Voorliggend onderzoek is uitgevoerd als onderdeel van de afstudeerstage van Floor Hermans aan de WUR. Dit onderzoek is uitgevoerd in samenwerking met RIWA-Maas en HKV Lijn in Water. Deze oplegnotitie is een korte samenvatting van het werk van Floor.

Introductie

De waterbeschikbaarheid in de Maas neemt in de toekomst sterk af. Door klimaatverandering neemt het aanbod af en door economische ontwikkeling neemt de vraag toe.

Deltares heeft in opdracht van RIWA-Maas in 2020 een knelpuntenanalyse zoetwater uitgevoerd op basis van de Deltascenario's 2017, waarin de KNMI'14-klimaatscenario's de basis vormen. Deze analyse is uitgevoerd met het RIBASIM-model van het Maasstroomgebied. De knelpuntenanalyse laat zien waar in het Maasstroomgebied de watervraag in de toekomst hoger zal zijn dan het wateraanbod in tijden van droogte.

Recent heeft het KNMI de nieuwste klimaatscenario's voor Nederland gepubliceerd, de KNMI'23-klimaatscenario's. De impact van deze klimaatscenario's op de waterbeschikbaarheid is nog onbekend. Floor Hermans heeft in haar afstudeerstage het onderzoek van Deltares geactualiseerd met de nieuwste klimaatscenario's, met een focus op de ontwikkelingen in het Franse en Belgische deel van de Maas.

Onderzoeksdoel

Het identificeren van **toekomstige knelpunten in waterbeschikbaarheid** in het Maas-stroomgebied door het effect van verwachte **klimaatverandering** en **sociaaleconomische ontwikkelingen** te analyseren.

Belangrijkste resultaten

- De 10-daags gemiddelde jaarlijks minimale Maasafvoer neemt in ieder toekomstig klimaatscenario af;
- De maximale afname van de Maasafvoer is kleiner dan volgens de KNMI'14-klimaatscenario's;
- De spreiding in de afvoerafnames is kleiner dan in de KNMI'14-klimaatscenario's;
- De nat-droog-klimaatprojecties hebben vooral invloed op het aantal toekomstige waterbeschikbaarheidsknelpunten, terwijl uitstootscenario's invloed hebben op de ernst van toekomstige waterbeschikbaarheidsknelpunten;
- Knelpunten nemen naar verwachting toe in de toekomst: hierdoor is minder water beschikbaar voor gebruik in Nederland.

Advies

Het onderzoek van Floor Hermans laat zien dat de waterbeschikbaarheid in de Maas de komende decennia afneemt in Frankrijk en België. Nederland ligt benedenstrooms en is daarmee afhankelijk van de keuzes die in Frankrijk en België gemaakt worden. De hoeveelheid water die bij Borgharen via de Maas Nederland instroomt, neemt door klimaatverandering dus af. Door keuzes bovenstrooms kan deze afname nog groter worden.

Daarom wordt aanbevolen internationaal samen te werken in het Maasstroomgebied, omdat waterbeschikbaarheid in de Maas niet alleen een nationaal probleem is. Naast de aanbeveling voor samenwerking wordt ook vervolgonderzoek naar onderstaande vragen aanbevolen:

- Is het huidige waterbeheer in Nederland adequaat genoeg voor de toekomst?
- Moet de focus liggen op beheer van reservoirs bovenstrooms of op maatregelen in Nederland?

This research was conducted as part of Floor Hermans' graduation internship at WUR. The research was carried out in collaboration with RIWA-Maas and HKV Lijn in Water. This memorandum is a brief summary of Floor's work.

Introduction

Water availability of the Maas river will decrease in the coming years. Due to climate change, the supply is decreasing, and due to economic development, the demand is increasing.

In 2020, Deltares conducted a bottleneck analysis of freshwater for RIWA-Maas using the KNMI'14 climate scenarios. This analysis was conducted using the RIBASIM model of the Meuse basin. The bottleneck analysis shows the locations in the Maas basin where the future water demand will be higher than the water supply during dry summer periods.

> Recently, KNMI published the latest climate scenarios for the Netherlands, the KNMI'23 scenarios. The impact of these climate scenarios on water availability is still unknown. During her graduation internship, Floor Hermans updated Deltares' research with the latest climate scenarios, focusing on developments in the French and Belgian parts of the Maas.

Research Objective

To identify future bottlenecks in water availability in the Meuse river basin by analyzing the effects of expected future climate change and socio-economic developments.

Key Findings

- The 10-day average annual minimum Maas discharge decreases in every climate scenario;
- The maximum discharge reduction is smaller than in the KNMI'14 scenarios;
- The spread in discharge reduction is smaller than in the KNMI'14 scenarios;
- The wet-dry climate projections mainly affect the number of future water availability bottlenecks, while emission scenarios affect the severity of future water availability bottlenecks;
- Bottlenecks are expected to increase in the future: less water will be available for the Netherlands!

Recommendations

Floor's research shows that water availability in the Maas will decrease in the coming decades in France and Belgium. The Netherlands is located downstream and therefore depends on the decisions made in France and Belgium. The amount of water flowing into the Netherlands via the Maas at Borgharen will decrease due to climate change. Upstream decisions can further exacerbate this decrease.

Therefore, international cooperation in the Maas basin is recommended, as water availability in the Maas is not only a national issue. Besides recommending cooperation, further research into the following questions is also recommended:

- Is the current water management in the Netherlands adequate for the future?
- Should the focus be on managing upstream reservoirs or on measures within the Netherlands?

Water availability bottlenecks in the French-Belgian Meuse catchment

The impact of climate change and socio-economic developments

Floor Hermans

March 2024

Internship report

Water availability bottlenecks in the French-Belgian Meuse catchment: the impact of climate change and socio-economic developments

Floor Hermans
Student number: 1009831
Course code: HWM-70424

November 2023 - March 2024

Supervisors:

Ryan Teuling
Hydrology and Environmental Hydraulics chair group, Wageningen University

Roy Daggenvoorde
HKV lijn in water

Michiel Pezij
HKV lijn in water

Maarten van der Ploeg
RIWA-Maas

Source cover photos:

Top: RIWA-Maas,
https://www.riwa-maas.org/riwa-maas/

Bottom: Information on France, https://www.informationfrance.com/ardennes

Summary

The impact of climate change on the terrestrial hydrological cycle poses a significant threat to water availability in the Meuse catchment. A study by KNMI and Deltares showed the impact of the new KNMI'23 climate scenarios on the future discharge projections of the river Meuse at the Dutch border. The impact of these scenarios specifically on water availability in the French-Belgian part of the Meuse catchment has not yet been studied. Therefore, the aim of this project was to identify future water availability bottlenecks in the French-Belgian Meuse catchment by assessing the impact of projected climate change and of socio-economic developments.

The discharge of the Meuse River is simulated using the River Basin Simulation Model (RIBASIM). The annual mean discharge and the annual 10-day minimum discharge were simulated for the KNMI'23 scenarios for the time horizons 2033, 2050, 2100 and 2150. The KNMI'23 scenarios are based on three CO_2 emission pathways (low, moderate, and high), each having a wet and dry variant. The annual mean discharge decreases under most climate scenarios, only the wet and high scenario show an increase. The trend for the annual 10-day minimum discharge under the KNMI'23 scenarios is a consistent decrease, although less extreme than the older KNMI'14 scenarios. Dry scenarios show a more pronounced decline, suggesting that the wet-dry configuration of climate scenarios has a bigger impact on the Meuse discharge than the specific emission pathway. Water demand scenarios for 2050, representing socio-economic growth and decline, show a slight increase in water availability, partly due to reduced cooling water use. This suggests that human choices, particularly those related to energy transition, can potentially mitigate some of the climate-induced reductions in water availability. However, climate change has a greater impact on water availability than socio-economic developments have. The analysis showed that there will be an increase in the number of bottlenecks under all climate scenarios. The wet-dry configuration of climate scenarios mainly influences the number of water availability bottlenecks, while the emission pathway influences the severity of existing bottlenecks. Dry climate scenarios will therefore lead to more widespread challenges throughout the catchment.

This study emphasis the need for a more comprehensive analysis, including groundwater dynamics, water quality, and more details on the spatial variability within the Meuse catchment. This will reveal more potential bottlenecks and their impact on already identified ones. Improvements to the RIBASIM model and involvement of local stakeholders is necessary to achieve this. The current water management lacks an international approach to water availability issues. By focusing on the international aspect, this study contributes to a better understanding of the catchment-wide impact of climate change. Addressing water availability issues at the catchment scale is only possible through international collaboration, which requires discussion on shared responsibilities and cross-border measures.

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1 Introduction

1.1 Context

Anthropogenic climate change poses a significant threat to the terrestrial water cycle, influencing water availability on land and may trigger more hydrological extremes, such as floods and droughts (Byun et al., 2019; Gudmundsson et al., 2021). These changes have critical impacts on both the natural ecosystems and human society. This is highlighted by the unprecedented rate of temperature rise reported by the IPCC (IPCC, 2021), leading to increased frequency and intensity of heatwaves, extreme precipitation, and droughts (Gudmundsson et al., 2021). KNMI recently published an updated version for Dutch climate scenarios to gain understanding of the effects of global climate change in the Netherlands (KNMI, 2023). In addition, Deltares and KNMI studied the impact of the projected climate on the river discharges of the Rhine and the Meuse entering the Netherlands (Buitink et al., 2023). That study, using the Wflow_sbm model, only considered natural flow, and did therefore not include any man-made abstractions for waterways, like the Albert Canal (Buitink et al., 2023). Also, this study did not include a translation for what the changing climate and discharge regimes mean for the water availability for water users in the catchments.

Water availability is the balance between water supply and demand. This multifaceted concept depends on both environmental processes as well as socio-economic developments in a catchment (Mishra et al., 2021). Although water availability can include both surface water and groundwater, in this study only surface water availability is simulated. Surface water supply depends on environmental processes like meteorological conditions and river basin characteristics. Surface water supply faces challenges from increased variability due to climate change (Mishra et al., 2021). Having a stable water supply is desirable, as it prevents people being exposed to water scarcity and ensures stable activity for water-dependent sectors (Bisselink et al., 2020). A decreased surface water supply has negative impacts on agriculture, industry, shipping, electricity production, and drinking water production in the Meuse catchment (Gudmundsson et al., 2021; RIWA-Maas, 2022). All these user functions have a certain water demand, depending on the type of activity, and can change due to socio-economic developments (Mishra et al., 2021).

1.2 Problem definition

The Meuse is a river which experienced low discharges in recent years, affecting water users throughout the catchment (RIWA-Maas, 2023). Anthropogenic climate change is expected to cause more occurrences of low discharges in the Meuse (Gudmundsson et al., 2021; Buitink et al., 2023). This change in water supply, will affect the water availability in the Meuse catchment. On the other hand, socio-economic developments can lead to a change in water demand, and thus also affect water availability (Wolters et al., 2018a; Wolters et al., 2018b; Mishra et al., 2021). As climate change and socio-economic developments are happening at the same time, it is good to know how they individually, and combinedly impact the water availability in the catchment.

1.3 Research objective

The research objective for this study is to identify future water availability bottlenecks in the French-Belgian parts of the Meuse catchment by assessing the impact of projected climate change and socio-economic developments.

2 Methodology

2.1 Research outline and steps

This chapter presents the research methodology. Figure 1 shows the structure of the study in a flow chart, which can be divided into three steps, indicated by the different coloured arrows. As mentioned before, the concept of water availability consists of water supply and water demand. In this study the discharge of the river Meuse is considered as the water supply, and water demand is the amount of water needed for the different user functions in the catchment.

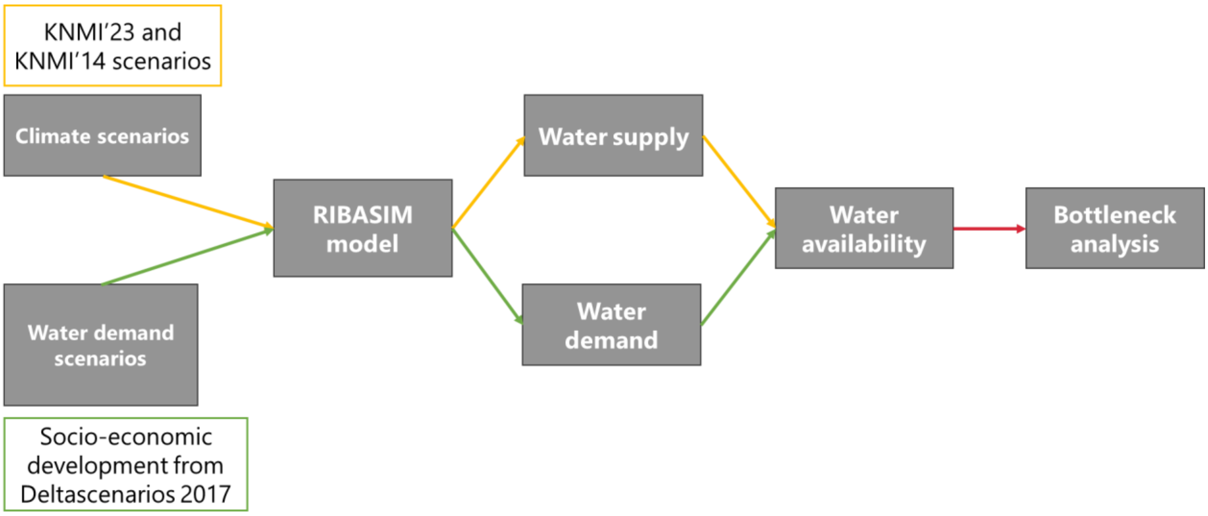


Figure 1. Flow chart of the research steps

The first step is to simulate the impact of climate change on the water availability for different locations in the Meuse catchment. This was done by carrying out a scenario analysis using the River Basin Simulation Model. This model simulates the Meuse discharge under the different KNMI'23 climate scenarios. The annual average and the annual 10-day minimum discharge for the different climate scenarios were compared to the current climate, as well as to the simulation of the older KNMI'14 scenarios. In addition, the seasonal patterns of the 70% and 90% dependable flow were studied. The dependable flow is the discharge that is exceeded 70 or 90% of the time and are considered thresholds for dry and very dry conditions respectively (Van der Krogt et al., 2022).

The second step of this study is to simulate the impact of socio-economic development on water availability. This was done by carrying out a scenario analysis, for which different water demand scenarios represent socio-economic growth and decline. These scenarios were based on the Deltascenarios 2017. The water demand scenarios were combined with the KNMI'23 scenarios to study the combined impact of socio-economic development and climate change on the water availability in the Meuse catchment. The scenarios were evaluated for different locations in the Meuse catchment. This was achieved by comparing the annual average and annual 10-day minimum discharge of the scenarios with the current climate and with scenarios that only considered climate change without socio-economic development. A sensitivity analysis was performed on the cooling water demand due to the assumption of a substantial decrease made in all the Deltascenarios 2017.

The main objective of this study was to identify the water availability bottlenecks in the French-Belgian Meuse catchment. As the water availability is the balance between water supply and water demand, a bottleneck is defined as a location where supply does not meet demand. This comparison was made for 40 locations throughout the catchment for which the water demand was known. To study the impact of climate change and socio-economic development on these bottlenecks, the analysis was carried out for different climate and water demand scenarios.

2.2 Study area

The study area is the French and Belgian part of the Meuse catchment, shown by the red outline in Figure 2. This cross-border river basin extends over Belgium, France, Germany, and the Netherlands. The river basin covers approximately 35000 km^2 and is home to nine million people (Bouaziz, 2021; Van der Krogt et al., 2022). The river Meuse has a south-north orientation and has a length of 874 km (Bouaziz, 2021). The land use in the catchment consists mainly of forest (35%), agriculture (32%), pasture (21%), and urban areas (9%) (Bouaziz et al., 2021). Various anthropogenic activities depend on water from the Meuse, like drinking water supply, cooling water for energy production, industrial demand, and irrigation water (Figure 5). The Meuse is also used as the discharge location for wastewater treatment plants, return flows from power plants and industry. In addition, various locations in the catchment have minimum discharge requirements, such as: fish ladders, nature areas, sluices, shipping requirements, and international agreements, like the Meuse Discharge Treaty between the Netherlands and Flanders (Maasafvoerverdrag, 1995; Van der Krogt et al, 2022).

The Meuse has a pluvial hydrological regime which is characterised by high discharges in winter and low discharges in summer. The average summer discharge is about one quarter of the average winter discharge (De Wit et al., 2007). The lowest measured discharge is 20 m^3/s, which occurred in Liege, Belgium, in 1976 (Het verhaal van de Maas, 2019). Precipitation in the catchment is uniformly distributed throughout the year but shows regional differences: 1000 to 1200 mm in the Ardennes to 700-800 mm in the Flemish and Dutch lowlands (De Wit et al., 2007). Thus, the seasonal discharge pattern is mainly caused by the seasonal variation of evaporation (Bouaziz, 2021; Van der Krogt et al., 2022). The average discharge at Borgharen, where the Meuse enters the Netherlands, is 230 m^3/s (Van der Krogt et al., 2022).

The basin has a maximum altitude around 700 m and can be divided in four main parts (Figure 2):

- the upstream part (Lorrain Meuse);
- the Ardennes Meuse;
- midstream part;
- downstream part, (Kramer, 2021).

The upstream part of the Meuse is characterised by wide floodplains with gentle slopes. These areas have relatively thick soils underlain by limestone, making the (sub)soil permeable and suitable for agriculture (Bouaziz, 2021; Kramer, 2021). Due to the large storage and buffering capacity in this part of the catchment, its contribution to the Meuse discharge during low flow is relatively large (Kramer, 2021).

The Ardennes part is characterised by its high elevation, steep slopes, and thin soils on relatively impermeable layers of slate and sandstone (Bouaziz, 2021; Kramer, 2021). These conditions contribute to a short response time of some of the tributaries, like the Semois, Virion, Lesse and Ourthe, which can cause a rapid rise in stream flow and flash floods in a matter of hours (Bouaziz, 2021; Kramer, 2021). The Ardennes region makes a significant contribution to the total discharge of the Meuse. However, during low flows, its contribution is proportionally smaller. The Sambre river, which has a large reservoir upstream, provides the largest contribution during low flow conditions (Kramer, 2021).

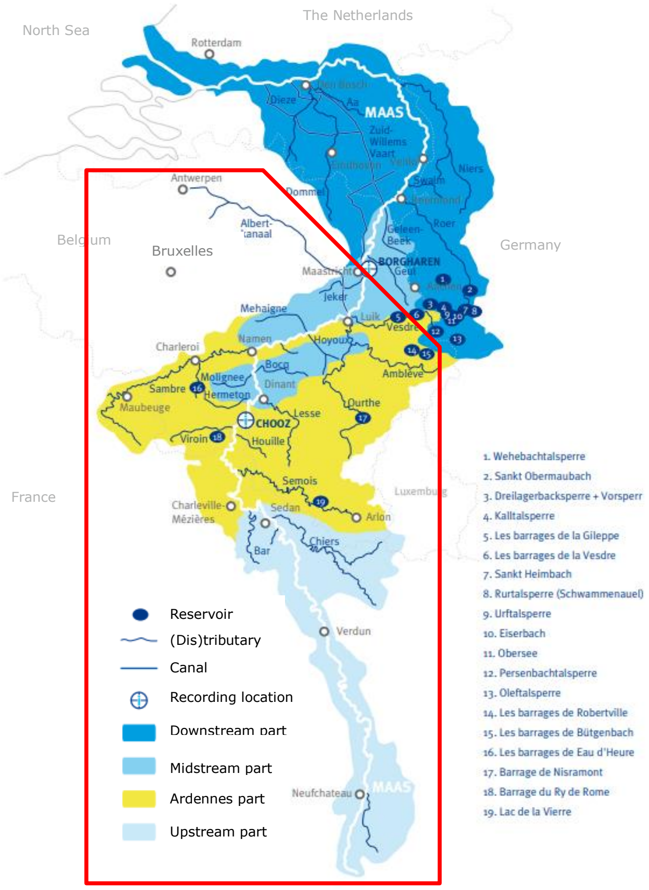


Figure 2. The Meuse catchment (Dutch: Maas) with its sub-division in four parts and the main surface water reservoirs. The red box indicates the study area of this project (adapted from Kramer, 2021).

Similar to the upstream area, the midstream part is characterised by a flat area underlain by deep layers of limestone, making the subsoil permeable. The contribution of the tributaries from this part of the catchment to the total discharge of the Meuse is relatively small but constant. This part has a relatively large contribution during low flow conditions (Kramer, 2021).

The most downstream part of the Meuse catchment is heavily managed with weirs, pumps, and canals. The goal of this management is to control the water levels of the surrounding lowlands and to ensure water levels deep enough to facilitate shipping. This area has a relatively larger contribution during low flow than during high flow conditions, due to reservoirs in the Eiffel and Rur catchment in Germany (Kramer, 2021). The Rur is the largest contributor to the Meuse discharge during low flow conditions (Kramer, 2021).

2.3 Input data

Table 1 shows the data that is used in this study for the scenario analysis. The runoff time series and current water demand are used for the simulation of the current climate, which forms the baseline for the other scenarios. The simulation of climate change is based on changes in the meteorological variables from the KNMI'23 climate scenarios and the hydrological variables from the Deltares discharge scenarios. Water demand scenarios are based on the 2017 Deltascenarios.

Table 1. Overview of the RIBASIM Input data for the scenario analysis.

Data	Based on	RIBASIM input	Resolution
Runoff time series	Wflow_sbm simulations Deltares (Van der Krogt et al., 2022)	Actual inflow	Daily, 1981-2020
Current water demand	Deltares inventory of water users and water infrastructure (Van der Krogt et al., 2022)	Water demand and minimum discharge requirements	Seasonal pattern in 10-day timesteps
Climate scenarios – meteorological variables	KNMI'23 climate scenarios (KNMI, 2023)	Actual rainfall, loss flow, open water evaporation, reference evapotranspiration	quarterly
Climate scenarios – hydrological variables	Deltares discharge timeseries Meuse (Buitink et al., 2023)	Relative change actual inflow and general district discharge	Model timestep (10 days)
Water demand scenarios	Deltascenarios 2017 (Wolters et al., 2018a)	Relative change for agricultural area and water demand (drinking water, industry, cooling water)	One change per sector

2.4 Hydrological modelling of the Meuse

This study uses the RIver BAsin SIMulation model (RIBASIM, version 7.01.25). RIBASIM was developed by Deltares in 1985 as a software package for simulating the water balance and behaviour of river basins under various hydrological, climatic, agricultural and water quality scenarios (Van der Krogt & Boccalon, 2013). RIBASIM has since been globally applied as a tool for conducting water resource management scenarios for both water supply and water demand (Van der Krogt & Boccalon, 2013). Deltares conducted a project for RIWA-Maas and Rijkswaterstaat Zuid-Nederland to assess the climate change impact of the KNMI'14 scenarios on the water supply in the Meuse catchment. The two deliverables of this project were a RIBASIM model for the Meuse (Figure 3), and an inventory list of water users and water infrastructure in the catchment (Van der Krogt et al., 2022). The RIBASIM model and inventory of water users were used in this study, and no changes were made to them. A validation using observed data for the Meuse discharge at the Dutch border was done to check if the model was suitable for this study, see Appendix A.1 for more details. The results from this validation showed that the model performs adequately to be used in this study.

The core element of the RIBASIM model is a network schematisation of the Meuse catchment, which shows the spatial relationships between elements in the basin (Figure 3). The schematisation comprises of nodes that represent catchment features that play a role in the water balance. Nodes are connected by links which represent flows in the catchment (Van der Krogt & Boccalon, 2013). The Meuse catchment has four main constituent groups that are included in the schematisation:

- Natural and man-made infrastructure: (potential) surface water reservoirs, rivers, canals, pumping stations, pipelines, and sluices;
- Water users or water related activities: shipping, nature, recreation, agriculture, and domestic, cooling water, and industrial water use;
- Management of water resources system: allocation methods and reservoir operation rules;
- (Geo) hydrology: runoff and precipitation (variable inflow), river flows, and evapo(transpi)ration loss flows.

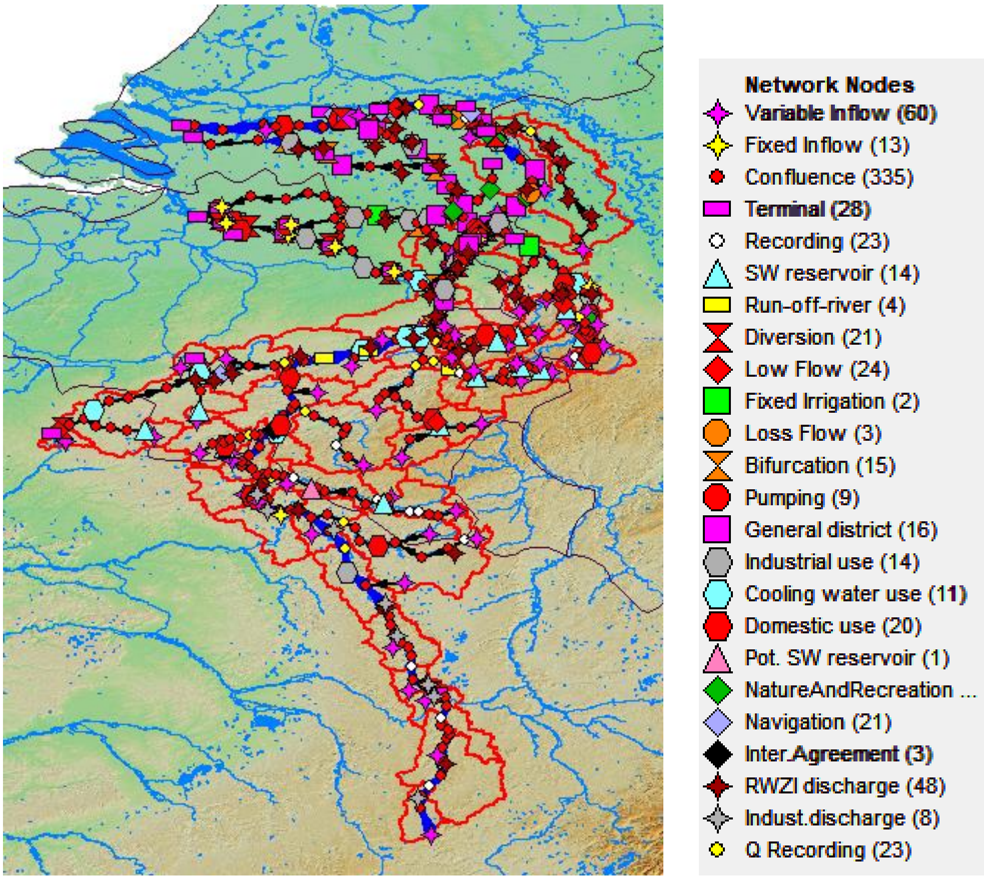


Figure 3. Network schematisation of the Meuse catchment as created by Van der Krogt et al. (2022). The black lines indicate country borders, and the red lines show the sub-catchments.

The base for the water balance calculations consists of daily time series for runoff, rainfall, and open water evaporation. These time series were created for the period 1981-2020 by Van der Krogt et al. (2022), using the Wflow_sbm rainfall-runoff model. This model only considers natural flow and could only be used for the part of the catchment upstream of Mook (white shaded area in Figure 5). Downstream of Mook, the timeseries are created using the national hydrologic model for the Netherlands (Landelijk Hydrologisch Model, LHM). The RIBASIM sub-catchments correspond to those of the Wflow_sbm model and the LHM, so each sub-catchment in RIBASIM has a variable inflow node where the hydrological inflow time series are set. RIBASIM calculates a water balance and streamflow for every timestep, which is a decade (10 days), in two phases:

1. target setting, determining water demands;
2. allocation, water distribution based on targets, availability, and priority rules.

Water allocation can be controlled by the modeller using a priority list. For each node in the basin this list outlines which other nodes are (potential) water supply sources. At basin scale, the water allocation shows which water demands are prioritised to receive the available water. In this study, the default option is used, which is a first come first served concept in a downstream direction. (Van der Krogt & Boccalon, 2013).

The different climate scenarios are simulated with RIBASIM by applying a percentage change for the different hydrological and meteorological variables. More information can be found in section 2.5.1. A similar approach was used for the water demands of in the catchment, see section 2.5.2.

This study focuses on the French-Belgian Meuse catchment, because:

- It is not possible to examine individual water users in the Dutch part of the catchment with sufficient accuracy, using the RIBASIM model. This is because the LHM is used to simulate the water demand in this area, which in RIBASIM is represented as general district nodes in the Meuse schematisation (Figure 3). These nodes represent the aggregated water demands for irrigation, industry, salt intrusion prevention, and water level maintenance (Van der Krogt et al., 2022).
- In addition, the German part of the network schematisation has been set to inactive, and therefore it was not possible to examine the water shortages for individual users. The discharge from this part of the catchment is dominated by reservoir operations which could not be simulated with enough accuracy. This is because they depend too much on human operational decisions (Van der Krogt et al., 2022). To simulate the inflow from the Rur to the Meuse, a recorded time series from the recording station at Stah has been used instead of the RIBASIM network schematisation.

2.5 Scenario analysis

2.5.1 Climate change

The first part of the scenario analysis of this study is the simulation of future Meuse discharges as projected by the KNMI’23 scenarios. These scenarios are based on CO_2 emission pathways and a wet-dry configuration. There are three CO_2 emission pathways: low (L), medium (M), and high (H). These pathways are based on the scenarios developed by the IPCC: SSP1-2.6, SSP2-4.5 and SSP5-8.5, respectively (Buitink et al., 2023; KNMI, 2023). The wet-dry configuration was created to represent the uncertainty in the climate response of the different models used to construct the KNMI’23 scenarios. A wet (n) scenario projects strong wetting in the winter and a mild drying in summer. The dry (d) scenario projects mild wetting in winter and strong drying in summer. These scenarios are simulated for different time horizons (2033, 2050, 2100, and 2150), which results in a total of 15 scenarios (Table 2). Each time horizon represents a surrounding 30-year period (i.e. 2050 = 2036-2065). The Ln scenario for time horizon 2033 represents the 1.5 degrees temperature increase of the Paris agreement. The results of these time horizons will be compared to the current climate, represented by the period 1991-2020.

For each climate scenario, Deltares generated projected discharge time series for the Meuse at the Dutch border using the rainfall-runoff model Wflow_sbm (Buitink et al., 2023). These time series are used as input for the RIBASIM model in this study. The low emission pathway showed no significant difference in climate between the time horizons. Therefore, Deltares represented all these time horizons by the single simulation for the time horizon 2100 (Buitink et al., 2023).

Table 2. Overview of KNMI’23 climate scenarios used for this study.

		Emission pathway		
		Low (L)	**Medium (M)**	**High (H)**
Variant	**Dry (d)**	**Ld** 2100	**Md** 2050, 2100, 2150	**Hd** 2050, 2100, 2150
	Wet (n)	**Ln** 2033 (Paris), 2100	**Mn** 2050, 2100, 2150	**Hn** 2050, 2100, 2150

Four meteorological variables (actual rainfall, loss flow, open water evaporation, and reference evapotranspiration for agricultural crops) and two hydrological variables (actual inflow and general district discharge), have been adapted to implement the climate scenarios in RIBASIM. For the meteorological variables a relative change was applied per season based on data published by the KNMI (KNMI, 2023), see Table 3. For the hydrological variables the annual pattern of relative change was determined by comparing measurements of the Meuse for the period 1991-2020, with the discharge time series created by Deltares (Buitink et al., 2023), see Figure 4. Climate change is assumed to not vary spatially, so the same relative changes are applied for all sub-catchments.

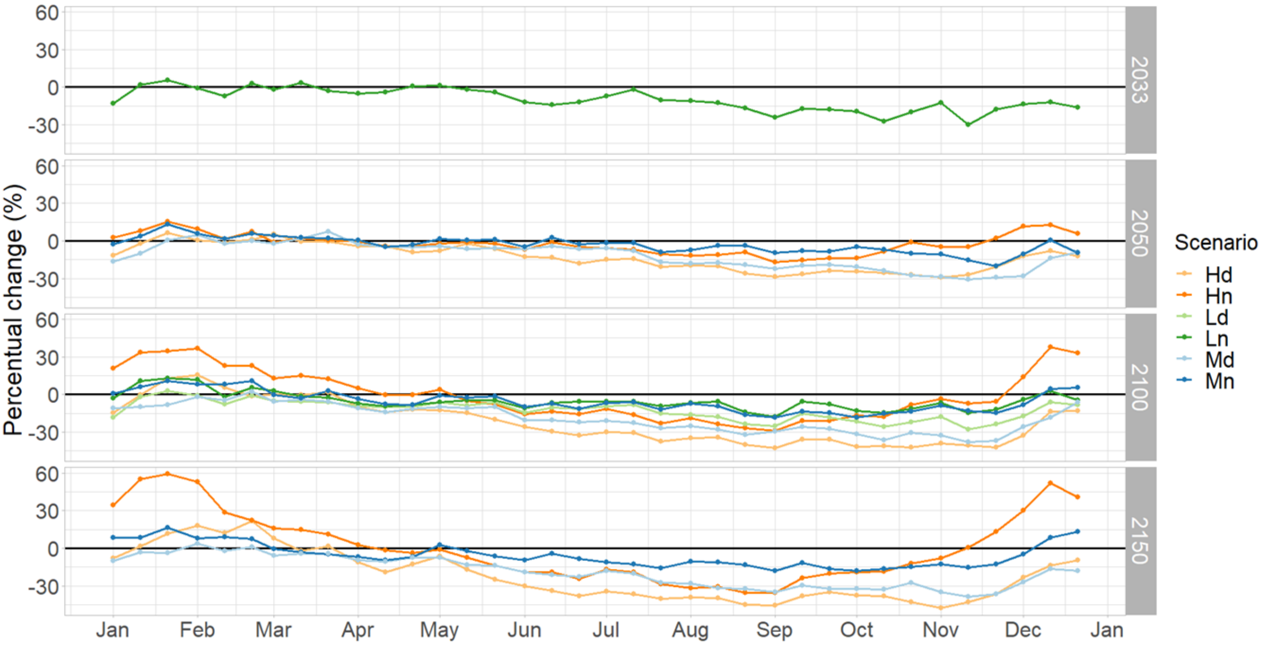


Figure 4. The relative difference in the discharge for the Meuse at the Dutch border between the current climate and the different scenarios of KNMI'23. The high climate scenarios are shown in orange (Hd=dry, Hn=wet), the moderate scenarios in blue (Md=dry, Mn=wet), and the low scenarios in green (Ld=dry, Ln=wet).

Table 3. Overview of the relative changes for the different seasons applied to the meteorological variables in RIBASIM based on the KNMI'23 scenarios (winter: DJF, spring: MAM, summer: JJA, autumn: SON).

		Actual rainfall				**Loss flow, Open water evaporation, Reference evapotranspiration crops**			
Time horizon	**climate scenario**	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
2033	Ln	5%	1%	-3%	3%	5%	5%	6%	6%
2050	Md	+4%	+1%	-9%	+2%	+6%	+5%	+8%	+6%
	Mn	+5%	+3%	-2%	+4%	+5%	+4%	+6%	+6%
	Hd	+4%	0%	-13%	+1%	+7%	+6%	+11%	+10%
	Hn	+7%	+4%	-5%	+4%	+6%	+4%	+7%	+6%
2100	Ld	+4%	+1%	-8%	+4%	+6%	+6%	+8%	+7%
	Ln	+5%	+3%	-2%	+5%	+7%	+5%	+6%	+7%
	Md	+5%	+4%	-15%	+3%	+6%	+7%	+12%	+9%
	Mn	+10%	+7%	-3%	+7%	+7%	+4%	+8%	+7%
	Hd	+14%	+4%	-29%	+1%	+11%	+10%	+22%	+20%
	Hn	+24%	+10%	-12%	+13%	+9%	+6%	+14%	+13%
2150	Md	+7%	+4%	-16%	+3%	+7%	+7%	+13%	+11%
	Mn	+12%	+8%	-4%	+9%	+7%	+4%	+8%	+8%
	Hd	+23%	+5%	-31%	+4%	+13%	+11%	+27%	+24%
	Hn	+35%	+12%	-14%	+18%	+12%	+7%	+19%	+19%

2.5.2 Water demand

In addition, two water demand scenarios were simulated. These demand scenarios are based on the Deltascenarios 2017, which were developed to show a coherent picture of both climate and socio-economic developments, and the implications for water management (Wolters et al., 2018a; Wolters et al., 2018b). The Deltascenarios include four scenarios, based on climate change (moderate or high) and socio-economic developments (growth or decline). The Deltascenarios are developed for the Netherlands. For this study it is assumed that similar trends in water demand change can be expected in the French and Belgian parts of the Meuse catchment.

The Deltascenarios show the relative change of various water-dependent functions: potentially irrigated agricultural area and the water demand for drinking water, industry, and cooling water. In this study these relative changes have been applied to the 2050 moderate (Md and Mn) and high (Hd and Hn) climate scenarios. Table 4 shows the relative changes per sector for all scenarios. These relative changes are implemented in RIBASIM by applying them to corresponding nodes. Potentially irrigated agricultural area is applied to the fixed irrigation node in RIBASIM. The change in drinking water demand is applied to all domestic nodes. Cooling water demand is applied to the cooling water nodes and the water demand for industry is applied to all the abstractions of industrial nodes. The relative changes presented in Table 3 are assumed to be constant throughout the year.

An 80% reduction in cooling water demand is applied across all scenarios, as shown in Table 4. Given the substantial change in this assumption, a sensitivity analysis was carried out to study the effect of various reductions in cooling water use on the annual 10-day minimum discharge.

Table 4. Overview of the different water demand scenarios used in this study with their relative changes in water demand for different sectors, based on the Deltascenarios 2017 (Wolters et al., 2018a).

Climate change	**Moderate** Md and Mn	**High** Hd and Hn	**Moderate** Md and Mn	**High** Hd and Hn
Socio-economic development	**Growth**	**Growth**	**Decline**	**Decline**
Based on Deltascenario	Druk	Stoom	Rust	Warm
Potentially irrigated agricultural area	+4%	+55%	+8%	+8%
Water demand drinking water	+10%	+35%	-10%	0%
Water demand cooling water	-80%	-80%	-80%	-80%
Water demand industry	-30%	+15%	-40%	-10%

2.6 Water availability bottleneck analysis

The last part of this study was the water availability bottleneck analysis. The goal of this analysis was to identify which locations in the French-Belgian part of the Meuse catchment will suffer from surface water shortages under the current and future climate.

In this study a bottleneck is defined as a location where the supply does not meet the demand. Therefore, the bottleneck analysis could be done for the 40 sites for which Van der Krogt et al. (2022), investigated the water demand, see Figure 5. These sites include both water users, i.e. parties that actively abstract surface water from the Meuse or (dis)tributaries, and locations for which discharge requirements are in place. The supply is defined as the local discharge of the Meuse or (dis)tributaries.

To quantify bottlenecks, a shortage ratio is used. This ratio is defined as:

$$shortage\ ratio = \frac{water\ demand}{supply}$$

The shortage ratio is calculated for each time step for both the current climate, as well as for the different climate and water demand scenarios. The maximum value for each year in the 30-year period of each scenario is determined and the average of these 30 maxima was calculated. This provides an average maximum shortage at each site that occurs once a year on average. Sites with an average ratio larger than 1 [-] were identified as bottlenecks.

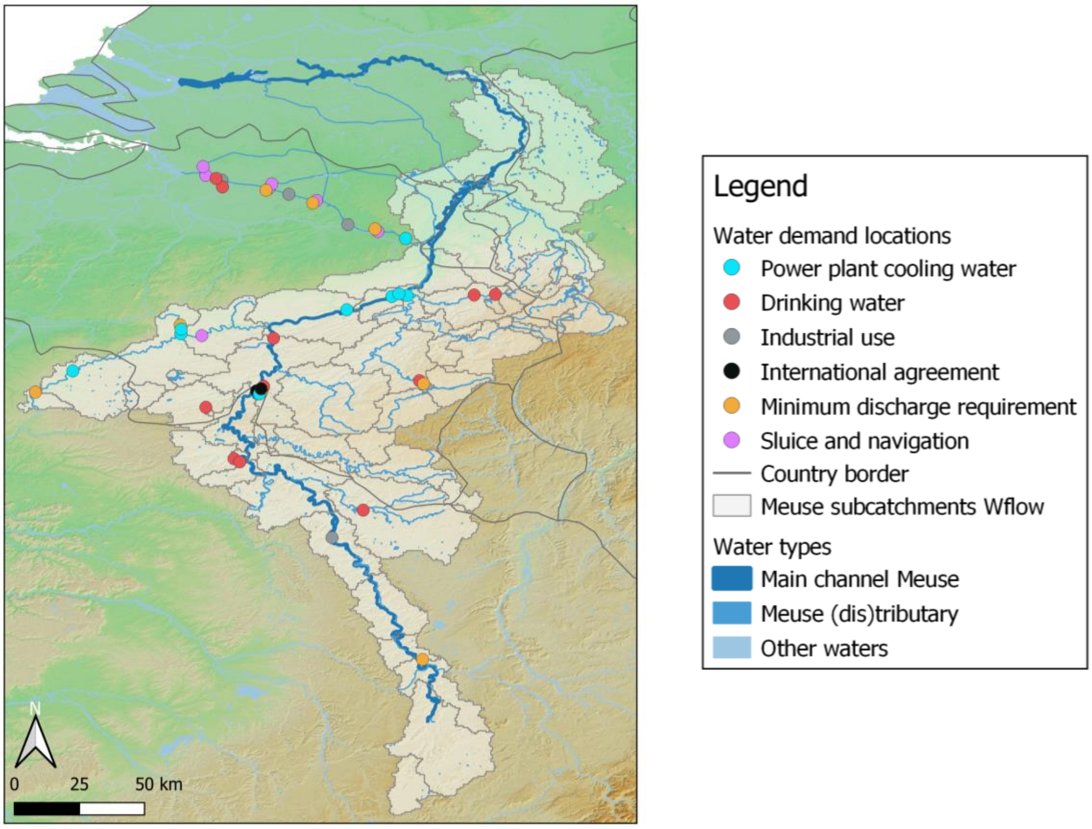


Figure 5. Sites of the water users and minimum discharge requirements in the French-Belgium Meuse catchment. The white shaded area shows the sub-catchments from the Wflow_sbm model, used to create input time series for the RIBASIM model.

To study the impact of climate change and socio-economic developments, both the number of bottlenecks as well as the severity of a bottleneck is analysed. This is done by dividing bottlenecks in five categories, based on the shortage ratio: 0.5 or smaller, 0.5-1, 1-1.5, 1.5-2, and larger than 2. This means, for example in the category of >2, on average at least once a year the water demand is twice as high as the water supply.

3 Results

This chapter presents the outcomes of the climate change and water demand scenario analysis as well as the bottleneck analysis. These statistics are all presented for the Meuse at Monsin. At this location the Albert Canal has not yet diverted from the Meuse, so therefore it is a good location to compare the discharge with the thresholds set in the Meuse Discharge Treaty, an agreement between the Netherlands and Flanders (Maasafvoerverdrag, 1995). Appendices A.2 and A.3 show the results for other locations in the catchment. The impact of socio-economic developments on future water availability is also presented for the Meuse at Monsin. Details on the other locations can be found in appendices A.4 and A.5.

In this study, boxplots have been used to understand the hydrological response to the different climate scenarios and water demand scenarios. This does not only make for easier comparison of the different scenarios with each other and the current climate, but also shows the variability inside a single scenario. The boxplots shown in this chapter all represent a 30-year period around a time horizon, therefore all boxplots consist of 30 values. The box represents the 25-75% data range, and the horizontal line within the box represent the median value. Outliers are visualised by individual points. The boundaries of the whiskers are based on 1.5 times the interquartile range (the distance between the box boundaries), which are either added or subtracted from the box boundaries to form the upper and lower whisker, respectively.

3.1 Impact of climate change on water supply

3.1.1 Effect on annual average discharge

Figure 6 shows the relative change in the annual average discharge for the KNMI’23 scenarios of the Meuse at Monsin compared to the current climate. There is a clear difference between the trends of the wet and dry scenarios. The dry scenarios show a clear decrease over time until 2100 (Md: -14.2%, Hd: -13.5%), and then maintain the same approximate value until 2150 (Md: -13.8%, Hd: -11.2%). The moderate and high emission pathways for the dry scenarios show similar values for the median, but they differ in the range, indicated by the whiskers.

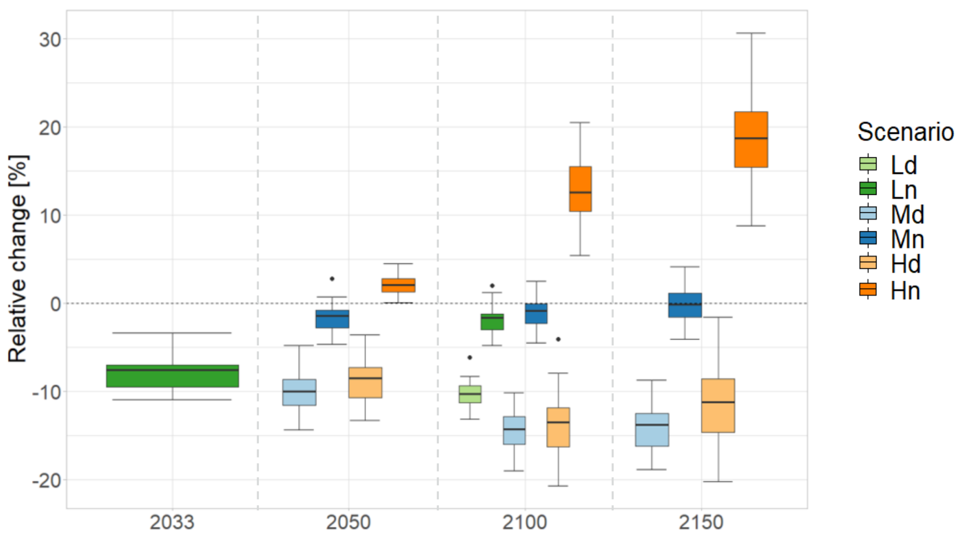


Figure 6. Relative change in the annual average discharge of the Meuse at Monsin for the future climate, as (time horizons on the x axis). Green boxes present the low climate change scenarios (Ln=wet and Ld=dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry), and orange boxes present the high scenarios (Hn=wet and Hd=dry).

The Hd scenarios show an increase in the range over time, while the Md scenario keeps a constant range. The moderate and low wet scenarios show a more stable trend resulting in annual average discharges comparable to the current climate. The high wet scenario (Hn) shows an increasing trend, and goes from 2.1% in 2050, up to +18.7% in 2150.

Figure 7 shows the absolute values of the annual average discharge under the current climate, and both the KNMI’23 and the KNMI’14 scenarios. A larger number of the KNMI’23 scenarios project a decrease in annual average discharge than in the KNMI’14 scenarios. Four of the KNMI’14 scenarios (GL, GH, WL, and WH) simulate an increase in the annual average discharge, which is comparable to the discharges simulated by Hn in 2100 and 2150. The WHdry scenario of KNMI’14, representing strong global warming and an extreme decrease in precipitation, shows a decrease of the annual average discharge, which is smaller than the decrease simulated by the dry scenarios of KNMI’23. This all lead to the variation between the new scenarios being smaller than the variation between the KNMI’14 scenarios.

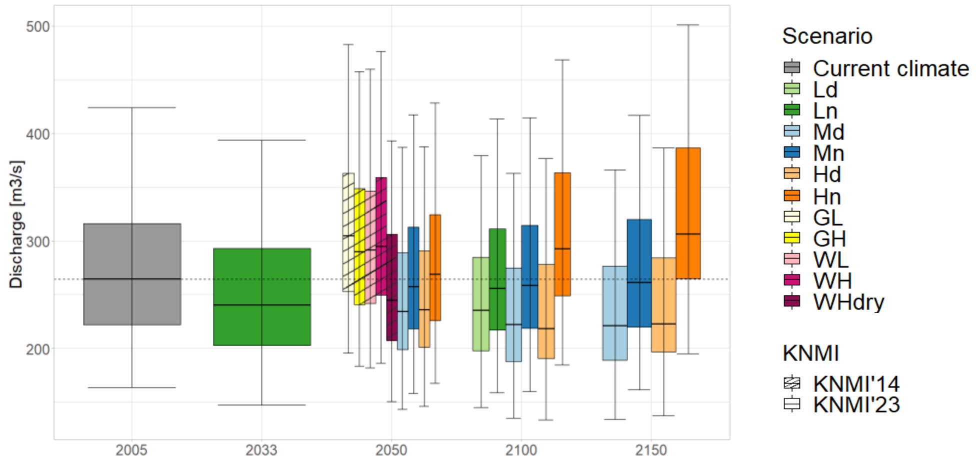


Figure 7. The annual average discharge of the Meuse at Monsin for the current climate and future climate (future time horizons on the x-axis). Green boxes present the low climate change scenarios (Ln=wet and Ld=dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn=wet and Hd=dry). The striped yellow and purple boxes show the different KNMI’14 scenarios.

3.1.2 Effect on the annual 10-day minimum discharge

Figure 8 shows the relative change in the annual 10-day minimum discharge of the Meuse for the different KNMI’23 scenarios compared to the current climate. There is a clear downward trend over time visible for all scenarios. The Paris scenario already simulates a median decrease of 16% by 2033. The most extreme decreases are found under the high and dry scenario (Hd), about 40% by 2100 and 2150. For all time horizons, the dry scenarios show a larger decrease than their wet counterparts and the wet scenarios with higher emission pathways. This is illustrated by the moderate dry scenario (Md), which has larger decreases than the high emission wet scenario (Hn) for all time horizons. Furthermore, the low dry scenario (Ld) shows a similar decrease as Hn for 2100, 19% and 21% respectively. This shows that with a dry configuration, a lower emission pathway can already lead to similar effects as higher emission pathways, with a wet configuration.

This suggests that the wet or dry climate configuration has a greater effect on the 10-day minimum discharge than the severity of emission pathway.

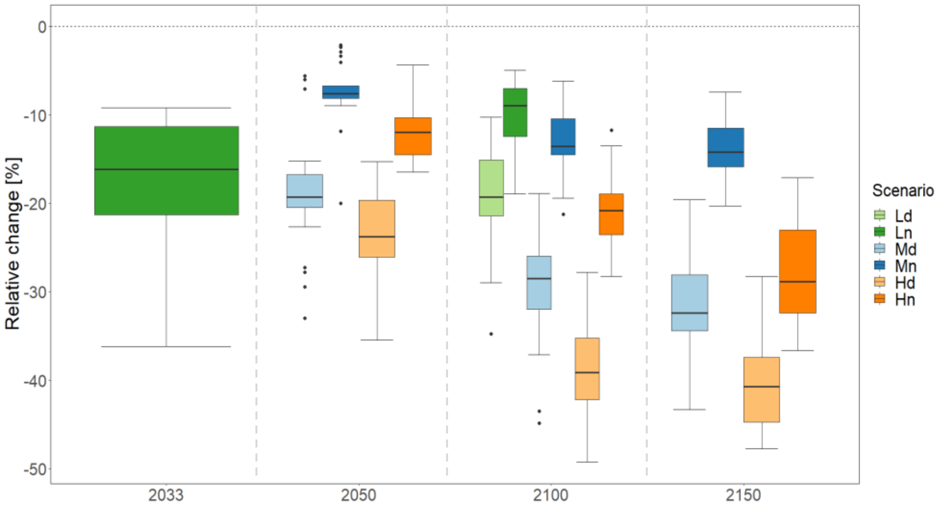


Figure 8. Relative change in the annual 10-day minimum discharge of the Meuse at Monsin for the future climate, as (time horizons on the x axis). Green boxes present the low climate change scenarios (Ln=wet and Ld=dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry), and orange boxes present the high scenarios (Hn=wet and Hd=dry).

Figure 9 shows the absolute values of the annual 10-day minimum discharge under the current climate and the future climate as simulated with the KNMI’23 and KNMI’14 scenarios. A comparison of the KNMI’23 and KNMI'14 scenarios for 2050 shows a more consistent change under the new scenarios than for the old ones. The KNMI’23 scenarios show a decrease for all scenarios compared to the current climate. Under the KNMI’14 scenarios the GL scenario, indicating moderate global warming and small changes in precipitation, showed an increase in the annual 10-day minimum discharge. On the other hand, WHdry, representing strong global warming and an extreme decrease in precipitation projects a more extreme decrease in the annual 10-day minimum discharge than any of the KNMI’23 scenarios. WHdry has a median value of 27.2 m^3/s for 2050, while the median value for Hd in 2150 is 28.3 m^3/s. The other KNMI’14 scenarios, GH, WL and WH all project annual 10-day minimum discharges which are in the same order of magnitude as the KNMI’23 scenario projections for 2050.

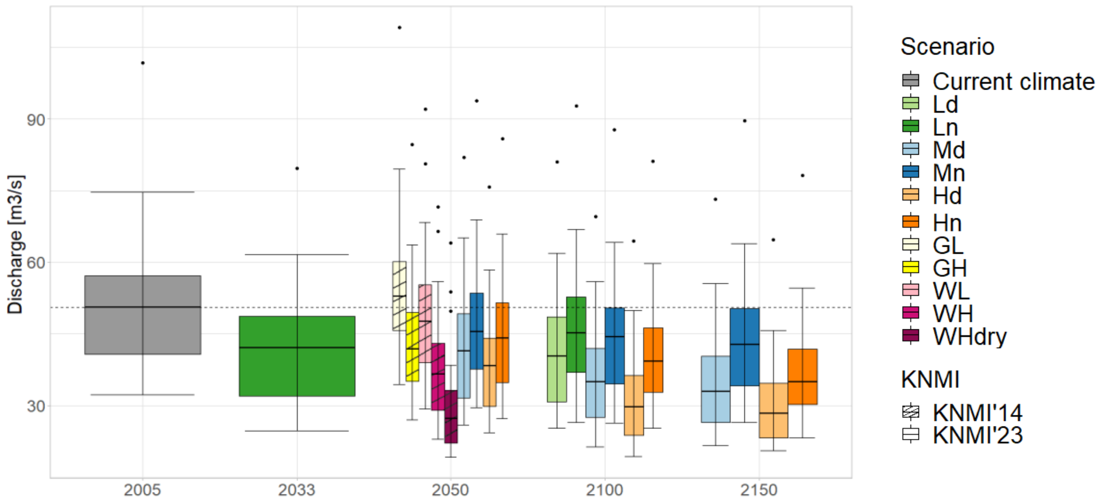


Figure 9. the annual 10-day minimum discharge of the Meuse at Monsin for the current climate and future climate (future time horizons on the x-axis). Green boxes present the low climate change scenarios (Ln=wet and Ld=dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn=wet and Hd=dry). The striped yellow and purple boxes show the different KNMI’14 scenarios.

3.1.3 Effect on the dependable flow

This section discusses the impact of climate change on the 90% dependable flow. Details on the 70% dependable flow can be found in appendix A.6. The results are presented for the Meuse at Monsin.

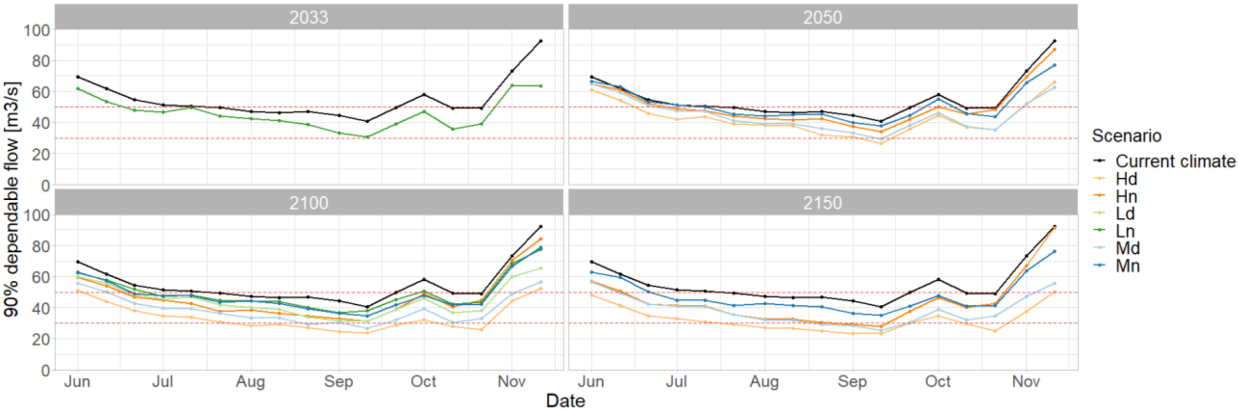


Figure 10. The 90% dependable flow of the Meuse at Monsin from June to November. The different panels indicate the different time horizons. The black line shown in all panels represents the current climate. The dashed red lines indicate the thresholds of 30 and 50 m^3/s which are set in the International Meuse Treaty between Flanders and the Netherlands.

Figure 10 shows the 90% dependable flow of the Meuse at Monsin from June to November. The figure also shows two red lines representing two thresholds of 50 m^3/s and 30 m^3/s to indicate the alarm phase and the crisis phase as defined in the Meuse Discharge Treaty (Maasafvoerverdrag, 1995). In the current climate, the 90% dependable flow of the current climate exceeds the 50 m^3/s threshold between mid-July and the end of September. This means that during this period the alarm phase of the Meuse Discharge treaty is active 10% of the time, or once every 10 years on average. For all future scenarios the 90% flow is lower, with dry scenarios leading to a lower 90% flow than wet scenarios and higher emission pathways leading to a lower 90% dependable flow. This decrease results in an extension of the period during which the threshold of 50 m^3/s is exceeded, and the alarm phase would be active. Under the 2033 Paris scenario, this period would be two months longer, from the end of June to the end of October, than under the current climate. By 2100 and 2150, this period is extended to all of summer and autumn (beginning of June to beginning of November). In addition to an extension of the 50 m^3/s exceedance, the 90% dependable flow is also approaching and exceeding the 30 m^3/s crisis threshold under the Md and Hd scenarios. This means the activation of the crisis phase of the Meuse Discharge Treaty would occur every 10 years on average.

3.2 Impact of socio-economic developments on future water availability

3.2.1 Effect on the annual average discharge

The effect of different water demand scenarios, representing socio-economic growth and decline on the annual average discharge for 2050 is shown in Figure 11. Looking at the median values, the figure clearly shows a decrease in annual average discharge for the dry climate scenarios (Md and Hd) with current water demand. The wet climate scenarios (Mn and Hn) have median values which are more comparable to the current climate. Lower discharges mean, lower water availability, and conversely higher discharges mean a higher water availability. For all climate scenarios, the water demand scenarios representing socio-economic growth and decline resulted in a small increase in the median value of the average discharge. This implies a small increase in the water availability compared to climate change + current water demand scenarios. The differences between the socio-economic growth and decline scenarios are negligible. This means that the combined effect of changes in water demand in the different sectors is similar for both scenarios and leads to an increase in water availability in the French-Belgian part of the Meuse catchment. The impact of climate change and socio-economic development on water availability was compared. The difference between the climate change + current water demand scenarios and the current climate is much larger than the difference with the socio-economic development scenarios. That shows that the impact of projected climate change is greater than the impact of socio-economic development.

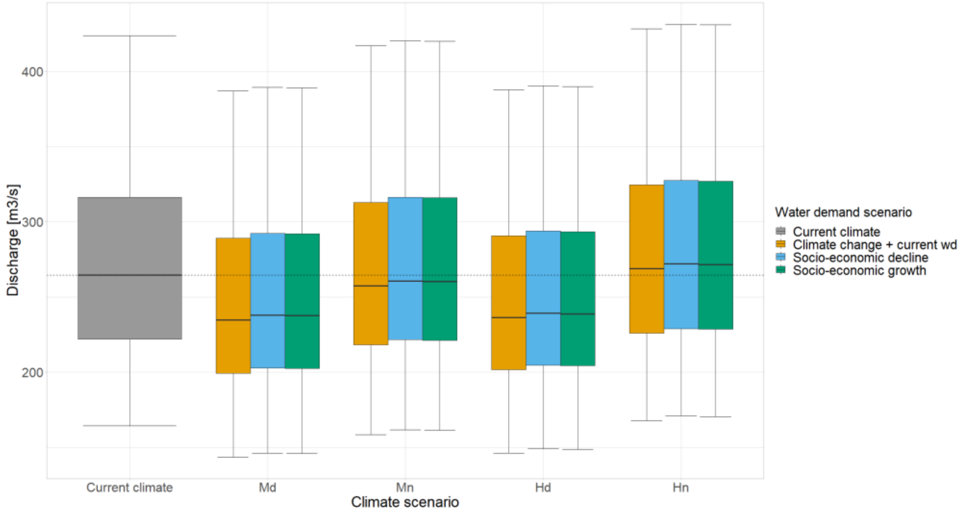


Figure 11. The annual average discharge of the Meuse at Monsin for the current climate and climate scenarios for the year 2050 (wd = water demand).

3.2.2 Effect on the 10-day minimum annual discharge

Figure 12 shows the effect of the different climate and water demand scenarios on the annual 10-day minimum discharge. This figure shows the consistent decrease in the median value of the annual 10-day minimum discharges for all climate scenarios as a result of climate change, as described in section 3.1.2. Similar to the impact of the socio-economic development on the annual average discharge (section 3.2.1.), the annual 10-day minimum discharge shows a small increase under the socio-economic growth and decline scenarios. For the annual 10-day minimum flow, the differences between the socio-economic growth and decline are larger than for the annual average flow, but are still very small. For the Hn, Mn, and Hd scenarios the median value of the socio-economic decline scenario is higher than the median value of the socio-economic growth scenario. The opposite is true for the Md scenario. The water demand scenarios do not have much influence on the spread of the annual 10-day minimum discharge, as the whiskers for the different scenarios are of similar length. As seen for the annual average discharge, the impact of climate change on the water availability seems larger than the impact of socio-economic developments, and both water demand scenarios lead to an increase in the water availability in the French-Belgian part of the Meuse catchment.

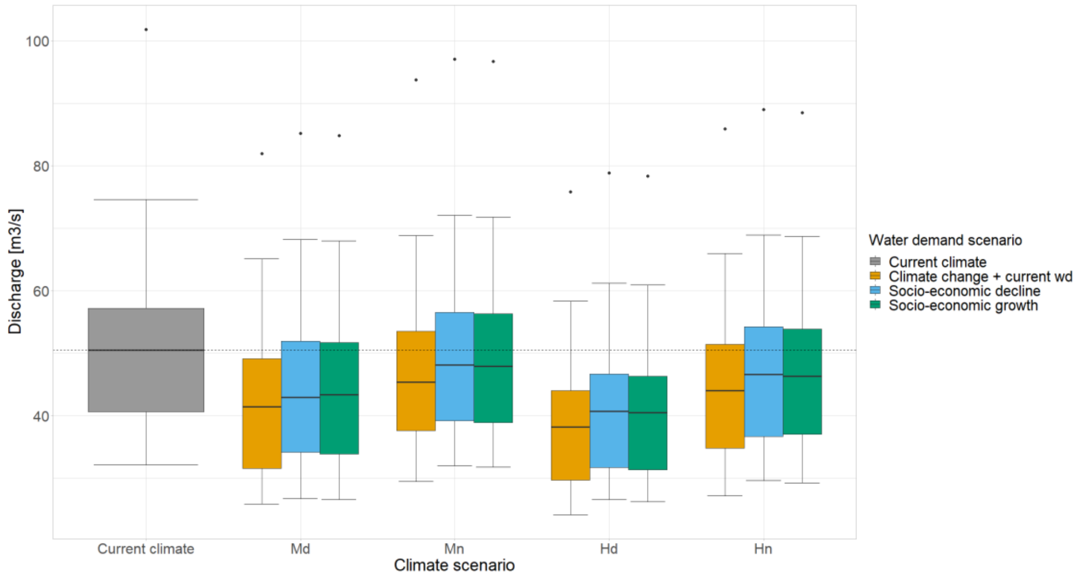


Figure 12. The annual 10-day minimum discharge of the Meuse at Monsin for the current climate and climate scenarios for the year 2050 (wd = water demand).

3.2.3 Sensitivity analysis for cooling water use

As described in the methodology, one of the assumptions made for the water demand scenarios was to apply an 80% reduction in cooling water demand for all scenarios. Figure 13 shows the sensitivity of the annual 10-day minimum discharge for the 2050 Hd scenario to different reductions in cooling water demand. This figure shows that for both socio-economic growth and decline, the greater the reduction in cooling water demand, the greater the overall water availability. For a 25% reduction in cooling water demand, the annual 10-day minimum discharge is not significantly different from the climate change + current water demand scenario. This suggests that changes in water demand from other sectors do not contribute significantly to the increase in water availability seen in the water demand scenarios. The substantial 80% reduction in cooling water demand is the main reason for the increase in water availability mentioned in the previous sections. Changes in cooling water demand are therefore the most dominant socio-economic development in the French-Belgian part of the Meuse catchment in terms of water availability.

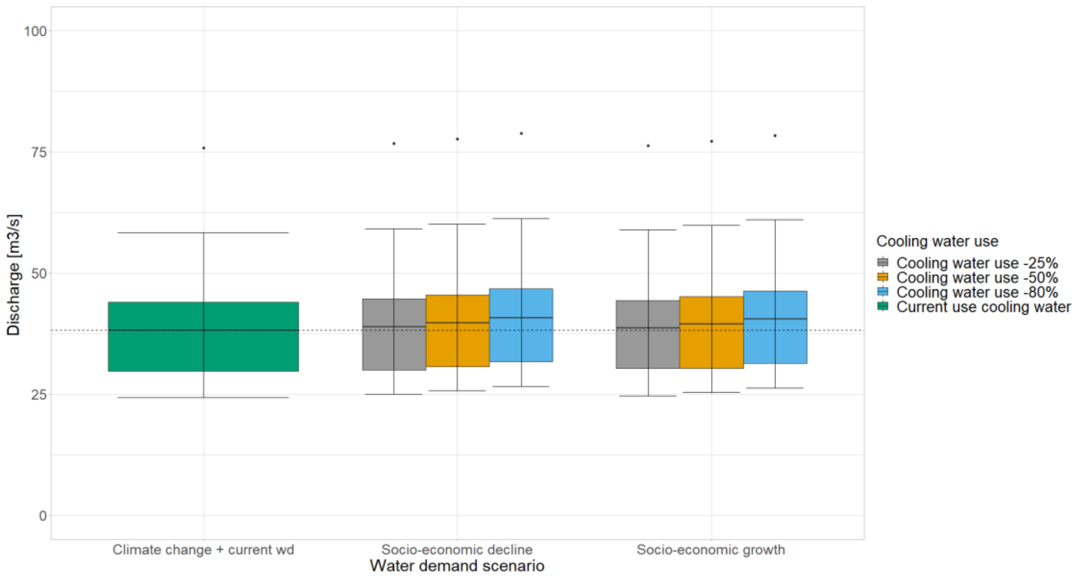


Figure 13. The annual 10-day minimum discharge of the Meuse at Monsin for the dry and high climate scenario (Hd) for 2050. The green box indicates the scenario with climate change and the current water demand.

3.3 Water availability bottleneck analysis

In this chapter the bottlenecks under the current climate will first be discussed, followed by the impact of climate change and socio-economic developments on the bottlenecks.

3.3.1 Current water availability bottlenecks

The average yearly maximum shortage ratio was determined for 40 sites in the French-Belgian part of the Meuse catchment for which water demand was known. These sites include both water users that abstract water from the Meuse and sites with minimum discharge requirements. Sites with a ratio larger than 1 are identified as bottlenecks, meaning that there is at least one 10-day period, when the water supply does not meet the local demand at a site. Under the current climate, 13 out of 40 sites have been identified as water availability bottlenecks (Figure 14). A large portion of these bottlenecks are located in the Flemish canals and the French-Walloon border region. The majority of these sites have values between 1 and 1.5 [-]. The Tihange nuclear power plant and the Olen sluice have scores between 1.5 and 2 [-]. The drinking water abstraction at the Ry de Rome reservoir and the Wijnegem sluice have a ratio larger than 2, indicating that on average every year there are periods where the supply is smaller than half the demand. The Reservoir Ry de Rome abstraction point is located directly downstream of the reservoir, so shortages can be directly linked to reservoir operations.

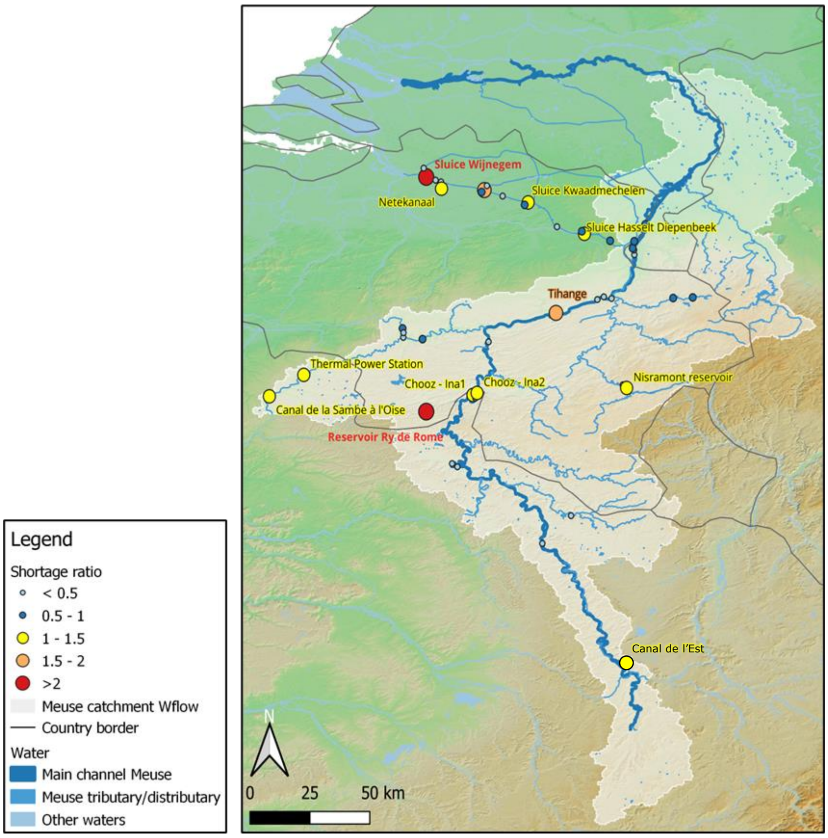


Figure 14. Map of the current bottlenecks in part of the Meuse catchment under the current climate.

3.3.2 Effect of climate change on water availability bottlenecks

To study the effect of climate change on the water availability bottlenecks, the number of sites in each shortage category is shown for the current climate and future climate scenarios for different time horizons (Figure 15). The total number of bottlenecks is the sum of all sites with a shortage ratio larger than one (i.e. the combined number of yellow, orange, and red categories). This figure shows that all climate scenarios have a higher number of bottlenecks than the current climate. The moderate and high climate scenarios show an increase in the number of bottlenecks over time, especially in the most severe category. In the Hd scenario, half of all sites are identified as a bottleneck by 2150.

A comparison between the different emission pathways shows that the Mn and Hn scenarios lead to the same number of bottlenecks for all time horizons, but there are more severe bottlenecks under the higher emission pathway. For the dry scenarios, the higher emission pathway has both more bottlenecks and more severe bottlenecks than the moderate dry scenario Md. This suggests that the specific emission pathway mainly affects the severity of bottlenecks.

When comparing the wet and dry scenarios of a specific emission pathway for each time horizon, for both the moderate and high scenarios the total number and the number of severe bottlenecks is higher under the dry scenarios. The differences between wet and dry climate scenarios are larger than between the different emission pathways, suggesting that the wet-dry configuration of climate scenarios is more important for the number of bottlenecks than the specific emission pathway.

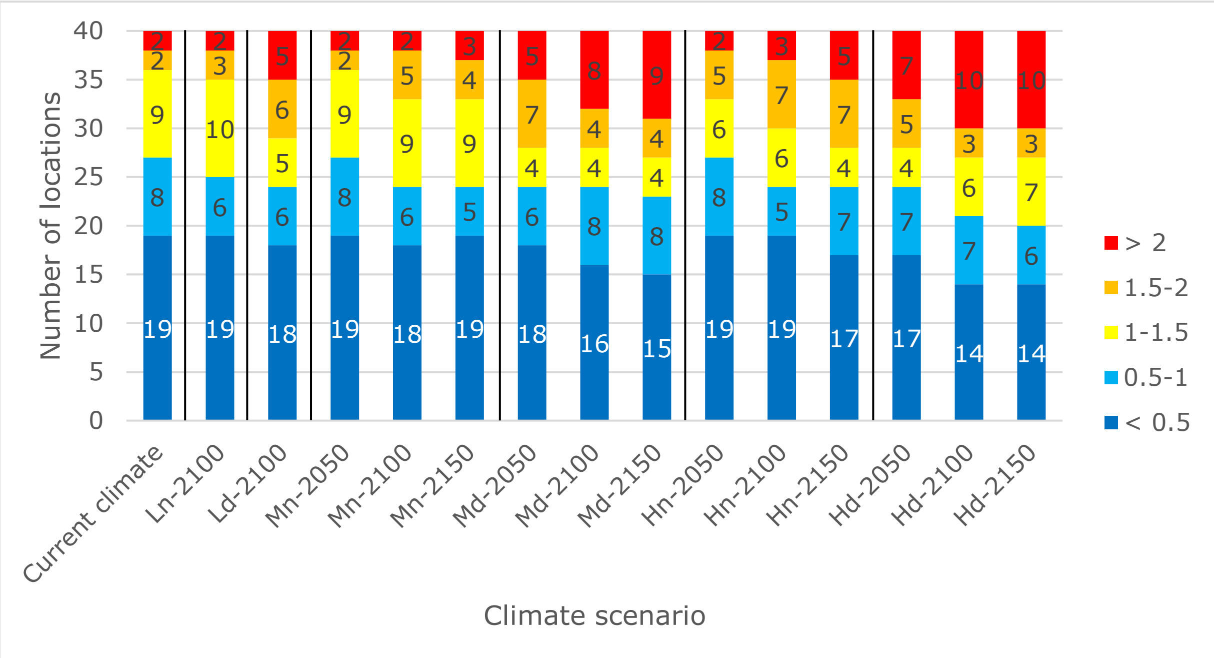


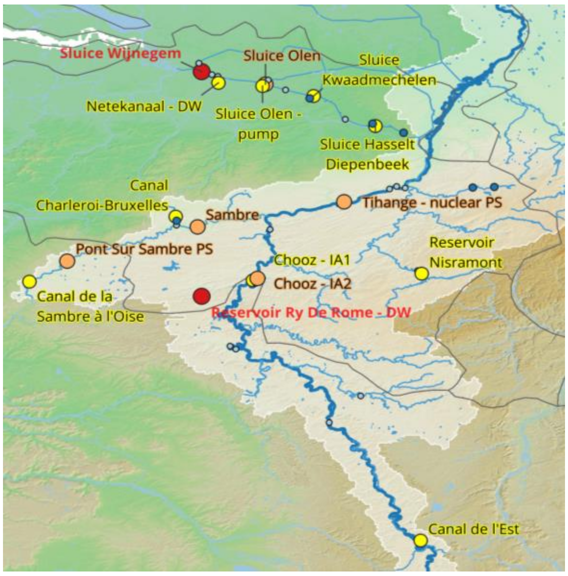
Figure 15. The number of locations in each shortage ratio class for the current climate and different climate scenarios and time horizons.

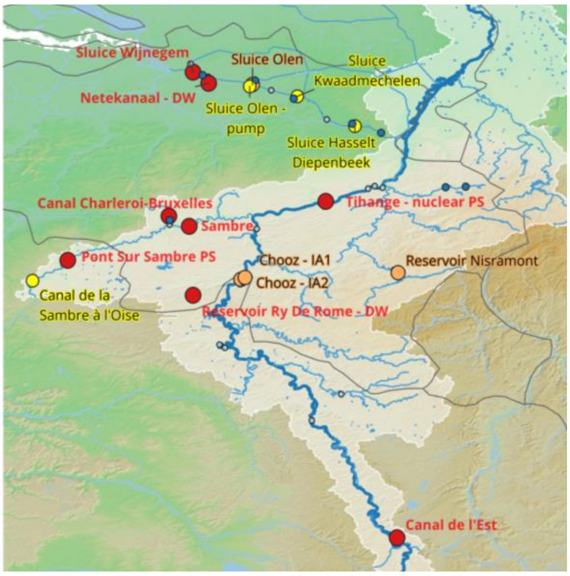
The distribution of bottlenecks across the catchment under different climate scenarios is shown in Figure 16. Bottleneck maps for the other time horizons can be found in appendix A.7. These maps confirm that higher emission pathways result in a larger number of severe bottlenecks and that dry scenarios have a larger total number of bottlenecks than wet scenarios. Compared to the current climate, one of the severe bottlenecks that occurs under the different scenarios is for shipping in the Sambre and the Canal Bruxelles-Charleroi. In the Netekanaal, the shortages for drinking water are exacerbated, making it a severe bottleneck in all dry scenarios. In the Hd scenario, two power station shortages are classified as the highest severity and two other power station are newly identified as water availability bottlenecks.

	Wet (n)	Dry (d)

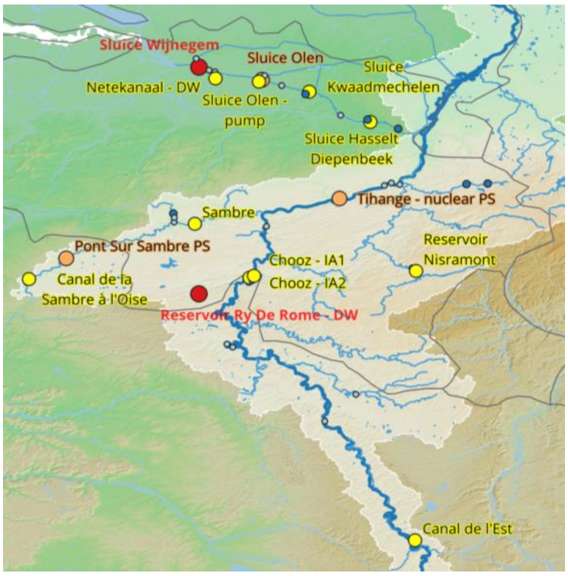
High (H)

Moderate (M)





Low (L)



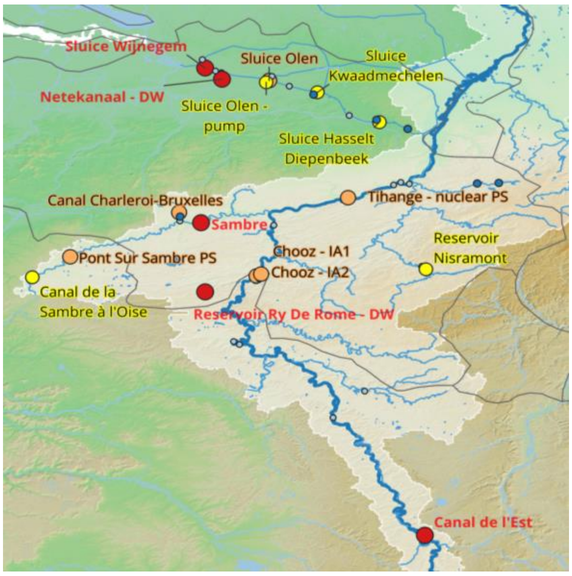


Figure 16.Maps showing the locations of bottleneck for 2100 under the different climate scenarios. Top left: Hn, top right: Hd, middle left: Mn, middle right: Md, bottom left: Ln, bottom right: Ld.

3.3.3 Effect of socio-economic developments on water availability bottlenecks

The effects of socio-economic developments on the number of water availability bottlenecks in 2050 is shown in Figure 17. The scenarios with climate change and current water demand (current wd) show the situation with the effects of climate change only. Under the Md, Hn, and Hd scenarios there is an increase in the number of water availability bottleneck compared to the current climate. When comparing the different water demand scenarios, it is noticeable that for both high emission pathways, the number of severe bottlenecks increases, while the total number of bottlenecks remains about the same. For Md this is not the case and there is a decrease in both total number of bottlenecks and the number of severe bottlenecks. With current water demand, the Mn scenario has the same number of bottlenecks as under the current climate. Under the different water demand scenarios the total number of bottlenecks decreases slightly, while the number of severe bottlenecks increases. For all climate scenarios there is no significant difference between the number or severity of the bottlenecks under the socio-economic growth scenario and the socio-economic decline scenario.

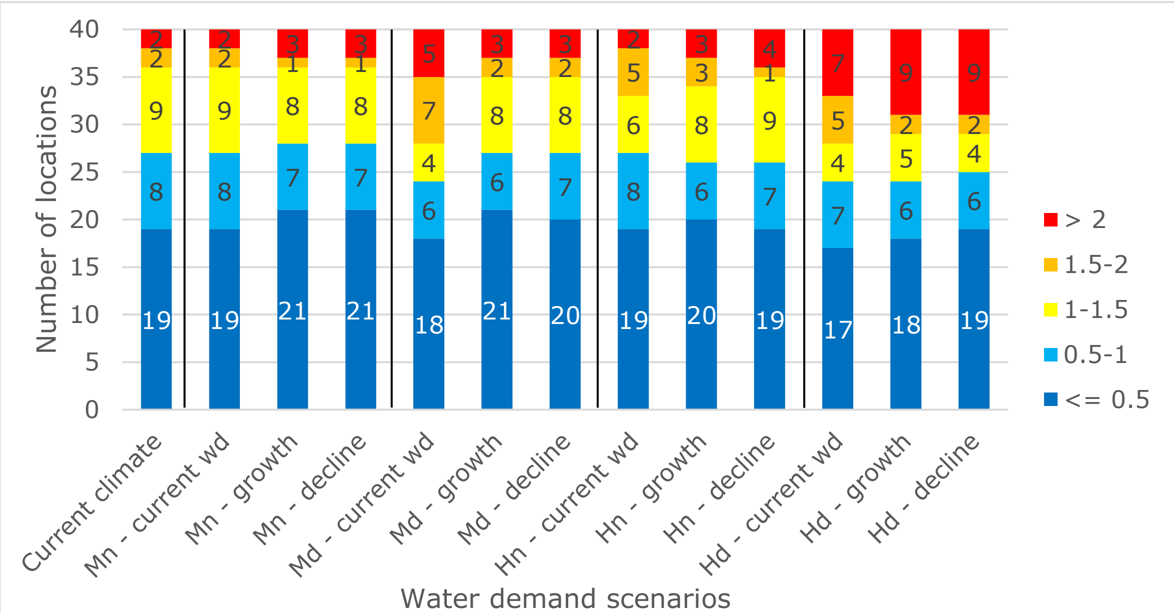
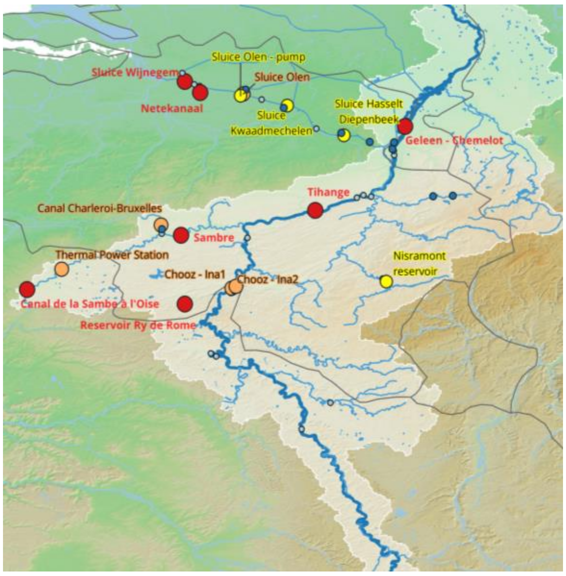


Figure 17. The number of locations in each shortage ratio category for the current climate and different climate and water demand scenarios for 2050.

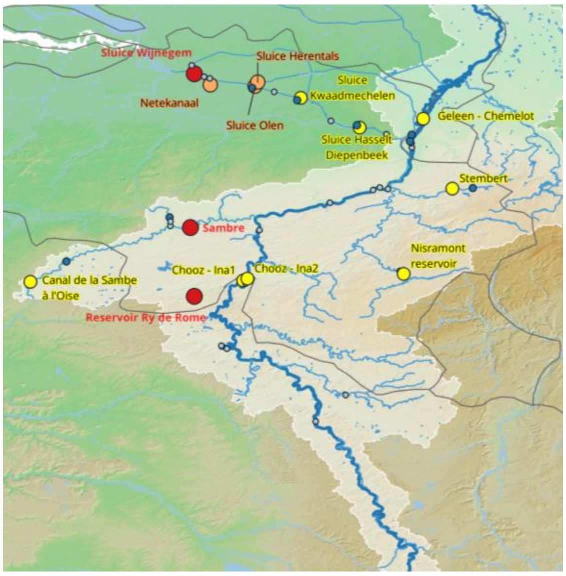
The spatial distribution of bottleneck sites for the high emission pathway scenarios (Hn and Hd) and different water demand scenarios for 2050 are shown Figure 18. Similar maps for the moderate climate scenarios can be found in the appendix A.8 . These maps show that the power stations at Tihange and the thermal power station, disappear as a bottleneck. On the other hand, the shipping in the Sambre and the Canal Charleroi-Bruxelles appear as a bottleneck, and a few locations in the Flemish canals suffer from increasing shortages.

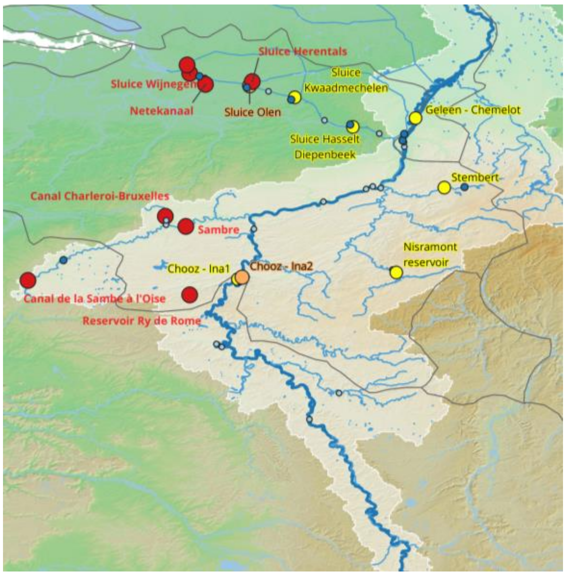
	Hn	Hd

Climate change + current water demand

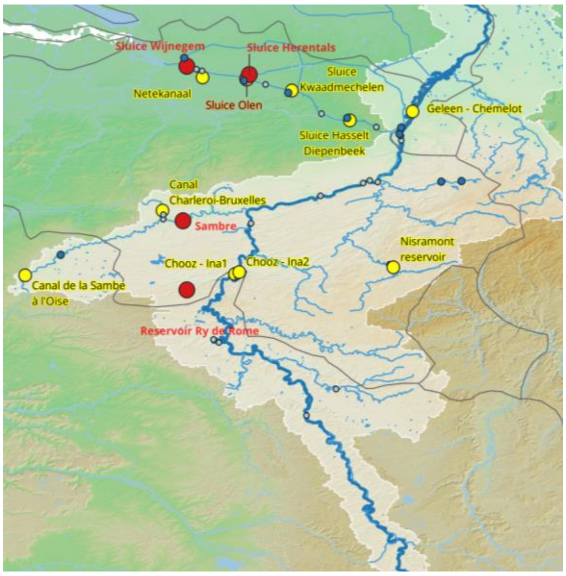


Socio-economic growth





Socio-economic decline



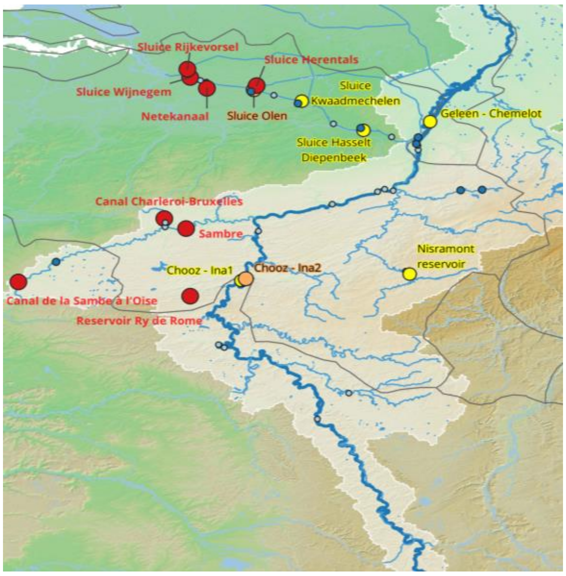


Figure 18. Maps with the locations of bottlenecks in 2050 under different water demand scenarios. Left column is the high and wet scenario, the right column the high and dry scenario.

4 Discussion

This chapter firstly discusses the implications of the results on water management. This is followed by the implications of the modelling choices and assumptions made in the scenario analysis for climate change and socio-economic developments.

4.1 Implications for water management

This study showed that water availability bottlenecks in the Meuse catchment will increase in number and severity under all climate scenarios. Although the analysis was limited to the French and Belgian parts of the catchment, it shows how widespread the water availability problems could become. Similar trends can be expected in Germany, and the situation could worsen downstream in the Netherlands. This raises concerns about the ability of current water management to cope with the anticipated effects of climate change. Currently, there is no integral international approach to address water availability issues in the entire Meuse catchment area. Conducting a study that focuses on the entire catchment area, rather than just one locality, can provide a better understanding of the full range of problems that may arise due to climate change. Furthermore, this study solely focuses on the quantity aspect of surface water availability. Taking into account both the quantity and the quality of water, including temperature and both chemical and biological quality, the issue of water availability may be even greater than what is presented in this study. Increased awareness of potential water availability problems in the Meuse catchment should shift the focus towards determining the best approach to tackle catchment-wide water availability issues with a focus on both water quantity and quality. To support this, further research could focus on the effectiveness of collaborative measures taken upstream in the catchment area, rather than downstream, to improve water availability. Solving water availability problems at the catchment scale is only possible through international collaboration and requires discussions on shared responsibilities and transboundary measures.

4.2 Implications of modelling choices and assumptions

The current network schematisation of the Meuse catchment is made by Deltares (Van der Krogt et al., 2022). Based on the current RIBASIM model, the Dutch and German parts of the Meuse catchment had to be excluded from the analysis in this study. In order to draw conclusions for the whole catchment, a catchment-wide model should be developed. The German part was excluded in this study because the operation of the surface water reservoirs depends too much on human decisions and therefore cannot be simulated with sufficient accuracy (Van der Krogt et al., 2022). It is important to better understand the German water management decisions to be able to draw conclusions about water availability bottlenecks in this part of the Meuse catchment. To achieve this, it is important to involve German water management stakeholders in order to share information. For the Dutch part of the Meuse catchment, only some of the individual water users are currently identified, while other water demands are aggregated in general district nodes. This makes it impossible to use RIBASIM to draw conclusions about water availability bottlenecks and, in particular, the impact of socio-economic developments on them. Adaptations to the RIBASIM network schematisation are needed to overcome this limitation. Currently, the project 'Delta Programme Freshwater supply Bottleneck analysis' (Ne: Knelpuntenanalyse Deltaprogramma Zoetwater) investigates water availability bottlenecks in the Dutch part of the Meuse catchment. This study mainly focuses on water shortages for irrigation, maintaining water levels and preventing salt intrusion, rather than on individual industrial or domestic water users (Mens et al., 2020). However, if the distinction between all these different water demands can be made for the Dutch part of the Meuse catchment, then the RIBASIM network can be adapted to be consistent with the Frech and Belgian parts of the network. In this way, the analysis done in this study can be extended to the Dutch part of the Meuse catchment as well.

Furthermore, this schematisation only includes surface water elements and does not consider groundwater elements. However, groundwater provides a baseflow to the Meuse, particularly in the upstream parts of the catchment (Bouaziz, 2021; Kramer, 2021). Therefore, including groundwater dynamics could provide more insight into the impact of climate change and socio-economic development on the baseflow of the Meuse. Changes in groundwater use can have an impact on the baseflow towards the Meuse. This, in turn, may affect water availability for surface water users in other parts of the catchment. To gain a more comprehensive understanding of water availability bottlenecks in the Meuse catchment, it is essential to consider groundwater dynamics.

As a form of validation, the relative change in 10-day minimum discharges simulated in this study (Figure 8) was compared with the annual 7-day discharges found by Deltares (Buitink et al., 2023), see Figure 19. The two studies differ in methodology, as the Deltares study used the Wflow_sbm model for the Meuse, a rainfall-runoff model that only considers the natural flow. This model has a 7-day timestep and does not include any extractions for water users or canals. The RIBASIM model used in this study, on the other hand, has a 10-day timestep and includes these extractions. A comparison of Figure 8 and Figure 19 shows similar trends in the annual minimum discharge near the Dutch border: a decrease in the minimum discharge over time and dry variations of the climate scenarios simulate a larger decrease in the minimum discharge than wet variations do. Differences can also be observed: the relative change in the minimum annual discharge in this study is larger than in the Deltares study, but they are still in the same order of magnitude. This study also shows a larger spread in the minimum annual discharge, as the whiskers are longer. Both differences are likely to be caused by the abstraction of water for the Flemish canals, which is simulated by the RIBASIM model and not by the Wflow_sbm model (Buitink et al., 2023), which would lead to lower discharges near the Dutch border.

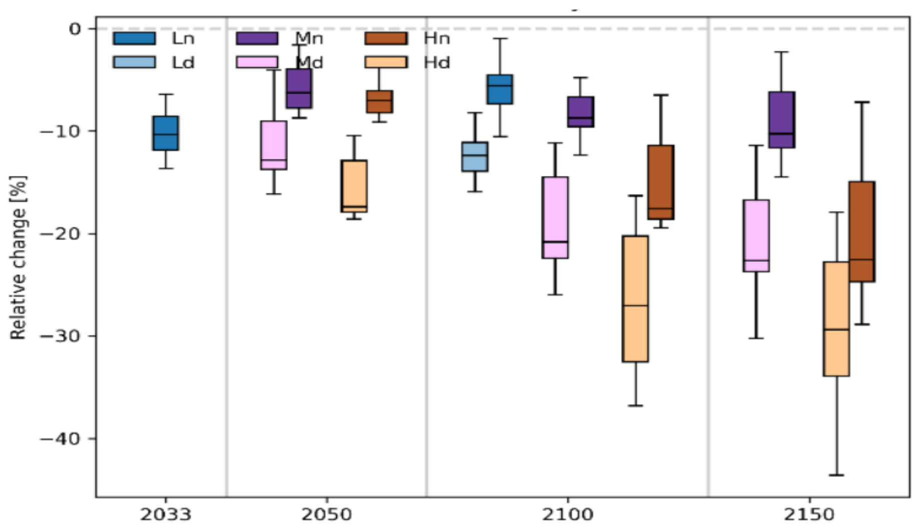


Figure 19. Change in the annual 7-day minimum discharge at the Dutch border for future climate scenarios

4.3 Implications of climate change assumptions on bottleneck analysis

In this study, climate change is simulated using a percentage change per season. This applies the same climate change to the whole catchment and does not take into account the spatial variability of climate change (Van der Krogt et al., 2022). Buitink et al. (2023) showed that the effects of climate change on the precipitation will not be uniform across the catchment. They showed that increase in winter precipitation is smaller for the area upstream of Chaudfontaine (Belgium). In summer, there are regional differences in the decrease of precipitation, depending on the exact climate scenario. The use of a single climate change rate for the whole catchment may lead to the exclusion of regional extremes, both for high and low discharge conditions. To improve this aspect of the research, transformed time series at sub-catchment level should be used for the meteorological variables, instead of applying the average relative changes for the Netherlands over the whole of the Meuse catchment. The same applies to the hydrological input time series. These should be regenerated with the rainfall-runoff model Wflow_sbm and linked to the RIBASIM model instead of applying a percentage change. This will result in a more realistic representation of the regional variability within the catchment.

4.4 Implications of socio-economic developments on bottleneck analysis

In the current network schematisation, most water users and minimum discharge requirements have a fixed demand throughout the year, except for irrigation which has a seasonal pattern. Other seasonal changes in water demand are not considered. The different water demand scenarios simulate a change in water demand by a single percentage change throughout the year, so seasonal changes in the water demand are not considered. Furthermore, the water demand scenarios only consider a change in water demand for already existing water users, but with a changing climate it is very well possible that new (ground)water demands will emerge, for example for irrigation or the prevention of salt intrusion. These potential new (ground)water users are not considered in this study, but they may become potential bottlenecks, or they can affect existing water users, causing them to become bottlenecks.

Changes in land use or management (reservoirs, sluices, agriculture) are not considered in this study. Some of these changes are included in the storylines of the Deltascenarios (Wolters et al., 2018a), but they could not all be implemented in the RIBASIM model. The trends described in the Deltascenarios 2017 are based on the Dutch system and socio-economic trends (Wolters et al., 2018a; Wolters et al., 2018b). The question is, to what extent these socio-economic trends are applicable to the other countries in the Meuse catchment, as they have (economic) activities that do not occur in the Dutch part of the Meuse catchment and are therefore not considered in the Deltascenarios 2017. For example, there are nuclear power plants in the French and Belgian parts of the catchment. In the Deltascenarios, a decrease of 80% is assumed for each cooling water user due to the transition to more renewable forms of energy (Wolters et al., 2018a). In Belgium, the Tihange nuclear power plant will be completely shut down in the coming years (Federaal Agentschap voor Nucleaire Controle, 2024), but it is less likely that this would happen to the French nuclear power plants (World Nuclear Association, 2024). In addition, the French, Belgian and German parts of the Meuse catchment have surface water reservoirs. Climate change will also affect the sub-catchments and therefore changes to current operations are expected (Van der Krogt et al., 2022). Potential changes in these operations have not been considered in this study. This would be a good point for improvement as they can have a significant impact on the discharge of the Meuse (Pyka et al., 2016) and could therefore affect the number or severity of bottlenecks in the downstream parts of the catchment. Furthermore, there are lignite mines in the German Meuse catchment, which will be phased out over time and converted into opencast mine lakes (Berkner et al., 2022). These developments will have a significant impact on local and regional water balances (Berkner et al., 2022), and would therefore affect downstream water users. Any developments in the Rur catchment are particularly important for The Netherlands, as the Rur is the largest contributor to the Meuse discharge during low flow conditions (Kramer, 2021). These types of developments are very important to consider in studies assessing potential future bottlenecks, as they can have a significant impact on the outcome.

5 Conclusions and recommendations

The objective of this study was to identify future water availability bottlenecks in the French-Belgian part of the Meuse catchment by assessing the impact of projected climate change and socio-economic developments. The study found that the number and severity of water availability bottlenecks will increase under the projected climate change. The wet-dry configuration of climate scenarios showed to have a larger impact than the specific CO_2 emission pathway.
For most climate scenarios, the changes in water demand will result in a decrease in the total number of bottlenecks, but an increase in number of bottlenecks in the most severe category. However, the impact of socio-economic developments was small and no significant differences were found between the two water demand scenarios. The sensitivity analysis revealed that cooling water demand is the highest impacting societal change and a decreased demand, resulting from the energy transition, could therefore lead to an increase in water availability.

This study provides an initial overview of the bottlenecks in surface water availability in the Meuse catchment. However, a more comprehensive analysis is needed that includes groundwater dynamics, water quality, and more focus on the spatial variability within the catchment.
To address these issues improvements to the RIBASIM network schematisation and input data have to be made. This could potentially reveal additional bottlenecks in the catchment or threats to the bottlenecks identified in this study.

Climate change is expected to increase the number of bottlenecks in Belgium and France. It is likely that the Netherlands and Germany will follow this trend, but this should by verified by a further comprehensive analysis for these areas. To do so, improvements have to be made to the RIBASIM model and the Meuse network schematisation. Extending the study area would require international collaboration and more detailed information on individual water users.

The trends presented in this study indicate that water availability bottlenecks pose increasing challenges for the field of water management. The current water management lacks an integral and international approach to address catchment-wide water availability issues. By focusing on the international aspect, this study contributes to a better understanding of the catchment-wide water availability bottlenecks. Solving water availability problems at the catchment scale is only possible through international collaboration, which requires discussions on shared responsibilities and transboundary measures.

6 Reference list

Berkner, Andreas et al. (2022) : *Lignite planning, structural change and coal phase-out in Germany*, Positionspapier aus der ARL, No. 140, Verlag der ARL - Akademie für Raumentwicklung in der Leibniz-Gemeinschaft, Hannover, https://nbn-resolving.de/urn:nbn:de:0156-01403

Bisselink B., Bernhard J., Gelati E., Adamovic M., Guenther S., Mentaschi L., Feyen L., and de Roo, A, *Climate change and Europe's water resources*, EUR 29951 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10398-1, doi:10.2760/15553, JRC118586.

Bouaziz, L. J. E. (2021). *Internal processes in hydrological models: A glance at the Meuse basin from space*. https://doi.org/10.4233/uuid:09d84cc1-27e2-4327-a8c7-207a75952061

Buitink, J., Tsiokanos, A., Geertsema, T., Ten Velden, C., Bouaziz, L., & Sperna Weiland, F. (2023). *Implications of the KNMI'23 climate scenarios for the discharge of the Rhine and Meuse*. Deltares. https://open.rijkswaterstaat.nl/open-overheid/onderzoeksrapporten/@268796/implications-the-knmi-23-climate/

Byun, K., Chiu, C., & Hamlet, A. F. (2019). Effects of 21st century climate change on seasonal flow regimes and hydrologic extremes over the Midwest and Great Lakes region of the US. *Science of The Total Environment*, 650, 1261–1277. https://doi.org/10.1016/j.scitotenv.2018.09.063

Federaal Agentschap voor Nucleaire Controle. (2024, 23 February). *Stopzetting van de activiteiten en ontmanteling van de Belgische kerncentrales*. https://fanc.fgov.be/nl/dossiers/kerncentrales-belgie/stopzetting-van-de-activiteiten-en-ontmanteling-van-de-belgische

Gudmundsson, L., Boulangé, J., Hong, X., Gosling, S. N., Grillakis, M., Koutroulis, A., Leonard, M., Liu, J., Schmied, H. M., Papadimitriou, L., Pokhrel, Y., Seneviratne, S. I., Satoh, Y., Thiery, W., Westra, S., Zhang, X., & Zhao, F. (2021). Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, 371(6534), 1159–1162. https://doi.org/10.1126/science.aba3996

Het verhaal van de Maas (2019). *Het verhaal van de Maas, de Maas uit balans?* Het Platform Rivierkennis van Rijkswaterstaat

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

KNMI (2023) *KNMI'23-klimaatscenario's voor Nederland*, KNMI, De Bilt, KNMI-Publicatie 23-03.

Kramer, N. (2021). *Lage afvoeren in de Maas – Bijdrage zijrivieren,* Deltares & RIWA-Maas

Krogt, W. van der, Becker, B., Boisgontier, H. (2022). *Low river discharge of the Meuse – A Meuse River basin water management modelling study using RIBASIM*, Deltares & RIWA-Maas

Krogt, W.N.M van der & Boccalon, A. (2013). *River Basin Simulation Model RIBASIM Version 7.00*

Maasafvoerverdrag. Verdrag tussen het Koninkrijk der Nederlanden en het Vlaams Gewest inzake de afvoer van het water van de Maas, Antwerpen, 17-01-1995

Mens, M.J.P., J. Hunink, J.Delsman, J. Pouwels, F. Schasfoort (2020). *Geactualiseerde knelpuntenanalyse voor het Deltaprogramma Zoetwater fase II.* Deltares rapport11203734-003ZWS-0002, Delft.

Mishra, B. K., Kumar, P., Saraswat, C., Chakraborty, S., & Gautam, A. (2021). Water security in a changing environment: concept, challenges and solutions. *Water*, 13(4), 490. https://doi.org/10.3390/w13040490

Pyka, C., Jacobs, C., Breuer, R., Elbers, J., Nacken, H., Sewilam, H., & Timmerman, J. (2016). Effects of water diversion and climate change on the Rur and Meuse in low-flow situations. *Environmental Earth Sciences*, *75*(16). https://doi.org/10.1007/s12665-016-5989-3

RIWA-Maas. (2023). *RIWA Jaarrapport 2022 De Maas*. https://www.riwa-maas.org/wp-content/uploads/2023/09/IDF3064-RIWA-MAAS-Jaarrapport-NL-2022-digitaal.pdf

Wit, M.J.M. de, Hurk, B. van den, Warmerdam, P.M.M. et al. Impact of climate change on low-flows in the river Meuse. *Climatic Change 82*, 351–372 (2007). https://doi.org/10.1007/s10584-006-9195-2

Wolters, H.A., Born, G.J. van den, Dammers, E., Reinhard, S., 2018a, *Deltascenario's voor de 21^e^ eeuw, actualisering 2017,* Deltares, Utrecht

Wolters, H.A., Hunink, J., Delsman, J., Lange, G. de , Born, G.J. van den, Reinhard, S., 2018b, *Deltascenario's voor de 21^e^ eeuw, actualisering 2017, Achtergrondinformatie over gebruiksfuncties en sectoren*, Deltares, Utrecht

World Nuclear Association. (2024, March). *Nuclear Power in France | French Nuclear Energy - World Nuclear Association*. https://world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx#:~:text=Government%20policy%2C%20set%20under%20a,consider%20building%20a%20further%20eight.

Appendix

A.1 RIBASIM model validation

Method

To check if the Meuse002 RIBASIM model performs sufficiently enough, a validation was executed. This was done by comparing the RIBASIM simulation for the current climate with daily observations taken at Monsin for the period 1981-2015. To match the 10-day timestep from RIBASIM, the 10-day average value was taken from the daily observations. The model performance evaluation was done using three performance metrics: percent bias (PBIAS), coefficient of determination (R^2), and model efficiency (KGE'). These performance metrics are typically used in literature for evaluating hydrological models (Moriasi et al., 2015). The performance metrics applied to all observations, but also specifically for the 30% lowest flows.

The percent bias (PBIAS) is a metric used to assess the average tendency of simulated data to be either larger or smaller than the observed counterparts (Moriasi et al., 2015). PBIAS is calculated according to the following equation (Moriasi et al., 2015):

$$PBIAS = \frac{\sum_{i=1}^{n} O_i - P_i}{O_i} \times 100$$

With O and P indicating the observed and projected values respectively. Over- or underprediction is expressed as a percentage ranging from −∞ to +∞, with a n optimum value of 0% (Moriasi et al., 2015). Important to note is that PBIAS can give misleading assessments of model performance if the model overpredicts as much as it underpredicts. In such cases, the PBIAS ends up being zero, even with a poor model simulation. Prevent situations like these, the PBIAS as a performance metric is combined with other performance metrics.

The coefficient of determination (R2) quantifies the degree of correlation between the simulated and measured data (Moriasi et al., 2015). The R2 is calculated according to the following equation:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2} \sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \right]^2$$

Here, O and P refer to the observed and projected values, respectively. The value of R2 ranges from 0.0 to 1.0, with 1.0 being the optimal value (Moriasi et al., 2015)

The third performance metric used for the model performance evaluation was the modified Kling-Gupta efficiency (KGE'). The original KGE is derived from the decomposition of the Nash-Sutcliffe efficiency (NSE) into three separate terms: correlation, bias, and variability (Gupta et al., 2009). As a result, it offers valuable insights into model efficiency and enables a multi-objective assessment of trade-offs among these components (Gupta et al., 2009). The introduction of the KGE' aimed to avoid potential interactions between bias and variability that may affect the original KGE (Kling et al., 2012). The KGE' is calculated according to the following equations (Kling et al., 2012):

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta - 1)^2 + (\gamma_{KGE'} - 1)^2}$$

$$\beta = \frac{\mu_P}{\mu_O} \qquad \gamma_{KGE'} = \frac{\left(\frac{\sigma_P}{\mu_P}\right)}{\left(\frac{\sigma_O}{\mu_O}\right)}$$

With r being the correlation coefficient between the simulated and observed data, β the bias ratio, γ the variability ratio, μ the mean value, σ the standard deviation, and the indices P and O represent the projected and observed values, respectively. KGE' values range from −∞ to 1.0, where the optimal value is 1.0. From a hydrological perspective, the use of KGE′ makes sense, because there the aim is typically to reproduce temporal dynamics (measured by r), while preserving the flow distribution (flow duration curve), which is summarised by β and γ.

Additionally, to the model performance metrics, the flow duration curves of the observations and the RIBASIM simulation were compared. To quantify this comparison the root mean square error (RMSE)was calculated for different parts of the flow duration curve. This was done according to the following equation (Moriasi et al., 2015):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}$$

With n being the number of observations, and O and P representing the observed and projected values, respectively. The RMSE values ranges from 0.0 to ∞, and has an optimal value of 0.0.

Results

The simulated discharge of the Meuse at the Flemish-Dutch border was compared with observed data (Figure 20). There seems to be a good fit between the simulation and the observation, however the RIBASIM simulation seems to overpredict most of the high peak flows. This is confirmed by the PBIAS, which is -3.03%, implying overall a slight overestimation by the model. However, the model performance can is considered "good" based on the PBIAS (± 3% < PBIAS ± 10%) (Moriasi et al., 2015). The R^2 for the simulation is 0.90, which can be classified as "very good" (R^2 > 0.85) (Moriasi et al., 2015). The KGE′ value is 0.89. This high value indicates a good overall performance. Other than for the PBIAS and R2, the KGE′ does not have specific benchmark values to distinguish between good and bad performance, highlighting the importance of using multiple performance metrics. Overall, it can be concluded that the RIBASIM model performs good for simulating the Meuse discharge at the Flemish-Dutch border.

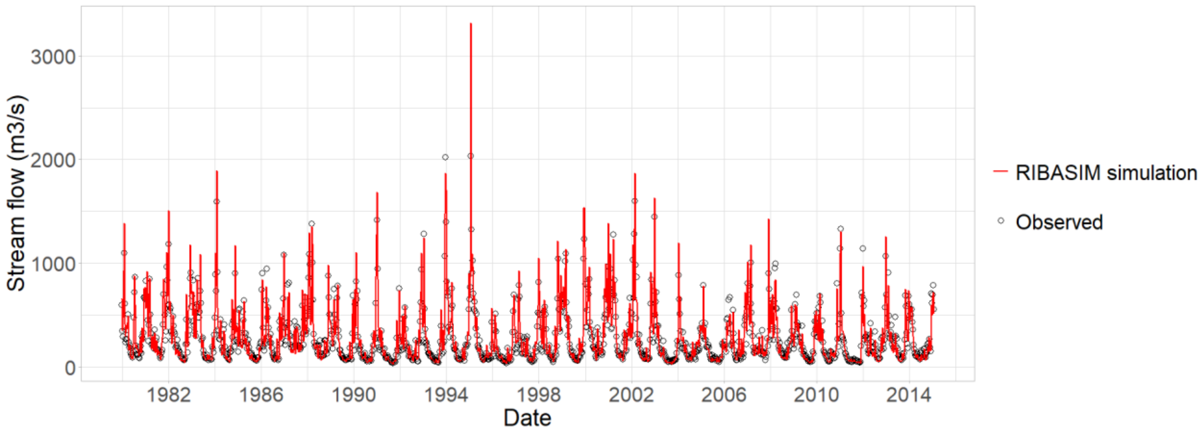


Figure 20. Discharge of the Meuse at the Flemish-Dutch border for the validation period (1980-2015). Observations in black and the RIBASIM simulation in red.

The performance of the RIBASIM model is also evaluated for the 30% of the lowest flow of the validation period (1980-2015), see Figure 21. The closers points are located near the orange 1:1 line, the better the RIBASIM simulation matches the observations. Points located above this line are overestimated by the model, and points below the line are underestimated by the model. The PBIAS for the low flows is 4.68%, suggesting that the RIBASIM underestimates these low flows. Although this PBIAS is larger than when all flows were considered, this value still indicates a "good" performance (± 3% < PBIAS ± 10%) (Moriasi et al., 2015). The same is true for the other model performance metrics. With a R^2 value of 0.76, and KGE′ value of 0.86, the performance for the low flows only is less good, but performance can still be classified as good (KGE′ > 0.70 and 0.70 ≤ R^2

≤ 0.85) (Moriasi et al., 2015; Knoben et al, 2019). This suggest that the RIBASIM performs sufficiently for simulating the lowest flows, which are of main interest for this study.

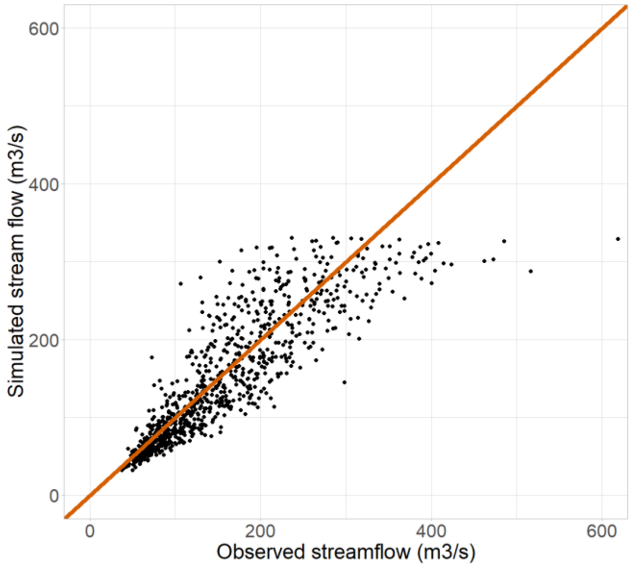


Figure 21. The relation between the observation and RIBASIM simulation of the 30% lowest discharges during the validation period (1980-2015). The orange line is the 1:1 line.

The last part of the validation is comparing the flow duration curves of the RIBASIM simulation with the observations (Figure 22). The RMSE is shown for different parts of the flow duration curve. For the high flows (exceedance probability < 20%), the RIBASIM simulation overestimates the observations, as could also be seen in the hydrograph of Figure 20. On the other end of the flow duration curve, the flow duration curve shows that RIBASIM underestimates the observations for low flows (exceedance probability > 70%). This is also shown by the large RMSE of 254.2 m^3/s, for this part of the flow duration curve. The underestimation is even larger for the extreme low flows (exceedance probability > 95%), as the RMSE is 1095.5 m^3/s.

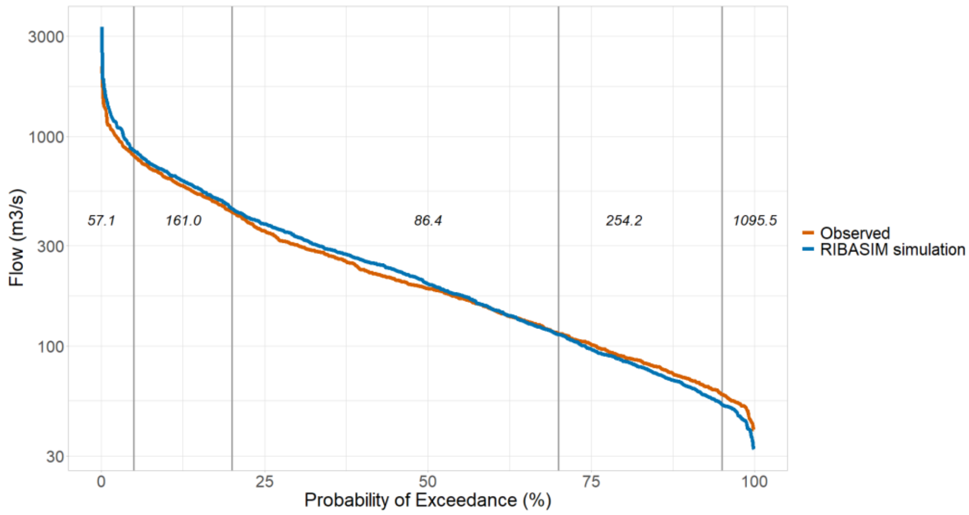


Figure 22. Flow duration curve for the observations (orange) and simulations (blue for the Meuse at the Dutch border for the period 1980-2015. The root mean square error is shown for different parts of the flow duration curve.

A.2 Effect climate change on annual average discharge, various locations throughout the catchment

Stenay

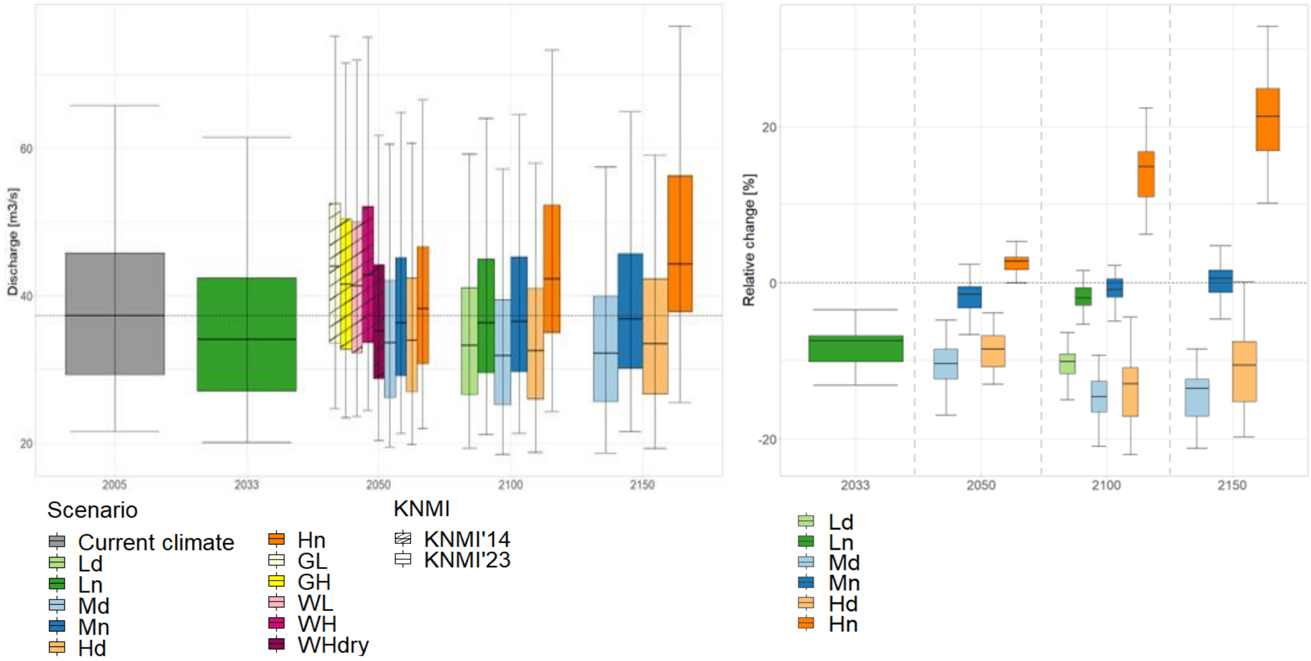


Figure 23. Change in the annual average discharge of the Meuse at Stenay for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

Sedan

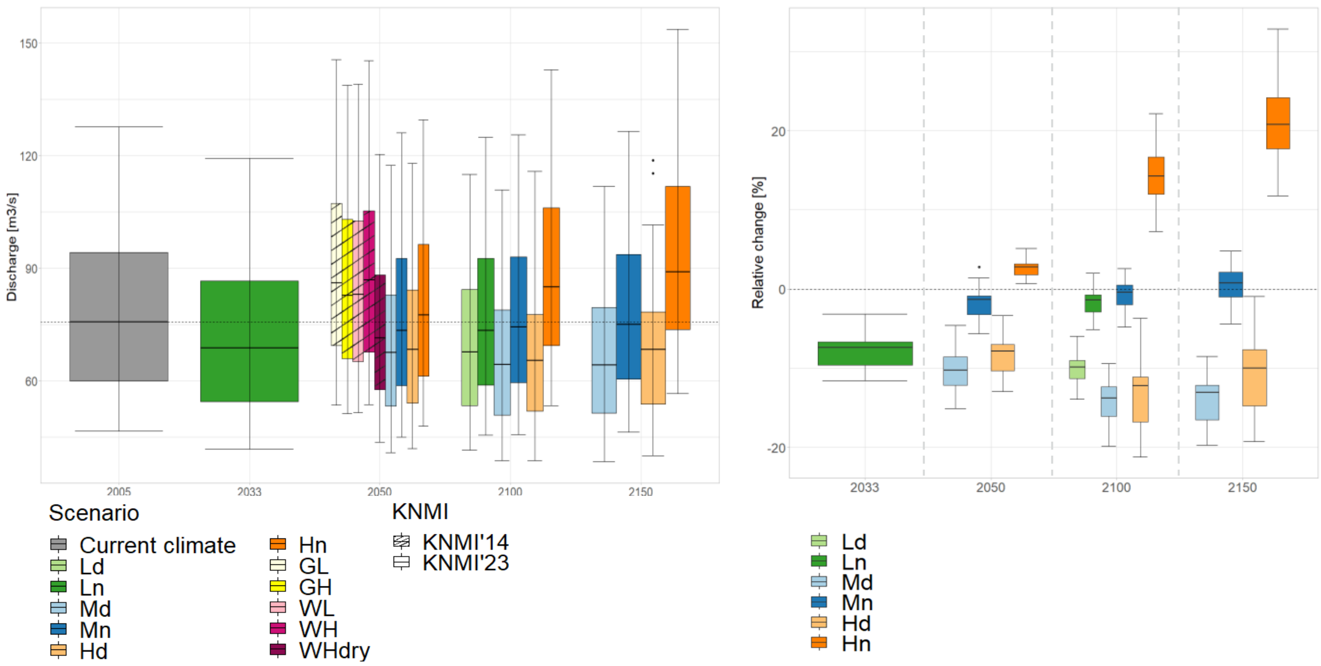


Figure 24. Change in the annual average discharge of the Meuse at Sedan for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

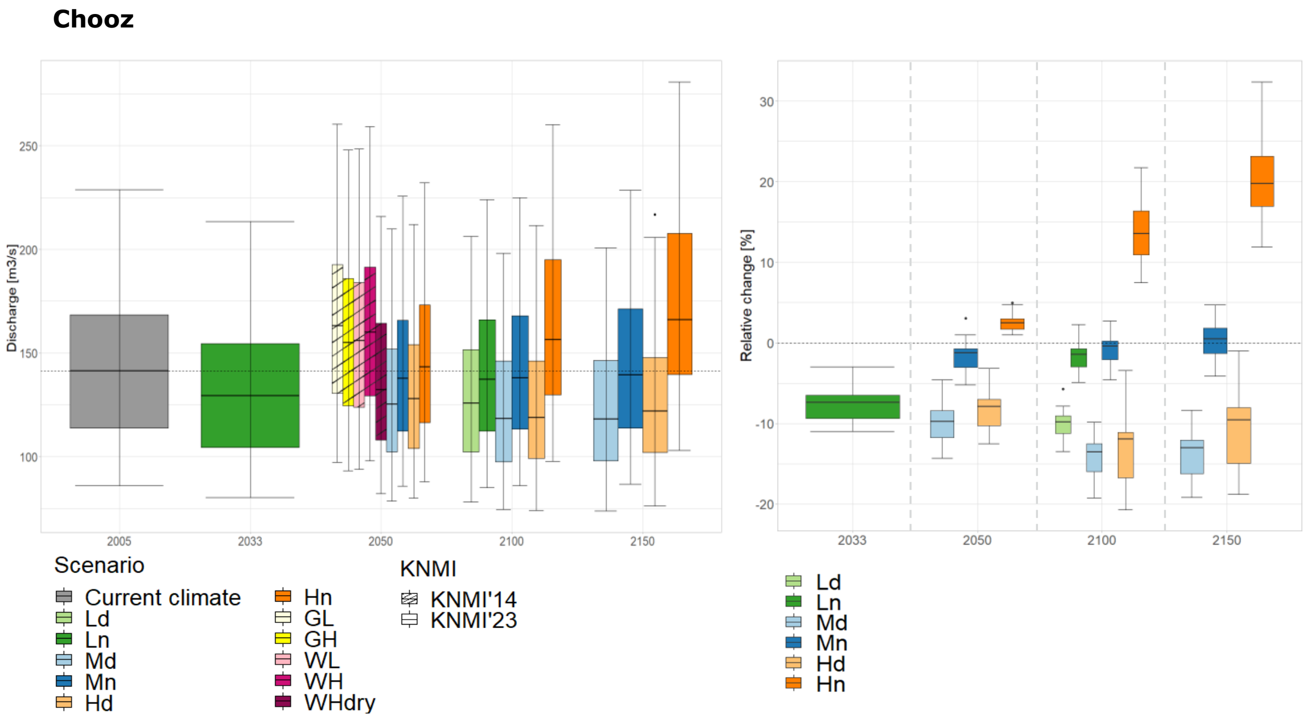


Figure 25. Change in the annual average discharge of the Meuse at Chooz for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

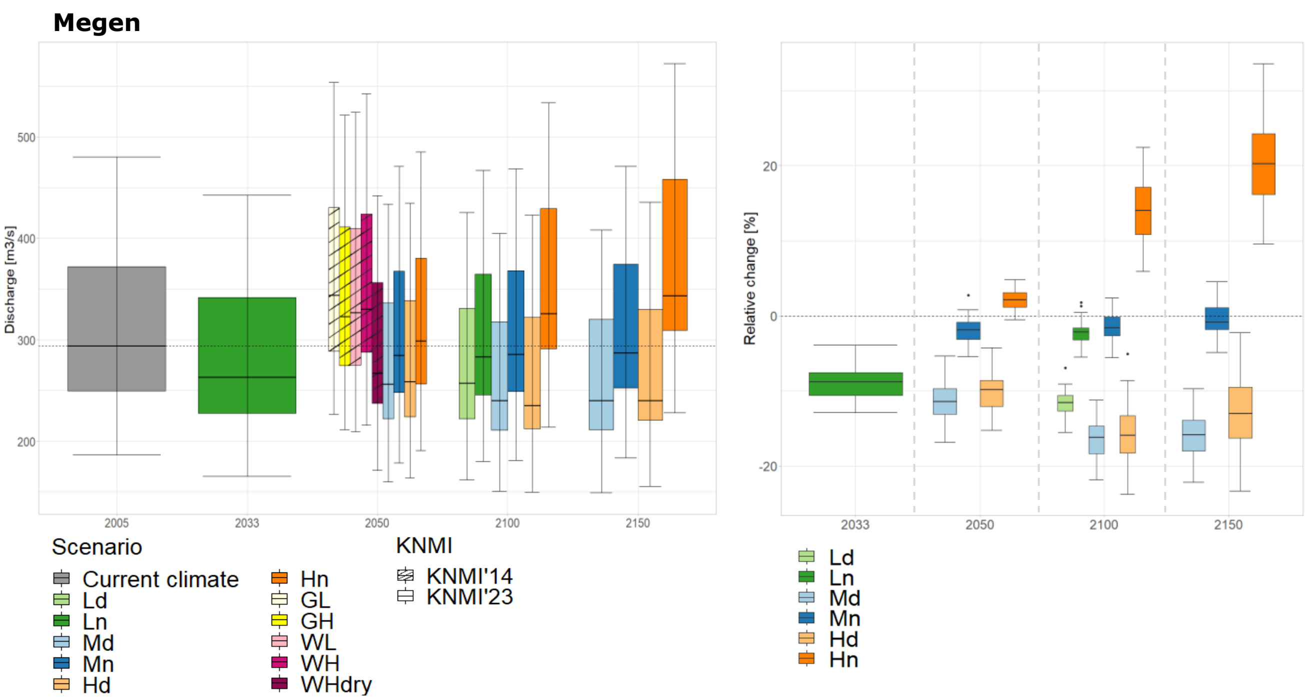


Figure 26. Change in the annual average discharge of the Meuse at Megen for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

A.3 Effect climate change on annual 10-day minimum discharge, various locations throughout the catchment

Stenay

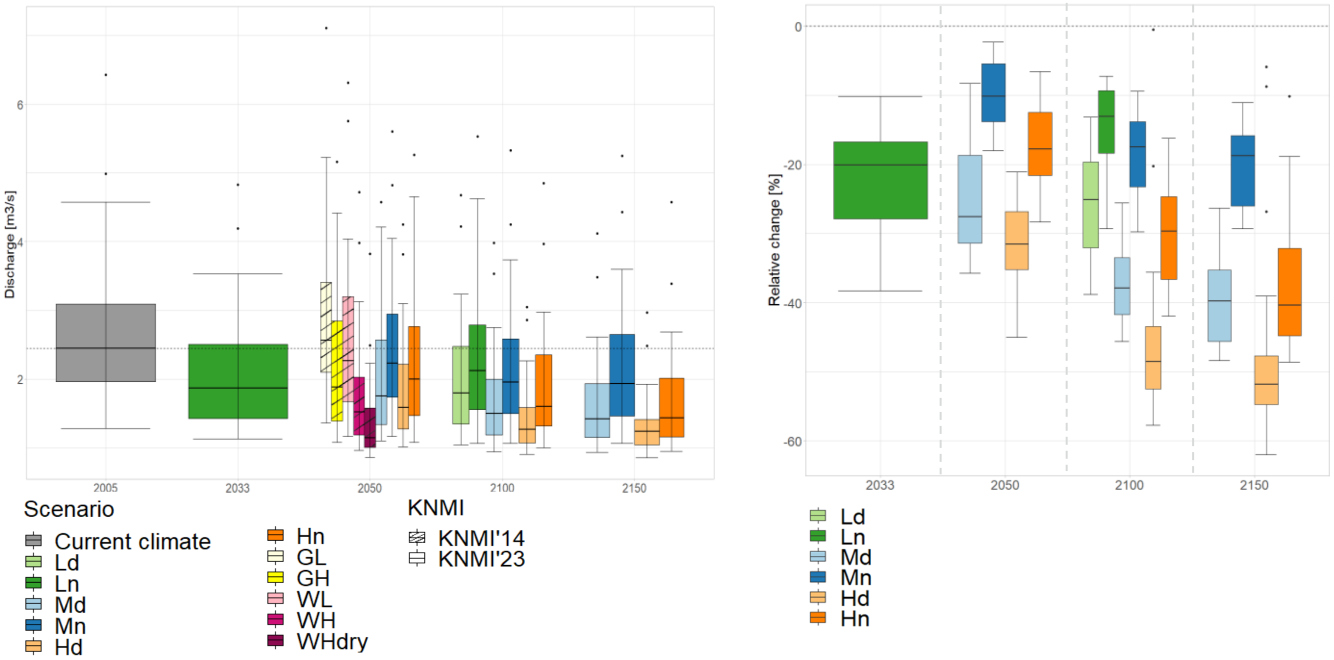


Figure 27. Change in the annual 10-day minimum discharge of the Meuse at Stenay for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

Sedan

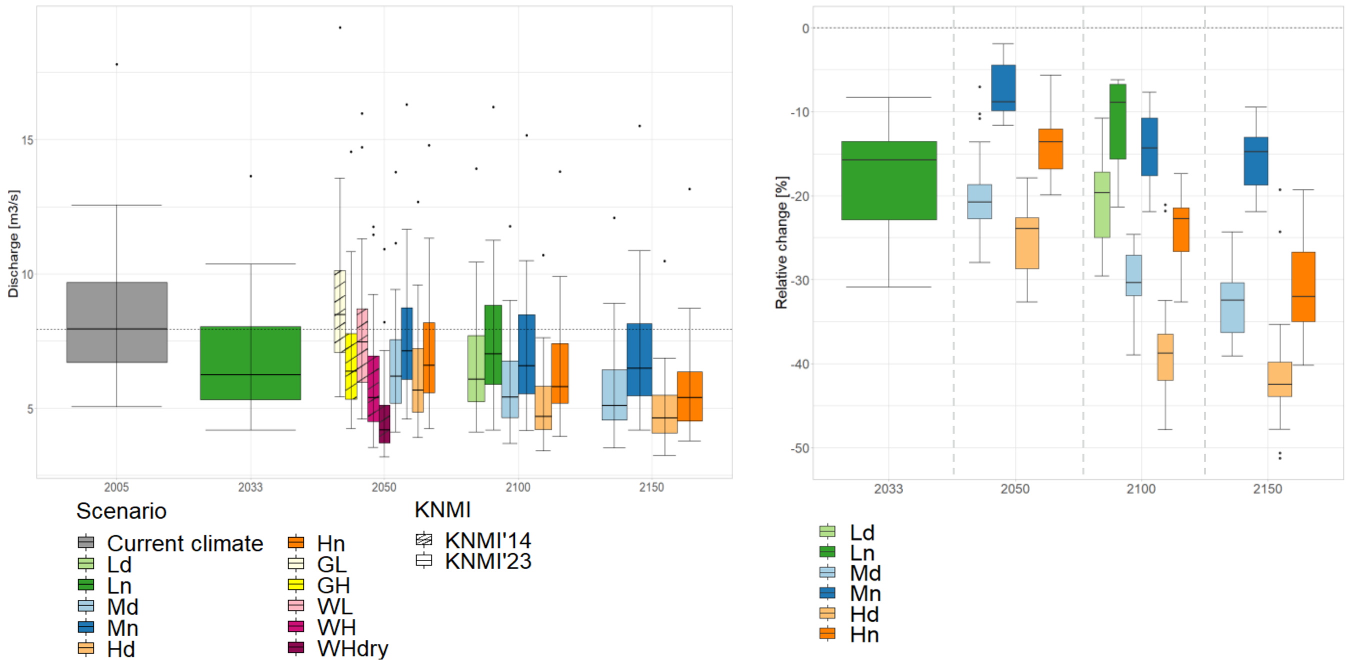


Figure 28. Change in the annual 10-day minimum discharge of the Meuse at Sedan for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

Chooz

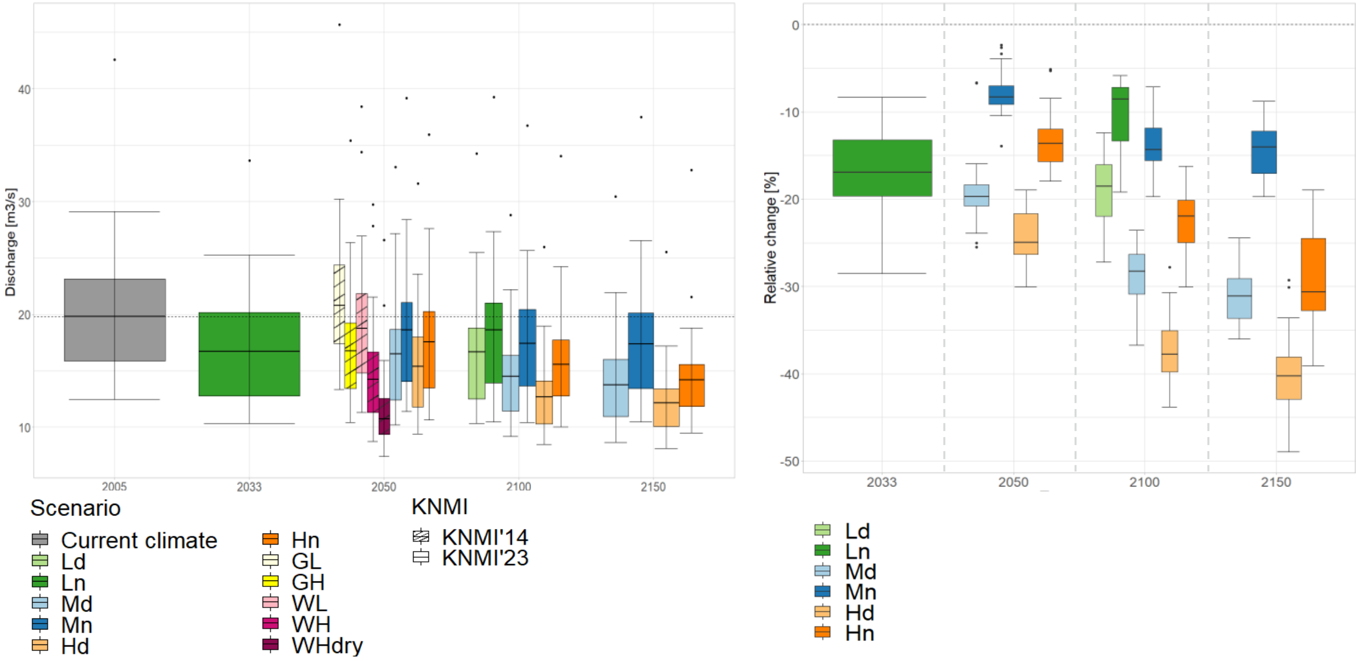


Figure 29. Change in the annual 10-day minimum discharge of the Meuse at Chooz for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

Megen

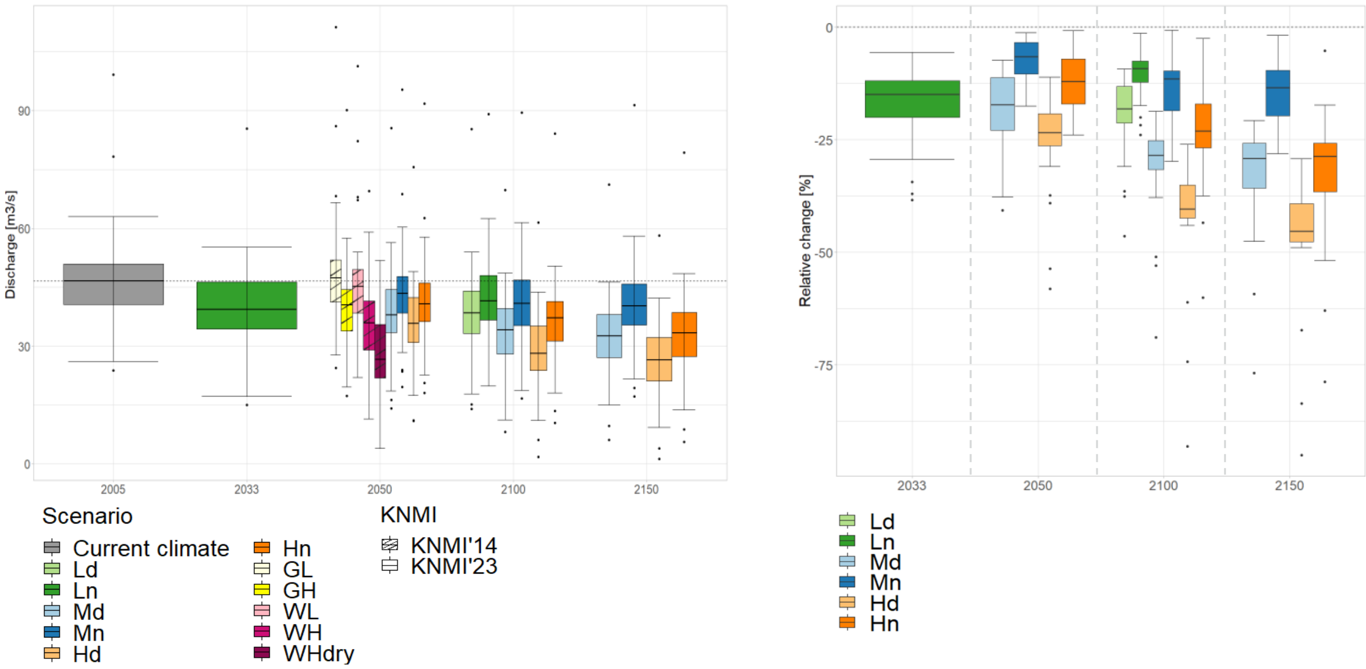


Figure 30. Change in the annual 10-day minimum discharge of the Meuse at Stenay for current and future climate (time horizons on the x axis). Left panel shows the absolute values, right panel shows the relative changes compared to the current climate for the KNMI'23 scenarios. Green boxes present the low climate change scenarios (Ln = wet and Ld= dry), blue boxes present the moderate scenarios (Mn=wet and Md=dry) and orange boxes present the high scenarios (Hn = wet and Hd =dry).

A.4 Effect water demand changes on annual average discharge, various locations throughout the catchment

Stenay

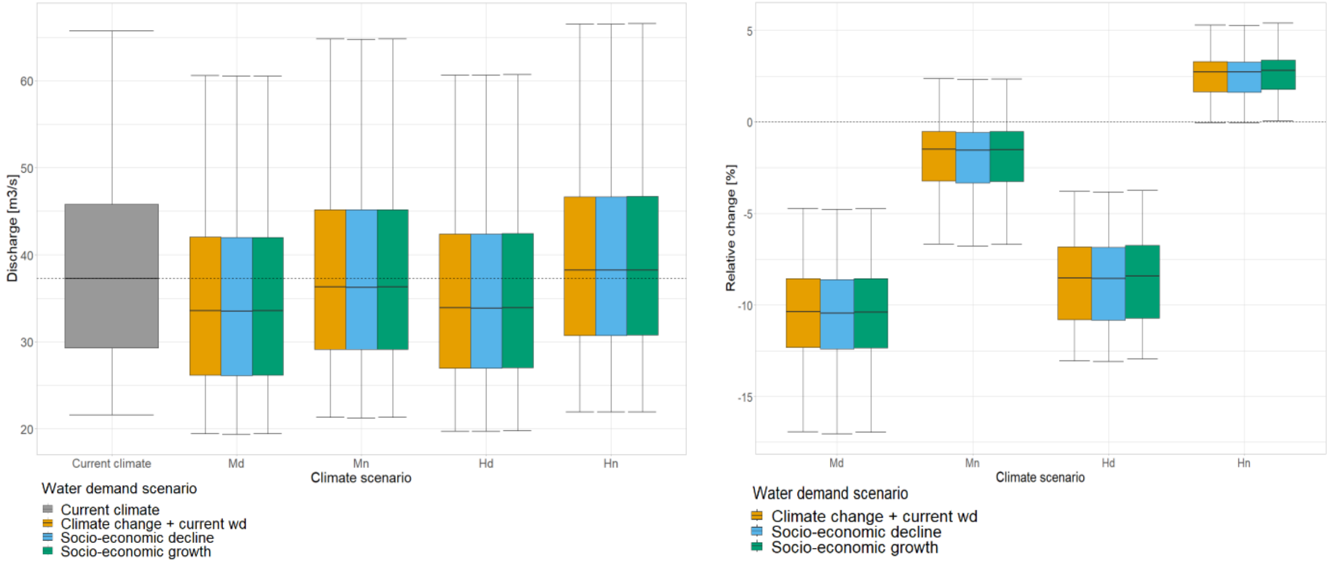


Figure 31. Change in the annual average discharge of the Meuse at Stenay for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Sedan

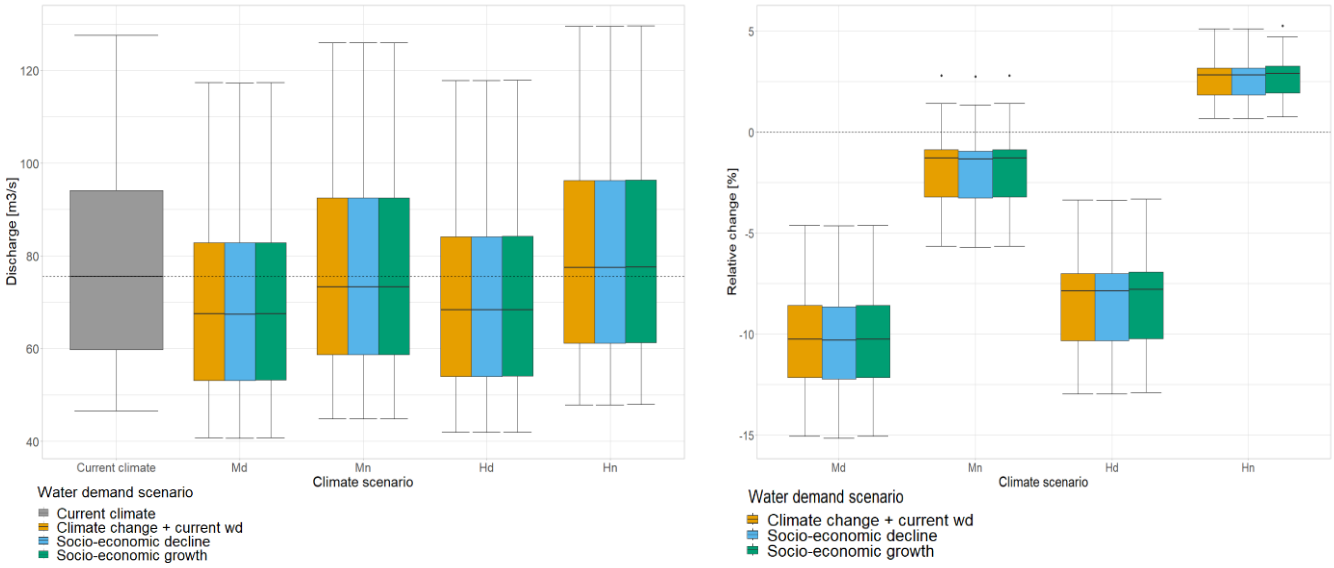


Figure 32. Change in the annual average discharge of the Meuse at Sedan for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Chooz

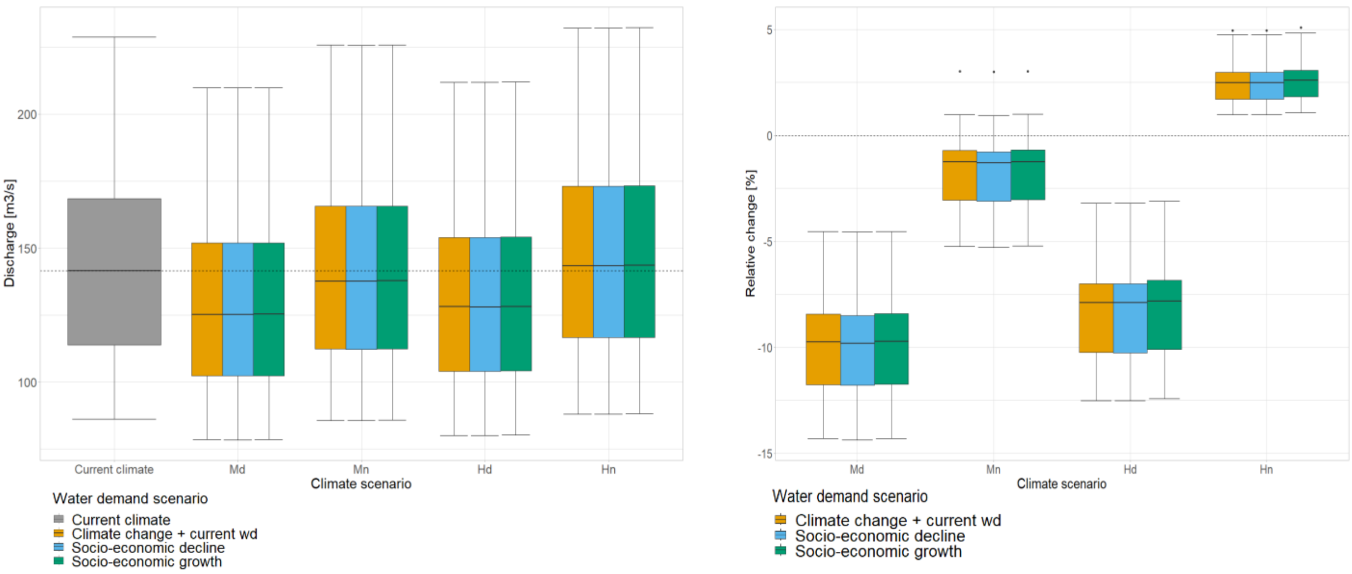


Figure 33. Change in the annual average discharge of the Meuse at Chooz for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Megen

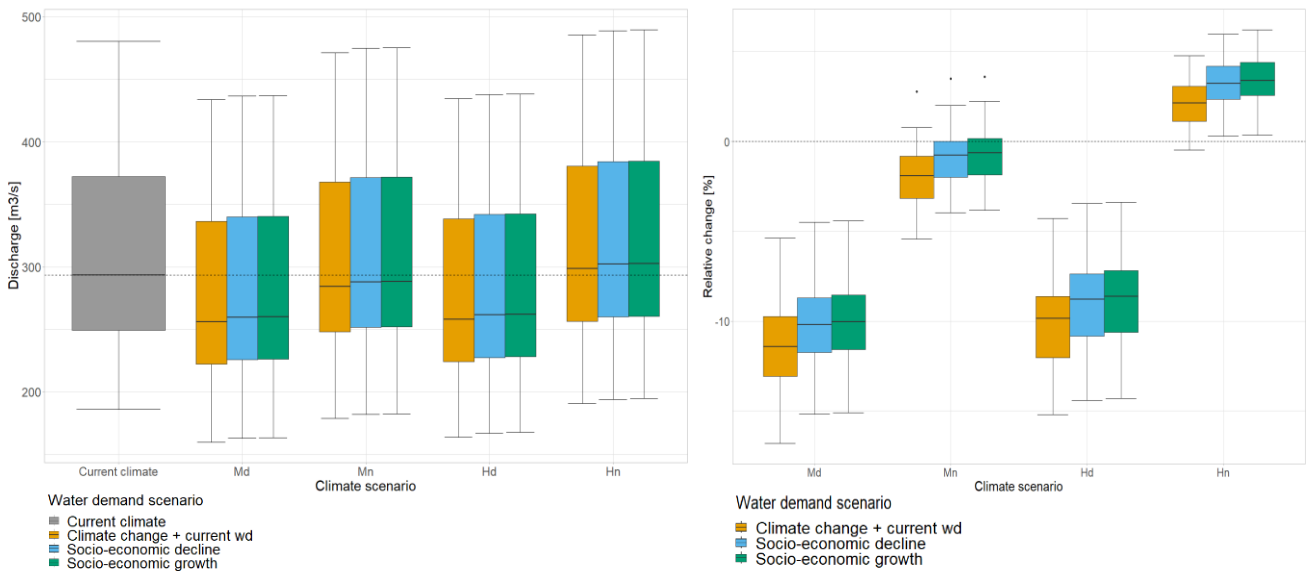


Figure 34. Change in the annual average discharge of the Meuse at Megen for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

A.5 Effect water demand changes on annual 10-day minimum discharge, various locations throughout the catchment

Stenay

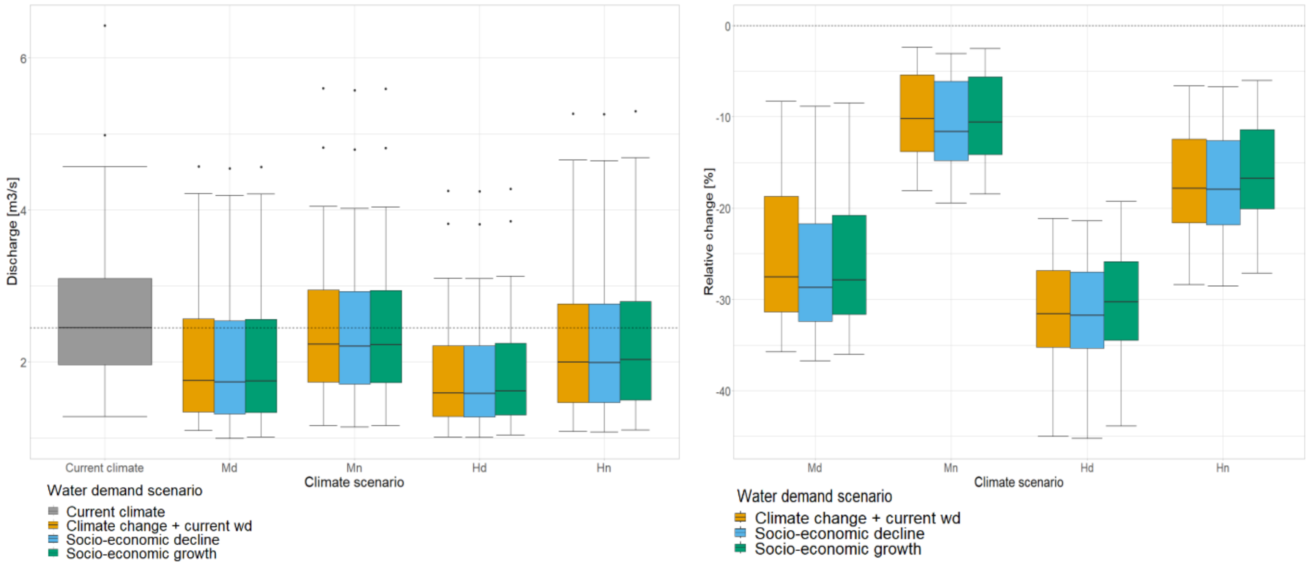


Figure 35. Change in the annual 10-day minimum discharge of the Meuse at Stenay for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Sedan

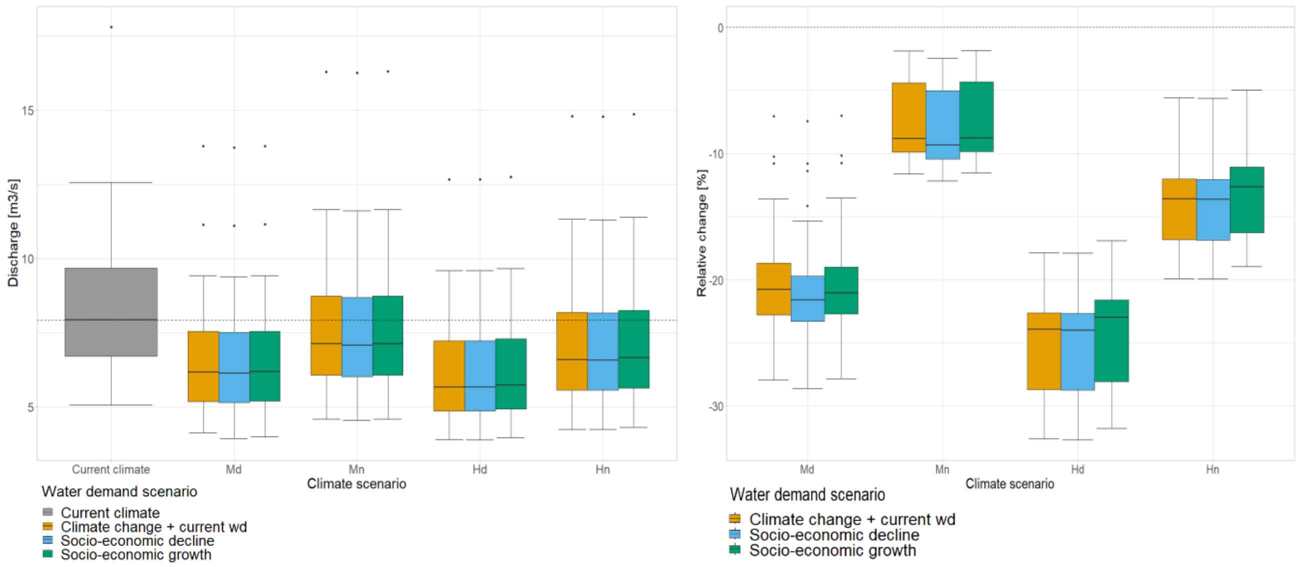


Figure 36. Change in the annual 10-day minimum discharge of the Meuse at Sedan for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Chooz

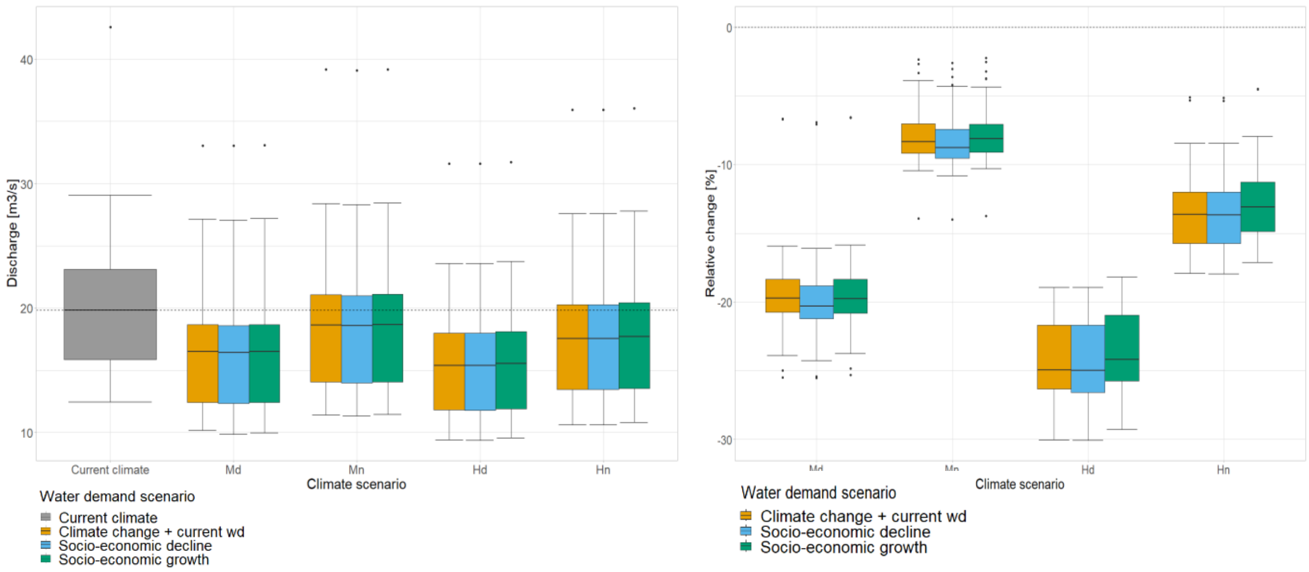


Figure 37. Change in the annual 10-day minimum discharge of the Meuse at Chooz for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

Megen

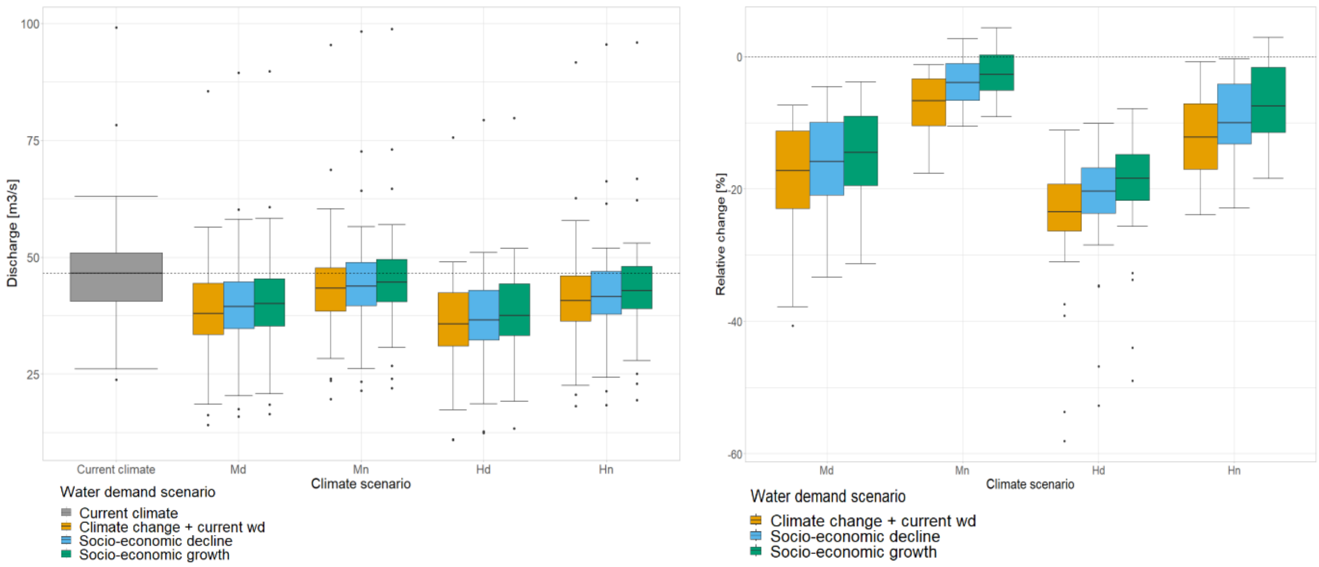


Figure 38. Change in the annual 10-day minimum discharge of the Meuse at Megen for the current climate and the moderate (Md = dry, Mn = wet) and high (Hd = dry, Hn = wet) climate scenarios for 2050, under different water demand scenarios Left panel shows the absolute values, right panel shows the relative changes compared to the current climate (wd= water demand).

A.6 Effect climate change on 70% dependable flow

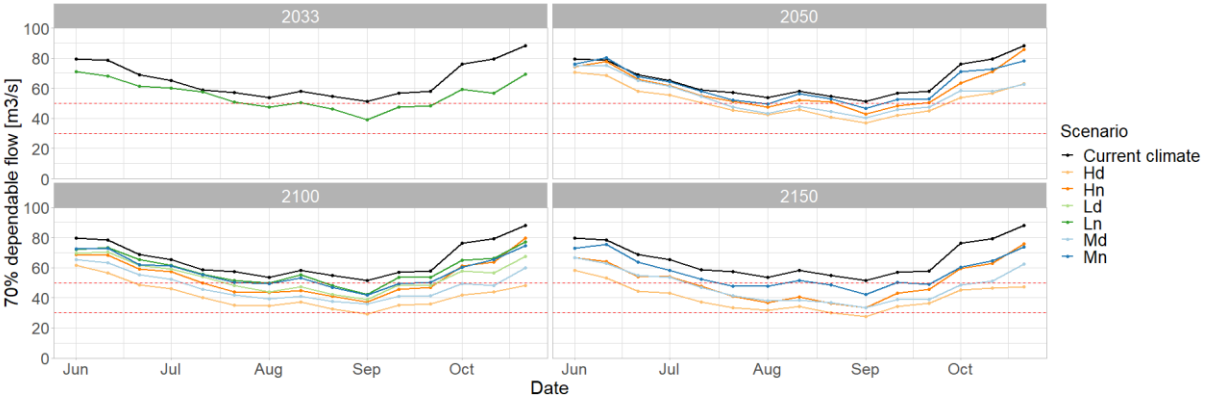


Figure 39. The 70% dependable flow of the Meuse at Monsin from June to November, the discharge which is exceeded 70% of the time and indicates at which discharges conditions are considered dry. The different panels indicate the different time horizons. The black line represents displayed in all panels represents the current climate. The dotted red lines indicate the threshold values of 30 and 50 m^3/s which are set in the International Meuse agreement between Flanders and the Netherlands.

A.7 Maps water availability bottleneck analysis climate scenarios 2050 and 2150

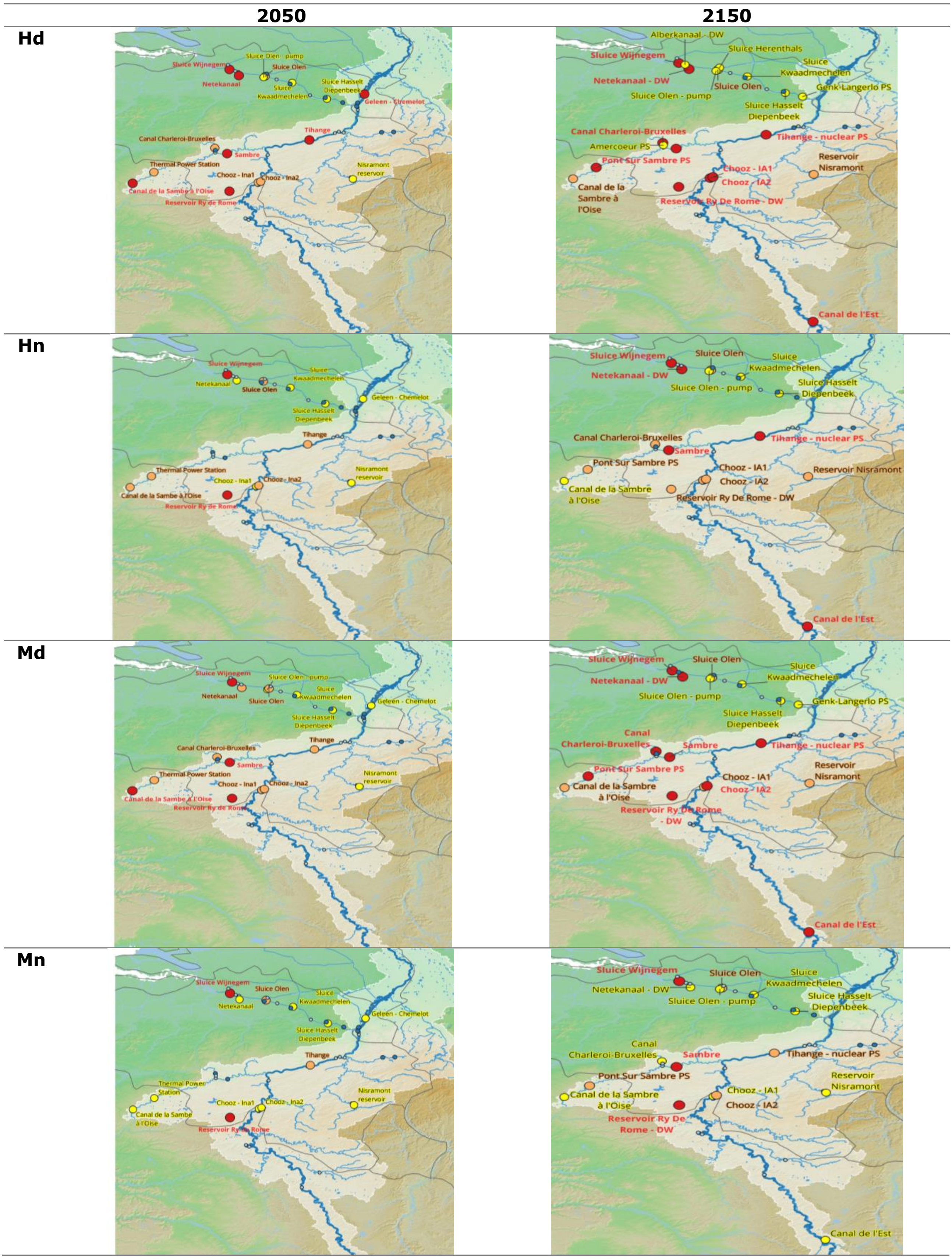


Figure 40. Maps showing the locations of bottleneck for 2050 (left) and 2150 (right) under the different climate scenarios.

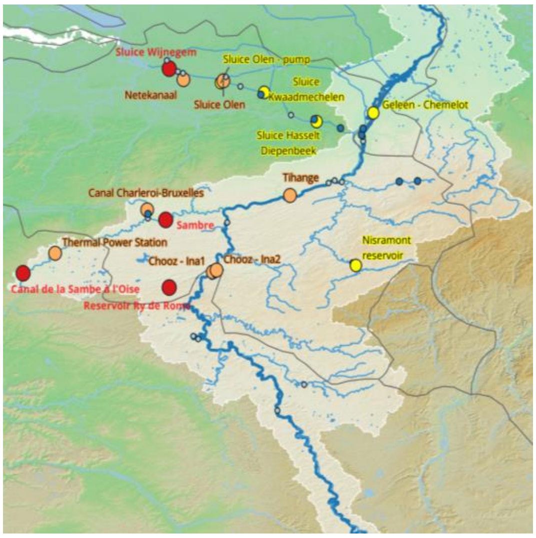
A.8 Maps bottleneck analysis water demand scenarios for moderate climate scenarios

	Mn	Md

Climate change + current water demand

Mn:

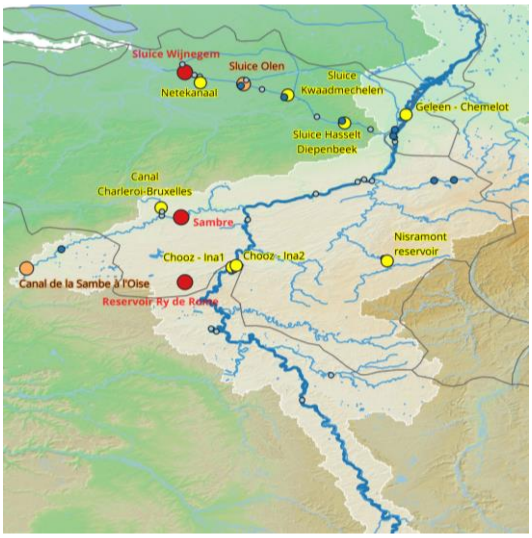
Md:



Socio-economic growth

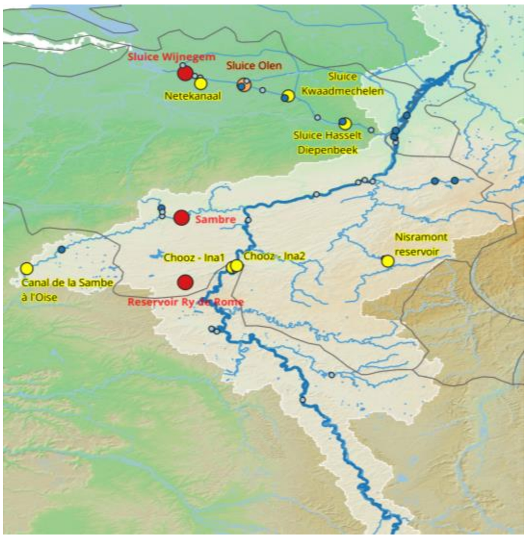
Mn:

Md:



Socio-economic decline

Mn:



Md:

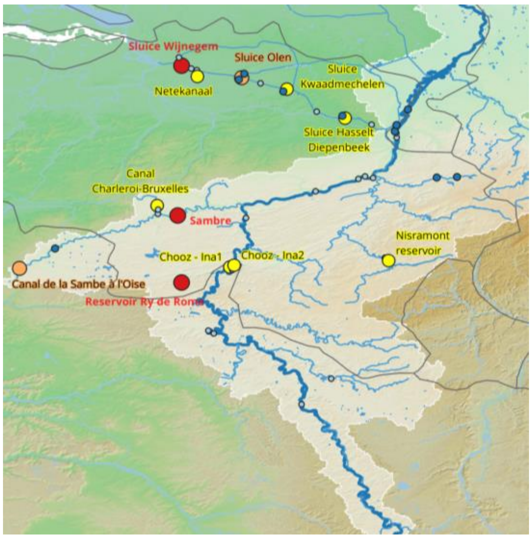


Figure 41. Maps showing the locations of water availability bottlenecks for the moderate climate scenarios (Mn = wet, Md = dry) for 2050 for different water demand scenarios