Deltares

RIWA-Meuse

Low river discharge of the Meuse

A Meuse River basin water management modelling study using RIBASIM

RIWA - Vereniging van Rivierwaterbedrijven

Colofon

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Foreword

Background and research objective

The river Meuse is the source of drinking water for 7 million people living in the Netherlands and Belgium. In order to guarantee the supply of safe drinking water, it is indispensable to safeguard the supply of sufficient water of good quality in the Meuse.

Deltares knowledge and research institute has – on behalf of RIWA-Maas (in representation of its Dutch members Dunea, Evides, and WML) and Rijkswaterstaat Zuid-Nederland - developed the RIBASIM model which serves as a tool to predict and further understand water availability in the Meuse catchment. Based on this collaborative project, this research study arose out of a dual concern, on the one hand on the low discharge levels of the Meuse in recent years, and on the other hand on the negative impacts that climate change will have on (water) discharge in the river (as predicted by the Intergovernmental Panel on Climate Change (IPPC) amongst others). This research has the objective of implementing the model to shed light on the impacts that climate change can have on water supply in the international river basin of the Meuse. Therefore, the research shows the projected impacts on future water availability in Meuse as a result of climate change.

Design and results of the study

For the purpose of this study, Deltares developed a RIBASIM water balance model for the entire Meuse catchment. Deltares analysed historical discharge data of the last 40 years from four important locations along the river Meuse in France, Belgium and the Netherlands. The changes in low water discharge in moderate, average, and extreme climate scenarios for the years 2050 and 2085 were simulated with the model. The results of the model present a clear trend: in almost all investigated climate scenarios and for all locations considered, the model predicted longer periods of low discharges in summer periods. The model also revealed that the tributaries that feed the Meuse in the Netherlands, such as the Roer and the Niers, play a major role in the water availability for the Netherlands.

Result interpretation

The results of this study present a worrying condition for drinking water companies: lower water discharge levels in the Meuse will occur more frequently and for longer periods of time in the entire river basin. Climate change will have adverse consequences for the Dutch drinking water that is extracted from the Meuse: during periods of low water discharge the river will be exposed to more contamination incidents or (industrial) discharges as it will lose its capacity to dilute pollutants. This can lead to situations whereby drinking water companies are forced to temporarily stop the intake of water from the Meuse more frequently in the future. A prolonged interruption of water intake endangers the drinking water supply of 7 million people. Furthermore, the drinking water sector is currently already facing several challenges, such as an anticipated growth in the demand for drinking water due to population growth as well as an increased concentration of in harmful substances in the Meuse water that also threatens the quality of drinking water. Lastly, extended periods of low water discharge in the Meuse will also affect many other sectors, such as shipping, agriculture and industry located along the catchment, as well as vulnerable and protected ecological areas that depend on the Meuse.

Petition of the members of RIWA-Meuse

This study ultimately confirms the trend of longer periods of low water discharge in the Meuse during summertime, as we have already witnessed in recent years. This disturbing trend can lead to major problems in the drinking water supply. However, it is not too late to translate the insights from this report into tangible actions and solutions. To some extent, drinking water companies can solve these problems themselves. For example, they are already actively investigating and commissioning additional drinking water sources.

Despite these advancements, the Deltares report has prompted members of RIWA-Maas to call on all parties that make use of the Meuse to work together and identify the best solutions to use and manage river's water in a robust and sustainable way. The RIBASIM water balance model of the Meuse, which was developed jointly with this study, is a valuable tool to explore and identify different solutions. Moreover, an important reason behind the development of this model was to encourage and start a dialogue to take measures to tackle prolonged periods of water scarcity, as well as to calculate the effects of these measures at the level of the entire river basin.

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[1] *RIBASIM – River Basin Planning and Management.*

Summary

Insight into current and future water availability in the Meuse River basin is important to be able to anticipate future socio-economic and climatic changes, especially during the summer period when low flows occur. The possible impact of water extraction of various socio-economic sectors on low flows in the Meuse River basin, in combination with decreasing water availability due to climate change, is crucial for the drinking water companies that use the Meuse as source for the public water supply of 7 million persons in the Netherlands and Belgium. Therefore, RIWA-Meuse initiated two research projects, in cooperation with drinking water companies Dunea, Evides, WML and Rijkswaterstaat Zuid-Nederland: one looking into the contribution of different tributary rivers of the Meuse River flow during periods of drought (research project A), and one looking into future changes of water availability and demand (research project B).

Research project A deals with the contribution of the inflow from tributaries to the discharge for the Meuse during low-level water conditions based on historical flow time series. Research project B deals with the usage and distribution of available Meuse water during periods of low river discharge based on historical flow time series generated by a rainfall-runoff model, and under various climate change scenarios.

This report describes the results of sub-project B. The two products of this project are an inventory list of water users and other human interventions in the Meuse river basin and a detailed water demand- and allocation (water balance) model of the whole Meuse River basin starting off from the open global datasets. This Meuse002 model was implemented in the RIBASIM river basin modelling software. RIBASIM is a generic model package for simulating the behavior of river basins under various hydrological, socio-economic, agriculture, climate change and water quality scenarios. The Meuse002 model covers the whole Meuse River basin from its source in France to the Haringvliet in the Netherlands. The existing and potential water users and major water storage infrastructure like dams, reservoirs and natural lakes are considered. The hydrological boundaries (runoff, rainfall, evaporation) were generated with the rainfall-runoff model of the Meuse (Wflow). The Meuse002 model simulates multiple year time series with time steps of one decade (10 days).

The model has been validated against measured discharges from gauging stations along the Meuse. The validation shows a good match between the measured and simulated discharge for the locations along the mainstream. For gauging station Megen this could not be achieved without adding an additional time series that accounts for unknown water usage and water losses during the exceptional dry years of 2018, 2019 and 2020.

Eleven simulation cases were run: the base case of the present situation and ten future scenarios that correspond with the inflow (runoff) change of the five KNMI climate change scenarios GH, GL, WL, WH and WHdry for the target years 2050 and 2085. Model results have been evaluated for the observation points Chooz, Monsin, Borgharen and Megen. Indicator plots show that under climate change conditions critical thresholds of low flow discharge will be reached more often and for a longer period during the summer months. Chooz shows bottle necks already for the base case, which represents the current and historic situation. For Monsin, mainly the W-scenarios show significant bottle necks. The bottle necks shown for Monsin translate to Borgharen, where the Meuse water is divided between the Common Meuse and the Juliana Canal. At Megen the Meuse has received additional inflow from tributaries, with the Rur and the Niers as the two largest. The percentages of time steps below threshold indicators at Megen are smaller than for Monsin.

This is because of the additional inflow from the Rur, but also because of the threshold values that have been applied here for the calculation of the indicators. In the W-scenarios, however, the discharge falls below the thresholds for a significant period as well.

The dependable flow is the flow value assigned to a specific time in a year (a decade) that is exceeded by 70 % or 90 % of the simulated years. Dependable flows are thus a measure for the discharge one can rely on throughout the year. Practically all future scenarios show lower dependable flows than the base case for the summer months.

In terms of low flow, it is very likely that low flow periods become more critical in the future. The dependable flows reach their lowest values during August and September. Note that in the wet months the dependable flow can reach higher values than in the base case, because with climate change more extreme storm events in winter and more severe droughts in summer are expected.

With the Meuse002 model a planning tool is now available that can be used to simulate the behavior of the Meuse River basin under various scenarios. Scenario runs that account for the effect of climate change on the hydrological inflow have already been carried out. Beside the climate changes, also economic developments, land use changes and intervention in the Meuse and her tributaries can affect the water balance and can be simulated. 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 Meuse River Basin. The reliability of the model will grow each time more local knowledge and expertise will be transferred into the tool. It is recommended to further develop the model coming year based on the guiding principles of participative approach, integration and exchange of data and co-creation of knowledge.

Abbreviations

DPZW	Delta Programma Zoet Water
IMC	International Meuse Commission
KA	Kläranlage (German for Wastewater treatment plant)
LDD	local drain direction
LHM	Landelijk Hydrologisch Model is an integrated nationwide ground- and surface water model of the Netherlands consisting of the coupled models: • MODFLOW (verzadigde zone), • MetaSWAP (onverzadigde zone) • MOZART (regionaal oppervlaktewater) • Distributiemodel (DM, landelijk oppervlaktewater) • WOFOST (gewasgroei) • TRANSOL (Zoet-zout-modellering)
Mcm	Million cubic metre, 106 m
MLNBK	Midden Limburg Noord Brabantse Kanalen, a canal system that comprises Wilhelminakanaal, Zuid-Willemsvaart, Maximakanaal, Noordervaart and Kanaal Wessem-Nederweert.
NWM	Nationaal Watermodel (National water model of the Netherlands)
RIBASIM	River basin simulation model
RIWA	Vereniging van Rivierwaterbedrijven, Sectie Maas
RIZA	Rijksinstituut voor integraal zoetwaterbeheer en afvalwaterbehandeling
RWS	Rijkswaterstaat the Netherlands
RWZI	Wastewater Treatment plant, Dutch: rioolwaterzuiveringsinstallatie
sbm	A hydrological modelling concept in Wflow (Wflow_sbm)
STEP	Waste water treatment plant, French: station d’épuration des eaux usée
WML	Waterleiding Maatschappij Limburg (Dutch drinking water supply company)

Inhoud

1

Introduction

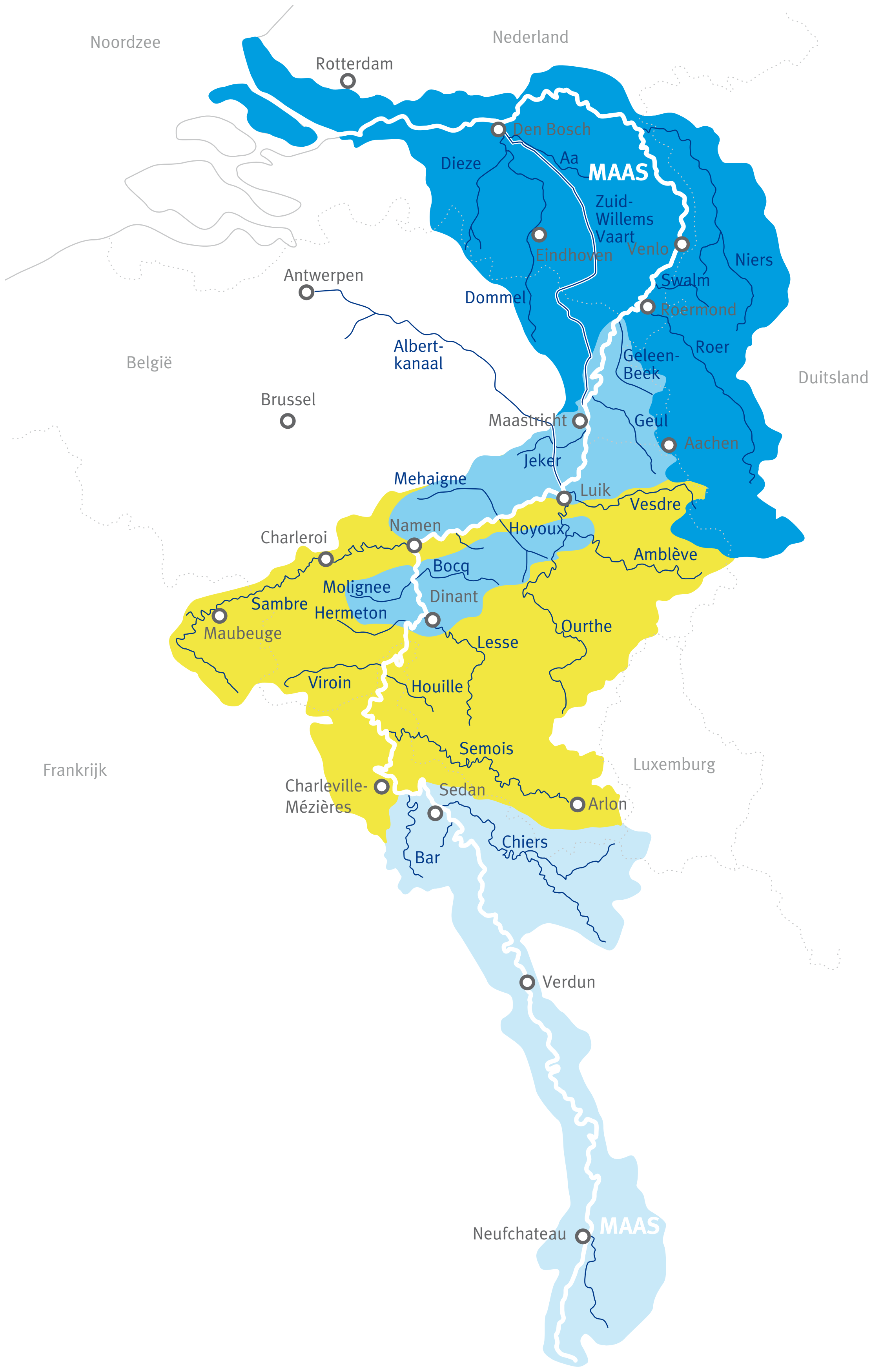
1.1 Background

The Meuse originates in France and flows to sea via Belgium and the Netherlands. On its way through France, Wallonia, Luxembourg, Germany, Flanders, and the Netherlands, many large and small tributaries feed into it (Figure 1). By the time the water from the Meuse flows into the North Sea, it has been of service to various users for domestic use, navigation, industry, and energy provision, nature, agriculture, and recreation. The Meuse is an important source of drinking water: 7 million people in Belgium and the Netherlands are provided with drinking water that originates from the Meuse (Bannink et al. 2019). In order to safeguard the continued supply of drinking water, a minimum inflow of good quality water is required. This principle is endangered in times of long-term drought – not only because during droughts the water availability decreases and the demand increases at the same time, but also because less water means less dilution of pollutants. Problem substances are no longer washed away following an emission/discharge incident. Additionally, it is generally expected that, due to climate change, periods of low water levels will occur with greater frequency and severity. It is therefore important to gain good insight into present and future water availability, combined with current and future usage.

The Meuse discharge is composed of discharges from various tributaries. To improve insight into the question of where Meuse water originates from in times of low river discharge, RIWA-Meuse commissioned Deltares for an in-depth study into a period of low-level Meuse discharge (August 2018) in 2019 (Bannink et al. 2019). The results show that in August of 2018, both the Sambre in Wallonia and the Rur in Germany were relatively large tributaries to the Meuse. The largest contribution to Meuse water in August 2018 came from France and may be attributed to outflowing groundwater. For the sake of comparison, a period of high-level river discharge was also reviewed (February 2019). For this period, a larger number of major rivers and tributaries was found to have contributed to the main flow of the Meuse.

The analysis of low Meuse discharges shows that the low flow discharge is characterized by the contribution of a small number of tributaries (Kramer 2021; Bouaziz 2020a). The main contributors are the Chiers, the Sambre and the Rur; another major flow component comes from the upstream reach of the Meuse. The contribution of each tributary can vary with the year (Kramer 2021). This indicates that the river system of the Meuse is vulnerable during periods of low river discharges. As the discharge distribution may vary from any period of high or low water to the next, a better understanding of the discharge distribution of the Meuse over time is important. So far, the most extreme low flow situations have been observed in summers that were the preceded by a dry winter (De Wit 2008) with less groundwater recharge than average. The Meuse is a true rain-fed river, making discharges erratic by nature. Climate models indicate that future summer periods will be drier, thereby directly affecting Meuse discharge. Simultaneously, the demand for water from various users is expected to increase. Therefore, RIWA-Meuse initiated further research into the sources of the Meuse River flow during periods of drought, and into potential future changes of water supply and demand.

Figure 1 The Meuse, major tributaries and the Meuse catchment, divided into sections according to De Wit 2008; Berger & Mugie 1994



Source RIWA-Meuse

1.2 Research project “Low river discharge of the Meuse” and structure of this report

The research project “low river discharge of the Meuse” addresses two research questions:

1. What is the contribution of the inflow from tributaries to the discharge of the Meuse during low-level water conditions based on historical flow time series? (Kramer 2021)
2. What is the usage and distribution of available Meuse water during periods of low river discharge based on historical flow time series?

This report describes the results of sub-project B. The objective of the study is to gain insight into:

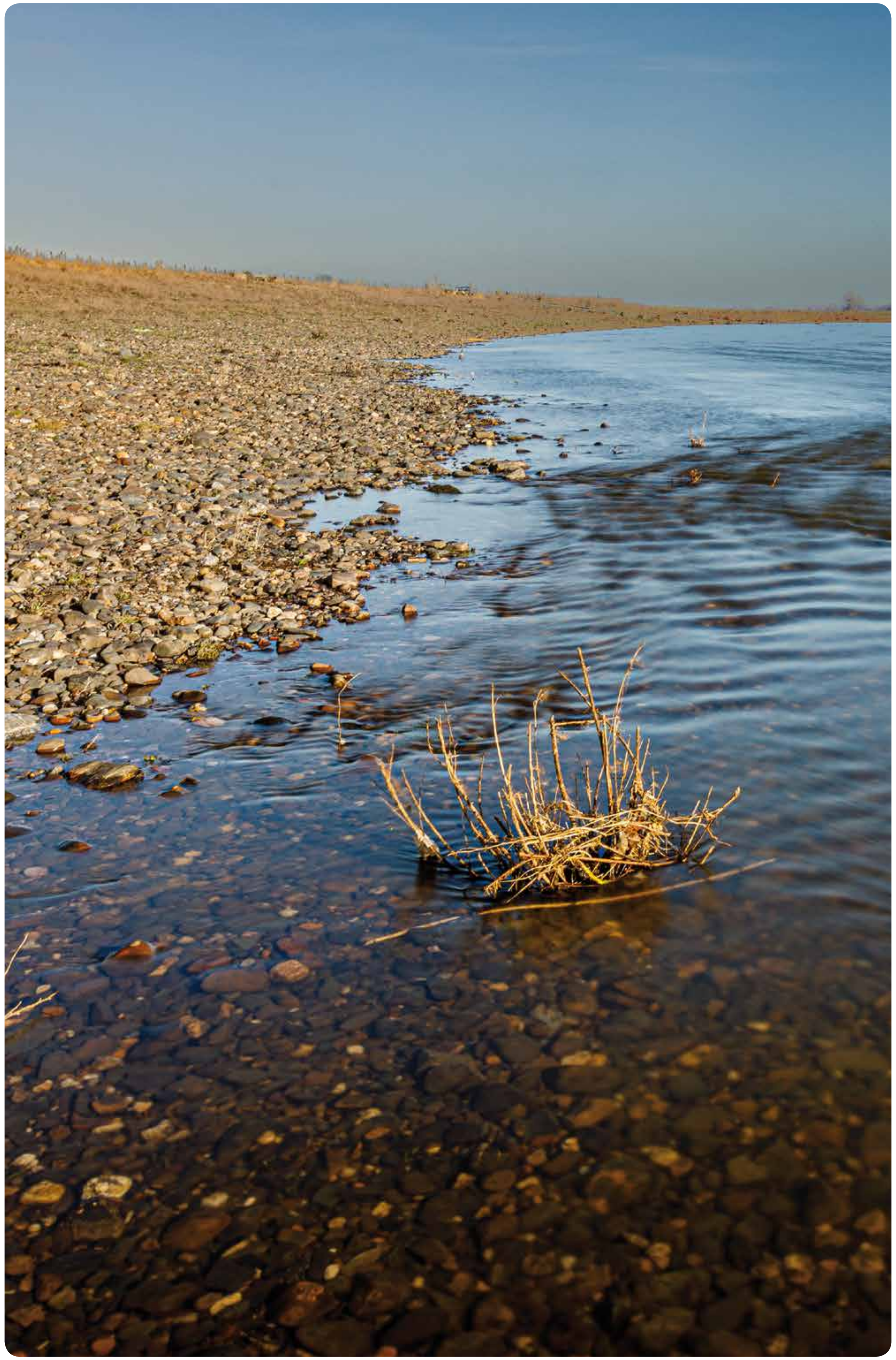
- The volumes of water available (during low water level),
- The source of the water (historical data-based study into main rivers and tributaries in the basin),
- Identification of the water users in the basin,
- Quantitative amounts of abstracted and returned water and the impact of low water level water on these users.

The two products of sub-project B are:

1. An inventory list of water users and other human interventions in the Meuse River basin.
2. A river basin water management model of the whole Meuse River basin. The model is powered by the rainfall-runoff modelling software Wflow (https://www.deltares.nl/en/software/Wflow-hydrology/) and the water demand and allocation modelling software RIBASIM (https://www.deltares.nl/en/software/ribasim/).

We have named the RIBASIM model **Meuse002**, because a first RIBASIM model **Meuse001** has been developed earlier as part of a Master’s thesis (Johnen et al. 2021; Johnen 2020). The Meuse001 model covers the Meuse River basin downstream from the border between France and Belgium, while the current model Meuse002 covers the whole catchment of the Meuse.

The RIBASIM modelling software is introduced in Chapter 3, after the study area and an inventory of water users and infrastructure has been introduced in Chapter 2. Chapter 4 describes the Meuse002 model and Chapter 5 the illustrative model applications. Finally, in Chapter 6 some conclusions are drawn and the outlook of potential use of the model is outlined. The annexes contain a list of the project meetings and more details on the developed Meuse002 RIBASIM model.



2

Study area and inventory of water users and water infrastructure in the Meuse catchment

2.1 The study area: the Meuse river basin

The source of the Meuse is located in France and on its way to the North Sea the Meuse flows through Belgium and the Netherlands. The catchment has an area of about 36 000 km^2. The majority of the basin is located in France, Belgium and the Netherlands, and small parts also in Germany and Luxembourg.

We have adopted the division of the Meuse into four sections, as suggested by De Wit 2008 and Berger & Mugie 1994:

- The upper reach reaches from the source at Pouilly-en-Bassigny to the mouth of the Chiers tributary. In the upper reach the Meuse flows over high permeable ground and has a small slope. Rainfall can easily percolate into the soil, consequently there are not many creeks in this region.
- In the Ardennes the Meuse cuts through hard rock and has developed a high slope. Water cannot easily infiltrate into the low-permeable rock, in the Ardennes swampy areas have developed. Major tributaries are the Semois, Viroin, Lesse and the Ourthe
- The middle reach covers the areas between the cities of Namur, Liège, Dinant, Maastricht and Aken. Like in the upper reach, the soil is highly permeable, and the Meuse has developed a comparatively small slope here.
- The lower reach begins at Maasbracht and ends at the moth in the North Sea. Here the Meuse is controlled with large weirs.

2.2 The inventory of water users and water infrastructure

The inventory of water users and water infrastructure of the Meuse catchment has produced a list of water use functions and infrastructure along the Meuse and its tributaries. The inventory is primarily carried out as preparation for the model development, but it has also a value by itself, because it helps to gain insight in the functioning of the Meuse catchment in general, and in particular into the different water use functions in the catchment.

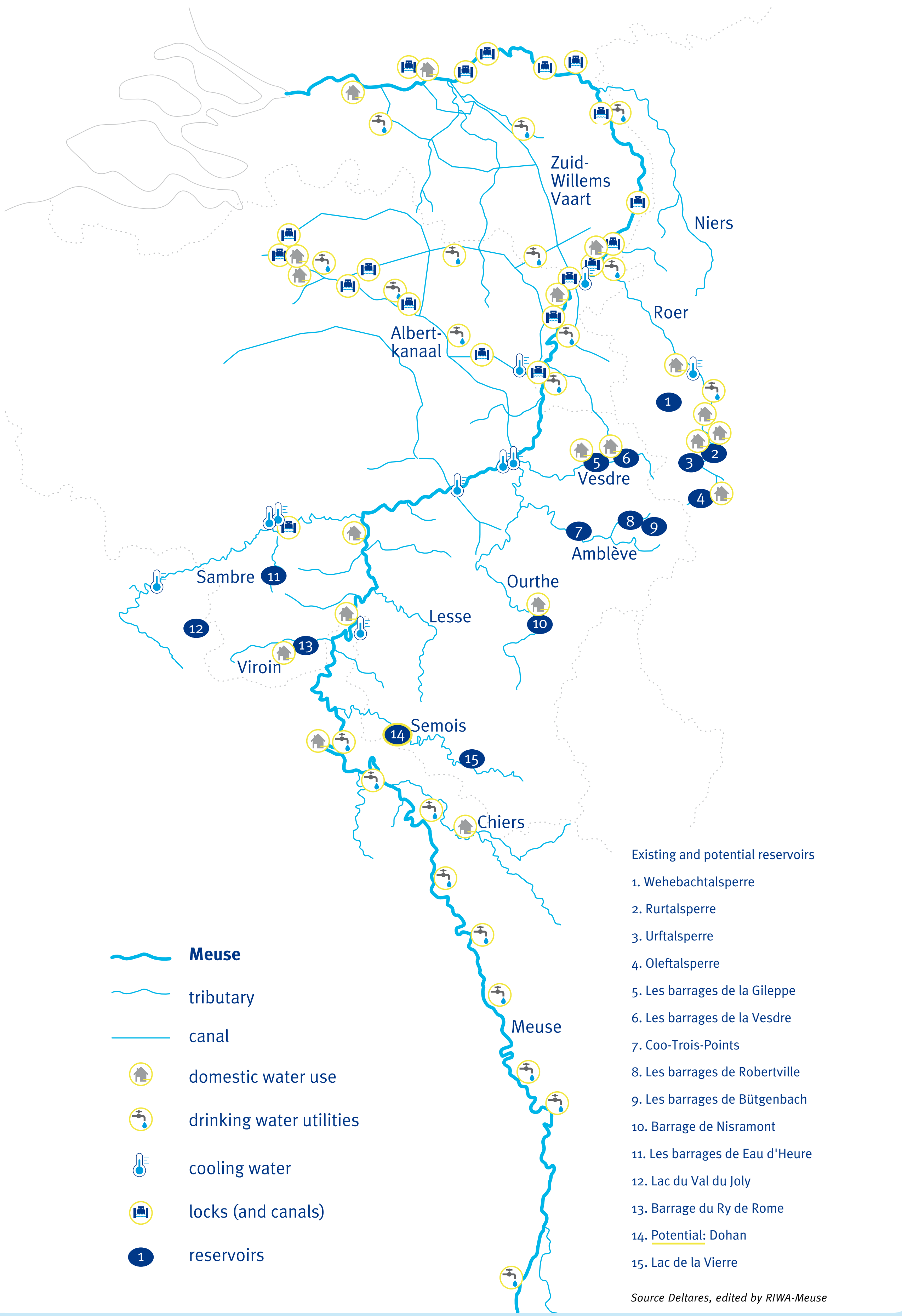
We see this inventory as a dynamic product – the inventory data will be completed, refined and changed in the future – consequently we have set up this inventory as a spreadsheet which is accompanied by maps files to be displayed in geographic information systems and stored in a repository (see Appendix B for more details). The inventory has been compiled from literature sources, including reports on earlier studies, interviews with stakeholders and experts and internet resources. The inventory contains the following items with the corresponding GIS filenames in brackets:

Rivers and streams
- River Meuse and tributaries with names in different languages

Infrastructure
- Weirs, locks and pump station (Weirs.shp)
- Reservoirs (Reservoirs.shp)

Water users, categorizes in water use for
- Agriculture
- Drinking water supply
- Energy production, including cooling water
- Industrial water use
- Ecology
- Wastewater treatment plants (WastewaterTreatmentPlants.shp)

Figure 2 The inventory of water users and water infrastructure



Existing and potential reservoirs
1. Wehebachtalsperre
2. Rurtalsperre
3. Urftalsperre
4. Oleftalsperre
5. Les barrages de la Gileppe
6. Les barrages de la Vesdre
7. Coo-Trois-Points
8. Les barrages de Robertville
9. Les barrages de Bütgenbach
10. Barrage de Nisramont
11. Les barrages de Eau d'Heure
12. Lac du Val du Joly
13. Barrage du Ry de Rome
14. Potential: Dohan
15. Lac de la Vierre

Source Deltares, edited by RIWA-Meuse

Minimum flow requirements

- General minimum flow requirement
- Minimum flow for cargo ship navigation

Water exchange across the catchment boundary.

Other points of interest (PointOfInterest.shp)

The water network and the infrastructure form the basis of the model schematization. For the other item groups not only the location is of interest, but also corresponding discharge values for water extraction, discharge or minimum flow requirements. The inventory contains the corresponding values as constant or time-dependent information.

We will not repeat the content of the inventory here in detail and refer to the inventory files instead. The following sections summarize the content of the inventory, main data sources and assumptions. The inventory items with the highest uncertainty are the water exchange across the catchment boundary and water usage for agriculture and industry. If possible, these items should be addressed with priority for future updates.

2.3 Rivers, canals and streams

Table 1 lists rivers, canals and streams in the Meuse catchment with their names in different language, sorted in alphabetical order by the name that is commonly used in English.

2.4 Infrastructure

The inventory contains 53 weirs in the Meuse and tributaries. The impact of weirs on the water balance for the catchment scale and the time resolution of the river basin water management model is neglectable, so they do not appear explicitly in the model.

Larger weirs are often combined with hydropower units and locks. Beside the weirs, the lock “Ecluses de Lanaye” / “Sluizen Ternaaien” and the pump station “Gemaal van Sasse” are listed.

The reservoirs in the Meuse catchment are summarized in Table 2. The inventory contains the following information if available: the name of the lake in different languages (where applicable), the reservoir volume, the reservoir surface area, the full supply level, years of construction, dam height and the river that flows into the reservoir.

Table 1 Rivers and streams in different languages

Name (English)	Name (Nederlands)	Name (Français)	Name (Deutsch)
Aa	Aa		
Albert Canal	Albertkanaal	Canal d’Albert	Albertkanal
Amblève	Amblève	Amblève	Amel
Canal Briegden-Neerharen	Kanaaal Briegden-Neerharen		
Canal Dessel-Kwaadmechelen	Kanaal Dessel-Kwaadmechelen		
Canal Dessel-Turnhout-Schoten	Kanaal Dessel-Turnhout-Schoten		
Canal Bocholt-Herentals	Kanaal Bocholt-Herentals		Maas-Schelde-Kanal
Canal Wessem-Nederweert	Kanaal Wessem-Nederweert		
Chiers	Chiers	Chiers	
Dieze	Dieze		
Geleenbeek	Geleenbeek		
Geul	Geul		Göhl
Grote Molenbeek	Grote Molenbeek		
Inde			
Jeker	Jeker	Geer	
Juliana Canal	Julianakanaal		Julianakanal
Kempen canals	Kempische Kanalen: • Kanaal Bocholt-Herentals • Zuid-Willemsvaart • Albertkanaal • Kanaal Dessel-Turnhout-Schoten • Kanaal naar Beverlo • Kanaal Dessel-Kwaadmechelen • Kanaal Briegden-Neerharen		
Lateraal Canal	Lateraalkanaal		
Lesse	Lesse	Lesse	
l’Helpe Majeure		l’Helpe Majeure	
Meuse	Maas	Meuse	Maas
Meuse (Common Meuse)	Grensmaas	Meuse commun	Grenzmaas
Canals in Midden Limburg and North Brabant (MLNBK)	Midden Limburg Noord Brabantse Kanalen (MLNBK): • Wilhelminakanaal • Zuid-Willemsvaart • Maximakanaal • Noordervaart • Kanaal Wessem-Nederweert		
Mouzon	Mouzon	Mouzon	
Nete Canal	Netekanaal		
Nette	Nette		Nette
Niers	Niers		Niers
Noordervaart	Noordervaart		
Ourthe	Ourthe	Ourthe	Urt
Rur	Roer		Rur
Salm			Salm
Sambre	Sambre	Sambre	
Schwalm	Zwalm		Schwalm
Semois	Semois	Semois	
Vair	Vair	Vair	
Vence	Vence	Vence	
Vesdre	Vesdre		Weser
Vierre	Vierre		
Viroin	Viroin	Viroin	
Wilhelmina Canal	Wilhelminakanaal		Wilhelminakanal
Zuid-Willemsvaart	Zuid-Willemsvaart		

Table 2 Reservoirs in the Meuse catchment

Country	Name of the lake
Belgium	Bütgenbacher See
Belgium	Lac de Coo
Belgium	Lac de Falemprise
Belgium	Lac de Féronval
Belgium	Lac de la Gileppe
Belgium	Lac de la Plate Taille
Belgium	Lac de la Vierre
Belgium	Lac de l'Eau d'Heure
Belgium	Lac de Nisramont
Belgium	Lac de Robertville
Belgium	Lac des Doyards
Belgium	Lac du Ry-Jaune
Belgium	Les lacs de l'Eau d'Heure
Belgium	Wesertalsperre, lac d'Eupen, Vesdre-reservoir, Eupener Talsperre
France	Basin de Whitaker
France	Bassin des Marquisades
France	Lac de Bairon
France	Lac des Vieilles Forges
France	Lac du Val-Joly
Germany	Dreilägerbachtalsperre
Germany	Kalltalsperre
Germany	Olefstausee
Germany	Perlenbachtalsperre
Germany	Rursee
Germany	Stauanlage Heimbach
Germany	Staubecken Obermaubach
Germany	Uftstausee
Germany	Wehebachtalsperre
Netherlands	Cranenweyer

2.5 Water usage

Water users are grouped in the following categories:

- Agricultural
- Cooling water
- Drinking water
- Energy
- Industrial
- Nature Navigation
- Lock leakage losses
- Wastewater treatment plants
- Minimum flow Canal leakage losses
- “Maasplassen” evaporation losses

Where available, we have collected the following parameters:

- Water user name
- Country
- Location
- River Literature reference
- A discharge value:
  - Expected abstraction (sink) or discharge (source)
  - Licensed abstraction (sink) or discharge (source)
  - Minimum flow

Expected and license abstraction or discharge apply for withdrawal from or release into the river or stream, while a minimum flow applies in the river or stream. Most discharge values are only available as a constant abstraction or discharge, but agricultural use and water demand for regional water management is implemented as time-variant over the year.

Water extractions for agriculture is mainly present in Flanders and in the Netherlands, but agricultural water extractions are also present along the Rur between Linnich and the Dutch-German border. The amount of extracted water is very uncertain, because farmers usually do not report the extracted amount, and unlicensed extractions may take place also. The main source for data related to agricultural water use is Raadgever 2004 and the National Water Model (Rijksoverheid 2021). In France (Terrier et al. 2018) and in the Belgian Ardennes irrigated agriculture is hardly present and not documented.

In the French part and the Walloon part of the Meuse the drinking water is mainly supplied from groundwater resources, because groundwater usually has a better quality than water from other sources. Consequently, there are only a few drinking water abstraction points from the Meuse in France and Wallonia. With Heel, Brakel and Bergse Maas in the Meuse and the extraction points in the Albert- and Netekanaal Flanders and the Netherlands have large extraction points for drinking water supply. The city of Brussels extracts at Tailfer in the Walloon region water from the Meuse to supply water to the metropolitan area of Brussels. Drinking water is also one of the use functions of multi-purpose reservoirs in the Vesdre and in the Rur reservoirs.

As mentioned above, weirs in Belgium and in the Netherlands are equipped with turbines and water is used for hydropower generation, but this water usage has no impact on the water balance. A couple of thermal and nuclear power plants use water from the Meuse as cooling water, with the nuclear power plants at Chooz in France and Tihange in Belgium and thermal plants in Awirs, Seraing and Angleur in Belgium as well as the Clauscentrale near Maasbracht in the Netherlands. Cooling water is released back into the river after use, but a certain percentage is lost by evaporation. The power plant Weisweiler is located in Germany and is cooled with drainage water from the lignite mines, and the cooling water is discharged via the Inde into the Rur (Becker 2018).

Water from the Meuse and tributaries is used by industry. In the upstream part of the Meuse the industrial water use is comparatively low, while Belgium and the Netherlands have larger industrial use along the Albert Canal and Meuse. The industrial water use is quite divers, and the extraction and discharge data comes with a high degree of uncertainty. More details can be found in the inventory files.

Ecological motivated abstraction is located around the nature areas Groote Peel, Mariapeel, Deurnese Peel and the Peel remains. The water is needed to maintain certain ecological target water level in these areas. Beside this abstraction, there are some nature-conservation requirements for a minimum discharge. Regional water authorities in the Netherlands use water to maintain a certain water level during the summer. This water use is at least partly motivated by ecological reasons, but it is difficult to separate it from agricultural water usage. The source of water demand for water management in the Netherlands is the National Water Model (Rijksoverheid 2021).

Wastewater treatment plants (short: WWT, RWZI for Dutch: rioolwaterzuiveringsinstallatie, STEP for French: station d'epuration, KA for German: Kläranlage) release water into a river or stream after it has been used by public households and industry connected to the sewer system.

During low flow the release of treated waste water can contribute significantly to the total discharge of rivers and streams. Discharge from wastewater treatment plants has been estimated by the following data:

- Last reported inflow to the wastewater treatment plant (Netherlands)
- Population equivalent with an average water consumption of 120 l/day (France, Wallonia)
- Hydraulic dry weather load (Trockenwetterzufluss, Germany)

Discharge from waste water treatment plant originates either from groundwater or from surface water extraction. In case of the latter it is like a return flow from a drinking water extraction; if the public water use is supplied from groundwater it appears like a base flow in the water balance. Hydrologic models usually account for the contribution from wastewater treatment plants implicitly, because they are calibrated on a total discharge. For this reason, only larger wastewater treatment plants with a discharge of 0.05 m^3/s and those that are located at the Meuse itself or a Meuse tributary that is part of the RIBASIM model were considered in the inventory.

Minimum flow requirements apply to the Rur river. With a discharge of 5 m^3/s the Rur is considered to be able to supply local industrial and public water demand without ecological damage. Consequently, the minimum release from the Rur reservoirs is 5 m^3/s. A discharge of 7.5 m^3/s allows canoeing below Heimbach. Minimum flows apply for the Dutch lock pounds to feed fish ladders and to compensate lock losses. Navigational water demand is also applied as minimum flow. The minimum flow value corresponds to a minimum water depth for cargo ships.

2.6 Water exchange across the catchment boundary and points of interest

Water exchange with other catchments is given by the following canal connections:

- Water supply for the Canal de la Marne au Rhin
  - le Vidus
  - Troussey
- Water supply for the canal des Ardennes et le lac de Bairon at la Bar
- Outflow from Meuse to the Waal via
  - the Maas-Waal-Kanaal through the sluice compound Heumen
  - the Kanaal van Sint Andries through lock Sint Andries
  - the Afgedamde Maas via lock Andel
  - Water supply for the canal Charleroi-Brussel
  - Water supply for the Canal De La Sambre á l'Oise
  - Water supply for the Nete Canal

The amount of water exchange is unknown in most cases, so we made assumptions based on the literature.

A point of interest is the Crossing Meuse - Canal de la Marne au Rhin-Ouest. This crossing has no effect on the water balance.

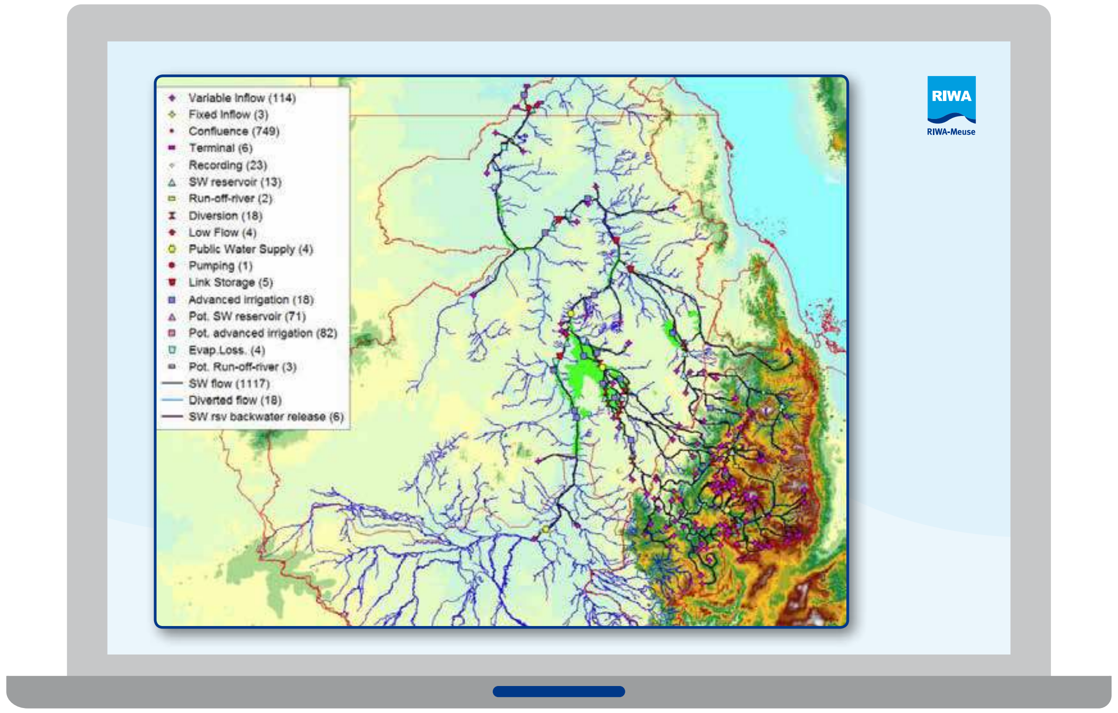
3

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 the 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. Examples are the RIBASIM model of the Ganga river (India) and the RIBASIM model of the Nile (Figure 3). Figure 4 shows a photograph from a RIBASIM workshop where local experts were instructed in the usage of the RIBASIM software.

Figure 3 RIBASIM network schematization of the Nile River basin



Source Deltares, edited by RIWA-Meuse

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. More info about RIBASIM can be found on the website www.deltares.nl/en/software/ribasim.

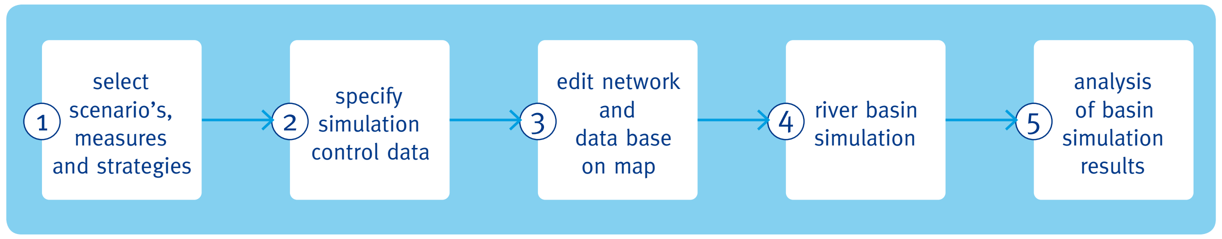
Figure 4 RIBASIM training

Source Deltares

3.2 The modelling process with RIBASIM

The main RIBASIM user interface is presented as a flow diagram of blocks representing the steps in the modelling 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 steps 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.

Figure 5 The user interface of RIBASIM presented by block flow diagram



Source Deltares, edited by RIWA-Meuse

3.3 Principles of river basin schematization

A core element of a RIBASIM model is a network schematization of the basin. The schematization contains all the necessary features of the basin as nodes, and nodes are 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. There are four main groups of elements to be schematized:

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

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

3.4 Interactive schematization of the river basin

A RIBASIM schematization can be prepared interactively from a map. The user can select from nodes for 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. A RIBASIM network represents all of the basin’s features which are significant for its water balance and it can be adjusted to provide the required level of detail. An example is shown in Figure 6.

The boundary of 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 (Figure 7) and linked to the map of the river basin and its network schematization. Data consistency tests are an integral part of the RIBASIM software.

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 8. The model data base contains the data that describes the network schematization of the existing and the 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.

Different future and potential situations and system configurations can be modelled by defining scenarios and management actions (strategies, interventions).

Figure 6 Interactive design of river basin network schematization for Samon River basin - Dry Zone, Myanmar

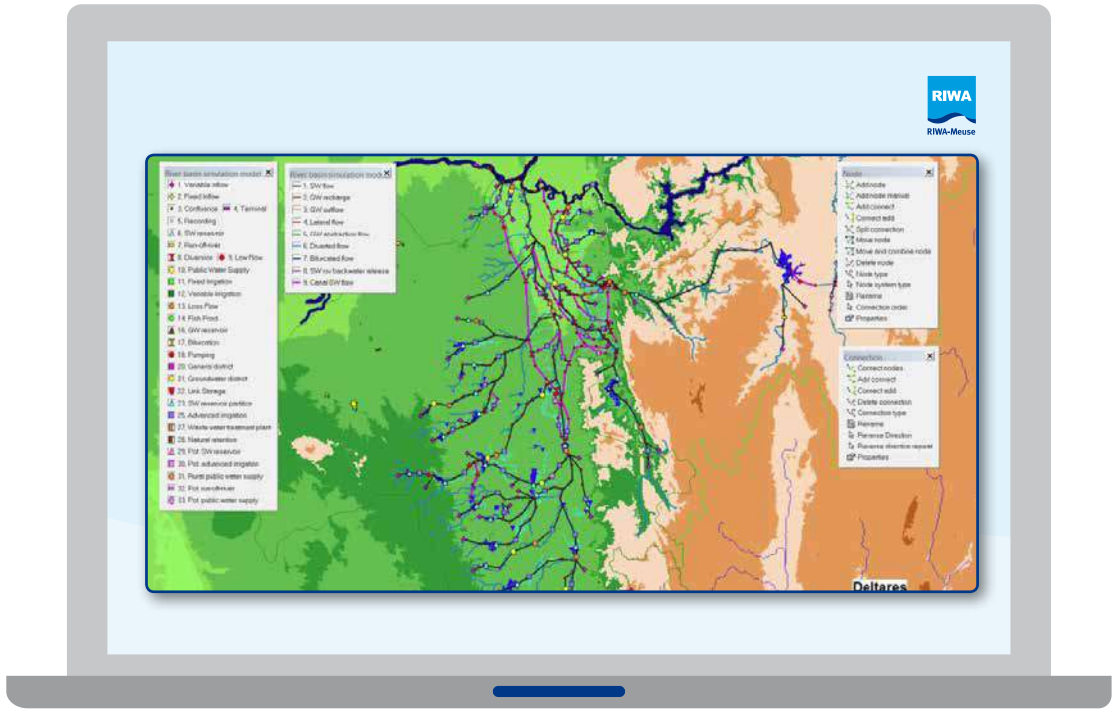


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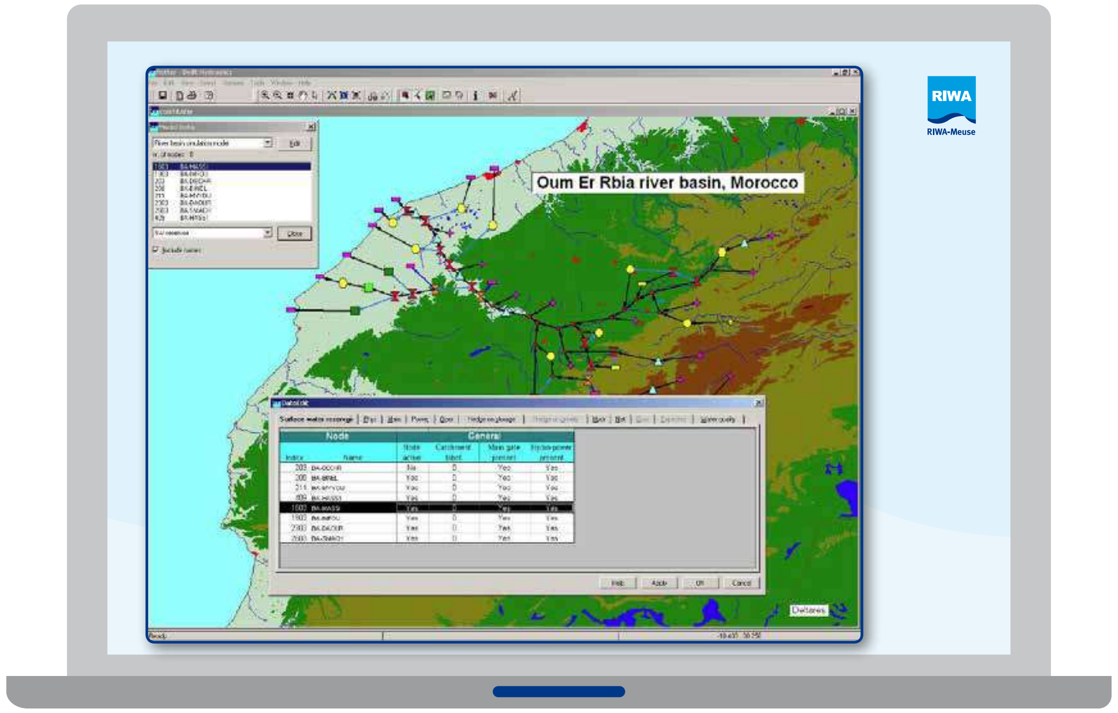
Figure 7 Spreadsheet based interactive entry of reservoir node model data



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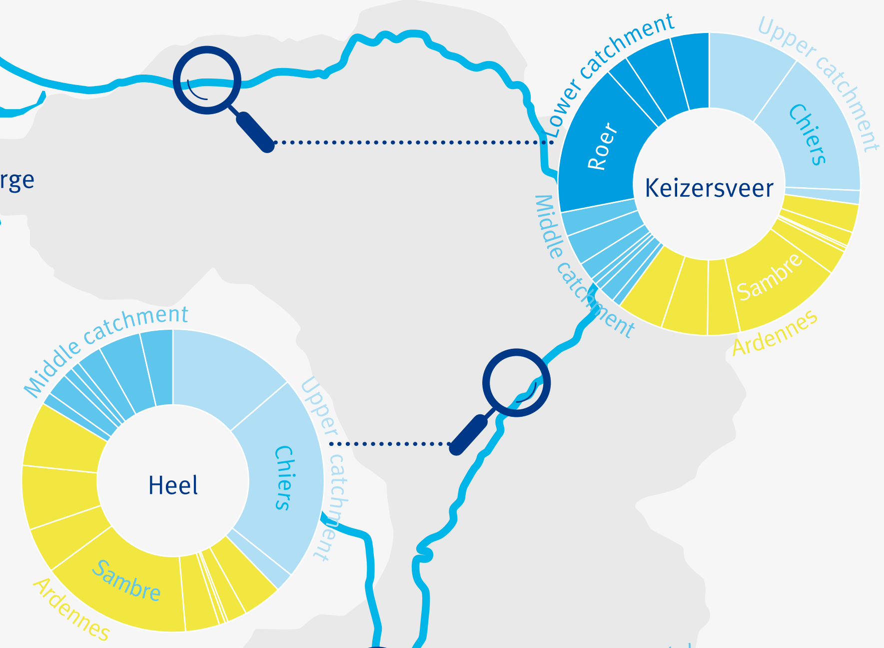
Deltares

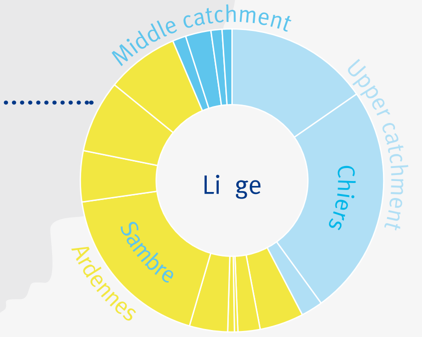
Water Balance Model for the Meuse

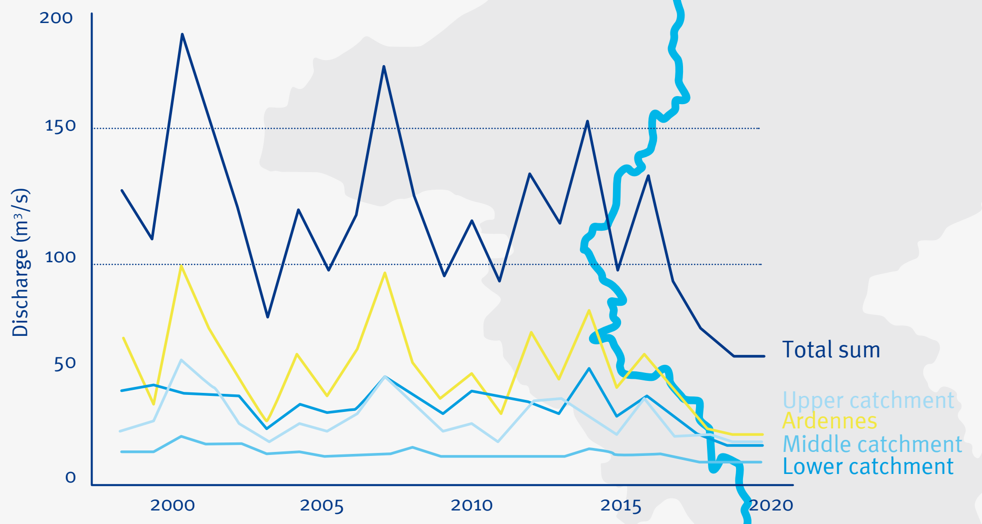
A model to gain insight into the current and future water availability in the river Meuse basin:

- Understanding the hydrological system including all tributaries.
- Instrument for dialogue and exchange between users and countries.
- Insights into the impact of low river discharge on water availability:

Composition of the Meuse discharge along the river
[July-September 2020]







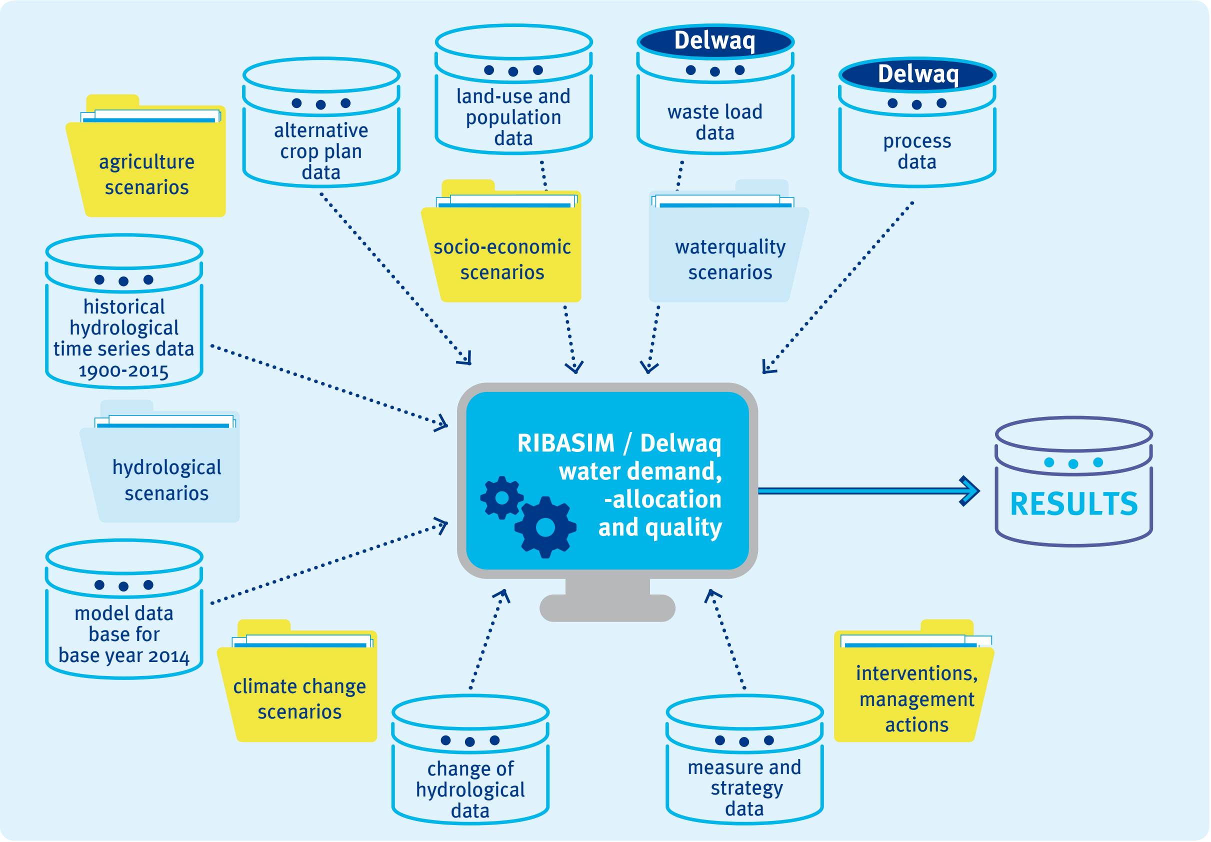
Discharge of different tributaries per area and per summer (July-Aug-Sept) in the period 1998-2020.

STEPS for analysis and modelling

1. Selection of hydrological and water quality scenarios
2. Specify the data simulation and control
3. Edit the catchment's network and database on the map
4. Simulate the catchment area
5. Analyze the results of the simulation

Source Deltares, edited by RIWA-Meuse

Figure 8 Input- and output structure of the RIBASIM with Delwaq water quality model



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The following options are available:

1 Hydrological scenarios. This scenario type covers multiple years and annual time series of runoff, flow, rainfall, groundwater exfiltration and evaporation;

2 Climate change scenarios. This scenario type contains the percentage change of the hydrological variables defined in the hydrological scenarios due to climate changes;

3 Land-use and population scenarios. This socio-economic scenario type contains the percentage change in irrigated area, population numbers and industrial demand per catchment of base year (stored in the model data base) for future demand years;

4 Agriculture scenarios. This scenario type contains the alternative future crop plans per catchment;

5 Water quality scenarios. Depending on the run mode one of the following scenarios are used:

   A Basic water quality scenario. This scenario type is used in the run mode without the water quality module "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 the Delwaq water quality module and contains the waste load related data like emission factors and treatment efficiency, and chemical and biological process data. The data is used by the waste load estimation model to compute the industrial, domestic and agriculture waste loads;

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

3.6 River basin simulation

Simulations are usually made over long time series (multiple years) that include dry as well as wet periods. The simulation time steps used are variable and are defined by the user. Within each time step RIBASIM determines the water demand by evaluating 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.

The underlying modelling concept is a water balance equation. No flow routing is taken into account, water can reach any location within the same time step. The time step size must be chosen accordingly in order to avoid instabilities and unexpected results. This approach allows for very fast simulations, an advantage that comes to bear especially for simulations with a large time horizon.

Water allocation to users can be configured in several ways: at its simplest, water is allocated with a “first come, first served” principle along the natural flow direction. More complex allocation schemes include rules which take into account priorities of the different water users, threshold values, or water allocation as a proportional function of the demand.

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

3.8.1 Source analysis

RIBASIM supports a default and user-defined source analysis (*fraction computation*) that gives insight in the water’s origin and residence time at any location of the basin and at any time within the simulation period. As an example, in Figure 9 the change in composition of the water is shown for a surface water reservoir over a number of years, expressed in fractions (0,0 – 1,0). This representation allows to assess the residence time (indicated by red arrow), i. e. the time needed for the original water content of the reservoir to be entirely renewed.

Figure 9 Flow composition of water in Massira reservoir from 1940-1949 (Oum Er Rbia River basin, Morocco)

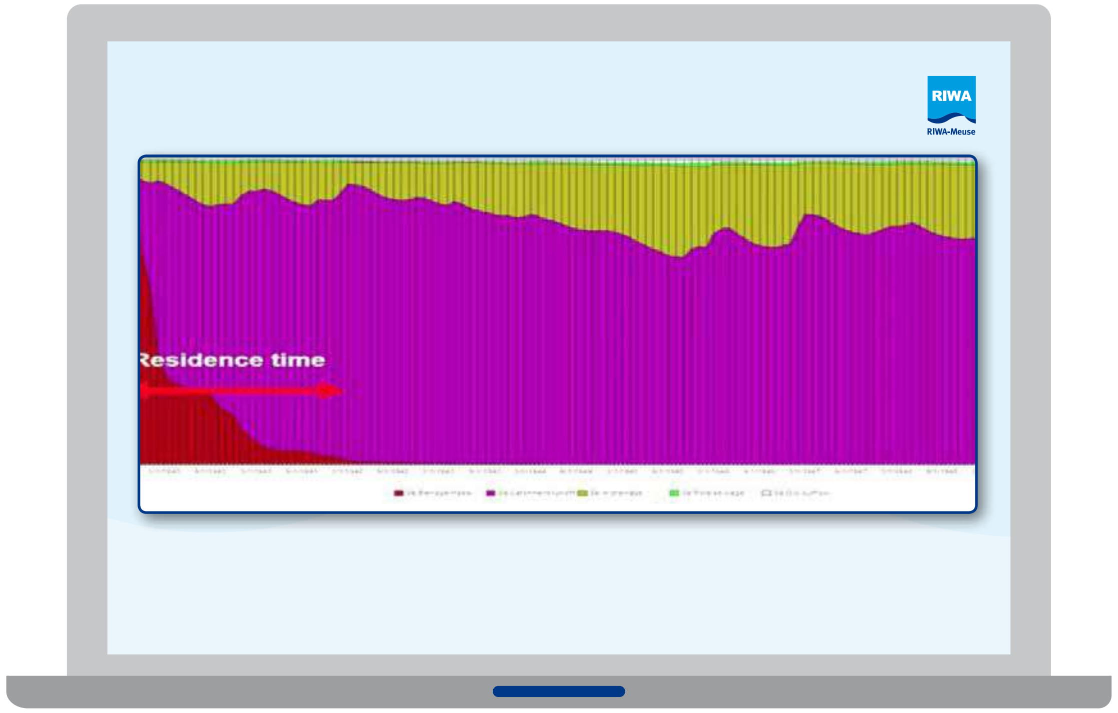

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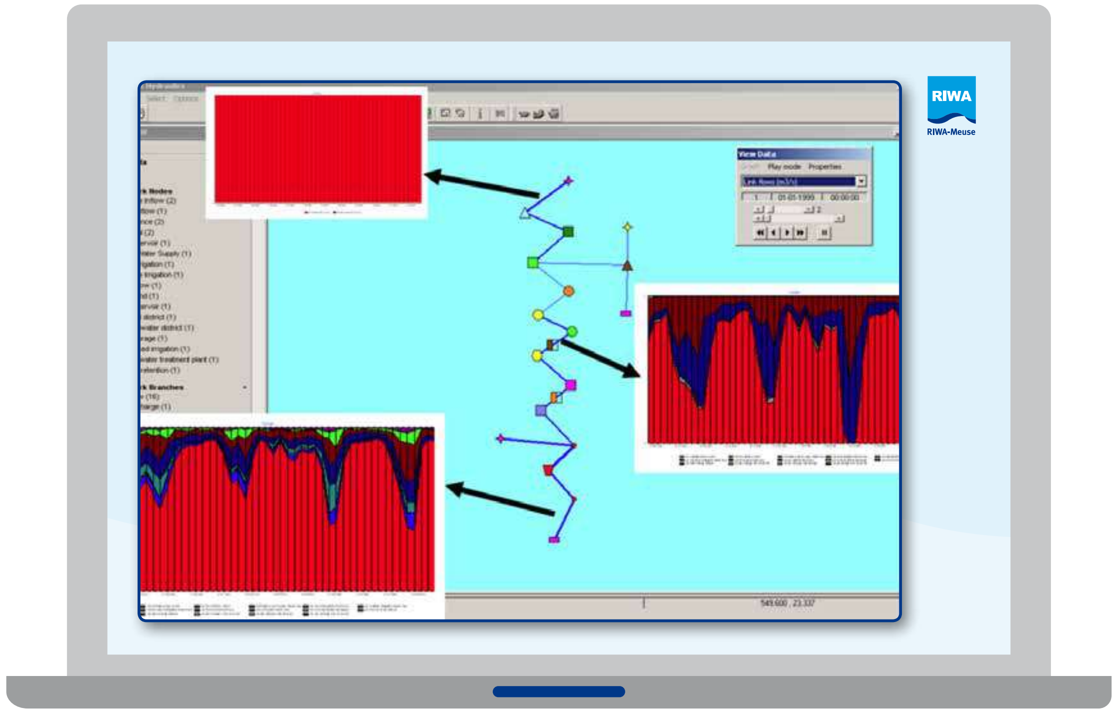
Figure 10 Change in flow composition in downstream direction over several years of simulation (wet / dry cycle visible)



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With the source analysis water from different sources can be tracked, and this makes it possible to follow the changes in the source of the water in time, e. g. the percentage of water coming from glacier melt in Switzerland or from certain tributaries in different seasons and in wet / dry years. An example of such a tracking activity is shown in Figure 10, where the inflow from a tributary, and the return flow from irrigation and waste water, slowly takes over the original uniform composition (red colour from top source). This is a very strong tool for analysis of the system behaviour of a river basin and can be used in the future to show the change in behaviour due to development scenarios and climate change.

3.8.2 Advanced irrigation simulation

RIBASIM has an integrated agriculture water demand, water allocation, crop yield and production costs model based on crop and soil characteristics, crop plan, irrigation and agriculture practise, expected and actual rainfall, reference evapotranspiration, seepage, actual field water balance, potential crop yield and production costs. RIBASIM has a fully graphical user interface for designing the river basin network but also for crop cultivation planning, see Figure 11 for an example.

In the Meuse002 model, this advanced irrigation option has been used as it allows for a sophisticated assessment of the water demand for irrigated agriculture.

3.8.3 Source priority list

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

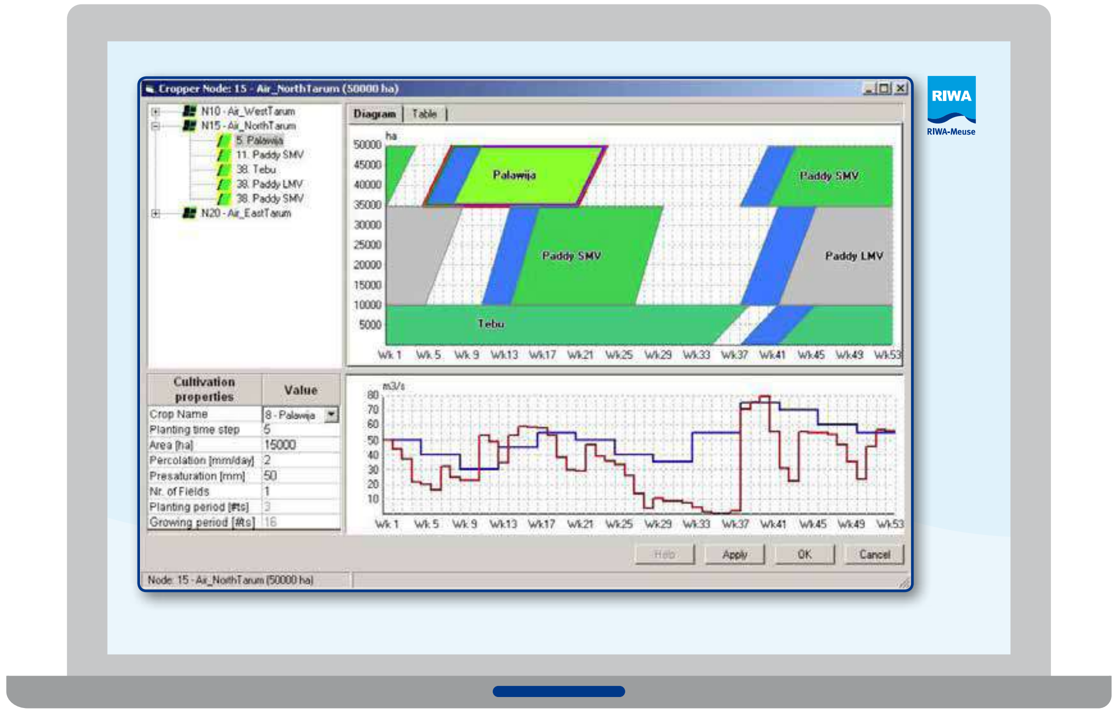
- Inflow / runoff: Variable inflow, Snow melt and Glacier melt
- Drainage / return flow: Public water supply, Industrial use and Cooling water
- Drainage: Fixed irrigation
- Discharge: General district

The order of the source nodes in the list is the order in which the nodes are chosen by the model to fulfil the water demand. So, the order of the nodes in the list is important. The model initially generates a default source priority list when the network was designed and setup on the map. The order in which the different node types are included in the default list is defined in the fixed data of RIBASIM. In the Meuse002 model only variable inflow node types are used. The generated list is in most of the situations correct and no additional checking and updating is needed. However, it can be overruled by the user, using the source priority list editor, e.g. in case the user decides that a certain source should be avoided for a specific water user.

3.8.4 Water allocation priority

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

Figure 11 Interactive graphical design tool of a crop plan for the North Citarum irrigation area (Indonesia)



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)

Source Deltares, edited by RIWA-Meuse

ooThe 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. In case that the available water is less than the water user demands also considering return flows from upstream users then the shortages will occur at the user demands with the lowest water allocation priorities.

3.8.5 Miscellaneous features

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

For more information on RIBASIM see the user manual (van der Krogt 2019; van der Krogt & Boccalon 2013) and technical reference manual (van der Krogt 2008).

4

The river basin water management model for the Meuse

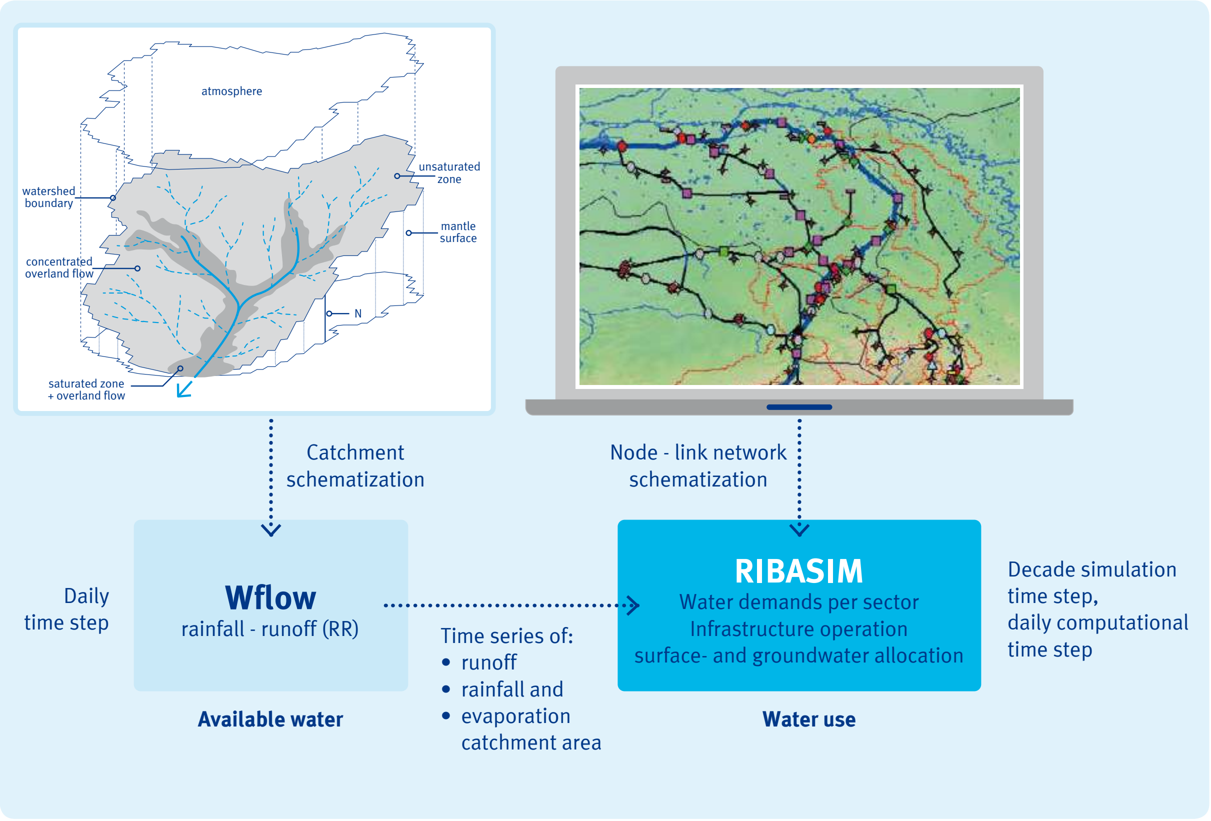
4.1 Introduction

A completely new water management model of the Meuse River basin has been set up with the RIBASIM software: the Meuse002 model. The model accounts for water demand, water allocation and flow composition. It can be extended to water quality modelling in a later stage. The model covers the whole Meuse river basin from its source in France to the outflow to the North Sea at the Haringvliet in the Netherlands. The hydrological inflow (boundary condition) has been taken from the Wflow rainfall-runoff model for the Meuse catchment. This model was already in place and covers the entire Meuse river basin from its source in France up till the recording station Mook in the Netherlands.

The Meuse002 model includes all major storage capacity at reservoirs in the Meuse river basin. The demands are lumped into a demand per water user type based on the inventory of water users (see chapter 2). The aim is to improve and extend the modelling of the infrastructure and the demands in new versions of the model. The simulation period of the model is set by the length of the simulations in the Wflow hydrology model and runs from 1980 to 2020.

The development of the Meuse002 model was carried out in two steps, as outlined in Figure 12. The first step is the design of a catchment schematization of Meuse River basin based on the location of dams, irrigation area intakes, towns/cities, flow monitoring stations and specific desired boundaries. This schematization forms the basis for the input simulated by the hydrological model Wflow, which computes daily runoff series for each catchment, as well as rainfall and evaporation/evapotranspiration. These time series are input of RIBASIM. The second step is the design of a node-link network schematization, as outlined in Chapter 3.3.

Figure 12 Interaction between the Wflow hydrological model and the RIBASIM water management model.



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The Wflow rainfall-runoff model computes with a daily timestep. RIBASIM simulates with simulation time steps of ten days (a decade) and an internal daily computational time step. Decade means that each month is split into 3 timesteps, which makes total 36 timesteps per year. For water balance modelling of the Meuse river basin the time step should not be smaller than 10 days. The reason is that water should pass the whole system within one time step. If the travel time through the system is larger than the time step size, the modelling concept of a water balance no longer holds. Other hydrological or hydraulic modelling concepts that account for flow dynamics are necessary in this case.

The maximum simulation time period is 41 years of historical time series from January 1980 till December 2020. This can be extended in the future when additional years of measurement become available.

The Wflow model has been chosen here as source for the hydrological input for reason of consistency, because the Wflow model covers the whole Meuse catchment. In principle, the hydrological inflow data from the Wflow model can be replaced by results of other hydrological model sources, e. g. the national rainfall-runoff models from the Meuse River riparian countries.

4.2 The Meuse Wflow hydrological model

4.2.1 Introduction

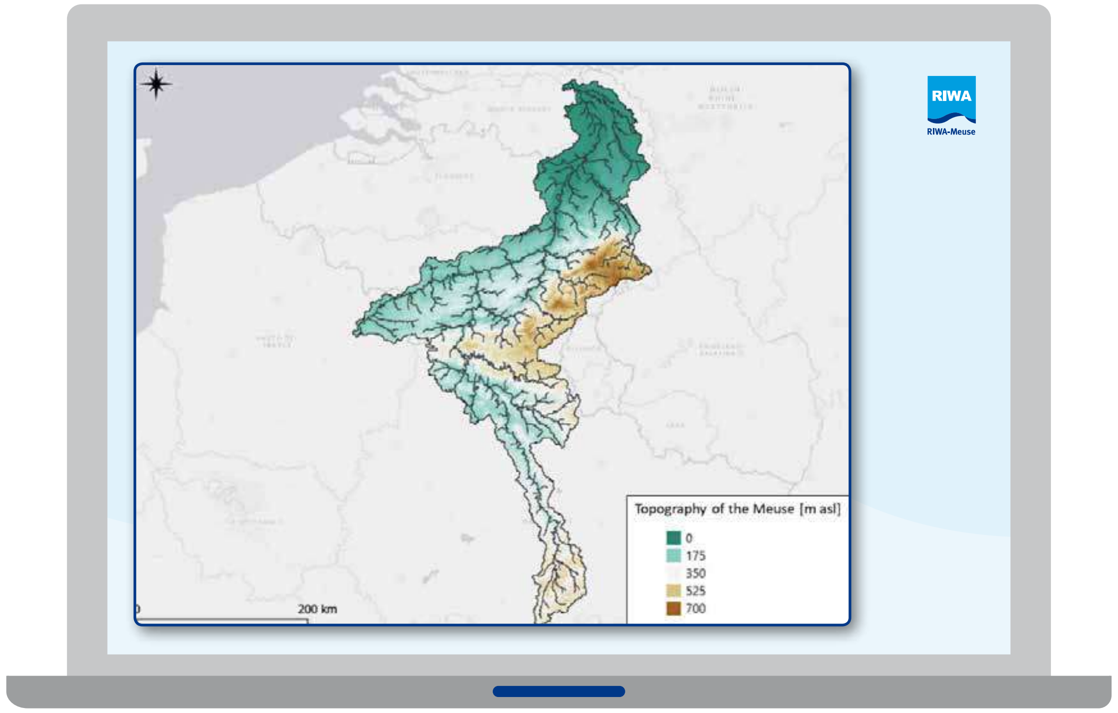
4.2.1.1 The hydrology of the Meuse river basin

The Meuse river basin covers approximately 35 000 km2. It is a transboundary river basin extending over Belgium, France, Germany, Luxembourg and the Netherlands, with a South-North orientation. It originates in France, where it crosses wide floodplains with gentle slopes, and flows through the Ardennes in Belgium with steeper slopes in its central part, before finally reaching the Dutch lowlands and the North Sea via the Rhine-Meuse delta.

Hydrologically, the Meuse has a pluvial regime, with a distinct seasonal behaviour of the discharge, with high values in the winter and low flows in the summer, due to seasonal variations of the evaporation. It is also characterized by small response time and travel time in the basin. Flash floods can occur in the basin where the Meuse tributaries have very high and coincidental response time due to the basin's topography (de Boer-Euser et al. 2017). In the Netherlands, the Meuse crosses then the more controlled Dutch lowlands and then mixes with the Rhine and Waal rivers in the delta.

The hydrological model of the Meuse River basin used in the Wflow model comprises the Meuse upstream of recording station Mook in the Netherlands and of the Maas-Waal canal. The corresponding basin is approximately 28 000 km2 and ends before the lowland and delta influenced areas of the basin (Figure 13).

Figure 13 Topography of the Meuse basin upstream of Mook



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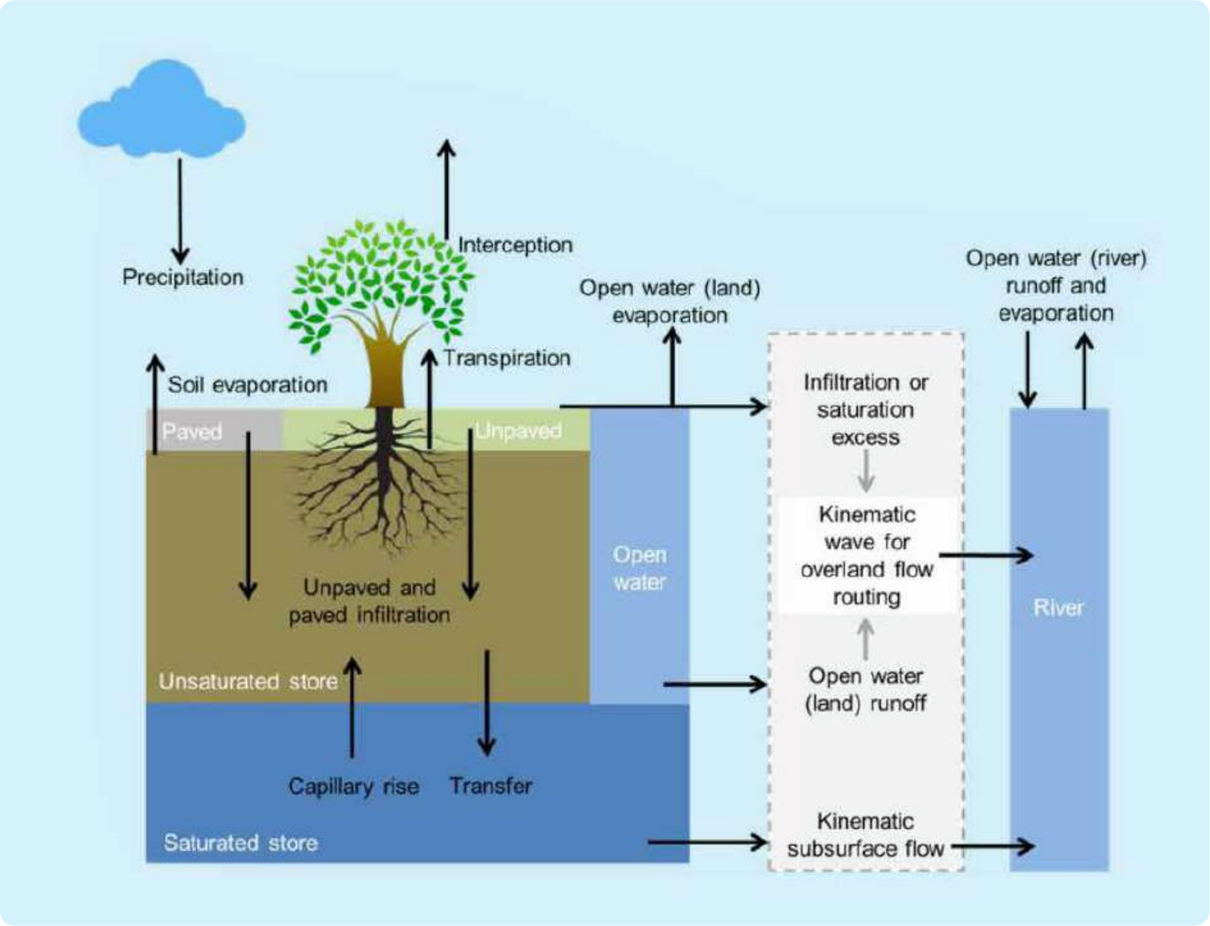
4.2.1.2 The Wflow_sbm model concepts

Hydrology is the understanding of the processes that transforms rainfall into surface runoff and river discharge in inland water networks. Its main goal is to enable the prediction of water movements and generation of surface water in a catchment depending on its characteristics (elevation, land use, soil) and the climatic events studied (precipitation, temperature, potential evapotranspiration).

Wflow_sbm is the open source distributed hydrology model developed by Deltares (Schellekens et al. 2019). In this model, the catchment and hydrological processes are divided into a grid of regular cells with their own physical characteristics (land use, soil type). When precipitation occurs, the model first considers that, part of it, is intercepted by the vegetation. Rainfall then reaches the soil and infiltrates the different layers present in the saturated and unsaturated store. If the soil is entirely saturated, the rainfall cannot infiltrate anymore and excess overland flow is produced. The excess water is then transported downslope through the catchment and river network with the kinematic wave equation. The routing process of both surface and subsurface flows is modelled according to a local drain direction (LDD) map (1D direction of the flow to the lowest neighbour elevation cell). Snow processes can also be modelled. Figure 14 summarizes the different flows and layers defined in each cell of a wflow_sbm model.

Figure 14 Overview of the different layers and flows in a Wflow sbm cell (Deltares 2022; Bouaziz 2020b)



Source Deltares

Wflow_sbm is an open source and freely available software. It is a distributed (gridded) model and results can be obtained for any location/cell in the modelled catchment. It can also easily be linked to available, global or local datasets. Python scripts are used to setup the Wflow_sbm model for any basin around the world, using freely available global datasets and requiring minimum calibration, by using state-of-the-art parameter estimation techniques and (pedo)-transfer functions. These (pedo)-transfer functions are using different datasets (e. g. clay content of the soil, sand content of the soil, etc.) to combine into model parameter values based on experience from different models around the world.

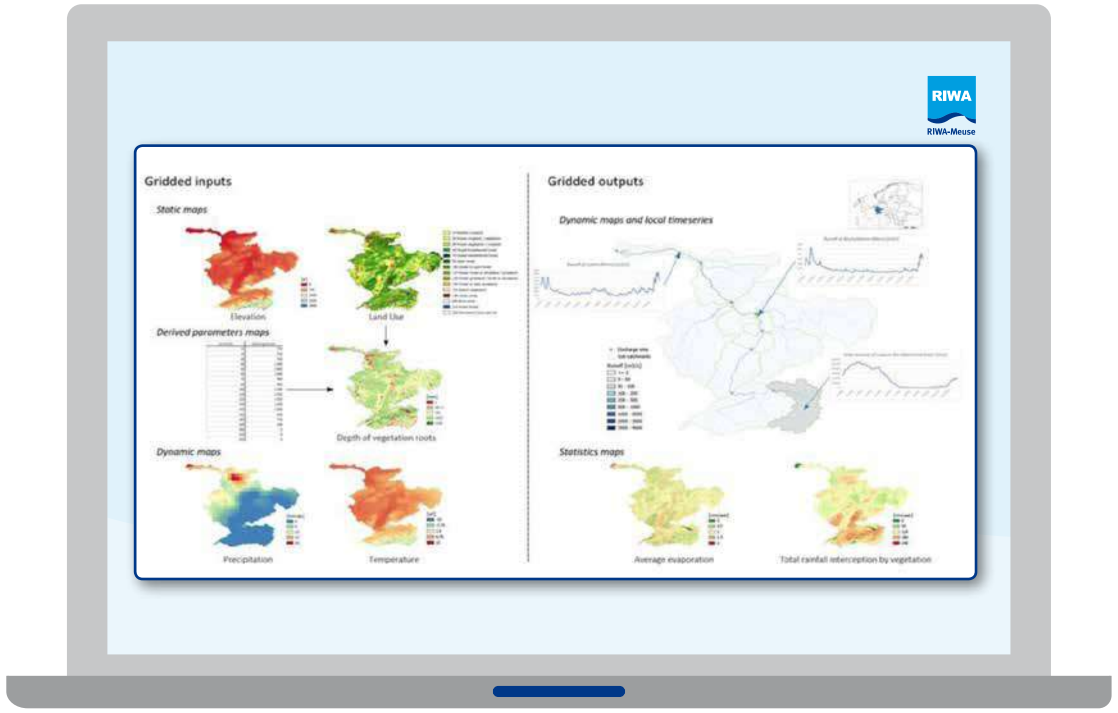
The Wflow model for the Meuse has been set up in latitude / longitude coordinates to optimally make use of available global datasets. Model coordinates are therefore in WGS84 (EPSG:4326) and the model resolution is 0.0083333° (approximately 1000 meters).

4.2.2 Model preparation and datasets used

A Wflow_sbm model requires three main types of inputs (Figure 15):

1 static data, such as a Digital Elevation Model (DEM), land use and river network;
2 dynamic data, such as precipitation, potential evapotranspiration and air temperature;
3 model parameters such as soil hydraulic conductivity or surface roughness.
4 A first setup of the model was built using global and open access data sources with the Deltares HydroMT Python tool (Deltares 2021).

Figure 15 The three types of main input data and two types of main output results of Wflow_sbm model.



Source Deltares, edited by RIWA-Meuse

4.2.2.1 Catchment properties

Wflow uses a combination of static data (data that do not vary in time) to describe fixed catchment properties such as elevation, land use, soil type. The different data sets used for the Meuse model are:

- The global 3 arc second (~90 meters) MERIT Hydro Adjusted Elevations dataset (Yamazaki et al. 2019) for model elevation and associated topological information (catchment delineation, flow direction (1D), slope, river network and its characteristics)
- The global 250 meters SoilGrids Database (Hengl et al. 2017) for soil properties (clay, silt, and organic carbon content as well as bulk density)
- The global 300 meters GlobCover map for 2009 (Arino et al. 2012) for land-use, land-cover classes
- The Global Reservoir and Dam database GRanD (Lehner et al. 2011) for reservoir location and information
- The HydroLAKES database (Messager et al. 2016) for lake location and information.

A first setup of model parameters was derived using (pedo)-transfer functions or optimized values from the literature from soil and land use data (Imhoff et al. 2020).

4.2.2.2 Meteorological data

Wflow_sbm requires three main dynamic meteorological variables:

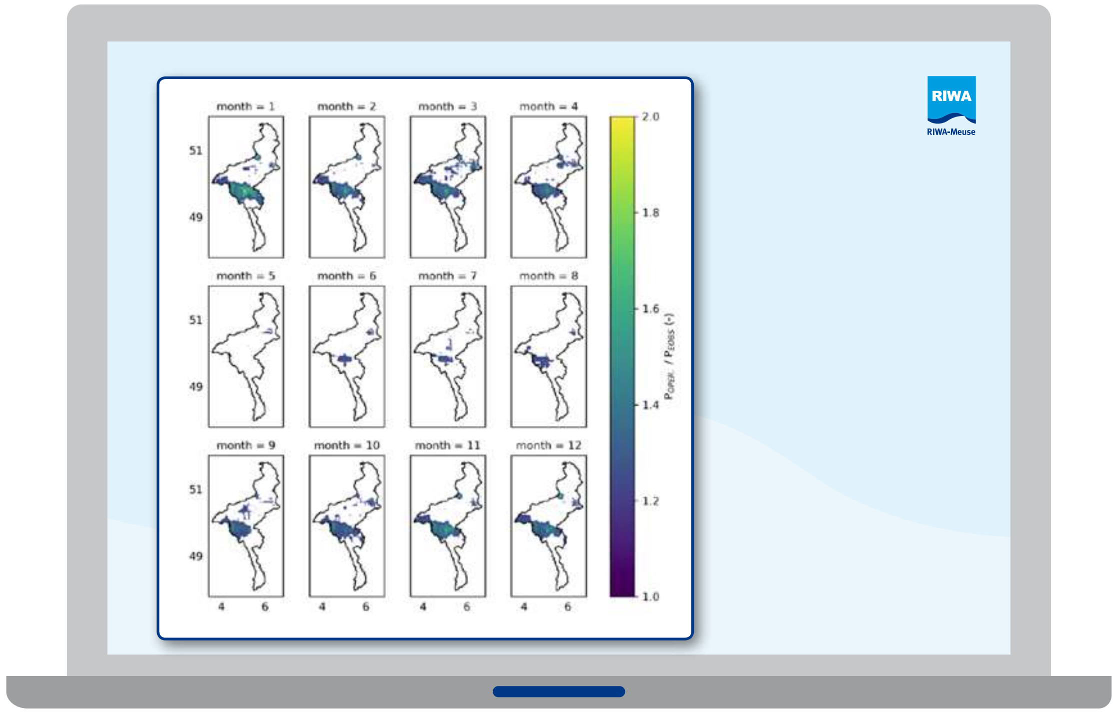
1 Total precipitation in mm/timestep
2 Average air temperature in °C
3 Potential evapotranspiration in mm/timestep

The dynamic data were derived from the E-OBS dataset (v20.0e) includes daily precipitation, temperature and radiation fields for the period 1980 onwards at a 25 km2 resolution (Cornes et al. 2018). The data are based on station data collated by the European Climate Assessment & Dataset (ECA&D) initiative. A problem with global radiation is reported for version v20.0e for 2019. Temperature is downscaled using the digital elevation model. Potential evaporation is estimated with the Makkink formula.

When comparing the E-OBS precipitation data to observations, Bouaziz 2020b found that there were areas in the basin for which the precipitation is underestimated, especially in the Sambre and Semois basin. Monthly correction factors were then applied to E-OBS precipitation (Figure 16).

The dataset was later extended for the complete 2019 and 2020 using the new published E-OBS version (v22.0e) and the same processing and correction factors.

Figure 16 Multiplication factor used to correct E-OBS in the area which is underestimated by more than 20% per month compared to station data (Bouaziz, 2020).



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4.2.3 Analysis of the hydrological model and its use within the RIBASIM model

4.2.3.1 Model calibration

The Wflow_sbm model for the Meuse has been calibrated and adjusting according to Bouaziz 2020b. In a similar study, she found that most default model parameters from the global version gave satisfactory results and only two parameters were adjusted:

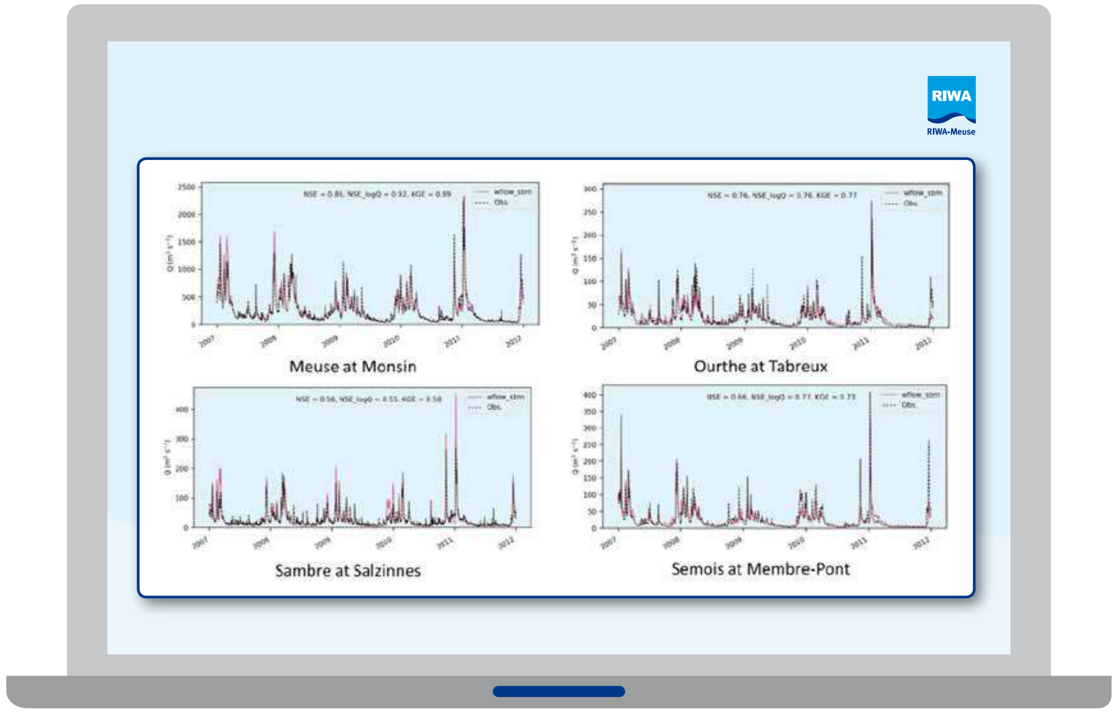
- The M parameter, controlling the decrease of the soil saturated hydraulic conductivity (Ksat) was computed using a linear regression method instead of the optimized default method.
- The KsatHorFrac parameter, which determines the ratio of horizontal over vertical saturated hydraulic conductivity, was adjusted for the whole basin including findings from Imhoff et al. 2020 for the Rhine, and further increased in areas underlain by highly productive fissured aquifers (including karstified rocks). This leads to an increase of the modelled baseflow. The adjusted KsatHorFrac values are shown in Figure 17. A value of 1 indicates that vertical conductivity is the same as horizontal conductivity. The higher the value, the higher is the resistance to vertical percolation with respect to the horizontal flow properties.

For this study the same changes were applied to the model. When using these parameters, results of the modelled discharge with Wflow_sbm compared to observations were very representative for both the peaks and low flow periods both for the Meuse and its tributaries. Results from Bouaziz 2020b are shown in Figure 18 for some of the observation stations.

Figure 17 Calibrated KsatHorFrac parameter (values range from 250, green, to 1000, brown)

Source Deltares, edited by RIWA-Meuse

Figure 18 Modelled and observed discharge with the calibrated Wflow_sbm model for the Meuse of some of its tributaries (Bouaziz 2020b)



Source Deltares, edited by RIWA-Meuse

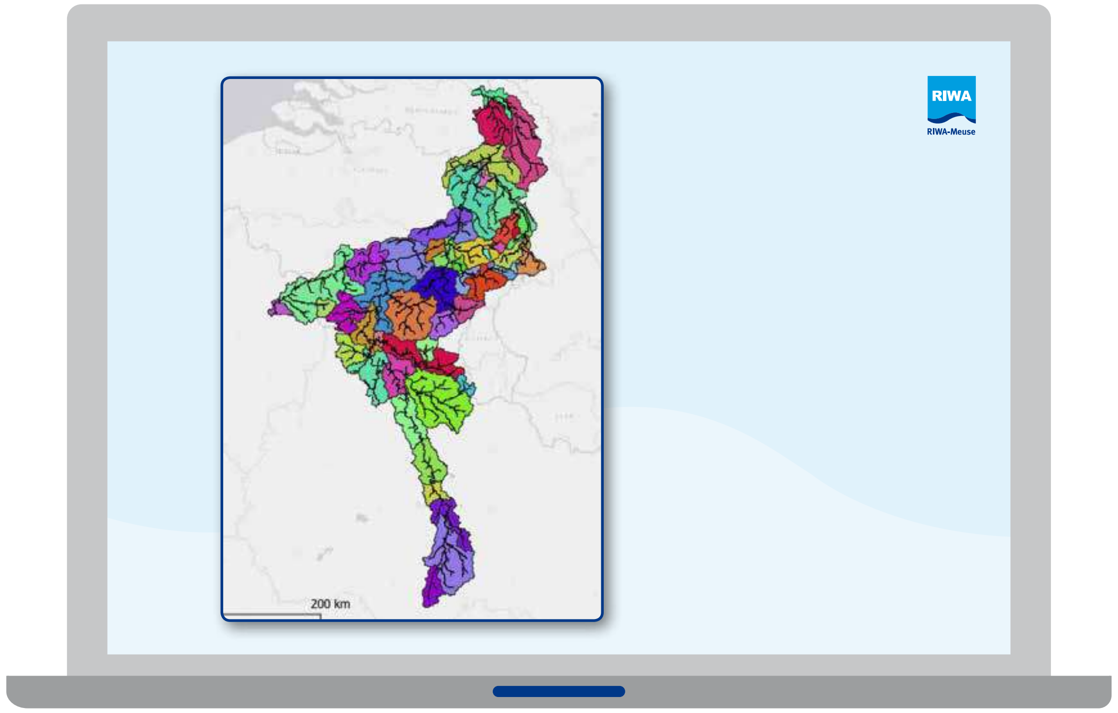
4.2.3.2 Usage for the RIBASIM model

The hydrological Wflow_sbm model is used to prepare meteorological and hydrological timeseries for the water balance model RIBASIM. These timeseries are:

- Inflow or runoff for each catchment / sub-basin (RIB_VARINF)
- Precipitation for the reservoir locations (RIB_RSV)
- Potential evapotranspiration for the reservoir locations (RIB_RSV).

The Meuse River basin is divided into 59 hydrological sub-basins. The sub-basins have been chosen based on the location of reservoirs (dams), flow monitoring stations, canal intakes and river mouths. The RIBASIM sub-basins were derived from the Wflow model using the drainage direction map feature. Figure 19 shows the Wflow sub-catchments, the total area of all sub-basins is 28,586.6 km2. In addition to the 56 sub-catchments shown in Figure 19 there are three more sub-catchments downstream of Mook. Because these sub-catchments are heavily modified and controlled, they are not included in the Wflow model.

Figure 19 Catchment schematization of Meuse River basin upstream of Mook split into 56 sub-basins



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4.3 The Meuse002 RIBASIM water management model

4.3.1 Catchment schematization

Each sub-basin is represented in the RIBASIM network schematization with a variable inflow node, where the inflow time series from the hydrological model Wflow (see previous chapter) is set. A list of all variable inflow nodes and the size of the sub-basin area (km2) is given in chapter C.5.

Reservoirs are represented with a reservoir node. RIBASIM reservoir nodes (RSV) and inflow nodes (VAR-INF) are connected to the corresponding Wflow cell as shown in Figure 20. The downstream boundary of the Wflow Meuse model is the recording station at Mook just downstream of the Maas – Waal Canal at Heumen. The schematization of the Netherlands downstream of Mook including the canal system in Middle Limburg and North Brabant are based on the 17 regions identified for the "Delta Programma Zoet Water" (DPZW).The 17 regions are shown in Figure 21 and listed in Table 3. The regions 2, 3, 7 and 14 are connected to the Meuse.

Figure 20 Linking Wflow sub-catchments and RIBASIM model nodes for the Meuse.

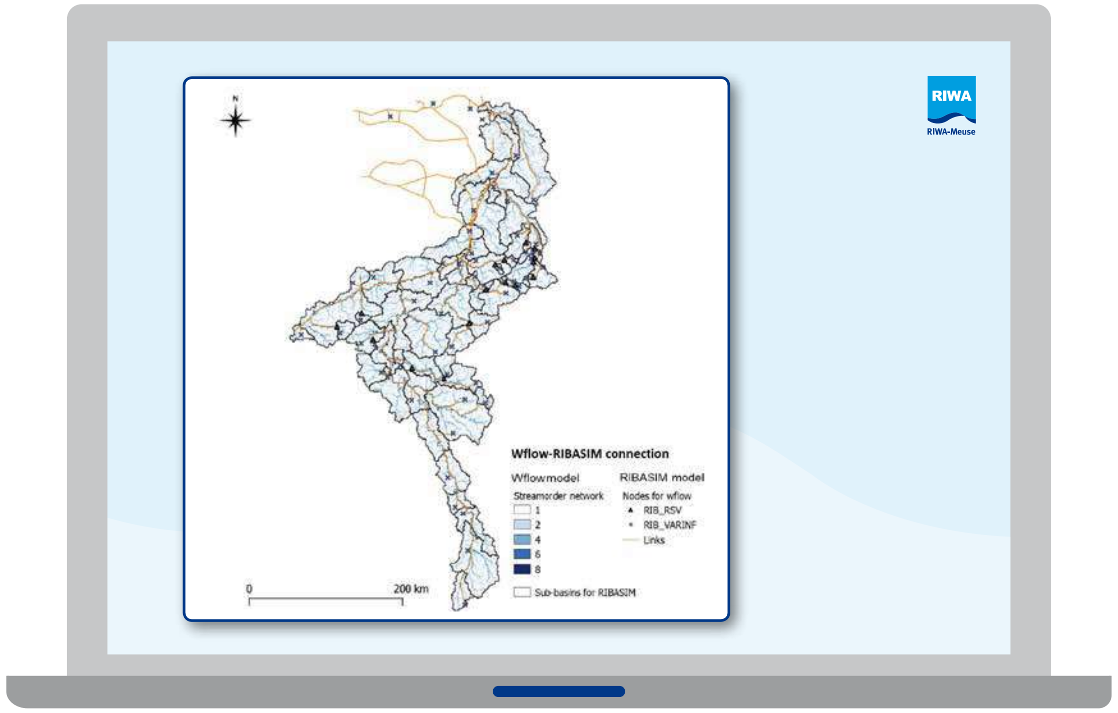

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Figure 21 The 17 regions for the "Delta Programma Zoet Water", the Netherlands.

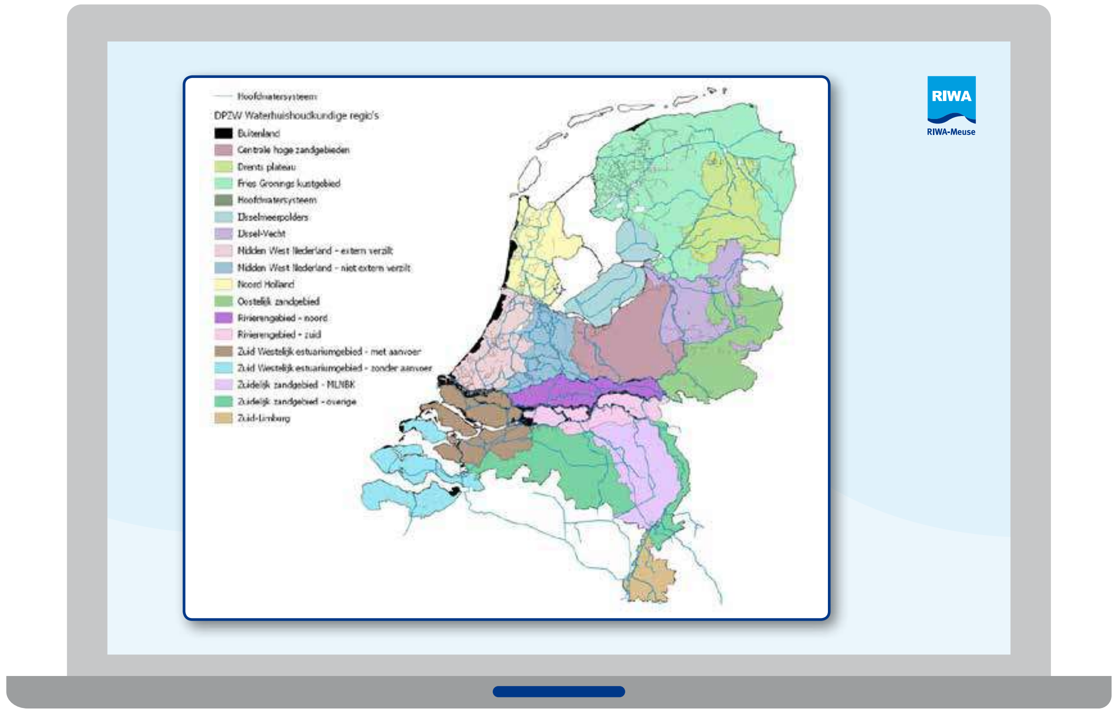

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Table 3 Overview of the DPZW regions.

Id	DPZW region
1	Waddeneilanden
2	Zuidelijk zandgebied - MLNBK
3	Zuidelijk zandgebied - overige
4	Centrale Hoge Zandgebieden
5	Oostelijk zandgebied
6	Rivierengebied - noord
7	Rivierengebied - zuid
8	Fries Gronings kustgebied
9	Noord Holland
10	Midden West Nederland - extern verzilt
11	Midden West Nederland - niet extern verzilt
12	Zuid Westelijk estuarium gebied - met aanvoer
13	Zuid Westelijk estuarium gebied - zonder aanvoer
14	Zuid Limburg
15	Ijsselmeer polders
16	Ijssel-Vecht
17	Drentsplateau

4.3.2 Network schematization

The node-link network schematization of the Meuse002 model is presented in Figure 22, Figure 23 and Figure 24. The main Meuse river and the tributaries Chiers, Semois, Viroin, Lesse, Sambre, Ourthe, Ambleve, Vesdre, Rur and Niers are represented in the network. The following sources, among others, have been consulted for the development of the model schematization: Commission Internationale de la Meuse 2020; Terrier et al. 2018; Asselman et al. 2017; Baetens et al. 2006.

Table 4 outlines the number of nodes and links per type, with a distinction in active and inactive nodes in the model.

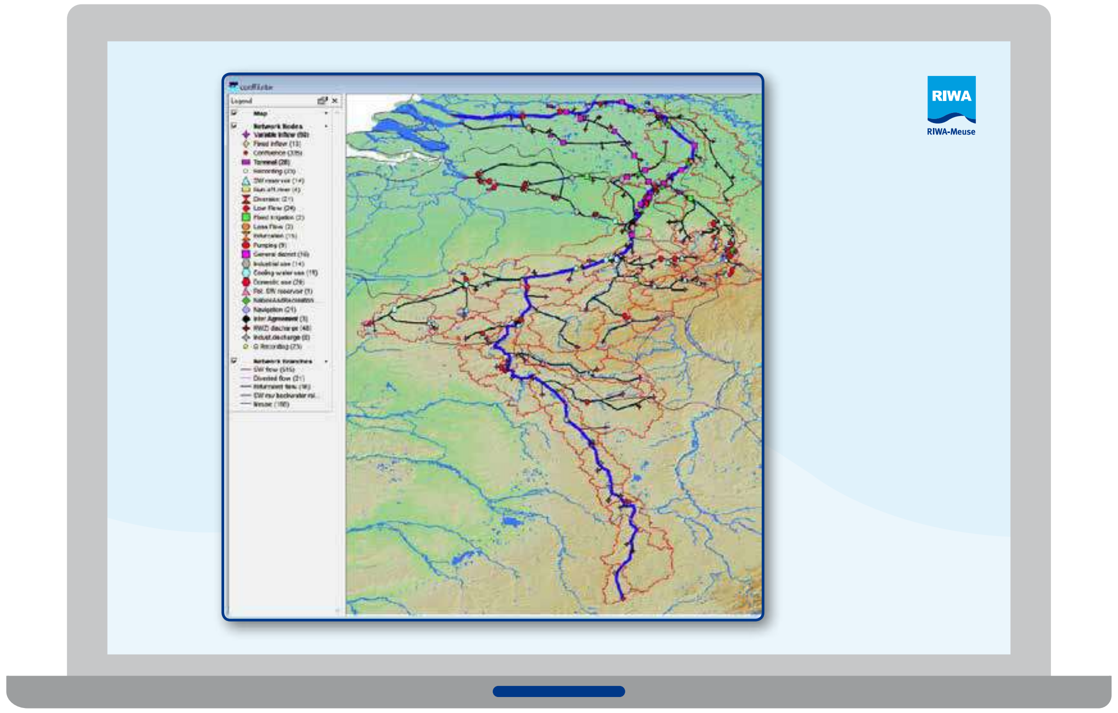
Active nodes and links are nodes and links which are part of the present situation, the Base case. Inactive nodes and links can be potentially activated in the context of specific developments and measures to be simulated.

The operation of the four reservoirs of the Rur River basin was difficult to implement in RIBASIM with sufficient accuracy, because especially during the dry years the reservoir release depends on operational decisions. For this reason, the inflow from the Rur into the Meuse upstream from Roermond has been modelled by connecting the monitored flow time series of recording station Stah as inflow to the Meuse. The part of the network schematization representing the Rur tributary with users and infrastructure has been set to inactive and is skipped in the simulation. Note that this part of the schematization is still part of the model and can be activated if necessary.

Table 4 Overview of dimensions of the Meuse002 network schematization

Type of nodes	Total	Active nodes	Inactive nodes
Total number of nodes	731	681	50
Total number of links	751	750	1
Bifurcation nodes - canal distribution	11	11	0
Bifurcation nodes - canal leakage	4	4	0
Confluence nodes	335	335	0
diversion nodes	21	21	0
Fixed inflow nodes - loop inflow	10	10	0
Fixed inflow nodes - industrial discharge	8	8	0
Fixed inflow nodes - boundary inflow	3	2	1
Fixed inflow nodes - waste water treatment plant	48	43	5
Fixed irrigation nodes	2	1	1
Low flow nodes - international agreement	3	3	0
Low flow nodes - nature and recreation	15	15	0
Low flow nodes - navigation	21	21	0
Low flow nodes - sluice leakage	8	8	0
Low flow nodes - pump-up of lock losses	8	8	0
Low flow - reservoir and canal operation	8	8	0
Public water supply nodes - cooling water	11	10	1
Public water supply nodes - domestic use	20	15	5
Public water supply nodes - industrial use	14	14	0
Loss flow - "Maasplassen" evaporation	2	2	0
Loss flow: extreme dry year increased water loss and use	1	1	0
Loss flow - extreme dry year increased water loss and use	9	9	0
Pumping nodes	46	23	23
Recording nodes	16	16	0
General district nodes - extraction and discharge of LHM regions and Dieze River	4	4	0
Run-of-river nodes	15	10	5
Surface water reservoir nodes	4	4	0
Terminal nodes - canal leakage loss	11	11	0
Terminal nodes - downstream boundary outflow	10	10	0
Terminal nodes - loop outflow	3	3	0
Terminal nodes - nature outflow	60	51	9
Variable inflow nodes - Wflow runoff + Stah recording station	731	681	50

Figure 22 The Meuse002 model network schematization



Source Deltares, edited by RIWA-Meuse

Figure 23 The Meuse002 network schematization without map

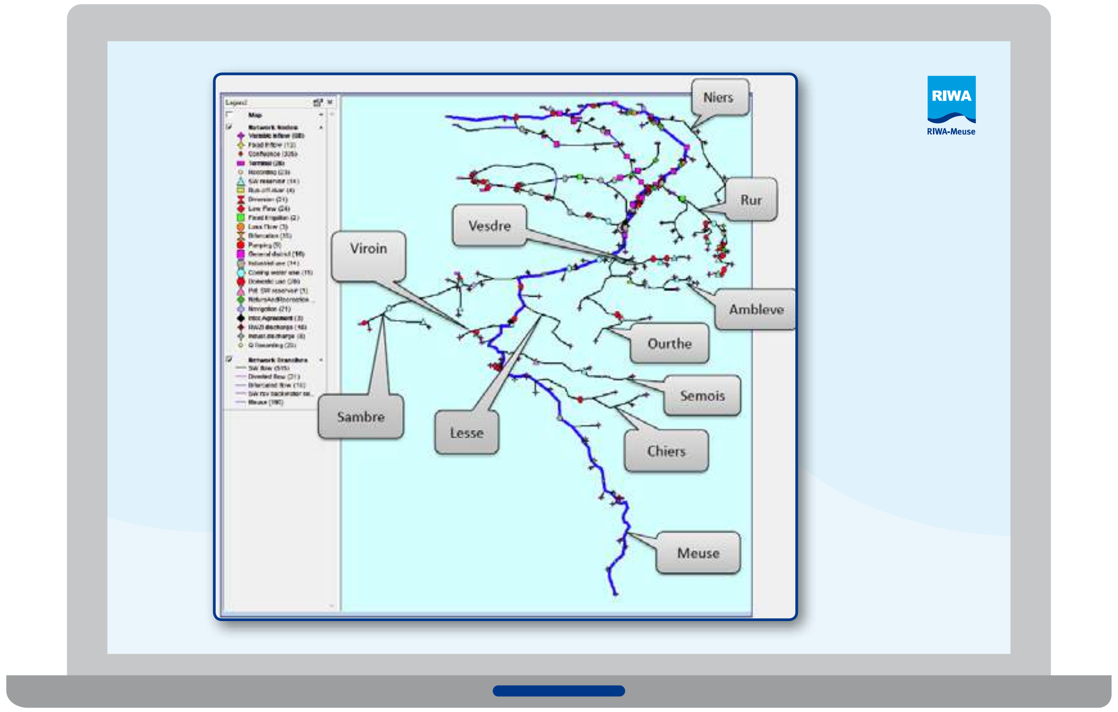


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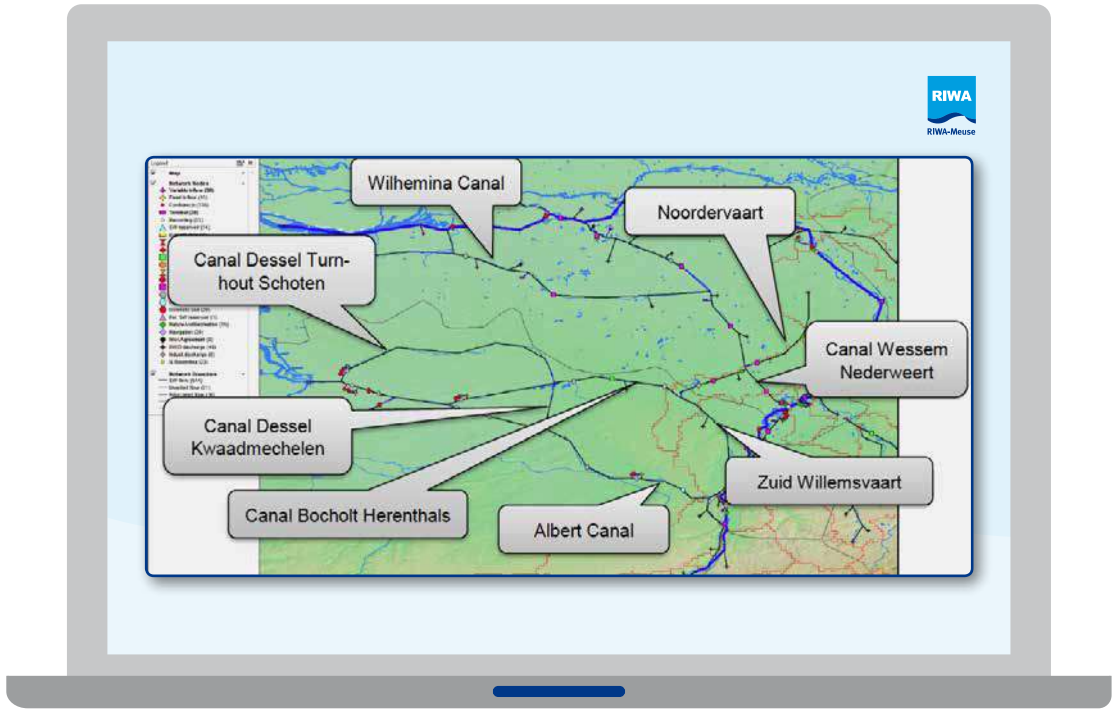
Figure 24 The Meuse002 RIBASIM schematization of canal system in Belgium and the Netherlands



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4.3.3 Modelling features

4.3.3.1 Hydrological boundary conditions: multiple year time series

The hydrological boundary parameters consisting of multiple year time series of daily values are:

1 The runoff for each sub-basin
2 The actual rainfall at reservoirs
3 The open water evaporation at reservoirs
4 The monitored flow at recording stations

Additionally, multiple year time series of timestep values is:

5 The general district discharge at Dommel, Aa and Dieze

The runoff time series are generated by the Wflow model of the Meuse River basin. The length of the time series is 41 years, from January 1980 till December 2020. In chapter 4.2 more details about the Wflow model are given.

The Wflow runoff time series did not fit the recorded time series at station Kessel in the Niers river satisfactorily. In order to get a good match between simulated and monitored flow at station Kessel a correction factor of -40 % has been applied on the hydrological inflow time series for the months July to November. The RIBASIM feature “local consumption” has been used to implement this correction into the model. The inaccuracy probably originates from the Wflow model, so the improvement of the Wflow model for the Niers sub-catchment is recommended.

Table 5 shows the average annual natural flow in the Meuse River at the locations of the confluence with the various tributaries. The natural flow (in 106 m^3) is the flow computed by the RIBASIM model for a river with all infrastructure and all demands set to inactive. The boundaries of the sub-basins / catchments in the catchment schematization as shown in Figure 19 do not always fit exactly the tributary boundaries, so the annual flow values do not exactly represent the tributary contribution. Table 5 shows the contribution of each tributary and the main river as percentage of the total average annual natural flow. The main river “Meuse” covers the minor tributaries that flow directly into the main river and are not listed in Table 5.

These are Vair, Vrigne, Bar, Vence, Sormonne and Houille in France, Hermeton, Moligne, Bosq, Mehaige, Hoyoux, Berwijn and Oeter in Belgium and Voer, Jeker, Geul, Geleenbeek, Thornerbeek, Maasnielderbeek, Swalm, Neerbeek, Kwistbeek and Groote Molenbeek in the Netherlands.

Table 5 Average annual natural flow (Mio. m^3) in Meuse and the contribution of each sub-basin (106 m^3) from source to mouth using Wflow results.

Tributary	Average annual natural flow in Meuse (Mio. m^3)	Contribution of each sub-basin to the average annual natural flow (Mio m^3)
Meuse	1360.3	
Chiers	2667.1	1306.8
Meuse	3362.5	695.4
Semois	4282.9	920.3
Meuse	4563.1	280.2
Viroin	4804.8	241.7
Meuse	4804.8	0.0
Lesse	5425.4	620.5
Meuse	5865.0	439.6
Sambre	6930.5	1065.5
Meuse	7387.9	457.4
Ourthe incl. Ambleve and Vesdre	9325.6	921.6
Ambleve		622.7
Vesdre		393.3
Meuse	10250.1	924.5
Rur	10921.0	670.9
Meuse	11603.4	682.4
Niers	12002.1	398.7
Meuse	12288.0	285.9

Figure 25 shows the contribution (in 106 m^3) of each tributary to the average annual natural flow in a waterfall graph. Figure 26 shows the deviation from the average of the annual flow. The 18 years period from 2003 till 2020 has only one wet year, two average and 15 dry years. This figure illustrates that the recent period since the year 2000 is already dryer than the 20 years before 2000.

The daily actual rainfall and open water evaporation time series has been produced by the Wflow model of the Meuse River basin. The rainfall time series are from January 1962 till December 2020 and the evaporation time series from January 1980 till December 2020. In chapter 4.2 more details about the Wflow model are given.

Daily monitored flow time series from January 1980 till December 2020 are available for 23 recording stations. The series were produced in the sub-project A and can be used to compare with the simulated flows. More details are listed in chapter C.5.

The inflow from the rivers Dommel, Aa and Dieze into the Zuid Willemsvaart near the monitoring station Engelen is schematized as a General District node for which a discharge time series is specified. The time series is generated by the integrated nationwide ground- and surface water model of the Netherlands, LHM (Landelijk Hydrologisch Model).

Table 6 The contribution of each tributary to the average annual natural flow (%).

Tributary	Contribution to average annual natural flow (%)
Chiers	10.6%
Semois	7.5%
Viroin	2.0%
Lesse	5.0%
Sambre	8.7%
Ambleve	5.1%
Vesdre	3.2%
Ourthe	7.5%
Rur	5.5%
Niers	3.2%
Meuse	41.7%

Figure 25 Contribution of each tributary to the average annual natural flow in Meuse from source till mouth (106 m^3).

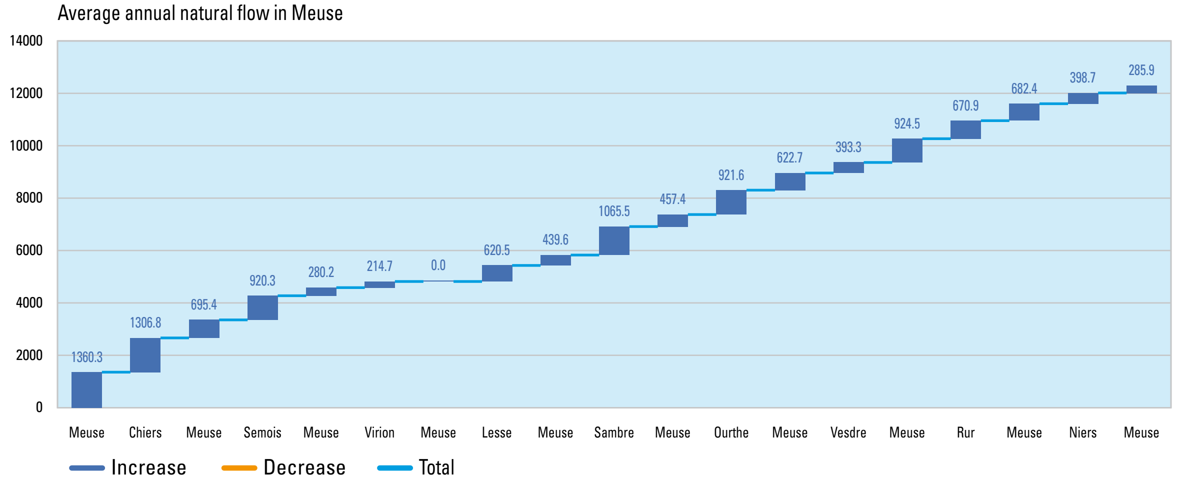

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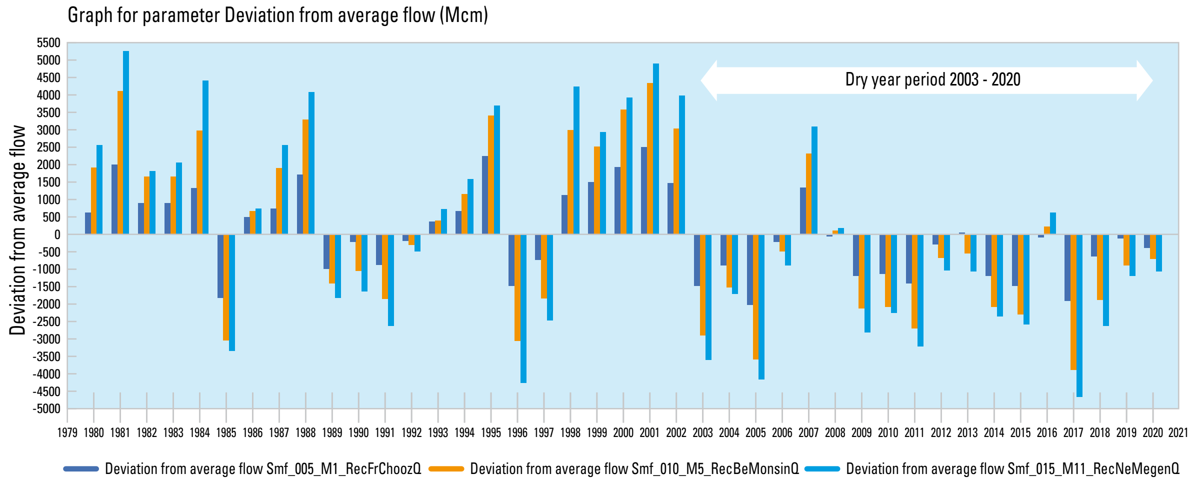
Figure 26 Deviation from average annual natural flow at monitoring stations Chooz, Monsin and Megen for 1980 till 2020.



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4.3.3.2 Hydrological boundary conditions: annual time series

The hydrological boundary parameters consisting of annual time series of decade values are:

1 The discharge from waste water treatment plants
2 The lignite mining drainage
3 The inflow from Canal des Ardennes
4 The industrial discharge

The model includes 48 fixed inflow nodes representing the discharge of the waste water treatment plants. Figure 27 shows the location of the WWTP on the map. Table 7 and Figure 28 shows the annual RWZI discharge per river and canal section of Meuse in downstream order. The annotations for the canal and river sections are outlined in Table 49. The annual discharge is 449 Mcm.

The drainage from the lignite mining in the Rur catchment is represented with a Fixed inflow node (node id 75 and node name “Fif_De_LigniteMineDrainage”) with an annual discharge of 50.5 Mcm. Figure 29 shows the location of the lignite mining drainage in the schematization of the Rur river basin.

The transboundary inflow from the Canal des Ardennes is also represented with a Fixed inflow node (node Id 172 and node name “Fif_Fr_CanalDesArdennes”) with an annual inflow of 0.0 Mcm. Figure 30 shows the location of the inflow from the Canal des Ardennes into the Meuse River basin section M0 in France.

The industry which does not abstract surface water but only discharge on the Meuse River is represented with a Fixed inflow node. Figure 31 shows the location of the 8 nodes in section M0 of the Meuse River in France. The annual discharge is 2.5 Mcm.

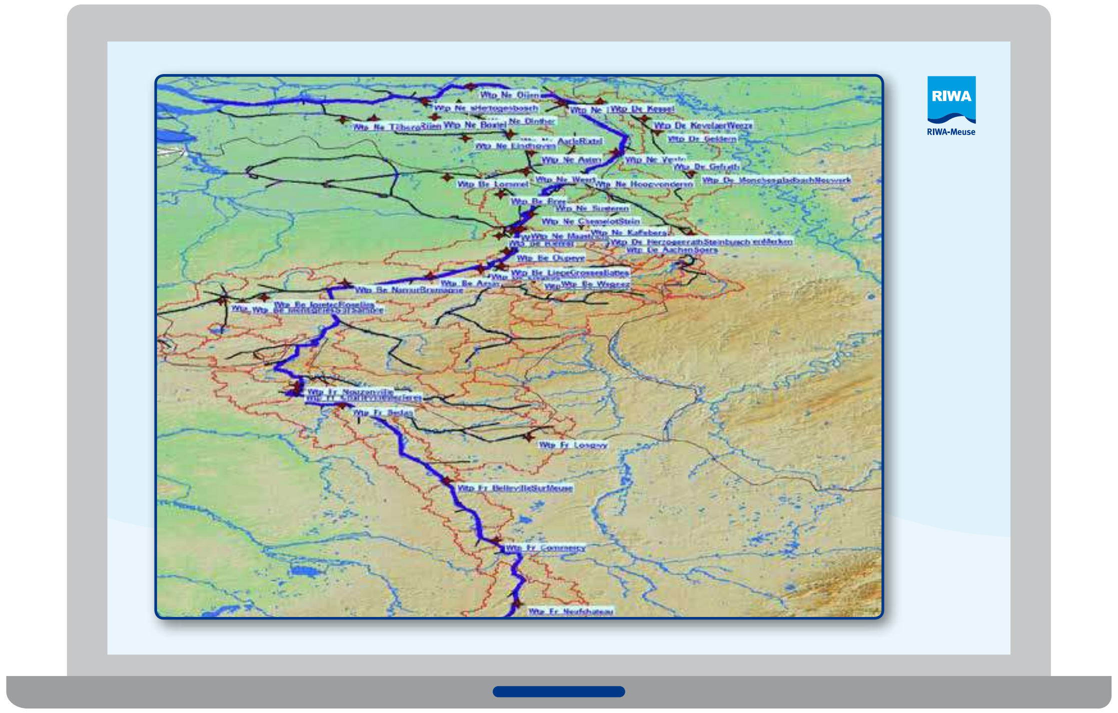
A fixed inflow node (node Id 727 and node name “Fif_Ne_DommelAaDieze”) has been added upstream of the general district node representing the inflow from the Dommel, Aa and Dieze (node Id 728 and node name “Reg_Ne_DommelAaDieze”) due to network schematization requirements. The inflow is 0.0.

Table 7 Annual WWTP discharge per river and canal section in downstream order (106 m^3).

River section, tributary or canal	Section	Annual inflow from WWTP (106 m^3)
Meuse	M0	10.439
Chiers	Chr	4.636
Sambre	Sam	17.817
Meuse	M3	4.068
Meuse	M4	8.294
Vesdre	Ves	7.884
Albert Canal	AC1	19.237
Canal Bocholt-Herenthals (Kempisch)	CBH1	10.848
Juliana Canal	JC	30.590
Wilhelmina Canal	WC	81.363
Zuid-Willemsvaart (Be + Ne)	ZWV1	9.240
Zuid-Willemsvaart	ZWV2	7.569
Zuid-Willemsvaart	ZWV3	72.218
Rur *	Rur	37.023
Meuse	M8	13.245
Meuse	M9	23.021
Meuse	M10	11.668
Niers	Nrs	60.897
Meuse	M11	18.922
Total		**448.979**

** All nodes representing the Rur River basin is set inactive and is not explicitly simulated.*

Figure 27 Overview of the 48 nodes representing the discharge of the waste water treatment plants in the Meuse model.



Source Deltares, edited by RIWA-Meuse

Figure 28 Annual RWZI discharge per river and canal section of Meuse in downstream order (106 m^3).

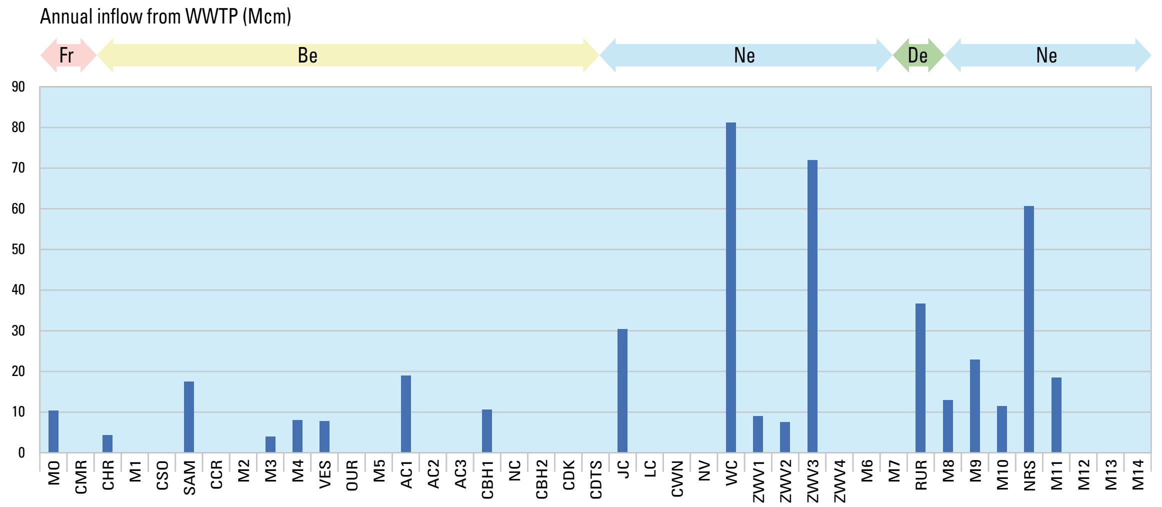


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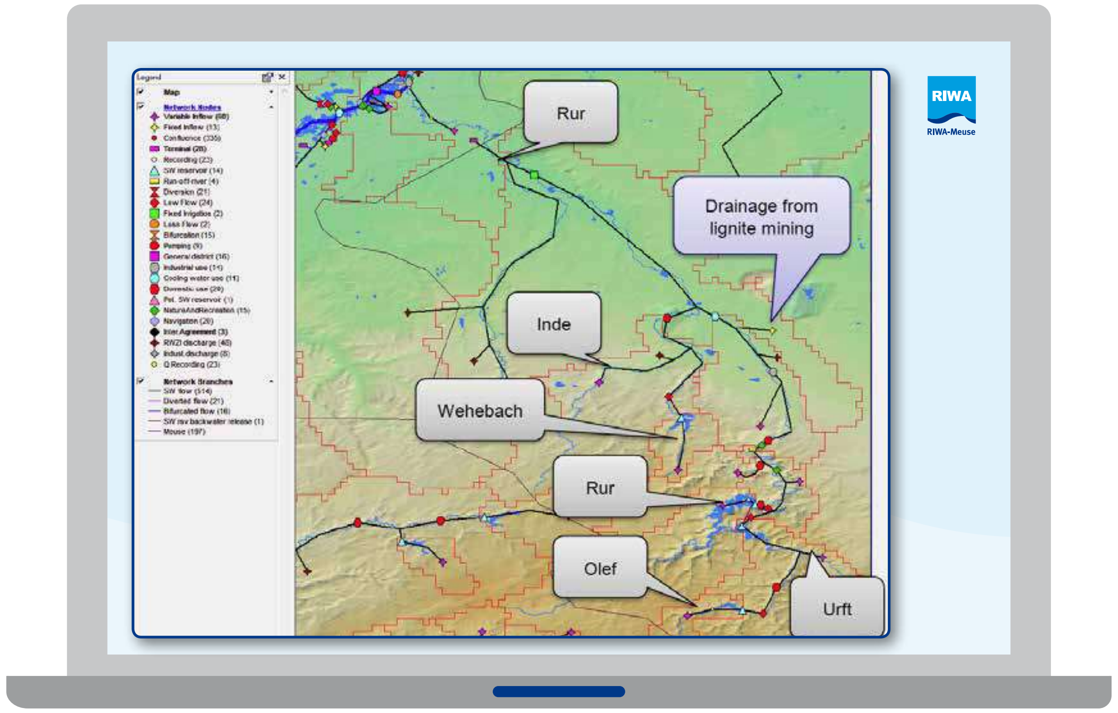
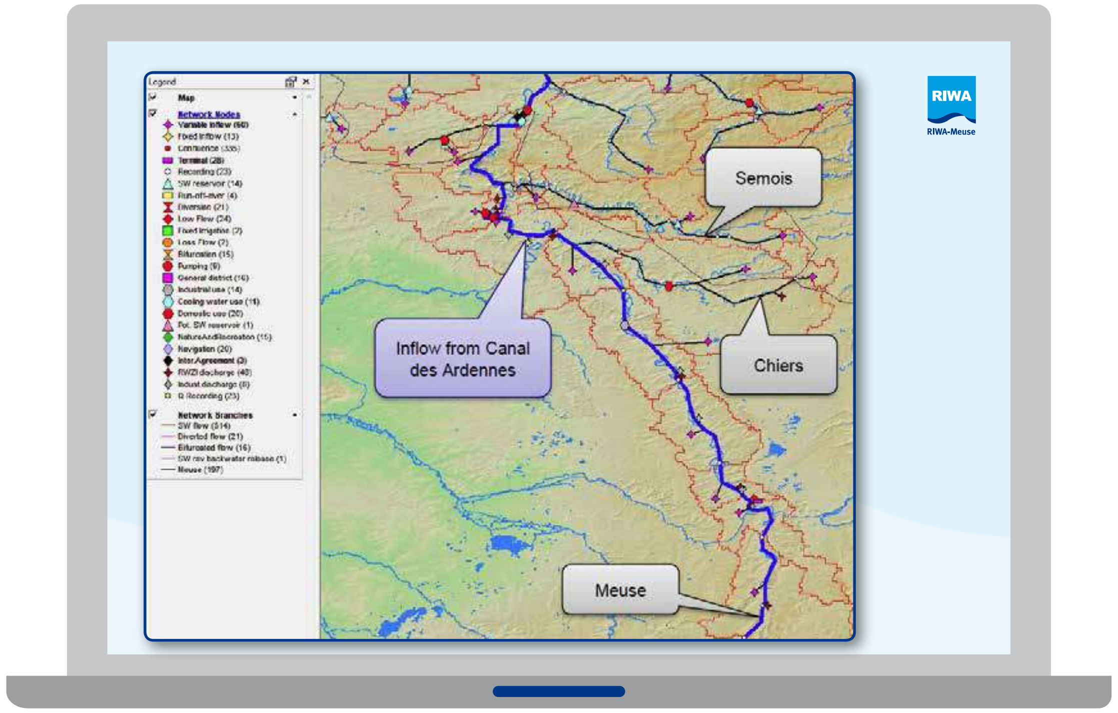
Figure 29 Location of the Fixed inflow node representing the drainage from the lignite mining in the Rur River basin.



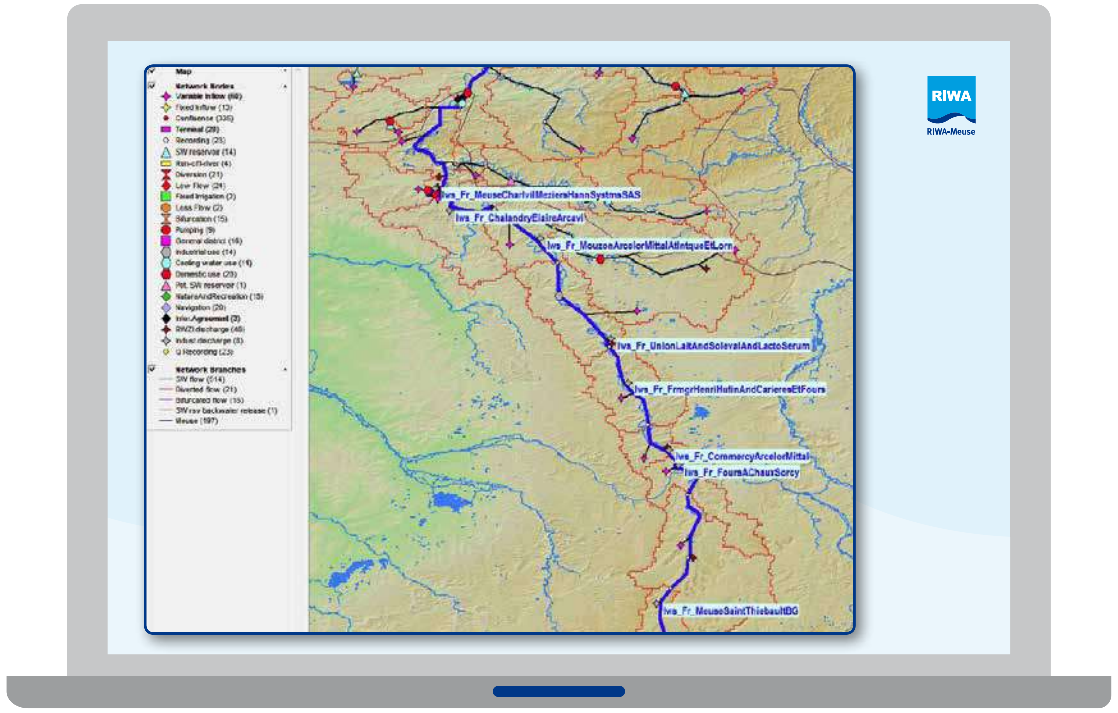
Source Deltares, edited by RIWA-Meuse

Figure 30 Location of the Fixed inflow node representing the inflow from the Canal des Ardennes in the upstream part Mo of the Meuse River basin in France.



Source Deltares, edited by RIWA-Meuse

Figure 31 Location of the Fixed inflow node representing the industrial discharge in the upstream part Mo of the Meuse River basin in France.



Source Deltares, edited by RIWA-Meuse

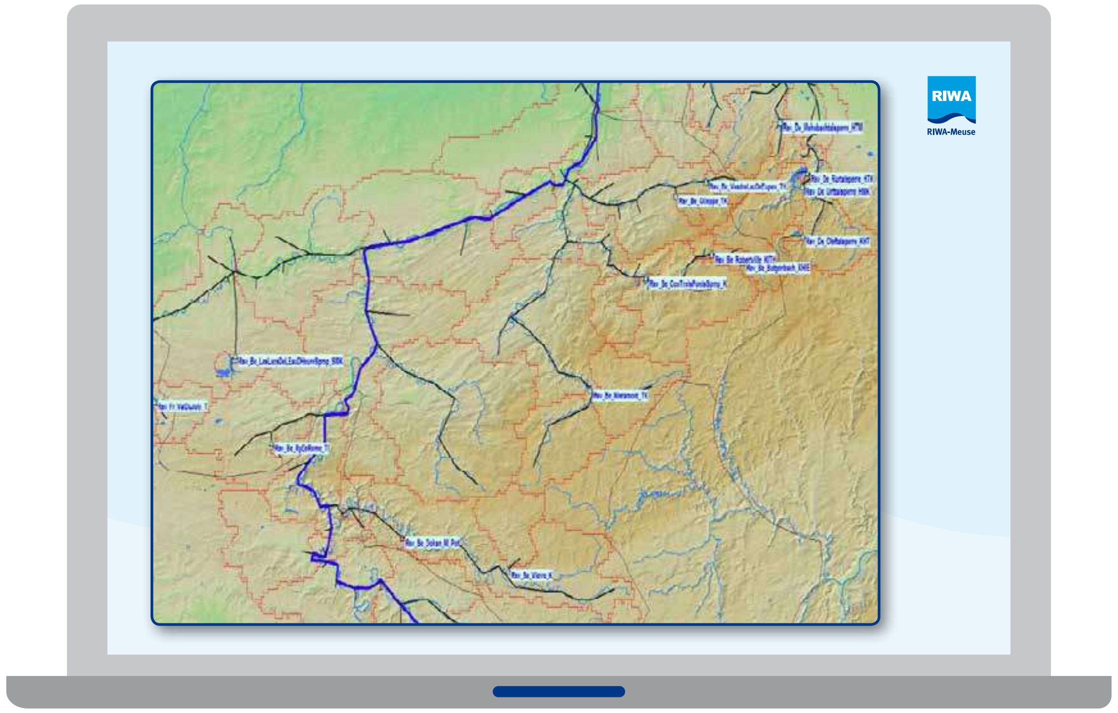
4.3.3.3 Infrastructure

The types of infrastructure identified to be represented in the model, are the reservoirs, the canals and weirs, and the run-of-river hydro-power stations.

The model network contains 14 existing reservoirs with a total volume of 442.2 106 m³ and one potential reservoir with a volume of 8.4 106 m³. The potential reservoir is the “barrage de Dohan” which was planned, but not realized in 1965-1966. Figure 32 shows the reservoir nodes on the map. The location spread over the Meuse riparian countries is listed in Table 8. Further details on the reservoirs in the model are provided in chapter C.6.1.

The network contains the following canals: the Albert Canal, Juliana Canal, Zuid-Willemsvaart, Lateral Canal, Canal Wessem-Nederweert and the Kempen Canals. Figure 34 shows the nodes representing a selection of canal intakes and canal leakages and its location on the map. Annex C.6.2 lists more details. The network contains four run-of-river hydro-power stations: Lorce Heid De Goreux, Andenne Seilles, Ampsin Neuville and Obermaubach. Those stations are not influencing the water distribution in the network but only the generated energy is computed. The nodes are added to the network schematization for orientation. The number of stations could be completed in next versions of the Meuse model. Figure 35 shows the location of the run-of-river hydro-power nodes on the map.

Figure 32 Overview the nodes of the existing and potential reservoirs in the Meuse model.

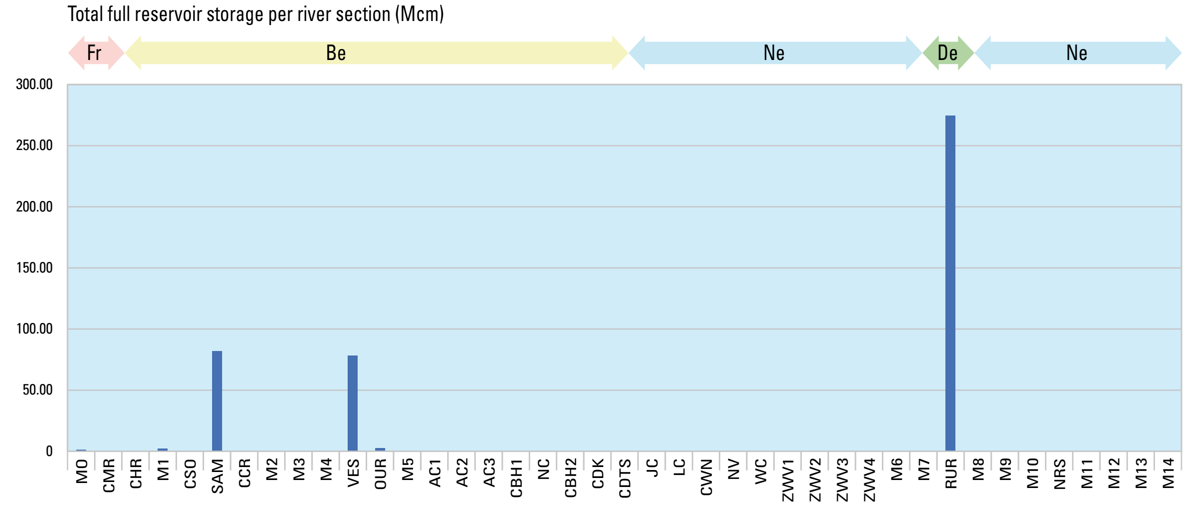


Source Deltares, edited by RIWA-Meuse

Table 8 Number of existing reservoirs in the model per country and the total storage capacity (106 m³).

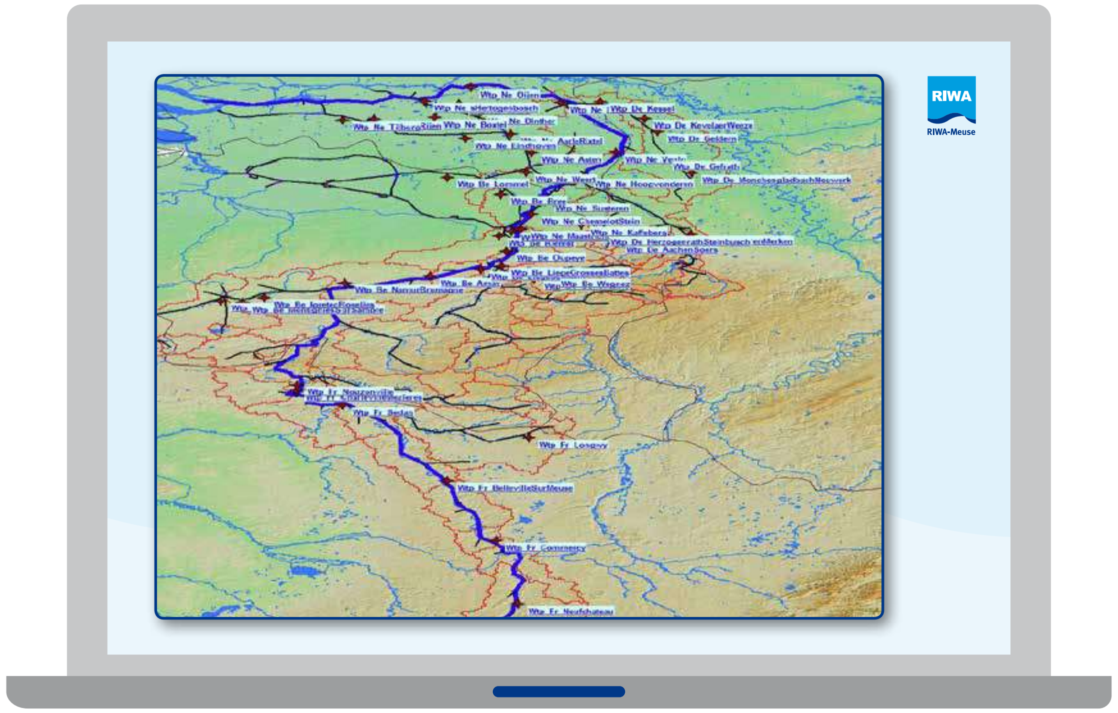
Country	Number of reservoirs	Total capacity of reservoirs (106 m³)	Percentage of total storage (%)
Belgium	9	164.01	37%
Germany	4	274.63	62%
France	1	3.60	1%
Total			**442.24**

Figure 33 Total full reservoir storage per river section of the Meuse in downstream order (106 m³).



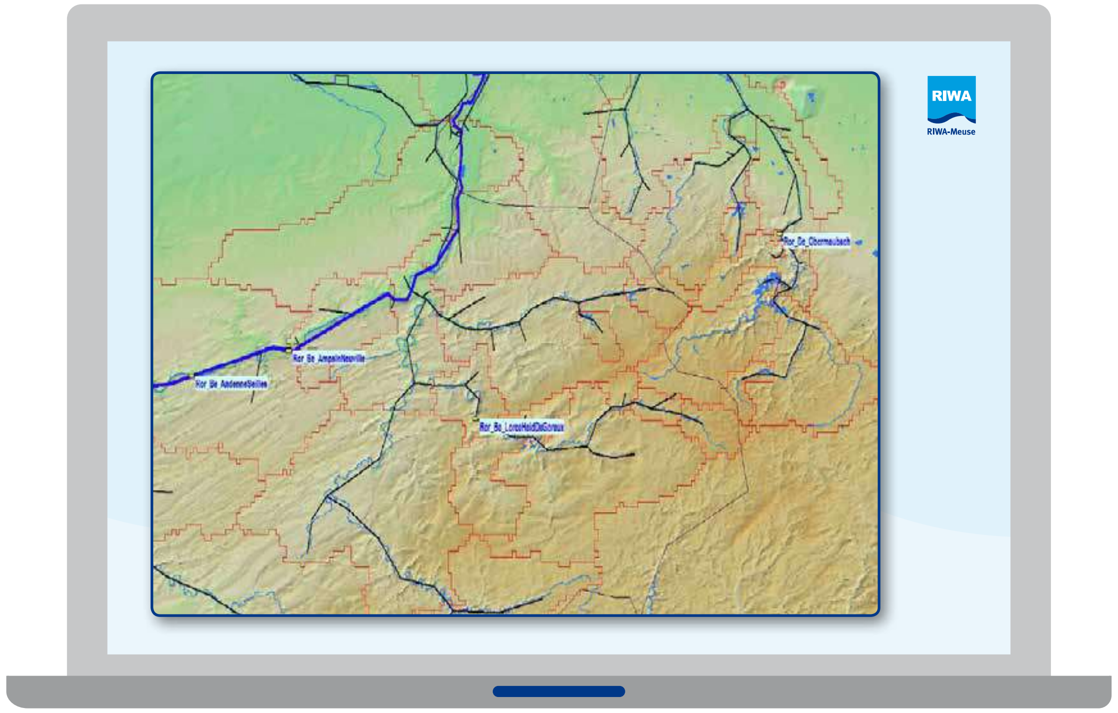
Source Deltares

Figure 34 Overview of a selection of nodes representing intakes of various canals and canal leakage in the Meuse model.



Source Deltares, edited by RIWA-Meuse

Figure 35 Overview of the nodes representing run-of-river hydro-power stations in the Meuse model.



Source Deltares, edited by RIWA-Meuse

Table 9 Annual domestic water demand per river and canal section (106 m^3).

River / canal	Section	Annual domestic water demand (106 m^3)
Meuse	M0	1.48
Chiers	Chr	0.73
Meuse	M1	3.00
Meuse	M2	52.67
Vesdre	Ves	29.33
Ourthe	Our	11.04
Albert Canal	AC3	52.79
Nete Canal	NC	96.47
Lateraal Canal	LC	52.67
Meuse (Common Meuse)	M6	1.01
Rur	Rur	50.14
Meuse	M13	324.19
Total		**675.50**

4.3.3.4 Water users and losses

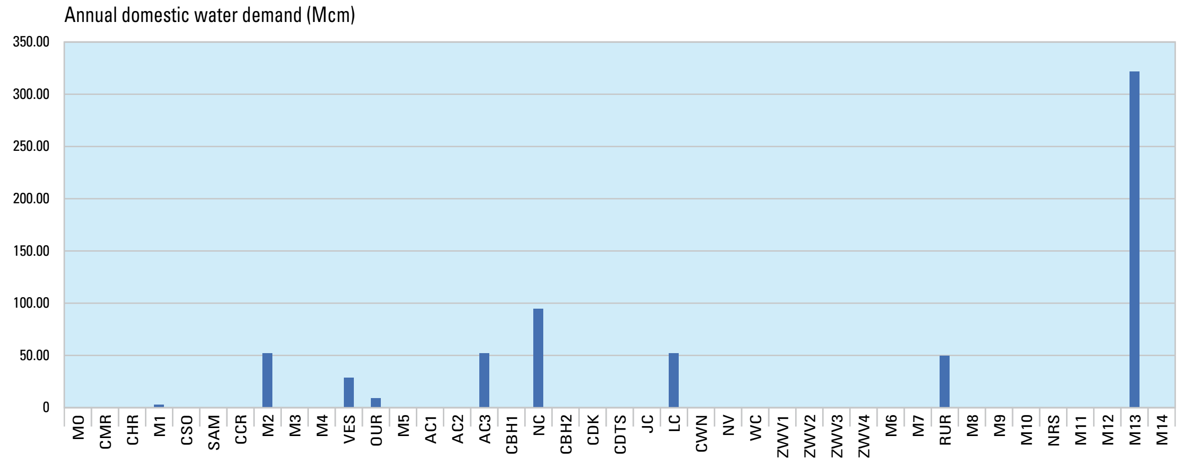
The following water using and consuming activities are identified and represented in the model.

1 Domestic water
2 Industrial water
3 Cooling water
4 DPZW region water based on LHM
5 Irrigated agriculture water
6 Nature and recreation
7 Navigation (lock loss) water demand
8 Sluice pump-up of lock losses
9 Sluice leakage
10 Canal leakage loss
11 “Maasplassen” evaporation losses
12 Reservoir operation
13 Inter-basin transfer
14 International agreements
15 Extreme dry year increased water loss and use

Table 9 till Table 23 list the annual water demand or water use for each activity per river and canal section. Figure 36 till Figure 48 show the demand per river and canal section of the Meuse in downstream order. A list of the river and canal sections is shown in Table 49 and Figure 91.

Detailed data are listed in annex C.7. Some domestic and industrial water users and the cooling water demand come with a return flow to account for a full or partly release of the extracted water after usage. The return flow is specified as absolute value or percentage, For details we refer to the model data or model inventory (Section 2).

Figure 36 Annual domestic water demand per river and canal section in downstream order (106 m^3)

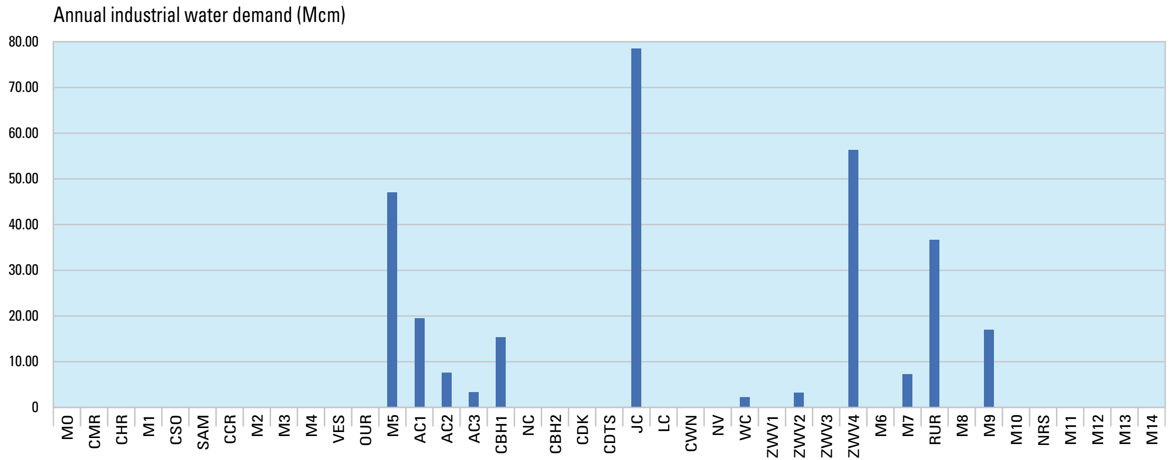


Source Deltares

Table 10 Annual industrial water demand per river and canal section (106 m^3)

River / canal	Section	Annual industrial water demand (106 m^3)
Meuse	M0	0.92
Meuse	M5	47.30
Albert Canal	AC1	19.55
Albert Canal	AC2	8.20
Albert Canal	AC3	3.78
Canal Bocholt-Herenthals (Kempisch)	CBH1	15.45
Juliana Canal	JC	78.84
Wilhelmina Canal	WC	2.84
Zuid-Willemsvaart	ZWV2	3.50
Zuid-Willemsvaart	ZWV4	56.45
Meuse	M7	7.44
Rur	Rur	36.90
Meuse	M9	17.35
Total		**298.51**

Figure 37 Annual industrial water demand per river and canal section in downstream order (106 m^3)

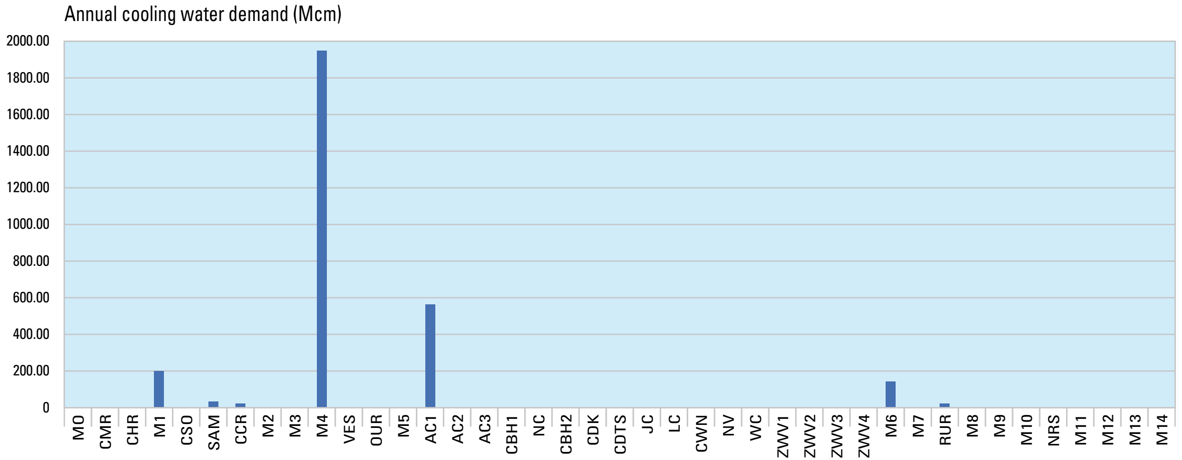


Source Deltares

Table 11 Annual cooling water demand per river and canal section (106 m^3)

River / canal	Section	Annual cooling water demand (106 m^3)
Meuse	M1	198.55
Sambre	Sam	27.75
Canal Charleroi - Bruxelles	CCB	13.50
Meuse	M4	1965.07
Albert Canal	AC1	189.22
Meuse (Common Meuse)	M6	145.07
Rur	Rur	11.98
Total		2551.14

Figure 38 Annual cooling water demand per river and canal section in downstream order (106 m^3).

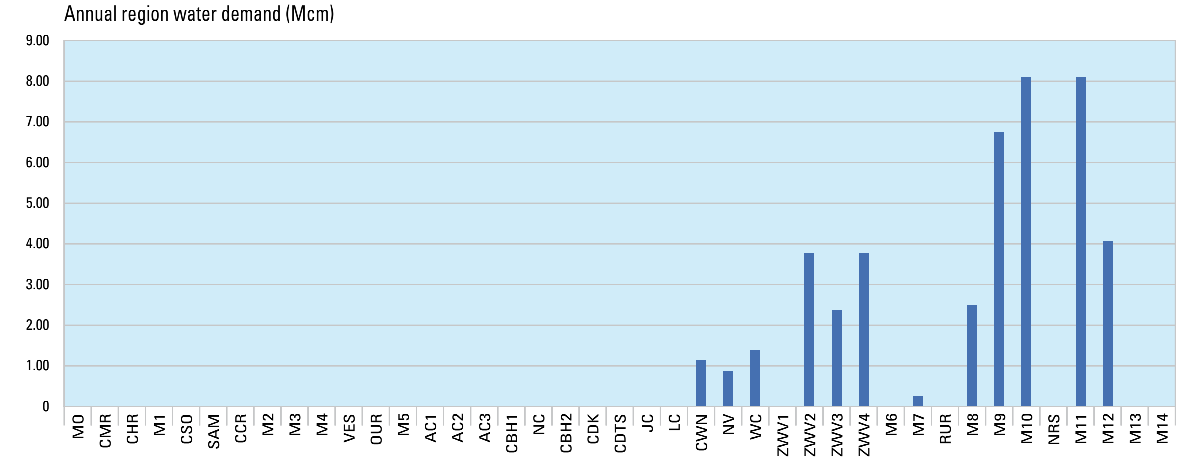


Source Deltares

Table 12 Annual average DPZW region water demand per river and canal section (106 m^3).

River / canal	Section	Annual region water demand (106 m^3)
Canal Wessem-Nederweert	CWN	1.14
Noordervaart	NV	0.88
Wilhelmina Canal	WC	1.41
Zuid-Willemsvaart	ZWV2	3.76
Zuid-Willemsvaart	ZWV3	2.39
Zuid-Willemsvaart	ZWV4	3.76
Meuse	M7	0.26
Meuse	M8	2.51
Meuse	M9	6.79
Meuse	M10	8.10
Meuse	M11	8.10
Meuse	M12	4.05
Total		43.15

Figure 39 Annual average DPZW region water demand per river and canal section in downstream order (106 m^3).

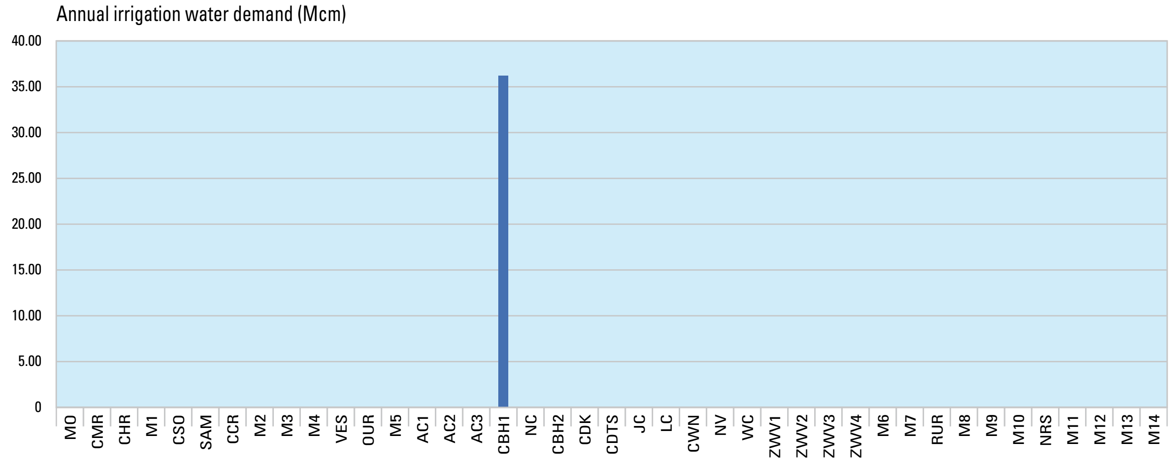


Source Deltares

Table 13 Annual irrigated agriculture water demand per river and canal section (106 m^3)

River / canal	Section	Annual irrigated agriculture water demand (106 m^3)
Canal Bocholt-Herenthals (Kempisch)	CBH1	36.13
Rur	Rur	0.03
Total		36.15

Figure 40 Annual average irrigation water demand per river and canal section in downstream order (106 m^3).

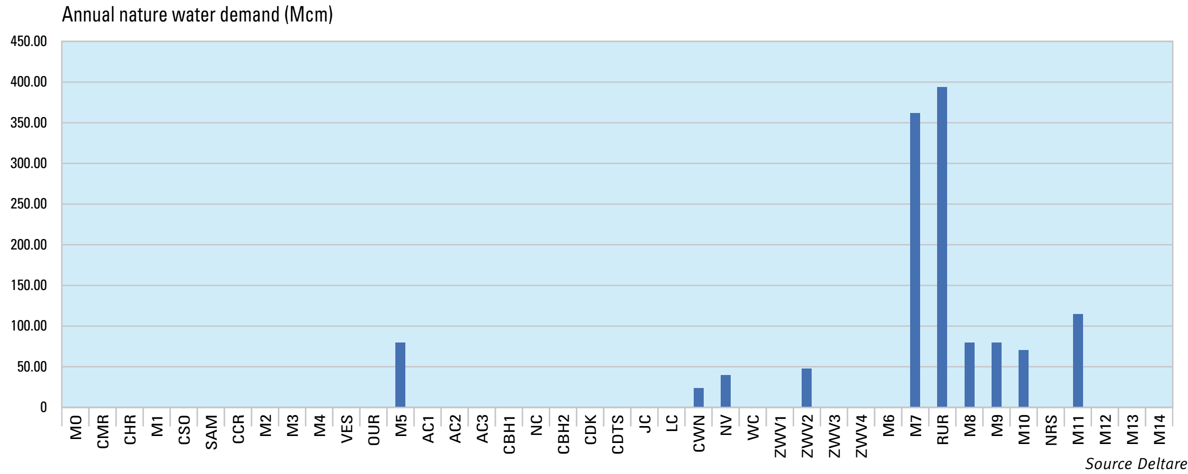


Source Deltares

Table 14 Annual nature and recreation water demand per river and canal section (106 m^3)

River / canal	Section	Annual nature water demand (106 m^3)
Meuse	M5	78.84
Canal Wessem-Nederweert	CWN	22.08
Noordervaart	NV	37.84
Zuid-Willemsvaart	ZWV2	47.30
Meuse	M7	362.66
Rur	Rur	394.20
Meuse	M8	78.84
Meuse	M9	78.84
Meuse	M10	69.38
Meuse	M11	113.53
Total		1283.52

Figure 41 Annual average nature water demand per river and canal section in downstream order (106 m^3).

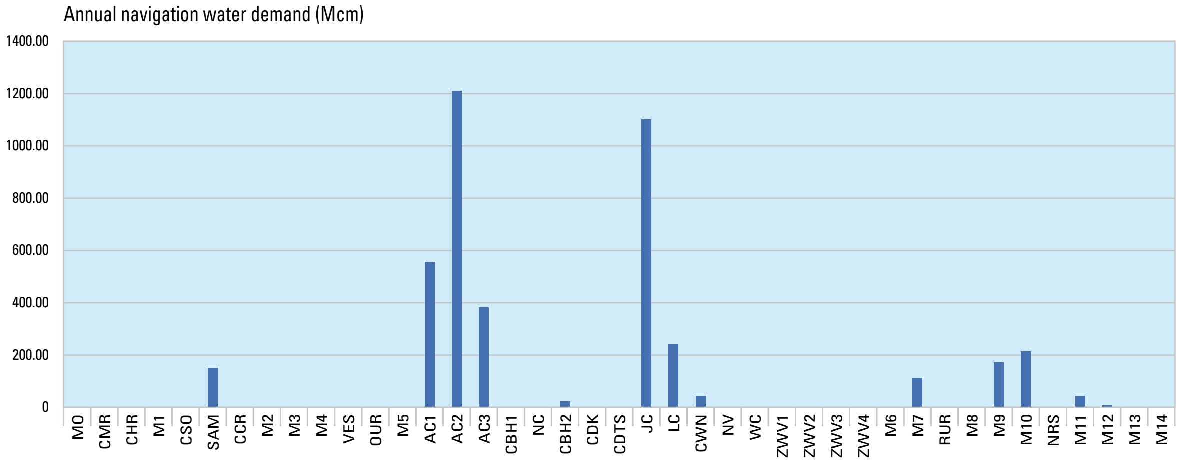


Source Deltares

Table 15 Annual navigation (lock losses) water demand per river and canal section (106 m^3)

River / canal	Section	Annual navigation water demand (106 m^3)
Sambre	Sam	157.68
Albert Canal	AC1	555.03
Albert Canal	AC2	1210.98
Albert Canal	AC3	378.43
Canal Bocholt-Herenthals (Kempisch)	CBH2	22.08
Canal Dessel-Turnhout-Schoten	CDTS	3.15
Juliana Canal	JC	1104.71
Lateraal Canal	LC	246.25
Canal Wessem-Nederweert	CWN	52.00
Meuse	M7	115.56
Meuse	M9	179.12
Meuse	M10	219.52
Meuse	M11	52.00
Meuse	M12	9.46
Meuse	M13	6.31
Total		4312.29

Figure 42 Annual average navigation water demand per river and canal section in downstream order (106 m^3).

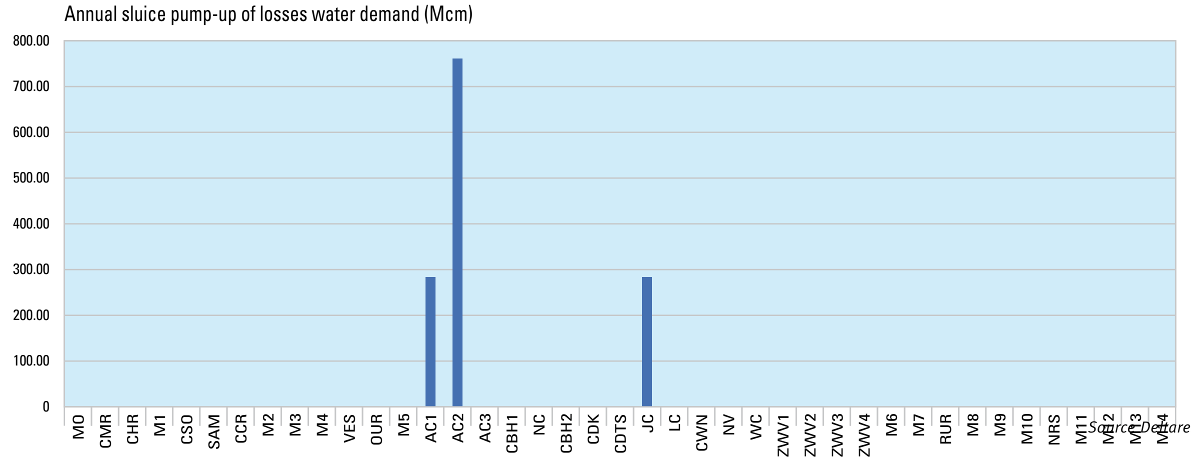


Source Deltares

Table 16 Annual average sluice pump-up of lock losses water demand per river and canal section (106 m^3)

River / canal	Section	Annual sluice pump-up of lock losses water demand (106 m^3)
Albert Canal	AC1	283.82
Albert Canal	AC2	756.86
Juliana Canal	JC	283.82
Total		1324.51

Figure 43 Annual average sluice pump-up of lock losses water demand per river and canal section in downstream order (106 m^3).

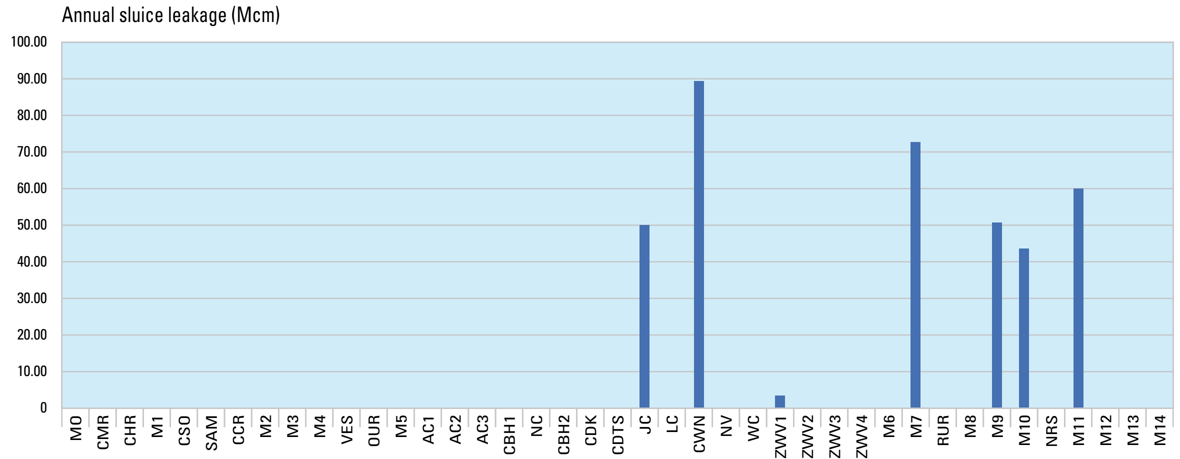


Source Deltares

Table 17 Annual sluice leakage per river and canal section (106 m^3)

River / canal	Section	Annual sluice leakage (106 m^3)
Juliana Canal	JC	50.46
Canal Wessem-Nederweert	CWN	89.31
Zuid-Willemsvaart	ZWV1	3.15
Meuse	M7	72.53
Meuse	M9	50.46
Meuse	M10	44.15
Meuse	M11	59.92
Total		369.98

Figure 44 Annual average sluice leakage per river and canal section in downstream order (106 m^3).

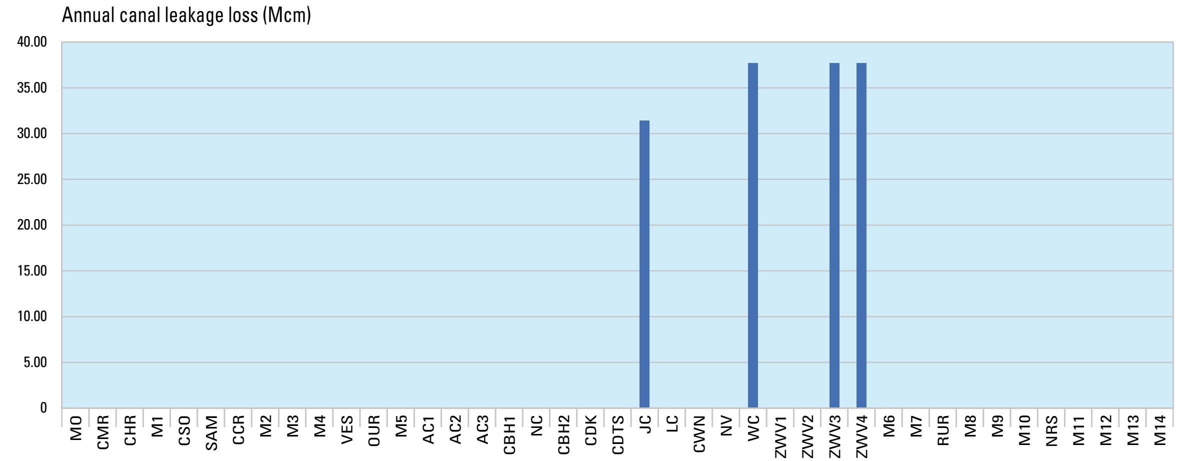


Source Deltares

Table 18 Annual canal leakage loss per river and canal section (106 m^3)

River / canal	Section	Annual canal leakage loss (106 m^3)
Juliana Canal	JC	31.56
Wilhelmina Canal	WC	37.87
Zuid-Willemsvaart	ZWV3	37.87
Zuid-Willemsvaart	ZWV4	37.87
Total		145.17

Figure 45 Annual average canal leakage loss per canal section in downstream order (106 m^3).

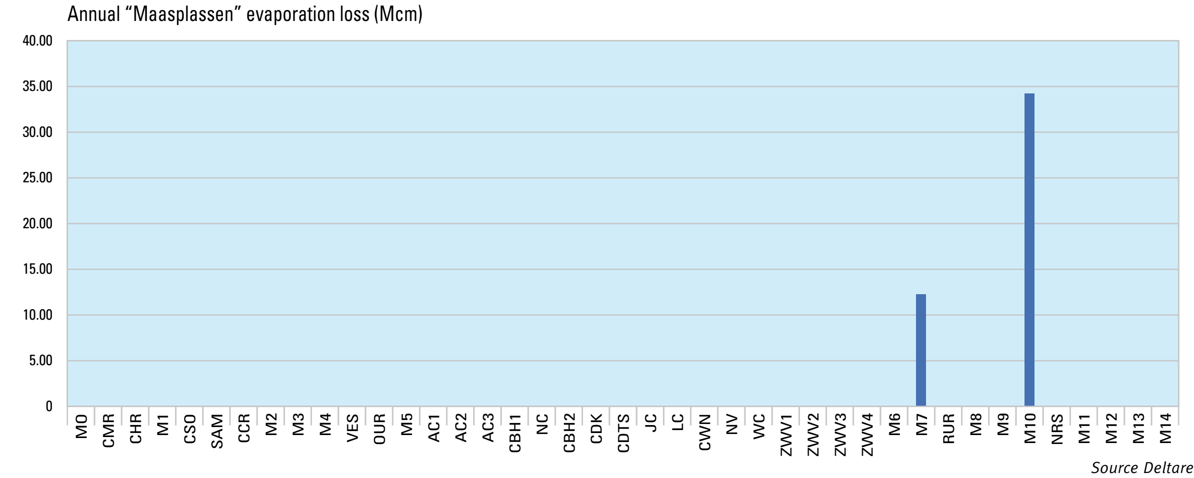


Source Deltares

Table 19 Annual average “Maasplassen” evaporation loss per river and canal section (106 m^3)

River / canal	Section	Annual “Maasplassen” evaporation loss (106 m^3)
Meuse	M7	12.17
Meuse	M10	34.03
Total		46.20

Figure 46 Annual average “Maasplassen” evaporation loss per river and canal section in downstream order (106 m^3)

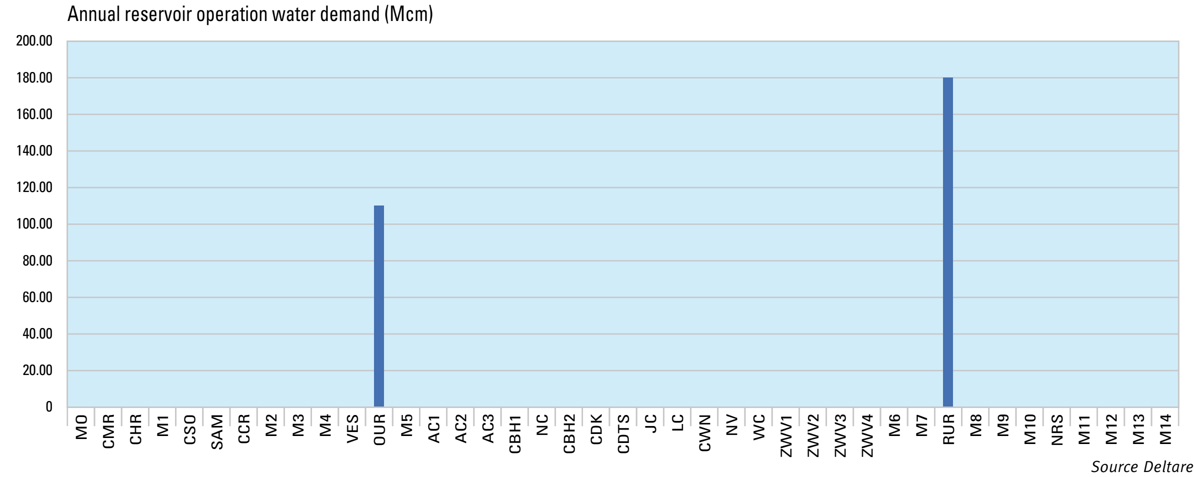


Source Deltares

Table 20 Annual average reservoir operation target release per river and canal section (106 m^3)

River / canal	Section	Annual reservoir operation water demand (106 m^3)
Ourthe	Our	110.38
Rur	Rur	179.76
Totaal		290.13

Figure 47 Annual average reservoir operation target release per river and canal section in downstream order (106 m^3)

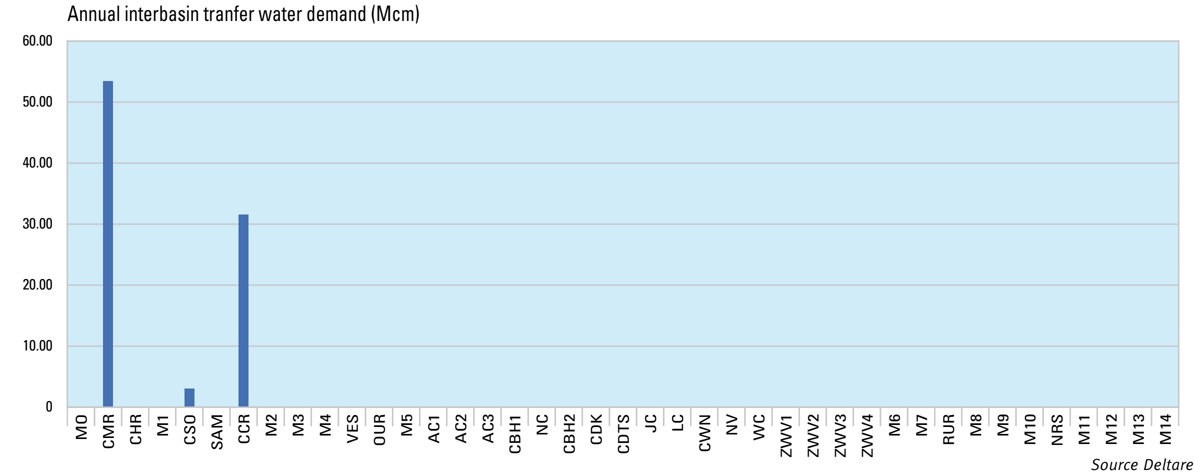


Source Deltares

Table 21 Annual inter-basin transfer water demand per river and canal section (106 m^3)

River / canal	Section	Annual inter-basin transfer water demand (106 m^3)
Canal Marne Au Rhin Ouest	CMR	53.61
Canal de la Sambre l’Oise	CSO	3.15
Canal Charleroi - Bruxelles	CCB	31.54
Total		88.30

Figure 48 Annual average inter-basin transfer water demand per river and canal section in downstream order (106 m^3)



Source Deltares

Table 22 Annual International agreement water demand per river and canal section (106 m^3)

River / canal	Section	Annual water demand (106 m^3)
Meuse (Chooz)	M1	630.72
Meuse (Common Meuse)	M6	315.36
Total		946.08

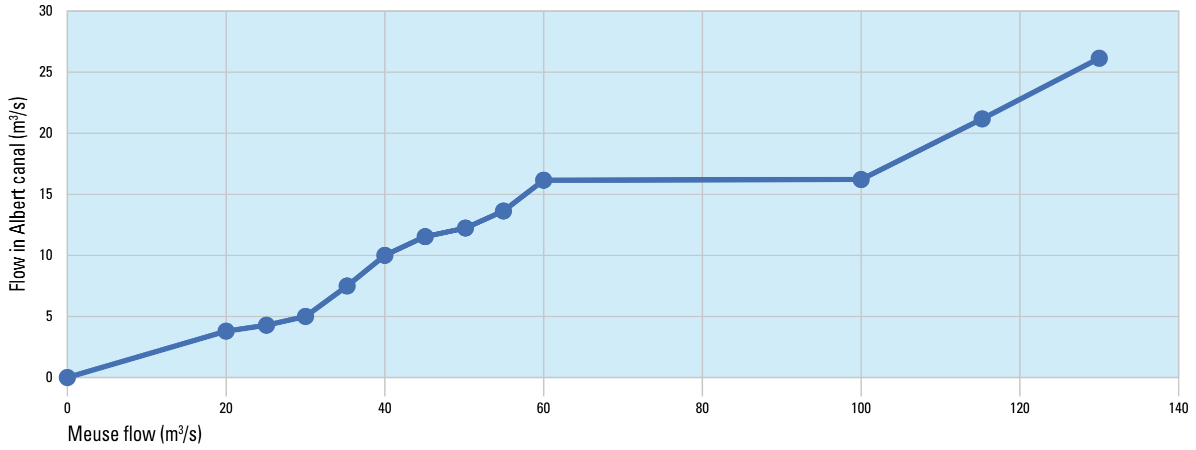
Table 23 The extreme dry year increased water loss and use for year 2018, 2019 and 2020 in Meuse section M9 near Venlo recording station (106 m^3).

Year	Annual extreme dry year increased water loss and use (106 m^3)
2018	44.07
2019	51.11
2020	52.14

4.3.3.5 Water distribution at bifurcations canals

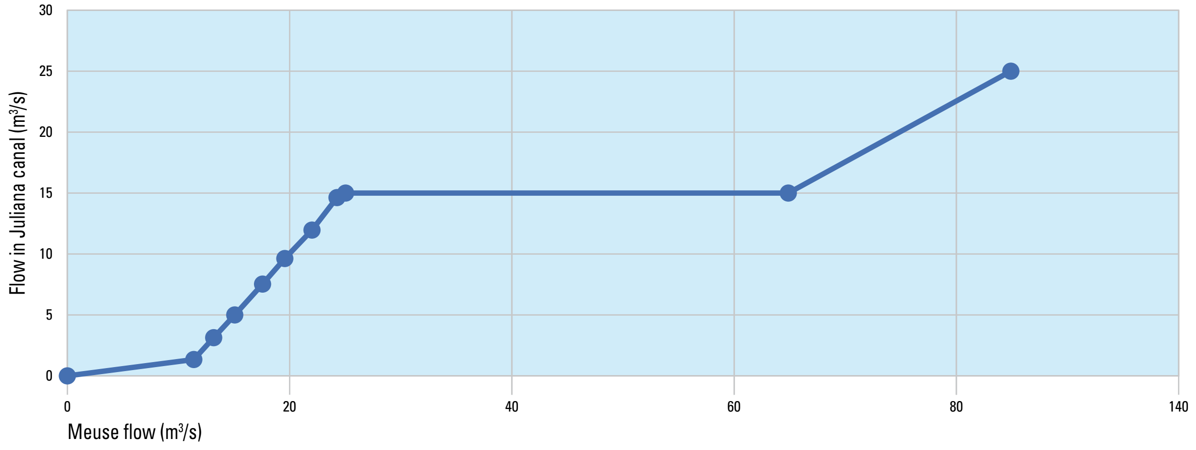
The river-canal network of the Meuse catchments contains bifurcations. At a bifurcation the distribution of flow over the bifurcation links is modelled with a relation between the upstream link flow and the bifurcated link flow. The relations for the Albert canal, the Juliana canal, the Lateral Canal and the Zuid-Willemsvaart are shown in Figure 49 till Figure 52. These relations account for operational practice and the international agreements, in particular the “Maasafvoerverdrag” on the distribution of water between the Albert Canal, the Common Meuse and the Juliana Canal (Table 22).

Figure 49 Relation between Meuse flow and bifurcated flow of Albert canal (m³/s).



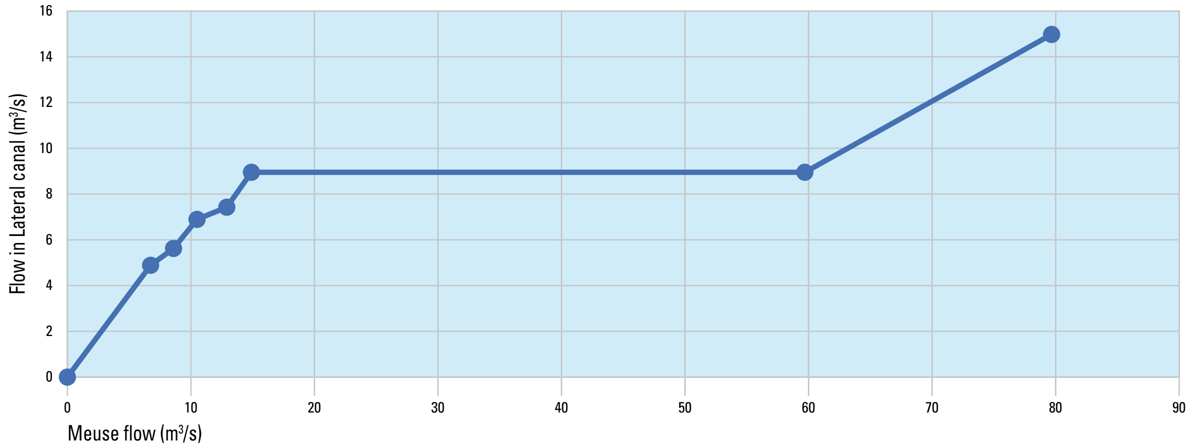
Source Deltares

Figure 50 Relation between Meuse flow and bifurcated flow of Juliana canal (m³/s).



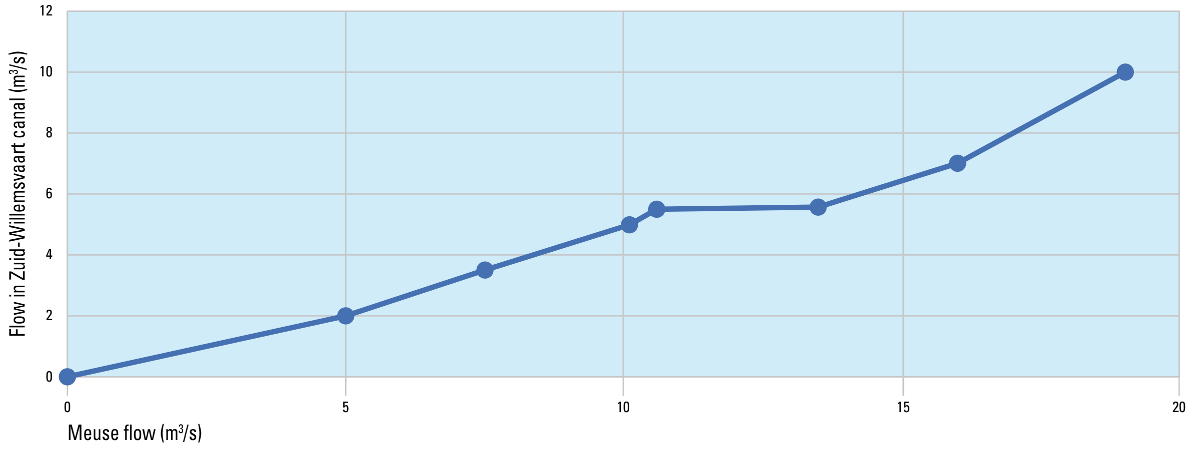
Source Deltares

Figure 51 Relation between Meuse flow and bifurcated flow of lateral canal (m³/s).



Source Deltares

Figure 52 Relation between Meuse flow and bifurcated flow of Zuid-Willemsvaart (m³/s).



Source Deltares

4.3.3.6 User defined flow components

RIBASIM computes the flow composition by defining user defined flow components. In order to analyse the flow composition of Meuse water, a basic water quality and flow composition (Lookup) scenario M02 has been set up. The flow components are listed in Table 24. The flow from each major tributary is defined as a flow component. Each flow component includes the runoff, the drainage and return flow from water usages. This means for example that the return flow from the cooling water node Tihange is labelled as “Meuse Belgium”.

Table 24 Overview of the user defined flow components in scenario Mo2.

Country	Id	Flow component name
France	2	Chiers
	11	Semois
	13	Viroin
	5	Meuse France
Belgium	3	Lesse
	10	Sambre
	8	Ourthe
	1	Ambleve
	12	Vesdre
	4	Meuse Belgium
Netherlands	9	Rur
	7	Niers
	6	Meuse Netherlands

4.3.4 Scenarios, measures and strategies

As described in chapter 3.5, various scenarios, measures and strategies can be simulated with RIBASIM. Presently, the model contains one hydrological scenario that represents the current situation (the base case) and ten climate change (CC) scenarios.

The hydrological scenario “W81” is named “Actualised LHM and Wflow timeseries Wflow Run 5 1962 - 2020 used 1980 - 2020”. This scenario includes the Wflow model results runoff, rainfall and open water evaporation and represents the historical water availability for the years from 1980 to 2020 (41 years). The scenario also includes the historical water demand and discharge from the DPZW regions computed by the LHM. We use this scenario as base case.

The ten climate change scenarios define a reduction of the inflow time series in the hydrological scenario “W81”, but the rainfall, evaporation, loss, demand and other discharge values are left unchanged. These climate change scenarios represent the years 2050 and 2085 under the five KNMI climate change scenarios (Table 25). Table 26 contains more details on the background of these scenarios.

Table 25 KNMI climate change scenarios

KNMI scenario	Target years
GH	2050, 2085
GL	2050, 2085
WH	2050, 2085
WHdry	2050, 2085
WL	2050, 2085

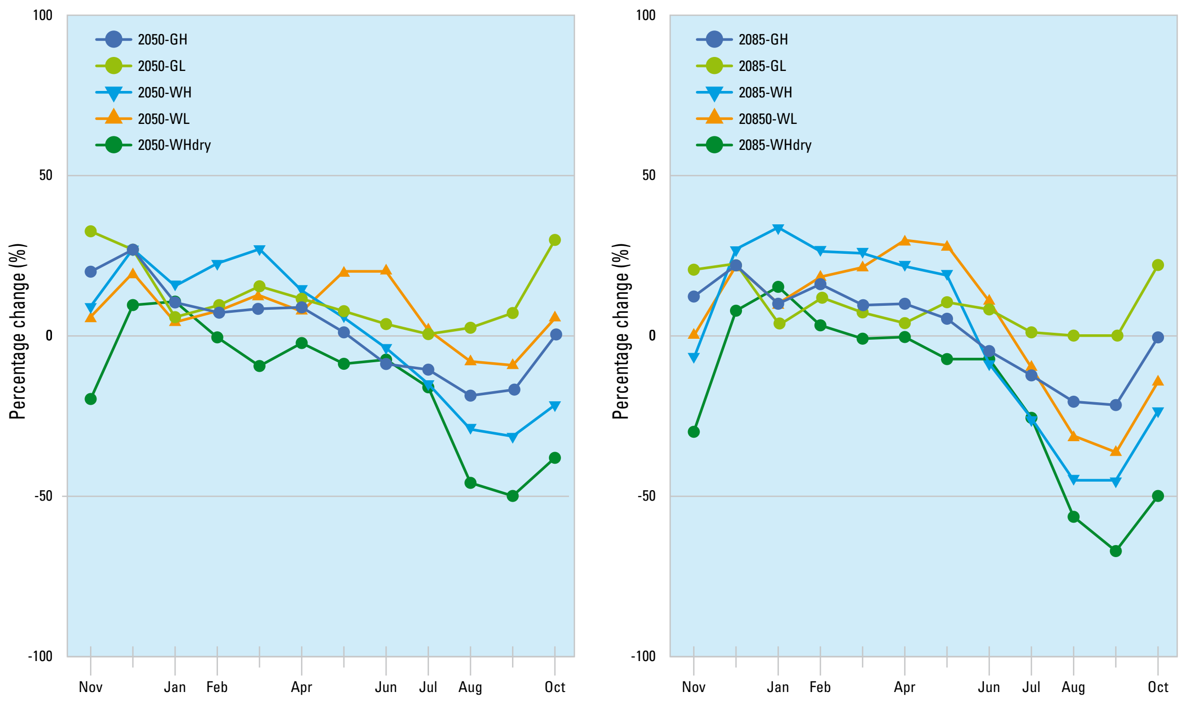
Table 26 Background of the KNMI ’14 climate change scenarios (in brackets information in Dutch)

KNMI scenario		Temperature rise 2050/2085
W	Warm (warm)	2/3.5°C
G	Moderate (gematigd)	1/1.5°C
L	No change in air current (luchtstroom)	
H	More high pressure during summer and low pressure during winter	
dry	Large scale drought during summer	

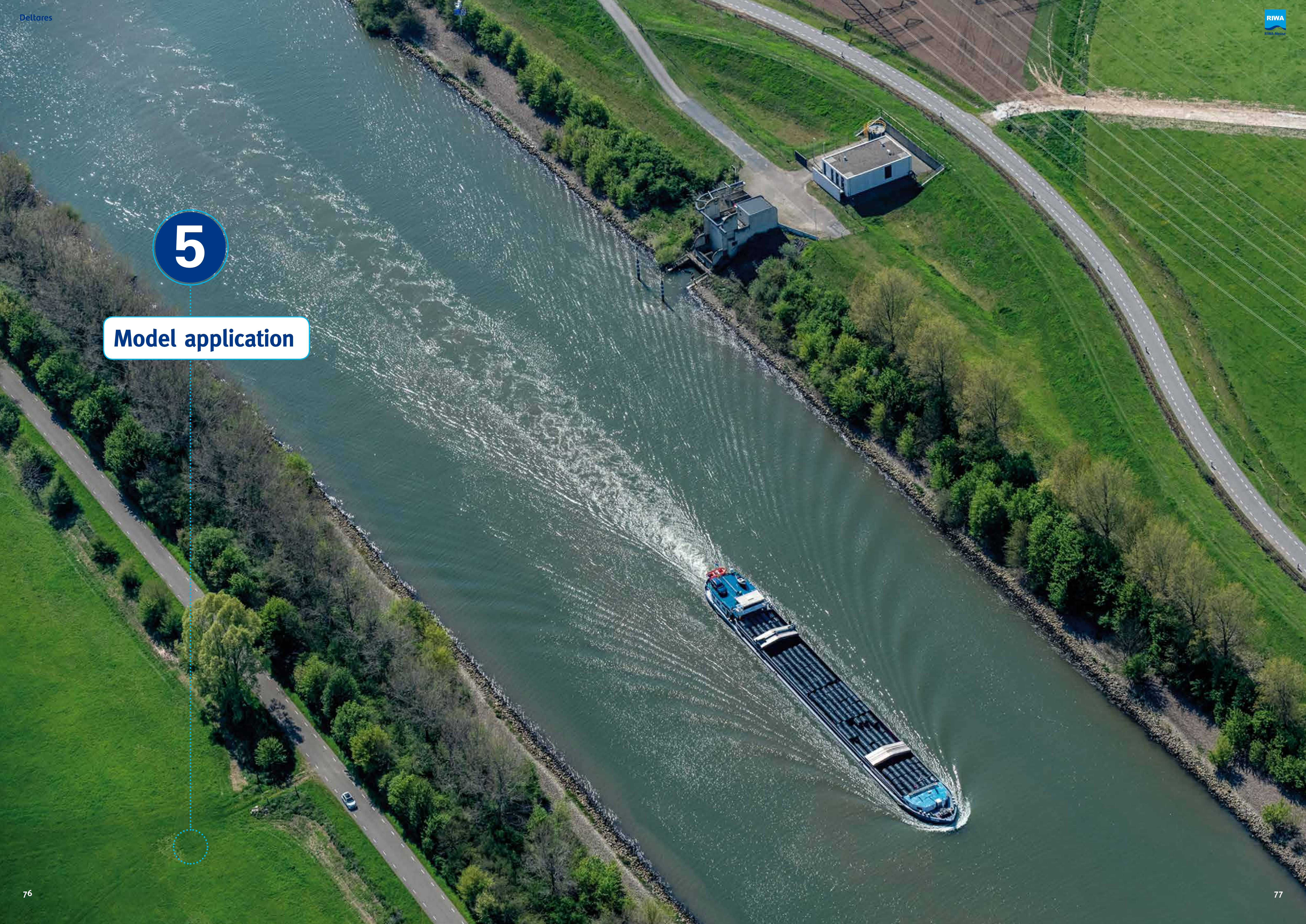
The scenario “WHdry” is the most extreme scenario of five KNMI scenarios. It represents a worst-case scenario. Klijn et al. 2015 expect a reduction of the average low flow by 45 % in 2050 and by 60 % in 2085 under WHdry conditions.

The climate change scenarios have been created by applying the climate change factors for the inflow time series after Klijn et al. 2015 to the Hydrological scenario “W81”. The simulation of the climate change scenarios illustrates the potential of the model for this study. Figure 53 shows two graphs with the percentage of increase and decrease of the inflow (runoff) per time step. The change is mostly positive in the winter (more water) and negative in the summer (less water). Narratively, one could express the basic idea of the scenario runs like “as if the last 41 years virtually take place under 2050 or 2085 conditions, respectively”.

Figure 53 The percentage increase and decrease of the inflow (runoff) per time step for the five climate change scenarios for target years 2050 and 2085 for location Borgharen (Klijn et al. 2015).



Source Deltares



5

Model application

5.1 Model reliability

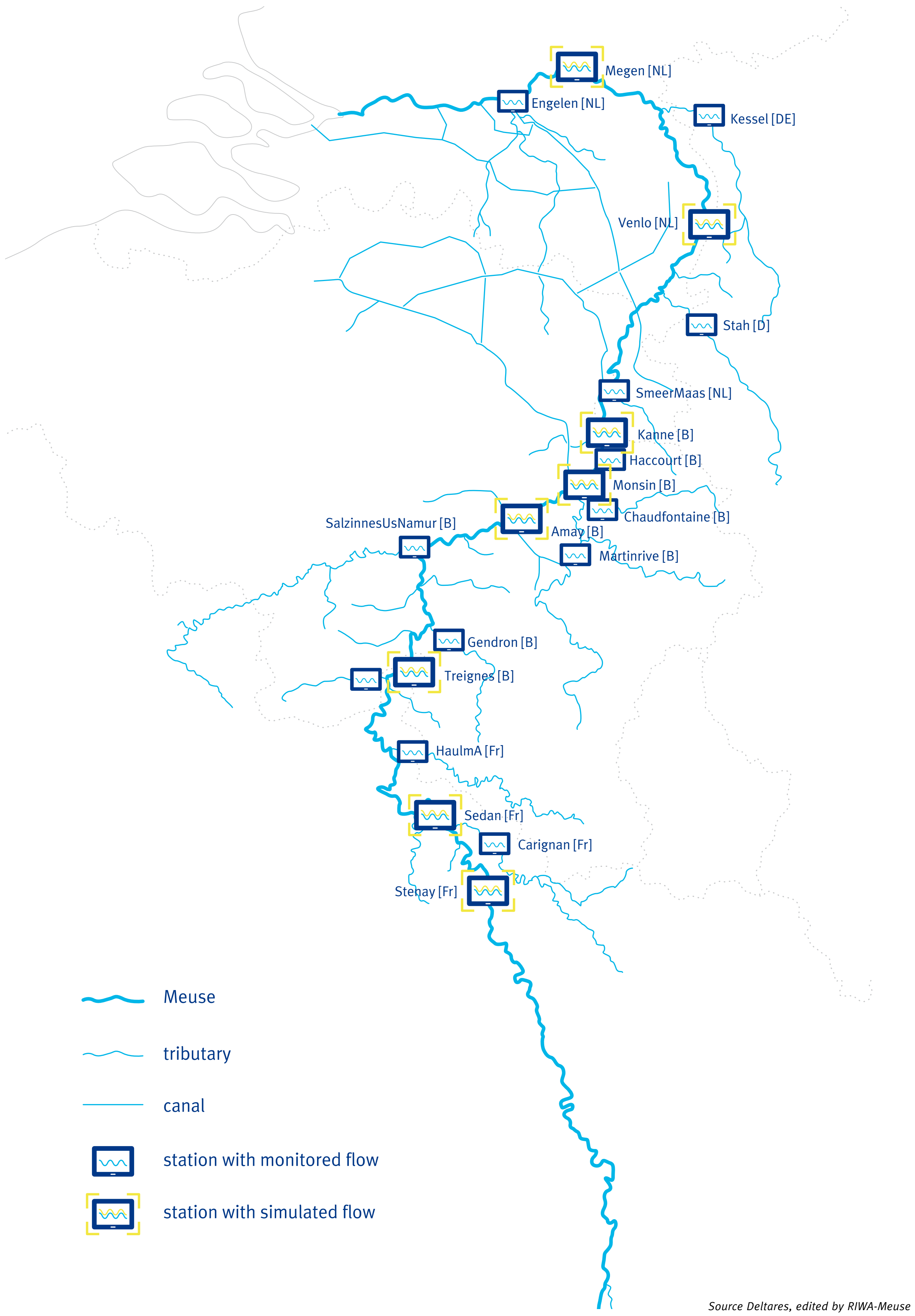
In order to assess the reliability of the model, simulated discharges have been compared to measured discharges from gauging (recording, monitoring) stations along the Meuse. Recording nodes have been introduced into the RIBASIM model which represent the gauging stations for this purpose. Table 27 shows the list of gauging stations which correspond with the stations used in sub-project A (Kramer 2021). Figure 54 shows the locations of the stations on the main Meuse river for which the simulated and monitored flow are compared.

Figure 55 to Figure 62 show the hydrographs of the stations for the period 1998 to 2020. The graphs for the whole period show a good match between the measured and simulated series for the locations along the mainstream. The match between observed and simulated values is not the same for all stations: for stations Stenay and Sedan the simulated results match less good than further downstream at Chooz and Monsin. However, in her upstream part, the Meuse has a comparatively small discharge, and discharge is mainly dominated by the hydrological inflow here. Given the good match at Chooz and Monsin, we consider the accuracy sufficient though.

Table 27 List of gauging station of sub-project A and its location in downstream order.

	Location	River / canal
1	Stenay	Meuse
2	Carignan	Chiers
3	Sedan	Meuse
4	Haulme	Semois/La Semoy
5	Treignes	Viroin
6	Chooz	Meuse
7	Gendron	Lesse
8	Salzinnes Ronet	Sambre
9	Amay	Meuse
10	Tabreux	Ourthe
11	Martinrive	Ambleve
12	Chaudfontaine Pisc	Vesdre
13	Monsin	Meuse
14	Haccourt	Albertkanaal
15	Kanne	Albertkanaal
16	Eijsden	Meuse
17	Smeermaas	Zuid Willemsvaart
18	Bunde	Julianakanaal
19	Stah	Rur
20	Venlo	Meuse
21	Kessel	Niers
22	Megen	Meuse
23	Engelen	Dieze

Figure 54 Location of the stations on the Meuse main river for which the simulated and monitored flows are presented in a graph (at yellow arrows).

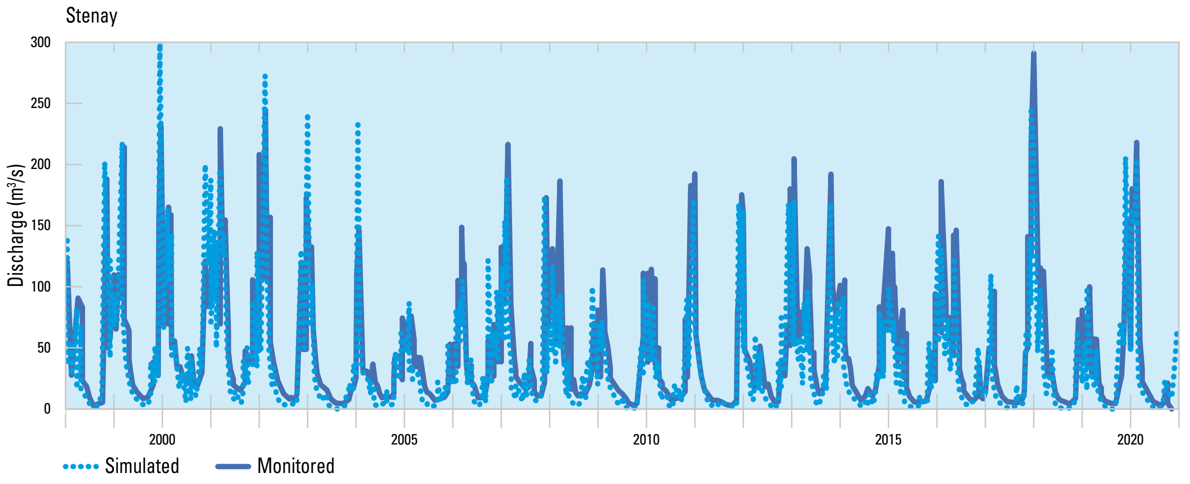


Source Deltares, edited by RIWA-Meuse

Figure 63 to Figure 65 show simulated and monitored discharged for the dry period from 2017 till 2020 and stations Chooz, Monsin and Megen. Figure 66, Figure 67 and Figure 68 zoom further into the low flow periods of these graphs. For Chooz and Monsin simulated and observed flows match well for the summer period. Note that a good match between monitored flow and simulated flow at Megen could not be achieved without adding an additional time series that accounts for unknown water usage and water losses during the exceptional dry years of 2018, 2019 and 2020 (Appendix C.7.15).

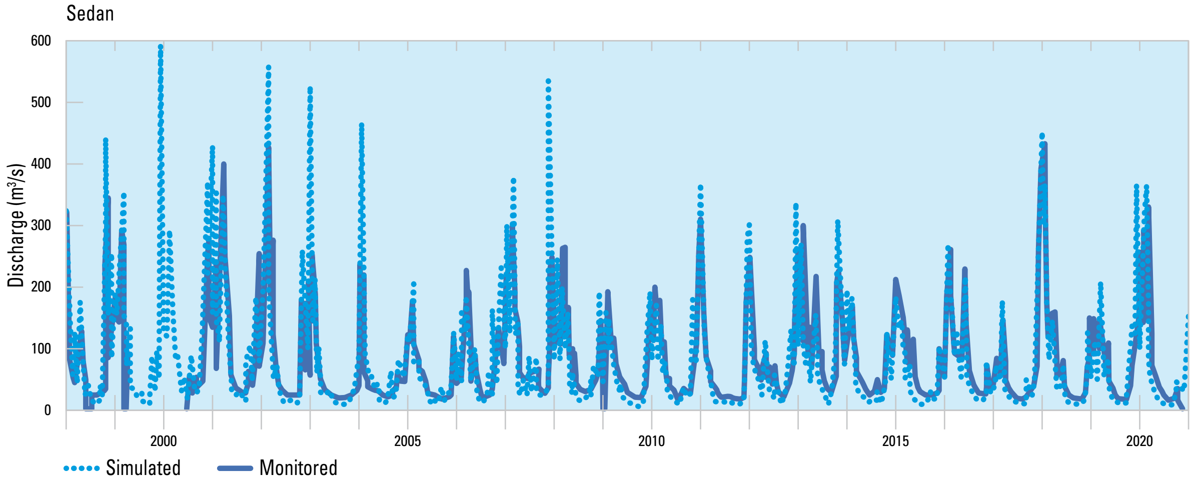
Figure 69, Figure 70 and Figure 71 compare monitored and simulated flow of the Niers for station Kessel. The Wflow runoff from the Niers has been corrected (see chapter 4.3.3.1), but still the simulated discharge is higher than the monitored flow during low flow periods. The model does not have any water usage objects for the Niers River basin. It is possible that water users are present in the Niers river basin that are unknown for this study, and that these water users have increased the water consumption during the dry period. For completeness, Figure 72 and Figure 73 show the discharge at station Stah (Germany) in the Rur. As explained in Section 4.3.2, the monitored flow time series of recording station Stah has been set as inflow boundary condition. Monitored flow is identical with simulated flow for this station, so only the simulated flow is presented in the figures.

Figure 55 Simulated and monitored decade flows at gauging station Stenay (France) from 1998 to 2020.



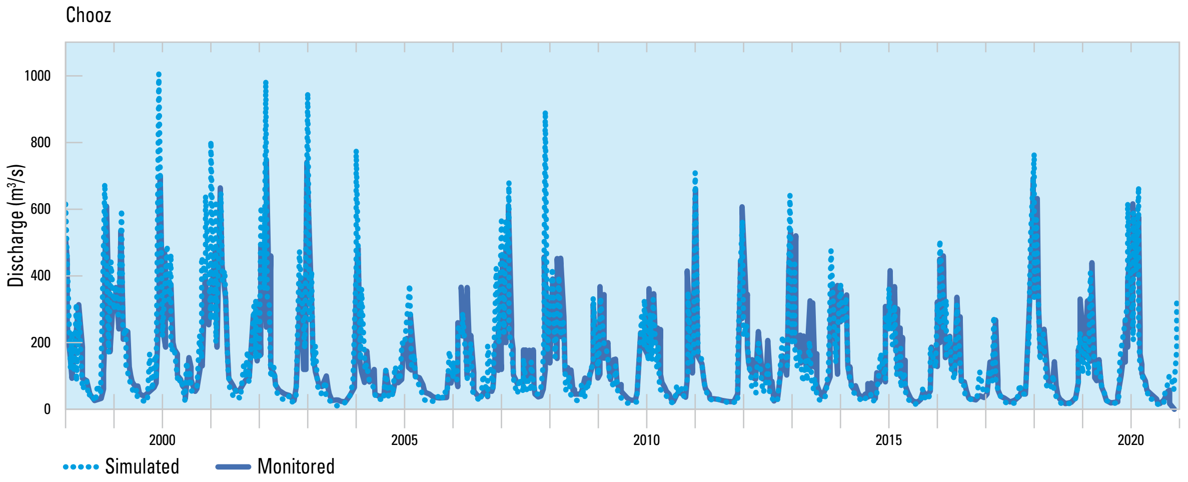
Source Deltares

Figure 56 Simulated and monitored decade flows at gauging station Sedan (France) from 1998 to 2020.



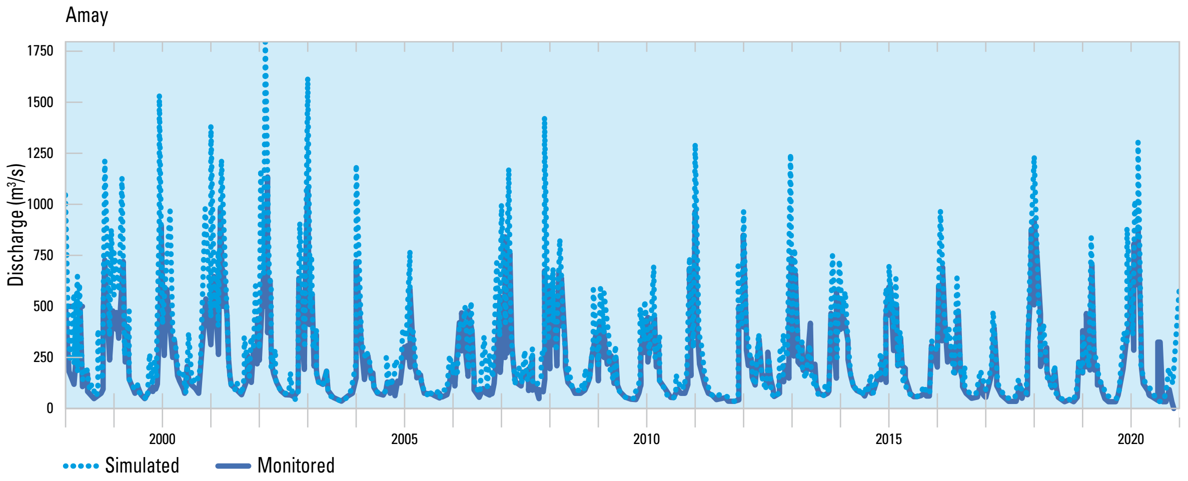
Source Deltares

Figure 57 Simulated and monitored decade flows at gauging station Chooz (France) from 1998 to 2020.



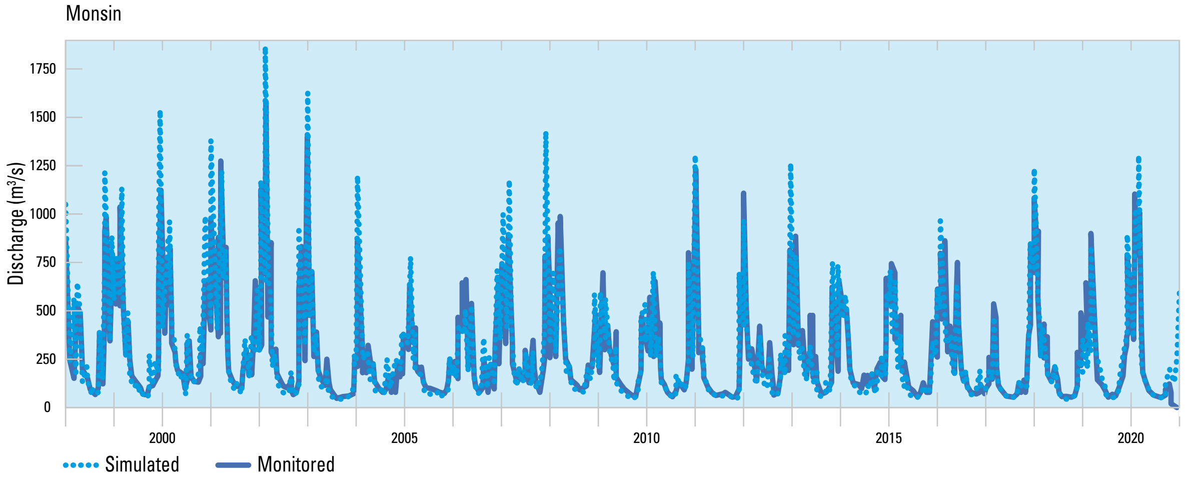
Source Deltares

Figure 58 Simulated and monitored decade flows at gauging station Amay (Belgium) from 1998 to 2020.



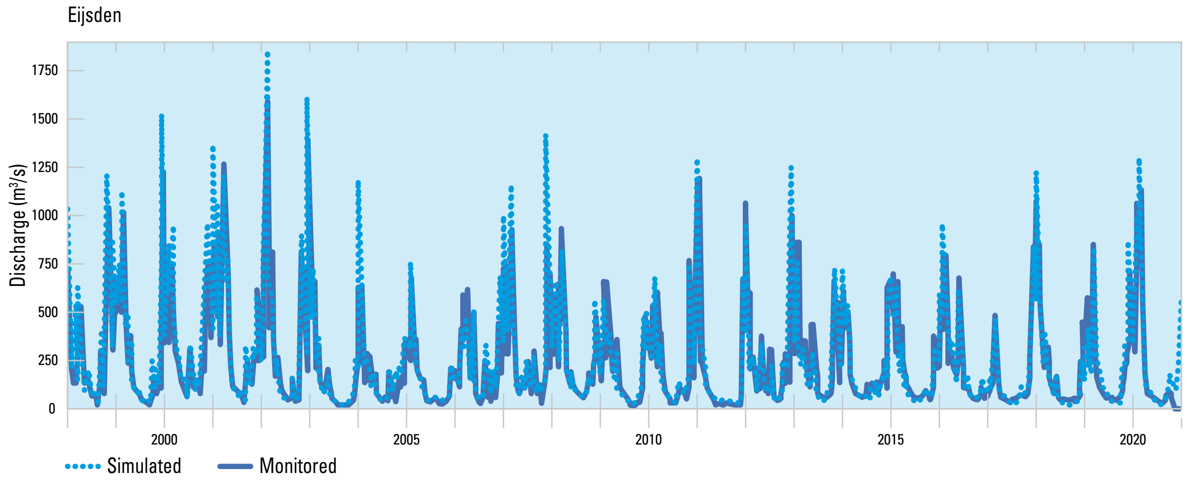
Source Deltares

Figure 59 Simulated and monitored decade flows at gauging station Monsin (Belgium) from 1998 to 2020.



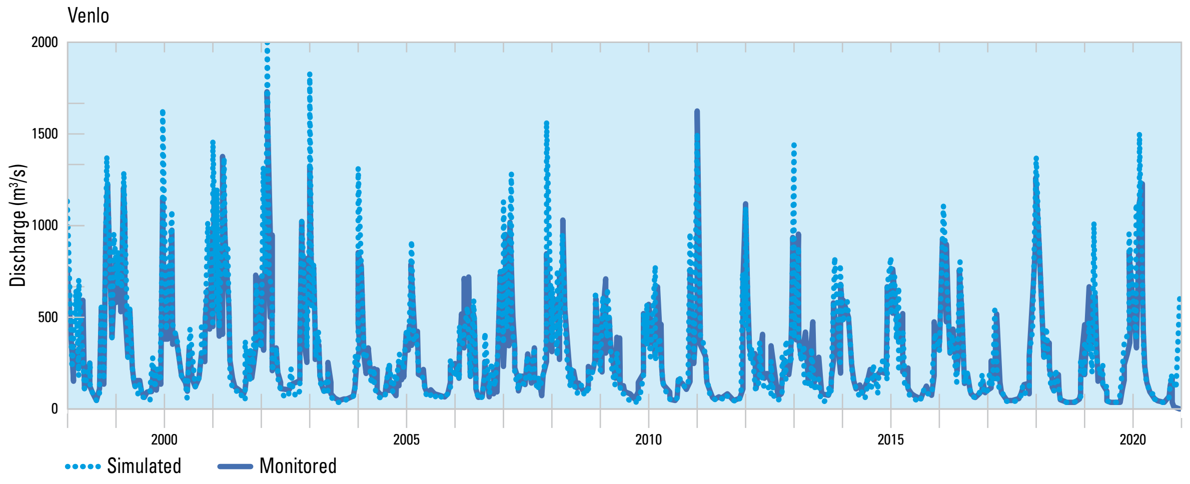
Source Deltares

Figure 60 Simulated and monitored decade flows at gauging station Eijsden (Netherlands) from 1998 to 2020.



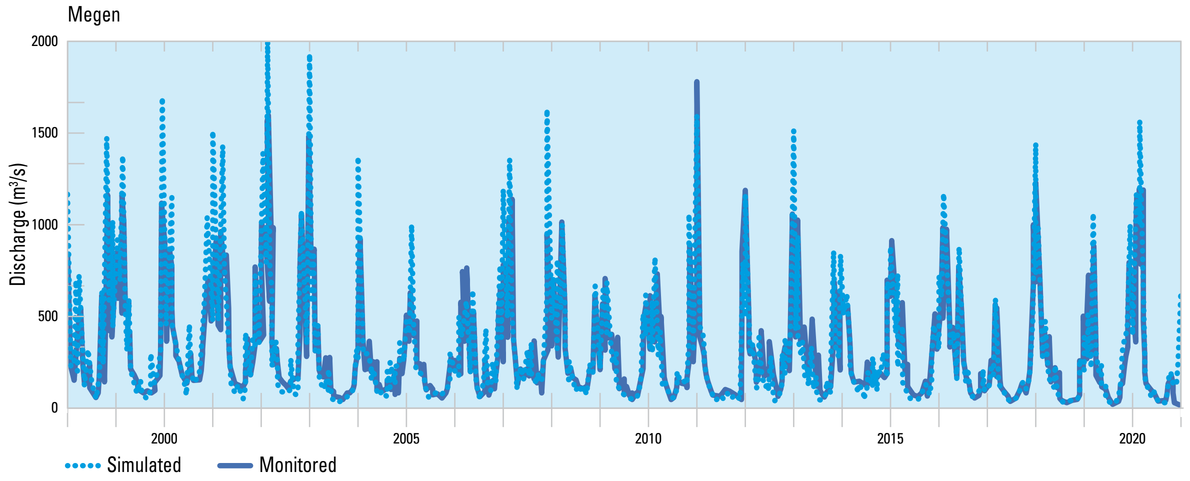
Source Deltares

Figure 61 Simulated and monitored decade flows at gauging station Venlo (Netherlands) from 1998 to 2020.



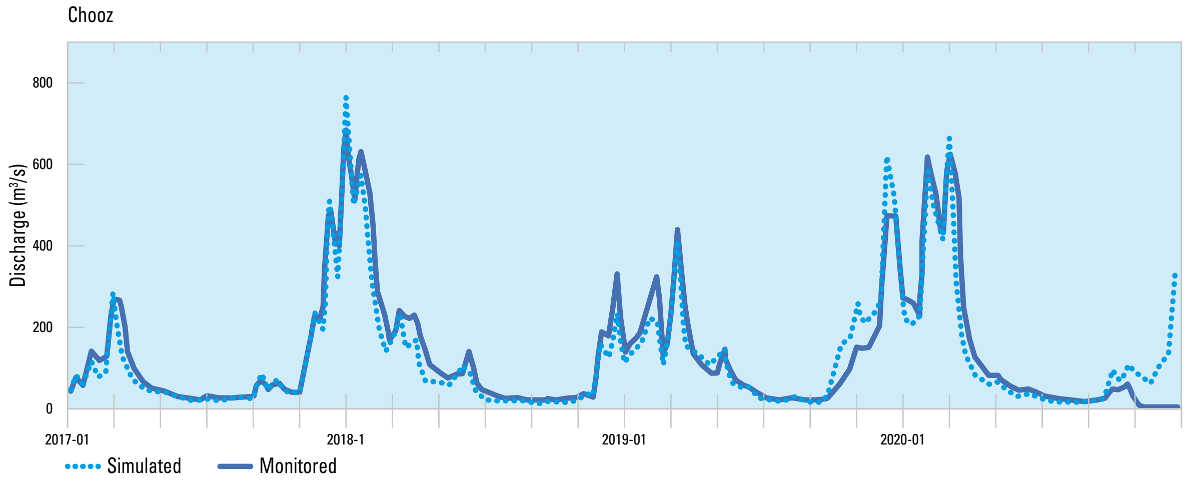
Source Deltares

Figure 62 Simulated and monitored decade flows at gauging station Megen (Netherlands) from 1998 to 2020.



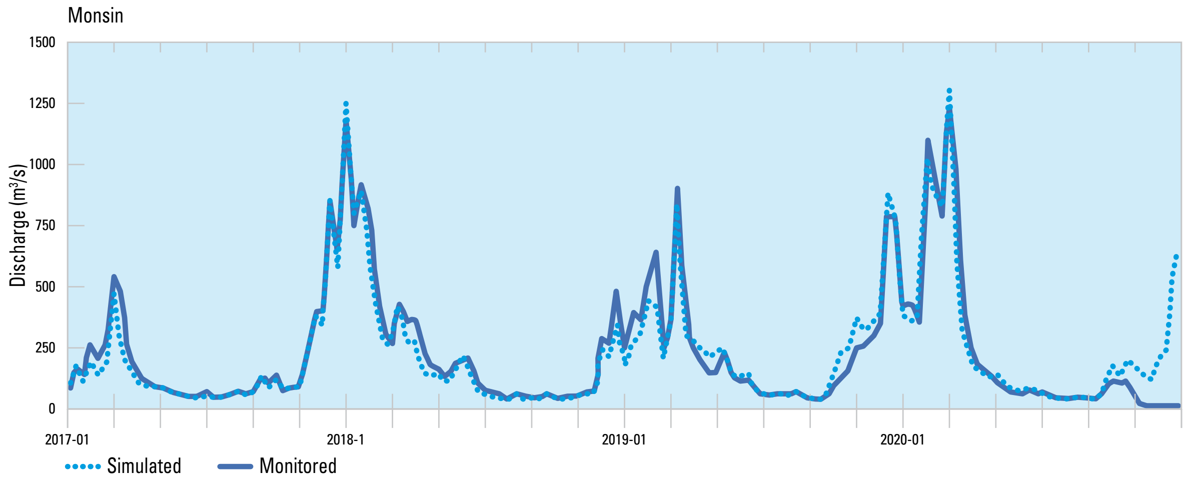
Source Deltares

Figure 63 Monitored and simulated flow at station Chooz for period 2017 to 2020.



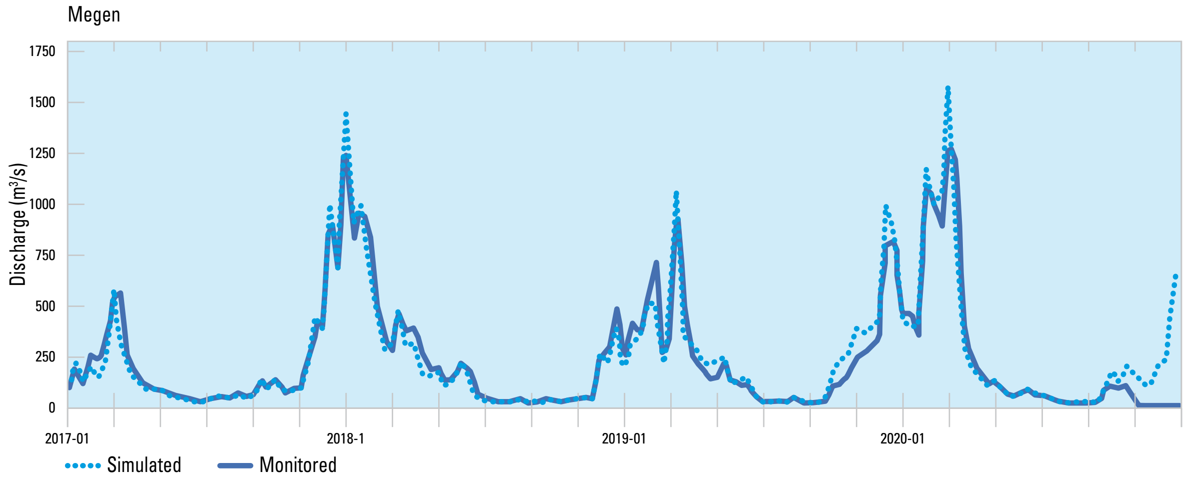
Source Deltares

Figure 64 Monitored and simulated flow at station Monsin for period 2017 to 2020.



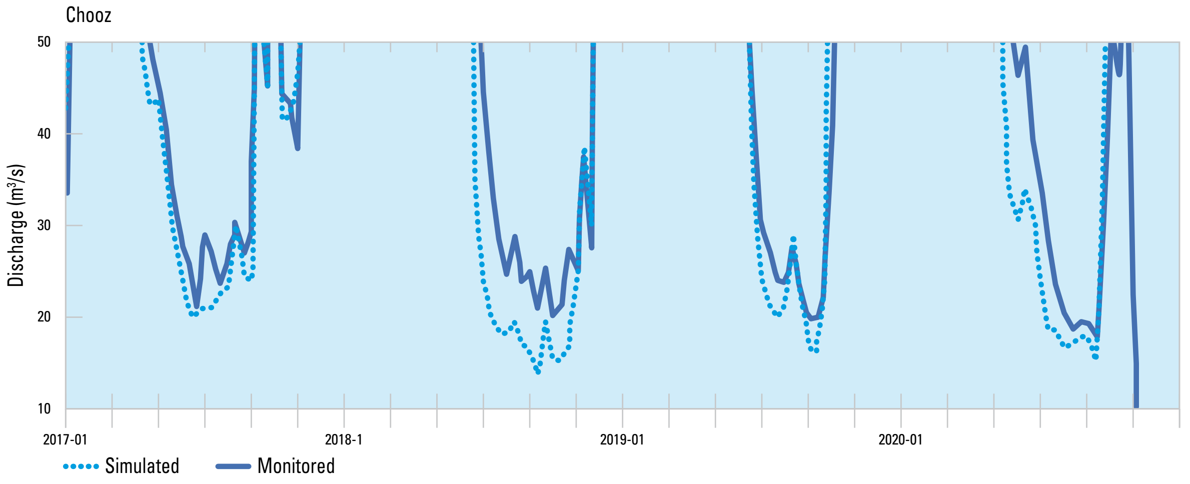
Source Deltares

Figure 65 Monitored and simulated flow at station Megen for period 2017 to 2020.



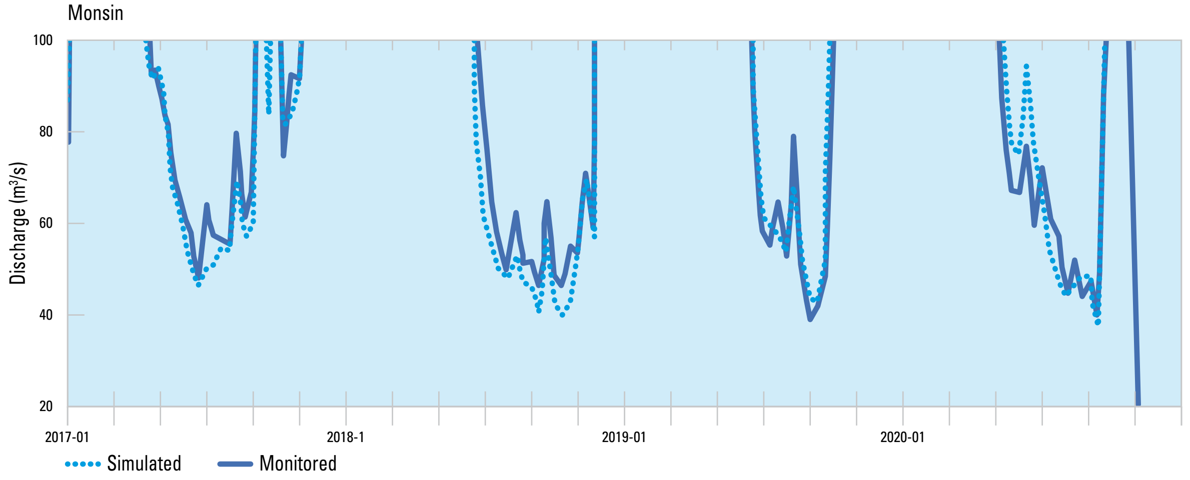
Source Deltares

Figure 66 Low flow close-up to monitored and simulated flow for Chooz station from 2017-2020.



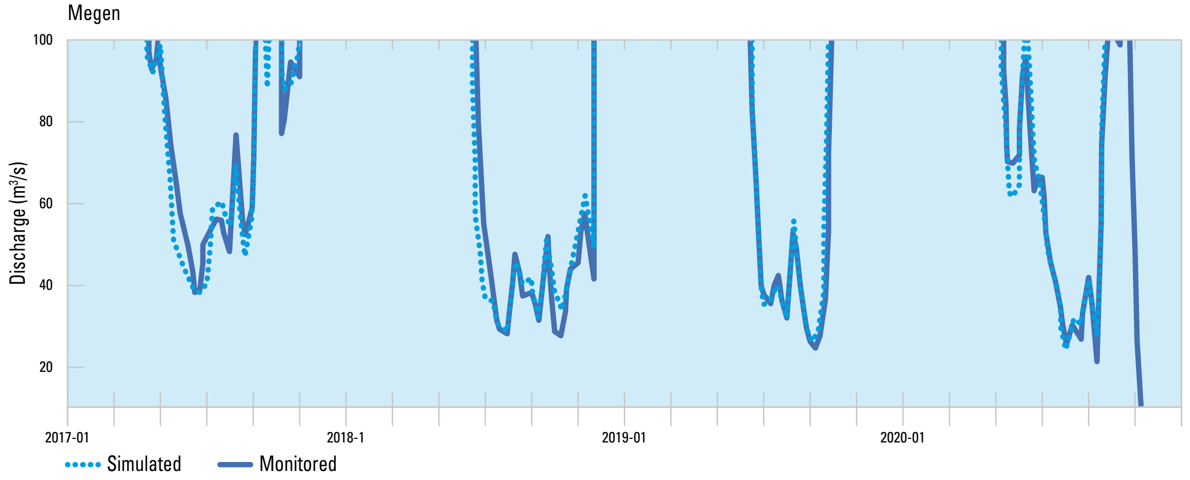
Source Deltares

Figure 67 Low flow close-up to Monitored and simulated flow for Monsin station from 2017-2020.



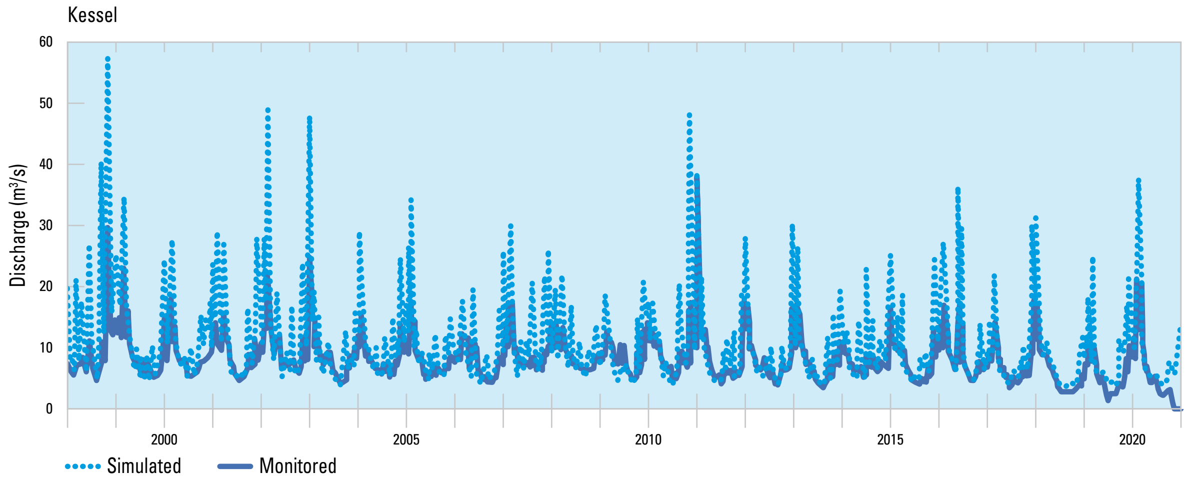
Source Deltares

Figure 68 Low flow close-up to monitored and simulated low flow graphs for Megen station from 2017-2020



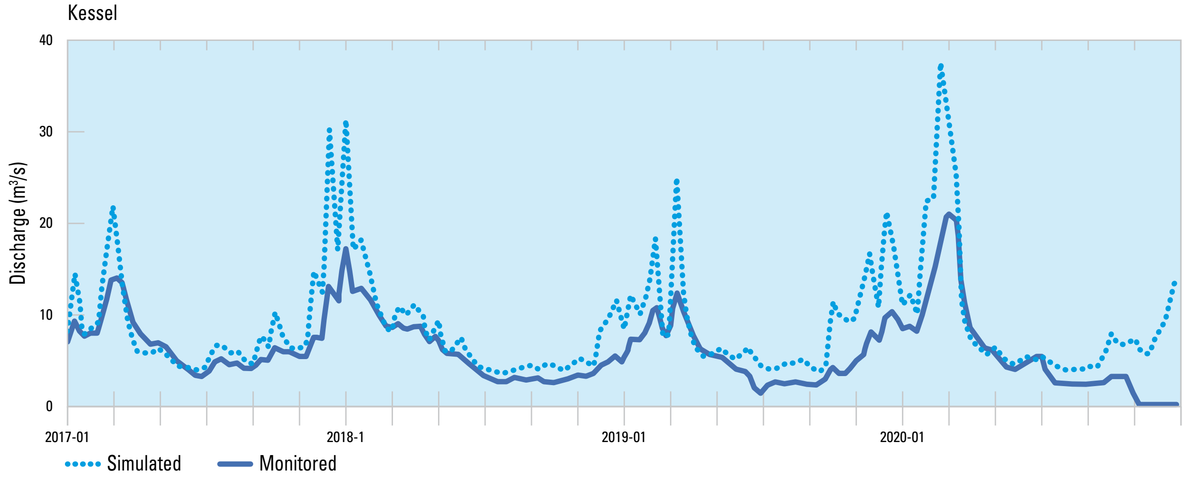
Source Deltares

Figure 69 Simulated and monitored decade flows at gauging station Kessel (Germany) from 1998 to 2020.



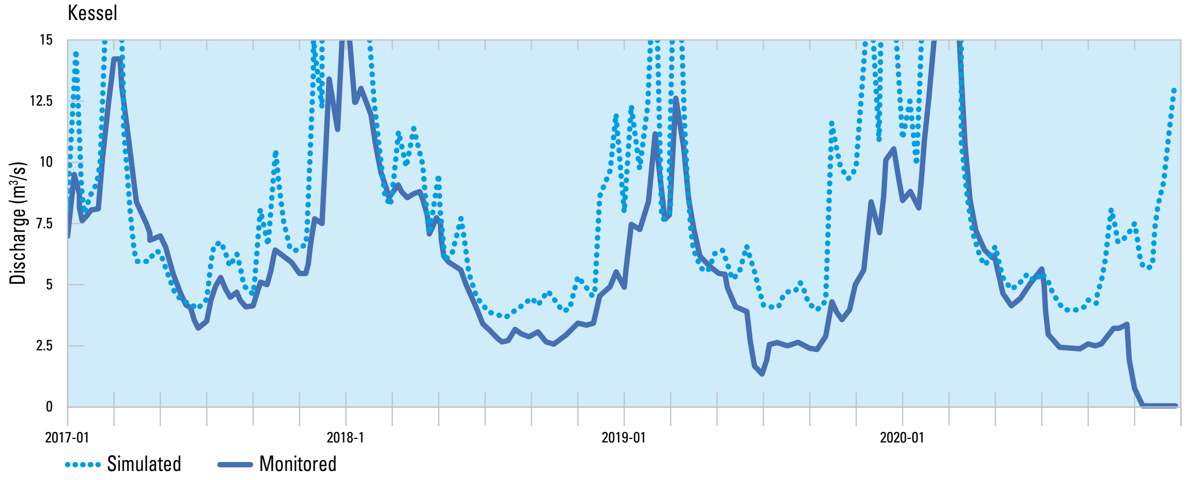
Source Deltares

Figure 70 Monitored and simulated flow at station Kessel for period 2017 to 2020



Source Deltares

Figure 71 Low flow close-up to monitored and simulated low flow graphs for Kessel station from 2017-2020.



Source Deltares

Figure 72 Simulated decade flows at gauging station Stah (Germany) from 1998 to 2020.

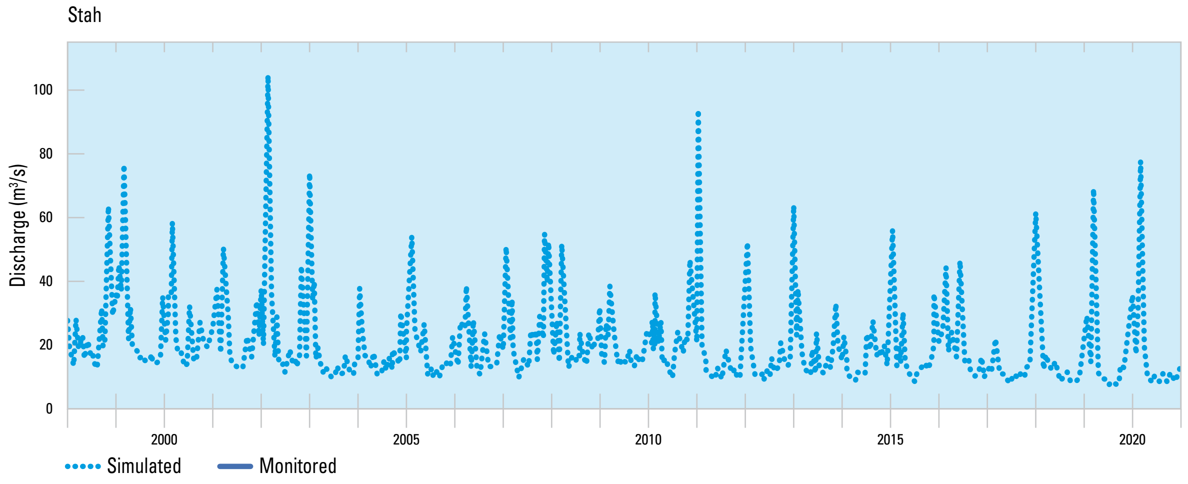


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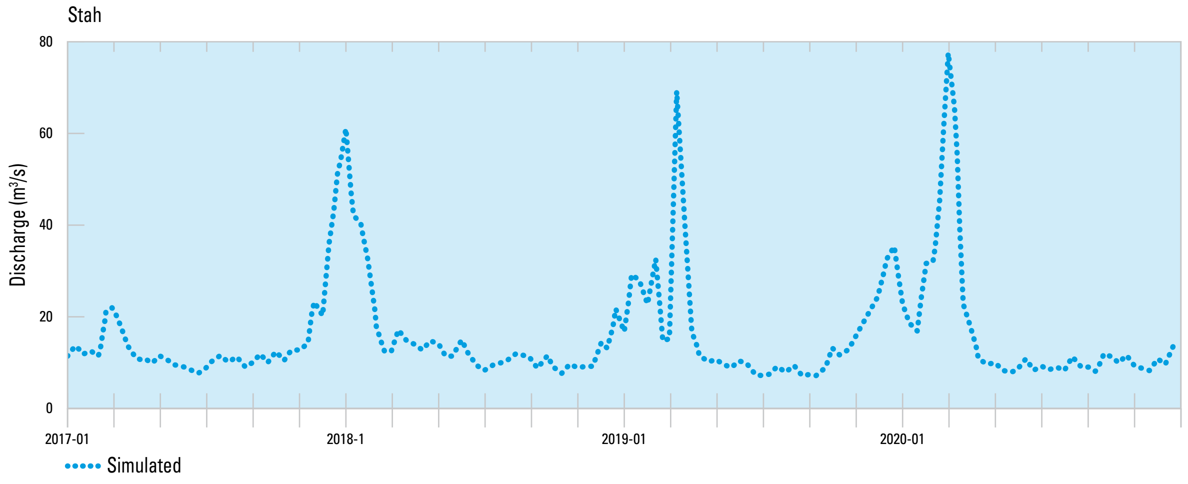
Figure 73 Low flow close-up to simulated low flow graphs for Stah station from 2017-2020.



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5.2 Base case and future scenarios

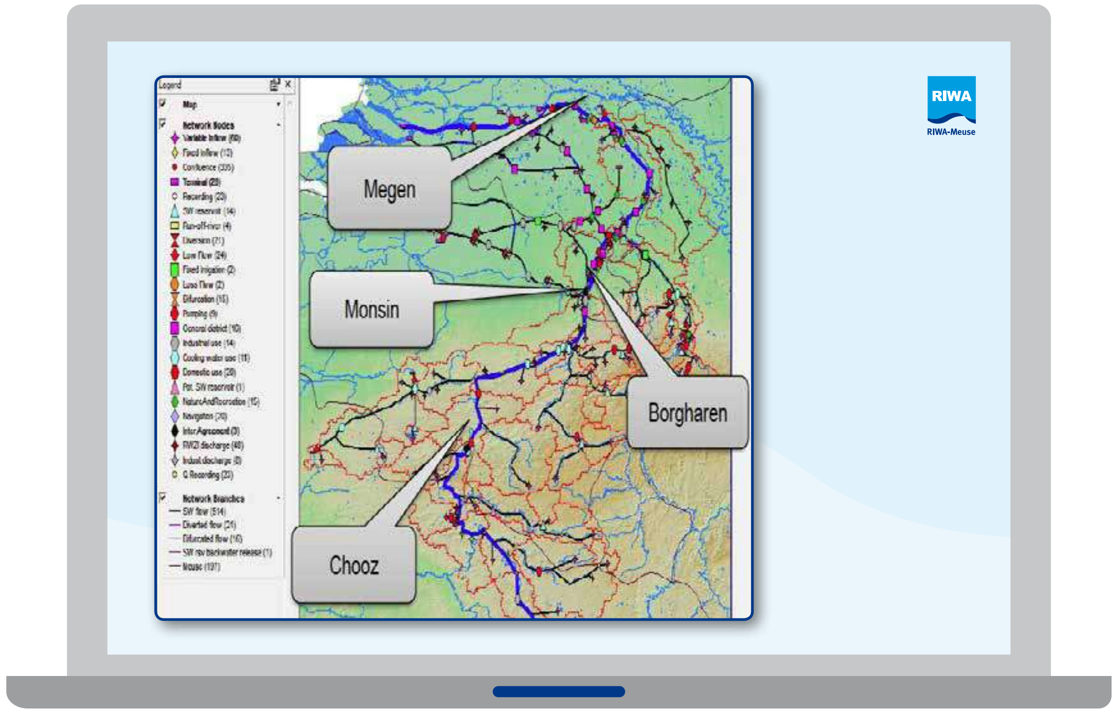
5.2.1 Introduction

In this section the results of the eleven simulation cases that have been run with the model are presented. These scenarios account for the impact of climate change on the hydrological inflow to the Meuse as explained in Section 4.3.4. Table 28 gives an overview on the scenarios.

Table 28 Overview of the 11 simulation cases.

Case name	Characteristics
BC2020	Base case 2020 representing the present situation
BC2020 + CC 2050-GH	Base case 2020 with inflow change due to CC scenario “GH for year 2050”
BC2020 + CC 2085-GH	Base case 2020 with inflow change due to CC scenario “GH for year 2085”
BC2020 + CC 2050-GL	Base case 2020 with inflow change due to CC scenario “GL for year 2050”
BC2020 + CC 2085-GL	Base case 2020 with inflow change due to CC scenario “GL for year 2085”
BC2020 + CC 2050-WH	Base case 2020 with inflow change due to CC scenario “WH for year 2050”
BC2020 + CC 2085-WH	Base case 2020 with inflow change due to CC scenario “WH for year 2085”
BC2020 + CC 2050-WHdry	Base case 2020 with inflow change due to CC scenario “WHdry for year 2050”
BC2020 + CC 2085-WHdry	Base case 2020 with inflow change due to CC scenario “WHdry for year 2085”
BC2020 + CC 2050-WL	Base case 2020 with inflow change due to CC scenario “WL for year 2050”
BC2020 + CC 2085-WL	Base case 2020 with inflow change due to CC scenario “WL for year 2085”

Figure 74 Overview of the 4 locations for which model results are presented.



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The results of the cases are shown for four locations: Chooz (France), Monsin (Belgium), Borgharen (Netherlands) and Megen (Netherlands). Figure 74 shows the locations on the network schematization.

Results are presented as:

1 Indicators
  - a the lowest discharge (m³/s) simulated.
  - b the percentage of time steps (decades) that the flow is below a threshold flow value

2 The 70% and 90% dependable flow. The 70% dependable flow is the flow value which is exceeded in 70% of the time, and the 90% dependable flow is the flow value which is exceeded 90% of the time.

In addition to these results, Annex C.9.1 contains detailed information on the flow composition of the Meuse water.

5.5.2 Indicators: lowest discharge and percentage of threshold flow value crossing

From the simulation results for the different scenarios the following indicators have been derived to illustrate the effect of the future scenarios on the water availability:

- Lowest discharge (m³/s)
- Percentage of time steps (decades) below an upper threshold flow value
- Percentage of time steps (decades) below a lower threshold flow value.

The threshold values are different for the locations. The threshold flow values are:

- Chooz: 20 and 22 m³/s. These values are threshold values for the reduction of cooling water intake at the power plant Chooz.
- Monsin: 30 and 50 m³/s. These values represent alarm levels according to the Bilateral Treaty on the Meuse discharge (Maasafvoerverdrag). If the discharge falls below the threshold of 30 m³/s the so-called crisis phase is entered.
- Borgharen (Common Meuse) and Borgharen (Juliana Canal): 8 and 10 m³/s. Within the crisis phase, the discharge is distributed equally between Albert Canal, Common Meuse and the Juliana Canal. 10 m³/s is the discharge in the Common Meuse and the Juliana Canal at the beginning of the crisis phase.
- Megen: 20 and 30 m³/s. These values represent a translation of the alarm levels according to the Bilateral Treaty on the Meuse discharge for Megen.

All indicators are applied to the summer months July to October. The indicators illustrate the effect of future scenarios on the water availability. Figure 75 to Figure 79 shows the indicators as bar plots for the different locations, the corresponding values are given in Appendix C.9.2. With respect to the threshold values, Chooz already shows bottle necks for the base case. For Monsin, mainly the W-scenarios produce significant bottle necks. Downstream of Monsin the water is distributed between the Albert Canal and the Meuse.

At Borgharen, the Meuse discharge is distributed into the Common Meuse (Grensmaas) and the Juliana Canal, represented by the respective observation points Borgharen (Common Meuse, also referred to as Borgharen Dorp), and Borgharen (Juliana Canal). The model contains minimum flow requirements in the Common Meuse (10 m³/s) and the Juliana Canal (15 m³/s), and the model distributes the water accordingly. Note that this is not necessarily how water is distributed exactly in practice. The minimum flow requirements are reflected by the indicators: the lowest discharge is close to 10 m³/s in the Common Meuse (Borgharen Weir) for all scenarios, but in the Juliana Canal (Borgharen Juliana Canal) some scenarios show a smaller value for the lowest discharge. The lowest discharge even falls below the lower threshold of 8 m³/s, which is reflected in the percentage of decades below the lower threshold. In principle, the bottle necks shown for Monsin are also visible at Borgharen. Due to the demand-driven water distribution within the model the bottle necks are mainly visible in the results for the Juliana Canal.

Figure 75 Lowest discharge (m³/s) and the percentage of timesteps below threshold flows at Chooz

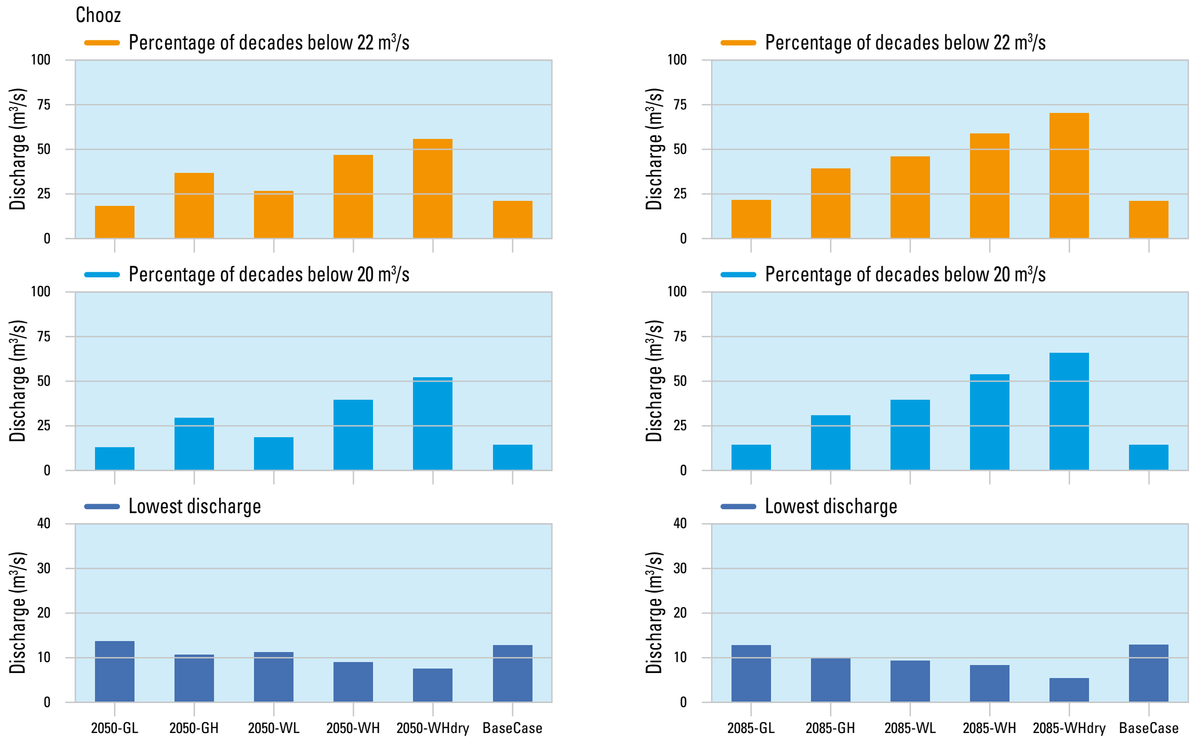

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Figure 76 Lowest discharge (m³/s) and the percentage of timesteps below threshold flows at Monsin

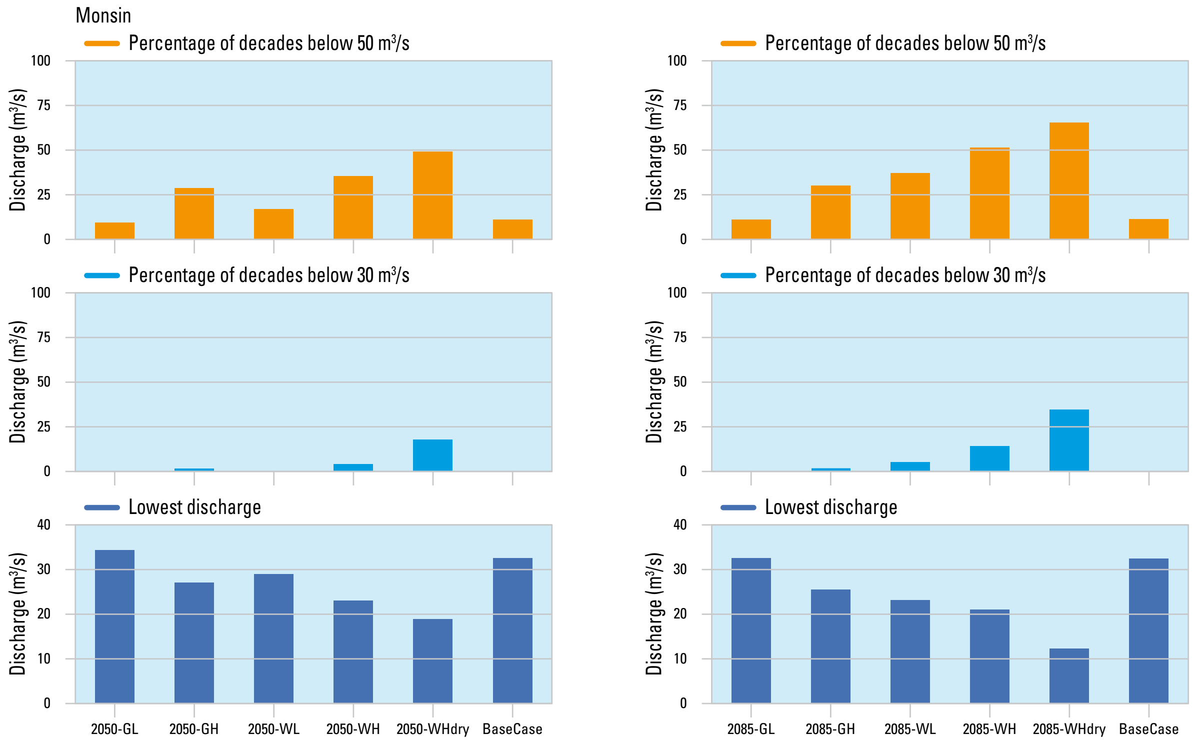

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Figure 77 Lowest discharge (m³/s) and the percentage of timesteps below threshold flows at Borgharen (Common Meuse)

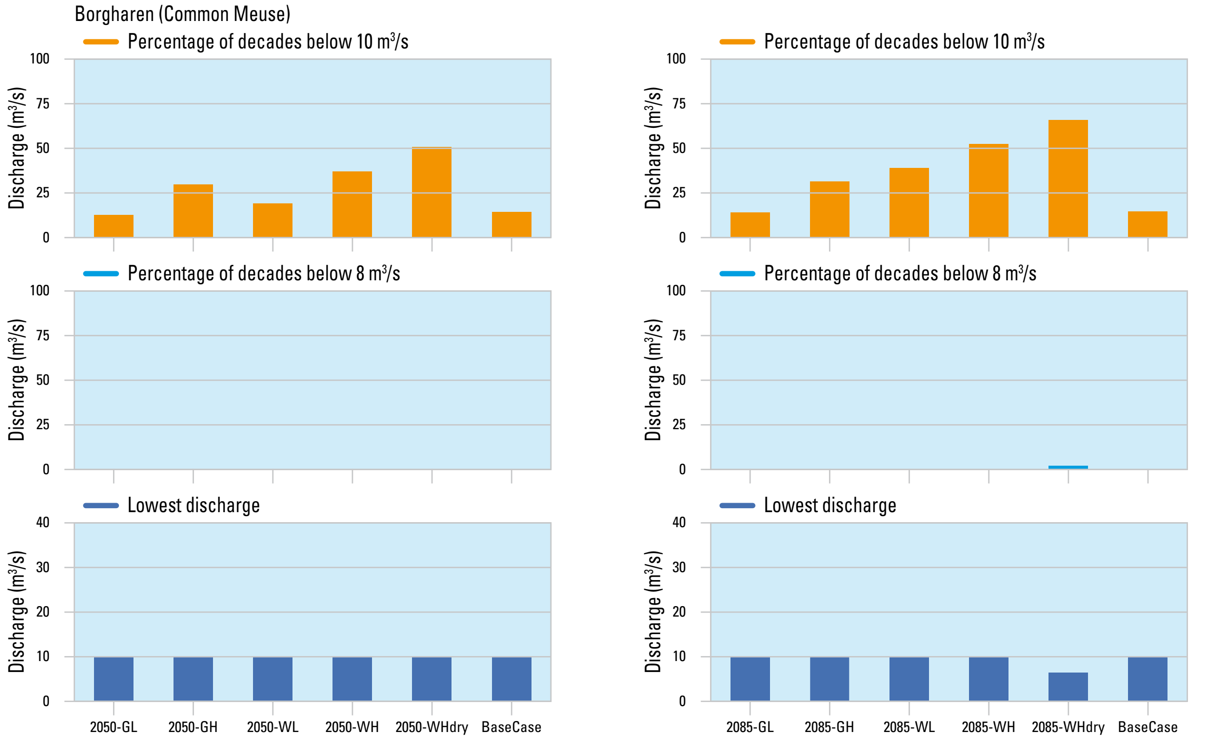

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Figure 78 Lowest discharge (m³/s) and the percentage of timesteps below threshold flows at Borgharen (Juliana Canal)

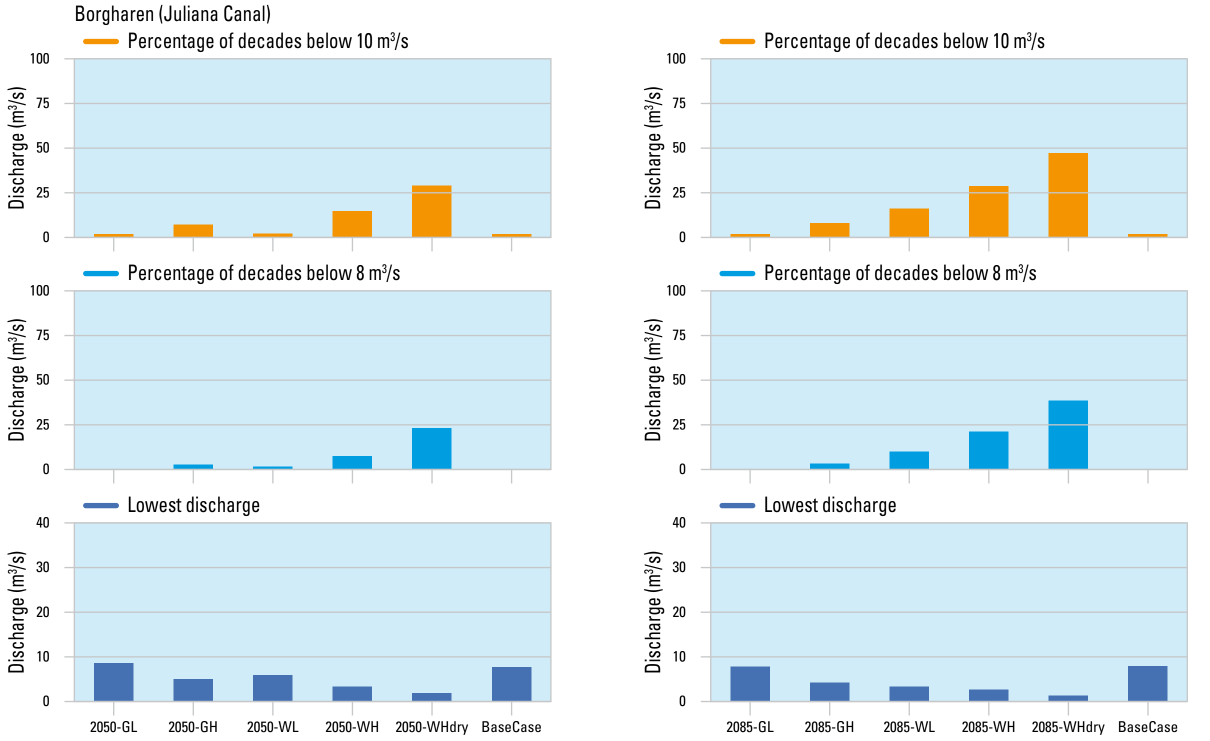

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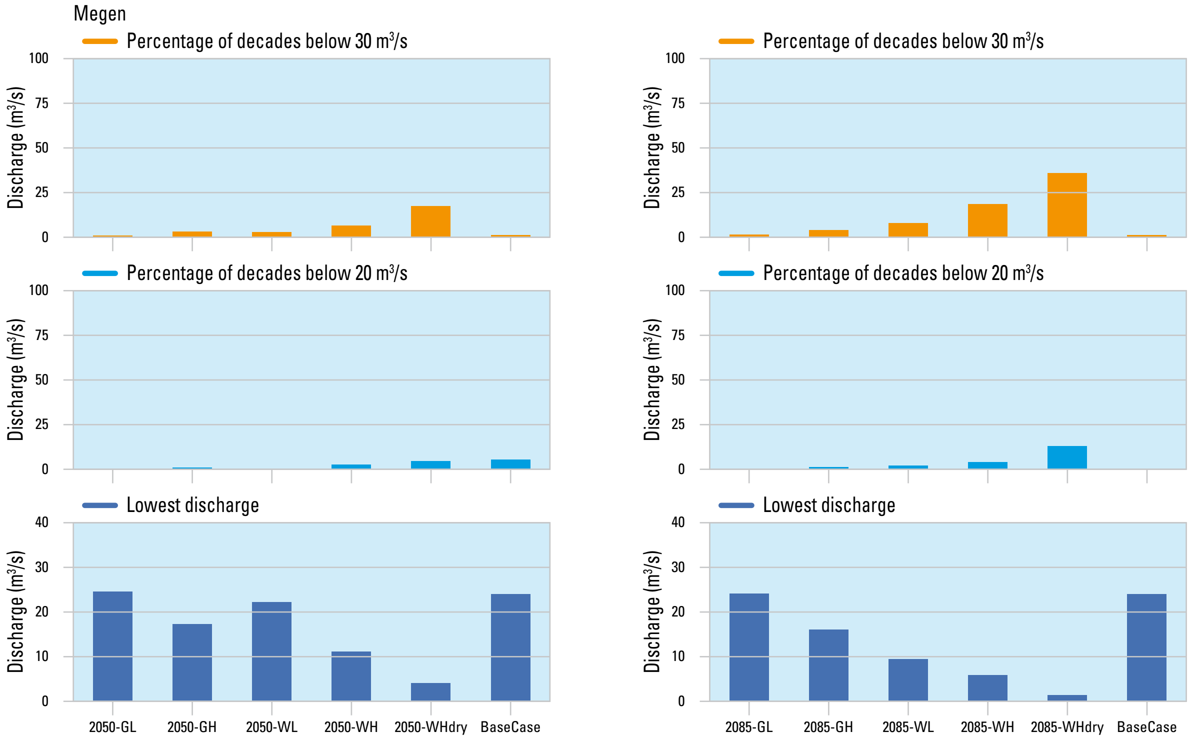
Figure 79 Lowest discharge (m³/s) and the percentage of timesteps below threshold flows at Megen



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At Megen the Meuse has received additional inflow from tributaries, with the Rur and the Niers as the two largest. It has been shown that the Rur contributes significantly to the discharge composition of the Meuse during low flow periods (Kramer 2021). The climate change affects the Rur tributary too, but the reservoirs in the Rur make it possible to ensure a minimum flow in the Rur. Climate change will also affect the Rur sub-catchment, and modifications of the current operational scheme for drought situations are in progress (Homann 2017). The percentages of time steps below threshold indicators are smaller than for Monsin. This is because of the additional inflow, but also because of the threshold values that have been applied here for the calculation of the indicators. In the W-scenarios, however, the discharge falls below the thresholds for a significant period of time as well.

5.2.3 70% and 90% dependable flow

The dependable flow is the flow value assigned to a specific time in a year (a decade) that is exceeded by 70 % or 90 % of the simulated years. Mathematically, the dependable flow is computed as a percentile. With a simulation period of 41 years that has been used here for all scenarios, the dependable flow of 70 % is the discharge value that is exceeded in 28,7 years out of all 41 years, and for the 90 % dependable flow it is the discharge that is exceeded in 36.9 years out of 41 for a specific time step. We plot the dependable flow for all simulation time steps during the summer period.

The 70 % and the 90 % dependable flow are thus a measure for the flow one can rely on throughout the year. The lower the dependable flow, the less water is available. The 90 % dependable flow is lower as the 70 % dependable flow, but more on the safe side. The graphs show how the low flow as it is incorporated in the future scenarios compare to the current situation, the base case.

Dependable flows are shown in Figure 80 to Figure 84 for different locations along the Meuse. For comparison, the discharge values of the dry year 2019 and the average flow over the dry years 2003, 2011 and 2017 to 2022 have been added to the graphs for those station where the data is available.

Dependable flows of the base case show already bottle necks: thresholds are touched, or the dependable flow is already below the threshold. Only the scenario 2050-GL shows a slight improvement with respect to the base case.

At Chooz, the two thresholds are close together, because they are driven by the cooling water demand for the power plant on the one hand and a minimum flow requirement for nature on the other hand. For the projection year 2085, most future scenarios show dependable flow values below the thresholds.

Monsin is located upstream of the diversion of the Albert Canal. The 70 % dependable flow for the base case is above, the 90 % dependable flow is below the upper threshold. The lower threshold is reached or hit by the more extreme scenarios only.

In the extreme scenario run 2085-WHdry the 70 % dependable flow crosses even the lower threshold, while all other scenarios don’t hit this mark.

Borgharen is located downstream of the Albert Canal diversion. As mentioned above, here the Meuse water is distributed into the Common Meuse (Grensmaas) and the Juliana Canal. The dependable flow graphs reflect the minimum flow requirement that has been applied in the model for the Common Meuse (10 m^3/s) and several flow requirements in the Juliana Canal (Borgharen Juliana Canal) for cargo ship navigation and the compensation of lock losses. These requirements add up to ca. 15 m^3/s. The model aims to meet flow requirements in both the Common Meuse and the Juliana Canal if possible, but with priority for the minimum flow requirement in the Common Meuse. In the Common Meuse, only the 2085-WHdry scenario undercuts the upper threshold of 10 m^3/s at one time step. For the most extreme combination, the 2085 projection and the 90 % dependable flow, all scenarios except the base case and the 2085-GL scenario show a dependable flow below the lower threshold for at least one time step. While the threshold of 10 m^3/s is met in the Common Meuse at nearly all times and for all scenarios, this is not possible for the Juliana Canal. Some of the dependable flow lines even fall below the lower threshold of 8 m^3/s. Again, the distribution of water between the Common Meuse and the Juliana Canal has been computed by the model based on flow requirements, this does not necessarily match the operations that are applied in reality.

The dependable flow at Megen shows less threshold crossings than Monsin. As explained above, the threshold values are less strict for Megen, and there is additional inflow from the tributaries upstream of this station, with the Rur and the Niers as major tributaries. Only the 70 % dependable flow from the 2085-WHdry scenario crosses the upper threshold. For the 90 % dependable flow, also the 2085-WH scenario crosses the lower threshold. Similar to location Monsin, the base case 70 % dependable flow follows the average of selected dry years, and the 90 % dependable flow is below the average of selected dry years. Comparison of the discharge from 2019 and the average discharge of dry years for the two locations shows that the drought year 2019 was more extreme at Megen than at Monsin: at Megen, the 2019 discharge values are lower than the corresponding average values of selected dry years, at Monsin the 2019 values are in the same range. This is also reflected in the dependable flows of the base case: the 70 % dependable flow for the base case is above the discharge from 2019. The observed values from 2019 are comparable to the WHdry scenario for location Megen, but for the other locations, the dependable flows of the WHdry scenario are lower than observed values of 2019. So WHdry will turn out more extreme than what has been observed in 2019 for most locations.

Practically all future scenarios show lower dependable flows than the base case for the summer months. In terms of low flow, it is very likely that low flow periods become more critical in the future. The dependable flows reach their lowest values during August and September. Note that in the wet months the dependable flow can reach higher values than in the base case, because with climate change more extreme storm events in winter and more severe droughts in summer are expected, and this is reflected in the climate change factors that have been used for the scenario definition (Figure 53).

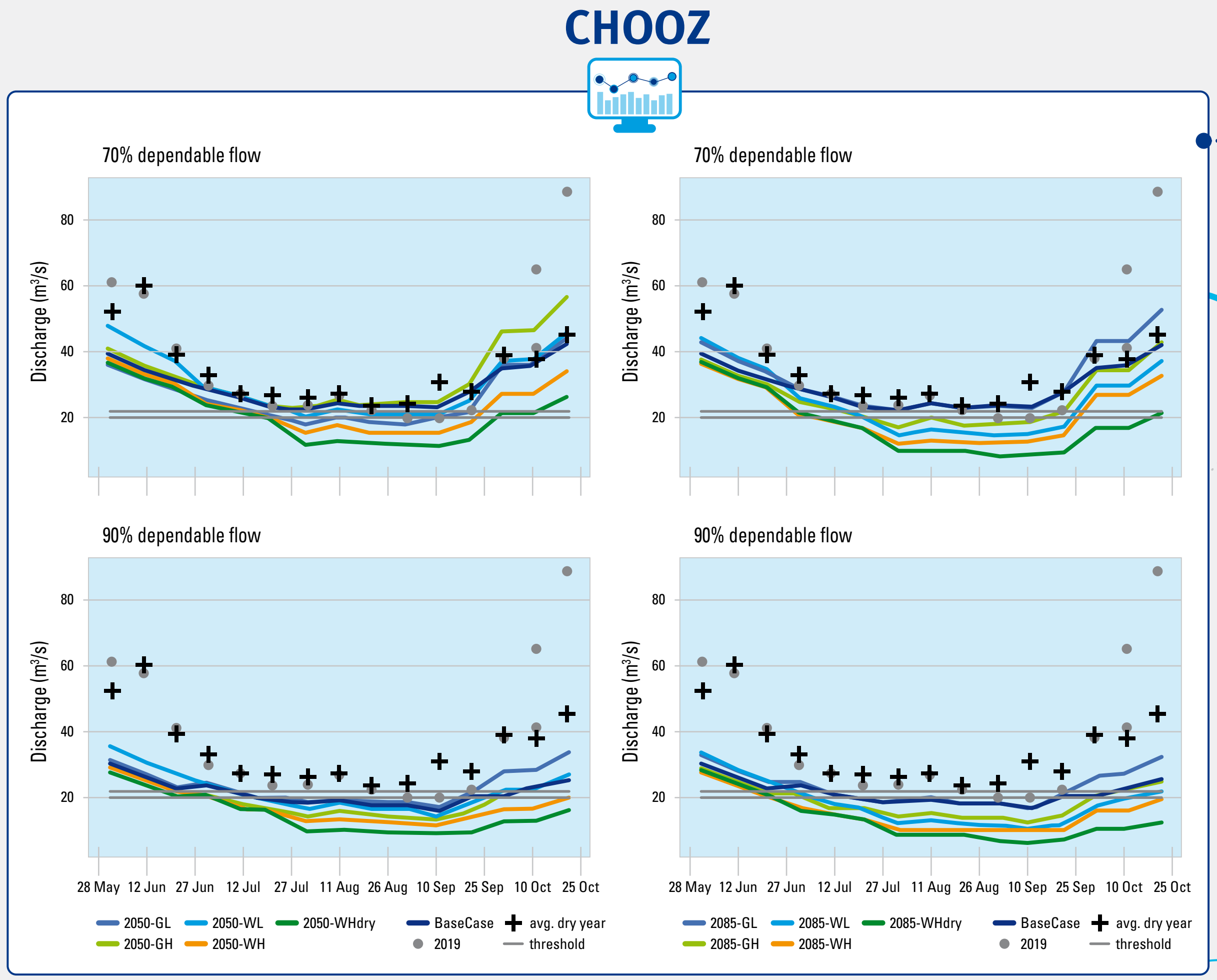


Figure 80 Dependable flow at Chooz for different scenarios, discharge from 2019 and average discharge of the drought years 2003, 2011 and 2017 to 2022

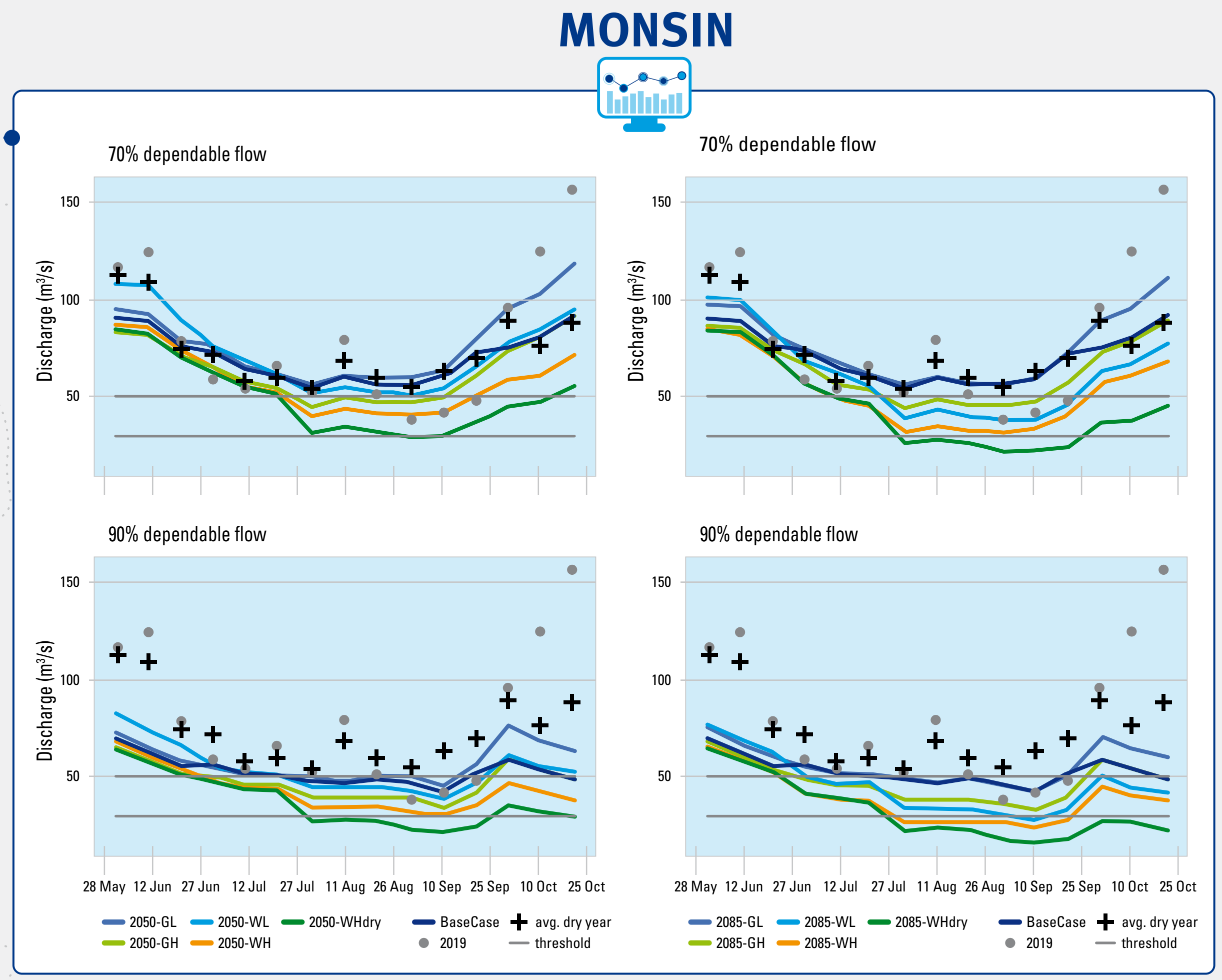
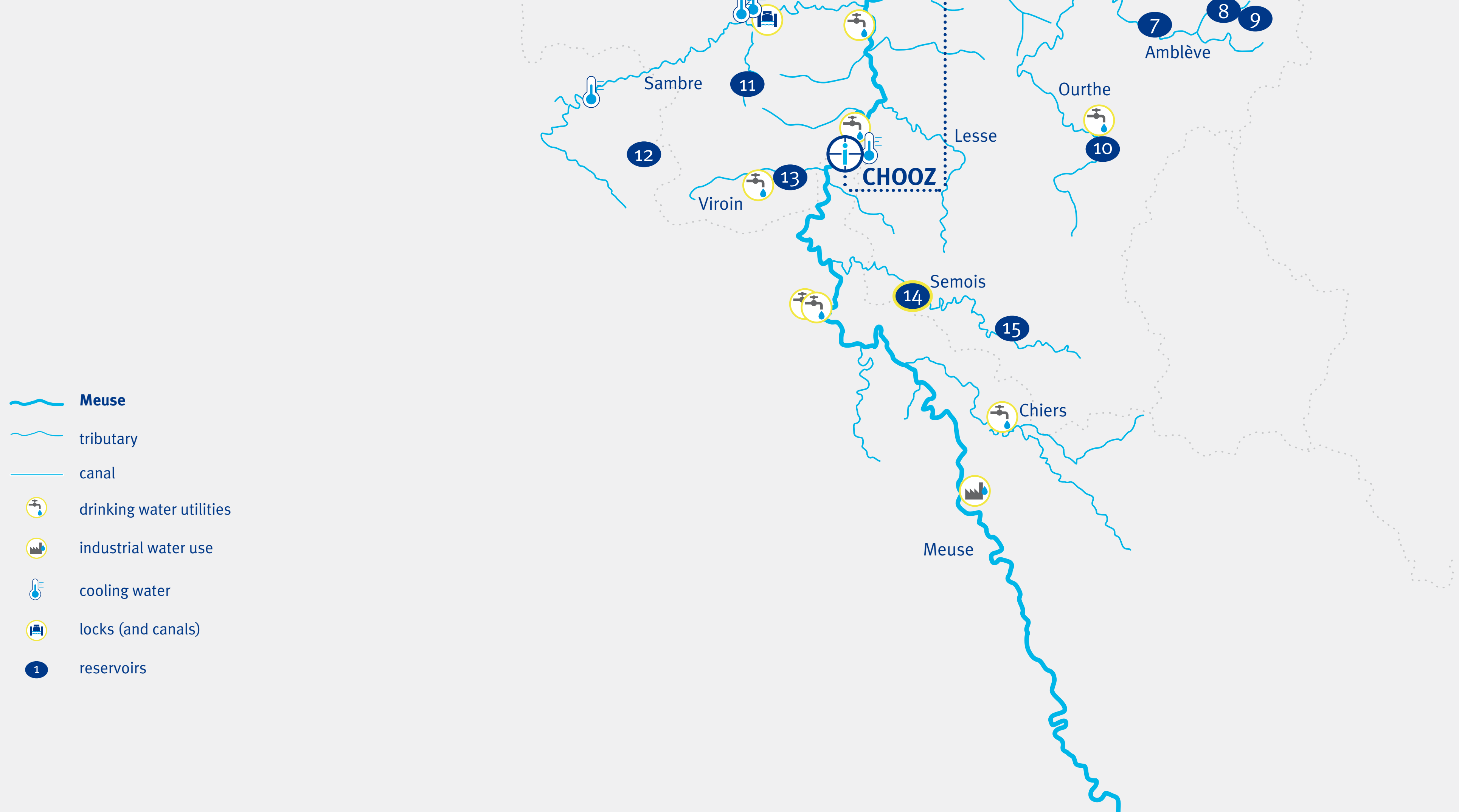


Figure 81 Dependable flow at Monsin for different scenarios, discharge from 2019 and average discharge of the drought years 2003, 2011 and 2017 to 2022



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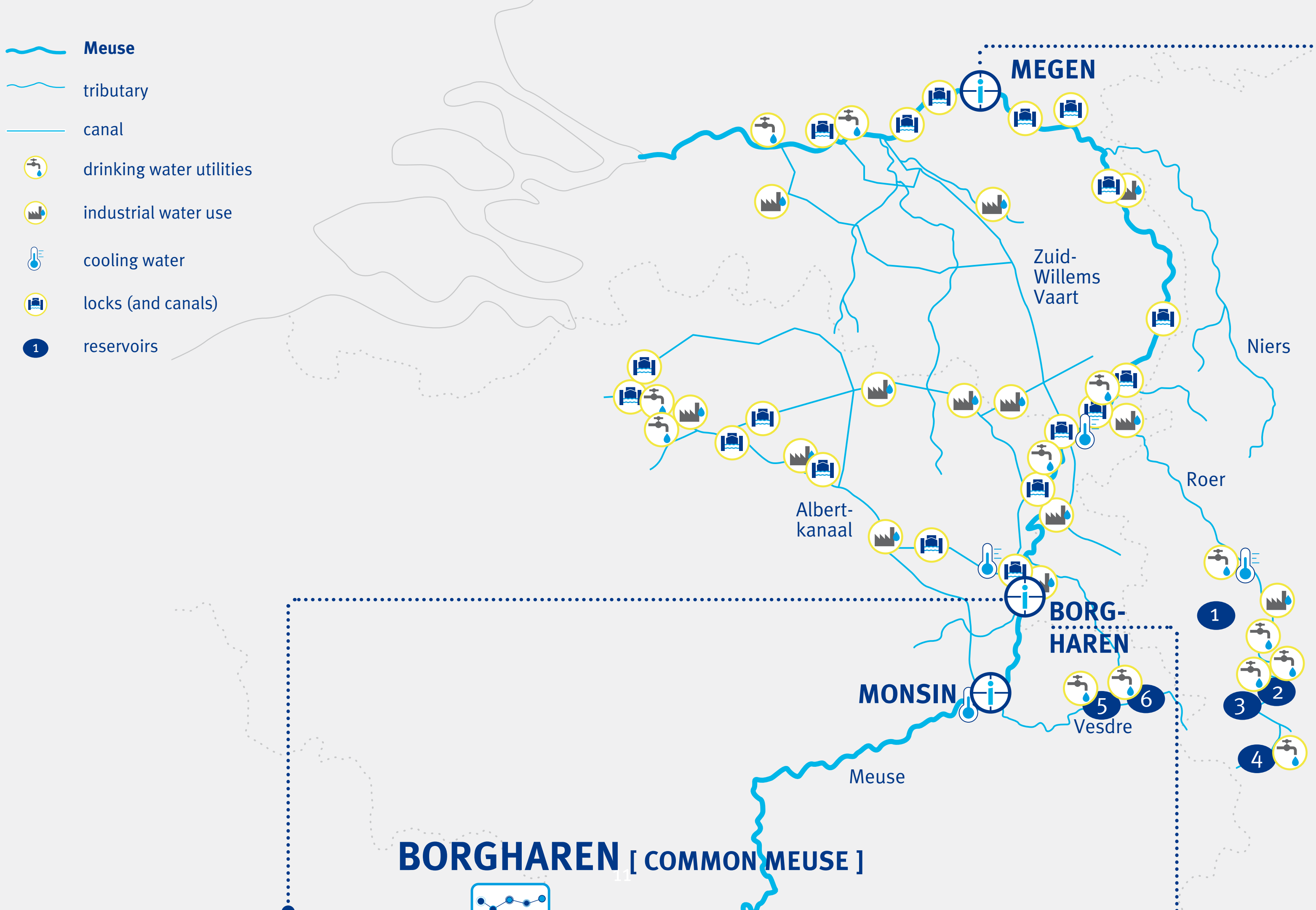


MEGEN

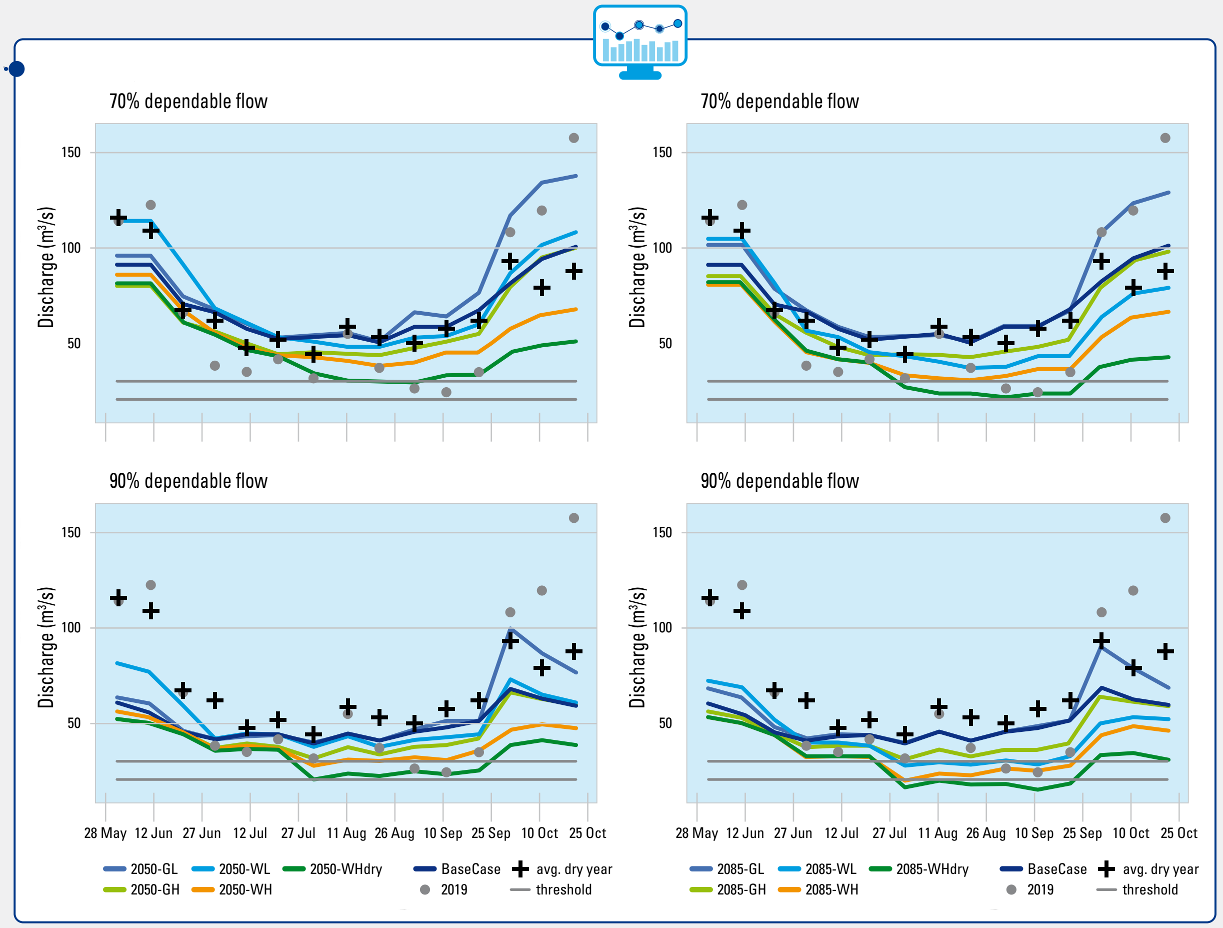


Figure 84 Dependable flow at Megen for different scenarios, discharge from 2019 and average discharge of the drought years 2003, 2011 and 2017 to 2022

BORGHAREN [COMMON MEUSE]

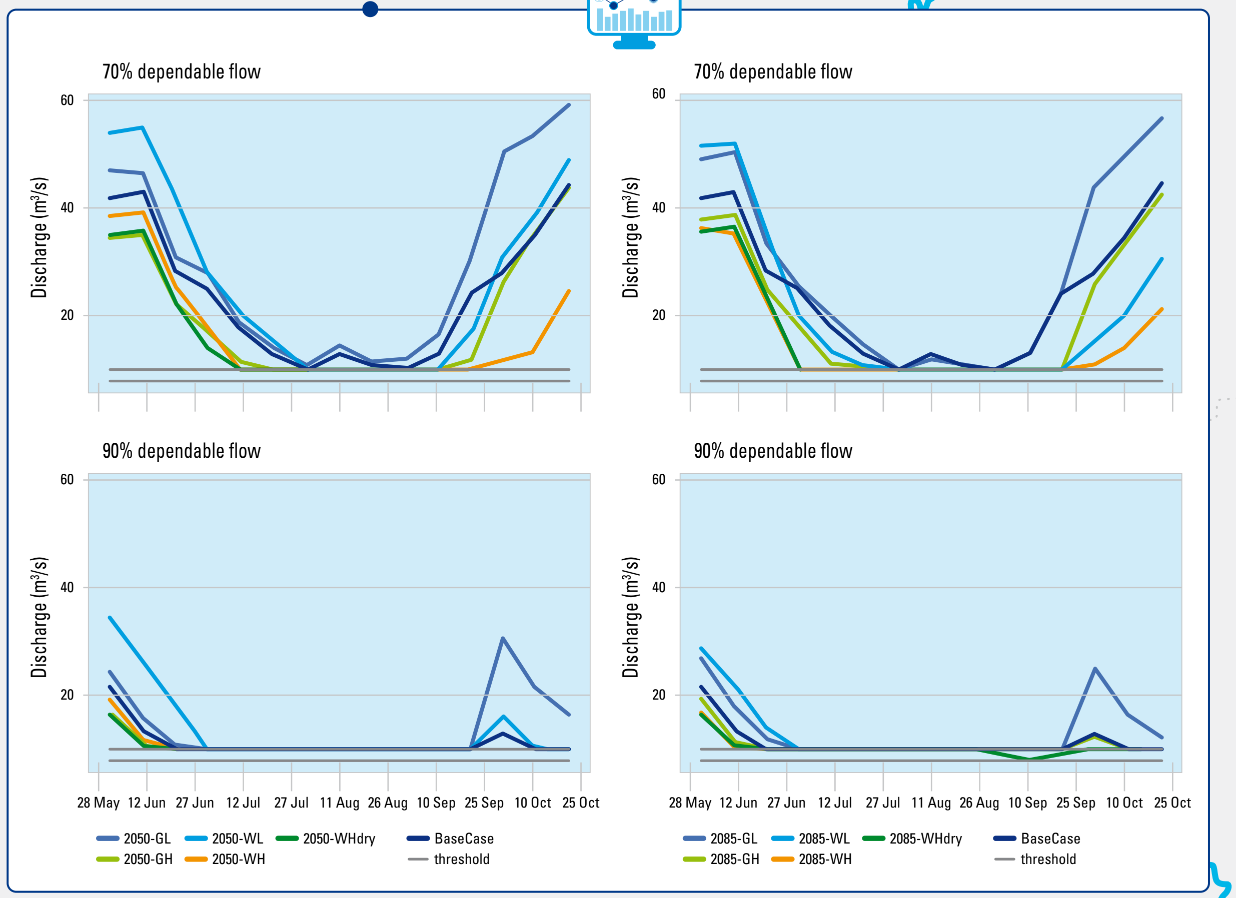


Figure 82 Dependable flow at Borgharen (Common Meuse) for different scenarios

BORGHAREN [JULIANA CANAL]

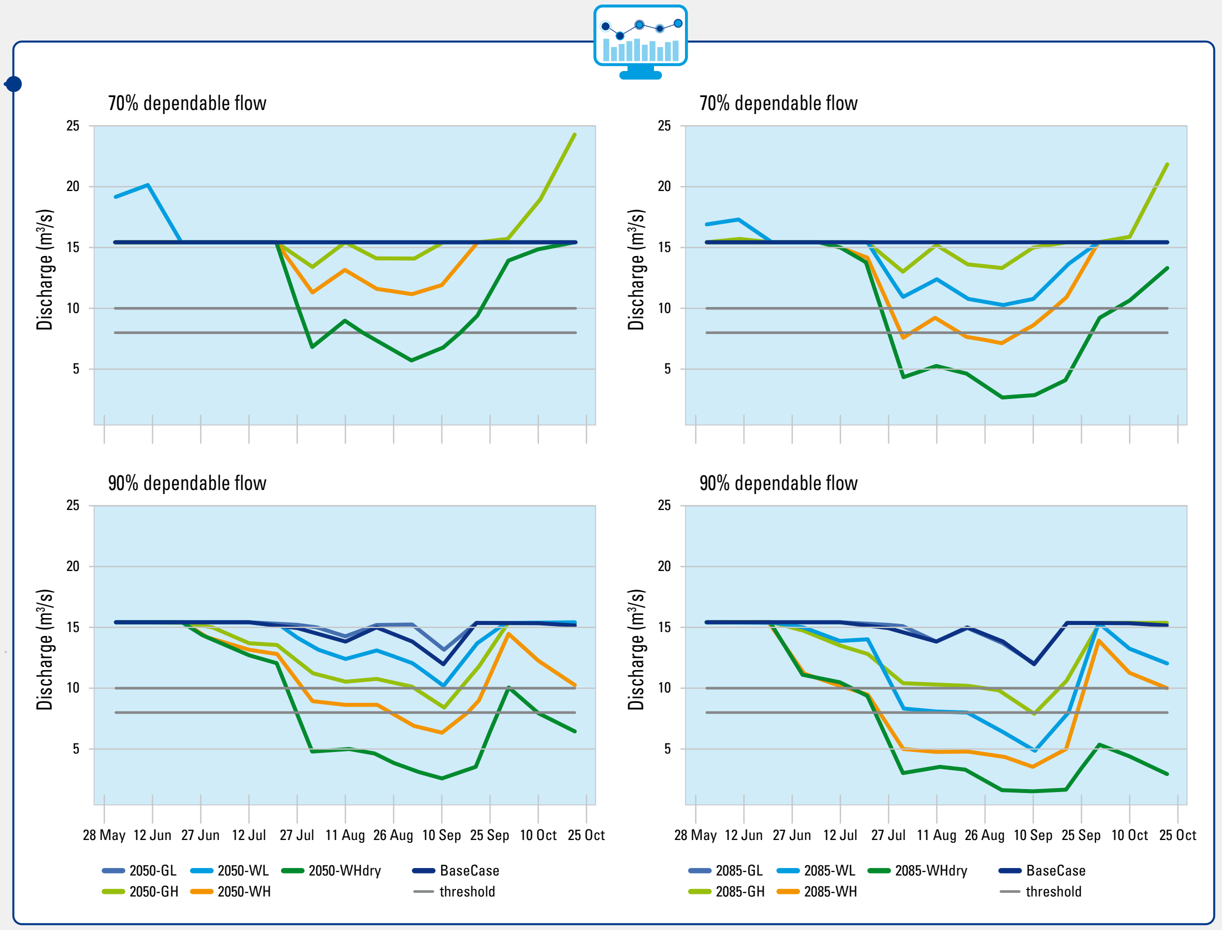


Figure 83 Dependable flow at Borgharen (Common Meuse and Juliana Canal) for different scenarios

Source Deltares, edited by RIWA-Meuse

6

Summary, conclusions and recommendations

6.1 The river basin water management model

Within this study a river basin water management model for the Meuse has been developed. To the best knowledge of the authors, this RIBASIM model “Meuse002” is the first water management model covering the whole catchment of the Meuse. This model allows simulation of the water demand, allocation and flow composition for the Meuse and major tributaries. The model is based on an inventory of water users and water infrastructure in the Meuse catchment. The model and the inventory provide a better understanding of the water usage and water management in the Meuse in an international context. Together with the hydrological model (Wflow) that provides the inflow from the Meuse catchments, the RIBASIM model “Meuse002” can be used for strategic planning studies to support discussions about future options.

The Meuse002 model includes the water-related infrastructure and water users in the Meuse basin: domestic water, industrial water, cooling water, irrigated agriculture water, ecology and recreation, lock operation losses (navigation), sluice and canal leakage, “Maasplassen” evaporation losses, minimum flows due to international agreements between countries, minimum reservoir release and canal flow, hydro-power production and inter-basin transfers. The modelling of the individual infrastructure and water users make it possible to simulate the effect of various types of scenarios: climate change, water use changes, impacts of infrastructural measures on flows, changes in the operation of structures, etc. This can provide a spatial insight on where gains and losses are to be expected in the basin under different scenarios in an international context.

One historic hydrologic scenario has been simulated with the Meuse002 model. This scenario comprises runoff time series from the rainfall-runoff model for the Meuse (Wflow) over a period of 41 years (1980–2020). The simulation results match well to the monitored flow time series for various gauging stations on the Meuse.

6.2 Scenario runs

In order to give an indication on how the model can be used for strategic planning, ten illustrative future scenarios have been simulated. The hydrological inflow of the base scenario has been adjusted with a factor to account for climate change according to the climate change scenarios after Klijn et al. 2015. The scenarios let the 41 historical years from the base case virtually take place under different climate change conditions for the projection years of 2050 and 2085, respectively. From the simulation period of 41 years indicators and the dependable flow have been derived for different locations. The analysis of the scenario runs lead to the following findings:

- The dependable flow, which is a measure for the water availability, drops during the dry period from June to October at all selected stations for practically all scenarios.
- The reduction of dependable flow varies with the time over the year. The lowest points are during August and September.
- The reduction of the dependable flow also varies in space along the course of the river Meuse. Thresholds are undercut by the more extreme scenarios in France and Belgium. For locations in the South of Netherlands the simulation runs show more critical results, because water is diverted from the Meuse into the Albert Canal.
- It has been shown that the Rur provides an important contribution to the discharge in the Meuse (Kramer 2021). The reservoirs in the Rur safeguard a minimum flow in the Rur. This is reflected in the model results, too. For locations downstream of the Rur confluence with the main river, the simulation results look less critical because of the additional inflow of the Rur tributary. Note that climate change also affects the discharge in the Rur itself. Therefore, reservoir operations will have to adapt to climate change and an operational plan for drought conditions is planned (Homann 2017).
- The lowest discharge per decade over the whole simulated period reduces for all locations along the Meuse and all scenarios. The WH and the WHdry scenario are the most extreme scenarios and show the lowest values.
- The number of decades in the dry period from July till September where the discharge falls below a certain threshold value increases for all stations along the Meuse river under climate change conditions.

In general, the scenario runs indicate that the periods of low flow will become longer and the discharge becomes smaller in the summer months.

Note that the scenario runs are not a detailed climate study. We would call it rather a bottleneck analysis that gives an indication on future climatic conditions, particularly droughts, and their possible impact on the water balance of the Meuse. Some simplifications, assumptions and uncertainties are briefly discussed in the following and should be considered when interpreting the simulation results:

- The climate change factors that have been applied to the inflow boundary conditions vary in time over the year, but are kept as a constant over the whole catchment. The scenario runs do not comprise any spatial distribution within the catchment.
- Climate change factors have only been applied for the part of the catchment that is covered by the Wflow model of the Meuse until Mook, because only in this part of the catchment the runoff is mainly driven by natural hydrological processes. In the lowland areas downstream of Mook human water management plays a major role in the inflow to the Meuse, so the application of climate change factors is not suitable here. The application of design climate change scenarios for this area needs further elaboration.

- Only the hydrological inflow to the Meuse (the water supply side) has been modified for the climate change scenarios. Water evaporation and other losses remain unchanged, also future changes in the water demand have not been considered. The water demand can have a dependency on the hydrological situation as well. This applies in particular for the water demand of irrigated agriculture.

Nevertheless, the illustrative scenarios emphasize the impact that climate change can have on the water availability along the river Meuse. The severity of bottle necks varies in time and space, but the model results show bottle necks for all countries.

6.3 Uncertainty in model data

Although we used a comprehensive set of data for the model, there are still uncertainties, particularly in the data on water users. Some water usage is not reported (e. g. supply of canals) or only the licensed amount (industrial water demand) or maximum capacity (wastewater treatment plant) is known. Some water users are unknown, because an inventory of water users is not maintained or is not published, and even illegal water extractions may take place. Water usage data comes thus with a significant uncertainty. The water balance model has been validated against observed data, but inaccuracies in the model input may lead to less accurate results on a local level.

The Dutch part of the Meuse catchment, represented by the recording stations Megen and Borgharen, is much more complex than the upstream parts in terms of hydrological processes.

The water availability in the Dutch part is dominated by the water usage for water management (maintenance of water levels, Dutch: peilbeheer) and irrigation (agriculture). These water balance components are not measured directly, and their quantification is the subject of various ongoing studies. For the Meuse002 model we have used the data from the Landelijk Hydrologisch Model (national hydrological model, LHM) for the water demand from agricultural water use and water management. Although for this study the latest data has been used, it was still necessary to add a time series to account for unknown water use during the exceptional dry years 2018, 2019 and 2020 (Appendix C.7.15).

The Meuse catchment has several reservoirs. Reservoir operations are difficult to model, because they are not driven by physical processes, but mainly by human decisions. Operational decisions are individual choices, which makes it difficult to capture them in general river basin water management models and introduces uncertainties into the model. The discharge in the Rur river and in the Vesdre river is dominated by reservoir operations. RIBASIM simulates reservoir operations on the basis of the water demand downstream, while for example the operations of the reservoirs in the Rur follow an operational plan which is called volume segment based release plan (“Lamellenplan”, Homann 2017). Additionally, the operational plan leaves some flexibility to the operators, and in particular during drought periods the release records show a more conservative pattern than the RIBASIM model shows. For this reason, we have used the flow monitoring time series at station Stah, downstream of the Rur, as inflow time series from the Rur into the Meuse. The part of the model that represents the Rur tributary with reservoirs and water users has been inactivated and is thus not included within the simulations. The Rur is still available in the model and can be activated again if necessary.

Given the data uncertainty, we see the water management model (software RIBASIM), the hydrological model (Wflow) and the inventory of water users and water infrastructure as a dynamic knowledge base. Models and inventory should continuously be updated and shared within stakeholders of the riparian countries of the Meuse. We recommend considering the following model improvements for the future:

- Update and improve the water use for water management and agriculture in the Netherlands from the National Water model (NWM) for the period 2012 till 2020 with emphasis on the consecutive dry years 2018, 2019 and 2020. As mentioned above, data is currently being prepared.
- Regular updating, calibration and validation of the Wflow model for low flow situations. A repository for the model (Appendix B) has been created to manage different versions of the model.
- Analyse in detail the water using and consuming activities in the Niers river basin.
- Refine, update and correct the inventory and the corresponding elements of the RIBASIM model schematization. In particular, the following items should be addressed:
  - Reservoirs and hydro-power stations,
  - Industrial water usage along the Sambre
  - Agricultural water uses in Flanders and in the Netherlands
  - Inter basin transfers like the flow in the canal Charleroi-Bruxelles, Canal de la Sambre à l’Oise, Canal Marne au Rhine Ouest and Canal des Ardennes
- Keep track on local and regional developments within the Meuse catchments and account for them within the model. Examples for such developments are recreational use of water within the tourism sector or changes in land cover due to the recent droughts (see also Becker et al. 2018).
- The RIBASIM model “Meuse002” balances the human water use and water availability. Beside the use function for human activities, attention should also be paid to the Meuse itself, i. e. ecology, biodiversity, and landscape.

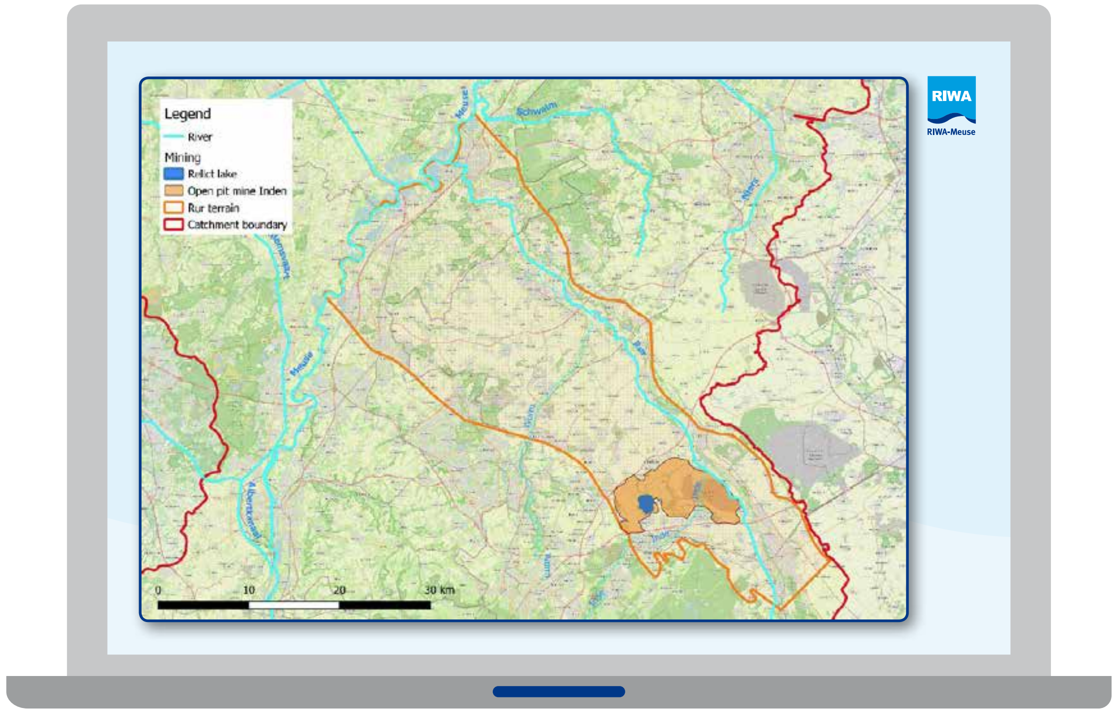
6.4 Future use of the model and possible extensions

The added value of the water management model of the Meuse and the inventory of water users comes to bear when they are used to support strategic planning or explorative studies. Some ideas about a future use of the model that arose during the project are given in the following:

- Increase a common understanding among all parties involved in the water resources management of the Meuse:
  - the temporal and spatial aspects of the water balance of the Meuse
  - the sources of water at different locations in the Meuse
- Identify present and future bottlenecks in the supply of water and the potential impact of water scarcity on the economy (see also Sinaba et al. 2013).
- Analyse spatial dependencies of possible measures: who benefits from certain measures (water savings, constructions, operation) on different locations, and where do the costs appear (if any)? Most likely this will include cross-border aspects. This can create synergies and opportunities: interests from stakeholders in different countries are not necessary conflicting, often there is a common interest.
- Evaluate the effect of alternative operation of the reservoirs in an international context. It has been shown that the inflow from the Rur tributary is an important component of the Meuse discharge during low flow periods (Kramer 2021), consequently the operation of the reservoirs in the Rur have a significant impact on the discharge in the Meuse during low flow periods. Less is known about the role of other large reservoirs on the discharge in the Meuse during low flow periods, this should also be addressed in this context.

- A more detailed analysis of the impact of climate change on water supply security (the water availability side). Within this study a start has been made with the illustrative scenario runs based on the KNMI climate change scenarios. The Intergovernmental Panel on Climate Change has published the Sixth Assessment Report (AR6) recently. Climate change scenarios for the Meuse region derived from this report should be used when available.
- Compare the results of the Meuse002 model with the results of available models at institutes and universities in the Meuse riparian countries. Different organizations use different modelling software, but still, the inventory of the water users can form a common base for collaborative modelling.
- Search for international cooperation and contribute to a common research agenda.
- Analysis of socio-economic developments (the water demand side), for example
  - Increased cargo ship navigation
  - Future water demand from the Meuse per sector
  - Closure of lignite mining in Germany
  - Change in agricultural patterns
  - Land use changes
- Evaluate future measures, water resource management strategies, development and adaptations pathways.
- Use the model not only for quantitative studies, but extend the application to sedimentation, waste load, plastics transport and water quality analysis. Beside the discharge, the water temperature is a crucial parameter for ecology and water users, in particular where water is used as cooling water for power plants.

Figure 85 Location of the relict lake “Blausteinsee”, historic (Zukunft, Inden I) and active (Inden) open pit mines in the Rur terrain (Rurscholle, Roerdalslenk) and the Meuse catchment



Source Deltares, edited by RIWA-Meuse

We recommend developing future scenarios that account both for the hydrological side (climate change) and the water usage side (human water use) within a series of international scenario workshops. For both, different approaches and requirements will exist in the different riparian countries, and the different views should be aligned. From the discussions within an international community the understanding and insights in water users will increase and improve the quality of the model.

Within the Hotspot Analysis Meuse (Becker 2018; Becker et al. 2018) future developments in the Meuse catchment have been identified from a Dutch perspective. This study might provide some inspiration for scenario development.

Depending on the objective of the study the model is applied for, it can make sense to extend the model with selected groundwater processes. Firstly, groundwater is an important water resource in some parts of the catchment. Secondly, the mine operations in open pit mine Inden have an impact on the groundwater flow. After the end of the mine operations in 2030 the groundwater level will rise gradually, and this will result in a small additional base flow. On the other hand, the discharge of drainage water via the Rur will cease accordingly (Becker 2018; Becker et al. 2018; Bachmann et al. 2007; Becker & Klauder 2007). The construction of a relict lake for the open pit mine Inden, the so-called “Indescher See”, is planned. This lake will be about 180 m deep and have an area of 11,6 km² and might serve as an additional water reservoir. Figure 85 shows the geological unit “Rur terrain” (Dutch: Roerdalslenk, German: Rurscholle) with the location of open pit mines and the “Blausteinsee” relict lake, which is already there. RIBASIM can handle groundwater reservoirs as a water balance component, but any extension of the RIBASIM model with groundwater processes must be aligned with the Wflow hydrological model.

If reservoir operations of the reservoirs in the Rur are analysed with the model, it can be necessary to extend the present modelling of reservoir operation by a new programme feature that simulates the “volume section based release plan” (Lamellenplan).

7

References

Arino, O.; Ramos Perez, J. J.; Kalogirou, V.; Bontemps, S.; Defourny, P.; Van Bogaert, E. (2012):
Global Land Cover Map for 2009 (GlobCover 2009). © European Space Agency (ESA)
& Université catholique de Louvain (UCL).
URL: https://doi.pangaea.de/10.1594/PANGAEA.787668 (Checked: 09/28/2021).

Asselman, N.; Barneveld, H.; Klijn, F.; van Winden, A. (2017):
Het Verhaal van de Maas / De Maas uit balans?
URL: https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/rivierkennis/verhaal-maas/ (Checked: 01/06/2020).

Bachmann, D.; Becker, B.; van Linn, A.; Köngeter, J. (2007):
The large-scale groundwater model Rurscholle. Grundwasser Vol. 12 (2007) No. 1 pp. 26–36.
DOI: 10.1007/s00767-007-0020-2.

Baetens, J.; Scheltjens, T.; van Eerdenbrugh, K.; Peeters, P.; Danckaerts, C.; Maeghe, K.; Meire, P.; Mostaert, F. (2006):
Omgaan met watertekorten in het Albertkanaal en de Kempense kanalen. Water Vol. 2006 (2006)
No. September-Oktober pp. 1–7.

Bannink, A.; van der Ploeg, M.; van Schothorst, B.; Schauff, E. (2019):
Jaarrapport 2018 / De Maas / Goede bron voor drinkwater / Droogte toont kwetsbaarheid.
RIWA - Vereniging van Rivierwaterbedrijven. ISBN 978-90-6683-172-8.
URL: https://www.riwa-maas.org/wp-content/uploads/2019/09/RIWA-MAAS-Jaarrapport-2018.pdf.

Becker, B. (2018):
Hotspotanalyse Maas. Deltares. Deltares memo 11200588-019-ZWS-0003-v3.

Becker, B.; Klauder, W. S. (2007):
Gekoppeltes Grundwassermodell Erftscholle, Rurscholle und Venloer Scholle / Prognoserechnungen.
Lehrstuhl und Institut für Wasserbau und Wasserwirtschaft Rheinisch-Westfälische Technische
Hochschule Aachen. Wissenschaftliche Untersuchung im Auftrag des Landesamtes für Natur,
Umwelt und Verbraucherschutz Nordrhein-Westfalen Bericht I/2007.

Becker, B.; Mens, M.; van der Mark, R. (2018):
Impacts of developments in neighbouring countries on the Dutch Meuse. 5th symposium on
the hydrological modelling of the Meuse basin, September 13, 2018, Liège.
URL: https://publicwiki.deltares.nl/display/HydrologyMeuse/5th+symposium+on+the+hydrological+modelling+of+the+Meuse+basin (Checked: 01/24/2020).

Berger, H. E. J.; Mugie, A. L. (1994):
Hydrologische systeembeschrijving Maas. Directoraat-Generaal Rijkswaterstaat.
ISBN 90-369-0164-2. URL: https://puc.overheid.nl/rijkswaterstaat/doc/PUC_63737_31/.

**de Boer-Euser, T.; Bouaziz, L.; De Niel, J.; Brauer, C.; Dewals, B.; Drogue, G.; Fenicia, F.; Grelier, B.; Nossent, J.;
Pereira, F.; Savenije, H.; Thirel, G.; Willems, P. (2017):**
Looking beyond general metrics for model comparison – lessons from an international model
intercomparison study. Hydrology and Earth System Sciences Vol. 21 (2017) No. 1 pp. 423–440.
DOI: 10.5194/hess-21-423-2017.

Bouaziz, L. (2020a):
Oorsprong van Maaswater tijdens de droogte van 2019. Deltares.
Deltares-memo 11205325-010-ZWS-0001_v1.0.

Bouaziz, L. (2020b):
Evaluation of hydrological models of the Meuse river basin. Deltares.
Deltares report 11205237-002-ZWS-0009.

Commission Internationale de la Meuse (2020):
Plan d'approche pour la gestion des étiages exceptionnels dans le bassin versant de la Meuse.
Commission Internationale de la Meuse. Publication de la Commission Internationale de la Meuse.
URL: http://www.meuse-maas.be/Publications/2020-(1).aspx?lang=fr-BE.

Cornes, R. C.; van der Schrier, G.; van den Besselaar, E. J. M.; Jones, P. D. (2018):
An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. Journal of Geophysical
Research: Atmospheres Vol. 123 (2018) No. 17 pp. 9391–9409. DOI: 10.1029/2017JD028200.

De Wit, M. (2008):
Van regen tot Maas. Diemen: Uitgeverij Veen Magazines. ISBN 978-90-8571-230-5.
URL: http://www.bol.com/nl/p/van-regen-tot-maas/1001004006422183/ (Checked: 12/23/2015).
Deltares (2022): The wflow_sbm Model - wflow documentation.
URL: https://wflow.readthedocs.io/en/latest/wflow_sbm_old.html (Checked: 04/19/2022).

Deltares (2021):
hydroMT: Build and analyze hydro models.
URL: https://github.com/Deltares/hydromt (Checked: 09/28/2021).

Helmyr, S.; Jaskula-Joustra, A. (2001):
Laagwaterbeleid. Rijkswaterstaat Directie Limburg.

**Hengl, T.; Jesus, J. M. de; Heuvelink, G. B. M.; Gonzalez, M. R.; Kilibarda, M.; Blagoti , A.; Shangguan, W.;
Wright, M. N.; Geng, X.; Bauer-Marschallinger, B.; Guevara, M. A.; Vargas, R.; MacMillan, R. A.; Batjes, N. H.;
Leenaars, J. G. B.; Ribeiro, E.; Wheeler, I.; Mantel, S.; Kempen, B. (2017):**
SoilGrids250m: Global gridded soil information based on machine learning.
PLOS ONE Vol. 12 (2017) No. 2 pp. e0169748. DOI: 10.1371/journal.pone.0169748.

Homann, C. (2017):
Modelling, operation and management of Reservoirs in the Rur catchment during low flow. P
resentation 4th symposium on the hydrological modelling of the Meuse basin, October 13, 2017, Liège.
URL: https://publicwiki.deltares.nl/display/HydrologyMeuse/4th+symposium+on+the+hydrological+modelling+of+the+Meuse+basin.

Imhoff, R. O.; van Verseveld, W. J.; van Osnabrugge, B.; Weerts, A. H. (2020):
Scaling Point-Scale (Pedo)transfer Functions to Seamless Large-Domain Parameter Estimates for
High-Resolution Distributed Hydrologic Modeling: An Example for the Rhine River. Water Resources
Research Vol. 56 (2020) No. 4 pp. e2019WR026807. DOI: 10.1029/2019WR026807.

Johnen, G. (2020):
Development of a transnational showcase to assess the performance of RIBASIM for lowland rivers /
the Meuse catchment. Deltares. Internship report.

Johnen, G.; Becker, B.; Bouaziz, L.; Piovesan, T.; Dacheneder, F.; Snippen, E. (2021):
Optimale Talsperrenbewirtschaftung und ihr Nutzen für ein adaptives Einzugsgebietsmanagement:
Eine Fallstudie für das Maas-Einzugsgebiet. 44. Dresdner Wasserbaukolloquium 04. – 05. März 2021,
2021 in Dresden.

Klijn, F.; Hegnauer, M.; Beersma, J.; Sperna Weiland, F. (2015):
Wat betekenen de nieuwe klimaatscenario's voor de rivierafvoeren van Rijn en Maas? Samenvatting
van onderzoek met GRADE naar implicaties van nieuwe klimaatprojecties voor rivierafvoeren.
Deltares en Koninklijk Nederlands Meteorologisch Instituut. Rapport 1220042–004.
Maasafvoerverdrag: Verdrag tussen het Koninkrijk der Nederlanden en het Vlaams Gewest
inzake de afvoer van het water van de Maas. Maasafvoerverdrag, 17-01-1995.
URL: https://wetten.overheid.nl/BWBV0001232/1996-07-01 (Checked: 04/21/2022).

Kramer, N. (2021):
Lage afvoeren in de Maas / Bijdrage zijrivieren / Inzicht waar het water van de Maas vandaan komt.
RIWA - Vereniging van Rivierwaterbedrijven. ISBN 978-90-830759-4-5.

van der Krogt, W. N. M. (2019):
RIBASIM. Deltares. User Manual Addendum 2 Version 7.01.

van der Krogt, W. N. M. (2008):
RIBASIM. Deltares. Technical Reference Manual Version 7.001.
van der Krogt, W. N. M.; Boccalon, A. (2013): River Basin Simulation Model RIBASIM. Deltares. User Manual Version 7.00.

Lehner, B.; Reidy Liermann, C.; Revenga, C.; Vorosmarty, C.; Fekete, B.; Crouzet, P.; Doll, P.; Endejan, M.; Frenken, K.; Magome, J.; Nilsson, C.; Robertson, J. C.; Rodel, R.; Sindorf, N.; Wisser, D. (2011):
Global Reservoir and Dam Database, Version 1 (GRanDv1): Dams, Revision 01. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). URL: https://doi.org/10.7927/H4N877QK.

Messager, M. L.; Lehner, B.; Grill, G.; Nedeva, I.; Schmitt, O. (2016):
Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications Vol. 7 (2016) No. 1 pp. 13603. DOI: 10.1038/ncomms13603.

Raadgever, T. (2004):
Schademodellering laagwater Maas. Een onderzoek naar de omvang en de opbouw van de schade ten gevolge van lage Maasafvoeren in de huidige situatie en in een aantal scenario's voor autonome ontwikkelingen en beheer. Universiteit Twente.

Rijksoverheid (2021):
Nationaal Water Model. URL: https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/watermanagement/watermanagement/nationaal-water-model/ (Checked: 09/28/2021).

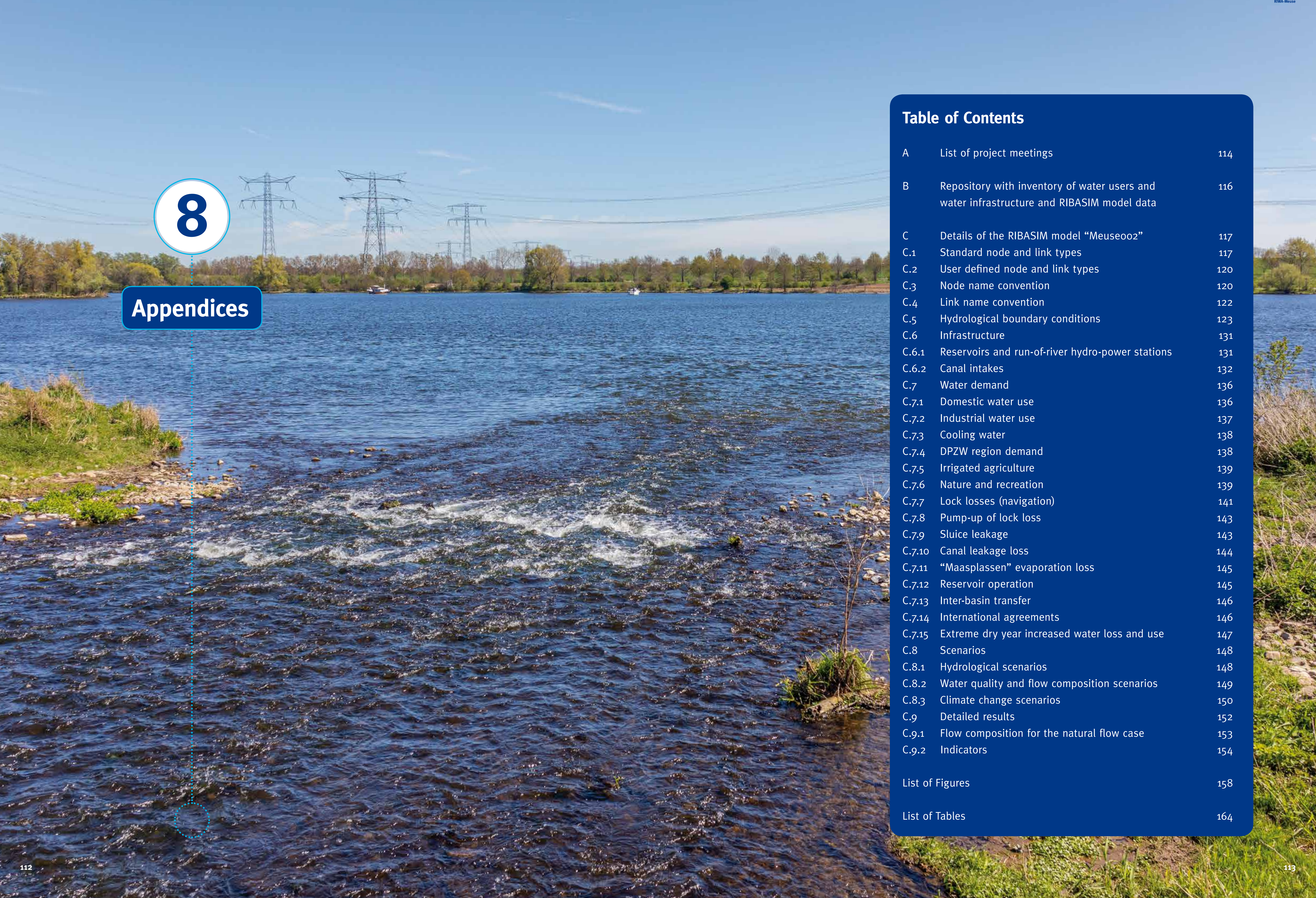
Römgens, H. (2013):
Climate change and the impact on drinking water supply in the Meuse river basin. In: Dewals, B., Fournier, M. (Eds.): Transboundary Water Management in a Changing Climate. London: Taylor & Francis Group. ISBN 978-1-138-00039-1.

Schellekens, J. W.; van Verseveld, W.; Visser, M.; Winsemius, H.; Euser, T.; Bouaziz, L.; Thiange, C.; de Vries, S.; Boisgontier, H.; Eilander, D.; Tollenaar, D.; Weerts, A.; Baart, F.; Hazenberg, P.; Lutz, A.; ten Velden, C.; Jansen, M.; Benedict, I. (2019):
Wflow 2020.1 release. URL: https://doi.org/10.5281/zenodo.3528154.

Sinaba, B.; Döring, R.; Kufeld, M.; Schüttrumpf, H.; Bauwens, A. (2013):
Impacts of future floods and low flows on the economy in the Meuse basin. In: Dewals, B., Fournier, M. (Eds.): Transboundary Water Management in a Changing Climate. London: Taylor & Francis Group. ISBN 978-1-138-00039-1.

Terrier, M.; Perrin, C.; Thirel, G. (2018):
Projet CHIMERE 21 / Vers une estimation des débits naturels sur le bassin versant de la Meuse. irstea. report.

Yamazaki, D.; Ikeshima, D.; Sosa, J.; Bates, P. D.; Allen, G. H.; Pavelsky, T. M. (2019):
MERIT Hydro: A High-Resolution Global Hydrography Map Based on Latest Topography Dataset. Water Resources Research Vol. 55 (2019) No. 6 pp. 5053–5073. DOI: 10.1029/2019WR024873.



8

Appendices

Table of Contents

A List of project meetings

During the project execution the following meetings have been organised:

Date	Organiser	Participants
25 Nov 2020	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares
19 Jan 2021	Maarten van der Ploeg (RIWA)	Maarten van der Ploeg (RIWA) Thomas Oomen (RIWA) Peter van Diepenbeek (WML) Arnoud Wessel (Evides) GertJan. Zwolsman (Dunea) Jaap Mos (Dunea) Co Dongen (Dunea) Aleksandra Jaskula (RWS Zuid West Ned) Lianita Suryawinata (RWS) Alinda van Ankum (RWS) Bernhard Becker (Deltares) Wil van der Krogt (Deltares) Nienke Kramer (Deltares)
5 Feb 2021	Maarten van der Ploeg (RIWA)	Maarten van der Ploeg (RIWA) Thomas Oomen (RIWA) Patrick Willems (Univ Leuven) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
9 Feb 2021	Maarten van der Ploeg (RIWA)	Maarten van der Ploeg (RIWA) Jean-Noël Pansera (IMC) Jérôme Delvaux (IMC) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
15 March 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares) Patrick Willems (Univ Leuven), absent
1 April 2021	Maarten van der Ploeg (RIWA)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares) Nienke Kramer (Deltares) Arnoud Wessel (Evides) Peter Diepenbeek(WML) Aleksandra Jaskula Joustra (RWS ZN) Bannink (RIWA) Gertjan Zwolsman (Dunea)
20 April 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
5 May 2021	Bernhard Becker (Deltares)	Frank Heijens (Waterschap Limburg) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
4 June 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
20 July 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
7 September 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares)
		Wil van der Krogt (Deltares)
7 October 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares) 2 guest participants
16 November 2021	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares)
14 December	Bernhard Becker (Deltares)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Aleksandra Jaskula (RWS) Harold van Waveren (RWS) Wim Werkman (RWS) Marieke van Gerven (Evides)
8 February 2022	Maarten van der Ploeg (RIWA)	Maarten van der Ploeg (RIWA) Bernhard Becker (Deltares) Wil van der Krogt (Deltares) Aleksandra Jaskula (RWS) Harold van Waveren (RWS) Wim Werkman (RWS) Marieke van Gerven (Evides) Mika den Hollander (Evides/RIWA)

B Repository with inventory of water users and water infrastructure and RIBASIM model data

Inventory of water users and water infrastructure in the Meuse and the RIBASIM water management model are stored in the SVN (Subversion) repository: https://repos.deltares.nl/repos/MeuseWaterBalanceModel/

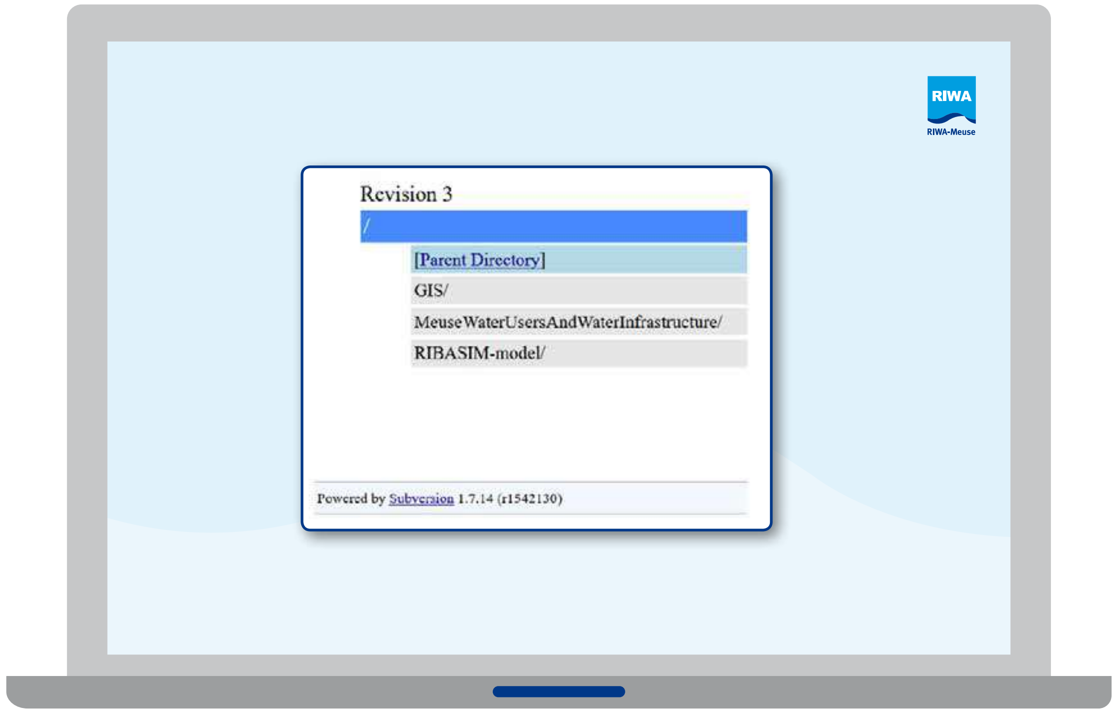
For read and write access please contact us by sending an e-mail to Bernhard.Becker@deltares.nl. The repository allows to track changes, to assign version numbers (the so-called revisions and to compare files between different versions. These features are in particular of interest when working with multiple organizations.

The repository is structured as follows:

- MeuseWaterBalanceModel
  - GIS
    This folder contains several GIS files that accompany the model and the inventory.
  - MeuseWaterUsersAndWaterInfrastructure
    This folder contains the Excel workbook with water users and water infrastructure in the Meuse:
    - MeuseWaterUsersAndWaterInfrastructure.xlsx
  - RIBASIM-model
    RIBASIM model input and output files (Meuse002.rbn)

The respository can be accessed with a web browser (Figure 86).
A client like Tortoise SVN (https://tortoisesvn.net/) allows to make use of advanced SVN features.

Figure 86 Screenshot from the repository view in a web browser.



Revision 3

/

[Parent Directory]
GIS/
MeuseWaterUsersAndWaterInfrastructure/
RIBASIM-model/

Powered by Subversion 1.7.14 (r1542130)

Source Deltares, edited by RIWA-Meuse

C Details of the RIBASIM model "Meuse002"

C.1 Standard node and link types

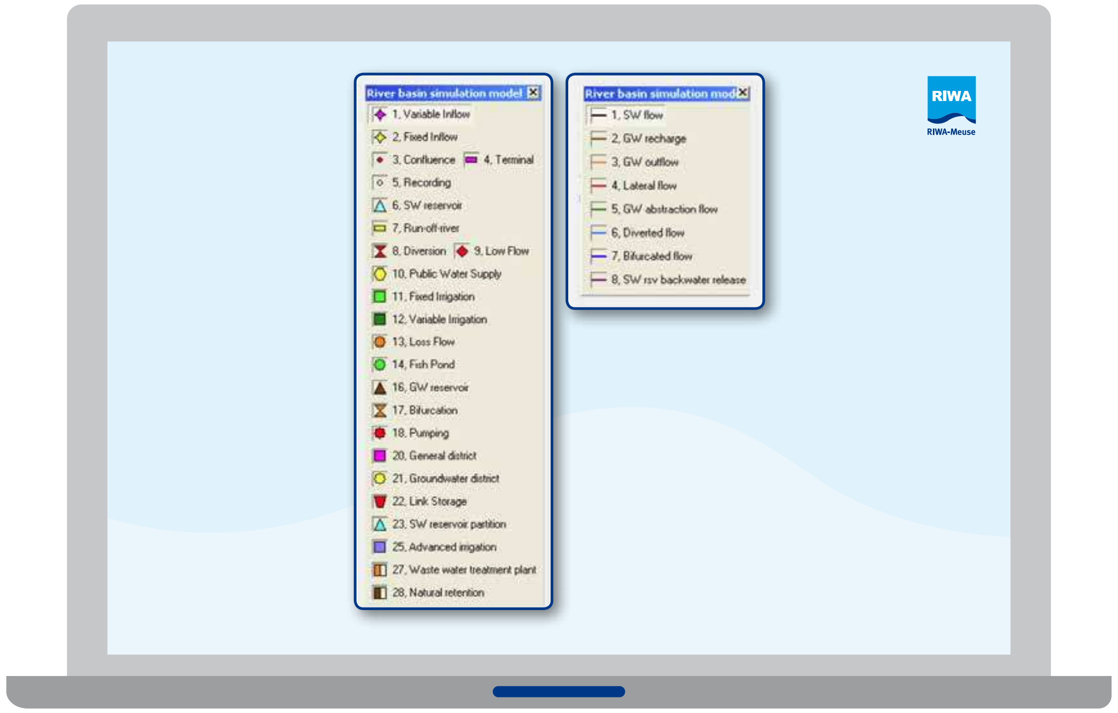
RIBASIM knows four main groups of elements:

- 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 87 and the Table 29 till

Table 32 list the standard types of nodes and links which can be used to build a RIBASIM network schematization.

Figure 87 Overview of the standard RIBASIM node and link types used to design the river basin network schematization.



Source Deltares, edited by RIWA-Meuse

Table 29 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 30 Overview of the demand (activity, water user) node types

Node type name	Representation
Fixed, variable and advanced irrigation nod	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 31 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 32 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.

C.2 User defined node and link types

In RIBASIM the user can define his own node and link types. Those user defined types are based on the standard node and link types as the parent type. The users defined types can be presented differently in the network design tool and at the presentation of results on map. Table 33 lists the user defined node and link types for the Meuse002 model.

Table 33 Overview of the user defined node and link types.

Node / link type name	Parent node / link type	Representation
Industrial use	Public water supply node	Industrial water use
Cooling water use	Public water supply node	Cooling water use
Domestic use	Public water supply node	Domestic and drinking water use
Pot. SW reservoir	Sw reservoir node	Potential surface water reservoir
Nature and recreation	Low flow node	Nature and recreational water use
Navigation	Low flow node	Navigation lock loss
Inter. agreement	Low flow node	International agreement between countries
RWZI discharge	Fixed inflow node	Waste water treatment plant discharge
Indust. discharge	Fixed inflow node	Industrial discharge
Meuse	Surface water flow link	Meuse river branche

C.3 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 In which country it is located
- For reservoirs: what is the purpose(s) is
- 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 "_Pot" to the names. Those nodes are set on inactive in the model data base.
The conventions for the node names are outlined in Table 35 to Table 38. Example node names and description of interpretation are shown in Table 34.

Table 34 Example node names.

Node name	Description
Rsv_De_Urfttalsperre_HMK	Reservoir Urftalsperre in Gemany with purpose flood protection, minimum / environmental flow and hydro-energy production
End_Fr_CanalMeuseCanalMarneAuRhinOuest	Terminal node at canal de la Marne au Rhine in France
Iws_Fr_CommercyArcelorMittal	Industrial water supply to Arcelor Mittal industry at Commercy in France
Reg2_Ne_ZuidWillemsVaart3	DPZW region 2 extraction from and discharge on part 3 of Zuid Willemsvaart in the Netherlands
Iir_Be_KanaalBocholtHerentals	All irrigation areas abstracting from Kanaal Bocholt-Herentals in the Belgium

Table 35 General node name convention.

Character	Description
1-3	Node type identification (3 characters, see Table 36)
4	Underscore
5-6	Identification of the country in which the node is located (2 characters, see Table 37)
7	Underscore
8	Identification of the purpose(s) of the reservoir (see Table 38)
9	Underscore
10-40	Name of representation e.g. location with: No spaces and underscores ('_') in the name. For potential structures and users "_Pot" is added at the end of the name.

Table 36 Node type identification.

Node type identification	Node type description
Bif	Bifurcation
Col	Public water supply: cooling water
Con	Confluence
Div	Diversion, weir and canal intake
Dom	Public water supply: drinking water (domestic and municipal water use)
End	Terminal: downstream boundary outflow
Fif	Fixed inflow: boundary inflow
Iir	Fixed irrigation
Ina	Low flow: international agreement
Iws	Fixed inflow: industrial discharge
Iws	Public water supply: industrial water use
Lfl	Low flow: reservoir operation and inter-basin transfer (canal operation)
Lkl	Terminal: canal leakage loss
Lpi	Fixed inflow: loop inflow
Lpo	Terminal: loop outflow
Nat	Low flow: nature and recreation
Nav	Low flow: navigation
Nto	Terminal: nature outflow
Pmp	Pump
Qls	Loss flow: "Maasplassen" evaporation Loss flow: extreme dry year increased water loss and use
Rec	Recording
Regxx	General district: DPZW region xx
Ror	Run-of-river hydro-power plant
Rsv	Surface water reservoir
Slk	Low flow: sluice leakage
Spm	Low flow: sluice pump-up of lock loss
Vif	Variable inflow (Wflow catchment runoff)
Wtp	Fixed inflow: waste water treatment plant discharge

Table 37 Country identification.

Country identification	Country name
Be	Belgium
De	Germany
Fr	France
Lu	Luxembourg
Ne	Netherlands

Table 38 Reservoir purpose identification.

Purpose identification	Purpose
A	Compensation reservoir
E	Recreation
F	Irrigated agriculture
H	Flood protection
I	Industrial water supply
K	Hydro-energy production
M	Minimum / environmental flow
S	Shipping / navigation
T	Drinking water supply

C.4 Link name convention

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

- What type of link it is;
- Which country it is located;

The conventions for the link names are mainly the same as for the node names. Table 39 shows some example link names. The link type identification is outlined in Table 40.

Table 39 Example link names.

Node name	Description
Swf_005_Wehebach	Surface water flow link with order number 005 in Wehebach River
Gwa_De_WeisweilerLignite MineDredgingWatr	Groundwater abstraction link at the Weisweiler lignite mine representing dredging water in Germany
Dvf_Ne_Noordervaart	Diverted flow link representing the intake to Noordervaart in the Netherlands

Table 40 Link type identification.

Link type identification	Link type description
Bff	Bifurcated flow link
Dvf	Diverted flow link
Gwo	Groundwater outflow link
Gwr	Groundwater recharge link
Swf	Surface water flow link

C.5 Hydrological boundary conditions

The hydrological boundary parameters for the Meuse002 model consist of:

a The inflow (runoff) for each variable inflow node
b The actual rainfall for each reservoir node
c The open water evaporation for each reservoir node
d The monitored flow for each recording node
e The demand and discharge for the general district nodes

The network schematization contains 60 variable inflow nodes. Figure 88 shows the Variable inflow nodes on the map and the sub-basin that the node represents. Table 41 lists the Variable inflow node index and name, sub-basin area (km2) and the area per country. The node name specifies the sub-basin location. The 60 nodes represent the following:

1. The 56 Wflow sub-basins for which multiple year runoff time series have been generated with the Wflow model. The sub-basin area is also generated with the Wflow model.
2. The 3 sub-basins identified in the Netherlands downstream monitoring station Mook represented by nodes 449, 451 and 452. The inflow time series for those nodes has been set to 0.0.
3. The flow from the Rur River basin into the Meuse River upstream of Roermond. This flow equals to the monitored flow at station Stah. As outlined in chapter 4.3.2 the part of the network schematization of the Rur river basin has been disconnected from the Meuse network schematization. The Rur river basin is represented by a separate variable inflow node (Node Id 48 and node name “Vif_De_Stah”), see Figure 89.

Time series of the Variable inflow nodes are stored in the hydrological scenario file Actinflw.tms.The multiple year actual rainfall and open water evaporation time series are generated with the Wflow model. Time series are available for the locations of each reservoir. The schematization contains 16 reservoir nodes: 15 existing and one potential reservoir. The 16 timeseries are stored in the hydrological scenario files Actrain.tms and Evaporat.tms file. The rainfall and open water evaporation is used in the model for the computation of the actual rainfall on and evaporation from the reservoir surface area.

The network schematization includes 46 recording nodes representing flow monitoring stations. The sub-project A (Kramer 2021) provided the daily flow time series for 23 stations from 1 January 1998 till 31 December 2020. Figure 90 shows those 23 recording nodes on the map. The name of those 23 recording nodes include the phrase “_Q”. The other 23 recording nodes do not have this phrase in the name. Table 42 lists the 23 recording nodes. The time series are used in RIBASIM and are stored in the hydrological scenario file Recrdflw.tms.

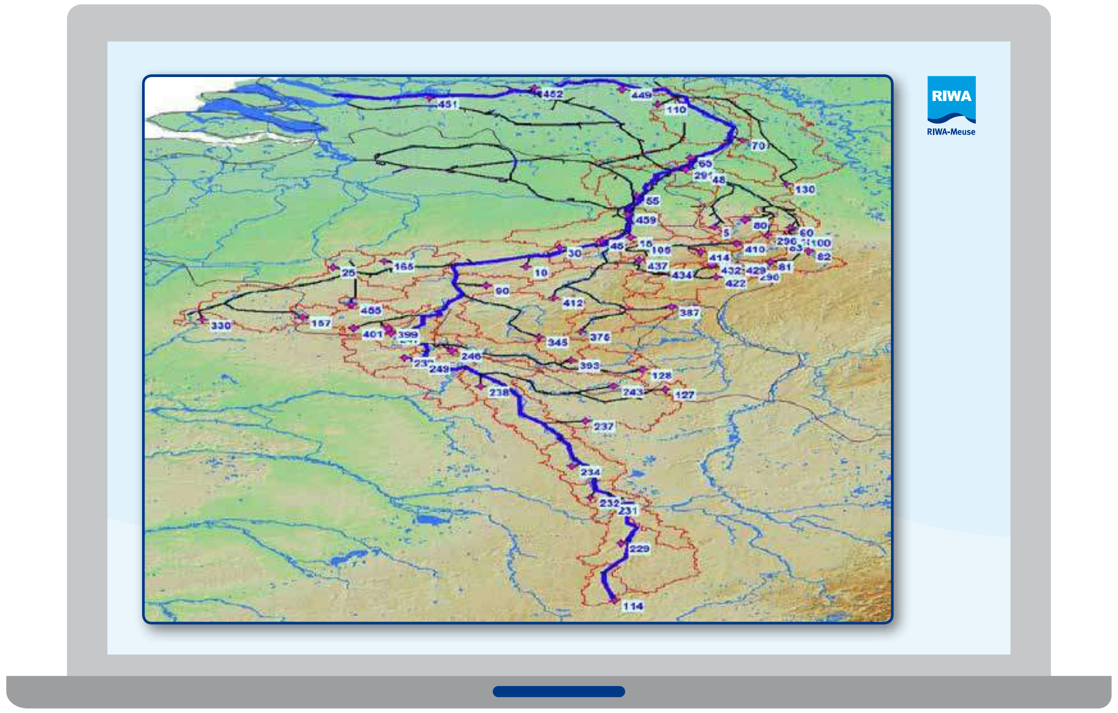
The network schematization includes 48 waste water treatment plant discharge nodes. The discharge time series is an annual time series. Table 43 and Table 44 list the nodes, the status (active or inactive) and the annual discharge.

The network schematization includes 16 general district nodes consisting of:

- 1 node for the discharge of the Dommel, Aa en Dieze
- 15 nodes for the demand and discharge from the DPZW regions 2, 3, 7 and 14 (see chapter 4.3.1). The demand and discharge time series are generated by the LHM. The distribution of the DPZW region demand and discharge over the 15 nodes is based on the percentages listed in Table 45 (Johnen, 2020).

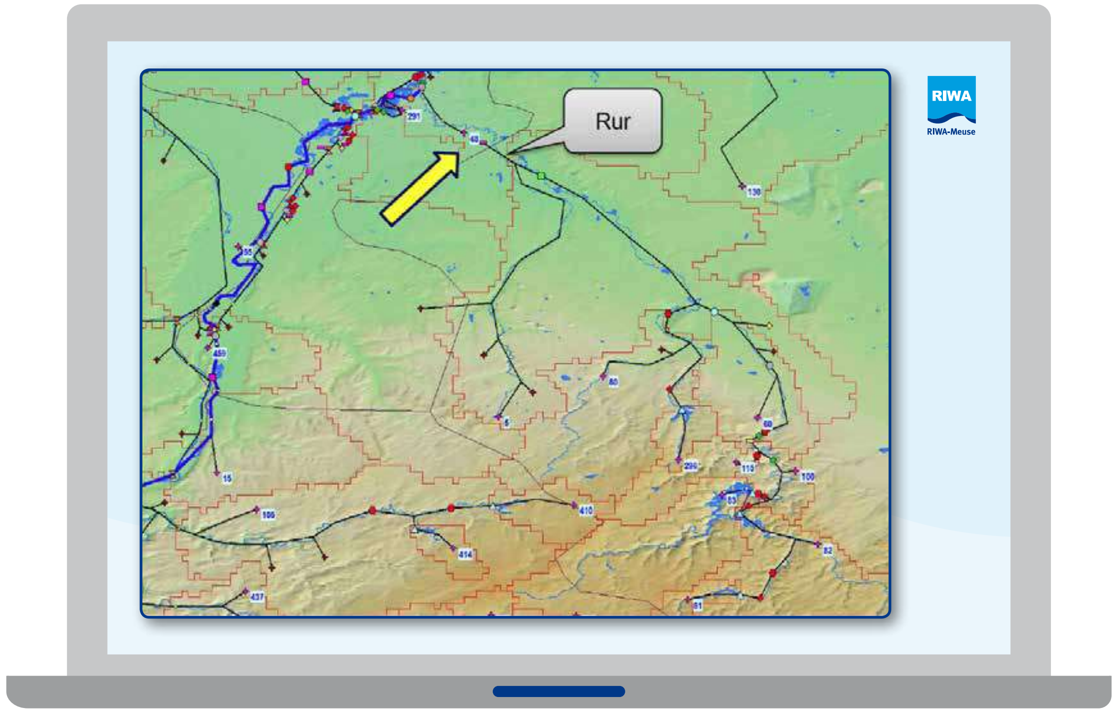
The network schematization includes 8 industrial discharge nodes. The discharge time series is an annual time series. Table 46 lists the nodes and the annual discharge.

Figure 88 Overview of the 60 variable inflow nodes (purple star) and node index.



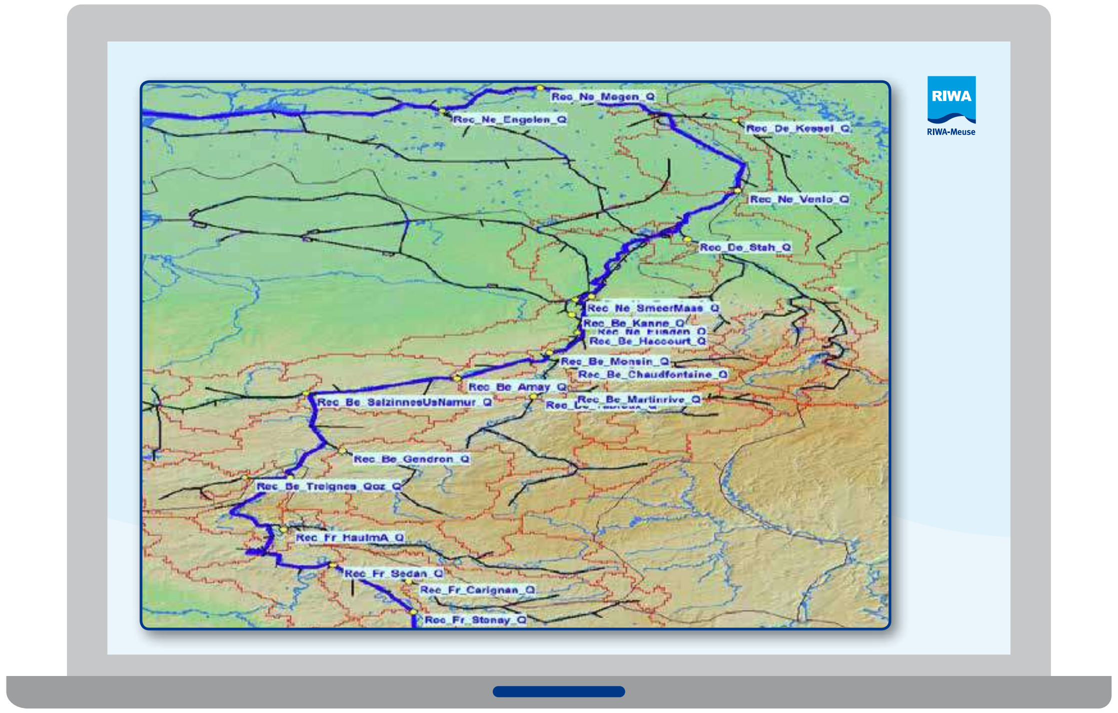
Source Deltares, edited by RIWA-Meuse

Figure 89 Part of the Meuse002 network schematization for the Rur River basin which has been disconnected from the Meuse network schematization at monitoring station Stah (yellow arrow).



Source Deltares, edited by RIWA-Meuse

Figure 90 Overview of the 23 recording nodes representing river flow monitoring stations of sub-project 1A.



Source Deltares, edited by RIWA-Meuse

Table 41 Overview of the 60 variable inflow nodes and sub-basin area (km²)

Node Id	Node name	Area (km²) *	Area per country (km²)
10	Vif_Be_DsPwsTailfrRecSlznnsDsNmrUsRecAmy	1013.4	
15	Vif_Be_M5DsBifAlbertKanaalUsRecEijsden	265.8	
25	Vif_Be_DsDivSambrOiseUsDivCnlChrlrBrxlls	1768.4	
30	Vif_Be_DsRecAmayUsIwsSeraing	207.9	
45	Vif_Be_DsRecChdfntDsIwsSrgUsBifAlbertKnl	293.6	
55	Vif_Be_M6DsBifJulinKnlUsBifKnlWssmNdrwrt	1339	
90	Vif_Be_DsRecChoozDsRecGendrnUsPwsTailfer	1150	
105	Vif_Be_DsRsvVesdreDsRsvGlpUsRecChaudfntn	573.1	
128	Vif_Be_SemoisDsRsvVierreUsRecMembre	996.9	
165	Vif_Be_DsCnlChrlrBrxllsUsRecSlznnsUsNamr	716.1	
246	Vif_Be_DsRecMembreUsRecHaulmA	94.9	
290	Vif_Be_UsRsvButgenbach	75.8	
345	Vif_Be_LesseUsRecGendron	1317.5	
375	Vif_Be_OurtheOccidentaleUsRecOrtho	394.1	
387	Vif_Be_OrientaleDsRecOrthoUsRsvNisramont	342.8	
393	Vif_Be_UsRsvVierre	242.8	
399	Vif_Be_UsRsvRyDeRome	9.4	
401	Vif_Be_DsRsvRyDeRomeUsRecTreignes	538.3	
410	Vif_Be_VesdreUsRsvVesdre	73.8	
412	Vif_Be_DsRsvNisramontUsRecTabreux	879.6	
414	Vif_Be_UsRsvGileppe	37.8	
422	Vif_Be_DsRecMalmedyUsRsvCoo	588.4	
429	Vif_Be_DsRsvButgenbachUsRsvRobertville	39.0	
432	Vif_Be_DsRsvRobertvilleUsRecMalmedy	32.9	
434	Vif_Be_DsRsvCooUsRecTargnon	219.4	
437	Vif_Be_DsRecTargnonUsRecMartinrive	115.2	
455	Vif_Be_EauDHeureUsRsvLesLacsDeLEauDHeure	78.3	
			13404.2
5	Vif_De_DsPwsIndeDsIwsWeisweilerUsRecStah	846.8	
60	Vif_De_DsRsvObermaubachUsIwsWeisweiler	160.7	
80	Vif_De_DsRsvWehebachtalsperreIUsPwsInde	313.5	
81	Vif_De_UsRsvOlef	49.4	
82	Vif_De_DsRsvOlefUsRsvUrfttalsperre	321.8	
83	Vif_De_UsRsvRurtalsperre	291.9	
100	Vif_De_DsRsvUrfttalsprreUsRsvObermaubach	57.4	
115	Vif_De_KallUsPwsKall	78.7	
130	Vif_De_NiersUsRecGoch	1402.8	
296	Vif_De_UsRsvWehebachtalsperre	42.0	
			3565.0
14	Vif_Fr_MeuseUsRecGoncourtPlateauLangres	365.3	
157	Vif_Fr_HelpeMajeureUsRsvValDuJoli	179.6	
229	Vif_Fr_DsRecGoncourtUsRecChalaines	1393.7	
231	Vif_Fr_DsRecChlnsUsDivCnlMarneAuRhnOuest	544.7	
232	Vif_Fr_DsCnlMrnAuRhnOuestUsRecSaintMhiel	255.4	

Table 41 Continued

Node Id	Node name	Area (km²) *	Area per country (km²)
234	Vif_Fr_DsRecSaintMihielUsRecBelleville	664.5	
237	Vif_Fr_DsRecBellevilleUsRecStenay	707.5	
238	Vif_Fr_DsRecStenayDsRecCarignanUsRecSedn	612.6	
239	Vif_Fr_SourceSormonneUsPriseDEauSormonne	442.1	
247	Vif_Fr_DsRecMntcyNtrDmDsRecTrgnsUsRecChz	513.9	
249	Vif_Fr_DsRecSdnDsPrsEauSrmnUsRecMntNtrDm	804.1	
330	Vif_Fr_SambreUsDivCanalDeLaSambreLOise	148.2	
			6631.6
127	Vif_Lu_ChiersUsRecLonglaville	151.4	
243	Vif_Lu_DsRecLonglavilleUsRecCarignan	1836.1	
			1987.5
65	Vif_Ne_M8DsConMeuseLateraalKnlUsRecVenlo	1108.0	
70	Vif_Ne_M9DsSluisBelfeldUsSluisSambeek	818.6	
110	Vif_Ne_M10DsRecGochDsSlsSambeekUsRecMook	293.8	
291	Vif_Ne_M7DsBifKnlWssmNdrwrtUsConLatrlKnl	108.2	
449	Vif_Ne_M11DsRecMookUsRecMegen	0.0	
451	Vif_Ne_M13DsConWilhelmnKnlUsEndHollndsDp	0.0	
452	Vif_Ne_M12DsRecMegenUsConMeuseWilhlmnKnl	0.0	
459	Vif_Ne_M6DsRecEijsdenUsBifJulianaKanaal	669.7	
			2998.3
	Total		**28586.6**
48	Vif_De_Stah	2135.2	

* Source of the area data is the Wflow model, only for node 48 the station Stah data.

Table 42 Overview of the 23 recording nodes representing river flow monitoring stations of sub-project A

Node Ix	Node name
122	Rec_Fr_Stenay_Q
133	Rec_Fr_Carignan_Q
144	Rec_Fr_HaulmA_Q
146	Rec_Fr_Sedan_Q
160	Rec_Be_Kanne_Q
170	Rec_Fr_Chooz_Q
190	Rec_Be_Tabreux_Q
271	Rec_Be_Gendron_Q
272	Rec_Be_Martinrive_Q
273	Rec_Be_Chaudfontaine_Q
274	Rec_Be_Amay_Q
278	Rec_De_Kessel_Q
283	Rec_Be_SalzinnesUsNamur_Q
334	Rec_Be_Haccourt_Q

Table 42 Continued

Node Ix	Node name
343	Rec_Ne_SmeerMaas_Q
397	Rec_Ne_Eijsden_Q
403	Rec_Be_Treignes_Q
405	Rec_Ne_Bunde_Q
453	Rec_Ne_Venlo_Q
454	Rec_Ne_Megen_Q
456	Rec_Ne_Engelen_Q
458	Rec_De_Stah_Q
515	Rec_Be_Monsin_Q

Table 43 Overview of the 29 variable inflow nodes representing the waste water treatment plants in Belgium, Germany and France, status, location and annual discharge (106 m^3).

Node Id	Node name	Node status *	River / canal section	Annual water discharge (10^6 m^3)	Annual water discharge per country (10^6 m^3)
616	Wtp_Be_MarchienneAuPont	Active	Sam	3.500	
617	Wtp_Be_MontigniesSurSambre	Active	Sam	8.767	
618	Wtp_Be_IgretecRoselies	Active	Sam	5.550	
619	Wtp_Be_NamurBrumagne	Active	M3	4.068	
620	Wtp_Be_Amay	Active	M4	2.365	
621	Wtp_Be_Wegnez	Active	Ves	4.352	
622	Wtp_Be_Goffontaine	Active	Ves	1.198	
623	Wtp_Be_LiegeGrossesBattes	Active	Ves	2.334	
624	Wtp_Be_LiegeSclessin	Active	M4	5.929	
626	Wtp_Be_Oupeye	Active	AC1	17.597	
627	Wtp_Be_Riemst	Active	AC1	1.640	
631	Wtp_Be_Bree	Active	ZWV1	4.194	
632	Wtp_Be_Lommel	Active	CBH1	10.848	
					72.342
634	Wtp_De_KlaranlageEschweiler	Inactive	Rur	3.406	
636	Wtp_De_DurenMerken	Inactive	Rur	13.497	
639	Wtp_De_MonchengladbachNeuwerk	Active	Nrs	30.306	
641	Wtp_De_Gefrath	Active	Nrs	13.214	
642	Wtp_De_Geldern	Active	Nrs	8.136	
643	Wtp_De_KevelaerWeeze	Active	Nrs	4.857	
644	Wtp_De_Kessel	Active	Nrs	4.384	
702	Wtp_De_AachenSoers	Inactive	Rur	15.768	
706	Wtp_De_HerzogenrathSteinbusch	Inactive	Rur	0.568	
					94.136
607	Wtp_Fr_Neufchateau	Active	M0	0.536	
608	Wtp_Fr_Commercy	Active	M0	0.347	

Table 43 Continued

Node Id	Node name	Node status *	River / canal section	Annual water discharge (10^6 m^3)	Annual water discharge per country (10^6 m^3)
609	Wtp_Fr_BellevilleSurMeuse	Active	M0	1.293	
611	Wtp_Fr_Longwy	Active	Chr	4.636	
612	Wtp_Fr_Sedan	Active	M0	3.122	
613	Wtp_Fr_CharlevilleMezieres	Active	M0	4.699	
614	Wtp_Fr_Nouzonville	Active	M0	0.442	
					15.075

Table 44 Overview of the 19 variable inflow nodes representing the waste water treatment plants in the Netherlands, status, location and annual discharge (106 m^3).

Node Id	Node name	Node status *	River / canal section	Annual water discharge (10^6 m^3)	Annual water discharge per country (10^6 m^3)
628	Wtp_Ne_MaastrichtBosscherveld	Active	ZWV1	5.046	
629	Wtp_Ne_MaastrichtLimmel	Active	JC	10.407	
633	Wtp_Ne_ChemelotStein	Active	JC	2.523	
637	Wtp_Ne_Susteren	Active	JC	17.660	
638	Wtp_Ne_Hoogvonderen	Active	M8	13.245	
646	Wtp_Ne_Venlo	Active	M9	23.021	
647	Wtp_Ne_LandVanCuijk	Active	M10	11.668	
648	Wtp_Ne_Asten	Active	ZWV3	5.046	
649	Wtp_Ne_AarleRixtel	Active	ZWV3	23.021	
651	Wtp_Ne_Eindhoven	Active	WC	53.927	
652	Wtp_Ne_sHertogenbosch	Active	ZWV3	18.922	
653	Wtp_Ne_Rijen	Active	WC	4.730	
654	Wtp_Ne_Tilburg	Active	WC	22.706	
656	Wtp_Ne_Oijen	Active	M11	18.922	
657	Wtp_Ne_Dinther	Active	ZWV3	16.083	
658	Wtp_Ne_Vinkel	Active	ZWV3	4.100	
659	Wtp_Ne_Boxtel	Active	ZWV3	5.046	
699	Wtp_Ne_Weert	Active	ZWV2	7.569	
708	Wtp_Ne_Kaffeberg	Inactive	Rur	3.784	
					267.426
	Total over all Wtp nodes				**448.979**

* If the node status is active or inactive which means that the node is part of the simulation or not.

Table 45 Distribution percentage of the DPZW region demand and discharge from LHM over the 15 General district nodes.

Node Id	Node name	DPZW region	Percentage
37	Reg2_Ne_M9	2	31.6%
39	Reg2_Ne_KanaalWessemNederweert	2	5.3%
41	Reg2_Ne_Noordervaart	2	4.1%
43	Reg2_Ne_ZuidWillemsVaart2	2	17.5%
44	Reg2_Ne_ZuidWillemsVaart3	2	11.1%
46	Reg2_Ne_ZuidWillemsVaart4	2	17.5%
91	Reg2_Ne_M7	2	1.2%
92	Reg2_Ne_M8	2	11.7%
42	Reg3_Ne_WilhelminaKanaal	3	100.0%
93	Reg7_Ne_M10	7	40.0%
94	Reg7_Ne_M11	7	40.0%
96	Reg7_Ne_M12	7	20.0%
6	Reg14_Ne_M6	14	25.0%
36	Reg14_Ne_M5	14	50.0%
38	Reg14_Ne_JulianaKanaal	14	25.0%

Table 46 Overview of the 8 industrial discharge nodes and the annual inflow (106 m³).

Node Id	Node name	Annual inflow (10^6 m³)	
717	Iws_Fr_MeuseSaintThiebaultBG	0.315	
718	Iws_Fr_FoursAChauxSorcy	0.063	
719	Iws_Fr_CommercyArcelorMittal	0.063	
721	Iws_Fr_FrmgrHenriHutinAndCarieresEtFours	0.505	
722	Iws_Fr_UnionLaitAndSolevalAndLactoSerum	1.451	
723	Iws_Fr_MouzonArcelorMittalAtIntqueEtLorn	0.032	
724	Iws_Fr_MeuseCharlvilMeziersHannSystmsSAS	0.032	
725	Iws_Fr_ChalandryElaireArcavi	0.032	
	Total		**2.493**

C.6 Infrastructure

C.6.1 Reservoirs and run-of-river hydro-power stations

All 14 existing reservoirs in the network schematization are listed in Table 47. The 4 nodes representing run-of-river hydro-power stations and the installed power capacity (MW) are listed in Table 48. The data has been collected from various sources, among others from Johnen 2020 and Berger & Mugie 1994.

Table 47 Overview of existing reservoirs, the location and the full reservoir storage (106 m³) in the Meuse model.

Node Ix	Node name	River	Full reservoir storage (10^6 m³)	Full storage per country (10^6 m³)	Percentage of total storage per country (%)
384	Rsv_Be_Nisramont_TK	Ourthe	3.00		
392	Rsv_Be_Vierre_K	Semois	1.50		
398	Rsv_Be_RyDeRome_TI	Viroin	2.20		
416	Rsv_Be_Gileppe_TK	Vesdre	26.50		
420	Rsv_Be_VesdreLacDeEupen_TH	Vesdre	25.00		
421	Rsv_Be_CooTroisPontsSpmp_K	Ambleve	8.40		
426	Rsv_Be_Robertville_KITH	Ambleve	7.68		
427	Rsv_Be_Butgenbach_KHIE	Ambleve	10.86		
460	Rsv_Be_LesLacsDeLEauDHeureSpmp_SMK	Eau d'heure	78.87		
				164.01	37%
77	Rsv_De_Oleftalsperre_KHT	Olef	19.30		
78	Rsv_De_Urfttalsperre_HMK	Urft	48.47		
210	Rsv_De_Rurtalsperre_HTK	Rur	181.80		
297	Rsv_De_Wehebachtalsperre_HTM	Wehebach	25.06		
				274.63	62%
156	Rsv_Fr_ValDuJoly_T	Helpe Majeure	3.60		
				3.60	1%
	Total			**442.24**	

Table 48 Overview of the run-of-river hydro-power stations and its installed capacity (MW) in the Meuse model.

Node Id	Node name	Installed capacity (MW)
428	Ror_Be_LorceHeidDeGoreux	8.10
469	Ror_Be_AndenneSeilles	9.00
471	Ror_Be_AmpsinNeuville	9.90
235	Ror_De_Obermaubach	0.65

C.6.2 Canal intakes

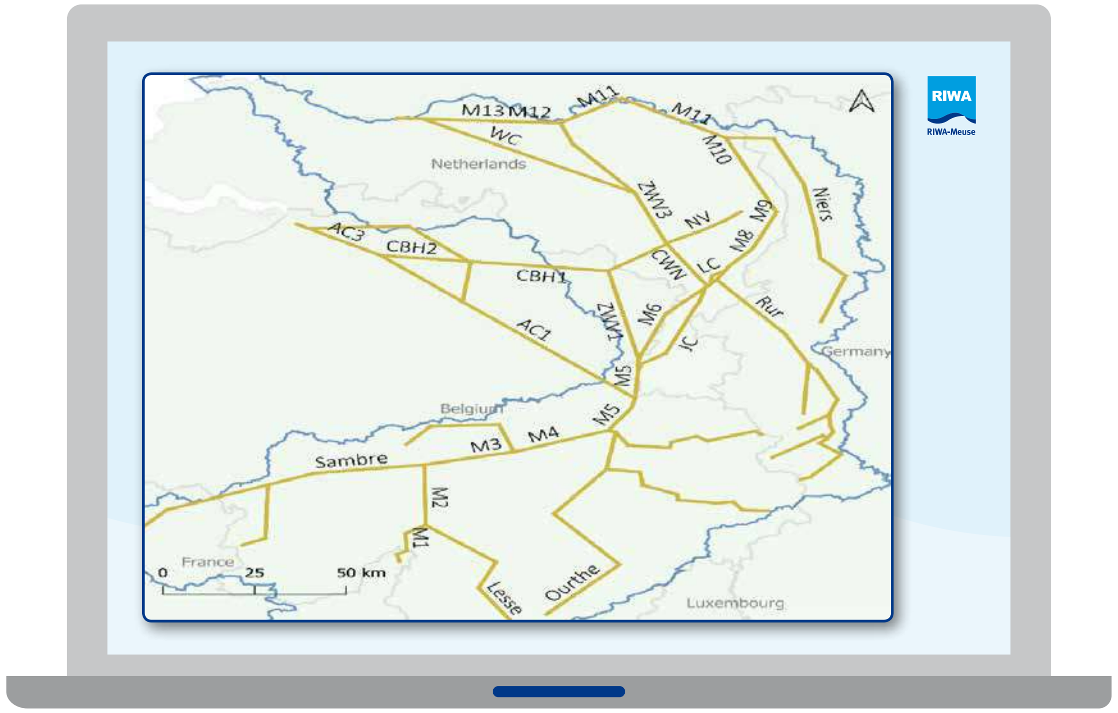
Many canals are part of the network schematization. Table 49 list the canal and river sections and its annotations which is used in this report. Figure 91 shows the annotations on a map. The row colours represent the countries.

Intakes of canals are schematized with the two node types: diversion and bifurcation nodes. Table 50 lists the diversion nodes and Table 51 lists the bifurcation nodes representing the intake of canals. At the diversion nodes the water distribution is based on the demand of the user(s) downstream. At the bifurcation node the water distribution is based on a relation between the upstream and downstream links. The implemented relations are based on the table shown in Table 54.

The model schematization contains 8 sluices for which an intake for pump-up of lock losses are represented with a diversion node. Table 52 list those nodes, sluices and the intake canal.

The model schematization contains 4 canals for which the canal losses are represented with a bifurcation node. Table 53 lists those nodes and the intake canal.

Figure 91 Annotations of Meuse River sections, tributaries and canals (Johnen 2020).



Source Deltares, edited by RIWA-Meuse

Table 49 List of annotations for the Meuse river sections, tributaries and canals.

Annotation	River section, tributary or canal	From-To
M0	Meuse	Source-Chooz
CMR	Canal Marne Au Rhin Ouest	
Chr		Chiers
M1	Meuse	Chooz-Anseremme (confluence of Meuse-Lesse)
CSO	Canal de la Sambre l'Oise	
Sam	Sambre	
CCB	Canal Charleroi - Bruxelles	Charleroi - Bruxelles
M2	Meuse	Anseremme (confluence of Meuse-Lesse) -Namur
M3	Meuse	Namur-Tihange
M4	Meuse	Tihange-Liege (confluence of Meuse-Outhe)
Ves	Vesdre	
Our	Ourthe	
M5	Meuse	Liege (confluence of Meuse-Outhe) -Borgharen
AC1	Albert Canal	Monsin (M5)-Kwaadmechelen
AC2	Albert Canal	Kwaadmechelen-Herenthals
AC3	Albert Canal	Herenthals-Schoten
CBH1	Canal Bocholt-Herenthals (Kempisch)	Bocholt-Dessel
NC	Nete Canal	
CBH2	Canal Bocholt-Herenthals (Kempisch)	Dessel-Herenthals
CDK	Canal Dessel-Kwaadmechelen	Dessel-Kwaadmechelen
CDTS	Canal Dessel-Turnhout-Schoten	Dessel-Turnhout-Schoten
JC	Juliana Canal	Borgharen-Linne
LC	Lateraal Canal	Linne-Buggenum
	CWN	Canal Wessem-Nederweert Linne-Nederweert
NV	Noordervaart	Nederweert-Beringe
WC	Wilhelmina Canal	Beek-Oosterhout
ZWV1	Zuid-Willemsvaart	Smeermaas-Bocholt
ZWV2	Zuid-Willemsvaart	Bocholt-Nederweert
ZWV3	Zuid-Willemsvaart	Nederweert-Beek
ZWV4	Zuid-Willemsvaart	Beek-Den Bosch
M6	Meuse (Common Meuse)	Borgharen-Linne
M7	Meuse	Linne - Roermond (confluence with Lateraal kanaal)
Rur	Rur	
M8	Meuse	Roermond (confluence with Lateraal kanaal) - Belfeld
M9	Meuse	Belfeld-Sambeek
M10	Meuse	Sambeek-Grave
Nrs	Niers	
M11	Meuse	Grave-Lith
M12	Meuse	Lith-Hedel (confluence with Dieze)
M13	Meuse	Hedel-Keizersveer
M14	Meuse	Keizersveer – Hollands Diep

Table 50 Overview of nodes representing canal intakes and its location in the Meuse model.

Node Ix	Node name	Location	Intake canal or river
267	Div_Be_CanalCharleroiBruxelles	Sambre	Canal Charleroi-Bruxelles
461	Div_Be_AlbertKanaalNeteKanaal	Albert Canal	Nete Canal
124	Div_Fr_CanalMeuseCanalMarneAuRhinOuest	Meuse	Canal Meuse - Canal Marne Au Rhine Ouest
161	Div_Fr_CanalDeLaSambreLOise	Sambre	Canal De La Sambre L'Oise
29	Div_Ne_PanheelSluice	Kanaal Wessem-Nederweert	Sluis Panheel
443	Div_Ne_MaasWaalKanalHeumenSluiceLockLoss	Meuse	Maas-Waal kanaal at Heumen
481	Div_Ne_LusVanLinne	Meuse	Lus Van Linne
501	Div_Ne_M6DSM	Juliana Kanaal	Intake of water supply DSM from Juliana Canal
524	Div_Ne_BosscherveldSluiceLockLoss	Zuid Willemsvaart	Meuse
688	Div_Ne_Sambeek	Meuse	Sambeek canal and Oeffeltse Raam
690	Div_Ne_GraafscheRaamNature	Meuse	Graafsche Raam
698	Div_Ne_SintAndriesSluiceLockLoss	Meuse	Kanaal van Sint Andries
714	Div_Ne_WilhelminaSluiceLockLossAndel	Meuse	Afgedamde Maas

Table 51 Overview of canal intakes represented by a bifurcation node.

Node Ix	Node name	Location	Intake canal or river
4	Bif_Be_KanaalDesselTurnhoutsSchoten	Canal Bocholt-Herenthals	Canal Dessel Turnhouts Schoten
7	Bif_Be_KanaalDesselKwaadmechelen	Albert Canal	Canal Dessel-Kwaadmechelen
464	Bif_Be_KanaalBriegdenNeerharen	Albert Canal	Canal Briegden-Neerharen
520	Bif_Be_AlbertKanaal	Meuse	AlbertKanaal
560	Bif_Be_ZuidWillemsvaartBocholt	Zuid Willemsvaart	Kanaal Bocholt-Herenthals
1	Bif_Ne_Noordervaart	Zuid Willemsvaart	Noordervaart
14	Bif_Ne_LateraalKanaal	Meuse	Lateraal Canal
373	Bif_Ne_MarkKanaal	Wilhelmina Kanaal	Mark Kanaal
535	Bif_Ne_JulianaKanaalMaastricht	Meuse	Juliana Canal
555	Bif_Ne_ZuidWillemsvaartMaastricht	Meuse	Zuid Willemsvaart
590	Bif_Ne_KanaalWessemNederweert	Meuse	Kanaal Wessem-Nederweert
615	Bif_Ne_WilhelminaKanaalBeekerheide	Zuid Willemsvaart	Wilhelmina Canal

Table 52 Overview of 8 diversion nodes representing the sluices with pump-up of lock loss, and intake canal.

Node Ix	Node name	Location	Intake canal or river
557	Div_Be_GenkSluicePumpUpLockLoss	Genk Sluice	Albert canal
565	Div_Be_KwaadmechelenSluicePumpUpLockLoss	Kwaadmechelen Sluice	Albert canal
573	Div_Be_OlenSluicePumpUpLockLoss	Olen Sluice	Albert canal
579	Div_Be_HeerenthalsSluicePumpUpLockLoss	Heerenthals Sluice	Kanaal Bocholt-Herenthals
581	Div_Be_WijnegemSluicePumpUpLockLoss	Wijnegem Sluice	Albert canal
582	Div_Be_RijkevorselSluicePumpUpLockLoss	Rijkevorsel Sluice	Canal Dessel Turnhouts Schoten
498	Div_Ne_BornSluicePumpUpLockLoss	Born Sluice	Juliana canal
532	Div_Ne_MaasbrachtSluicePumpUpLockLoss	Maasbracht Sluice	Juliana canal

Table 52 Continued

Table 53 Overview of 4 bifurcation nodes representing the canal losses.

Node Id	Node name	Canal
324	Clk_Ne_JulianaCanalLeakageLoss	Juliana Canal
547	Clk_Ne_WilhelminaCanalLeakageLoss	Wilhelmina Canal
548	Clk_Ne_ZuidWillemsVaart3LeakageLoss	Zuid Willemsvaart section 3
549	Clk_Ne_ZuidWillemsVaart4LeakageLoss	Zuid Willemsvaart section 4

Table 54 Base table for the distribution of Meuse water over the Common Meuse, the Juliana Canal and the other channels according to Helmyr & Jaskula-Joustra (2001) & Raadgever (2004).

CDTS	CDK	CBH2	CBH1	AC3	AC2	AC1	ZVW2	ZVW1	CWN	JC	M6	M5	Monsin
1	1.8	6.2	9	24	28	26	10	19	5.3	25	60	104	**130**
1	1.8	6.2	9	32	26	24	10	19	5.3	23	58	101	**125**
1	1.8	6.2	9	31	25	23	10	19	5.3	22	57	97.3	**120**
1	1.8	6.2	9	29	23	21	10	19	5.3	20	55	94	**115**
1	1.8	6.2	9	27	21	19	10	19	5.3	18	53	90.7	**110**
1	1.8	6.2	9	26	20	18	10	19	5.3	17	52	87.3	**105**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	50	84	**100**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	45	79	**95**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	40	74	**90**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	35	59	**85**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	30	64	**80**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	25	59	**75**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	20	54	**70**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	15	49	**65**
1	1.8	6.2	9	24	18	16	10	19	5.3	15	10	44	**60**
1	1.8	6.2	9	22	15	14	7.5	16.5	7.5	15	10	41.5	**55**
1	1.8	5.2	8	19	14	12	5.5	13.5	9	15	10	38	**50**
1	0.2	4.9	6.1	17	12	11	5.5	11.6	5.6	12	10	33.6	**45**
1	0.2	3.9	5.1	14	10	9.9	5.5	10.6	4.5	9.5	10	30.1	**40**
1	0.2	3.9	5.1	12	7.6	7.4	5	10.1	4.5	7.5	10	27.6	**35**
1	0.2	3.9	5.1	9	5.1	4.9	5	10.1	4.5	5	10	25.1	**30**
1	0.1	2.9	4	7.3	4.4	4.3	3.5	7.5	4.5	3.2	10	20.7	**25**
1	0.1	1.9	3	5.7	3.8	3.7	2	5	4.5	1.3	10	16.3	**20**

C.7 Water demand

In the next chapters the different types of water demand per river sections, tributary and canal are listed. Table 49 list the annotations of the canal and river sections.

C.7.1 Domestic water use

The network schematization contains 20 nodes representing domestic water demand. Table 55 lists the nodes, the river or canal sections from where water is abstracted (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 55 Overview of the 20 domestic water demand nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
64	Dom_Be_Eupen	Be	Ves	16.399	
66	Dom_Be_Stembert	Be	Ves	12.930	
370	Dom_Be_Tailfer	Be	M2	52.665	
389	Dom_Be_DomesticNisramontRsv	Be	Our	11.040	
462	Dom_Be_NeteKanaal	Be	NC	96.469	
600	Dom_Be_AlbertKanaal	Be	AC3	52.791	
606	Dom_Be_RyDeRomeRsv	Be	M1	2.523	
					244.82
85	Dom_De_Inde	De	Rur 1	15.768	
86	Dom_De_Olef	De	Rur 1	3.784	
87	Dom_De_Rur	De	Rur 1	13.876	
120	Dom_De_Kall	De	Rur 1	11.668	
245	Dom_De_RsvObermaubach	De	Rur 1	5.046	
					50.14
242	Dom_Fr_ChiersMontMedy	Fr	Chr	0.725	
248	Dom_Fr_PriseDEauSormonneChrlvillMezieres	Fr	M0	1.451	
256	Dom_Fr_MeuseGizet	Fr	M1	0.473	
257	Dom_Fr_MeuseCharlevilleMezieres	Fr	M0	0.032	
					2.68
326	Dom_Ne_Roosteren	Ne	M6	1.009	
630	Dom_Ne_Heel (licensed)2	Ne	LC	52.665	
705	Dom_Ne_Brakel (licensed)3	Ne	M13	110.376	
710	Dom_Ne_BiesboschKeizersveerGatVanKerkslt4	Ne	M13	213.814	
					377.86
	Total				**675.50**

1 All nodes representing the Rur River basin is set inactive and is not explicitly simulated.
2 Effective water usage ca. 10 · 106 m^3
3 Effective water usage ca. 80 · 106 m^3
4 Location of intake point has been moved recently to the Bergse Maas near Aakvlaai

C.7.2 Industrial water use

The network schematization contains 14 nodes representing industrial water demand. Table 56 lists the nodes, the river or canal sections from where water is abstracted (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 56 Overview of the 14 industrial water demand nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
9	Iws_Be_AlbertKanaal2	Be	AC2	8.199	
59	Iws_Be_AlbertKanaal1	Be	AC1	19.552	
61	Iws_Be_AlbertKanaal3	Be	AC3	3.784	
62	Iws_Be_KanaalBocholtHerentals1	Be	CBH1	8.830	
63	Iws_Be_Mol	Be	CBH1	6.623	
260	Iws_De_Rur	De	Rur *	36.897	
					46.99
236	Iws_Fr_FromagerieBelProductionMnksjoStny	Fr	M0	0.915	
					36.90
104	Iws_Ne_M7SmurfitKappaRoermond	Ne	M7	7.438	
					0.92
106	Iws_Ne_M9ForfarmersHeijen	Ne	M9	17.345	
109	Iws_Ne_ZWV2NyrstarBudelDorplein	Ne	ZWV2	3.500	
473	Iws_Ne_JulianaCanalChemelotGeleen	Ne	JC	78.840	
492	Iws_Ne_ZWV4FrieslandCampinaMars	Ne	ZWV4	56.449	
493	Iws_Ne_WilhelminaKanalalTataSteel	Ne	WC	2.838	
525	Iws_Ne_M5SappiMaastricht	Ne	M5	47.304	
					213.71
Total					**298.51**

** All nodes representing the Rur River basin is set inactive and is not explicitly simulated.*

C.7.3 Cooling water

The network schematization contains 11 nodes representing cooling water demand. Table 57 lists the nodes, the river or canal sections from where water is abstracted (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 57 Overview of the 11 cooling water demand nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Demand (m3/s)	Annual water demand (10^6 m^3)	Annual water demand per country (106 m^3)
58	Col_Be_ElectrabelGenk	Be	AC1	6.000	189.216	
113	Col_Be_Awirs	Be	M4	11.000	346.896	
468	Col_Be_Marcinelle	Be	Sam	0.380	11.984	
472	Col_Be_Angleur	Be	M4	0.112	3.532	
474	Col_Be_CentralDeAmercoeur	Be	CCB	0.428	13.497	
495	Col_Be_Tihange	Be	M4	48.000	1513.728	
505	Col_Be_Seraing	Be	M4	3.200	100.915	
						2179.77
270	Col_De_WeisweilerBrownCoal_Pot	De	Rur *	0.380	11.984	
						11.98
264	Col_Fr_ChoozEdfCnpe	Fr	M1	6.296	198.551	
604	Col_Fr_ThermalPowerStationPontSurSambre	Fr	Sam	0.500	15.768	
						214.32
585	Col_Ne_Clauscentrale	Ne	M6	4.600	145.066	
						145.07
	Total					**2551.14**

** All nodes representing the Rur River basin is set inactive and is not explicitly simulated.*

C.7.4 DPZW region demand

The network schematization contains 16 nodes representing Deltaprogramma Zoetwater (DPZW) regions for which the demand is computed with the Landelijk Hydrologisch Model (LHM) Version 4.2. Table 58 lists the nodes, the river or canal sections from where water is abstracted (see Table 49 for annotation description) and the annual demand (106 m^3). The length of the LHM generated decade time series were from 1 January 1980 till 31 December 2020.

Table 58 Overview of the 15 General district nodes representing the 4 DPZW region 2, 3, 7 and 14 and the annual water demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
39	Reg2_Ne_KanaalWessemNederweert	Ne	CWN	1.14	
91	Reg2_Ne_M7	Ne	M7	0.26	
92	Reg2_Ne_M8	Ne	M8	2.51	
37	Reg2_Ne_M9	Ne	M9	6.79	
41	Reg2_Ne_Noordervaart	Ne	NV	0.88	
43	Reg2_Ne_ZuidWillemsVaart2	Ne	ZWV2	3.76	
44	Reg2_Ne_ZuidWillemsVaart3	Ne	ZWV3	2.39	
46	Reg2_Ne_ZuidWillemsVaart4	Ne	ZWV4	3.76	
42	Reg3_Ne_WilhelminaKanaal	Ne	WC	1.41	
93	Reg7_Ne_M10	Ne	M10	8.10	
94	Reg7_Ne_M11	Ne	M11	8.10	
96	Reg7_Ne_M12	Ne	M12	4.05	
6	Reg14_Ne_M6	Ne	M6	0.00	
36	Reg14_Ne_M5	Ne	M5	0.00	
38	Reg14_Ne_JulianaKanaal	Ne	JC	0.00	
	Total				**43.15**

C.7.5 Irrigated agriculture

The network schematization contains two nodes representing irrigated agriculture water demand. Table 59 lists the nodes, the river or canal sections from where water is abstracted (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 59 Overview of the irrigated agriculture water demand nodes, the location and annual demand (106 m^3) (Johnen 2020).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
47	Irr_Be_KanaalBocholtHerentals	Be	CBH1	36.13	36.13
308	Irr_De_Rur	De	Rur	0.03	0.03
	Total				**36.15**

C.7.6 Nature and recreation

The network schematization contains 15 nodes representing nature and recreational water demand. Table 61 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the annual demand (106 m^3). Node “Nat_Ne_LusVanLinne” represents the minimum flow of 7 m^3/s in the Lus van Linne (Helmyr & Jaskula-Joustra, 2001). The values for the fish trap are according to Rijksdienst Limburg (2020) and are listed in Table 60.

Table 60 Minimum flow requirement for fish ladders (Rijkswaterstaat Dienst Limburg, 2020)

Fish ladder	Minimum flow requirement (m3/s)
Borgharen	2.5
Linne	2.0
Roermond	2.5
Belfeld	2.5
Sambeek	2.5
Grave	2.0
Lith	2.6

Table 61 Overview of the nature and recreational water demand nodes, the location and annual demand (106 m^3)

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
225	Nat_De_ReleaseCompRsvHeimbach	De	Rur *	236.52	
240	Nat_De_ReleaseRsvObermaubach	De	Rur *	157.68	
					394.20
2	Nat_Ne_PeelNature	Ne	NV	37.84	
97	Nat_Ne_BorgharenVistrap	Ne	M5	78.84	
98	Nat_Ne_RoermondVistrap	Ne	M7	78.84	
99	Nat_Ne_BelfeldVistrap	Ne	M8	78.84	
101	Nat_Ne_SambeekVistrap	Ne	M9	78.84	
102	Nat_Ne_GraveVistrap	Ne	M10	63.07	
103	Nat_Ne_LinneVistrap	Ne	M7	63.07	
482	Nat_Ne_LusVanLinne	Ne	M7	220.75	
496	Nat_Ne_LithVistrap	Ne	M11	81.99	
684	Nat_Ne_Wessem	Ne	CWN	22.08	
686	Nat_Ne_OeffeltscheRaam	Ne	M10	6.31	
691	Nat_Ne_GraafscheRaam	Ne	M11	31.54	
694	Nat_Ne_Nederweert	Ne	ZWV2	47.30	
					889.32
Total					**1283.52**

** All nodes representing the Rur River basin is set inactive and is not explicitly simulated.*

C.7.7 Lock losses (navigation)

Table 62 lists the present lock losses for the locks in the Meuse and the expected future developments without and with the “Meest Milieuvriendelijk Alternatief (MMA)” of the project “Modernisering Maasroute (MoMaRo)” (Helmyr & Jaskula-Joustra 2001). The numbers are indicative and based on the load capacity of the ships and not on the number of opening and closing of the locks. Recreational boating is not taken into account.

Table 62 The 24-hours lock losses on working days (m^3/s) for locks in the Meuse (Helmyr, Jaskula, 2001).

Locatie	Huidig	2002 Autonoom	2002 MMA	2010 Autonoom	2010 MMA
Bosscherveld	0,7	?	?	?	?
Born	13,1	15,8	15,8	17,3	16,8
Maasbracht[1]	14,9	20,3	20,3	21,7	21,8
Panheel[2]	+2,8	+2,1	+2,1	+1,5	+1,5
Heel	8,9	12,6	12,6	12,7	12,8
Linne	4,0	4,3	4,3	3,9	3,7
Roermond	1,8	1,2	4,6	1,5	1,4
Belfeld	6,1	8,1	9,7	8,3	8,5
Sambeek	6,6	7,6	7,9	7,8	8,0
Weurt	1,7	2,0	2,1	2,2	2,3
Grave	2,0	2,2	2,3	2,4	2,1
Lith	2,1	2,4	2,4	2,5	2,3
St. Andries					

[1] *Lock losses at Maasbracht are hitgher than those at Born, so lock losses at Maasbracht are leading for the Juliana Canal.*
[2] *The “+” sign indicates hat the lock losses are added to the Meuse, because the Canal Wessem-Nederweert has a higher elevation than the Meuse.*

The network schematization contains 21 nodes representing head lock losses and navigation water demand. Table 63 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 63 Overview of the water demand for lock losses (navigation) per node, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
69	Nav_Be_GenkDiepenbkHasseltSluiceLockLoss	Be	AC1	555.03	
71	Nav_Be_OlenSluiceLockLoss	Be	AC2	605.49	
72	Nav_Be_WijnegemSluiceLockLoss	Be	AC3	378.43	
73	Nav_Be_HerenthalsSluiceLockLoss	Be	CBH2	22.08	
74	Nav_Be_RijkevorselSluiceLockLoss	Be	CDTS	3.15	
353	Nav_Be_KwaadmechelenSluiceLockLoss	Be	AC2	605.49	
475	Nav_Be_SambreNavigationWaterQuality	Be	Sam	157.68	
					2327.36
13	Nav_Ne_HeelSluiceLockLoss	Ne	LC	246.25	
16	Nav_Ne_LinneSluiceLockLoss	Ne	M7	76.46	
22	Nav_Ne_BornSluiceLockLoss	Ne	JC	345.64	
23	Nav_Ne_MaasbrachtSluiceLockLoss	Ne	JC	759.07	
24	Nav_Ne_RoermondSluiceLockLoss	Ne	M7	39.11	
26	Nav_Ne_BelfeldSluiceLockLoss	Ne	M9	179.12	
27	Nav_Ne_SambeekSluiceLockLoss	Ne	M10	172.22	
28	Nav_Ne_GraveSluiceLockLoss	Ne	M11	52.00	
40	Nav_Ne_PanheelSluiceLockLoss	Ne	CWN	52.00	
363	Nav_Ne_WilhelminaSluiceLockLossAndel	Ne	M13	6.31	
442	Nav_Ne_MaasWaalKanalHeumenSluiceLockLoss	Ne	M10	47.30	
497	Nav_Ne_LithSluiceLockLoss	Ne	M11	0.00	
528	Nav_Ne_BosscherveldSluiceLockLoss	Ne	M5	0.00	
545	Nav_Ne_SintAndriesSluiceLockLoss	Ne	M12	9.46	
					1984.93
	Total				**4312.29**

C.7.8 Pump-up of lock loss

The network schematization contains 8 nodes representing sluice pump-up of lock losses. Table 64 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the annual demand to compensate the loss (106 m^3).

Table 64 Overview of the nodes representing pump-up of lock loss, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water loss / demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
559	Spm_Be_GenkSluicePumpUpLockLoss	Be	AC1	283.82	
566	Spm_Be_KwaadmechelenSluicePumpUpLockLoss	Be	AC2	378.43	
574	Spm_Be_OlenSluicePumpUpLockLoss	Be	AC2	378.43	
587	Spm_Be_WijnegemSluicePumpUpLockLoss	Be	AC3	0.00	
588	Spm_Be_RijkevorselSluicePumpUpLockLoss	Be	CDTS	0.00	
589	Spm_Be_HeerenthalsSluicePumpUpLockLoss	Be	CBH2	0.00	
519	Spm_Ne_BornSluicePumpUpLockLoss	Ne	JC	94.61	
					1040.69
534	Spm_Ne_MaasbrachtSluicePumpUpLockLoss	Ne	JC	189.22	
					283.82
	Total				**1324.51**

C.7.9 Sluice leakage

The sluice leakage is listed in Table 65 for each lock in the Meuse. Leakage losses are not withdrawn from the water system but passed from the upstream to the downstream reach.

Table 65 Leakage loss per sluice (m^3/s) (Helmyr, Jaskula, 2001)

Locatie	Leakage loss (m^3/s)
Bosscherveld	0,1
Born	0,5
Maasbracht	1,1
Panheel	0,1
Heel	-
Linne	-
Roermond	2,3
Belfeld	1,6
Sambeek	1,4
Weurt	-
Grave	-
Lith	1,9
St. Andries	

The leakage losses at the weir at Grave is considerable under normal situation. The leakage is reduced during periods of low water by putting needles between the bulkheads.

The network schematization contains 8 nodes representing lock loss represented by the low flow node type. Table 66 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the annual demand to compensate the loss (106 m^3).

Table 66 Overview of the sluice leakage nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
68	Slk_Ne_PanheelSluiceLeakageLoss	Ne	CWN	89.31	
521	Slk_Ne_BornSluiceLeakageLoss	Ne	JC	15.77	
529	Slk_Ne_BosscherveldSluiceLeakageLoss	Ne	ZWV1	3.15	
531	Slk_Ne_MaasbrachtSluiceLeakageLoss	Ne	JC	34.69	
541	Slk_Ne_RoermondSluiceLeakageLoss	Ne	M7	72.53	
542	Slk_Ne_BelfeldSluiceLeakageLoss	Ne	M9	50.46	
543	Slk_Ne_SambeekSluiceLeakageLoss	Ne	M10	44.15	
544	Slk_Ne_LithSluiceLeakageLoss	Ne	M11	59.92	
					369.98
	Total				**369.98**

C.7.10 Canal leakage loss

The canal leakage at the Juliana Canal is 0,1 m^3/s and at the lateral canal it is unknown according to Helmyr and Jaskula (2001). The canal leakage in the MLNBK is 3,6 m^3/s according to Watak. This number is split equally over the 3 canal sections: Wessem- and Lozen-Nederweert, Beek-Den Bosch (Zuid-Willemsvaart) en Beek-Oosterhout (Wilhemina canal).

The network schematization contains 4 nodes representing canal leakage loss represented by the bifurcation node type and the bifurcated flow link type. Table 67 lists the nodes, the river or canal sections where the bifurcation is set (see Table 49 for annotation description) and the maximum annual loss / demand (106 m^3).

Table 67 Overview of the canal leakage loss nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water loss (10^6 m^3)	Annual water loss per country (10^6 m^3)
324	Clk_Ne_JulianaCanalLeakageLoss	Ne	JC	31.56	
547	Clk_Ne_WilhelminaCanalLeakageLoss	Ne	WC	37.87	
548	Clk_Ne_ZuidWillemsVaart3LeakageLoss	Ne	ZWV3	37.87	
549	Clk_Ne_ZuidWillemsVaart4LeakageLoss	Ne	ZWV4	37.87	
					145.17
	Total				**145.17**

C.7.11 "Maasplassen" evaporation loss

The evaporation loss from the "Maasplassen" is presented in the model with 2 Loss flow nodes. Table 68 list the nodes and annual loss.

Table 68 Overview of the 2 Loss flow nodes repreenting the "Maasplassen" evaporation loss and the annaula loss (106 m^3)

Node Id	Node name	Country	River / canal section	Average annual "Maasplassen" evaporation loss	Average annual "Maasplassen" evaporation loss per country (10^6 m^3)
107	Qls_Ne_MaasNoordEvapLossMaasplassen	Ne	M10	34.032	
635	Qls_Ne_MaasZuidEvapLossMaasplassen	Ne	M7	12.168	
	Total				**46.20**

C.7.12 Reservoir operation

The network schematization contains 5 nodes representing minimum reservoir release. Table 69 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the minimum flow as annual demand (106 m^3).

Table 69 Overview of the reservoir target release nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand (10^6 m^3)	Annual water demand per country (10^6 m^3)
730	Lfl_Be_ReleaseRsvNisramont	Be	Our	110.380	
					110.38
88	Lfl_De_ReleaseRsvUrfttalsperre	De	Rur *	78.840	
89	Lfl_De_ReleaseRsvRurtalsperre	De	Rur *	78.840	
111	Lfl_De_ReleaseOleftalsperre	De	Rur *	9.461	
301	Lfl_De_ReleaseRsvWehebachtalsperre	De	Rur *	12.614	
					179.76
	Total				**290.14**

** All nodes representing the Rur River basin is set inactive and is not explicitly simulated.*

C.7.13 Inter-basin transfer

The network schematization contains 3 low flow nodes representing the canal target flows for inter-basin transfer. The target flow is a minimum demand flow. Table 70 lists the nodes, the river or canal sections where the minimum demand flow is set (see Table 49 for annotation description) and the annual demand (106 m^3).

Table 70 Overview of the target flow at the inter-basin transfer nodes, the location and annual demand flow (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand $(10^6\ m^3)$	Annual water demand per country $(10^6\ m^3)$
269	Lfl_Be_CanalCharleroiBruxelles	Be	CCB	31.54	
					31.54
154	Lfl_Fr_CanalMeuseCanalMarneAuRhinOuest	Fr	CMR	53.61	
163	Lfl_Fr_CanalDeLaSambreLOise	Fr	CSO	3.15	
					56.77
	Total				**88.30**

C.7.14 International agreements

The network schematization contains 3 low flow nodes to represent minimum flows for international agreements: 2 nodes for the border between France and Belgium and 1 node for the border between Belgium and the Netherlands. Two different threshold flows are considered for the border flow between France and Belgium. Table 71 lists the nodes, the river or canal sections where the minimum flow is set (see Table 49 for annotation description) and the annual demand (106 m^3).Node “Ina_Ne_Grensmaas” represents the minimum flow at the Grensmaas of 10 m^3/s (Liefveld & Jesse, 2006).

Table 71 Overview of the international agreement minimum flow demand nodes, the location and annual demand (106 m^3).

Node Id	Node name	Country	River / canal section	Annual water demand $(10^6\ m^3)$	Annual water demand per country $(10^6\ m^3)$
209	Ina_Fr_ChoozLevel1	Fr	M1	630.72	
					1324.51
716	Ina_Fr_ChoozLevel2	Fr	M1	693.79	
570	Ina_Ne_Grensmaas	Ne	M6	315.36	
					315.36
	Total				**1639.87**

C7.15 Extreme dry year increased water loss and use

The network schematization contains one loss flow node to represent unknown water usage and losses related to exceptional drought in the years 2018, 2019 and 2020. It was necessary to introduce this loss flow to obtain a better match between observed and simulated flows. Reduced availability of river water can coincide with an increase in demand (Römgens 2013). Possible unknown water losses or water usages are:

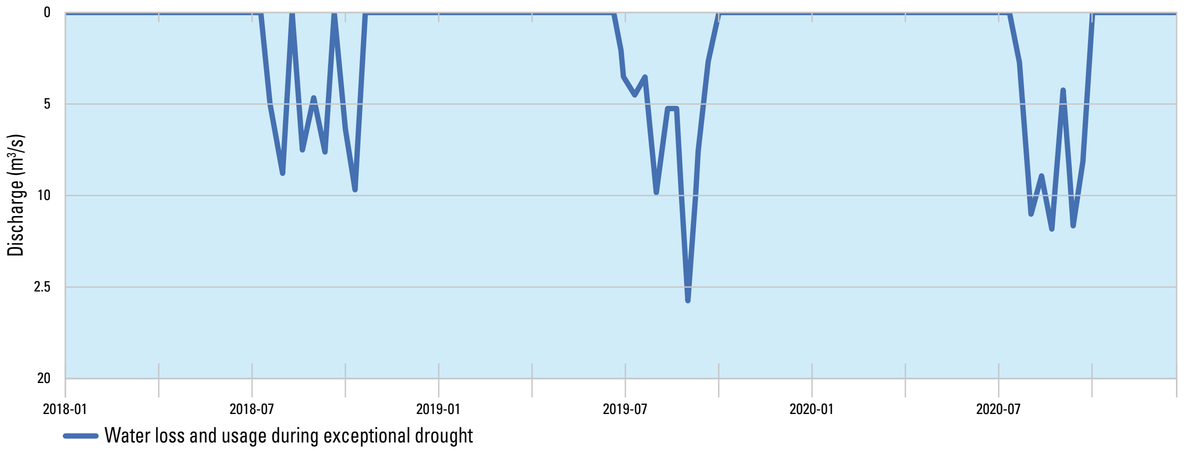
- Changes in surface water – groundwater interaction due to exceptional low groundwater levels
- Additional water demand for private irrigation (sprinkling gardens) and increased agricultural water demand
- Additional evaporation from open waters and the related water demand for maintenance of the water levels in tributaries.
- Wetting dikes to prevent drying cracks in the dikes.

The node Id is 731 and node name is “Qls_Ne_VenloDrySummerExtraMaasWaterLoss”. The node is located just upstream of the Venlo recording station at Meuse section M9. Table 72 lists the increased water loss and use per decade for the years 2018, 2019 and 2020, a graphical representation is shown in Figure 92. The values have been derived during the model calibration.

Table 72 Overview of the increased water loss and use during the summer of year 2018, 2019 and 2020 from Meuse section M9 near Venlo per decade (m3/s).

Time step index	Time step name	2018	2019	2020
19	Jul1	0.00	3.56	0.00
20	Jul2	0.00	4.63	0.00
21	Jul3	5.14	3.48	3.14
22	Aug1	8.86	9.86	11.11
23	Aug2	0.00	5.29	8.88
24	Aug3	7.54	5.23	11.89
25	Sep1	4.70	15.71	4.30
26	Sep2	7.64	7.71	11.68
27	Sep3	0.00	2.81	7.84
28	Oct1	6.14	0.00	0.00
29	Oct2	9.73	0.00	0.00
30	Oct3	0.00	0.00	0.00

Figure 92 Time series for unknown water losses and water usages during exceptional drought (only applied for 2018 till 2020)



Source Deltares, edited by RIWA-Meuse

C.8 Scenarios

C.8.1 Hydrological scenarios

One hydrological scenario W81 "Actualised LHM and Wflow timeseries Wflow Run 5 1962 - 2020 used 1980 - 2020" has been setup for the Meuse model. Table 73 lists the time series data and files in the scenario. All executed simulation cases have run for scenario W81.

The length of the flow monitoring time series from the sub-project A are from 1 January 1989 till 2 November 2020. The time series and files are filled with missing value.

Table 73 Time series data in hydrological scenario W81.

Data description	File name	Source of data	Time step	Start date	End date
Actual inflow	Actinflw.tms	Wflow, Sub-project A	Day	1 Jan 1980	31 Dec 2020
Actual rainfall	Actrain.tms	Wflow	Day	1 Jan 1962	31 Dec 2020
Open water evaporation	Evaporat.tms	Wflow	Day	1 Jan 1980	31 Dec 2020
District demand	Disdemnd.tms	LHM	Decade	1 Jan 1980	31 Dec 2020
District discharge	Disdisch.tms	LHM	Decade	1 Jan 1980	31 Dec 2020
Monitoring flow	Recrdflw.tms	Sub-project A, Wflow	Day	1 Jan 1980	31 Dec 2020
Loss flow	Lossflow.tms	QWAST spreadsheet, calibration	Decade	1 Jan 1980	31 Dec 2020

C.8.2 Water quality and flow composition scenarios

Two water quality and flow composition scenarios M01 and M02 have been setup for the Meuse model in directory "Lookup":

- M01 contains the user defined flow components per source as listed in Table 74.
- M02 contains the user defined flow components per tributary as listed in Table 24.

The model data are entered related to scenario M02. The executed simulation cases have been run for scenario M02.

Table 74 Overview of the user defined water flow components in scenario M01.

Seq id	Water flow component
1	Runoff Meuse
2	Runoff Ourthe
3	Runoff Lesse
4	Runoff Sambre
5	Runoff Vesdre
6	Runoff Lesse
7	Runoff Viroin
8	Runoff Semois
9	Runoff Chiers
10	Runoff Ambleve
11	Runoff Rur
12	Runoff Niers
13	Sluices France and the Netherlands
14	Industrial return flow
15	Domestic return flow
16	Cooling water
17	Irrigation drainage
18	Reservoir Belgium
19	Reservoir Deutschland
20	Reservoir France
21	Lignite mine drainage
22	Groundwater
23	Reservoir Belgium initial storage
24	Reservoir Deutschland initial storage
25	Reservoir France initial storage

C.8.3 Climate change scenarios

Ten scenarios have been setup for the Meuse model in directory “Climate”. The scenarios are listed in Table 75. The scenario is defined by a percentage change (increase or decrease) per time step for the inflow time series (Wflow generated time series and the monitored inflow time series at Stah in Rur, Germany) in the hydrological scenario W81. Table 76 list the percentage increase and decrease per month. Figure 93 shows the percentages per time step (decade) for each CC scenario.

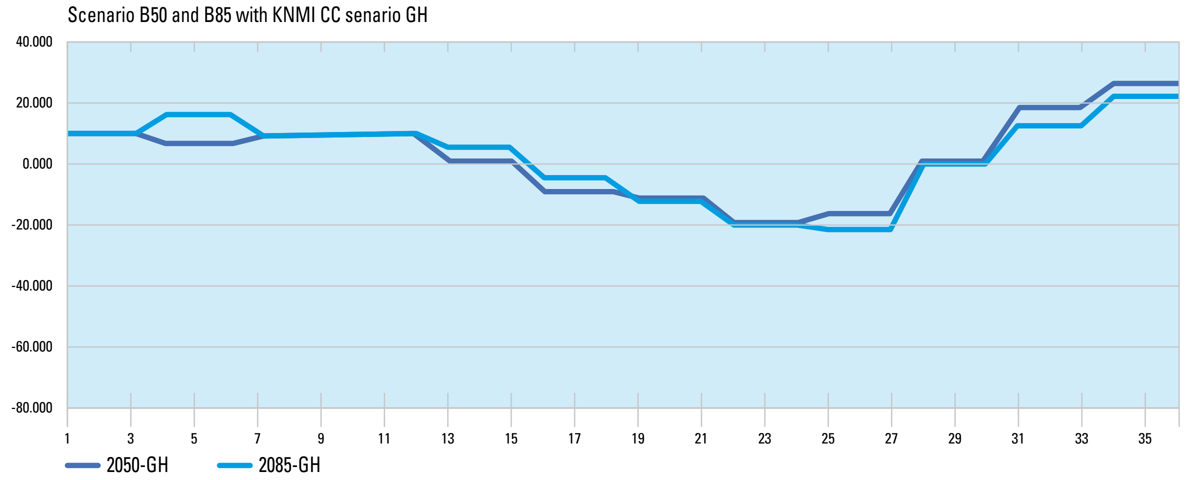
Table 75 Overview of the RIBASIM and KNMI climate change scenarios.

RIBASIM CC scenario	Target years	KNMI scenario
B50, B85	2050, 2085	GH
C50, C85	2050, 2085	GL
D50, D85	2050, 2085	WH
E50, E85	2050, 2085	WHdry
F50, F85	2050, 2085	WL

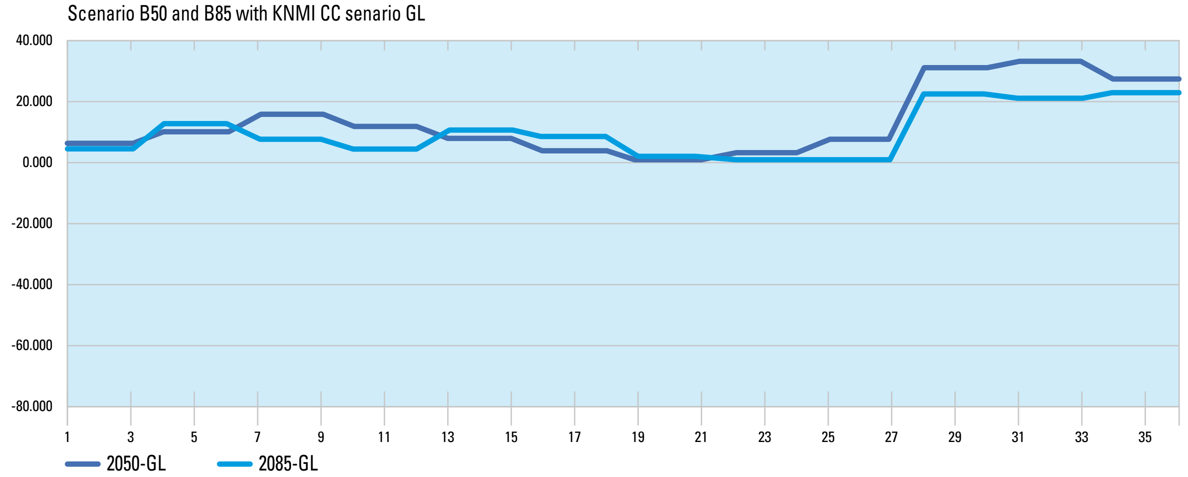
Table 76 Overview of the percentage increase and decrease per month of the runoff for the 10 CC scenarios.

Month	2050 -GH	2050 -GL	2050 -WH	2050 -WHdry	2050 -WL	2085 -GH	2085 -GL	2085 -WH	2085 -WHdry	2085 -WL
Jan	10.37	5.80	15.75	10.37	4.33	10.17	3.71	33.47	15.26	10.37
Feb	7.27	9.39	22.44	-0.73	8.57	16.24	12.13	26.82	3.13	18.40
Mar	8.41	15.10	26.85	-9.21	12.16	9.59	7.24	26.43	-0.99	21.14
Apr	8.57	11.35	14.78	-2.19	7.76	10.57	3.91	22.31	-0.20	29.17
May	1.23	7.60	5.80	-8.56	19.51	5.28	10.37	19.57	-7.25	27.80
Jun	-8.72	3.68	-3.99	-7.91	20.16	-4.71	8.02	-8.43	-7.25	10.76
Jul	-10.84	0.42	-14.76	-15.57	1.72	-12.34	1.17	-26.25	-25.27	-9.80
Aug	-18.51	2.21	-28.46	-45.60	-8.23	-20.37	-0.01	-44.45	-56.20	-31.53
Sep	-16.88	7.11	-31.40	-49.84	-9.54	-21.55	-0.01	-44.85	-66.78	-36.23
Oct	0.58	30.44	-21.45	-37.93	5.64	-0.99	21.92	-23.11	-49.94	-14.11
Nov	19.34	32.56	9.06	-19.49	5.47	12.52	20.55	-6.67	-29.38	0.19
Dec	26.52	26.85	26.03	9.39	19.34	22.12	22.31	26.43	8.02	21.33

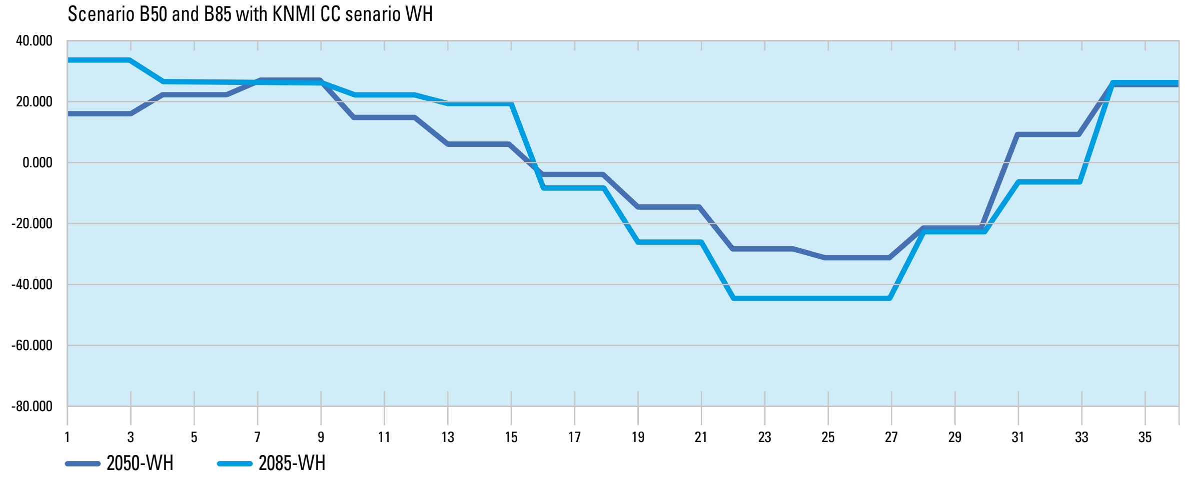
Figure 93 Percentage increase and decrease per time step of the runoff for the 10 CC scenarios.


Scenario B50 and B85 with KNMI CC senario GH

Source Deltares, edited by RIWA-Meuse

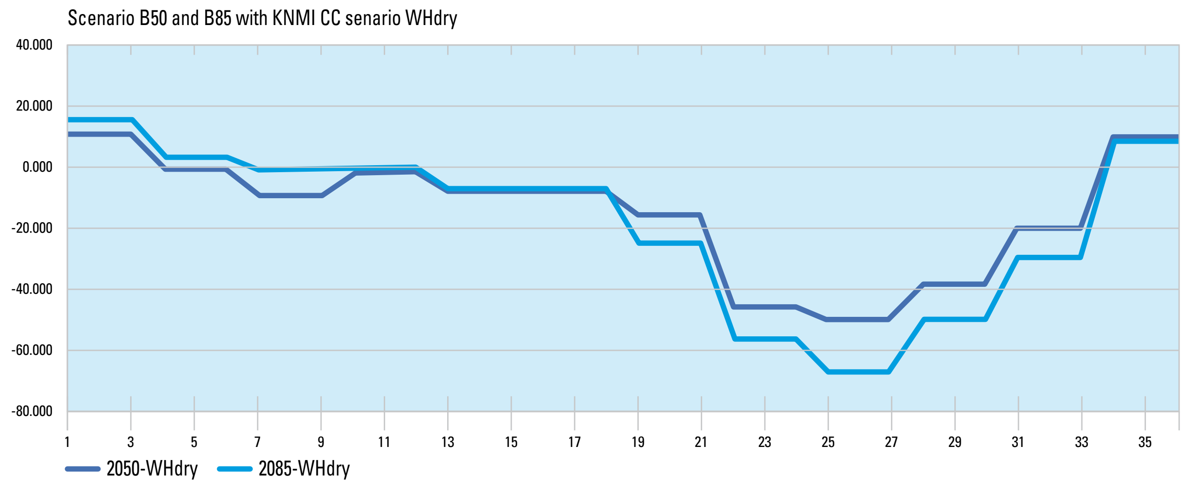

Scenario B50 and B85 with KNMI CC senario GL

Source Deltares, edited by RIWA-Meuse

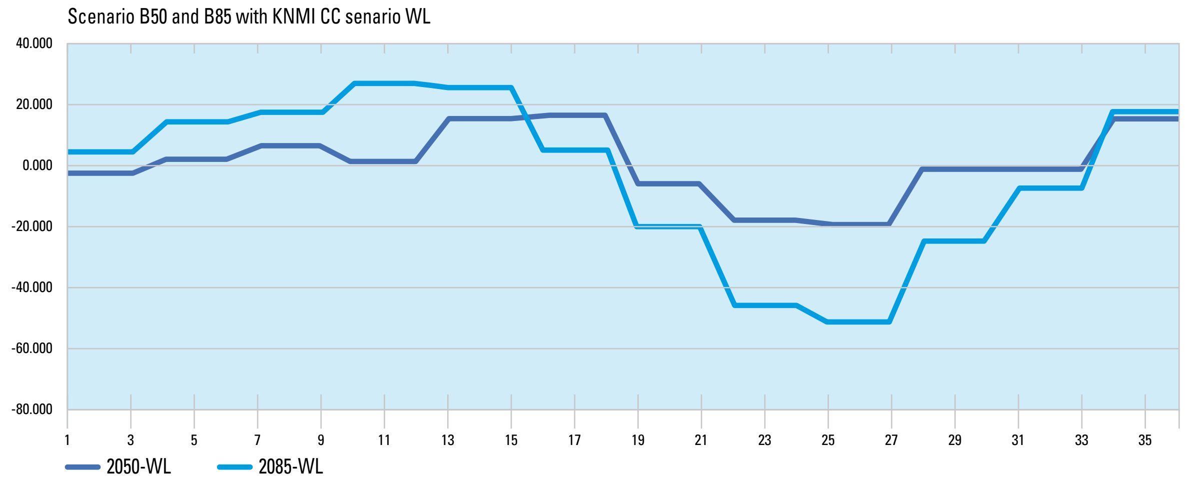

Scenario B50 and B85 with KNMI CC senario WH

Source Deltares, edited by RIWA-Meuse

Figure 93 (continuation)



Source Deltares, edited by RIWA-Meuse



Source Deltares, edited by RIWA-Meuse

C.9 Detailed results

The model results are analysed for various locations which are represented in the Meuse002 model. The nodes and links representing those locations are listed in Table 77.

Table 77 Locations and model node and link Id and name for which simulation results are presented.

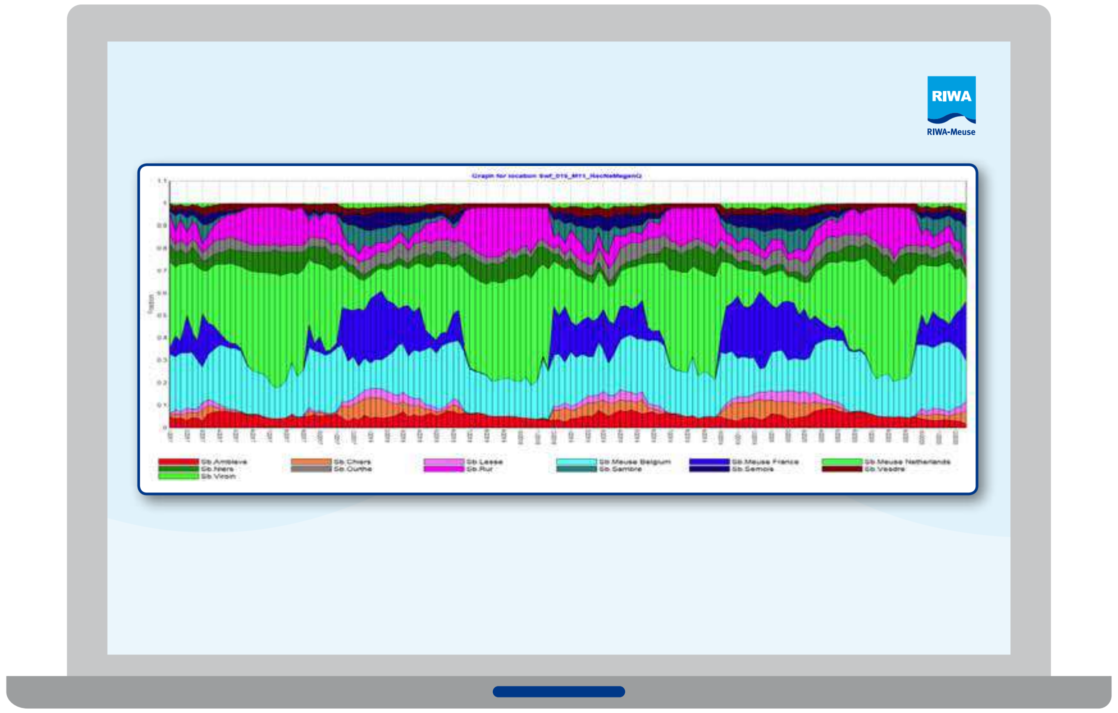
Location name	Node ID	Node name	Link ID	Link name
Chooz	170	Rec_Fr_Chooz_Q	132	Swf_005_M1_RecFrChoozQ
Monsin	515	Rec_Be_Monsin_Q	515	Swf_010_M5_RecBeMonsinQ
Megen	454	Rec_Ne_Megen_Q	105	Swf_015_M11_RecNeMegenQ

C.9.1 Flow composition for the natural flow case

The Meuse RIBASIM model also computes the flow composition: the percentage of the contribution of each tributary to the Meuse discharge. This can best be judged with the flow composition computation of the natural flow in the Meuse RIBASIM model. In this case the water users and the infrastructure are set inactive and only the inflow from the sub-basins (computed by Wflow) are active. The defined components are listed in Table 24. All inflows are labelled with the tributary name in which it is located as flow component. Figure 94 shows the results for Megen for the period 2017 till 2020. Some considerations:

- The definition of the components is specific for the Meuse model schematization.
- The reliability of the model has been checked for the flows at the Meuse main stream. The monitored and simulated flows fit well. The runoff from the sub-basins are computed with the Wflow model which may differ from the monitoring data. A higher then monitored inflow at one tributary can be compensated with a lower inflow at another.
- The water use and the operation of the infrastructure is not included in the natural flow simulation case.

Figure 94 Flow composition for the natural flow case for location at Megen for the period 2017-2020.



Source Deltares, edited by RIWA-Meuse

Table 78 Meuse components in RIBASIM Meuse model and related tributary components in project A.

Meuse component	Project A component
Meuse France	Stenay, Bar and Houile
Meuse Belgium	Hermeton, Molingnee, Bocq, Hoyoux and Mehaigne
Meuse Netherlands	Jeker, Geul, Geleenbeek, Swalm and Dieze.

Table 79 Average percentage contribution of various tributaries over period July, August and September for 6 dry years in Meuse model and the average over the 6 years for the natural flow case.

	Tributary / component	2020	2019	2018	2017	2011	2003	Avrg over the 6 dry years
1	Chiers	4.7%	5.1%	4.7%	4.7%	4.1%	5.0%	4.7%
2	Semois	6.6%	7.0%	7.0%	6.1%	5.4%	7.1%	6.5%
3	Viroin	1.1%	1.2%	1.1%	1.1%	1.0%	1.2%	1.1%
4	Lesse	4.6%	4.6%	4.6%	3.8%	3.8%	4.6%	4.4%
5	Sambre	6.0%	5.2%	5.2%	4.6%	7.7%	6.2%	5.8%
6	Ourthe	7.1%	7.4%	7.8%	6.2%	5.6%	6.8%	6.8%
7	Ambleve	7.6%	7.6%	9.0%	7.7%	5.6%	7.0%	7.4%
8	Vesdre	4.5%	4.6%	4.9%	4.8%	3.5%	3.9%	4.4%
9	Rur	10.8%	11.4%	10.5%	11.0%	8.9%	9.7%	10.4%
10	Niers	3.0%	2.8%	2.7%	3.5%	4.7%	4.5%	3.5%
11	Meuse France	10.3%	11.3%	10.5%	14.8%	12.7%	10.9%	11.7%
12	Meuse Belgium	10.1%	10.0%	9.5%	7.7%	8.5%	9.2%	9.2%
13	Meuse Netherlands	23.6%	21.8%	22.6%	24.0%	28.4%	24.0%	24.1%

C.9.2 Indicators

Table 80 Minimum flow (m³/s) and the percentage of timesteps below threshold flow at Chooz.

Case ID	Lowest discharge in Jul - Sep (m³/s)	Percentage of timesteps with flow below 22 m³/s (%)	Percentage of timesteps with flow below 20 m³/s (%)
BC2020 + CC 2050-GL	13.3	18.2	12.5
BC2020 + CC 2085-GL	12.5	21.7	13.6
BC2020 + CC 2050-GH	10.4	36.9	29.0
BC2020 + CC 2085-GH	9.9	39.3	30.6
BC2020 + CC 2050-WL	11.1	26.6	18.4
BC2020 + CC 2085-WL	9.1	46.3	38.8
BC2020 + CC 2050-WH	8.7	46.6	38.8
BC2020 + CC 2085-WH	8.1	59.1	53.4
BC2020 + CC 2050-WHdry	7.4	56.1	51.2
BC2020 + CC 2085-WHdry	5.1	69.9	64.8
BC2020	12.5	21.4	13.8

Table 81 Minimum flow (m³/s) and the percentage of timesteps below threshold flow at Monsin

Case ID	Lowest discharge in Jul - Sep (m³/s)	Percentage of timesteps with flow below 50 m³/s (%)	Percentage of timesteps with flow below 30 m³/s (%)
BC2020 + CC 2050-GL	34.4	10.3	0.0
BC2020 + CC 2085-GL	32.2	11.7	0.0
BC2020 + CC 2050-GH	27.0	29.0	1.4
BC2020 + CC 2085-GH	25.5	30.9	1.9
BC2020 + CC 2050-WL	29.2	17.1	0.3
BC2020 + CC 2085-WL	23.2	37.9	5.1
BC2020 + CC 2050-WH	23.2	36.0	3.5
BC2020 + CC 2085-WH	20.9	52.0	14.1
BC2020 + CC 2050-WHdry	19.1	50.1	17.9
BC2020 + CC 2085-WHdry	12.0	65.9	34.4
BC2020	32.2	11.7	0.0

Table 82 Minimum flow (m³/s) and the percentage of timesteps below threshold flow at Borgharen

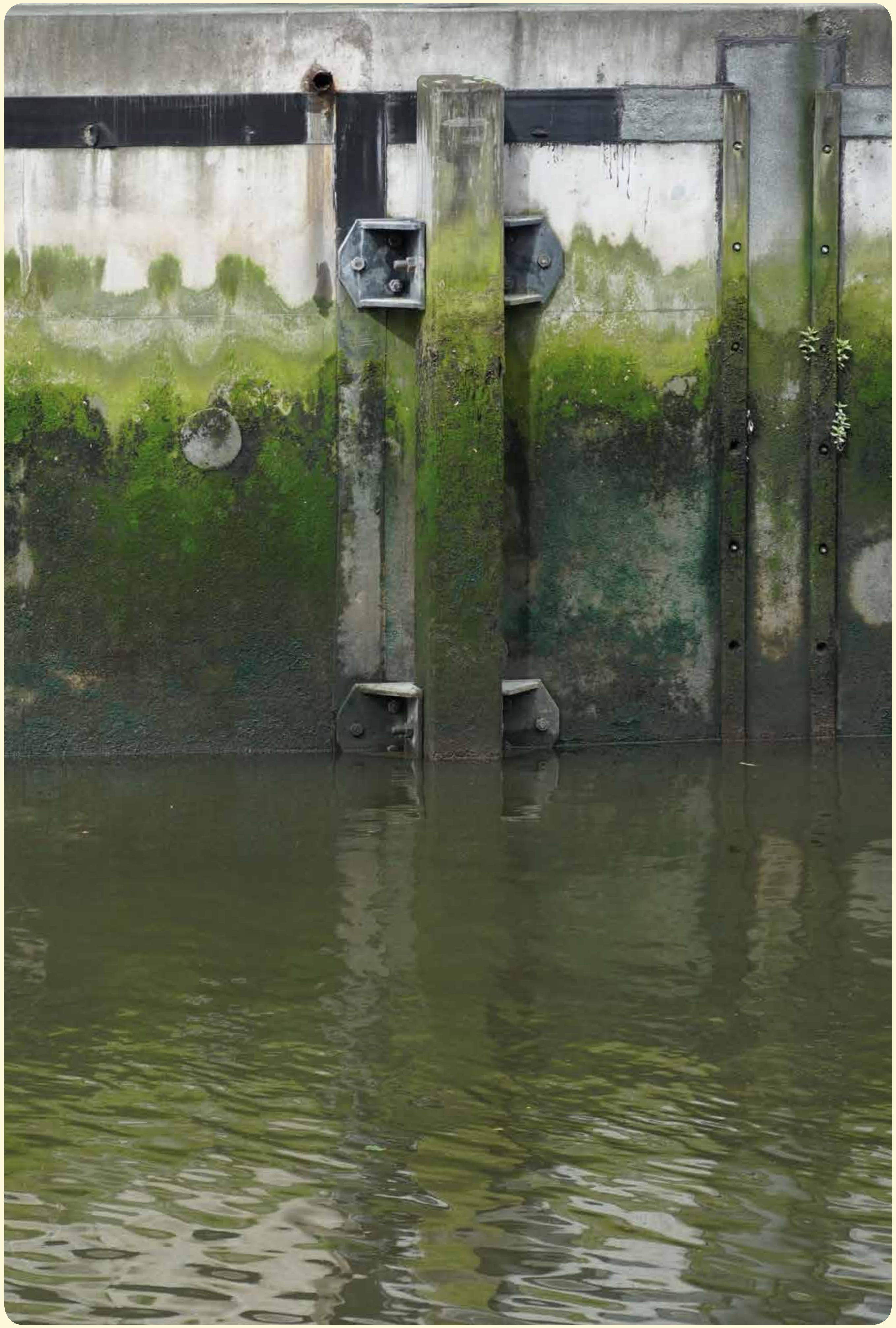
Case ID	Lowest discharge in Jul - Sep (m³/s)	Percentage of timesteps with flow below 30 m³/s (%)	Percentage of timesteps with flow below 20 m³/s (%)
BC2020 + CC 2050-GL	18.3	30.4	1.6
BC2020 + CC 2085-GL	17.3	32.0	1.9
BC2020 + CC 2050-GH	14.4	46.3	7.9
BC2020 + CC 2085-GH	13.8	49.1	9.5
BC2020 + CC 2050-WL	15.5	35.5	3.0
BC2020 + CC 2085-WL	12.9	54.7	17.3
BC2020 + CC 2050-WH	13.0	53.7	15.4
BC2020 + CC 2085-WH	12.0	66.4	30.1
BC2020 + CC 2050-WHdry	11.1	64.8	30.4
BC2020 + CC 2085-WHdry	7.1	74.5	48.2
BC2020	17.3	33.1	1.9

Table 83 Minimum flow (m³/s) and the percentage of timesteps below threshold flow at Megen

Case ID	Lowest discharge in Jul - Sep (m³/s)	Percentage of timesteps with flow below 30 m³/s (%)	Percentage of timesteps with flow below 20 m³/s (%)
BC2020 + CC 2050-GL	24.4	0.8	0.0
BC2020 + CC 2085-GL	24.0	1.6	0.0
BC2020 + CC 2050-GH	17.3	4.1	0.8
BC2020 + CC 2085-GH	16.1	4.1	1.1
BC2020 + CC 2050-WL	22.0	2.7	0.0
BC2020 + CC 2085-WL	9.3	8.1	2.2
BC2020 + CC 2050-WH	11.2	6.8	1.9
BC2020 + CC 2085-WH	5.7	18.4	4.3
BC2020 + CC 2050-WHdry	4.0	17.6	4.6
BC2020 + CC 2085-WHdry	1.3	36.0	13.0
BC2020	23.8	1.6	0.0

Table 84 Minimum flow (m³/s) and the percentage of timesteps below threshold flow for the three cases at Stah

Case ID	Lowest discharge in Jul - Sep (m³/s)	Percentage of timesteps with flow below 7,5 m³/s (%)	Percentage of timesteps with flow below 5 m³/s (%)
BC2020 + CC 2050-GL	7.1	0.5	0.0
BC2020 + CC 2085-GL	7.2	1.1	0.0
BC2020 + CC 2050-GH	5.8	4.1	0.0
BC2020 + CC 2085-GH	5.6	4.9	0.0
BC2020 + CC 2050-WL	6.5	1.6	0.0
BC2020 + CC 2085-WL	4.6	10.0	0.8
BC2020 + CC 2050-WH	4.9	7.3	0.3
BC2020 + CC 2085-WH	3.9	26.0	2.7
BC2020 + CC 2050-WHdry	3.6	29.0	3.8
BC2020 + CC 2085-WHdry	2.4	58.3	20.9
BC2020	7.1	1.1	0.0



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