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Summary

The results of the “Integrated Overview on the effects of socio-economic scenarios on the discharge of the Rhine river” 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 addition, it was recognized in the study that changes in reservoir management could influence the distribution in time of the discharge of the Rhine river significantly. In the meeting the 84th CHR-meeting in Dornbirn, October 2019, it was agreed to execute a follow up project, in which these three items are addressed. Original plan was to conduct 4 workshops with expert, 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 upon to postpone the workshops and start to build a planning tool for scenario exploration instead. The activity was preceded by a literature research study (Passchier et al, 2019).

The envisioned planing 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.

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** which was originally developed in Excel in the SES Rhine project (Socio-Economic Scenarios) and has been converted to RIBASIM. 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.
2. The **Rhine002 model** which has been developed making use of mainly open global datasets. The hydrological boundaries (runoff, rainfall, evaporation) are generated in the rainfall-runoff model Wflow. The 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 simulates multiple year time series of decade time step and a computational time step of 1 day. All existing and potential water users and major water storage infrastructure like dams, reservoirs and natural lakes are considered. This first version of a 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.

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.

Contents

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

1.1 Background

Low flows and the effects of water consumption of various socio-economic sectors 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 prepared in close cooperation with BfG for CHR an “*Integrated Overview of the effects of various Socio-Economic sectors and Scenarios on the discharge of the Rhine*”: the SES-Rhine project. 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.

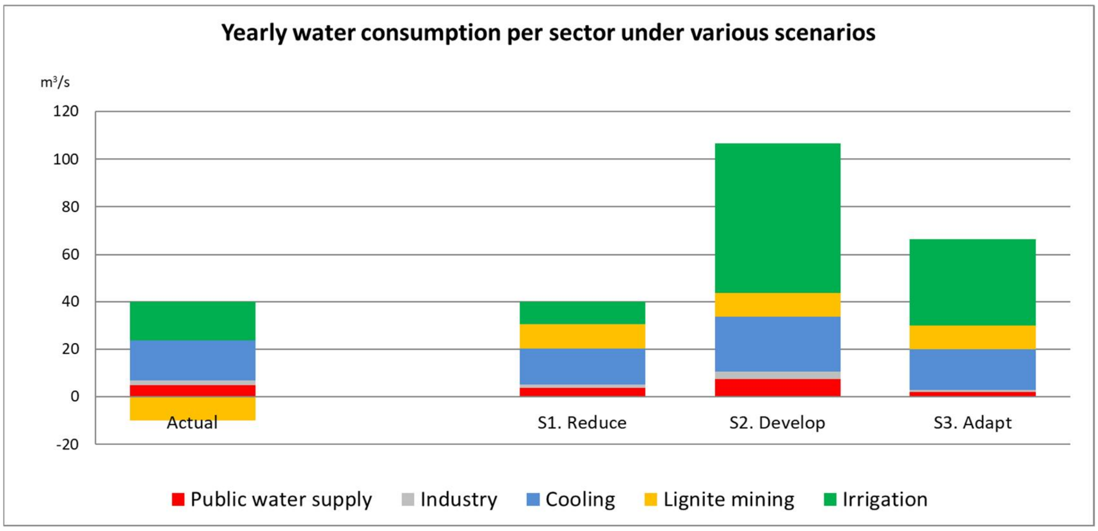


Figure 1-1 Estimated yearly consumption per sector in the Rhine river basin under various scenarios (Ruijgh, E. 2019)

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” (*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 (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*” 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 addition, it is recognized in the study that changes in reservoir management could influence the distribution in time of the discharge of the Rhine river significantly.

In the meeting 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) and
- 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 – in preparation of the workshops
- 3 Workshops with experts on the above-mentioned topics, 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. And 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 Austria, Switzerland and Germany, 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 (part of Phase B) was suspended for the time being. This issue was also discussed in the Steering Group meeting in October.

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 course, 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 we have followed in the previous stage of the SES-course (in 2018/2019).

In addition, end of 2019, the literature study report was submitted to the CHR (Passchier et al, 2019). The literature study together with the previous Integrated Overview in Excel 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 was originally developed in Excel in the previous phase of the Socio-Economic Scenarios course and has been converted to RIBASIM. 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 current situation and three scenarios.
2. The **Rhine002 model** which has been developed making use of mainly open global datasets. The hydrological boundaries (runoff, rainfall, evaporation) are generated in the rainfall-runoff model Wflow. The 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 simulates multiple year time series of decade time step and a computational time step of 1 day. All existing and potential water users and major water storage infrastructure like dams, reservoirs and natural lakes are considered. 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.

As was stated earlier, the model Rhine002 has already been used to include new information and data, and also use has been made of newly obtained results of hydrological model simulations with the wflow model of the Rhine basin.

1.4 Outlook Planning tool for scenario analysis

The planing 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. 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, 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. 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. Make the shift from open global datasets to national and local datasets, based modelling (RIBASIM 003 version) by engaging national expert representatives.
- 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.

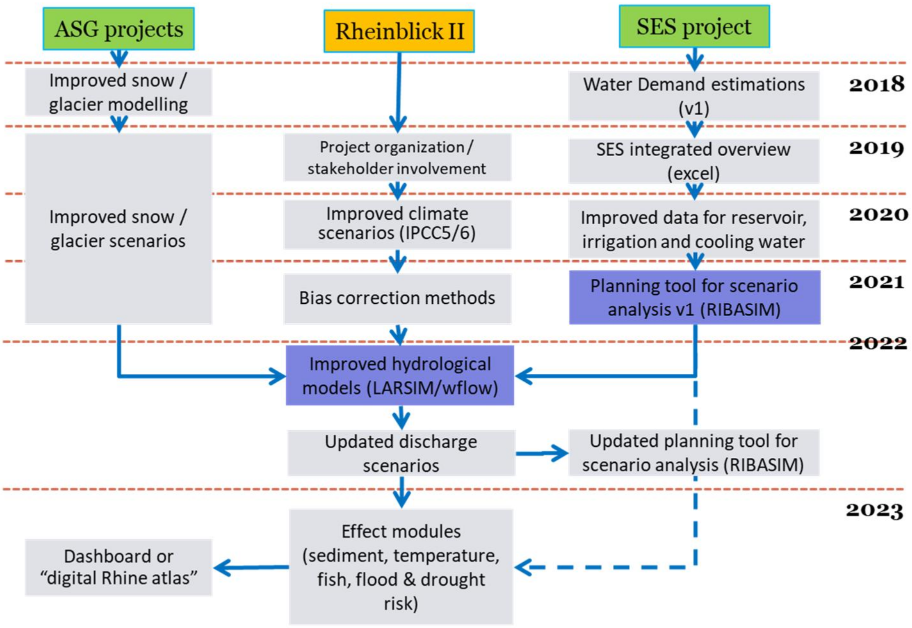


Figure 1-2 The three courses of the CHR

2 Introduction Rhine River Basin modelling

2.1 Model Simulation for the Rhine River Basin

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 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.
2. The **Rhine002.model** which has been developed based on open global datasets and in which the rainfall-runoff Wflow and the RIBASIM model is used in a detailed model for the whole Rhine river basin including the Netherlands.

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

Table 2-1 Differences between Rhine001 and Rhine002 models.

Rhine001 model	**Rhine002 model**
originally powered by Excel	powered by RIBASIM software
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 extendable	model is easily extendable
simulates on monthly time step	simulates on decade (10 daily) timestep with a computational time step of 1 day
simulates only 1 year	simulates multiple year time series

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 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 in detail (Chapters 4 and 5).

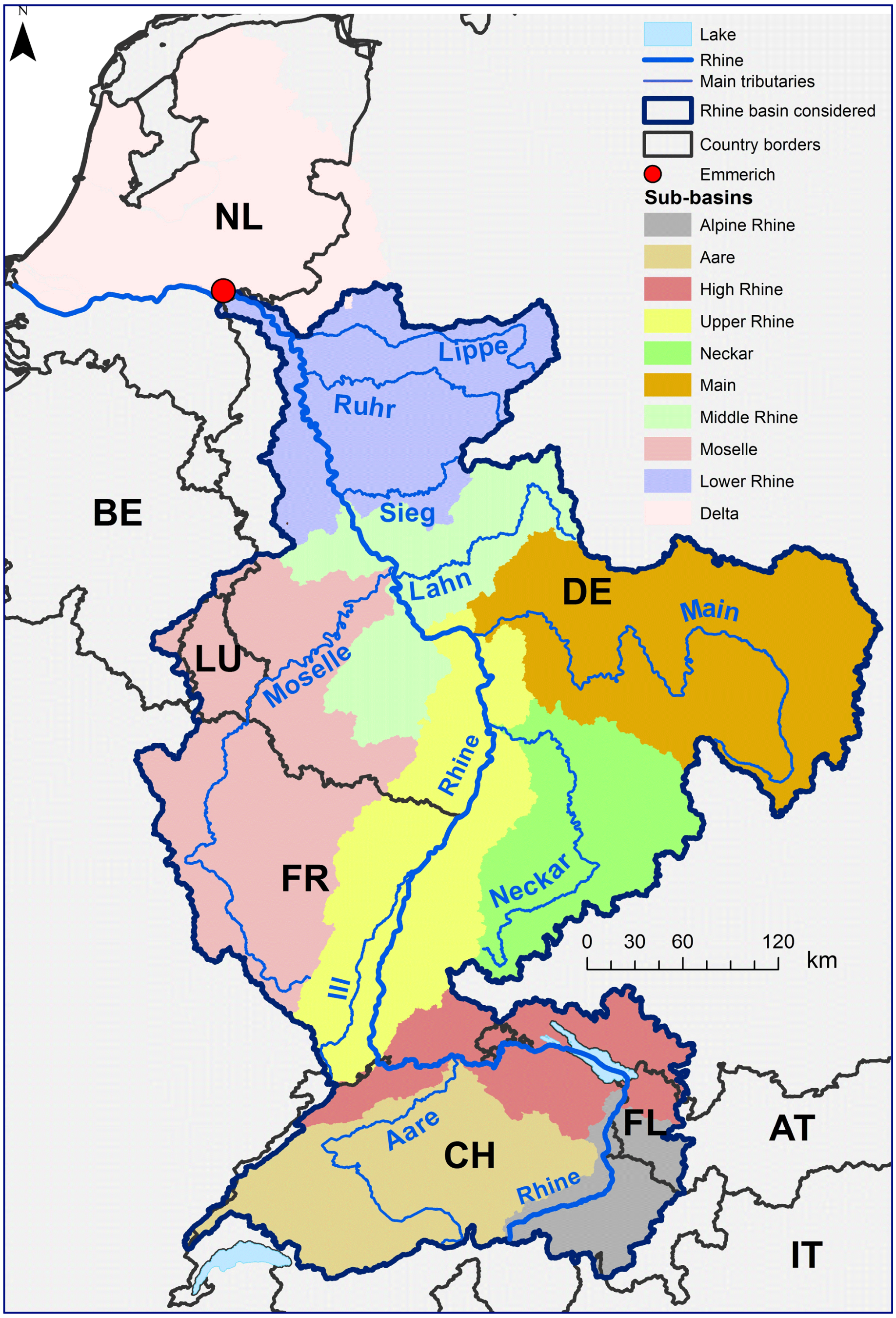


Figure 2-1The Rhine river basin and its sub-basins.

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. Info on site *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.

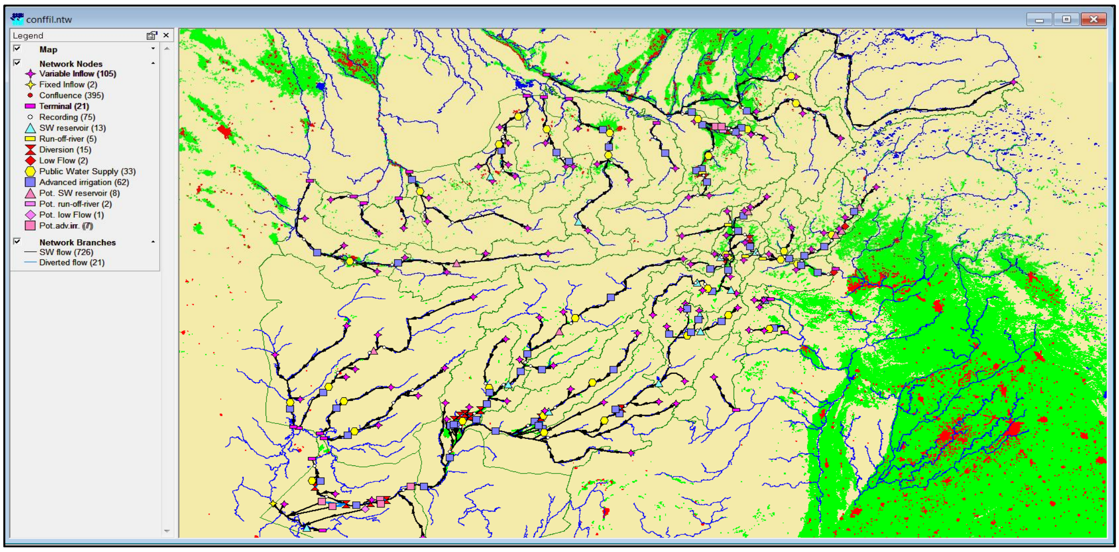


Figure 3-1 RIBASIM network Schematization of all river basins in Afghanistan.

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.

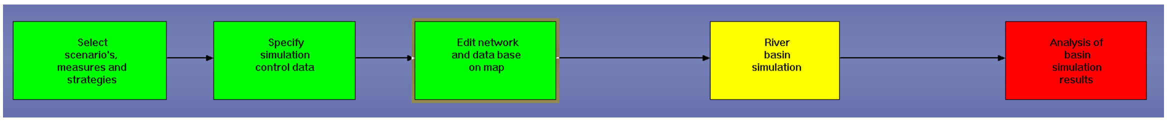


Figure 3-2 The user interface of RIBASIM presented by block flow diagram.

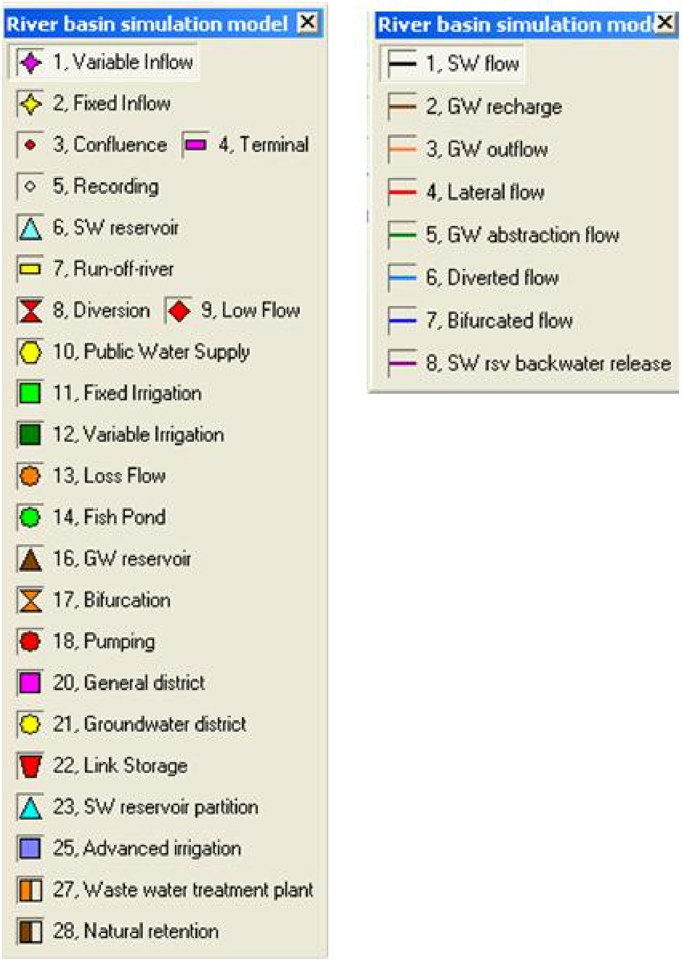
3.3 Principles of river basin schematization

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:

Infrastructure (surface and groundwater reservoirs, rivers, lakes, canals, pumping stations, pipelines), both natural and man-made.
Water users (public water supply, agriculture, hydropower, aquaculture, navigation, nature, recreation), or in more general terms: water related activities.
Management of the water resources system (reservoir operation rules, allocation methods).
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. Figure 3-3, Table 3-1 till Table 3-4 list the standard types of nodes and links which can be used to build a RIBASIM network schematization.

The user can also define node types based on one of the standard node types, called “parent node type”. This is for example applied to distinguish existing and potential reservoirs and irrigation areas in the network. The user defined node types can have different colours in the network schematization.



River basin simulation model

1, Variable Inflow
2, Fixed Inflow
3, Confluence
4, Terminal
5, Recording
6, SW reservoir
7, Run-off-river
8, Diversion
9, Low Flow
10, Public Water Supply
11, Fixed Irrigation
12, Variable Irrigation
13, Loss Flow
14, Fish Pond
16, GW reservoir
17, Bifurcation
18, Pumping
20, General district
21, Groundwater district
22, Link Storage
23, SW reservoir partition
25, Advanced irrigation
27, Waste water treatment plant
28, Natural retention

River basin simulation mod

1, SW flow
2, GW recharge
3, GW outflow
4, Lateral flow
5, GW abstraction flow
6, Diverted flow
7, Bifurcated flow
8, SW rsv backwater release

Figure 3-3 Overview of the standard RIBASIM node and link types used to design the river basin network schematization.

Table 3-1 Overview of the lay-out node types.

Node type name	**Representation**
Fixed and variable inflow node	The upstream boundary of the system where water enters the network. This inflow is specified as a time series. Two types of inflow node are available the “fixed” and “variable”. For the fixed inflow node an annual time series is used for each simulation year. For the variable inflow node multiple year time series are specified or the Sacramento rainfall-runoff model is used to compute the catchment runoff.
Terminal node	The downstream boundary of the system where water leaves the network. This node may be connected to a (fixed or variable) inflow node representing a delay of one simulation time step and which is used to represent loops.
Confluence node	The location where various river tributaries, canals and/or pipelines join.
Recording node	The flow gauging station in the network.

Table 3-2 Overview of the demand (activity, water user) node types

Node type name	**Representation**
Fixed, variable and advanced irrigation node	The water demand for irrigated agriculture. Three types are distinguished: the “fixed”, the “variable” and the “advanced” irrigation nodes. The difference consists in the level of detail in which the demand computations are carried out. At the “fixed” irrigation nodes only the net demand is specified. At “variable” irrigation nodes the gross demand is specified and the actual rainfall is explicitly taking into account. At the “advanced” irrigation nodes the most detailed procedure is applied based on the crop plan, crop-, soil- and irrigation practice-characteristics. Beside the water demand and allocation the crop yield and production costs are computed as well.
Fishpond node	Aquaculture activities. An explicit flushing requirement is specified.
Public water supply node	The demand for public water supply, generally comprising demands for domestic, municipal and industrial (DMI) purposes.
Loss flow node	Location where water “disappears” from the system in another way than through a demand or activity node (e.g. by leakage to groundwater). A time series of loss flows is explicitly connected to this node. The loss flow may flow into a groundwater reservoir node.
Low flow node	Location with a minimum flow requirement for example in view of maintaining a certain ambient water quality, a certain minimum water level in a canal (to allow navigation or for the intake of water for irrigation purposes) or a specific minimum environmental flow once in a number of years.
General district node	Location where a district’s net water extraction and discharge are connected to the network as a time series of demands and discharges computed outside RIBASIM.
Groundwater district node	District of sub-catchment covering local runoff, public water supply, irrigation and local groundwater storage. This can be represented in more detail using a combination of the following node types: inflow node, public water supply nodes, irrigation node and groundwater reservoir node.

Table 3-3 Overview of the control node types

Node type name	**Representation**
Bifurcation node	The (natural) subdivision of a flow over various downstream links.
Diversion node	Location of an intake structures or gates where water is diverted from a river or a canal to satisfy downstream demands along the downstream diverted flow links.
Groundwater reservoir node	Aquifer (groundwater reservoir). Water users abstract water depending on the groundwater level, pumping-depth and -capacity. Lateral flows may stream from one aquifer to another one. Outflows may stream to surface water (springs). The aquifer is filled up by groundwater recharge and lateral flows.
Surface water reservoir node	Surface water storage facility allowing to store and release water in a controlled way over time for flood control, satisfy downstream water demands (irrigation, DMI, nature, navigation, hydropower generation, etc.) depending on gate-levels and -capacities and the reservoir operation rules.
Link storage node	Storage in a river or canal section as a function of the flow described by the Manning formula, flow-level relation, Muskingum formula, Puls method or Laurenson method.
Relevant for energy consumption or generation only	
Pumping node	Pump station where water is pumped from the river to a canal or water user. Only the consumed energy is computed. Capacity constraints must be specified using the diverted flow link or surface water flow link.
Run-of-river node	Hydropower generation facilities without water storage capacity.
Relevant for water quality only	
Waste water treatment plant node	A plant where waste water is purified (artificial purification).
Natural retention node	The natural purification of polluting substances in the basin surface and sub-surface water.
Surface water reservoir partition node	Part of a surface water reservoir (applied only for reservoir water quality analysis). The total storage of the reservoir is separated over the various partitions.

Table 3-4 Overview of the link types.

Link type name	**Representation**
Groundwater recharge flow link	A flow into the aquifer which may come from an inflow node or from a loss flow node.
Groundwater abstraction link	A flow directly pumped from the aquifer by water users.
Lateral flow link	A flow between two water bodies represented by a surface water reservoir, groundwater reservoir and/or link storage node. The flow is computed based on Darcy’s law, the water level difference between the two linked water bodies, a flow threshold – storage relation, a fixed flow per time step or a groundwater storage relation.
Groundwater outflow link	A flow from the aquifer out of the system or to the surface water network (spring). The flow is a function of the groundwater depth.
Diverted flow link	A flow diverted from a river or canal at a diversion node. The flow depends on the operation of the diversion structure and/or downstream demands (targets).
Surface water flow link	A link between two nodes for surface water flow with limited flow capacity (canal or pipeline) or without any capacity constraint (river).
Reservoir backwater flow link	A flow abstracted directly from a surface water reservoir.
Bifurcated flow link	A downstream flow at a bifurcation node. The flow is a function of the upstream flow.

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 3-4. 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.

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 year 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.

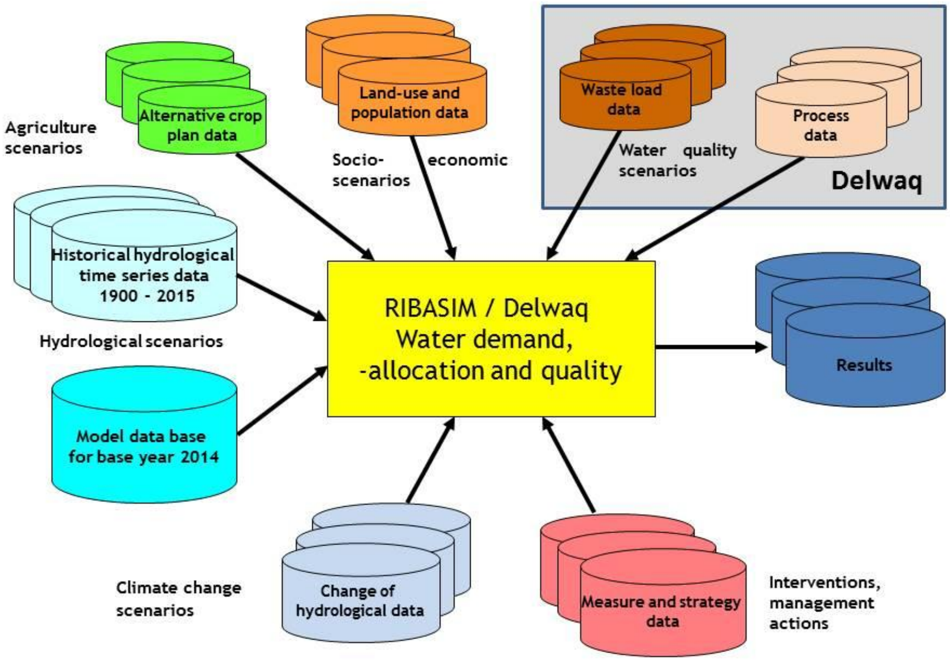


Figure 3-4 Input- and output structure of the RIBASIM with Delwaq model.

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.

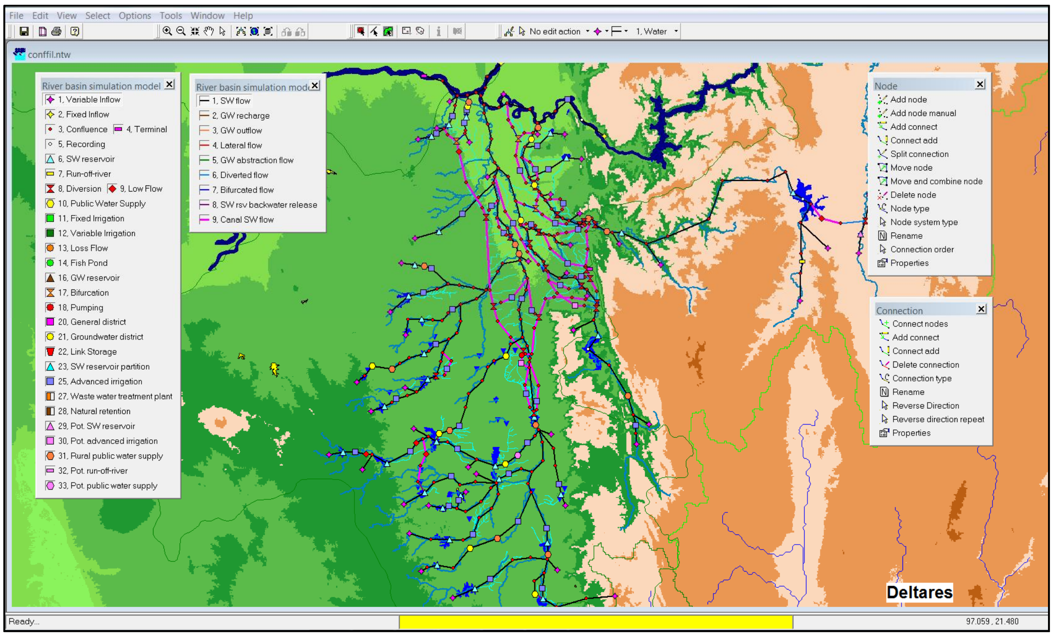
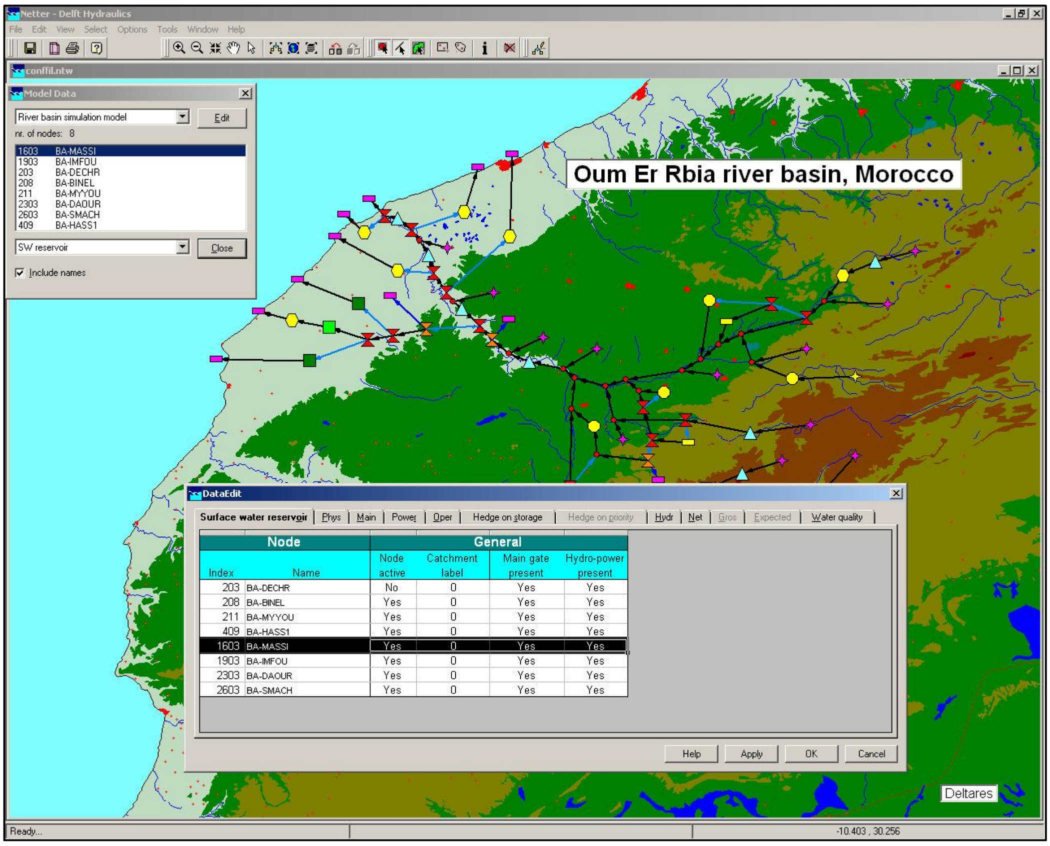


Figure 3-5 Interactive design of river basin network schematization for Samon River basin - Dry Zone, Myanmar.



River basin simulation model

nr. of nodes: 8

1603	BA-MASSI
1903	BA-IMFOU
203	BA-DECHR
208	BA-BINEL
211	BA-MYYOU
2303	BA-DAOUR
2603	BA-SMACH
409	BA-HASS1

SW reservoir

☑ Include names

Node		General			
Index	Name	Node active	Catchment label	Main gate present	Hydro-power present
203	BA-DECHR	No	0	Yes	Yes
208	BA-BINEL	Yes	0	Yes	Yes
211	BA-MYYOU	Yes	0	Yes	Yes
409	BA-HASS1	Yes	0	Yes	Yes
1603	BA-MASSI	Yes	0	Yes	Yes
1903	BA-IMFOU	Yes	0	Yes	Yes
2303	BA-DAOUR	Yes	0	Yes	Yes
2603	BA-SMACH	Yes	0	Yes	Yes

Figure 3-6 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:

- RIBASIM supports a default and user-defined source analysis (fraction computation) giving insight in the water’s origin and residence time at any location of the basin and at any time within the simulation period, see Figure 3-7;

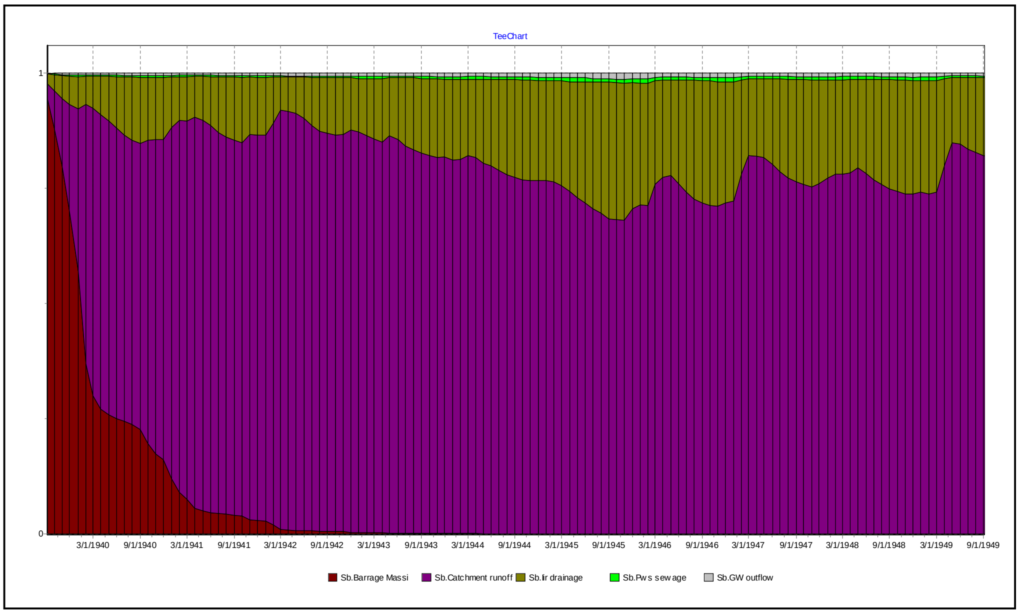
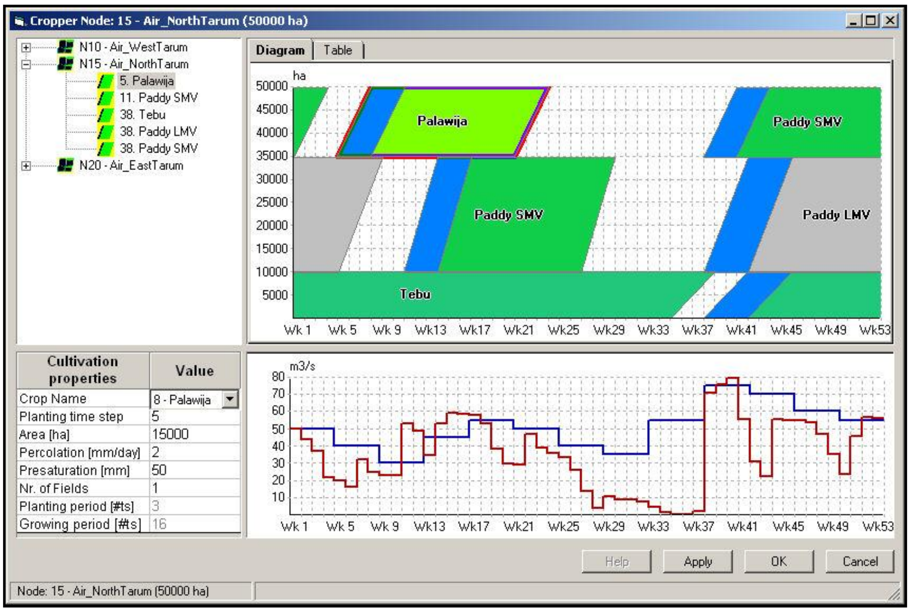


Figure 3-7 Flow composition of water in Massira reservoir from 1940-1949 (Oum Er Rbia River basin, Morocco).

- 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.



Cultivation properties	Value
Crop Name	8 - Palawija
Planting time step	5
Area [ha]	15000
Percolation [mm/day]	2
Presaturation [mm]	50
Nr. of Fields	1
Planting period [#ts]	3
Growing period [#ts]	16

Node: 15 - Air_NorthTarum (50000 ha)

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

- RIBASIM includes a basic water quality component which simulates 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 linked with the water quality process model DELWAQ is required.
- Groundwater can be modelled as separate source for various users with its own characteristics and water management
- Large and complex river basins can be modelled and simulated with RIBASIM;
- 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 an 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 in a RIBASIM node-link network model, 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 for 1 year on monthly simulation time step.

The four simulation cases have the same name as defined in the 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

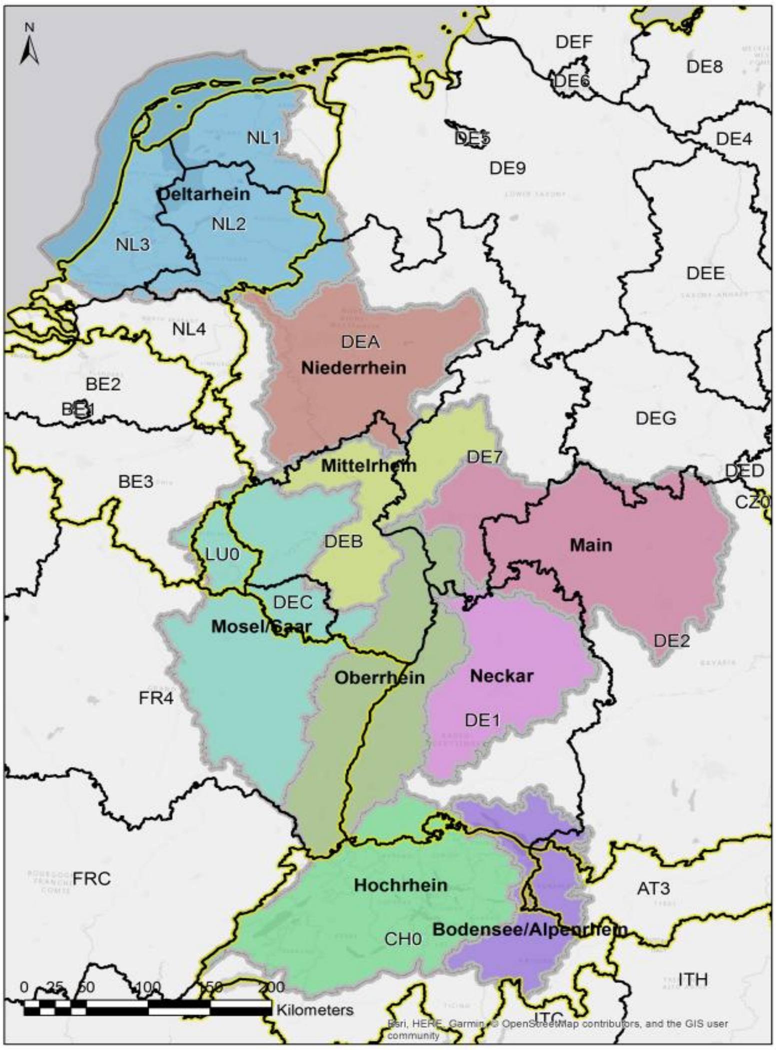


Figure 4-1 Rhine 001 catchment schematization: geographical delineation (Ruijgh 2019).

4.3 Network schematization

4.3.1 User defined node types

The standard RIBASIM node are listed in Figure 3-3. Additionally, the user defined node types are shown in Table 4-1. The user defined node types are explicitly defined as a new object in the network design component Netter with a different icon or colour in the network schematization.

Table 4-1 Overview of the user defined node types.

Node type name	Parent node type	Representation
Snow melt	Variable inflow	Inflow from melting snow
Glacier melt	Variable inflow	Inflow from melting glaciers
Industrial use	Public water supply	Industrial water use
Cooling water use	Public water supply	Cooling water use

4.3.2 Node name convention

The name of the nodes is defined in such a way that it is directly clear:

- What type of node it is;
- Which country it is located;
- The name representing the user or location.

The conventions for the node names are outlined in Table 4-3 till Table 4-5. Example node names and description of interpretation are shown in Table 4-2.

Table 4-2 Example node names.

Node name	Description
Run_AtChLiDe_BodenSeeAlpenRhein	Runoff inflow node representing the runoff of the sub-basin Boden See and Alpen Rhein in Austria, Swiss, Liechtenstein and Germany
Irr_FrLuBeDe_MoselSaar	Irrigation area in the sub-basin Mosel and Saar in France, Luxemburg, Belgium and Germany.
Lig_De_NiederRhein	Lignite mining water use in the sub-basin Nieder Rhein in Germany

Table 4-3 General node name convention.

Character	Description
1-3	Node type identification (see Table 4-4)
4	Underscore
5-7	Identification of the country or countries in which the node is located (see Table 4-5)
8	Underscore
9-40	Name of representation e.g. location:

Table 4-4 Node type identification.

Node type identification	Node type description
Iir	Advanced irrigation node
Col	Public water supply node: cooling water
Lig	Public water supply node: lignite mining
Pws	Public water supply node: drinking water (domestic use)
Rec	Recording node
End	Terminal node
Gla	Variable inflow node: glacier melt
Run	Variable inflow node: runoff
Snw	Variable inflow node: snow melt

Table 4-5 Country identification.

Country identification	Country name
At	Austria
Be	Belgium

Country identification	Country name
De	Germany
Fr	France
Li	Liechtenstein
Lu	Luxembourg
Nl	Netherlands
Ch	Switzerland

4.3.3 Modelling features

4.3.3.1 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 traced by the model searching for water to fulfil the demand. So, the order of the nodes in the list is important. The model initially generates the 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.

4.3.3.2 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 4-6 lists all node types for which a water allocation priority was specified. All priorities are value 1.

Table 4-6 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

4.3.4 Network

The network schematization of the Rhine001 model is presented in several screen captures in Figure 4-3 till Figure 4-6. The schematization contains 87 nodes and 86 links. Table 4-7outlines the number of nodes and links per type.

The demand and water user nodes representing irrigation, domestic, industrial, cooling and lignite mining water demand are outlined in Table 4-8 till Table 4-12. The annual demand (Mcm) for the actual case are listed as well and shown graphically in Figure 4-2.

The network also includes 5 recording nodes which are used to compare the results of the Rhine001 model and the data in the Excel spreadsheet. Table 4-13 lists those nodes.

Table 4-7 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

Table 4-8 Overview of Fixed irrigation nodes and annual demand (Mcm).

Node index	Node name	Irrigated area (ha)	Annual gross demand (Mcm)
90	Irr_De_NiederRhein	30,500	53.71
120	Irr_De_MittelRhein	18,100	30.20
155	Irr_FrLuBeDe_MoselSaar	24,700	42.21
190	Irr_De_Main	27,000	47.20
230	Irr_De_Neckar	12,800	21.70
260	Irr_DeFr_OberRhein	9,500	16.10
290	Irr_ChDe_HochRhein	11,400	19.30
325	Irr_AtChLiDe_BodenSeeAlpenRhein	4,900	8.40
425	Irr_DeNe_DeltaRhein	171,300	269.36
	Total	310,200	508.18

Table 4-9 Overview of Public water supply -domestic nodes and the population and annual demand (Mcm).

Node index	Node name	Population (-)	Unit demand (l/iter/capita/day)	Annual demand (Mcm)
70	Pws_De_NiederRhein	12,605,961	140	644.17
105	Pws_De_MittelRhein	2,721,839	140	139.09
140	Pws_FrLuBeDe_MoselSaar	4,541,365	140	232.06
170	Pws_De_Main	6,635,320	140	339.07
215	Pws_De_Neckar	5,456,522	140	278.83
245	Pws_DeFr_OberRhein	7,241,808	140	370.06
275	Pws_ChDe_HochRhein	6,740,925	140	344.46
310	Pws_AtChLiDe_BodenSeeAlpenRhein	1,565,779	140	80.01
410	Pws_DeNe_DeltaRhein	12,989,901	140	663.78

	Total	60,499,420		3091.52

Table 4-10 Overview of Public water supply – industry nodes and annual demand (Mcm).

Node index	Node name	Explicit demand (m3/s)	Annual demand (Mcm)
75	Ind_De_NiederRhein	7.515	236.99
110	Ind_De_MittelRhein	2.64	83.26
145	Ind_FrLuBeDe_MoselSaar	1.345	42.42
180	Ind_De_Main	4.489	141.57
220	Ind_De_Neckar	3.887	122.58
250	Ind_DeFr_OberRhein	4.377	138.03
280	Ind_ChDe_HochRhein	7.499	236.49
315	Ind_AtChLiDe_BodenSeeAlpenRhein	1.392	43.90
415	Ind_DeNe_DeltaRhein	8.194	258.41
	Total		1303.63

Table 4-11 Overview of Public water supply - cooling nodes and annual demand (Mcm).

Node index	Node name	Explicit demand (m3/s)	Annual demand (Mcm)
80	Col_De_NiederRhein	142.7	4500.19
115	Col_De_MittelRhein	30.81	971.62
150	Col_FrLuBeDe_MoselSaar	51.41	1621.27
185	Col_De_Main	75.11	2368.67
225	Col_De_Neckar	61.77	1947.98
255	Col_DeFr_OberRhein	81.98	2585.32
285	Col_ChDe_HochRhein	76.31	2406.51
320	Col_AtChLiDe_BodenSeeAlpenRhein	17.73	559.13
420	Col_DeNe_DeltaRhein	147.05	4637.37
	Total		21598.06

Table 4-12 Overview of General district nodes and annual demand (Mcm).

Node index	Node name	Explicit demand (m3/s)	Annual demand (Mcm)
85	Lig_De_NiederRhein	10.0	315.4
	Total		315.4

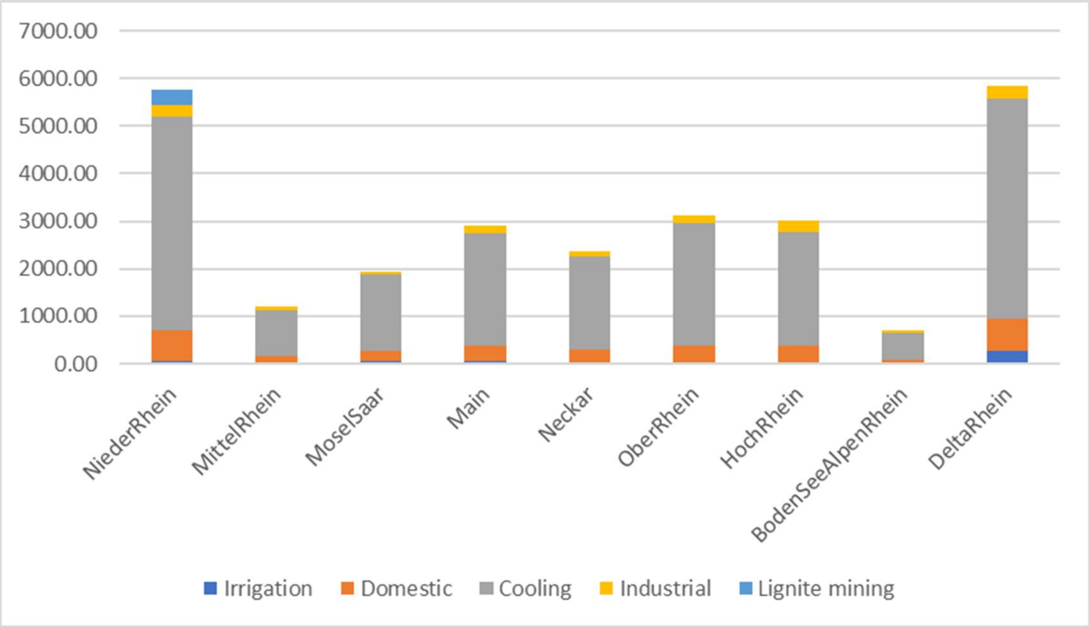


Figure 4-2 Stacked annual water demand per sub-basin and user (Mcm), actual case.

Table 4-13 Overview of Recording nodes.

Node index	Node name
335	Rec_Ch_Basel
375	Rec_De_Bingen
390	Rec_De_Bonn
400	Rec_De_Lobith
430	Rec_Ne_HoekVanHolland

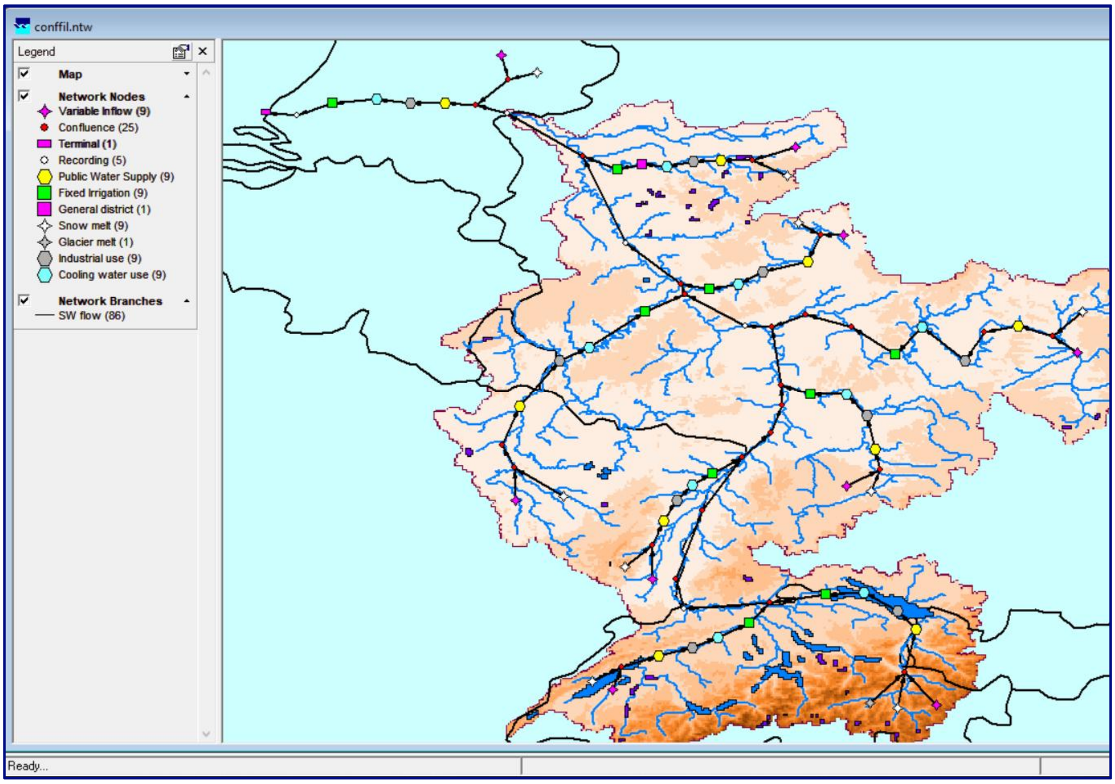


Figure 4-3 The Rhine001 network schematization with map.

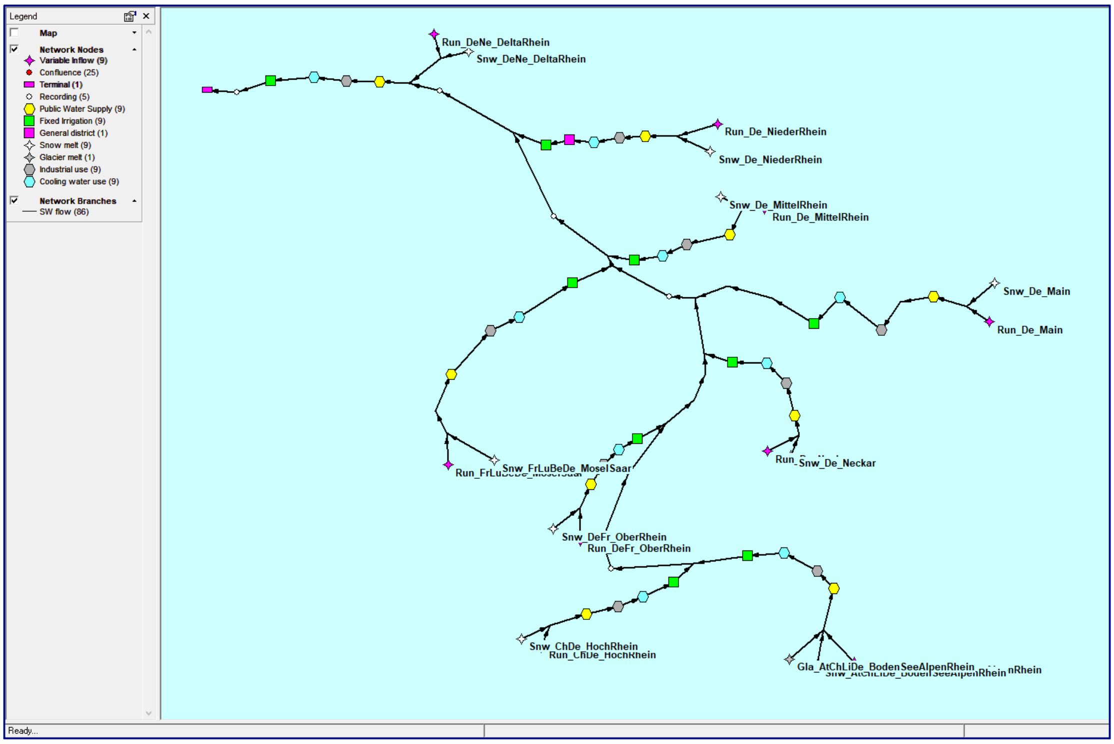


Figure 4-4 The Rhine001 network schematization without map and runoff, snow- and glacier-melt inflow node names.

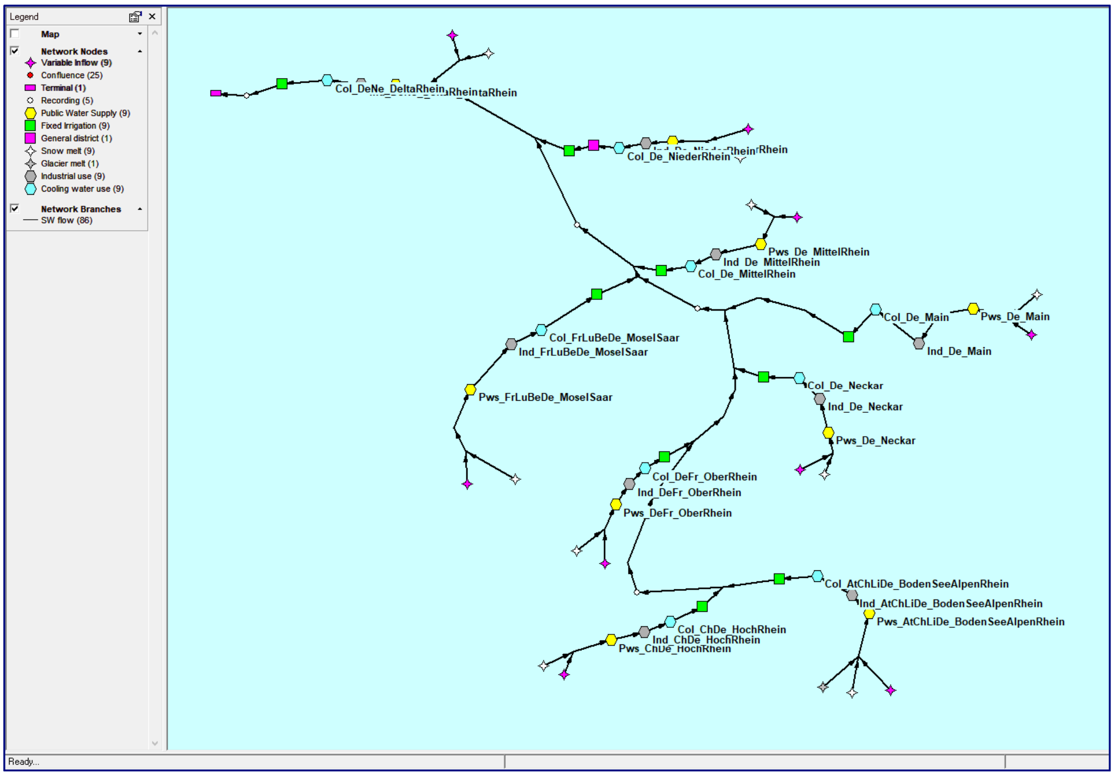


Figure 4-5 The Rhine001 network schematization without map and the domestic, industrial and cooling water use node names.

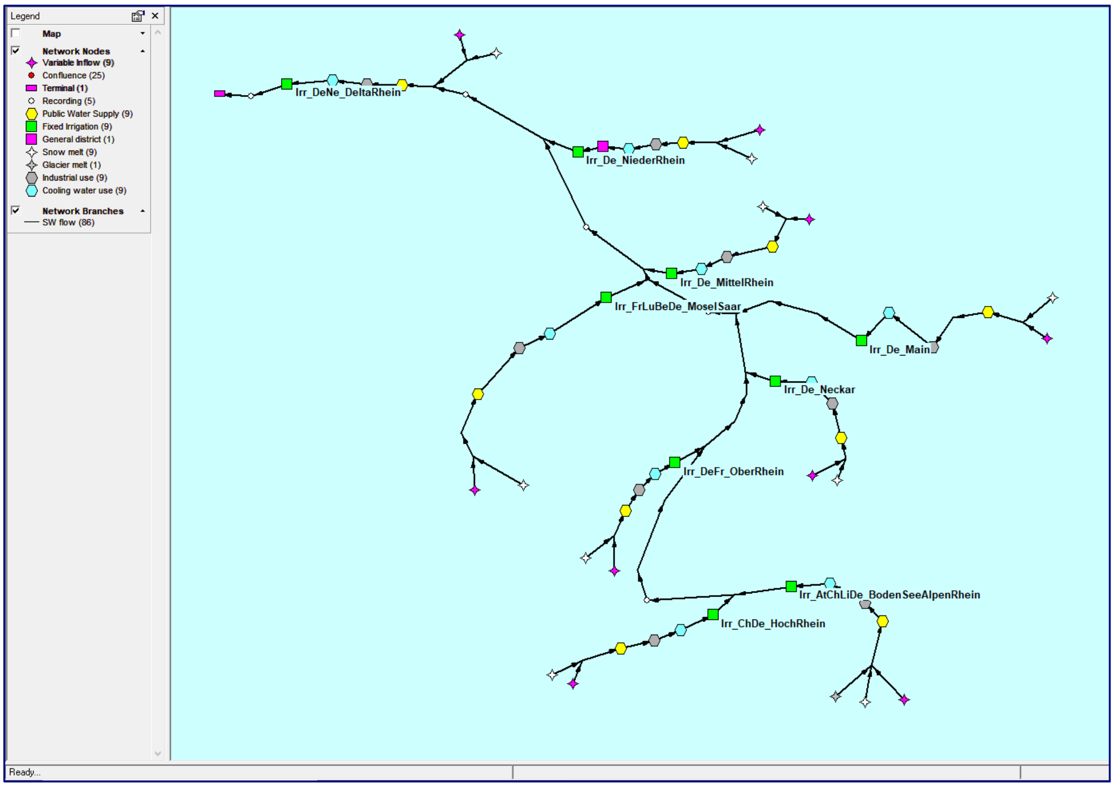


Figure 4-6 The Rhine001 network schematization without map and the irrigation area node names.

4.4 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.

4.5 Model verification

For model verification the natural flow of simulated and “recording” time series at the recording nodes are compared.

4.6 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 4-14. 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 4-14 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

5 The Rhine002 model

5.1 Introduction

The Rhine002 model consists of two model components:

1. Wflow Rainfall-runoff model which covers Rhine River basin uptill 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 covers 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 as 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.

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 is input for the hydrological model WFLOW which computes daily runoff series for each catchment. The time series of runoff, rainfall and evaporation / evapotranspiration are input of RIBASIM. The second step is the design of a node - link network schematization, as outlined in chapter 3.3.

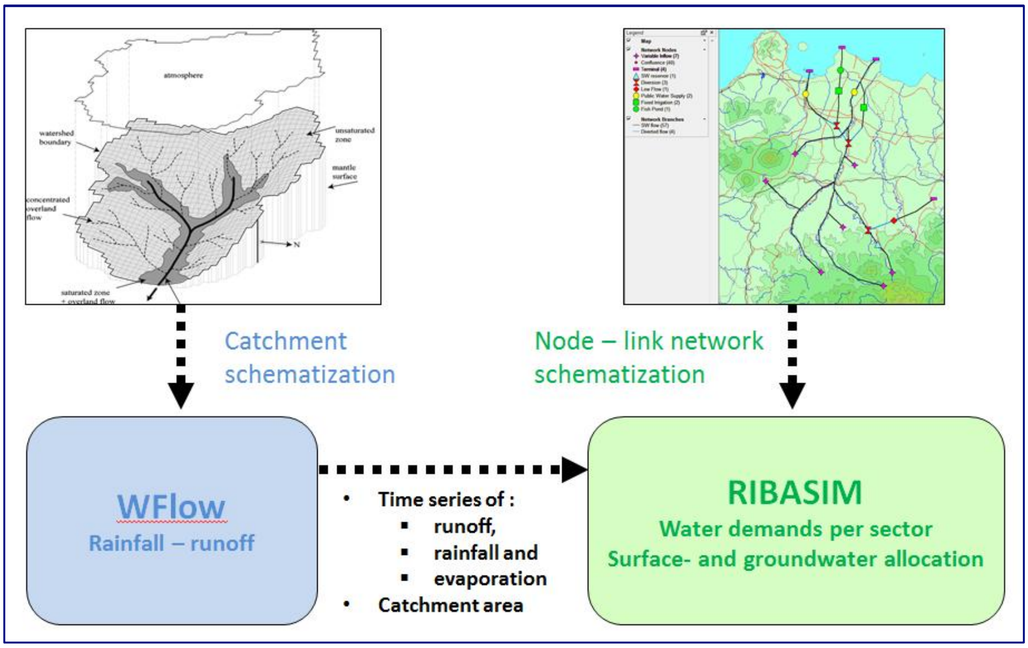


Figure 5-1 Link between Wflow and RIBASIM.

The Wflow Rainfall-runoff model computes with a daily timestep. RIBASIM simulates with a decade simulation time step and 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.

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

5.2 The Rhine002 Wflow 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).
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_sbm model directly.
The forcing data in the simulation is based on ERA5 re-analysis data (). 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 wflow_sbm model has not been fully calibrated yet. 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 the figure below.

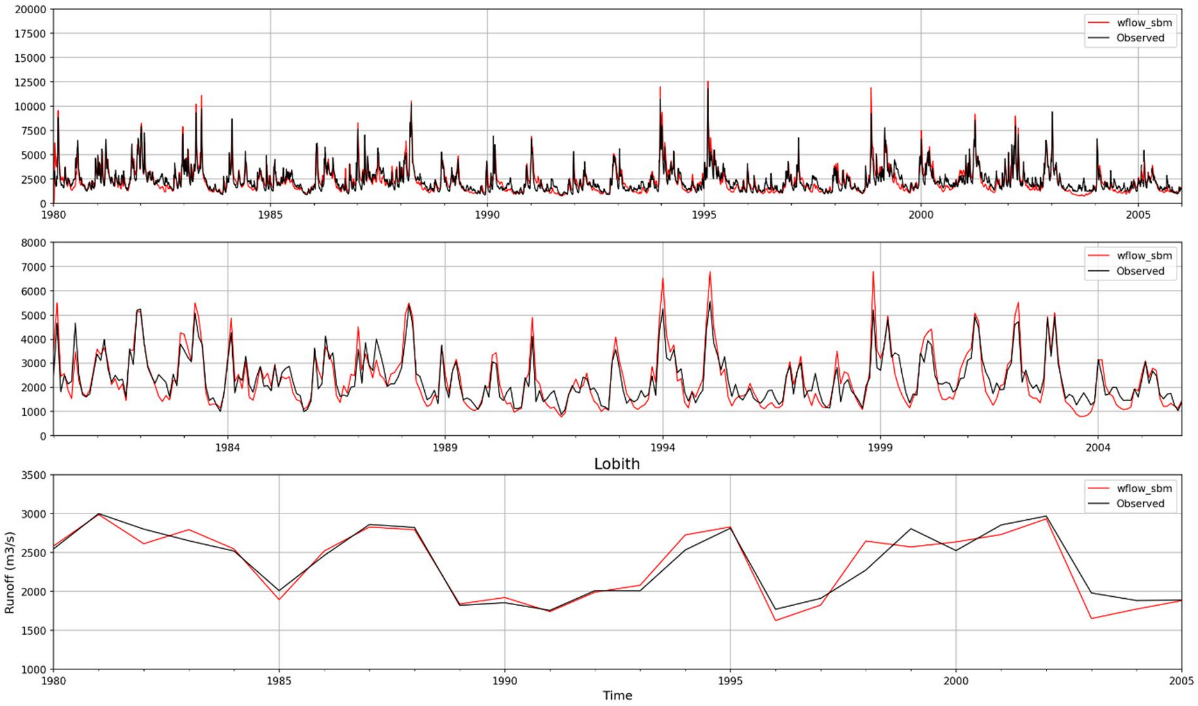


Figure 1. Overview of the results of the wflow model (red) at Lobith, compared to observations (black) and the HBV'96 model (blue).

To check in more detail the model performance, the annual runoff coefficients for several sub-basins have been checked. This is shown in the figure below. On average, the runoff coefficient is around 50%, with some variations depending on location and size of the basin.

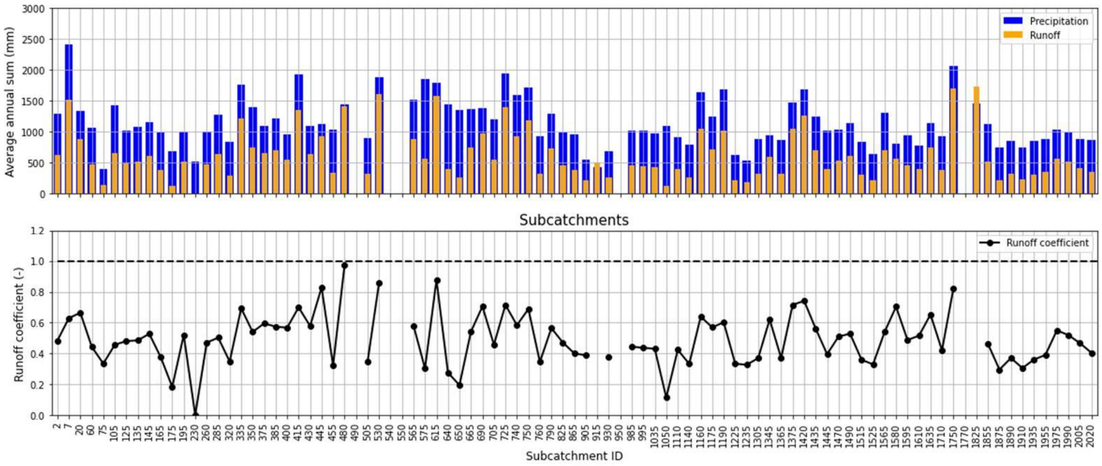


Figure 2. Runoff coefficients of the wflow for several sub-catchments.

In the meanwhile, some further analysis has been done on the performance of the wflow_sbm 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.

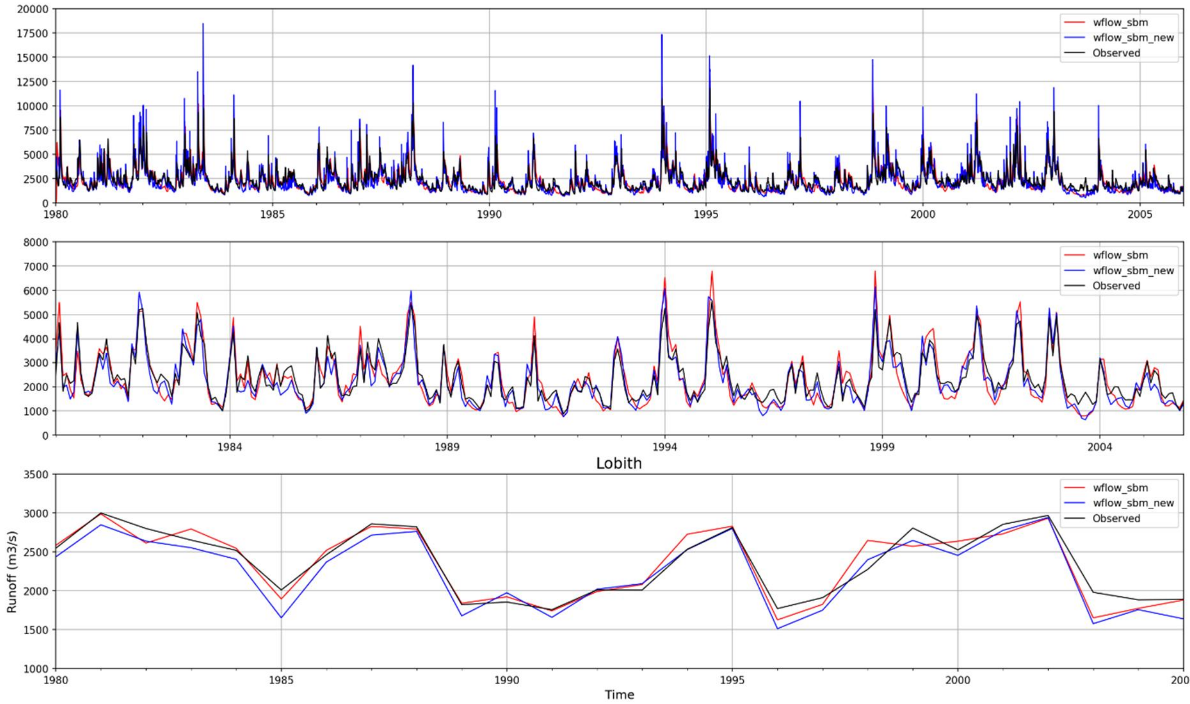


Figure 3. Overview of the results of the currently used wflow model (red) at Lobith, compared to observations (black) and latest wflow model results (blue).

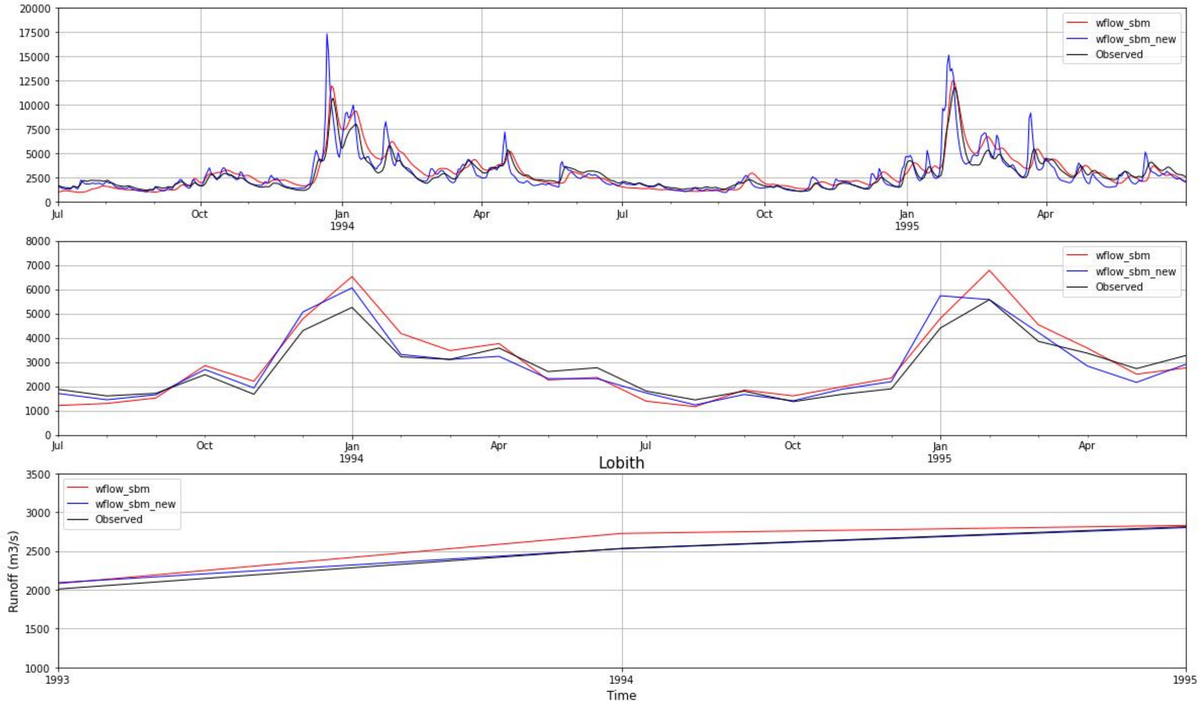


Figure 4. Overview of the results of the currently used wflow model (red) at Lobith, compared to observations (black) and latest wflow model results (blue), zoomed in to the period of 1993-95.

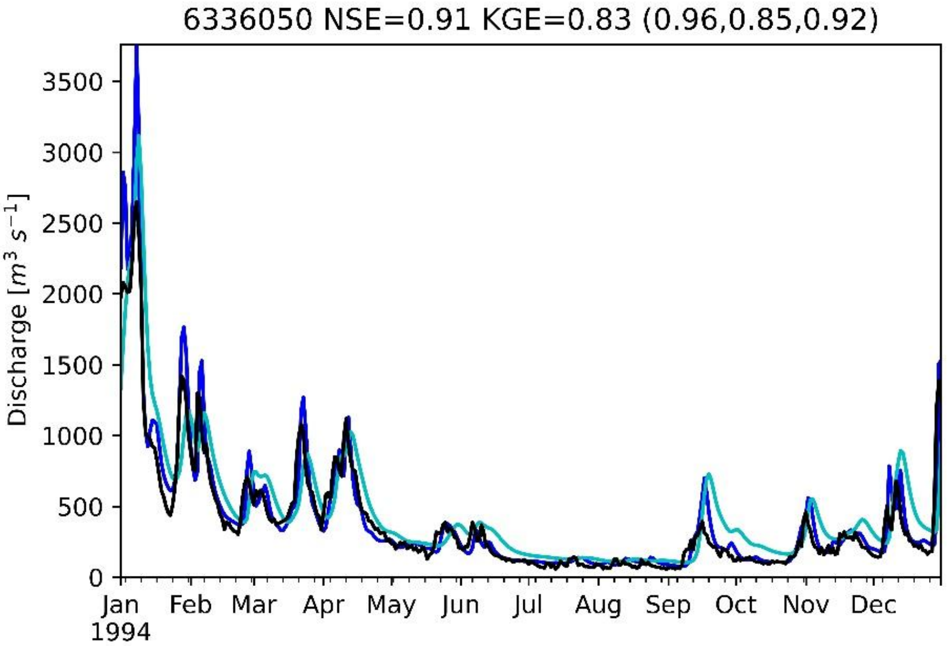


Figure 5. Comparison of the old and the new wflow model results at Cochem (Mosel).

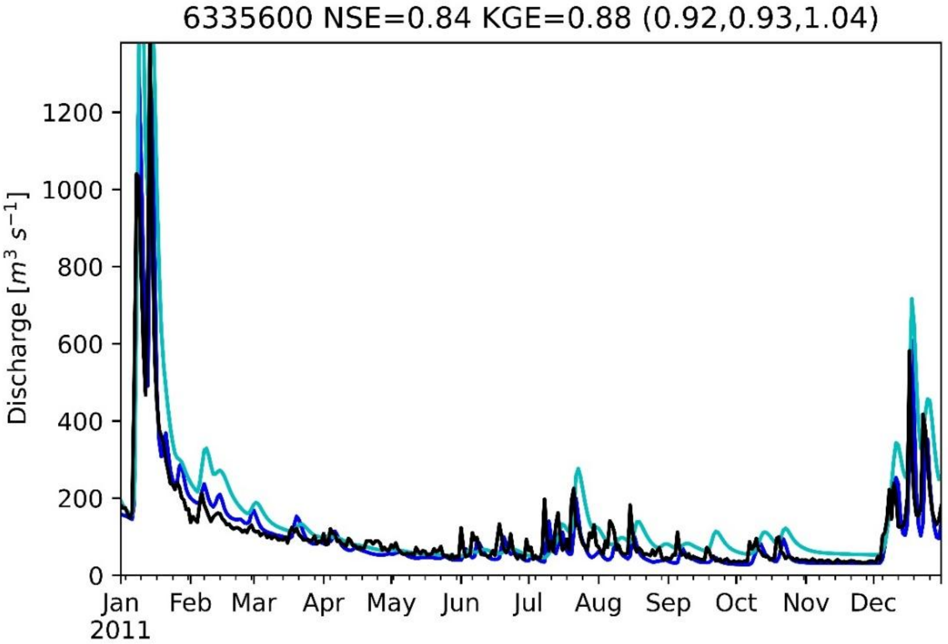


Figure 6. Comparison of the old and the new wflow model results at Rockenau (Neckar).

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 5-2 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 5-3) 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. Table 5-10 lists all variable inflow nodes and size of the sub-basin area (km2). The total area of all sub-basins is 185,000 km2.

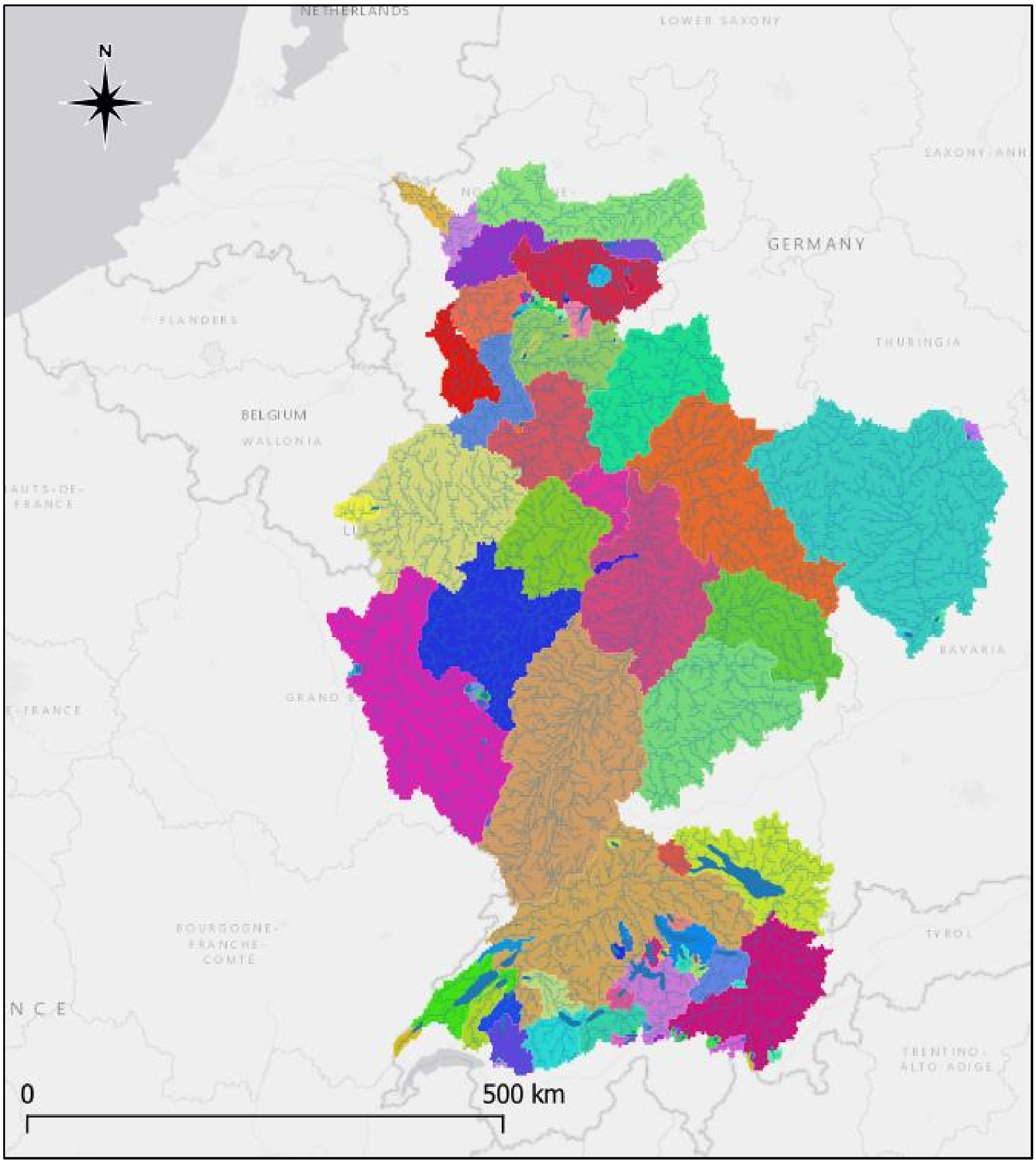


Figure 5-2 Catchment schematization of Rhine River basin split into 93 sub-basins.

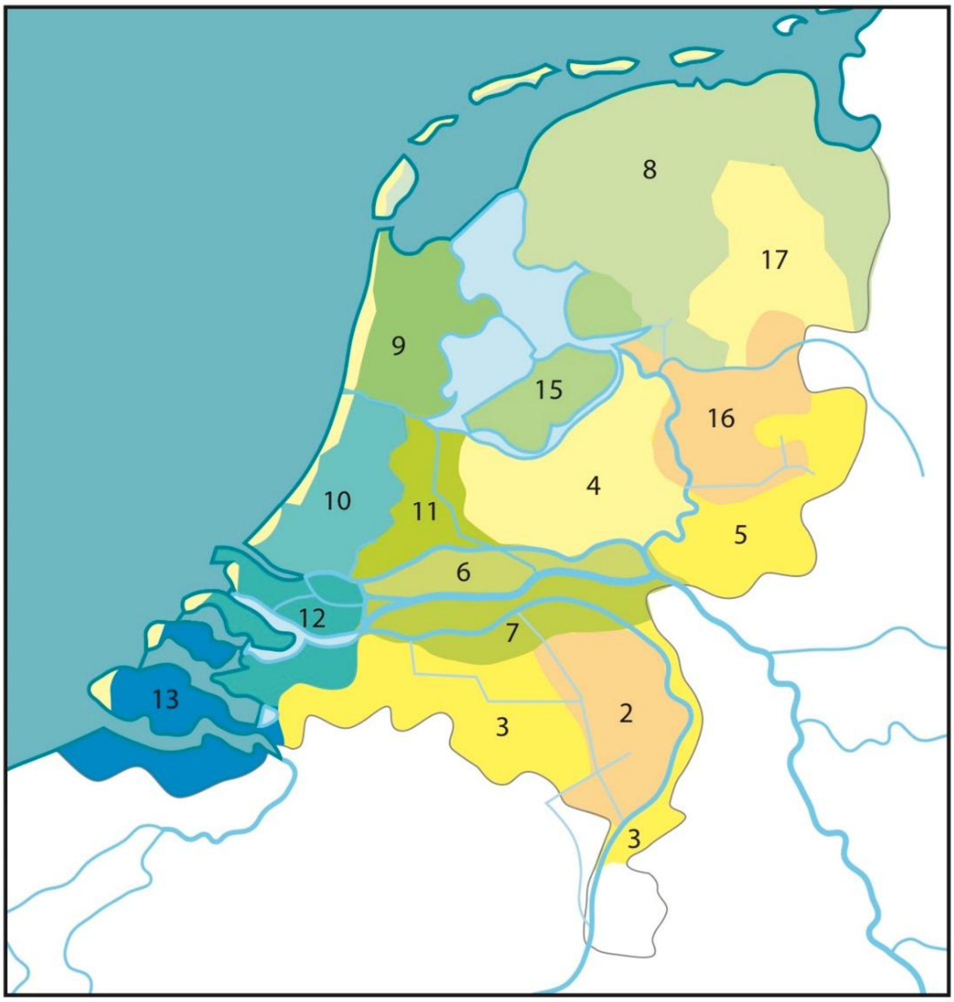


Figure 5-3 Regions in the Netherlands

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 5-4 till Figure 5-7. 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.

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

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

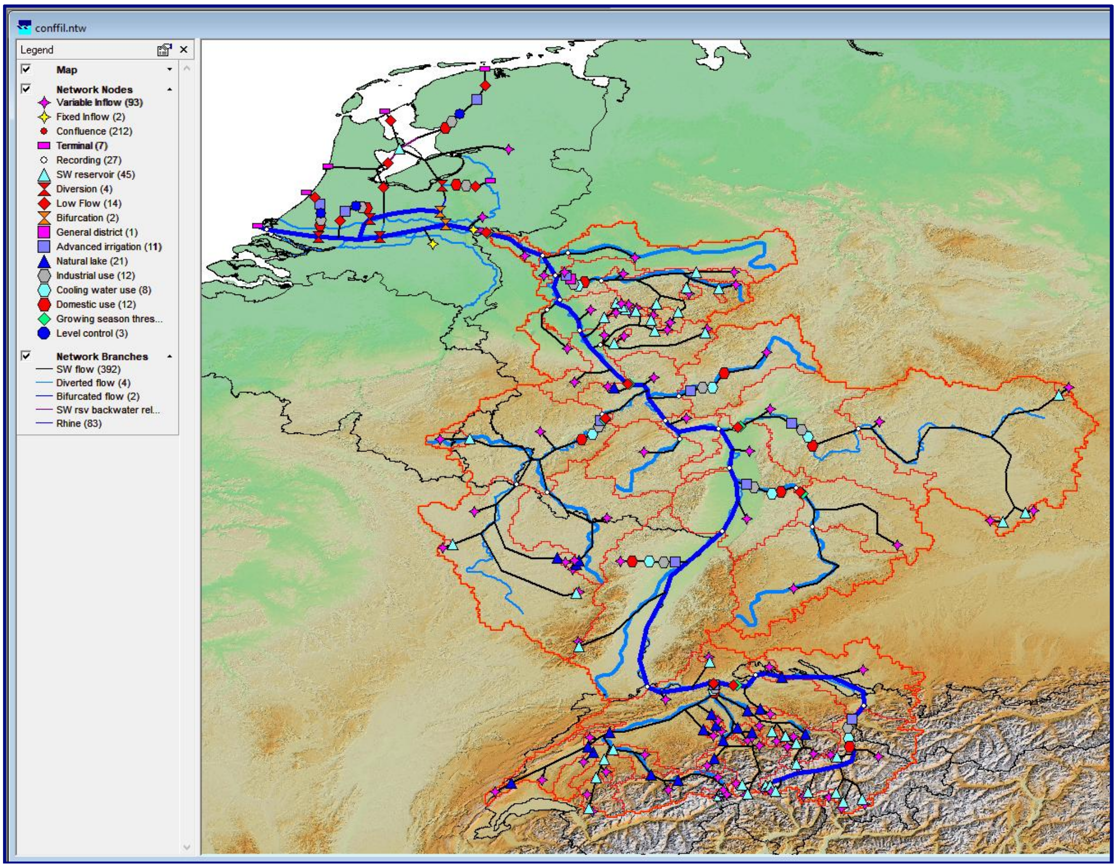


Figure 5-4 The Rhine002 network schematization with map.

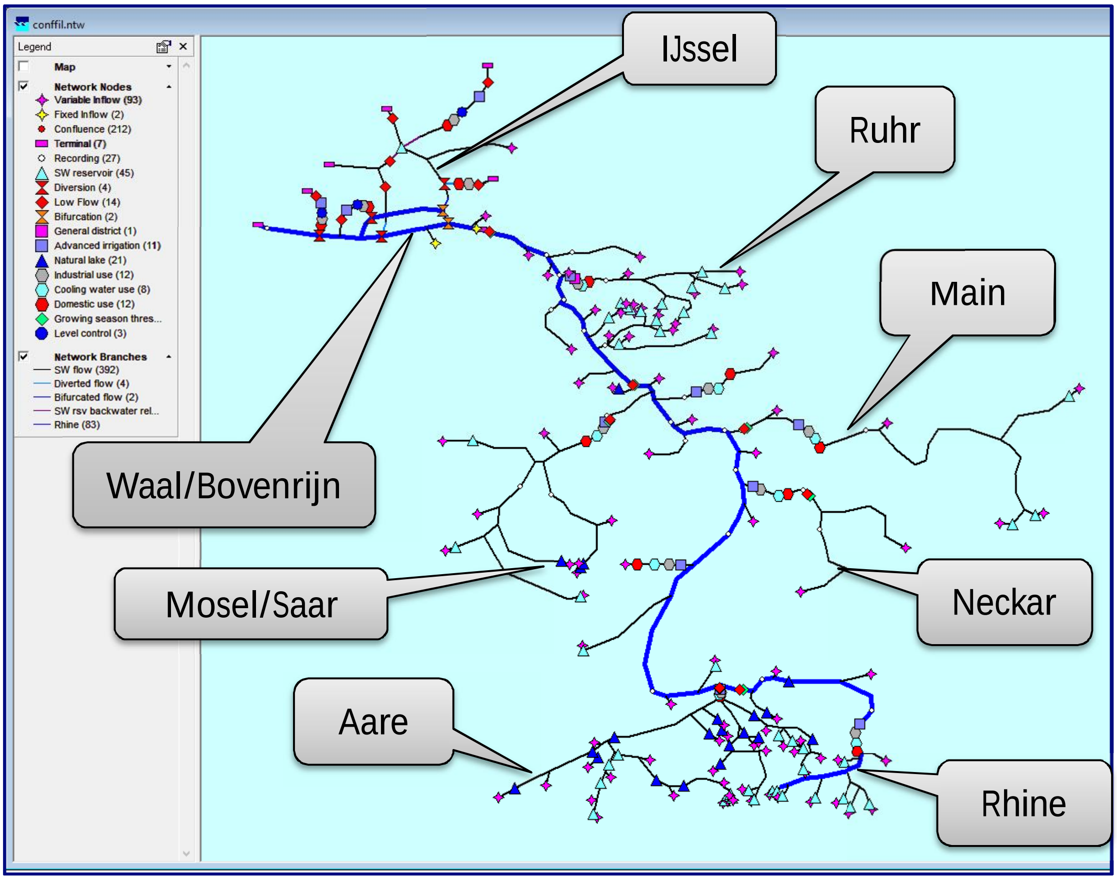


Figure 5-5 The Rhine002 network schematization without map.

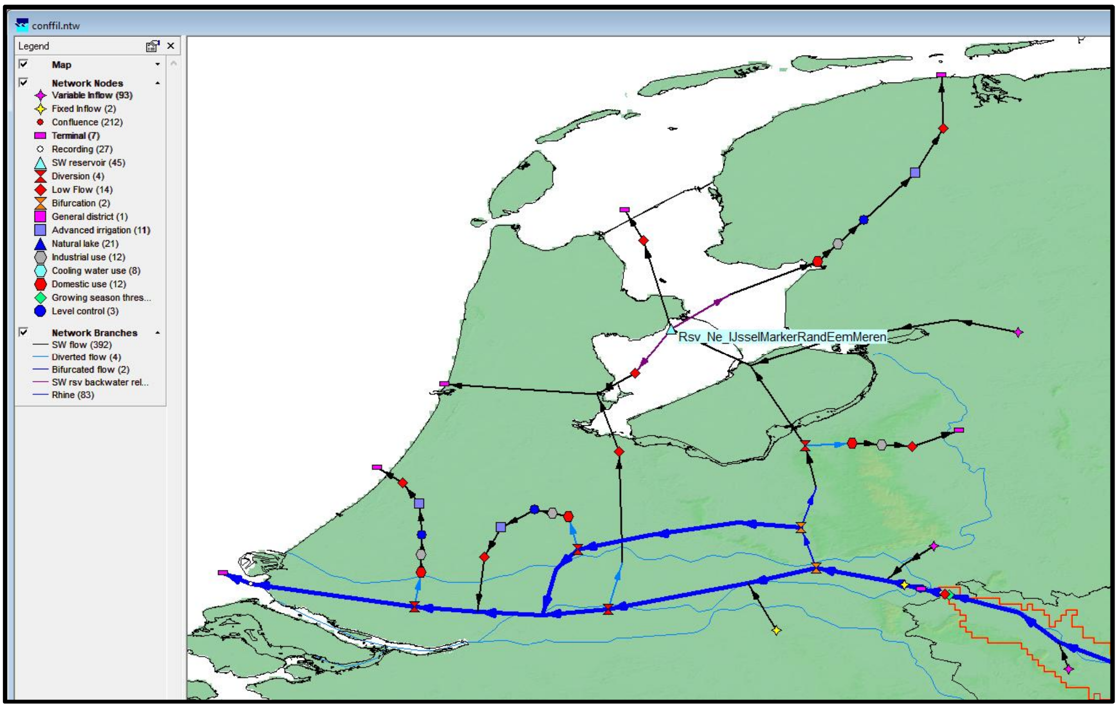


Figure 5-6 The Rhine002 RIBASIM schematization of the Netherlands.

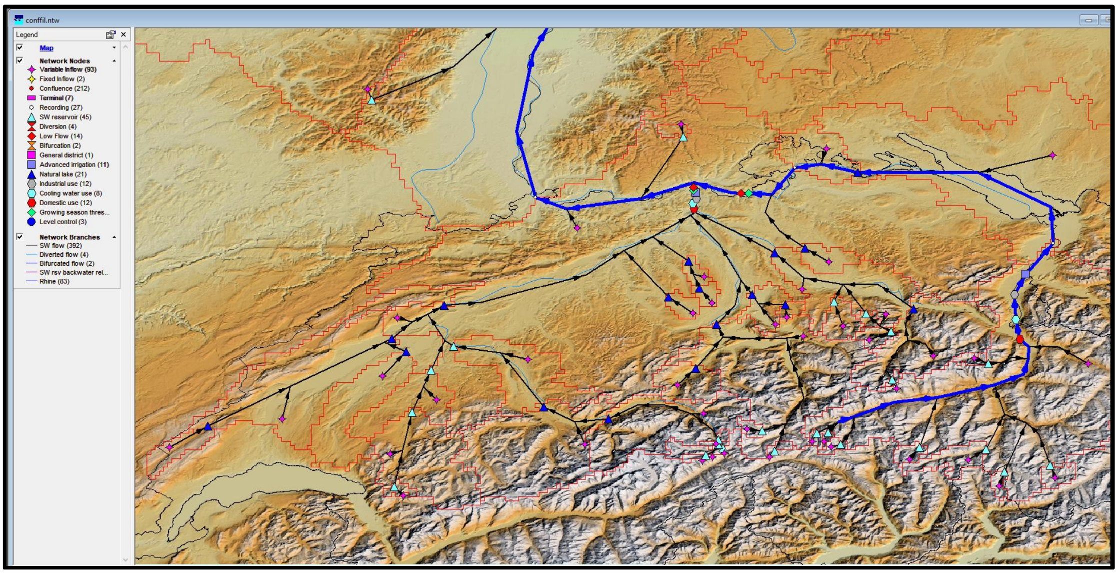


Figure 5-7 The Rhine002 RIBASIM schematization of Swiss.

5.3.3 User defined node and link types

The standard RIBASIM node and links are listed in Figure 3-3. Additionally, the user defined node and link types 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 an minimum river discharge at Lobith is extremely relevant for agricultural production, salt management and navigation in the Netherlands.

5.3.4 Node name convention

The name of the nodes is defined in such a way that it is directly clear:

- What type of node it is;
- Which country it is located;
- For reservoirs: what is the purpose(s);
- If it is an existing or potential structure or demand / user.

The basin schematization covers not only all elements of the base year but also all known under-construction, planned and potential elements e.g. new irrigation areas. This type of elements is indicated in the node name by adding “(P)” to the names. Those nodes are set on inactive in the model data base.

The conventions for the node names are outlined in Table 4-3 till Table 4-5. Example node names and description of interpretation are shown in Table 4-2.

Table 5-4 Example node names.

Node name	**Description**
Rsv_De_T_Kerspe	Reservoir Kerspe in Gemany with purpose drinking water supply
End_Ne_HoekVanHolland	Terminal node at Hoek van Holland in the Netherlands
Lig_De_NiederRhein	Lignite mining water use in the sub-basin Nieder Rhein in Germany
Irr_FrLuBeDe_MoselSaar	All irrigation areas in the sub-basin of the Mosel/Saar in France, Luxembourg, Belgium and Germany.

Table 5-5 General node name convention.

Character	**Description**
1-3	Node type identification (3 characters, see Table 5-6)
4	Underscore
5-6	Identification of the country in which the node is located (2 characters, see Table 5-7)
7	Underscore
8	Identification of the purpose(s) of the reservoir (see Table 5-8)
9	Underscore
10-40	Name of representation e.g. location with: • No spaces and underscores (‘_’) in the name. • For potential structures and users “(P)” is added at the end of the name.

Table 5-6 Node type identification.

Node type identification	**Node type description**
Vif	Variable inflow
Fif	Fixed inflow
End	Terminal nodes
Rec	Recording
Rsv	Surface water reservoir: reservoir
Nlk	Surface water reservoir: natural lake
Div	Diversion
Lfl	Low flow: flushing (“Doorspoeling”)
Gst	Low flow: growing season threshold
Nvt	Low flow: navigation
Ind	Public water supply node: industrial water use
Dom	Public water supply nodes: drinking water (domestic use)
Col	Public water supply node: cooling water
Lvc	Loss flow: level control in Dutch polders

Node type identification	Node type description
Bif	Bifurcation
Lig	General district: lignite mining
Iir	Advanced irrigation nodes

Table 5-7 Country identification.

Country identification	Country name
At	Austria
Be	Belgium
De	Germany
Fr	France
Li	Liechtenstein
Lu	Luxembourg
Nl	Netherlands
Ch	Switzerland

Table 5-8 Reservoir purpose identification.

Purpose identification	Purpose
T	Drinking water supply
H	Flood protection
K	Energy production
E	Recreation
I	Industrial water supply
S	Shipping / navigation
A	Compensation reservoir

5.3.5 Modelling features

5.3.5.1 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 5-8 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 5-9 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).

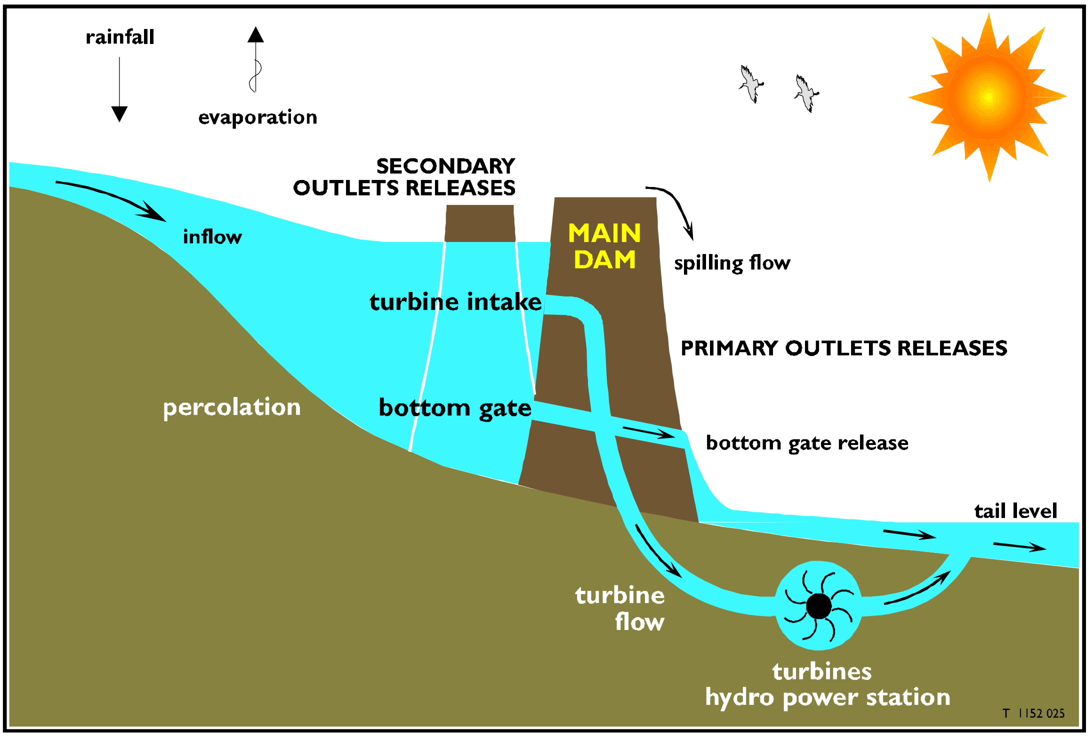


Figure 5-8 General representation of a reservoir in RIBASIM.

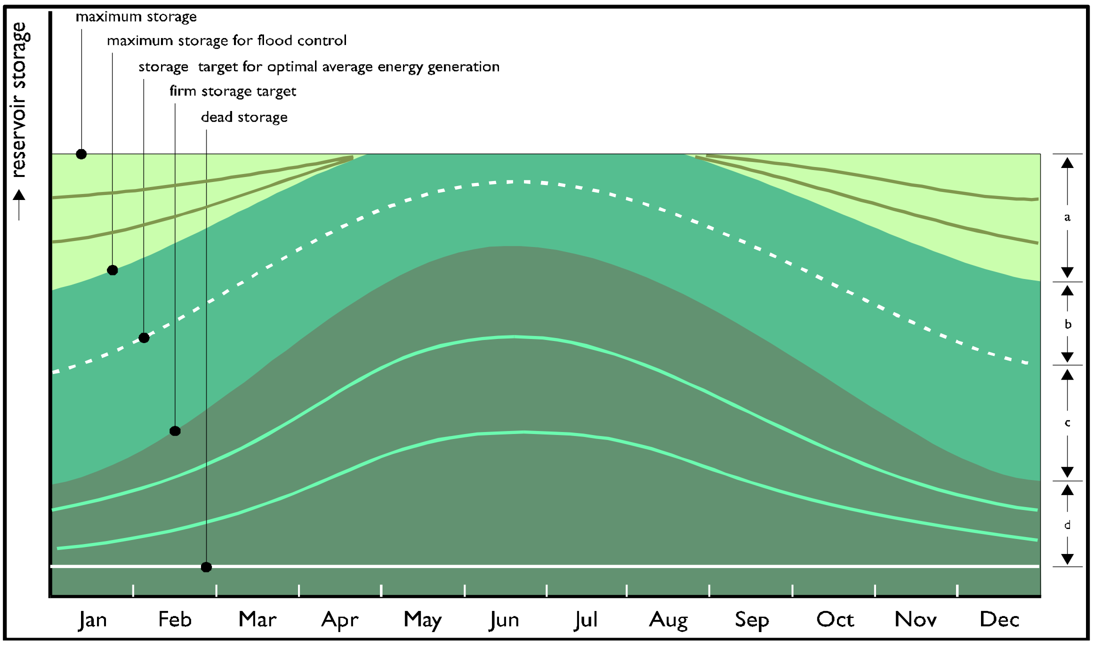


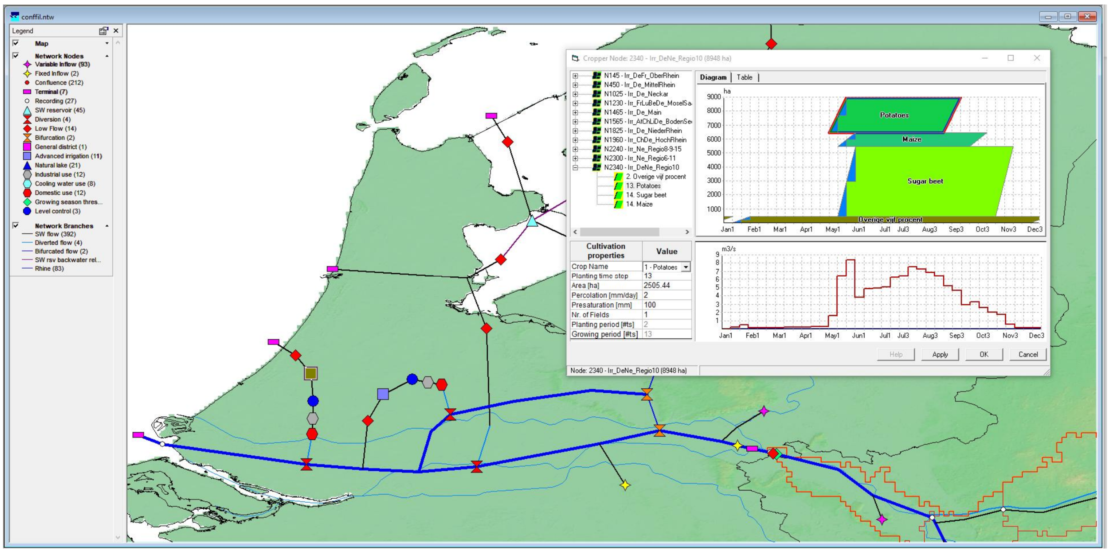
Figure 5-9 Reservoir operation rules in RIBASIM.

5.3.5.2 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 5-9. Different crop plans are defined for the various irrigation area. Figure 5-10 shows graphically the annual crop plan for Regio 10 in a crop-time diagram and the water demand over time.

Table 5-9 List of defined crops.

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



Cultivation properties	Value
Crop Name	1 - Potatoes
Planting time step	13
Area [ha]	2505.44
Percolation [mm/day]	2
Presaturation [mm]	100
Nr. of Fields	1
Planting period [#ts]	2
Growing period [#ts]	13

Node: 2340 - Irr_DeNe_Regio10 (8948 ha)

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

5.3.6 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

The multiple year runoff time series is generated with the Wflow model. Figure 5-11 shows the variable inflow nodes related to each sub-basin. Table 5-10 lists the Variable inflow node index and name, sub-basin area (km2). The name specifies the sub-basin location. The sub-basin area is also generated with the Wflow model. Presently only the 91 Wflow time series are stored in the runoff time series file Actinlfw.tms. The time series for the 2 variable inflow nodes in the Netherlands has been set to 0.0.

The multiple year actual rainfall time series are generated with the Wflow model. Time series are available for the locations of each natural lake, reservoir and sub-basin excluding the 2 sub-basins in the Netherlands. The 157 timeseries are stored in the file Actrain.tms. Not all time series are used in the model. The actual rainfall is used in the model for the irrigation, surface water reservoir and natural lake nodes.

The multiple year open water evaporation time series are generated with the Wflow model. Time series are available for the locations of each natural lake and reservoir. The 66 timeseries are stored in the Evaporat.tms file. The open water evaporation is used in the model for the surface water reservoir and natural lake nodes.

The annual reference crop evapotranspiration time series are the average over the multiple year potential evapotranspiration values generated by Wflow. The file contains time series for the 11 irrigation node. The 11 timeseries are stored in the file Refevapo.tms.

The 80% dependable rainfall is computed with the multiple year rainfall timeseries in file Actrain.tms. The 157 timeseries are stored in the file Deprain.tms. Not all time series are used in the model. The dependable rainfall is used in the model for the irrigation nodes.

The multiple year open water evaporation time series are generated with the Wflow model. Time series are available for the locations of each natural lake and reservoir. The 66 timeseries are stored in the Evaporat.tms file. The open water evaporation is used in the model for the surface water reservoir and natural lake nodes.

The multiple year recording flow time series are generated with the Wflow model. There are 61 time series / stations stored in the file Recrdflw.tms. Figure 5-12 shows the 27 recording nodes in the model. The nodes are listed in Table 5-11. Not for all 27 nodes are recording time series in the file Recrdflw.tms.

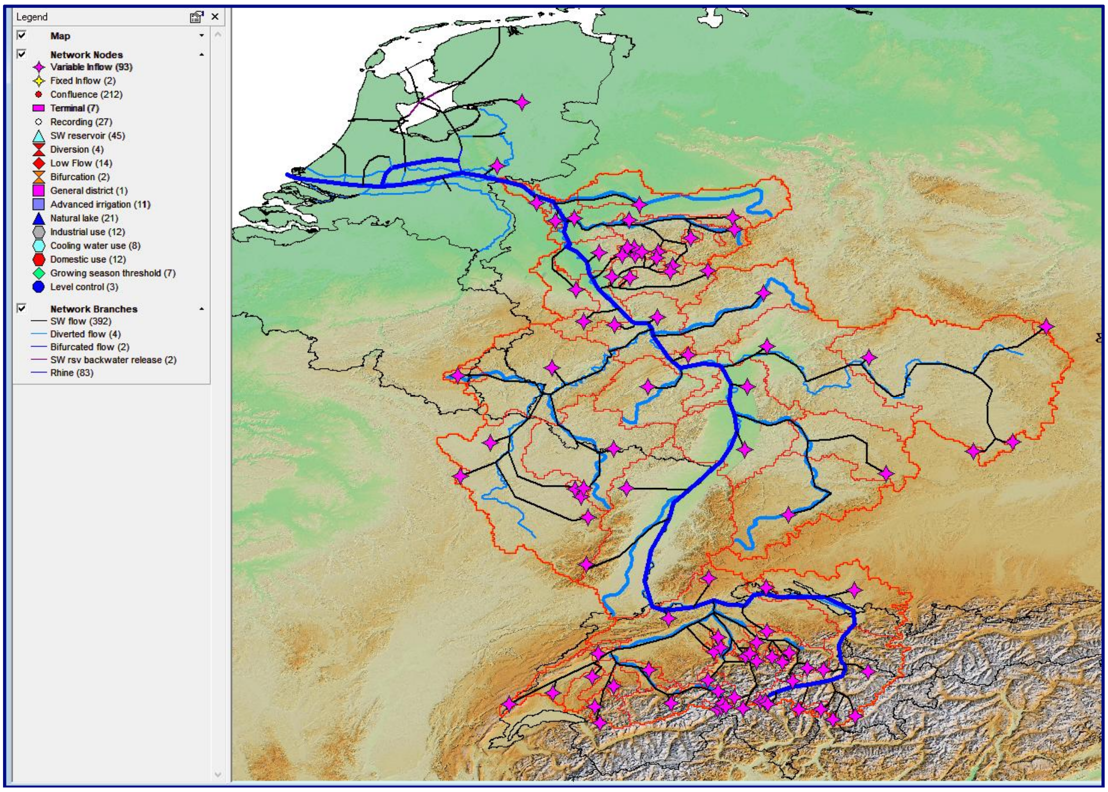


Figure 5-11 Overview of the inflow nodes representing the runoff of the 93 sub-basins.

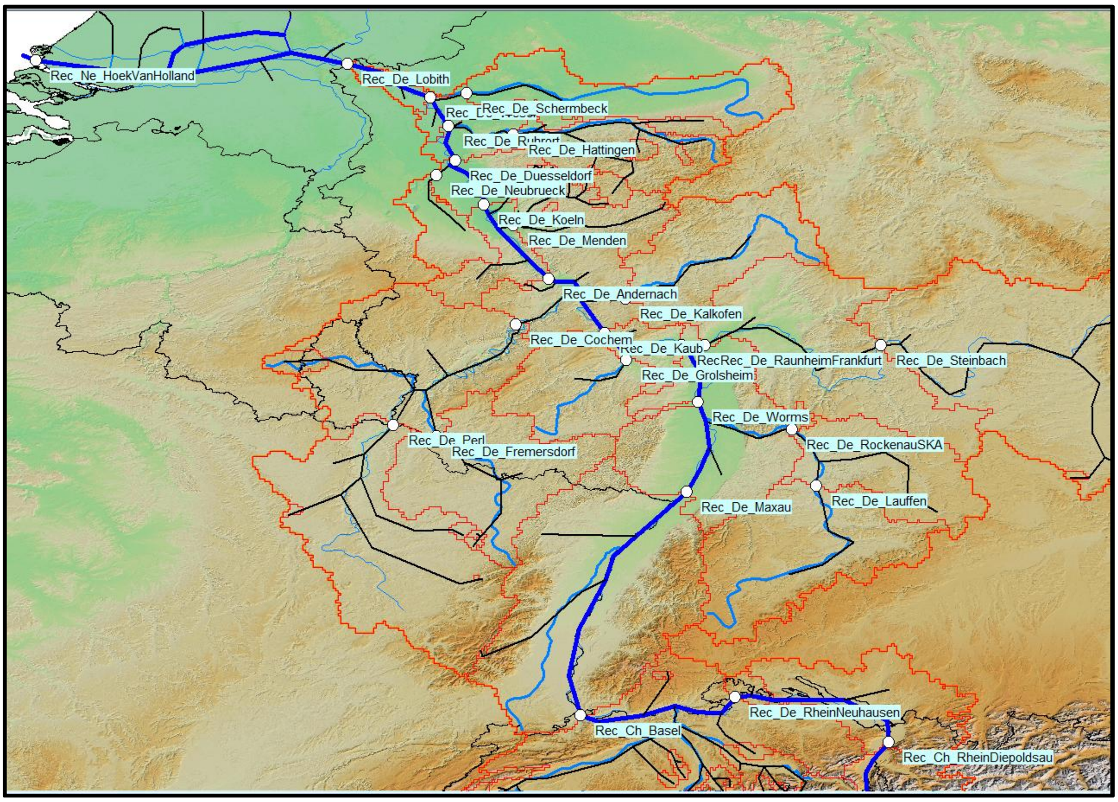


Figure 5-12 Overview of the recording nodes representing river flow monitoring stations.

Table 5-10 Overview of the sub-basin and area (km2).

Node Ix	Node name	Area (km2)	Node Ix	Node name	Area (km2)
5	Vif_De_UsRsvKerspe	28.12	825	Vif_Ch_UsRsvLimmern	18.84
25	Vif_De_UsRecMainz	7998.16	845	Vif_Ch_UsRsvKloental	84.53
30	Vif_Ch_UsRsvGigerwald	47.04	855	Vif_Ch_UsRsvSchrah	39.87
50	Vif_De_UsRecMenden	2643.77	870	Vif_Ch_UsRsvSihlsee	159.49
55	Vif_Ch_UsRsvMarmorera	87.75	880	Vif_De_UsRsvMauthausl	120.91
70	Vif_Ch_UsNlkNeuenburgersee	1688.57	900	Vif_Ch_UsRecRheinDiepoldsau	5833.88
75	Vif_De_UsRecLauffen	8011.86	910	Vif_Ch_UsNlkGreifensee	168.09
105	Vif_Ne_Vecht	0.00	935	Vif_Ch_UsNlkZurichsee	802.56
125	Vif_De_UsRecMaxau	14602.04	940	Vif_Ch_UsNlkBodensee	5093.28
150	Vif_Fr_UsRsvMadine	52.08	945	Vif_De_UsRsvSchluchsee	46.25
165	Vif_De_UsRecSteinbach	17714.15	955	Vif_De_UsRecRockenauSKA	4673.94
170	Vif_De_UsRecRheinNeuhausen	396.14	1030	Vif_Fr_UsNlkEtangDuStock	47.70
180	Vif_Ne_UsRecHoekVanHolland	25450.89	1035	Vif_Fr_UsNlkEtangDeGondrexange	56.85
230	Vif_Ch_UsRsvLacdHogrin	42.74	1060	Vif_Fr_UsNlkEtangDeLindre	111.23
240	Vif_Ch_UsNlkBrienzersee	987.92	1080	Vif_Fr_UsRsvVieuxPreLacDePierrePercee	9.14
245	Vif_De_UsRsvMoehne	436.11	1110	Vif_De_UsRecPerl	11320.18
260	Vif_De_UsRsvSorpe	174.59	1125	Vif_Lu_UsRsvEschSurSure	421.79
270	Vif_De_UsRsvBigge	322.93	1150	Vif_De_UsRecFremersdorf	6844.39
290	Vif_De_UsRsvAgger	41.16	1180	Vif_Fr_UsRsvKruthWildenstein	27.68
300	Vif_De_UsRsvVerse	23.78	1205	Vif_De_UsRecCochem	8310.77
320	Vif_De_UsRsvHenne	62.55	1260	Vif_De_UsRecGrolsheim	4028.59
355	Vif_De_UsRsvObernhau	13.04	1280	Vif_Ch_UsRecBasel	11509.08
385	Vif_De_UsRsvWiehl	47.78	1285	Vif_De_UsRecWorms	131.84

415	Vif_Ch_UsNlkMurtensee	710.59	1290	Vif_Ch_UsNlkLacDeJoux	187.02
425	Vif_De_UsRecKalkofen	5306.63	1355	Vif_De_UsRsvRothsee	42.74
460	Vif_Ch_UsRsvRossens	907.43	1365	Vif_De_UsRsvBrombach	56.35
475	Vif_Ch_UsRsvSchiffenen	434.22	1475	Vif_Ch_UsRsvValleDiLei	47.46
490	Vif_Ch_UsNlkThunersee	1375.35	1490	Vif_De_UsRecRaunheim	9154.56
495	Vif_Ch_UsRsvWohlenseeMuehleberg	725.20	1515	Vif_Ch_UsRsvSufers	201.37
500	Vif_Ch_UsNlkBielersee	231.82	1620	Vif_De_UsRecKaub	1221.18
505	Vif_Ch_UsNlkSempachersee	89.02	1625	Vif_De_UsRsvWahnbach	76.12
515	Vif_Ch_UsNlkBaldeggersee	65.54	1655	Vif_De_UsRecNeubrueck	1598.35
525	Vif_Ch_UsNlkHallwillersee	70.11	1680	Vif_De_UsNlkLaacherSee	30.76
540	Vif_Ch_UsNlkSarnersee	280.36	1700	Vif_De_UsRecAndernach	3564.21
550	Vif_Ch_UsNlkVierwaldstattersee	1904.82	1705	Vif_De_UsRecKoeln	1902.11
555	Vif_Ch_UsNlkAgerisee	46.87	1720	Vif_De_UsRsvEnnepe	84.40
565	Vif_Ch_UsNlkZugersee	196.82	1730	Vif_De_UsRsvBever	58.37
580	Vif_Ch_UsRsvOberaar	18.95	1745	Vif_De_UsRsvWupper	45.39
590	Vif_Ch_UsRsvRaterichsboden	18.93	1760	Vif_De_UsRsvGrosseDhunn	60.62
600	Vif_Ch_UsRsvGrimsel	82.86	1785	Vif_De_UsRecHattingen	3123.79
620	Vif_Ch_UsRsvGelmer	18.92	1835	Vif_De_UsRecDuesseldorf	1584.33
685	Vif_Ch_RsvGoescheneralp	44.91	1840	Vif_De_UsRecRuhrort	1654.94
695	Vif_Ch_UsRsvLucendro	28.40	1845	Vif_De_UsRecSchermbeck	4760.87
760	Vif_Ch_UsRsvCurnera	26.02	1880	Vif_De_UsRecWesel	576.70
770	Vif_Ch_UsRsvNalps	18.92	1885	Vif_De_UsRecLobith	557.43
785	Vif_Ch_UsRsvSantaMaria	37.87	1890	Vif_Ch_UsNlkWalensee	967.66
810	Vif_Ch_UsRsvZervreila	68.67			

Table 5-11 Overview of Rhine 002 model flow recording nodes.

Node Ix	**Node name**
1990	Rec_Ch_Basel
100	Rec_De_Lauffen
455	Rec_De_Kalkofen
1000	Rec_De_RockenauSKA
1120	Rec_De_Perl
1170	Rec_De_Fremersdorf
1245	Rec_De_Cochem
1275	Rec_De_Grolsheim
1440	Rec_De_Steinbach
1510	Rec_De_RaunheimFrankfurt
1570	Rec_Ch_RheinDiepoldsau
1595	Rec_De_RheinNeuhausen
1650	Rec_De_Menden
1675	Rec_De_Neubrueck
1795	Rec_De_Hattingen
1870	Rec_De_Schermbeck
2020	Rec_De_Maxau
2040	Rec_De_Worms
2055	Rec_De_Mainz
2075	Rec_De_Kaub
2110	Rec_De_Andernach
2130	Rec_De_Koeln

2150	Rec_De_Duesseldorf
2165	Rec_De_Ruhrort
2180	Rec_De_Wesel
2205	Rec_De_Lobith
2355	Rec_Ne_HoekVanHolland

5.3.7 Infrastructure

The network contains 45 reservoirs and 21 natural lakes with a volume of 10 Mcm or more and spread over the Rhine riparian countries is listed in Table 5-12. The natural lake nodes are listed in Table 5-13 and the reservoir nodes with the full reservoir storage in Table 5-14.

Table 5-12 Distribution of reservoirs and natural lakes with storage bigger then 10 Mcm in the model.

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

Table 5-13 Overview of natural lakes.

Node Ix	Node name
420	Nlk_Ch_Murtensee
510	Nlk_Ch_Sempachersee
520	Nlk_Ch_Baldeggersee
535	Nlk_Ch_Hallwillersee
545	Nlk_Ch_Sarnersee
560	Nlk_Ch_Agerisee
575	Nlk_Ch_Zugersee
655	Nlk_Ch_Brienzersee
665	Nlk_Ch_Thunersee
740	Nlk_Ch_Vierwaldstattersee
915	Nlk_Ch_Greifensee
1295	Nlk_Ch_LacDeJoux
1310	Nlk_Ch_Neuenburgersee
1325	Nlk_Ch_Bielersee
1585	Nlk_Ch_Bodensee
1910	Nlk_Ch_Walensee
1930	Nlk_Ch_Zurichsee
1685	Nlk_De_Laachersee
1040	Nlk_Fr_EtangDeGondrexange
1050	Nlk_Fr_EtangDuStock
1065	Nlk_Fr_EtangDeLindre

Table 5-14 Overview of reservoirs and full reservoir storage. (Mcm).

Node Ix	Node name	Full reservoir storage (Mcm)
35	Rsv_Ch_K_Gigerwald	33.40

60	Rsv_Ch_K_Marmorera	62.60
235	Rsv_Ch_HK_LacdHogrin	84.00
470	Rsv_Ch_K_Rossens	220.00
485	Rsv_Ch_K_Schiffenen	65.00
585	Rsv_Ch_K_Oberaar	61.00
605	Rsv_Ch_K_Grimsel	101.00
615	Rsv_Ch_K_Raterichsboden	27.00
630	Rsv_Ch_K_Gelmer	14.00
675	Rsv_Ch_K_WohlenseeMuehleberg	1.60
690	Rsv_Ch_K_Goescheneralp	76.00
700	Rsv_Ch_K_Lucendro	25.00
765	Rsv_Ch_K_Curnera	41.10
775	Rsv_Ch_K_Nalps	45.00
790	Rsv_Ch_K_SantaMaria	67.30
815	Rsv_Ch_K_Zervreila	100.50
830	Rsv_Ch_K_Limmern	93.00
850	Rsv_Ch_K_Kloental	56.40
865	Rsv_Ch_K_Schrah	150.00
875	Rsv_Ch_K_Sihlsee	96.50
1480	Rsv_Ch_K_ValleDiLei	200.00
1520	Rsv_Ch_K_Sufers	21.40
10	Rsv_De_T_Kerspe	15.50
255	Rsv_De_THKE_Moehne	140.80
265	Rsv_De_THKE_Sorpe	70.00
275	Rsv_De_THKE_Bigge	171.70
295	Rsv_De_THK_Agger	19.30
305	Rsv_De_TK_Verse	32.80
325	Rsv_De_THKE_Henne	38.40
360	Rsv_De_THS_Obernhau	14.90
390	Rsv_De_TH_Wiehl	31.50
885	Rsv_De_THK_Mauthausl	21.00
950	Rsv_De_K_Schluchsee	108.00
1360	Rsv_De_KE_Rothsee	11.70
1370	Rsv_De_HKE_Brombach	129.00
1630	Rsv_De_TH_Wahnbach	41.40
1725	Rsv_De_TKS_Ennepe	12.60
1740	Rsv_De_HSE_Bever	23.70
1755	Rsv_De_HKSE_Wupper	25.90
1770	Rsv_De_THS_GrosseDhunn	81.00
155	Rsv_Fr_TE_Madine	33.00
1085	Rsv_Fr_TK_VieuxPreLacDePierrePercee	55.00
1185	Rsv_Fr_TH_KruthWildenstein	12.00
1130	Rsv_Lu_TK_EschSurSure	62.00
2220	Rsv_Ne_IJsselMarkerRandEemMeren	7000.00

5.3.8 Water users

The location of the various nodes in the schematization representing the water users and sectors are shown in Figure 5-13 till Figure 5-18. 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.

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 m3/s and the discharge on 10 m3/s (Ruijgh, 2019).

Growing season flow threshold: Maintaining an 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).

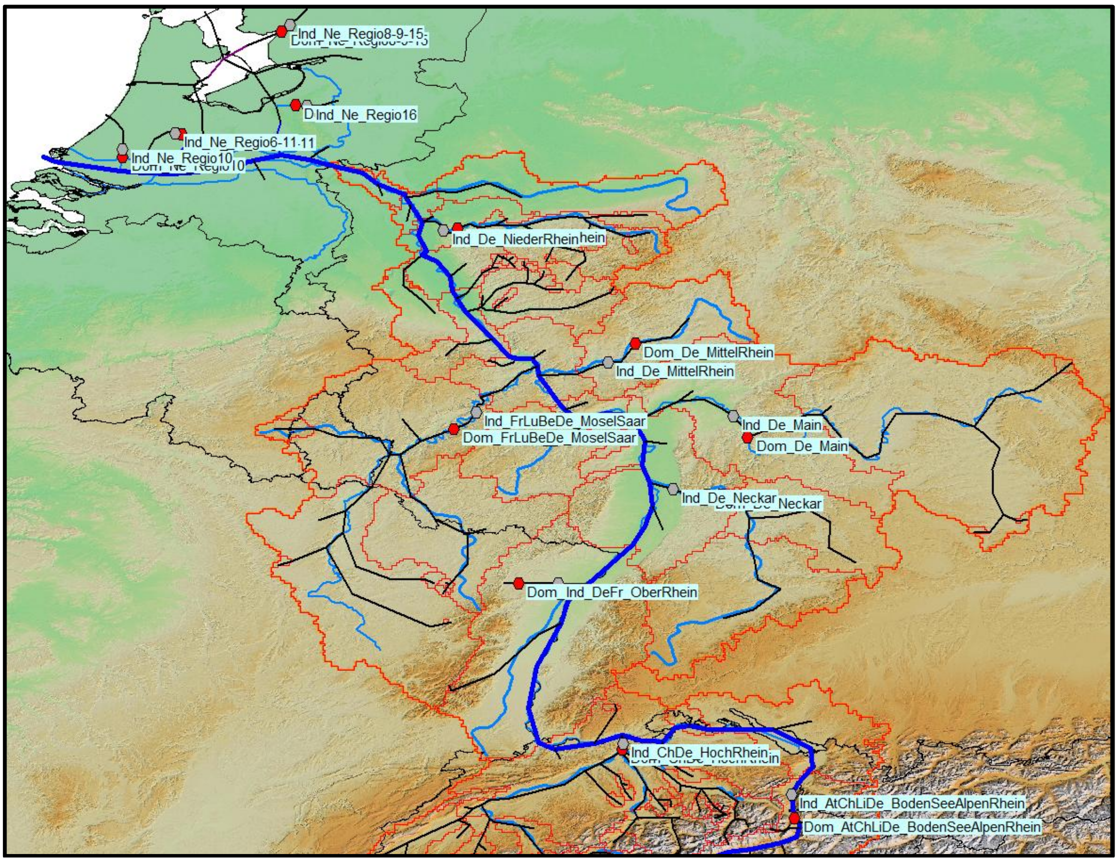


Figure 5-13 Overview of the domestic and industrial demand nodes

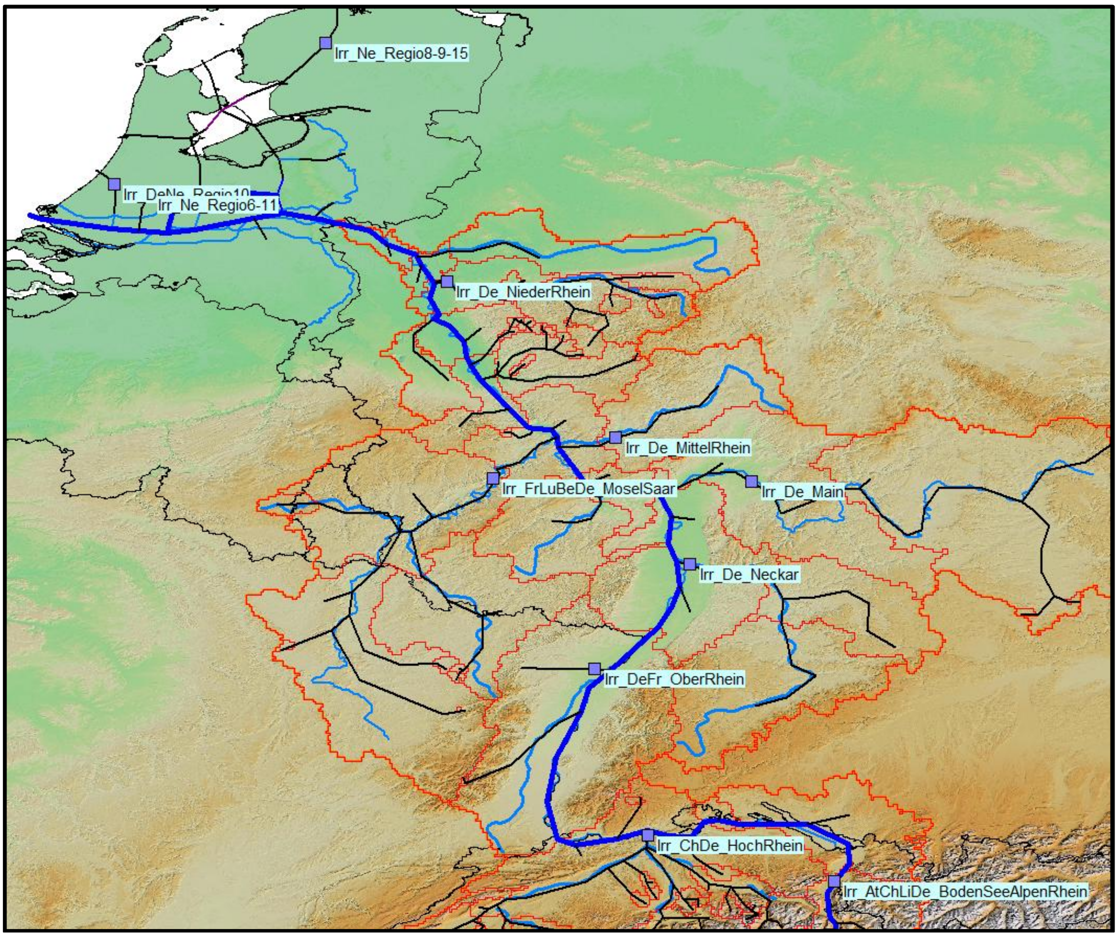


Figure 5-14 Overview of the irrigation nodes.

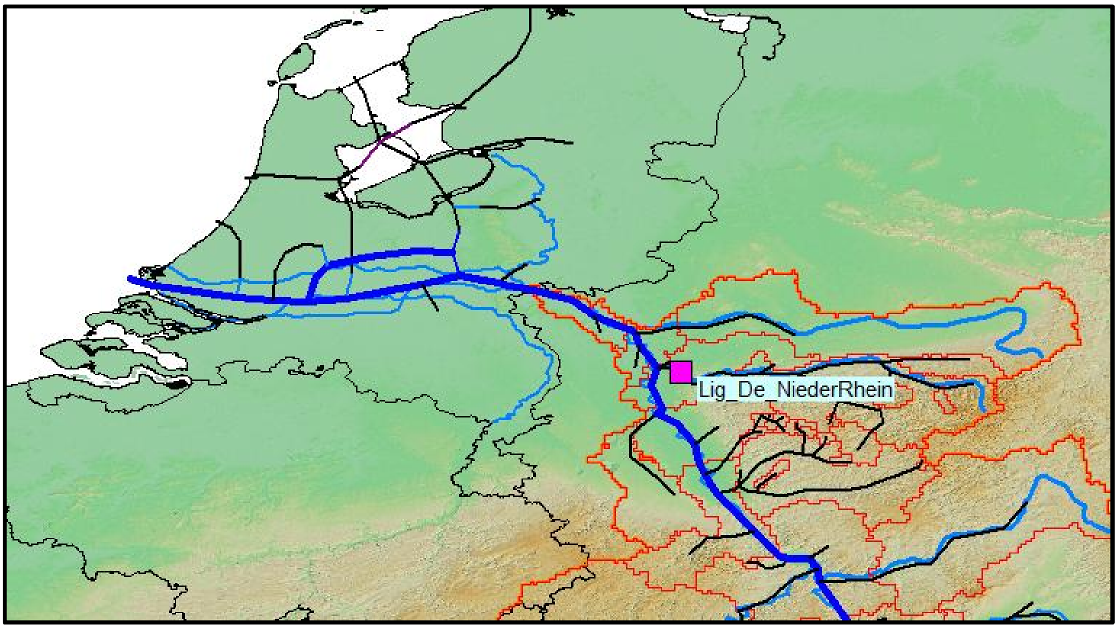


Figure 5-15 Overview of lignite mining node.

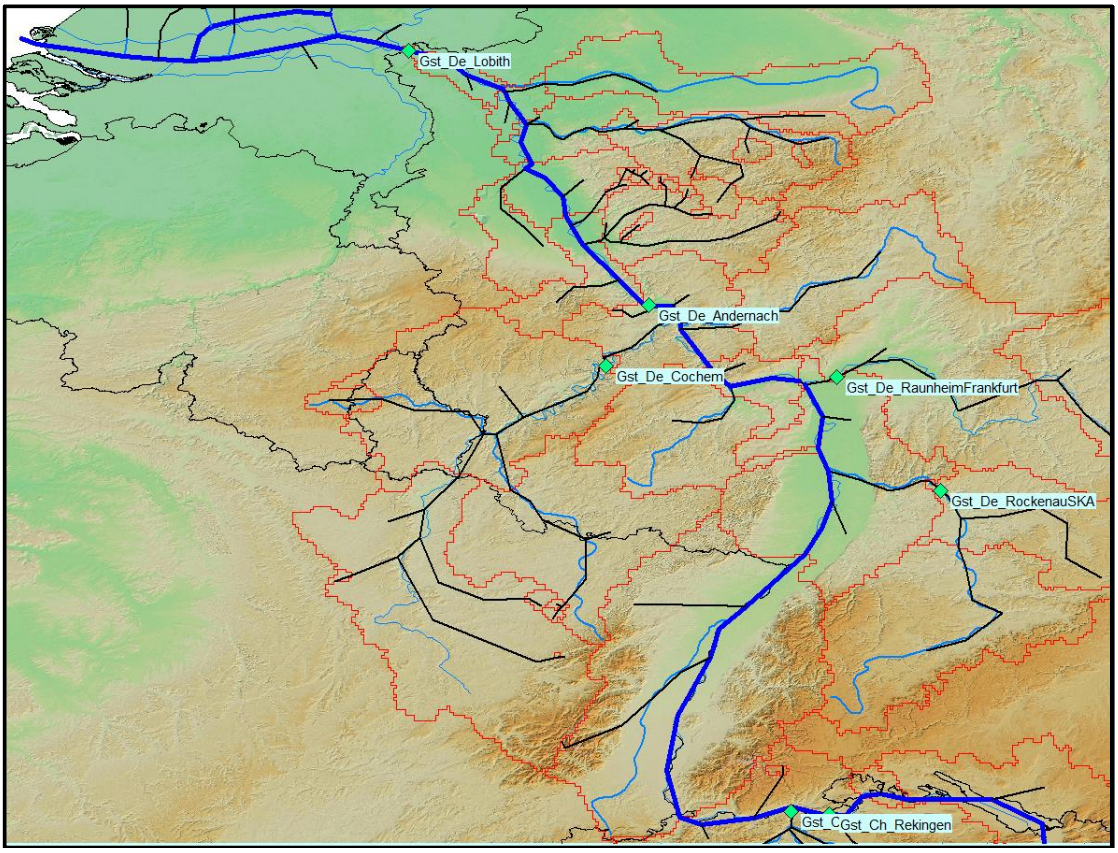


Figure 5-16 Overview of the Growing season flow threshold.

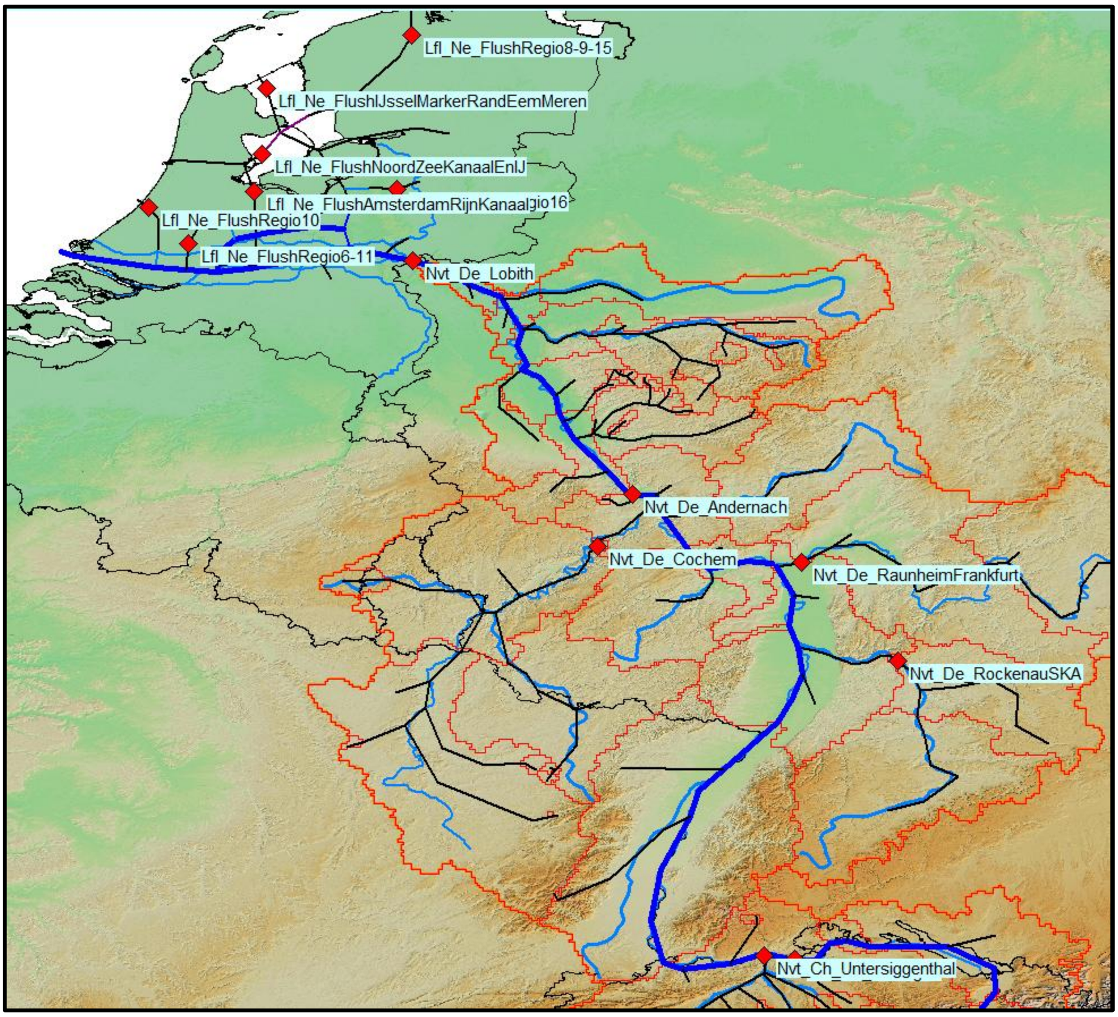


Figure 5-17 Overview of the flushing and navigation low flow nodes.

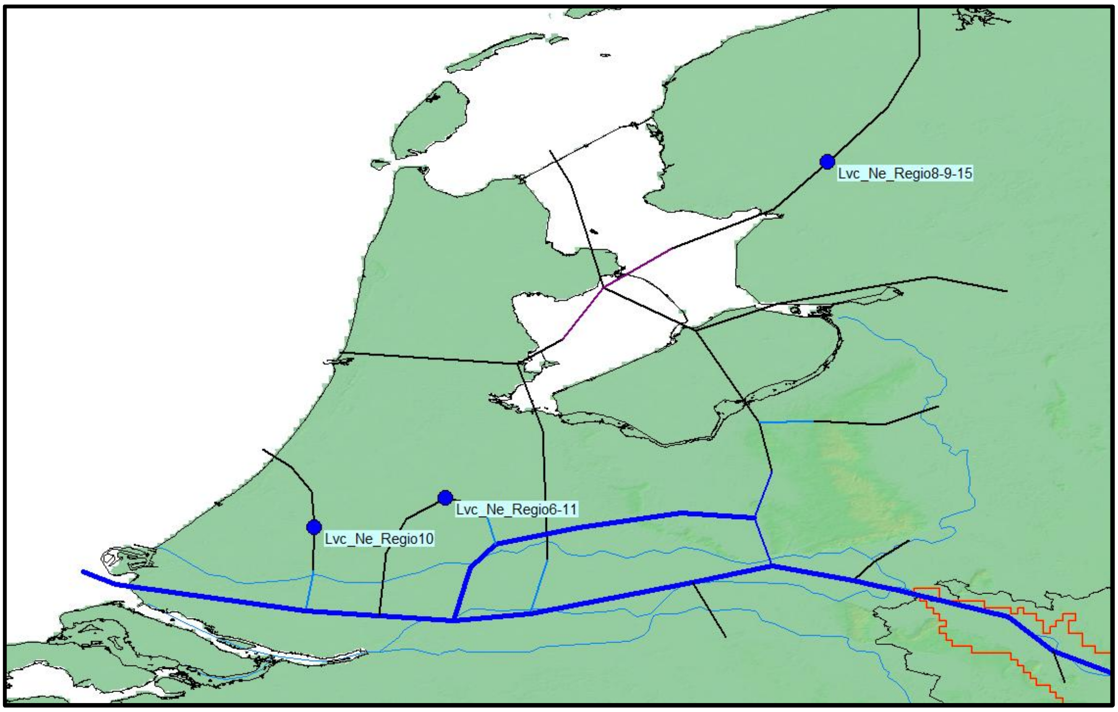


Figure 5-18 Overview of the level control (“peilbeheer”) nodes.”

5.3.9 Scenarios, measures and strategies

5.3.9.1 General

The scenarios and management actions which can be defined explicitly are: see Table 5-15

Table 5-15 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 will be updated with the specified percentage (%). Also the number of inhabitants (population) and explicit demand values of all public water supply nodes per catchment will 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 at 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 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 analyzed, 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 are overwriting 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 5.16 till Table 5.21. No measures are created yet.

Table 5.16 Hydrological scenarios in Rhine002 model (directory Hydrolog).

Scenario ID	**Scenario name**
W06	Wflow files run_catch_mm_20200625

Table 5.17 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 5.18 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 5.19 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 5.20 Management action (strategies) in Rhine002 model (directory Actions).

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

Table 5.21 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

5.3.10 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. The following stations were used, with a series of 1989 – 2000, grouped according their position (tributary or main river):

Table 5.22 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)

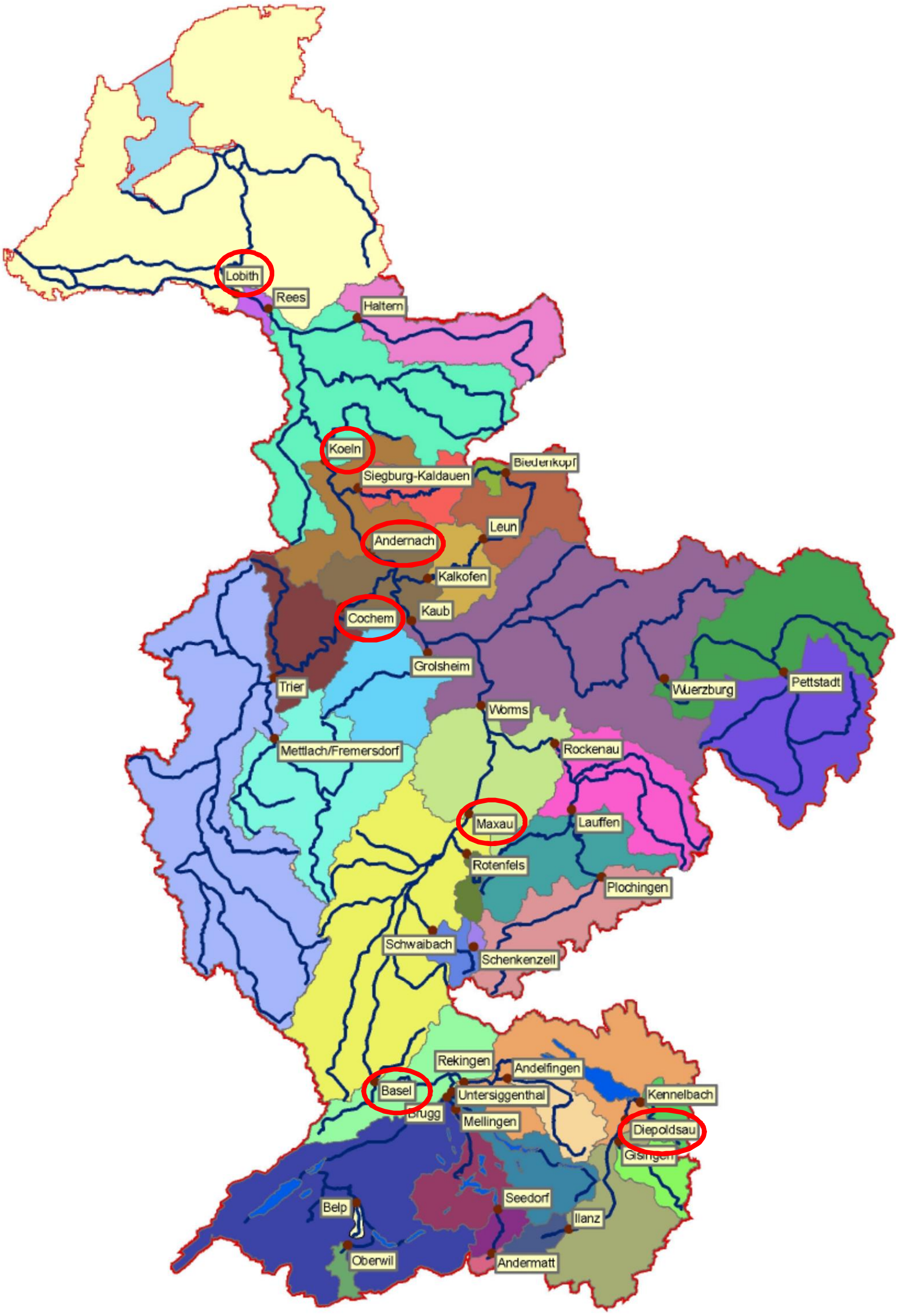


Figure 5-19 Location of the various gauging stations in the Rhine basin

In this paragraph, a number of graphs are shown for some of the tributaries. Although the fit is not always perfect, there is a good agreement between the measured and simulated series. For one of the largest tributaries, the Mosel, the graph in Figure 5-20 for Cochem shows that the hydrograph is very well reproduced for the lower discharges, while peak flows can be off.

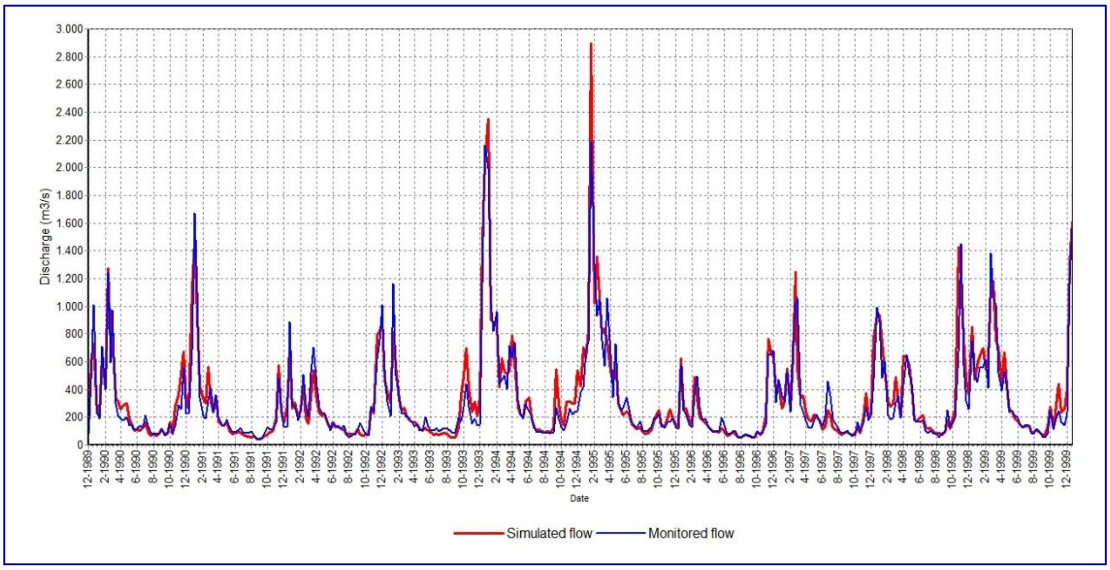


Figure 5-20 Simulated and measured monthly discharges at gauging station Cochem (Mosel)

Another example is shown for the Lippe at Schermbeck on the Lippe in Figure 5-21, 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. A different picture is seen for the flow from the Ruhr (Figure 5-22 and Figure 5-23), which is shown here for Hattingen and Menden. Here, the peak flows are underestimated, although this is clearer for Menden than at Hattingen.

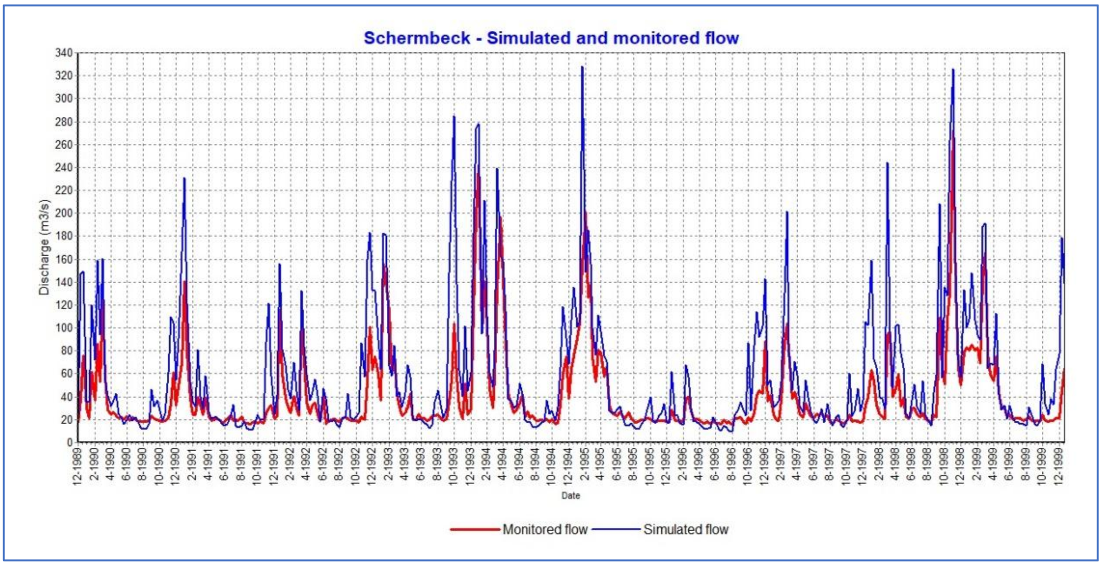


Figure 5-21 Simulated and measured monthly discharges at gauging station Schermbeck (Lippe)

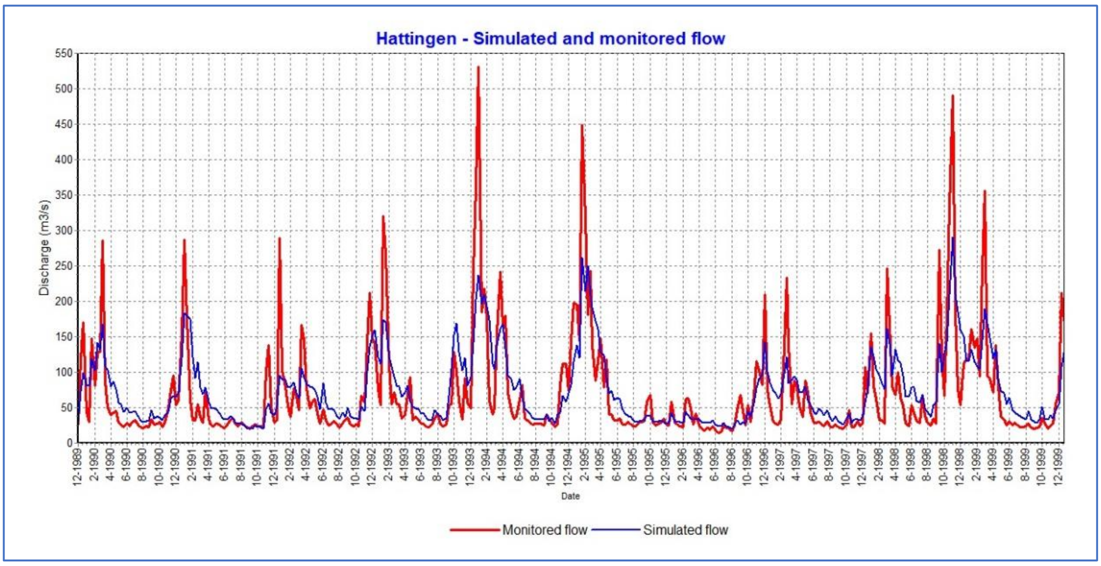


Figure 5-22 Simulated and measured monthly discharges at gauging station Hattingen (Rurh)

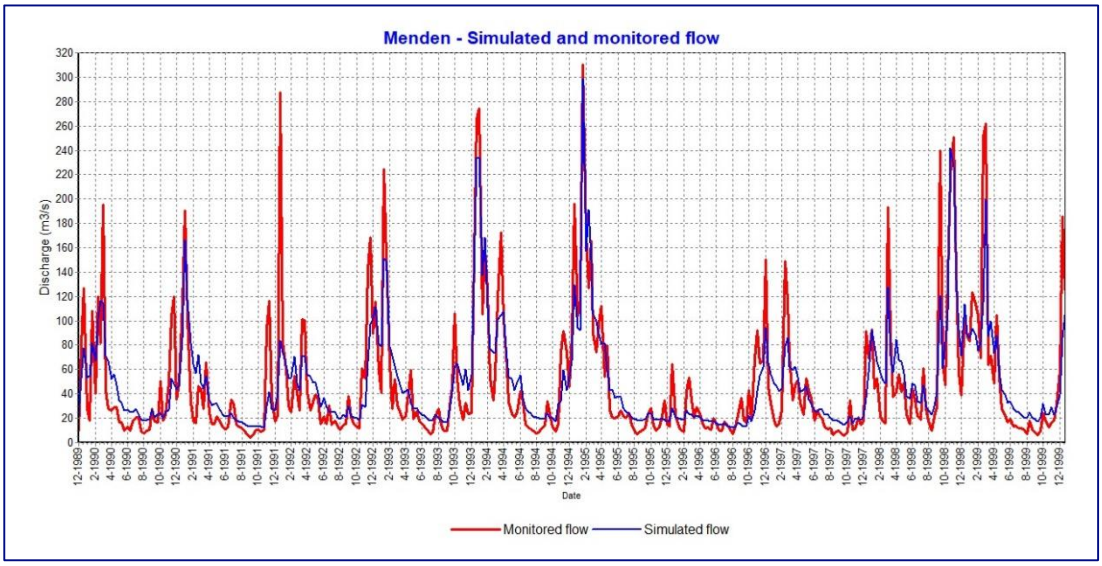


Figure 5-23 Simulated and measured monthly discharges at gauging station Menden (Rurh)

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 5-24), 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 5-25) when compared to Diepoldsau, with the former having a much higher and stable low flow.

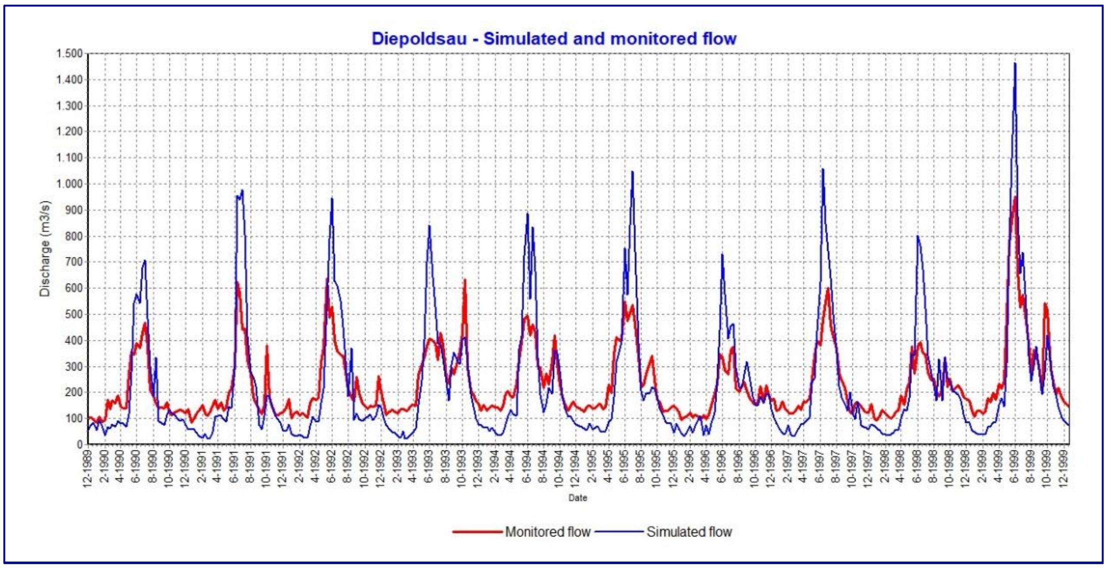


Figure 5-24 Simulated and measured monthly discharges at gauging station Diepoldsau (Rhein)

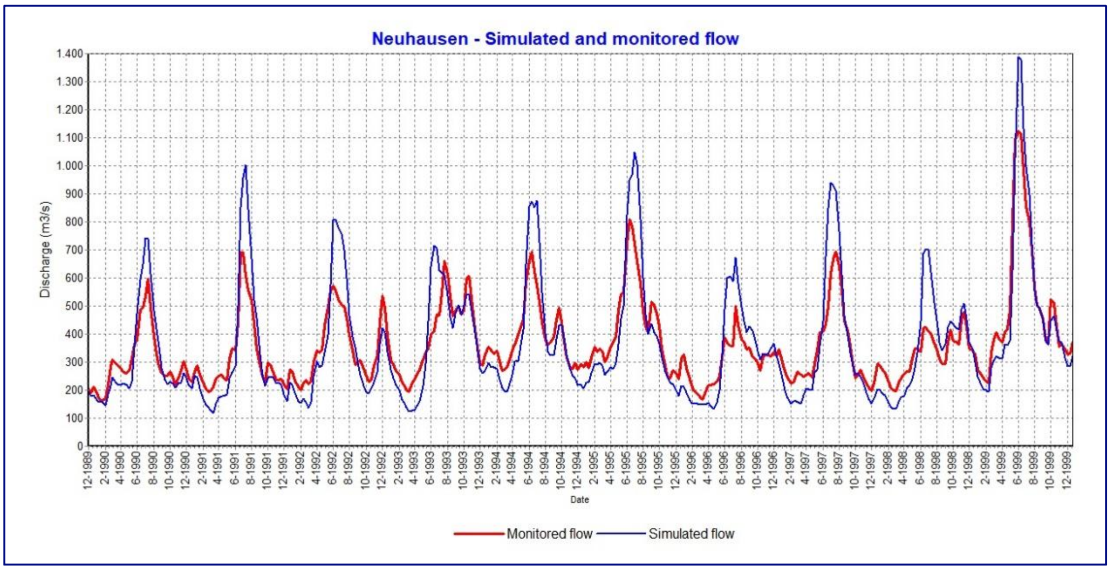


Figure 5-25 Simulated and measured monthly discharges at gauging station Neuhausen (Rhein)

On the main Rhine river, the station of Maxau downstream from Switzerland shows a similar pattern between simulated and measured flows (Figure 5-26), 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 5-27) and Andernach (Figure 5-28) 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 5-29) and Lobith (Figure 5-30) the low flows are represented very well, with only slight overestimation of the peak flows.

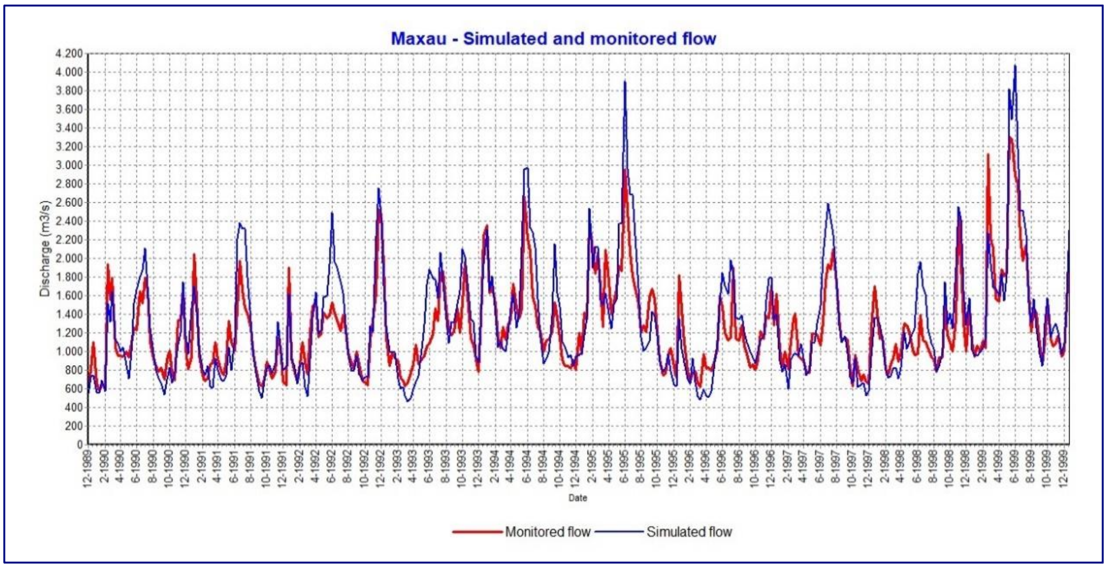


Figure 5-26 Simulated and measured monthly discharges at gauging station Maxau (Rhein)

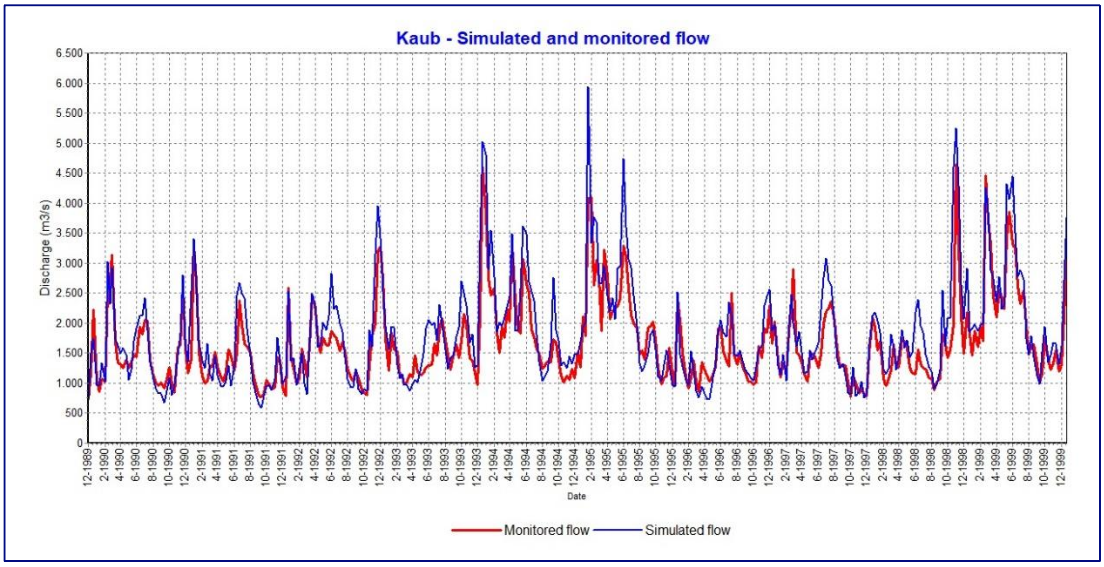


Figure 5-27 Simulated and measured monthly discharges at gauging station Kaub (Rhein)

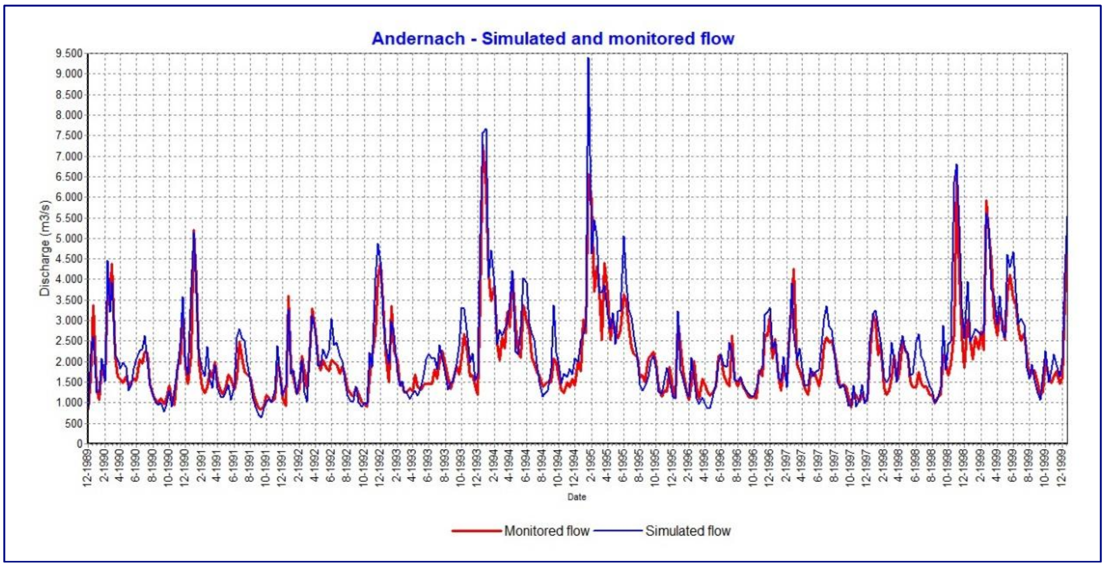


Figure 5-28 Simulated and measured monthly discharges at gauging station Andernach (Rhein)

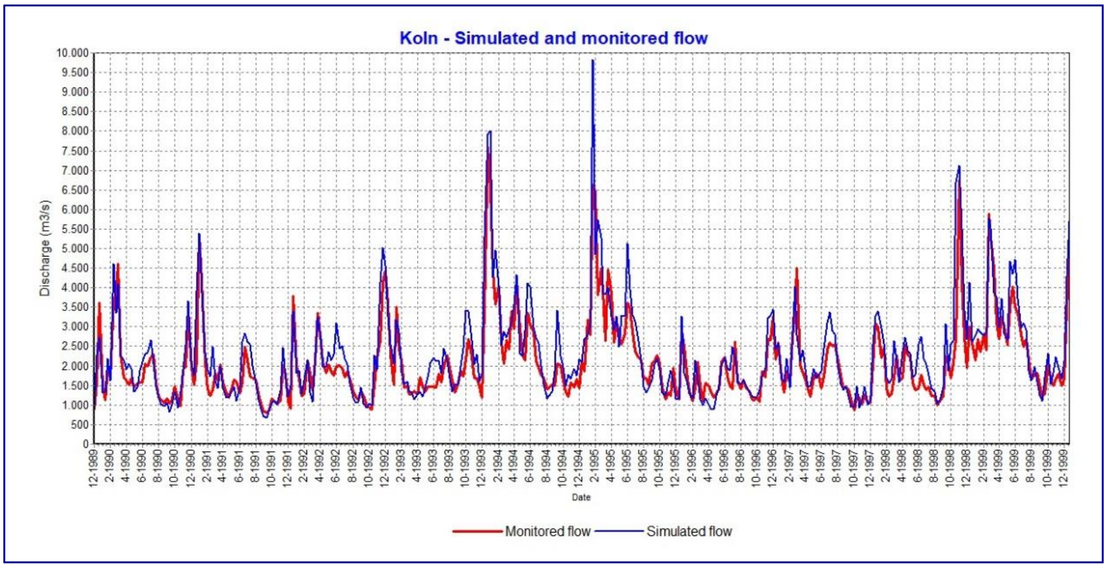


Figure 5-29 Simulated and measured monthly discharges at gauging station Koln (Rhein)

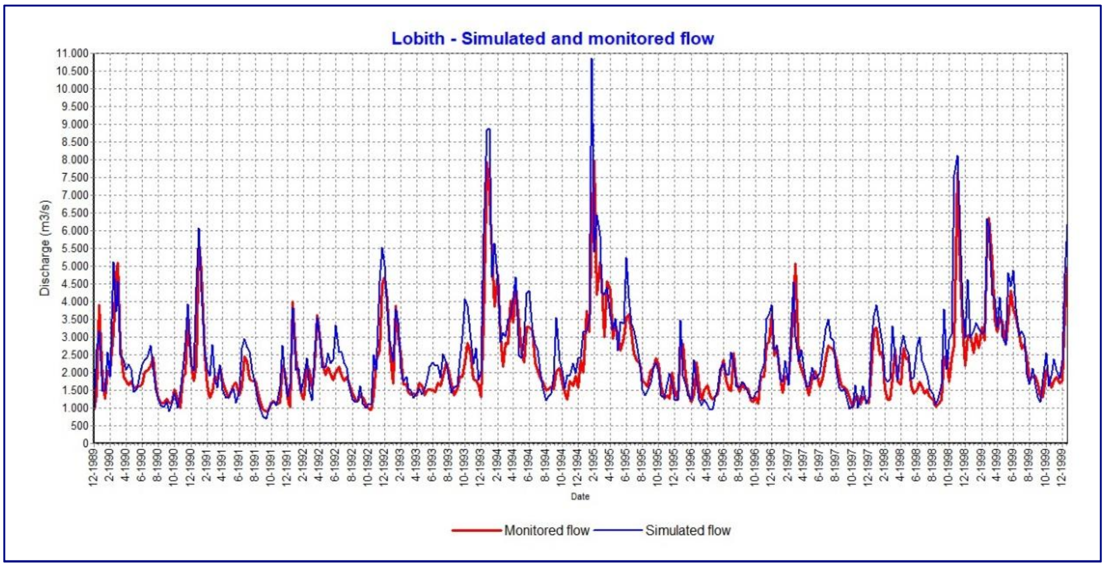


Figure 5-30 Simulated and measured monthly discharges at gauging station Lobith (Rhein)

6 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 for river basin simulation RIBASIM with the intention to improve it in the future. The model is not yet fully developed yet but when it is available a large variety of analysis could be done 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 crop characteristics must be checked and updated if needed.
4. The model data of the various demands has to be checked and improved.
5. Improved Wflow model is in progress 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.

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