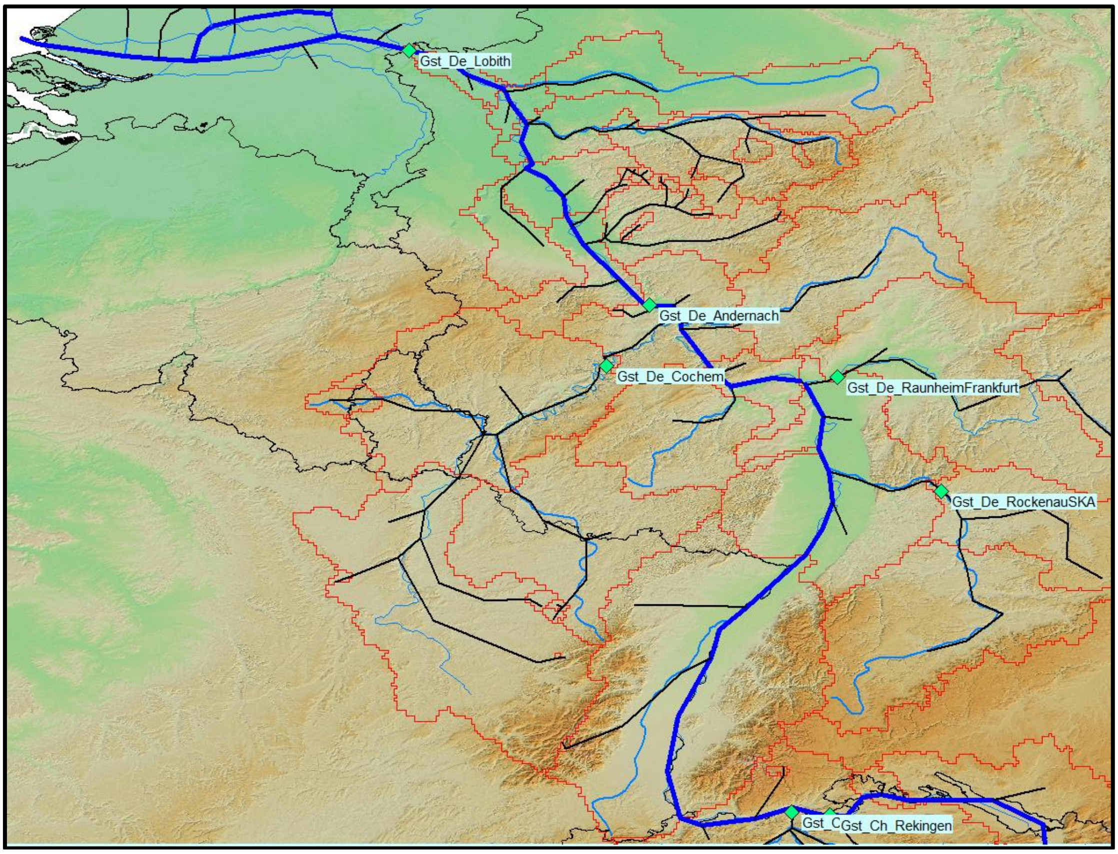

Figure 5-17 Overview of the Growing season flow threshold

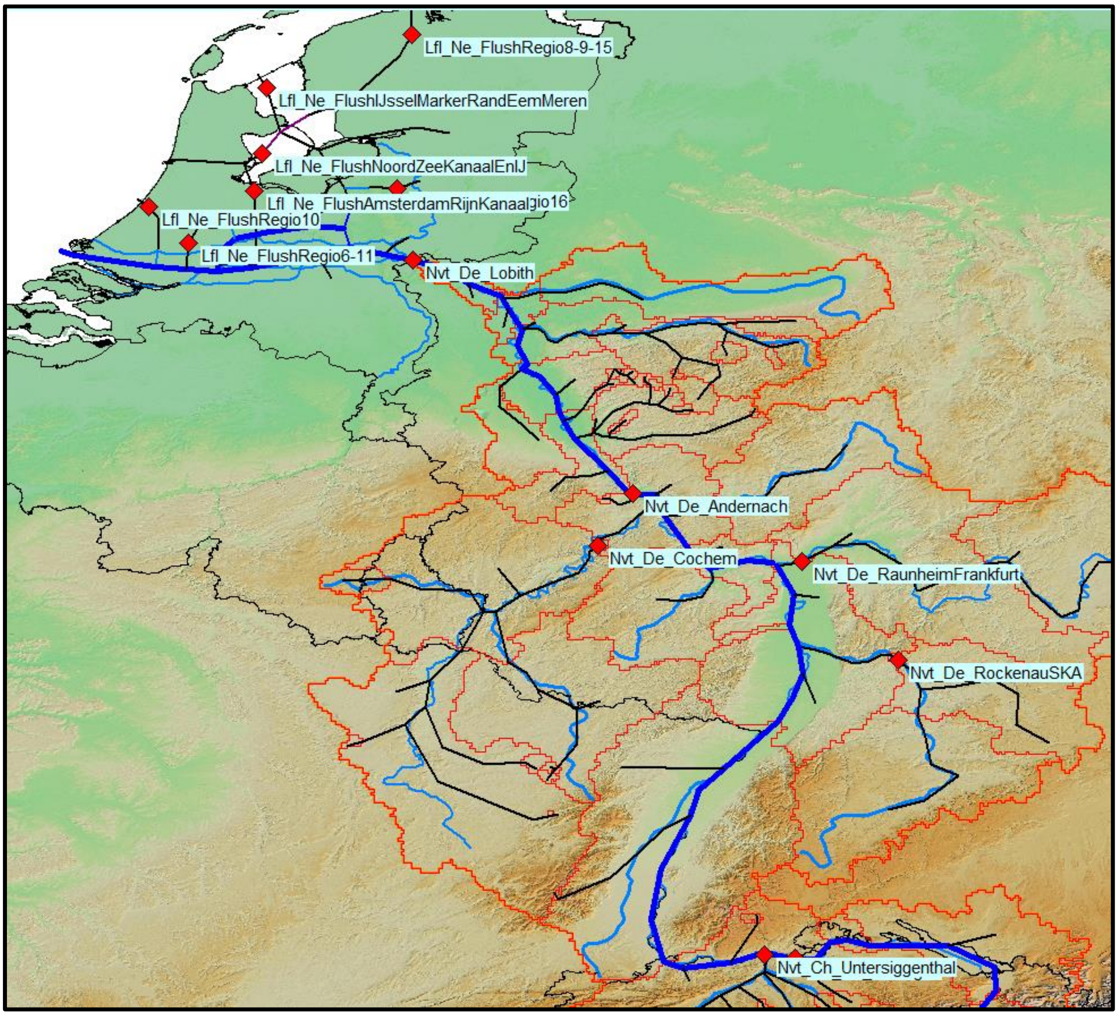

Figure 5-18 Overview of the flushing and navigation low flow nodes

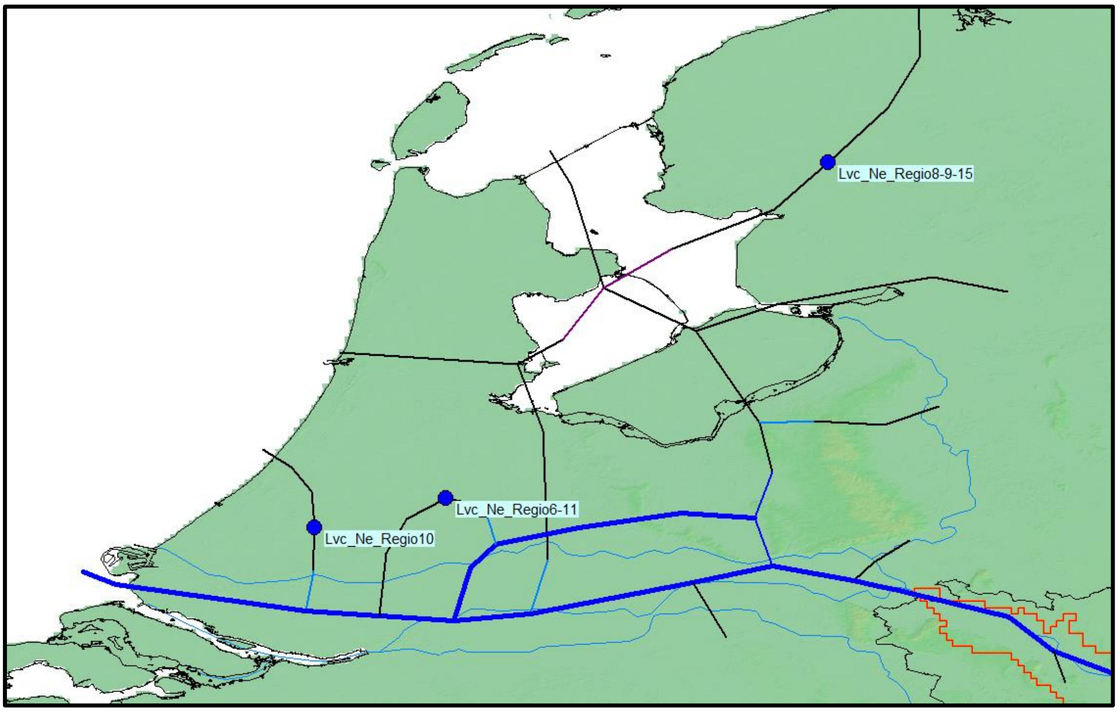

Figure 5-19 Overview of the level control ("peilbeheer") nodes

5.3.9 Scenarios, measures and strategies

5.3.9.1 General

The type of scenarios and management actions which can be defined explicitly are given in Table 5-6. Combination of scenarios are also possible.

Table 5-6 Type of scenarios and management actions

Hydrological	The set of hydrological time series like inflow, rainfall, evaporation, etc.
Climate change	The change in hydrological parameters due to climate change
Land-use and population	The size of the population and irrigation area change
Agriculture sector	The applied crop plan per catchment (sub-basin)
Basic water quality	The set of substances and associated waste loads and/or concentrations (in lookup table format). This scenario is only required if the basic water quality computation is used
Management action	The combination of measures (strategy)

Hydrological scenarios

A hydrological scenario consists of several time series files like runoff, rainfall, evaporation etc. Different hydrological scenarios can be defined and modelled by the creation of a scenario in the sub-directory "*Hydrolog*". The definition of hydrological scenarios is outlined in chapter 5.1 of the "*RIBASIM Version 7.00 User manual*".

Climate change scenarios

The annual and multiple year time series for rainfall, evaporation, discharge, drainage and runoff are stored in a hydrological scenario directory, as described in the appendix F of the "*RIBASIM Version 7.00 User manual*". Climate change can be interpreted as a variation on the hydrological time series. Different scenarios for climate change can be defined and modelled by the creation of a scenario in the sub-directory "*Climate*". The definition of climate change scenarios is outlined in chapter 5 of the "*RIBASIM Version 7.01 User manual Addendum*".

Land-use and population scenarios

A land-use and population scenario influence the public water supply nodes, and/or irrigation nodes in the river basin network schematization. Different land-use and population scenarios can be defined and modelled by the creation of a scenario in the sub-directory "*Landuse*". The definition of land-use and population scenarios is outlined in chapter 5 of the "*RIBASIM Version 7.01 User manual Addendum*".

The area of all irrigation nodes per catchment can be updated with a specified percentage (%). Also, the number of inhabitants (population) and explicit demand values of all public water supply nodes per catchment can be updated with the specified percentage (%). For example, in the model data base it is outlined that Public water supply node "Delft" is located in catchment with label 1 and that the number of inhabitants is 200,000. Further in the land-use and population scenario the change of population in the catchment with label 1 is specified as an increase of 10 %, then the model uses 220,000 inhabitants for Delft at the computation of the public water supply demand in the simulation.

Agriculture sector scenarios
An agriculture sector scenario is only used if the river basin network schematization contains one or more “Advanced irrigation nodes”. Different agriculture sector scenarios can be defined and modelled by the creation of a scenario in the sub-directory “*Agricult*”. The agriculture sector scenario contains the new crop plan for all irrigation areas per sub-basin (catchment). The crop plan is the list of cultivations adopted by each Advanced irrigation node. So the crop plan of the Advanced irrigation nodes stored in the model data base is overwritten by the crop plan of the agriculture sector scenario. The definition of agriculture sector scenarios is outlined in chapter 5 of the “*RIBASIM Version 7.01 User manual Addendum*”.

Basic water quality scenarios
A basic water quality scenario consists of the defined substances and the waste load look-up tables. The definition of (basic) water quality scenarios is outlined in chapter 5.2 of the “*RIBASIM version 7.00 User manual*”. This scenario is only used if the basic water quality option is switched on in the model (possible with the “Define simulation period” task block).

Management actions
RIBASIM7 has a measure and strategies (M&S) database in which all management actions are defined which might need to be simulated for the basin analysis. A management action consists of a combination of measures. Each measure is defined separately. The measure overrules the data in the model database. For example, the measure to “Increase the Bigge dam height” is defined in the M&S data base. For the simulation case in which the effect of the increase of the Bigge dam height must be analysed, this management action is selected in the user interface. When the simulation is executed first the data from the Model database are read and next the data from the selected management action, which consists here of a new set of Bigge dam and reservoir characteristics. Those data will overwrite the previous read data from the Model database and are thus used for the simulation.

The definition of measures and combination of measures (strategies) is outlined in chapter 5 of the “*RIBASIM Version 7.01 User manual Addendum*”.

5.3.9.2 Scenarios, measures and management actions in Rhine002 model
The defined hydrological, agriculture, land-use and population, basic water quality and flow composition scenarios, and management actions (strategies) are outlined in Table 5.7 till Table 5.12. No measures are created yet.

Table 5.7 Hydrological scenarios in Rhine002 model (directory Hydrolog)

Scenario ID	Scenario name
W06	Wflow files run_catch_mm_20200625

Table 5.8 Climate change scenarios in Rhine002 model (directory Climate)

Scenario ID	Scenario name	Remarks
000	No hydrological data change	No change.
A01	All parameters CC (%): one value per series	Illustrative scenario
A02	All parameters CC (%) per series	Illustrative scenario

Table 5.9 Agriculture sector scenarios in Rhine002 model (directory Agricult)

Scenario ID	Scenario name	Remarks
000	No agriculture scenario (crop plan) data defined	Crop plan of the model database is used.

Table 5.10 Land-use and population scenarios in Rhine002 model (directory LandUse)

Scenario ID	Scenario name	Remarks
000	No land-use and population scenario data defined	Data in the model data base is used.

Table 5.11 Management action (strategies) in Rhine002 model (directory Actions)

Management action ID	Name	Remarks
000	No management actions.	No measures.

Table 5.12 Basic water quality and user defined flow composition scenario in Rhine002 model (directory Lookup)

Scenario ID	Scenario name	Remarks
000	No flow composition and water quality data	
363	Example look-up tables: T36 - concentrations	Illustrative scenario
367	Rhein flow composition - user defined	User defined flow composition for the Rhine

6 Model application

6.1 First results of model reliability

In order to get an impression of the reliability of the present model setup, a comparison is made of the measured and simulated discharges at a number of gauging stations. In Table 6.1 a list is given of the gauging stations that were used, with series of 1989 – 2000, grouped according to their position (tributary or main river). More recent data were not available for the stations.

Table 6.1 Gauging stations

Main river (order upstream – downstream):	Tributary:
• Diepoldsau • Neuhausen • Basel • Maxau • Worms • Mainz • Kaub • Andernach • Koln • Dusseldorf • Wesel • Lobith	• Cochem (Mosel) • Hattingen (Ruhr) • Menden (Rurh) • Rurhort (Rurh) • Schermbeck (Lippe)

In Figure 6-1 the location of the various gauging stations is shown.

In this paragraph, a number of hydrographs are shown for some of the stations. Although the fit is not always perfect, there is a good agreement between the measured and simulated series.

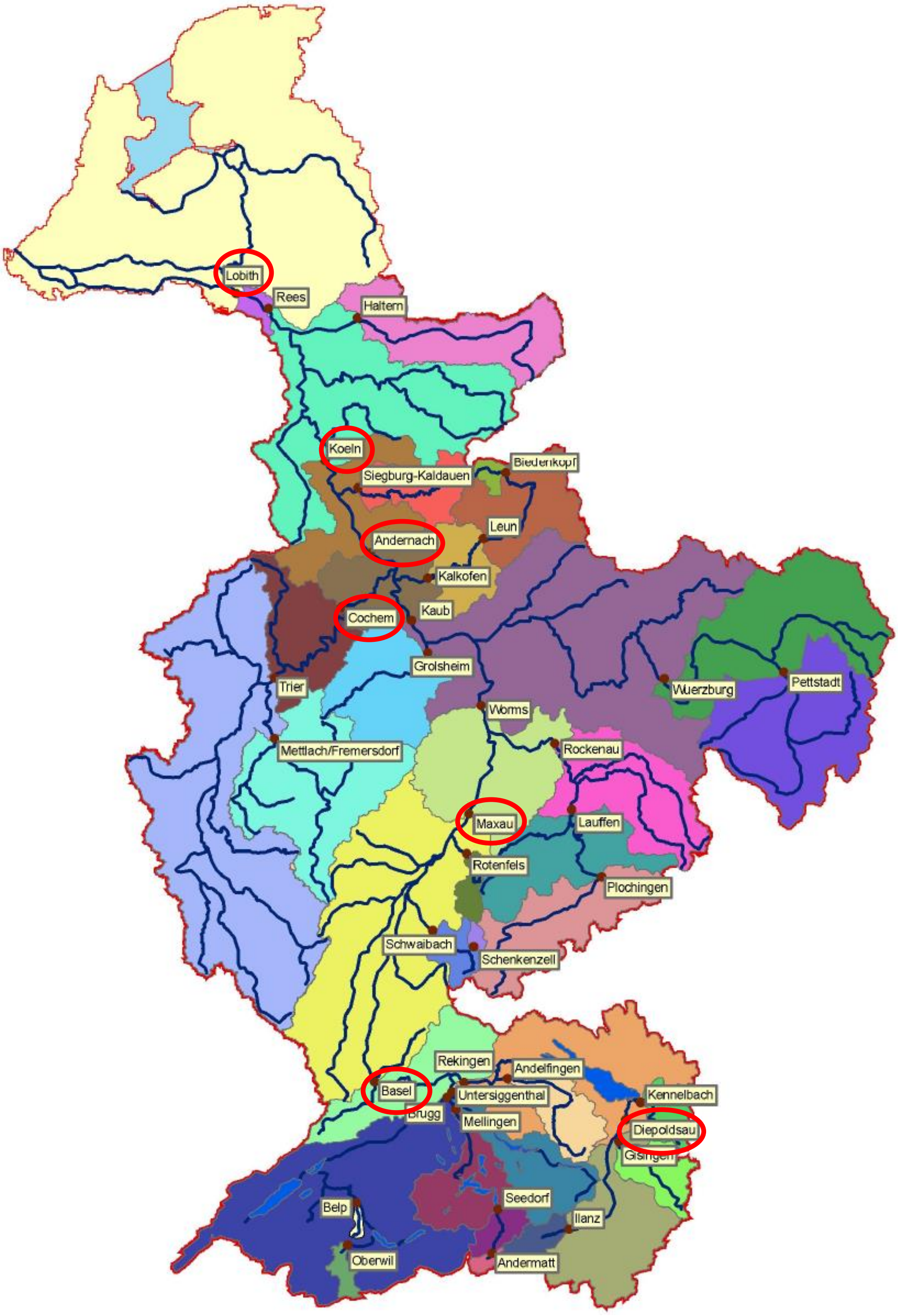

Figure 6-1 Location of the various gauging stations in the Rhine basin

For the flows from Switzerland, a discrepancy can be seen at the station of Diepoldsau, that can be taken as representative for the inflow towards the Bodensee (Figure 6-2), which shows an underestimation of the low flows, while the peaks are seriously overestimated. Most likely this is due to the lack of sufficiently accurate data on the reservoirs in this tributary. The damping of the Bodensee is clear from the graph for Neuhausen (Figure 6-3) when compared to Diepoldsau, with the former having a much higher and stable low flow.

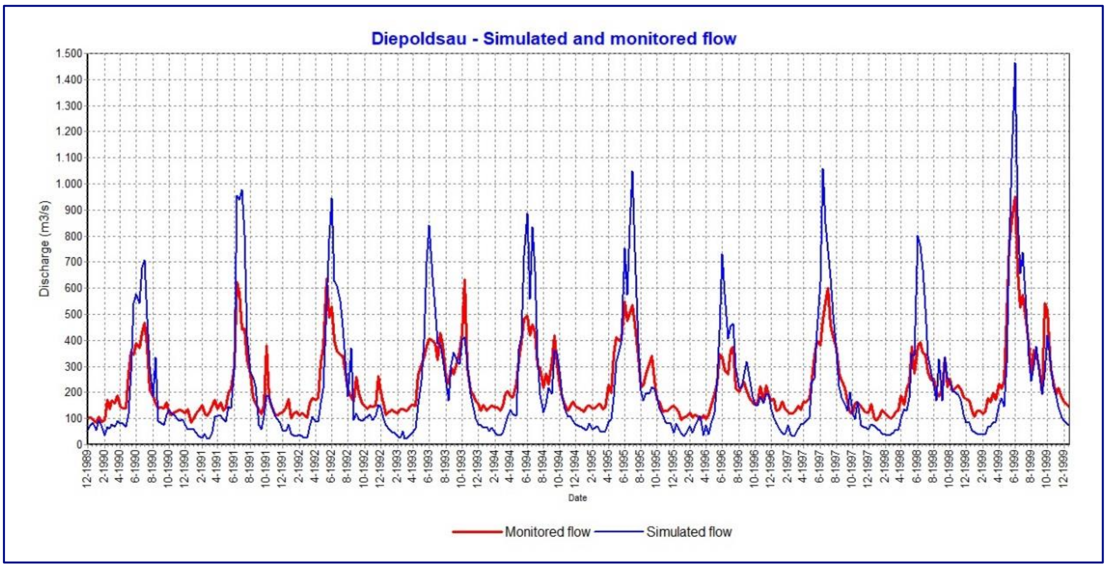

Figure 6-2   Simulated and measured monthly discharges at gauging station Diepoldsau (Rhein)

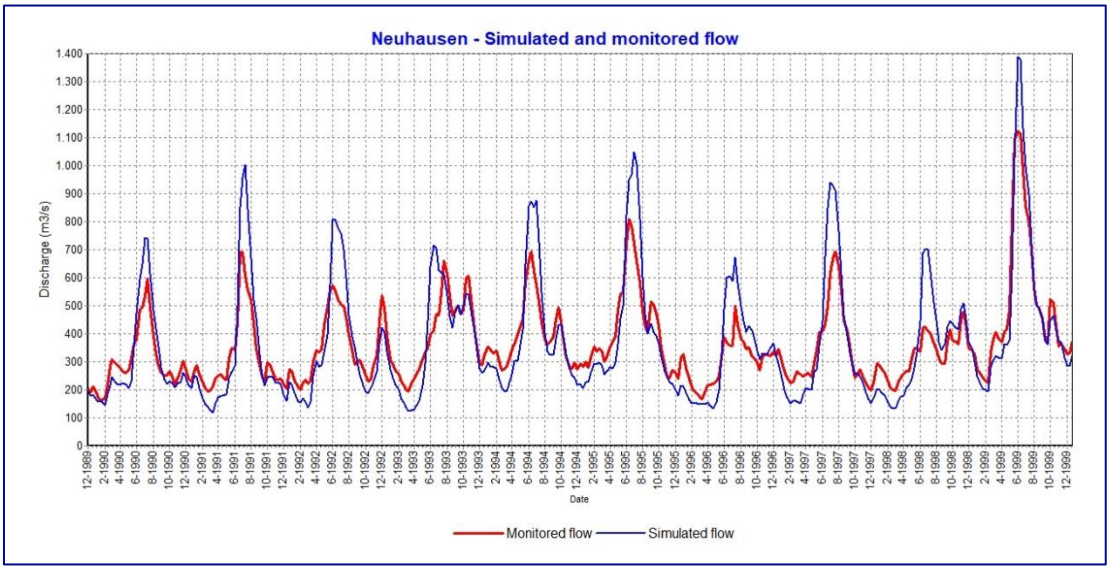

Figure 6-3   Simulated and measured monthly discharges at gauging station Neuhausen (Rhein)

For one of the largest tributaries, the Mosel, at the station of Cochem (Figure 6-4), the hydrograph is very well reproduced for the lower discharges, but peak flows can be off.

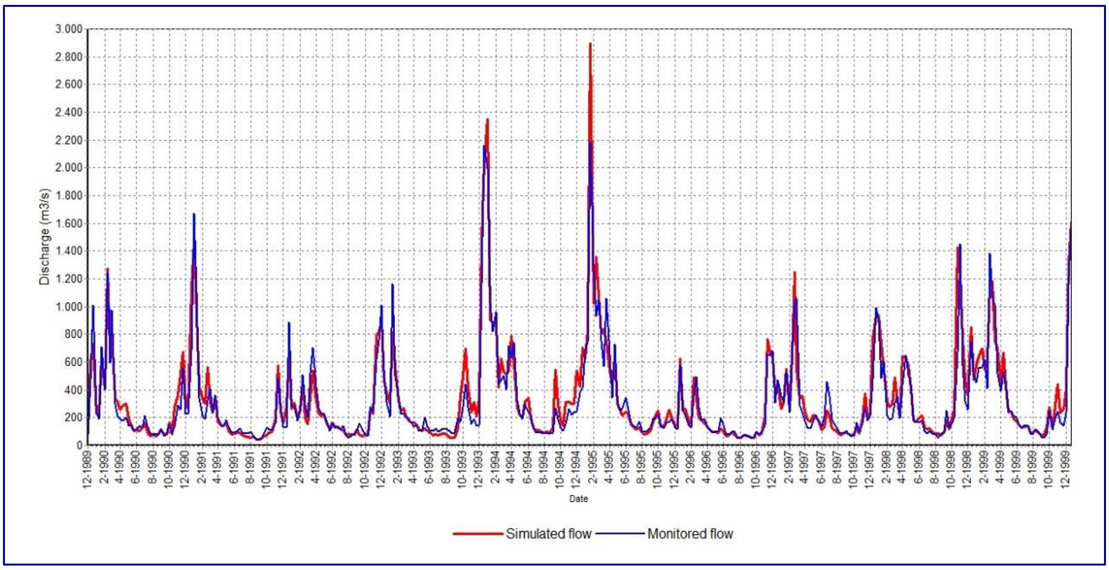

Figure 6-4   Simulated and measured monthly discharges at gauging station Cochem (Mosel)

Another example is shown for the Lippe at Schermbeck in Figure 6-5, which is a much smaller tributary. Also here the simulated hydrographs follows quite closely the measured values in the lower reach, but peak flows are seriously overestimated.

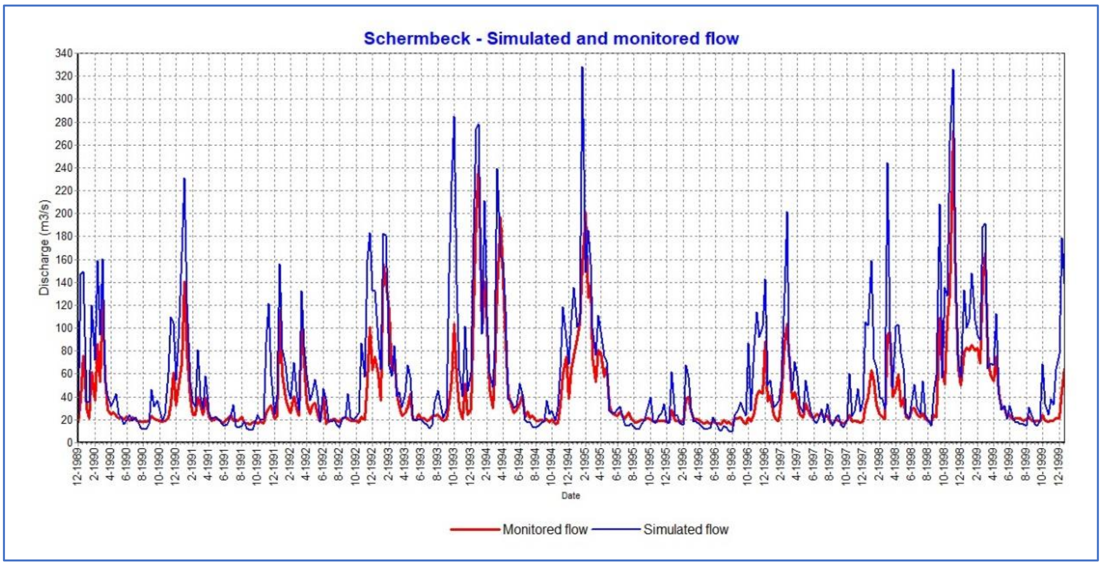

Figure 6-5   Simulated and measured monthly discharges at gauging station Schermbeck (Lippe)

The simulation of the Ruhr, represented by the stations Hattingen and Menden, shows a different picture (Figure 6-6 and Figure 6-7). Here, the peak flows are underestimated, although this is clearer for Menden than at Hattingen.

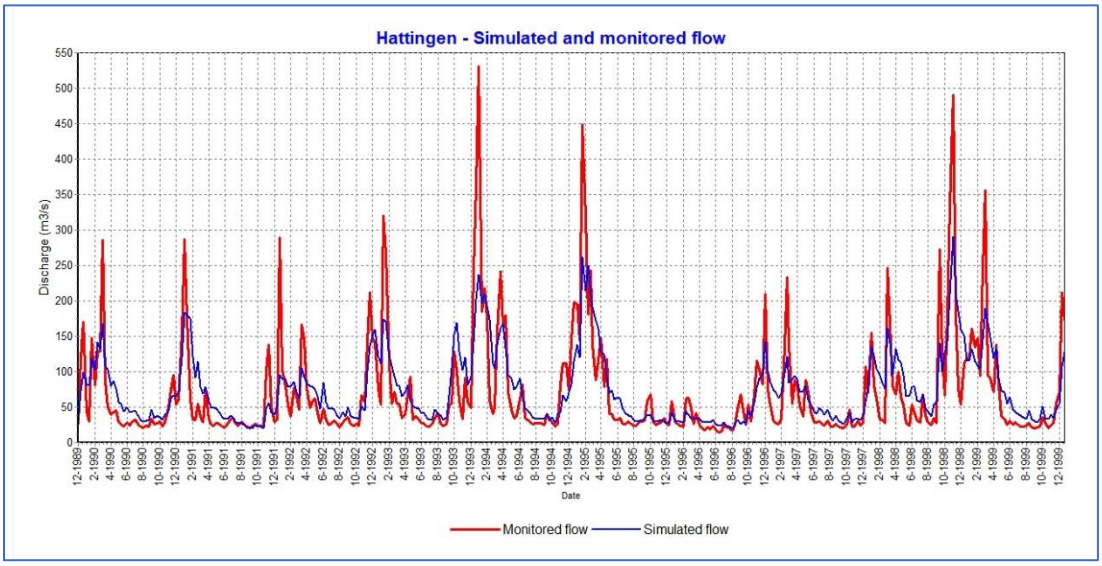

Figure 6-6   Simulated and measured monthly discharges at gauging station Hattingen (Ruhr)

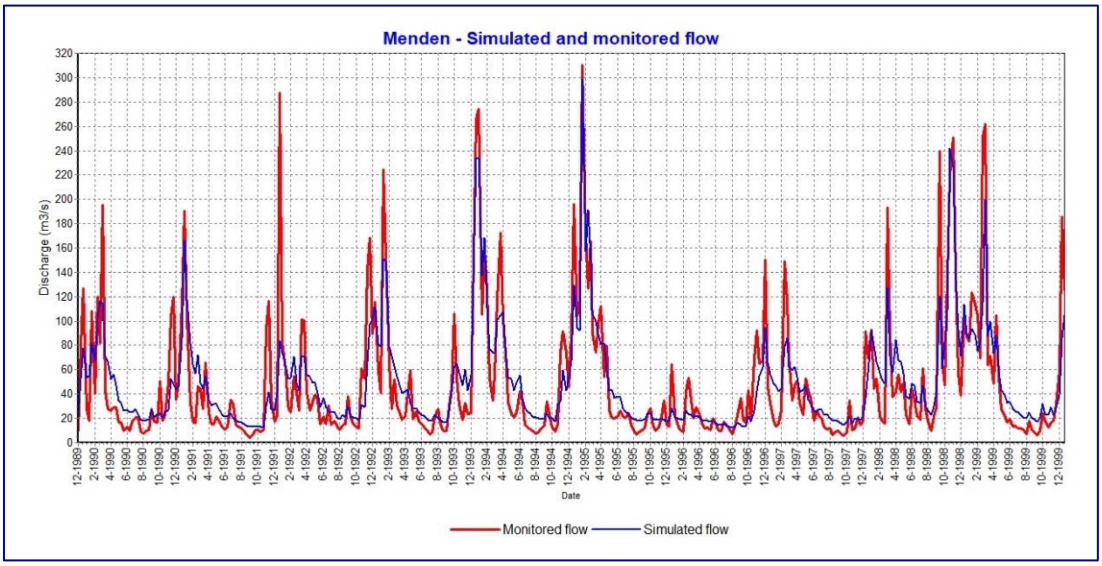

Figure 6-7   Simulated and measured monthly discharges at gauging station Menden (Ruhr)

On the main Rhine river, the station of Maxau downstream from Switzerland shows a similar pattern between simulated and measured flows (Figure 6-8), but much less pronounced, which indicates the inflow from the other tributaries downstream from the Bodensee, such as the Aare, are well represented. Further downstream, at Kaub (Figure 6-9) and Andernach (Figure 6-10) the same pattern occurs, with the latter slighter better, probably due to the good representation of the Mosel in the model. Further downstream, at Koln (Figure 6-11) and Lobith (Figure 6-12), the low flows are represented very well, with only slight overestimation of the peak flows.

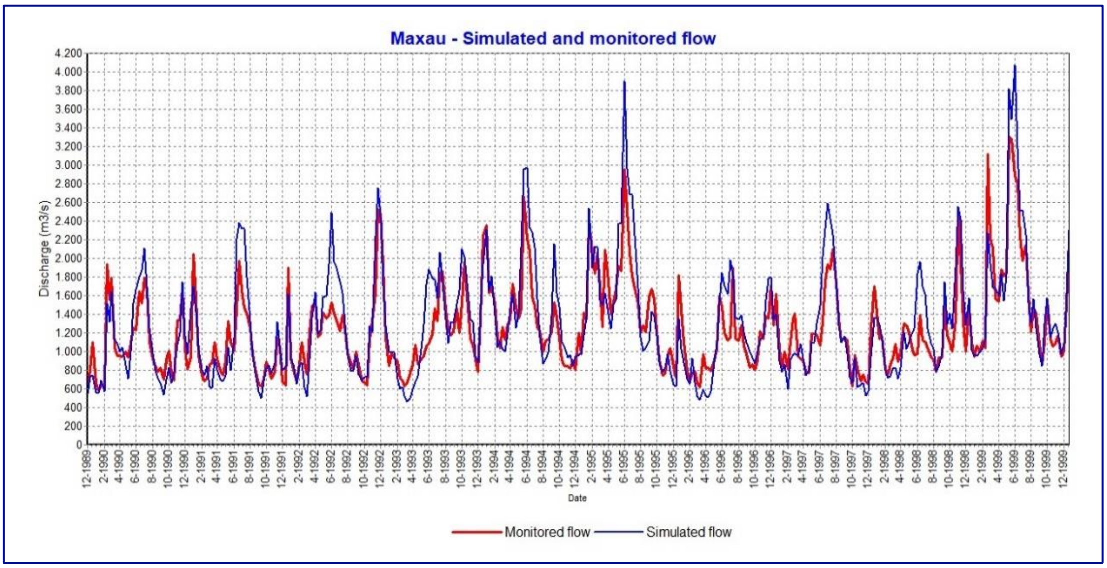

Figure 6-8 Simulated and measured monthly discharges at gauging station Maxau (Rhein)

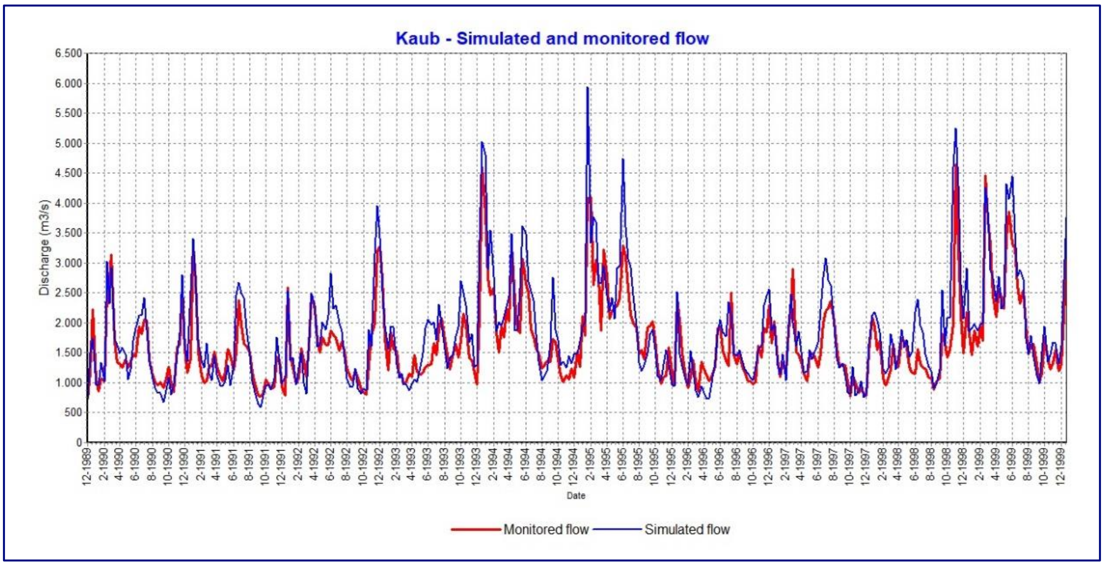

Figure 6-9 Simulated and measured monthly discharges at gauging station Kaub (Rhein)

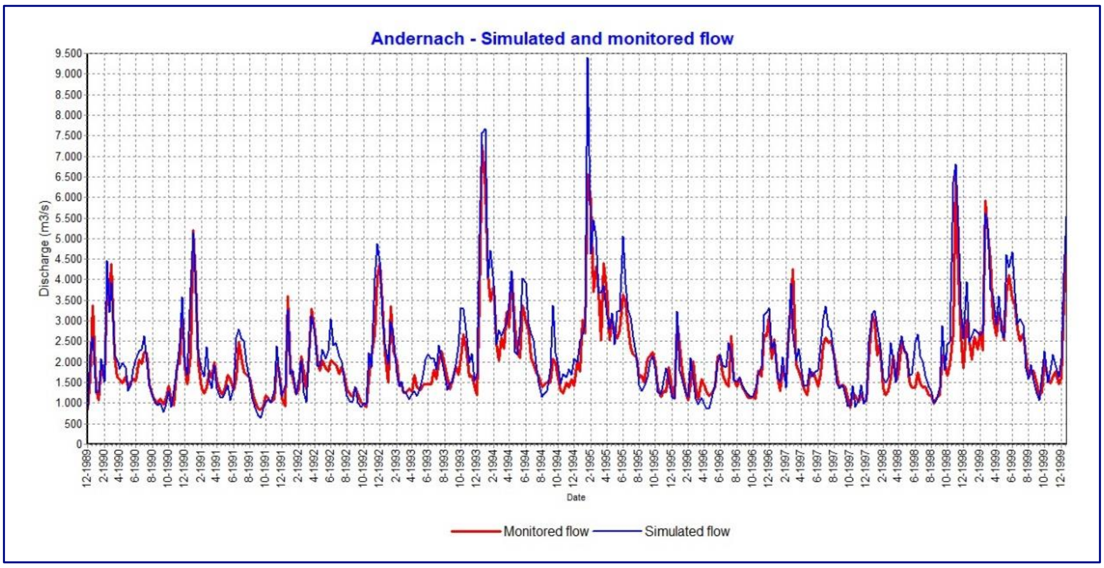

Figure 6-10 Simulated and measured monthly discharges at gauging station Andernach (Rhein)

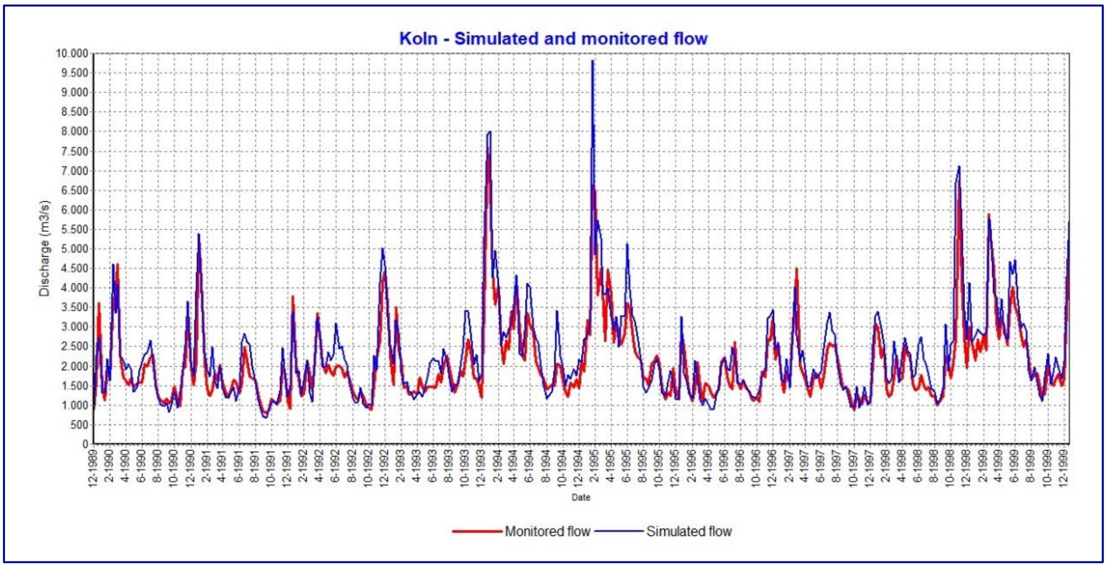

Figure 6-11 Simulated and measured monthly discharges at gauging station Koln (Rhein)

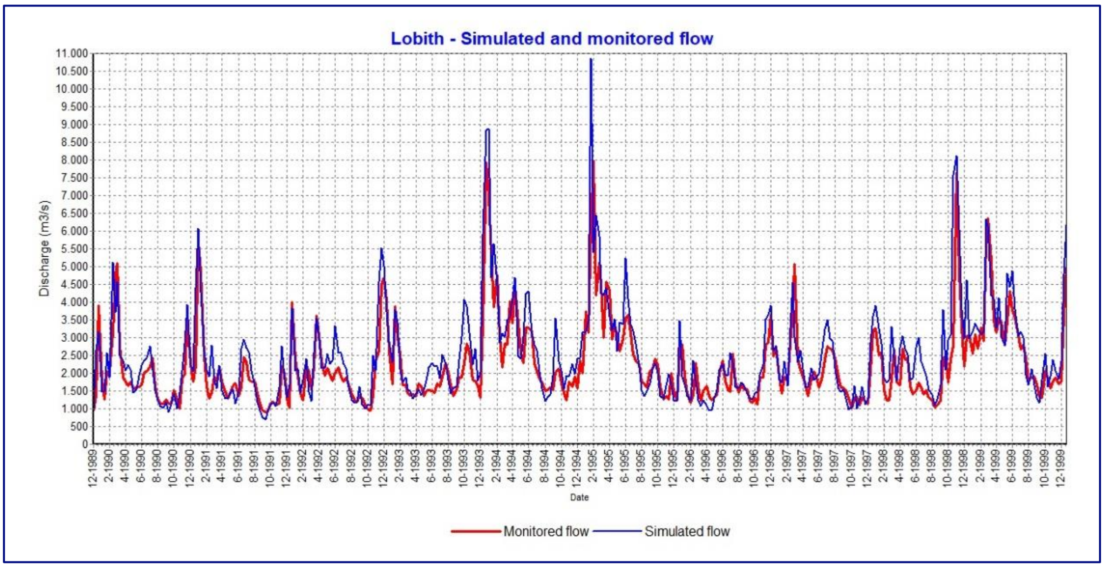

Figure 6-12 Simulated and measured monthly discharges at gauging station Lobith (Rhein)

6.2 Comparison water demand values Rhine001 and Rhine002.

As the two RIBASIM models of the Rhine basin make use of completely different information for their water demands, it is likely that this will also result in a difference in water demand values.

Especially for the irrigated agriculture, the differences are very large. In the next table, the results are shown for the two applications.

	RHINE001	RHINE002
Irrigation area	**m³/s**	**m³/s**
Irr_De_NiederRhein	1,703	7,515
Irr_De_MittelRhein	0,958	2,64
Irr_FrLuBeDe_MoselSaar	1,338	1,345
Irr_De_Main	1,497	4,489
Irr_De_Neckar	0,688	3,887
Irr_DeFr_OberRhein	0,511	4,377
Irr_ChDe_HochRhein	0,612	7,499
Irr_AtChLiDe_BodenSeeAlpenRhein	0,266	1,392
Irr_DeNe_DeltaRhein	8,541	8,194
TOTAL	**13,082**	**41,338**

As a result, in the Rhine002 model with the present hydrological situation, severe shortages are found as can be seen in Figure 6-13.

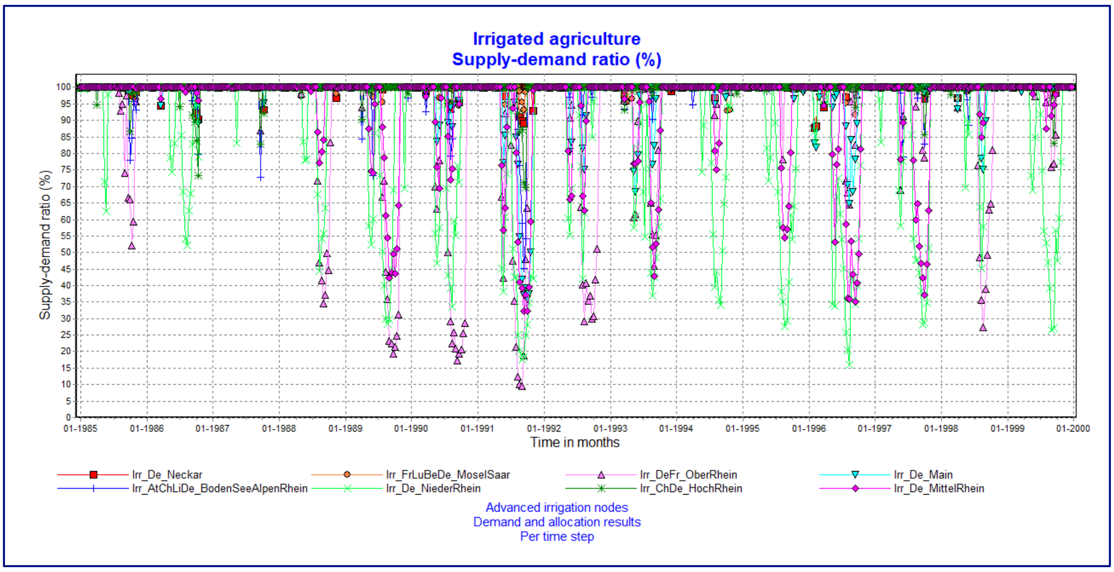

Figure 6-13 Supply-Demand ratio for Advanced Irrigation Nodes (Rhine002 model)

This forms a strong contrast with the Rhine001 model, and thus also with the original spreadsheet model, which showed no shortages for the irrigated agriculture, although that simulation was only made for a period of one year. Given that the demand values in the Rhine 002 model have been derived mainly from global data sets, it is important to contrast them with measured values as far as those are available. This highlights the importance of obtaining data from local sources on the water demands and discuss the present values in the model with regional experts.

6.3 Example of a Scenario analysis

The original spreadsheet model could also be used for scenario analysis, but this is rather limited as there is only one year of simulation. In the present Rhine002 model, it is possible to make simulations over longer time periods, in the order of 25 – 30 years, with historic inflow series. Therefore, it is also more interesting to examine the impact of expected changes in the future, both in terms of water availability (e.g. due to climate change) as well as due to socio-economic changes. As an example, in this paragraph, a scenario has been simulated with a 100% increase in irrigated area in all the irrigation nodes in the model. As the irrigated agriculture has shown already to experience severe shortages during the low flow periods, it is expected that such a drastic increase in the irrigated area will lead to much larger shortages. It is also important to examine what will happen to the flow on the main Rhine river. Although none of the irrigation areas takes water directly from the Rhine itself, but only from the tributaries, the major increase in demand will likely lead to a significant decrease in the flow in the Rhine itself.

First a comparison can be made between the supply-demand ratio (%) of the irrigated agriculture for the existing irrigated agriculture and the scenario with 100% increase in area. The former was shown in Figure 6-13, while the latter is shown in Figure 6-14.

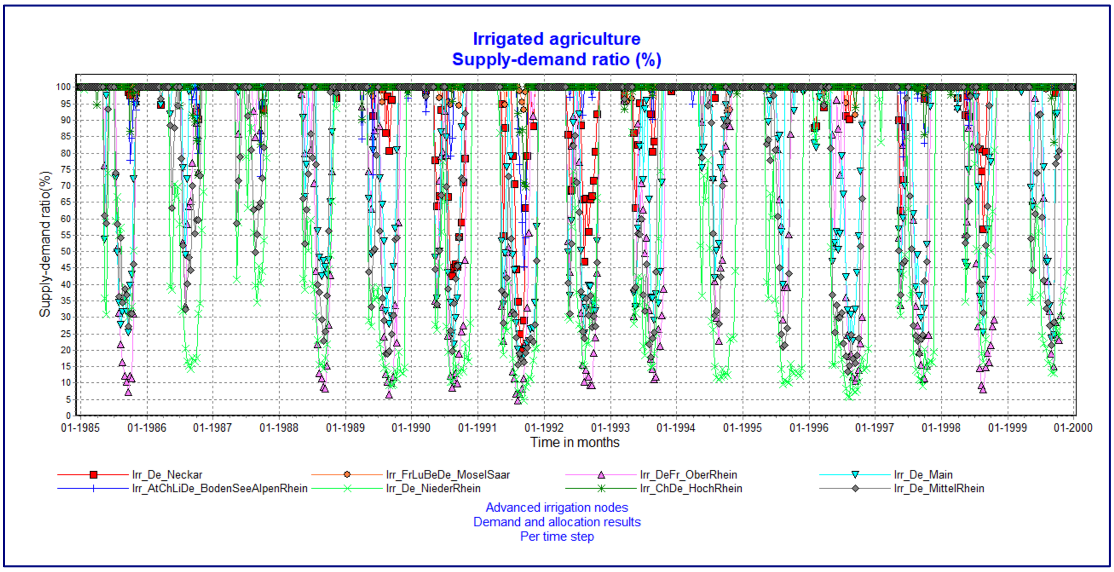

Figure 6-14 Supply-Demand ratio for Advanced Irrigation Nodes (double irrigation area)

It is clear that for the 100% increase scenario, a much more severe situation occurs with more frequent and larger shortages.

When looking more in detail to one of the irrigation areas, the Mittel Rhein, see Figure 6-15, it can be seen that the impact of the increase in irrigation area is very large.

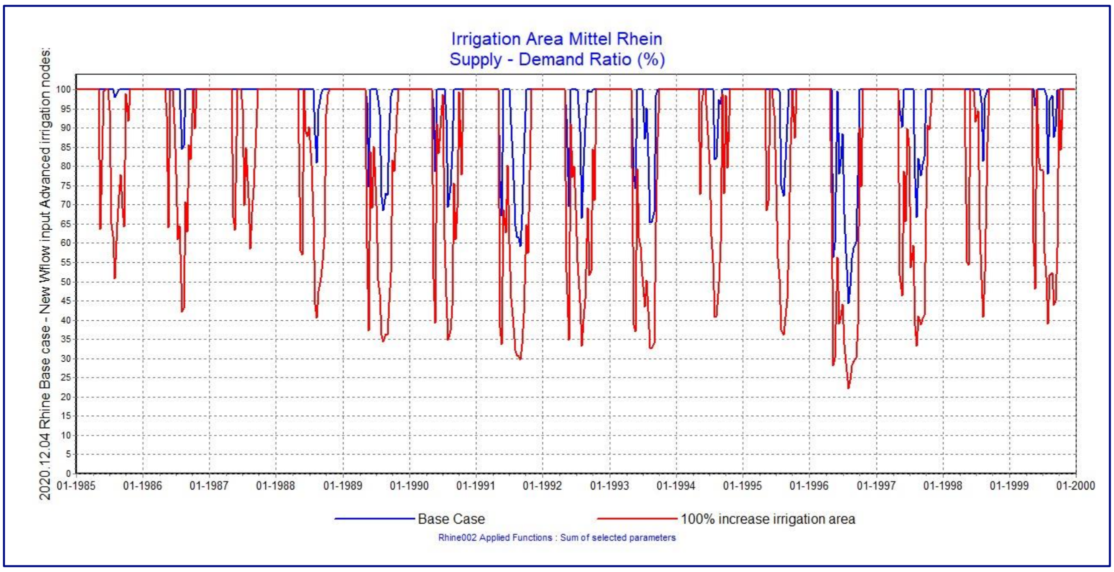

Figure 6-15 Supply-demand ratio for irrigation water (%) for Mittel Rhein irrigation areas (base case and 100% increase scenario)

In Figure 6-16 the absolute shortage (in m^3/s) is shown for the irrigated agricultural area of the Mittel Rhein for the base case and the 100% increase scenario. For the base case, occasional shortages occur, but for the 100% increase scenario, the shortages become much more frequent and severe.

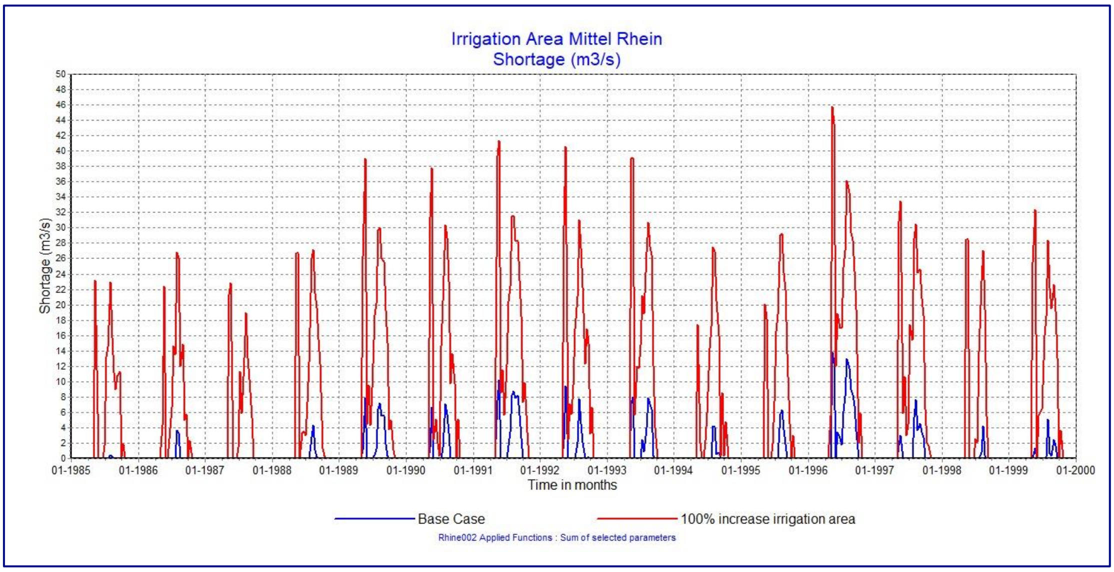

Figure 6-16 Shortages in supply to irrigation areas (Base case and 100% increase scenario)

Subsequently for a number of key locations, the impact of the increase in irrigation area is examined on the river discharge. For the average and above average flows, the change in irrigation water demand has a negligible impact on the river flow. However, during low flow situations, the change may become significant. As an example, in Figure 6-17 the change in flow is shown for the location of Andernach, focussing on the low flow. In order to show the actual impact on the flow, it is useful to make a graph of the absolute change in discharge, shown for Andernach in Figure 6-18. This figure shows that the change varies widely over the year, as also the irrigation water demand fluctuates strongly with the seasons.

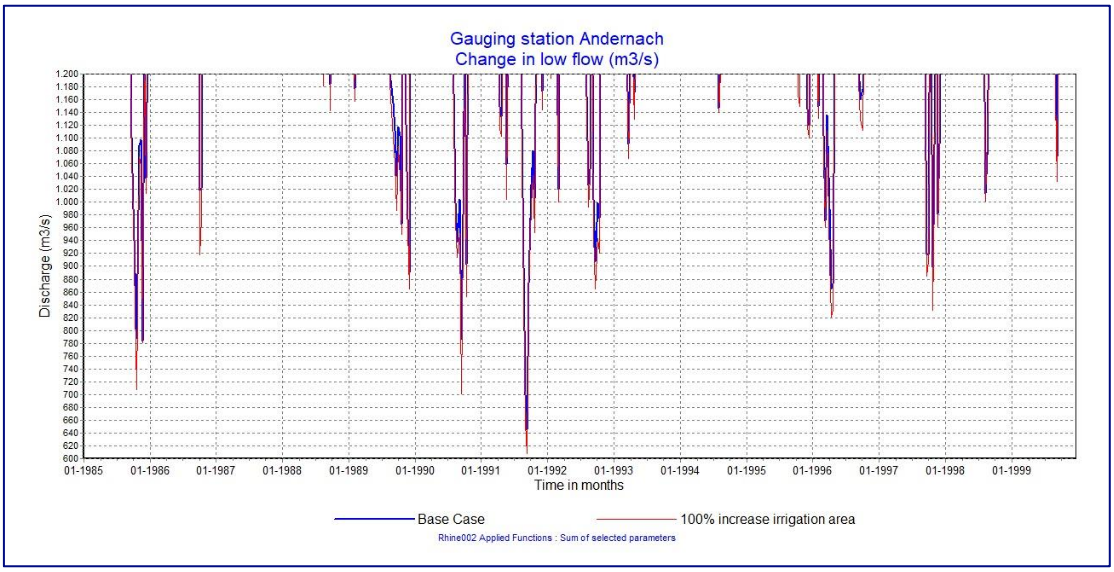

Figure 6-17 Low flow discharge hydrograph at Andernach for the two scenarios (y-axis cut off at 1200 m^3/s)

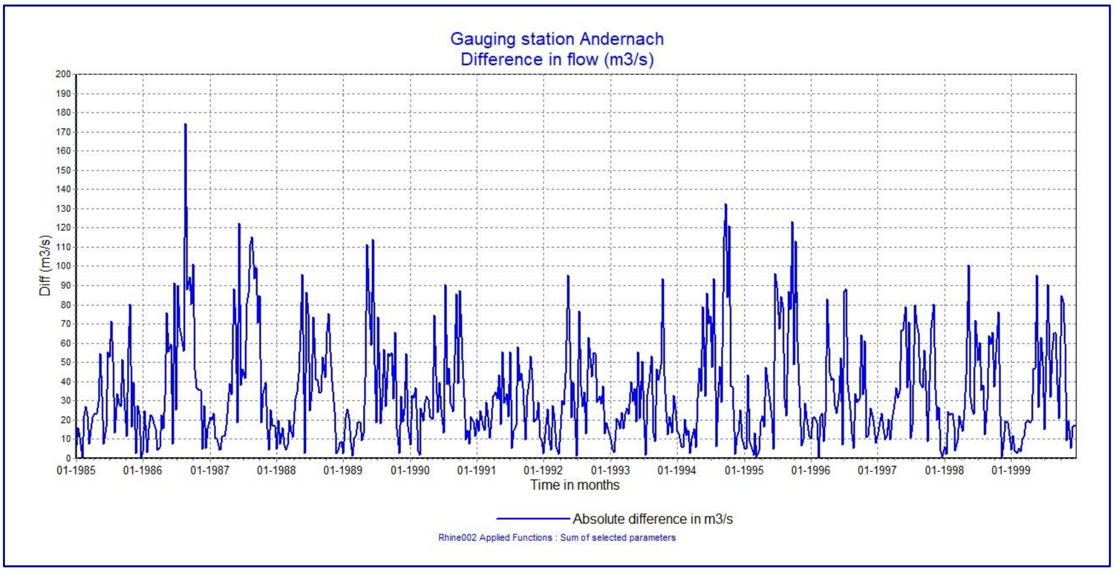

Figure 6-18 Absolute difference in m^3/s in river discharge at Andernach between the two scenarios

Further downstream the impact is likely to become larger. In Figure 6-19 the difference in river discharge due to the 100% increase in irrigation area is shown for four gauging stations along the main Rhine river, at Basel, Maxau, Kaub and Lobith. This shows how the impact of the scenario increases in downstream direction.

Using the Rhine002 model, there are many more possibilities to examine the impact of changes in the Rhine basin. However, in order to make well-founded decisions on the outcome of such a model, effort should still be made first to improve on the calibration of the model, both for the hydrological input as well as the various demand nodes in the model. The same applies to the reservoir characteristics that have a major influence on the behaviour of the river system.

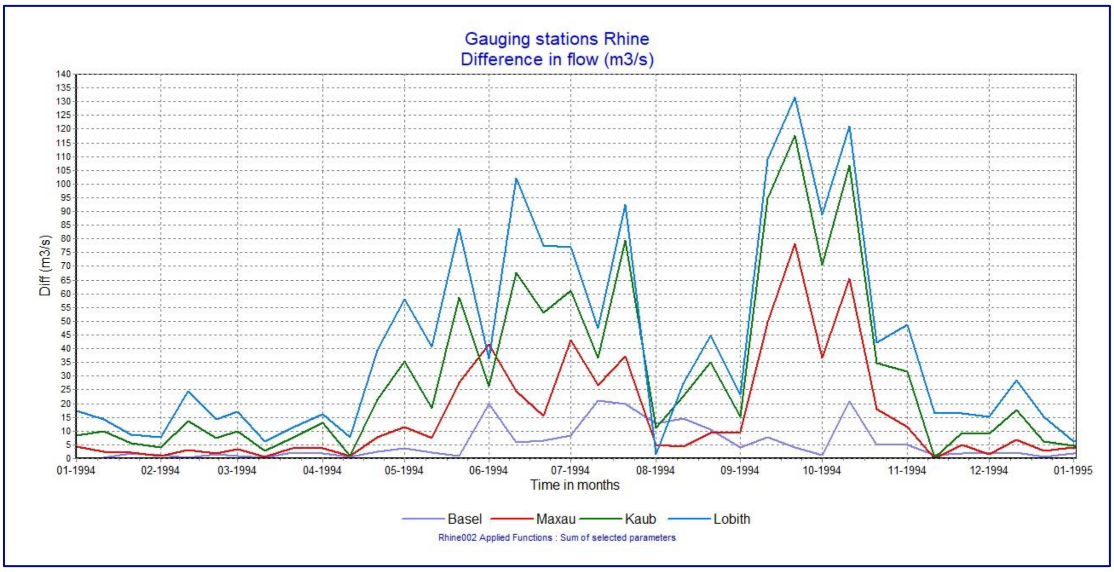

Figure 6-19 Absolute difference in m^3/s in river discharge for various stations between the two scenarios

7 Observations and recommendations

A first version of a detailed water balance model of the whole Rhine River basin has been setup using the Wflow rainfall-runoff model and the software RIBASIM for river basin simulation as first step in the development of a planning tool for the entire river basin. The model is not yet fully developed, but when in the future it can be used for a large variety of analysis related to:

- Changes in water availability, particularly due to climate change;
- Impact of socio-economic changes in the Rhine basin on the flow regime.

Although the present model provides a good basis for the start of simulations to examine behaviour of the system under different scenarios, a number of improvements are still foreseen. For this reason, we recommend the following activities:

1. The location of the major and most critical water user abstractions must be identified and explicitly included in the node – link network schematization. Now all water users in a sub-basin are lumped into 1 specific node;
2. The model data of the infrastructure dame, reservoirs and natural lakes is not complete yet. The data of the natural lakes is still missing so the natural lakes are inactive in the model. The data of the reservoirs must be checked and improved as various data has been entered as illustrative and best guess;
3. The present water demands for irrigated agriculture are based on global data sets of crop characteristics. The results should be checked and supplemented with local data and discussed with regional experts;
4. The model data of the other demand sectors, like public water supply, industry and cooling water is now based on global data. This can be checked and improved with local data from the Rhine countries, and discussed with regional experts;
5. The Wflow model is still being improved and the results can directly be added to the Rhine002 model as separate hydrological scenario;
6. When a complete model data base has been setup a model calibration and verification must be carried out.

8 References

EEA (European Environment Agency): Corine Land Cover (CLC) 2018, Version 20. Retrieved from https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata

Eilander, D., van Verseveld, W., Yamazaki, D., Weerts, A., Winsemius, H. C., and Ward, P. J.: A hydrography upscaling method for scale invariant parametrization of distributed hydrological models, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-582, in review, 2020.

Hengl, T., de Jesus, J. M., Heuvelink, G. B. M., Gonzalez, M. R., Kilibarda, M., Blagotic, A., et al.: SoilGrids250m: Global gridded soil information based on machine learning, 2017. PloS one, 12(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

Imhoff, R. O., van Verseveld, W. J., van Osnabrugge, B., & Weerts, A. H.: Scaling Point-Scale (Pedo)transfer Functions to Seamless Large-Domain Parameter Estimates for High-Resolution Distributed Hydrologic Modeling: An Example for the Rhine River, 2020 Water Resources Research, 56(4), [e2019WR026807]. https://doi.org/10.1029/2019WR026807

Passchier, R. and F. Sperna Weiland: KHR/CHR Umbrella project on Socio-economic Scenarios – Literature Study, Deltares, 2020.

Ruijgh, E, Integrated Overview of the effects of socio-economic scenarios on the discharge of the Rhine, Deltares, 2019

Schellekens, J., 2014. Wflow Documentation. The latest version can be obtained from http://wflow.readthedocs.io/en/latest/

Van der Krogt, W.N.M., Boccalon, A., River Basin Simulation Model RIBASIM Version 7.00 User Manual, Deltares, 2013

Van der Krogt, W.N.M., River Basin Simulation Model RIBASIM Version 7.01 User Manual Addendum, Deltares, 2015

Van der Krogt, W.N.M., River Basin Simulation Model RIBASIM Version 7.00 Technical Reference manual, Deltares, 2008

Wada, Y., van Beek, L.P.H. and Bierkens, M.F.P.: Modelling global water stress of the recent past: on the relative importance of trends in water demand and climate variability. Hydrology and Earth System Sciences, 15 (12):3785–3805, 2011b.

Wildenhahn, E., Klaholz, U.: Grosse Speigerseen im Einzugsgebiet des Rheins, Internationale Kommission fur die Hydrologie des Rheingebiet (CHR), 1996

Yamazaki D., D. Ikeshima, J. Sosa, P.D. Bates, G.H. Allen, T.M. Pavelsky MERIT Hydro: A high-resolution global hydrography map based on latest topography datasets. Water Resources Research, vol.55, pp.5053-5073, 2019, doi: 10.1029/2019WR024873

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