



**Suzanne de Groot**

# Assessing resilience of river systems

**Applied to the Meuse river system for  
shipping and drinking water production**



Cover photograph: the Meuse river (van Houdt, 2016)

# Assessing resilience of river systems

## Applied to the Meuse river system for shipping and drinking water production

By

Suzanne de Groot

in partial fulfilment of the requirements for the degree of

**Master of Science**  
in Civil Engineering

at Delft University of Technology,  
to be defended on Friday December 18<sup>th</sup>, 2020 at 9:00 AM.

Supervisor:

Thesis committee:

Dr.ir. M. Rutten  
Prof dr. F. Klijn,  
Dr. ir. E. Mosselman,  
Ir. A. te Nijenhuis,

TU Delft  
TU Delft  
TU Delft  
Deltares

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.



# Preface

In front of you is the report of my master thesis consisting of research conducted in order to obtain a master's degree in civil engineering. Over the course of the last nine months, I have conducted research into the assessment of resilience of river systems. I can honestly say that didn't quite go as expected. Between several days of power outages, seemingly endless struggles with the internet and of course a pandemic the day-to-day turned out somewhat differently than originally envisioned. However, despite a number of challenges I am happy to say that everything worked out in the end.

I would like to thank my committee for their feedback and support throughout this process. Thank you especially Martine, for your continued support and feedback every week to help keep me focussed and on track. Furthermore, I would like to thank Deltares for the facilities and expertise they have offered me to help me with this research. Finally, I would like to thank my family and friends for their support. Without you to pull me through the difficult times, especially in the final stages of this research, this report would not be here today.

I hope you enjoy reading.

*Suzanne de Groot  
Delft, December 2020*



# Contents

Summary .....	1
1. Introduction.....	3
1.1. Introduction.....	3
1.2. Problem statement .....	4
1.3. Scientific relevance.....	4
1.4. Objective .....	4
1.5. Structure of the report.....	5
2. Methods and materials .....	6
2.1. Methods.....	6
2.2. Materials.....	9
3. Literature review .....	11
3.1. Resilience.....	11
3.1.1. General definitions of resilience .....	11
3.1.2. Field-specific definitions of resilience .....	12
3.1.3. Improving resilience.....	13
3.1.4. Resilience aspects.....	14
3.1.5. Boundaries, internal and external factors.....	15
3.2. Resilience of river systems .....	16
3.3. Assessing resilience .....	17
3.3.1. Disturbance-impact graphs .....	17
3.3.2. Resilience classification.....	18
4. The resilience assessment approach.....	20
4.1. The resilience assessment approach.....	20
4.1.1. Step 1: System analysis .....	21
4.1.2. Step 2: Disturbance-impact graphs.....	22
4.1.3. Step 3: Resilience assessment of a function.....	24
4.1.4. Step 4: Resilience assessment of the river system .....	26
4.2. Using the approach for measures and future scenarios .....	26
4.2.1. Measures.....	26
4.2.2. Future scenarios.....	27
4.3. Additional stakeholder involvement.....	27
4.4. Examples of disturbance-impact graphs .....	27
5. River system analysis .....	30
5.1. System boundaries (step 1a) .....	30
5.2. External factors (step 1b).....	30
5.3. Characteristics (step 1c) .....	30
5.4. Functions (step 1d).....	30
5.5. Connections (step 1e).....	31
6. Shipping .....	41
6.1. Shipping on the Meuse river system .....	41
6.2. Julianakanaal shipping requirements (step 2a, 2b and 2c) .....	42

6.2.1.	Discharge requirements.....	42
6.2.2.	Water depth requirements .....	46
6.3.	Discharge in the Julianakanaal (step 2e) .....	46
6.4.	Water depth in the Julianakanaal (step 2e).....	49
6.5.	Conclusions for shipping on the Julianakanaal .....	51
7.	Drinking water production .....	52
7.1.	Drinking water production in the Meuse river system .....	52
7.2.	Drinking water production by Waterleiding Maatschappij Limburg (step 2a, 2b and 2c) .....	52
7.3.	Disturbances in production (step 2e) .....	56
7.4.	Conclusions for drinking water production by WML .....	58
8.	Discussion .....	59
8.1.	Resilience of river systems .....	59
8.2.	Shipping .....	59
8.3.	Drinking water production .....	60
8.4.	The resilience assessment approach.....	61
8.5.	Resilience of the Meuse river system .....	63
9.	Conclusions and recommendations .....	64
9.1.	Conclusions.....	64
9.2.	Recommendations.....	65
9.2.1.	Steps 3 and 4 of the resilience assessment approach .....	65
9.2.2.	Applicability to other river systems.....	65
9.2.3.	Applicability to characteristics .....	65
	References .....	66
	Appendix A Connections overview.....	70



# Summary

Rivers provide many of our day-to-day needs. They allow, for instance, the production of drinking water and the movement of goods via inland waterways. However, river systems experience disturbances, such as droughts and pollution plumes. These disturbances can impair the functioning of river systems and their ability to provide the desired functions and services.

Since some of these disturbances have very little impact while other cause many problems, it is important to determine how a river system handles different disturbances. Resilience is often used to indicate and assess the behaviour of systems with regard to disturbances. Using the concept of resilience with regard to river systems can help determine how well river systems handle disturbances.

In order to determine how resilient a river system is, a method to assess the resilience of river systems is needed. Research into the resilience of river systems has only been done with regard to flood resilience. This resilience does not consider other disturbances, such as droughts, and therefore does not represent the full resilience of the system. Furthermore, this research often resulted in suggestions and pointers to create and improve resilience, but not in a clear method to help assess it. Hence, the objective of this study was to develop a method to assess the resilience of river systems.

In order to create this method several questions need to be answered. First, a clear definition of resilience of river systems is needed. For this it should first be determined what resilience is. This is done using a literature study. The first part of this literature study focussed on general and field-specific definitions of resilience. This resulted in the definition of resilience of river systems as used in this study: the resilience of a river system is the ability of the system to continue functioning during a disturbance. Where continuation of functioning is defined as the continued achievement of the goal of a certain function, such as the continued production of crops for the function of agriculture, even if this only occurs to a smaller extent, and the continued shipping of goods for the function of shipping. The disturbances considered are short-term disturbances, such as droughts and pollution plumes.

After the determination of the definition of resilience of river systems several remaining questions need to be answered. The impact of disturbances on the different river system functions has to be determined and visualised. Next, the impact of these disturbances has to be classified. Finally, the resilience of river systems should be assessed using the classification for the impact of these disturbances. The second part of the literature study, focussing on the assessment of resilience, is used to help determine, visualise and classify the impact of disturbances. The development of the final method is an iterative process between application to a case study and the amendment of the method based on this application.

Using the results of the literature study, a first design of the resilience assessment approach, the method for the assessment of resilience of river systems, was made. This approach consists of four steps with several sub steps. In the first step a system overview is created. This step is based on the ideas of flood resilience theory. It states how a system overview should be created, what external factors, characteristics and functions should be included and how to categorise them. The second step consists of the creation of disturbance-impact graphs for the different functions and disturbances. These graphs, based on the idea of stressor-response graphs of system robustness analyses, are used to visualise the impact of the disturbances. The third step gives an assessment of the resilience of a function based on the disturbance-impact graphs and a resilience classification with associated scoring system, which is based on the ideas of a current impact classification used for droughts. The fourth and final step consists of the assessment of the resilience of the entire river system based on the assessment of the individual functions.

The approach was applied to a case study, the Meuse river system, to test it. This case study focussed on low discharges caused by droughts. The approach was applied to the whole system, thus to all its characteristics (water quality, water quantity, vegetation and fauna and sediment) and all its functions (shipping, electricity, industry, drinking water production, agriculture, flood protection and recreation), to create a system overview (the first step of the approach). The application focussed specifically on the functions shipping and drinking water production.

This application was used to check the content and applicability of the sub steps of the first step of the approach, using the system overview, and to check the content, applicability and order of the sub steps of the second step of the approach, using the functions shipping and drinking water production. The application of the system overview led to a clear distinction between external factors, characteristics and functions, which has been adopted in step 1. Furthermore, the application to the specific functions resulted in a clearer definition of system boundaries and a clearer link between the external factors and the disturbance. Finally, the application led to an additional sub step. This sub step consists of a check to determine whether the chosen disturbance is actually relevant for that specific function.

The application of the approach showed that both shipping and drinking water production of the Meuse river system appear to be very resilient with regard to low discharges due to droughts. This is likely due to fact that both functions have already been adapted to this disturbance. For shipping this is likely largely due to the fact that the water level in the Julianakanaal is managed to ensure continued shipping possibilities during discharge fluctuations. Pumping facilities have been constructed in order to maintain water levels even when very small discharges occur. The large resilience of the drinking water production by Waterleiding Maatschappij Limburg is likely largely due to the fact that the intake point is located in the Lateraalkanaal. The water level of this canal is managed using weir and sluices for shipping and drinking water production.

Only the first two steps of the approach have been tested using the case study. The final version of these steps, as found in this report, can be used in practice. The tested steps have shown to be applicable to the tested functions and it assumed that these steps are also applicable to the other functions.

The third and fourth step should be tested before they are used in practice. Especially step 3a (the assignment of the different levels of the resilience classification to the disturbance-impact graphs) might require additional adaptation.

# 1. Introduction

*This chapter gives an introduction to the study described in this report. First, a few examples of disturbances currently occurring in river systems are given. Then, the problem statement and scientific relevance of this research are described. Thirdly, the objective of this research is stated. Finally, the structure of the report is briefly presented.*

## 1.1. Introduction

Rivers provide of many of our day-to-day needs. Electricity plants use river water as cooling water, drinking water plants extract water from rivers to produce drinking water, agricultural companies extract water from the river for irrigation and many products are moved using inland waterways.

However, this river system experiences disturbances fairly often. These disturbances can be disruptions in discharge or the occurrence of pollution. As is shown in the examples below, the functions the river system provides are vulnerable to these disturbances.

Droughts can cause such disruptions in discharge. These droughts can occur due to excessive (ground)water withdrawals upstream, prolonged dry weather or due to climate change. When these conditions occur the demand for water availability can no longer be met. Drinking water plants, electricity plants, industry and agriculture all use water from the river system. During these shortages they are unable to extract all the water they need (van Heerder, 2019). Recently, the intake for drinking water production from the river Meuse had to be stopped due to water shortages and this is likely to happen more often due to climate change (Speksnijder, 2019).

Another threat to extraction from rivers is pollution. Pollution can be caused by, for example, industry or can enter the system upstream. Recently, cases of pollution with herbicides have stopped the intake for drinking water production. Lower discharges worsen this situation since the pollution will be less diluted (van Heugten & Horrichs, 2019).

Both high and low discharges, which can cause high and low water levels, cause problems for shipping. During low discharges locks are used sparingly to save water, causing waiting times of up to 4 hours (Transport Online, 2019). On the other hand, if water levels are too high, ships will be unable to pass underneath bridges. This means ships will either have to find an alternative route or will have to wait until the water levels lower again (Binnenvaart Krant, 2020). Both disturbances cause delays and increase the costs of shipping. Low water levels in 2018 caused 165 million euros in damage for direct effects and another 170 million is expected for indirect effects. Approximately 50% of these costs is for foreign companies. 65 to 155 million euro is estimated to be the costs of the effects for the Netherlands. However, this does not take into account any possible long-term effects of more expensive shipping in the Netherlands (van Hussen et al., 2019).

Agriculture uses water for irrigation to increase the yield of crops. River water is one of the sources used. During droughts less water is available for irrigation which can cause a decrease in crop quality and possible loss of crops. In the summer of 2018 extraction of water from rivers and groundwater was no longer allowed in several areas within the Netherlands due to drought (van Liere, 2018).

Rivers and areas connected to rivers are often used for recreational purposes. However, during the summer some of these are likely to be closed due to a decreased water quality. A decreased water quality can cause an outbreak of cyanobacteria. These bacteria are a health hazard and are difficult to remove from water bodies. This causes these recreational areas to be closed for days or weeks at a time to get rid of the cyanobacteria (Hoogheemraadschap van Delfland, 2019).

## 1.2. Problem statement

As shown river systems experience disturbances. Some of these disturbances have very little impact while others cause many problems. Resilience is often used to indicate and assess the behaviour of systems with regard to disturbances. Applying the concept of resilience to river systems can help determine how well a river system handles disturbances. In order to determine how resilient a river system is, and thus how well it handles disturbances, a method to assess the resilience of river system is needed. Before such an assessment can be made a clear definition of resilience of river systems is needed. However, no method for the assessment of this resilience is available yet, nor is a clear definition of the resilience of a river system.

## 1.3. Scientific relevance

Throughout literature and policies, the word resilience is used often. A simple Google Scholar search results in 1.350.000 hits since 2000 and the term resilience is also often used in the 4e Nota Waterhuishouding (Ministerie van Verkeer en Waterstaat, 1998). In fact, it has become somewhat of a buzzword. It is often left undefined or unspecified (Hussain, 2013). Consequently, it has become a vague term that is used to imply that something more is needed than is currently being done or that systems currently lack something and are therefore not resilient (Knuth, 2019). Many definitions of resilience exist but a clear definition of what resilience means or is for river systems has not yet been given.

The method for the assessment of the resilience of river systems will need to be tested. This will be done using a case study. This case study focusses a river system within the Netherlands. Much research on rivers within the Netherlands has focussed on the river Rhine. Lately that focus has started to shift toward the river Meuse. Some research has already been done and some projects are already in motion (Asselman et al., 2018; Chrzanowski, 2016; Rijkswaterstaat, 2020-a). The case study of this research will participate in this shift and focus on the river Meuse.

## 1.4. Objective

The objective of this research is to **develop a method to assess the resilience of river systems**. This method will be tested using a case study.

Several questions need to be answered in order to be able to develop this method. An overview of these questions can be found in Figure 1. As can be seen, in order to assess the resilience of a river system a definition of this resilience of river systems is needed. To be able to create this definition it should first be determined what resilience is. Once, this has been determined and a definition of resilience of river systems has been created, the impact of a disturbance needs to be determined and visualised. Next, the impact of disturbances has to be classified. Finally, the resilience of a river system has to be assessed using this classification for the impact of disturbances.

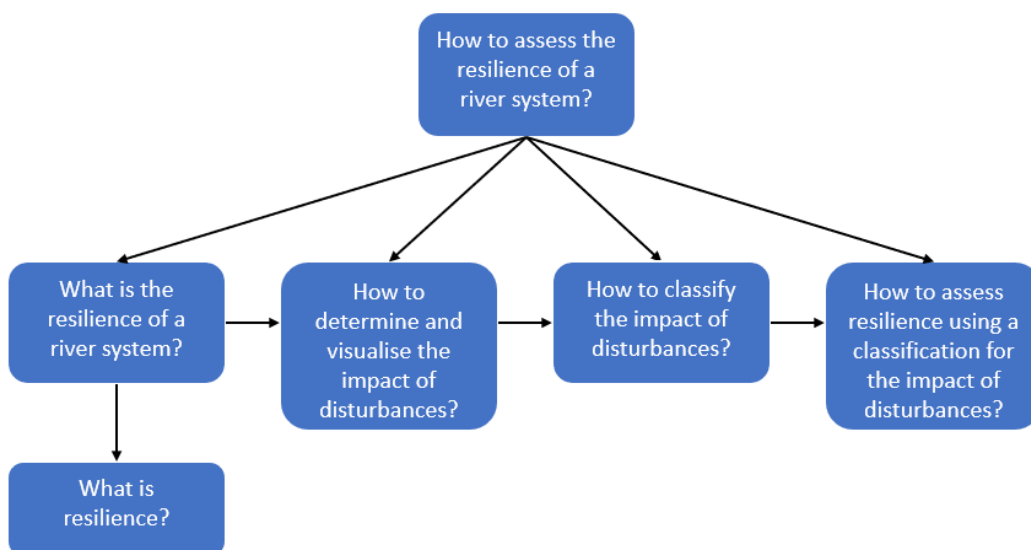


Figure 1 Overview research questions for the assessment of resilience of river systems

The method developed to assess the resilience of river systems will be applied to a case study in order to test it. This case study focusses on the Meuse river system and specifically on how this river systems handles droughts. These droughts will be considered as a decrease in discharge.

The application will focus on the functions shipping and drinking water production. Beside testing the applicability of the method, the application will also be used to give an estimate of the resilience of these functions. This leads to the final research questions of this research, as can be found in Figure 2.

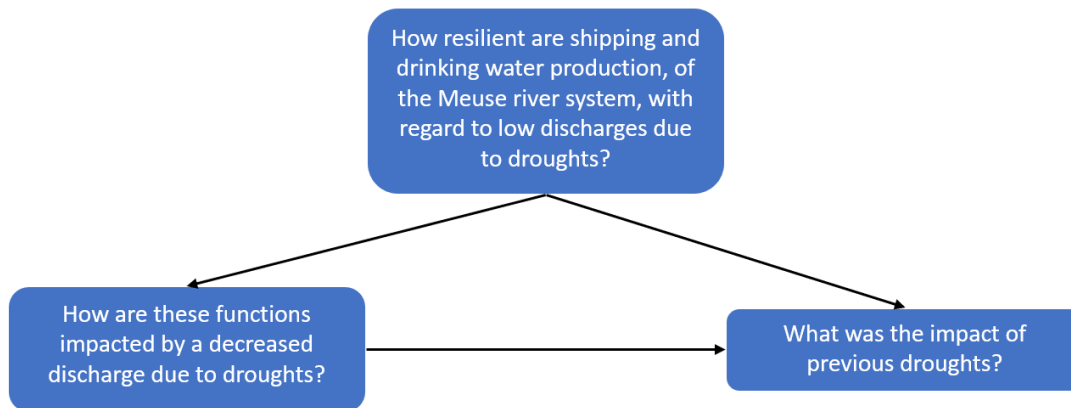


Figure 2 Overview research questions related to the functions of the case study

## 1.5. Structure of the report

This report consists of three distinct parts. In the first part the questions shown in Figure 1 are answered and the method for the assessment of resilience is presented. The second part contains the application of this method, using the case study. The third part reflects on the method and its development as well as the application to the case study.

The first part consists of Chapters 2 through 4 which contain the methods and materials used to achieve the objective of this study, the literature study on resilience and the assessment of resilience, the definition of resilience of river systems as used in this study and the explanation of the resilience assessment approach, the method used to assess the resilience of river systems.

The second part contains Chapter 5 through 7. In this part the resilience assessment approach is applied to the case study. This application contains the system analysis and the analyses of the functions shipping and drinking water production.

The third part of this study, Chapter 8 and 9, consists of a reflection on the resilience assessment approach and its application. In this part the approach and the application to shipping and drinking water production are discussed and the conclusions of this research and recommendation for further research are given.



## 2. Methods and materials

This chapter gives an overview of the different methods for the development of the method for the assessment of resilience of river systems as well as the data used in the analyses of the case study.

### 2.1. Methods

A flowchart of the methods used in this research can be found in Figure 3.

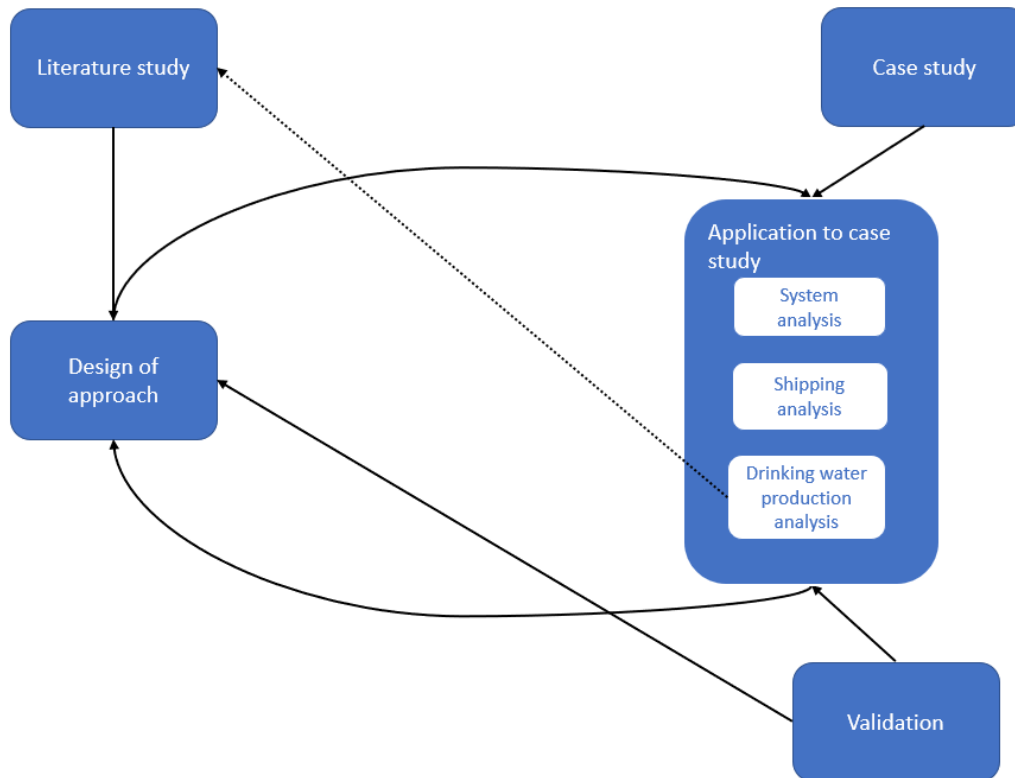


Figure 3 Flowchart methods

First, a literature study was done to help define and assess the resilience of river systems. The first part of this literature study focussed on general and field-specific definitions of resilience. These definitions were researched using Google Scholar and Web of Science. The keywords used were: resilience, resilience definitions, resilience rivers, resilience river system, resilience engineering and resilience aspects. These keywords result in many hits as can be seen in Table 1. This table only contains document published between 2000 to 2020. To decrease the number of documents to be considered only documents in English and Dutch were considered. It was assumed that the most relevant documents could be found within the first 150 hits. From this collection of documents relevant documents were selected based on the abstract. Documents considered relevant contained general definitions of resilience or information on resilience with regard to river systems, engineering or aspects of river systems. The selected documents were read and, if found to be useful, relevant literature considered in said document or study was considered as well.

Table 1 Results of keyword search

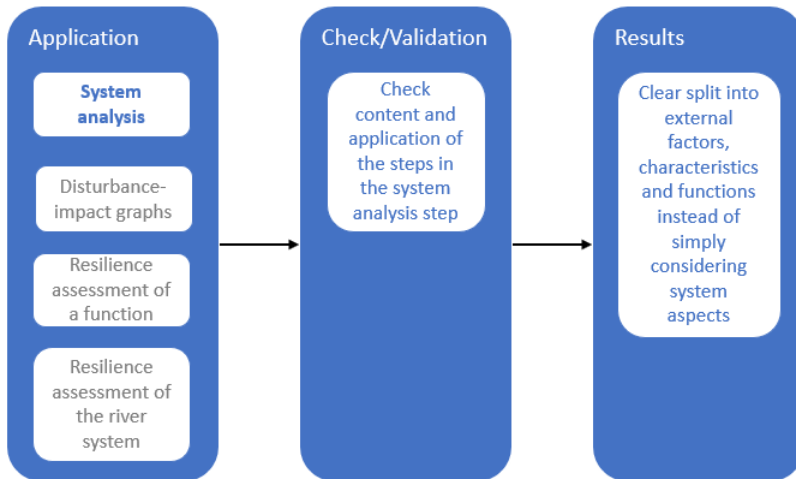
Keywords	Hits Google Scholar	Hits Web of Science	Total hits
Resilience	1,290,000	101,001	1,391,001
Resilience definitions	461,000	2,216	463,216
Resilience rivers	113,000	2,294	115,294
Resilience river system	132,000	1,000	133,000
Resilience engineering	932,000	5,743	937,743
Resilience aspects	1,400,000	7,993	1,407,993

The second part of the literature study focussed on the assessment of resilience. This part of the study focussed on methods to visualise the effect of a disturbance and methods to classify the impact of a disturbance. Literature used for the visualisation was obtained from experts from Deltares. These are experts in the fields of rivers and river engineering, resilience strategies and flood risk management. These have been consulted because their fields often deal with disturbances and their impact. Literature for the classification was obtained through a search using keywords: impact classification and drought classification. Since one of the first hits, using these keywords, already contained the desired information other documents or studies have not been considered.

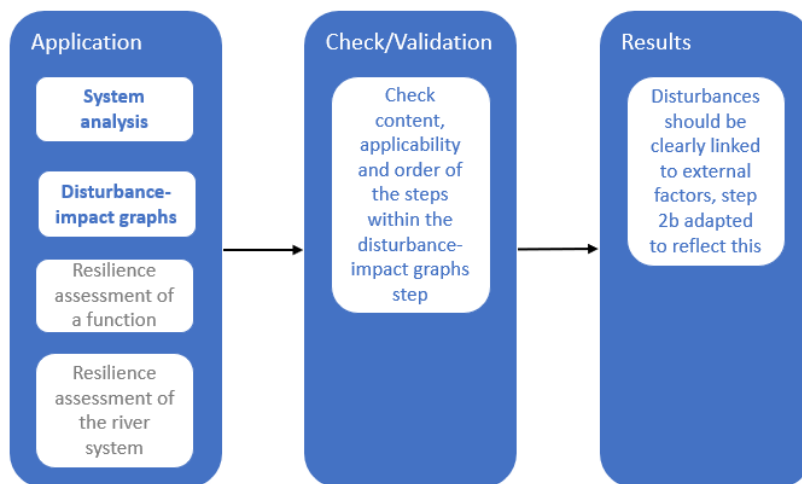
A case study was used to test the approach proposed to assess the resilience of a river system. This case study focussed on the river Meuse. Research was done to identify the important system aspects and current issues. This research was based on documents on the river Meuse retrieved from Rijkswaterstaat.

Then, a first version of the method for the assessment of resilience of river systems was created. This was done by combining the different phases and steps needed, as identified in the literature study on the assessment of resilience, while taking into account the important aspects of resilience, as identified in the literature study on resilience. The creation of the final version of the method was an iterative process in which an (adapted) version of the method was applied to the case study to see if more changes were required. An overview of the iterative process can be found in Figure 4. In this figure the steps of the method applied in the different analyses are indicated in blue.

## River system analysis



## Shipping



## Drinking water production

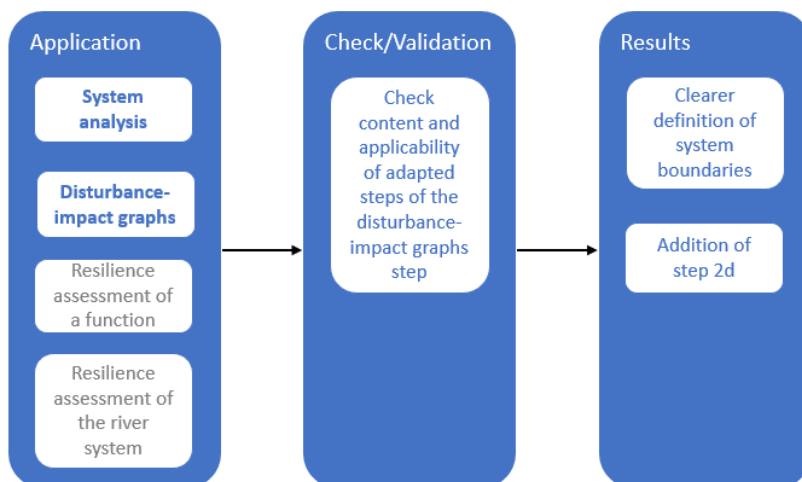


Figure 4 Iterative process of method creation

The application to drinking water production required clearer definitions of the system boundaries. The literature study on resilience was reconsidered to help define clearer system boundaries, specifically, for functions which use more sources or aspects than contained in the physical river stretch considered.

The application to drinking water production also showed that an additional disturbance check is necessary in order to determine whether a relevant disturbance has been selected. This additional check was implemented and this final version of the method can be found in this report.

Throughout the process the different versions of the method and the application of the method were validated by experts. These are experts in the fields of resilience strategies, flood risk management, hydrology, water resources and rivers and river engineering. They were asked whether they thought the method was applicable in its current version and whether they thought important aspects, in the method or the analyses, had been overlooked. The feedback of these conversations, which consisted mainly of suggestions to clarify the method and questions regarding the creation and application of the disturbance-impact graphs, was implemented in the method and the application was amended where needed.

## 2.2. Materials

An overview of the data used can be found in Table 2.

Table 2 Overview of used data

Data type	Source	Purpose	Time period	Measurement interval	Location measurements
Discharge	Prinsen (2008)	Shipping analysis	1935-2019	1 day	Monsin
Discharge	Rijkswaterstaat (2020-c)	Shipping analysis	2009-2019	1 day	Borgharen dorp, Smeermaas, Bunde
Water level	Rijkswaterstaat (2020-c)	Shipping analysis	2010-2019	10 minutes	Borgharen Julianakanaal
Evaporation	KNMI (2020)	Shipping analysis	2003-2019	1 month	Beek
Water level	Rijkswaterstaat (2020-c)	Drinking water production analysis	2000-2019	10 minutes	Heel boven
Water level	Rijkswaterstaat (2020-c)	Drinking water production analysis	2000-2019	1 hour	Heel beneden

The discharge data of Monsin was used to determine the discharge in the Julianakanaal. This was done using an allocation received from Prinsen (2008) based on the Maasafvoerverdrag (De Nederlandse Overheid, 1995). This allocation allowed the discharge at St. Pieter to be determined from the discharge at Monsin. Another allocation was needed to determine the discharge in the Julianakanaal based on the discharge at St. Pieter. This allocation is based on the discharge as measured at Borgharen dorp, Smeermaas and Bunde. The discharge in the Julianakanaal, which is the total discharge of the three locations minus the discharge at Smeermaas and Borgharen dorp, is determined relative to the total discharge at the three locations.

Using both these allocations and the discharge data of Monsin the discharge in the Julianakanaal was calculated using Python. This created dataset for the Julianakanaal was analysed using Python to determine how many times the discharge exceeded certain values.

The time period of the discharge data used to determine the allocation between Borgharen dorp, Smeermaas and Bunde was chosen to reflect the current operating policy of the managed water level in the Julianakanaal. The larger time period of the discharge at Monsin (and thus the discharge of the Julianakanaal in the analysis) starts right after the opening of the Julianakanaal. It has been chosen to consider this larger time period in order to assess the resilience of the Julianakanaal over its entire lifespan.

The water level data at Borgharen Julianakanaal has been converted into daily averages using Python. These daily averages have been plotted. The analysis actually required the water depth, however, since

this was unavailable the water level has been used. Since this water level can only be used as an indication a shorter time period was considered.

The evaporation data, needed for a water balance, contained the total evaporation per month per year. These values have been converted into daily averages per month per year using Excel. These daily averages have been used to calculate the daily average evaporation per month of the considered 16 years. These averages have been plotted. It was the intention to consider the entire lifetime of the canal, however, evaporation data before 2003 was unavailable.

The water balance was done using Excel. For this water balance the evaporation data was converted from mm/day to m<sup>3</sup>/s. This was done by multiplying with the length and width of the canal to get the total evaporation in the canal,  $E_c = E * L * W$ . The water balance contained the discharge entering the Julianakanaal, the evaporation and the discharge retained using pumps at the end of the canal, in order to determine the discharge leaving the canal,  $Q_{out} = Q_{in} - E_c - Q_M$ .

The water level data at Heel boven and Heel beneden have been converted into daily averages using Python. These daily averages have been plotted. The analysis actually required the discharge or the water depth, however, since this was unavailable the water level has been used. Since this water level can only be used as an indication a shorter time period was considered.



## 3. Literature review

*This chapter consists of a literature study. First, general definitions of resilience are researched in order to help define the resilience of river systems. This definition will be presented in the second part of this chapter. Finally, the literature study on the assessment of resilience is presented.*

### 3.1. Resilience

All definitions of resilience are defined with regard to disturbances. A disturbance is defined as “conditions or events that interrupt or impede normal operations by creating discontinuity, confusion, disorder or displacement” (Madni & Jackson, 2009).

Disturbances can have different timescales as indicated by Pahl-Wostl (2009): “Being resilient implies that basic functions of a regime are sustained despite of short-term disturbances or long-term societal or environmental changes”. Here two different timescales are considered. Some studies use only short-term disturbances (such as droughts or pollution plumes) while others also include long-term disturbances (such as climate change), although not every study indicates which timescales are considered.

#### 3.1.1. General definitions of resilience

Literature contains many general definitions of resilience. A simple Google Scholar search results in 1,350,000 hits when only considering sources from 2000 onward. Woods (2015) gives an overview of different general definitions of resilience used. Since many different definitions have been formulated within different fields, he attempts to classify them into the four categories below.

##### 1) Resilience as a synonym for robustness

As the ability to absorb disturbances, robustness can be seen as a system property which protects against a certain disturbance. However, for this robustness to be effective, the disturbance has to be modelled accurately. This system is only resilient against the disturbances that have been modelled. Using this definition, disturbances outside the scope of the design are not considered and thus not included in the decision as to whether the system is resilient or not. An example of this are flood walls. These flood walls only offer protection from floods up to the maximum flood magnitude they were designed for. If this magnitude is exceeded, they will fail and will have to be rebuilt.

##### 2) Resilience as rebound from trauma and return to equilibrium

The ability to overcome or to rebound depends on the resources present before the surprise or disturbance. Here, surprise is defined as an event that falls outside the scope of variations and possible disturbances that the system is capable of handling. This approach, however, implies that one always returns to a steady state while often after a large disturbance the system changes or adapts to be able to handle future occurrences of said disturbance. As an example, the ability to quickly pump water out of a flooded area after a dike breach.

##### 3) Resilience as the opposite of brittleness

Here brittleness is defined as the sudden failure when events push the system beyond its boundaries for handling disturbances. The opposite of this brittleness would be the capability to handle events which exceed the boundaries for handling disturbances. This is referred to as graceful extensibility, since the system stretches to accommodate the disturbance. This definition focusses on the behaviour of the system as it is pushed to and beyond its boundaries. It does not consider how well it operates when conditions fall within the boundaries. An example of this are dunes. After a severe storm, dunes will be damaged but they will not fail. They will change shape to accommodate the storm.

- 4) Resilience as the ability to adapt to future disturbances and surprises as conditions continue to evolve

When operating conditions continue to evolve, the system first has to adapt to these new conditions before it can adapt to any disturbances or surprises. This resilience shows whether the system has the capability to adapt to a disturbance even though it has already had to adapt to changing conditions.

The main difference between the first two definitions is that the first one focuses on disturbances that were expected and thus taken into account in the design or plan, while the second also includes disturbances that were not expected. The third definition includes adaptation to a disturbance. As a consequence of this, the system will not return to the same state as before the disturbance, but to a new, adapted one. The fourth definition builds on the third and considers future trends. It focuses on the continued ability to adapt after a system has adapted to new (evolved) base circumstances. These four definitions could be seen as an extension of one another, where the second one is an extension of the first one, the third one is an extension of the second one and the fourth of the third.

In the second definition the concept of returning to a steady state occurs. It seems to focus solely on returning to this steady state and not on how the system functions during the disturbance.

The fourth definition also includes long-term disturbances and therefore considers both timescales of disturbances. The timescale of the disturbance in the other three definitions is not stated.

None of the definitions suggest how to define the system or the steady state the system is in before the disturbance occurs. Despite this, the overview of the different general definitions is considered to be sufficient for this study.

### 3.1.2. Field-specific definitions of resilience

Besides general definitions several types of resilience have been defined, depending on their field of use. Below a brief clarification of resilience in two fields will be given: engineering resilience and ecological resilience as defined by Davoudi (2012).

Engineering resilience is seen as the ability of a system to return to an equilibrium or steady state after a disturbance. The degree of resilience can then be measured as the speed at which the systems returns to the steady state. In this definition, the emphasis is on the time needed to return to the original state, other aspects are not considered (Davoudi, 2012).

Ecological resilience is seen as the ability of a system to deal with disturbances without changes to the system's structure. Resilience can then be taken to include not only the speed at which the system reaches equilibrium again, but also the magnitude of the disturbance the system can handle before the critical threshold of change is reached and the system is unable to return to an equilibrium. The equilibrium reached after a disturbance does not have to be the same equilibrium the system started in. It can also be a new equilibrium which has adapted to the disturbance. However, if the system is pushed past the critical threshold it will be unable to reach any equilibrium (Davoudi, 2012).

The main difference between engineering resilience and ecological resilience is that engineering resilience focusses on one equilibrium while ecological resilience acknowledges the possible existence of multiple equilibria and defines resilience as reaching any of those. It could also be said that an engineering resilient system bounces back (to the original steady state) while an ecological resilient system bounces forth (to a new steady state) (Davoudi, 2012).

Both these definitions focus on returning to a steady state, however, no clear definition of this steady state is given nor an explanation of how to determine it. The timescale of the disturbances is not provided.

Compared to the general definitions of Section 3.1.1 engineering resilience is similar to the resilience as rebound from trauma and return to equilibrium as defined in the second definition of Woods (2015). Ecological resilience also contains this definition but it also includes the magnitude of the largest

disturbance the system can handle. This largest disturbance can be seen as the boundary between resilience and brittleness, as described in the third definition of Woods (2015).

As an example: if droughts cause a shortage of water for the intake for drinking water plants, a system that is resilient according to engineering resilience would be able to handle this shortage by using storage created before and would then return to the old situation once the drought is over. If the system is ecologically resilient it might create additional storage in order to lessen the impact of a similar disturbance in the future. Whether this increase in storage is considered to be a part of the system, and can thus be considered as ecological resilience, depends on the system boundaries.

Where the second general definition of Woods (2015) and the field-specific definitions of Davoudi (2012) focus on returning on a steady state, others focus on how a system functions during a disturbance. This can be seen in the third suggestion for improving resilience of the de Bruijn et al. (2017).

### 3.1.3. Improving resilience

De Bruijn et al. (2017) have formulated five suggestions on how to create and improve the resilience of systems. These suggestions are an attempt to make the occasionally abstract and multi-interpretable resilience concepts and definitions as presented by, amongst others, Davoudi (2012) more tangible. These suggestions can be found below.

- 1) Adopt a system's approach: looking at things from a system point of view allows the different subsystems and interactions between these to be taken into account. All these subsystems and their interactions will make for a complex system. This system can be modified and simplified to create models which can help identify important elements and connections. This reduces the risk that important connections or elements are overlooked or that the connections are made incorrectly.
- 2) Look at beyond-design events: during design the focus is often on rarely-occurring events with a very large impact while an often-occurring event with a small impact can be experienced as having a much larger risk than is calculated by engineering analysis. Looking beyond the design events, so to the whole spectrum of events, below as well as above the resistance threshold and even beyond the recovery threshold, allows the worst-case scenario and even the unimaginable scenario to be created. Looking at 'all' scenarios instead of the one scenario or event that would normally be used for the design is likely to result in a more 'all-round' system which is capable of handling many different kinds of disturbances.
- 3) Build and prepare infrastructure according to 'remain functioning' principle: systems designed to remain functioning do not have catastrophic consequences when they fail. It is accepted that failure cannot be prevented entirely, and the system is designed in such a way that the critical infrastructure or parts remains functioning, thus enabling better and faster recovery.
- 4) Increase recovery capacity by looking at social, institutional and economic capital: the recovery capacity determines how quickly a system recovers from a disturbance. The more quickly a system recovers, the smaller the long-term impact of disturbances will be. This recovery rate depends on social capital, institutional capital and economic capital. Social capital is the individual capability of people to recover, institutional capital is the ability to organise repair and reconstruction and economical capital is the ability to finance the institutional capital. If one of these capitals or elements is insufficient, recovery will be slower.
- 5) Remain resilient into the future: a currently resilient system might lose that resilience in the future due to, for example, climate change. In order to stay resilient, a system needs to be flexible, to learn and to have the ability to adapt to what has been learned as well as be willing to adapt when it is necessary.

The third suggestion focusses on certain aspects of the system that need to remain functioning to enable swift recovery. This remain functioning or continue functioning principle can be applied to more than just the critical aspects of a system in order to assess how a system handles a disturbance. However, a definition of this functioning is not given.

The main difference between the continue functioning approach and the approach focussing on returning to a steady state is the phase it focusses on with regard to the disturbance. The former focusses on how the system responds during the disturbance while the latter focusses on how the system responds after the disturbance.

### 3.1.4. Resilience aspects

Different definitions of resilience and suggestions on how to improve resilience have been presented, however, the aspects that make a system resilient have not been stated. Madni and Jackson (2009) suggest that these aspects emerge when designing a system focussed on being resilient.

This engineering for resilience is largely based on anticipation, survival, recovery and adaptation. Anticipation is based on the ability to look ahead to determine changes in for example the environment and to then decide on the actions needed in the present to circumvent disturbances in the future. Survival is the ability to prevent destruction of the system when faced with disturbances. Recovery is the ability to survive a major disturbance with temporarily reduced performance. The difference between survivability and recoverability is the ability to bounce back. When a system only has survivability, it will be able to survive the disturbance but will be unable to return to its previous state. Recovery is needed to return to a state in which the system is able to function like before. Adaptation is the ability to change the system to ensure proper functioning and survival in the future and under changing circumstances. Such a system has two types of resilience: reaction and adaptation, where reaction refers to the short term and adaptation to the long term (Madni & Jackson, 2009).

Even though not one widely used definition for resilience has been found, all use one or more of the previously named aspects. In Table 3 the most important aspects for different definitions of resilience (both general and field-specific) can be found. Of course, more aspects are important but the ones that are fundamental to each definition are shown here in order to see the differences between the definitions. The first four definitions are the four definitions of Woods (2015), the second two are from Davoudi (2012) and the last three are the third through fifth suggestions of de Bruijn et al. (2017).

Table 3 Resilience definitions and their aspects (clustering based on definitions given before)

	Survivability	Recovery	Anticipation	Adaptation
Robustness	X	X	X	
Rebound	X	X		
Opposite of brittleness	X	X		
Adaptation to future changes	X	X	X	X
Engineering	X	X		
Ecological	X	X		
'Remain functioning' principle	X	X		
Recovery capacity		X		
Remain resilient into the future				X

Anticipation has only been indicated for the definitions for which anticipation of disturbances has a large influence on the scope of the definition or where anticipating future trends is an important part of the definition. The first definition of Woods (2015) focusses only on the disturbances the system was designed for. Hence, anticipation is needed to decide which disturbances to take into account. The fourth definition assumes changes to the system are needed in order for the system to function in the future. The fifth suggestion of de Bruijn et al. (2017) focusses on adaptation in order to remain resilient in the future.

The first two suggestions of the de Bruijn et al. (2017) focus more on how a system should be treated when considering resilience than on what makes a system resilient. Hence, these two suggestions do not contain any of the aspects in the table and have therefore not been included.

Others, amongst whom Becker et al. (2020), have argued that adaptation should not be an aspect of resilience and should thus be considered separately. This adaptation refers to long-term changes, such as adaptation to climate change, and is often realised through planned changes to the system. It is argued that such long-term effects are not disturbances but trends. Since trends like climate change do not have a clear end, treating them as a disturbance makes it difficult to determine the timescale of the disturbance. Furthermore, if the end of the disturbance cannot be defined, the response of the system to the disturbance is also difficult to determine.

Resistance is occasionally considered to be an aspect of resilience as well. In other cases, it is considered separately. Regardless of whether it is considered to be an aspect of resilience, it is defined the same. Resistance can be seen as the threshold after which a disturbance is translated into impact. Therefore, the more resistance a system has, the larger the disturbance must be to have an impact on the system (Adger, 2000; Woods, 2015). If resistance is considered separately it occurs before the start of the resilience, which starts when the resistance threshold is exceeded.

### 3.1.5. Boundaries, internal and external factors

#### Boundaries

In order to formulate a definition of resilience of a system the system boundaries need to be determined. An additional review of the considered literature showed that a definition of these boundaries is not present in the studies. Fünfgeld & McEvoy (2012) have reached the same conclusion: “Researchers, planners and decision-makers rarely clarify at the outset how their system of concern is being defined, what its boundaries are, and how it interacts with others systems beyond these boundaries”.

There are several possible reasons for such an omission. As Woods (2015) suggests, “Of course, one difficulty is that the location of the boundary is normally uncertain and moves as capabilities and conditions change”. The fact that boundaries are not fixed makes it difficult to define them in such a way that they are applicable to the entire study or to the general definition. Davoudi (2012) points out that defining boundaries shifts focus to certain aspects, causing discounting of others and can lead to exclusionary practices. Hence, defining boundaries at the start will cause the exclusion of certain aspects which is undesirable when formulating a more general definition of resilience.

#### Internal and external factors

The system boundaries determine which factors are internal and which are external. Disturbances can be classified based on whether they are internal or external. Some definitions of resilience consider different disturbances with regard to the timescale, however, none of the considered definitions state whether the disturbance is caused by internal or external factors. Only Madni and Jackson (2009), who do not give a clear definition of resilience themselves, consider the origin of the disturbances.

While defining any system certain aspects will necessarily be excluded. However, these can still have an influence on the system. These aspects are the external factors. Factors within the system are known as internal factors. The system contains these internal factors and is influenced by the external factors. The resilience of the system is tested by disturbances. These disturbances can be specified as external and systemic (both internal and external). External disturbances are caused by factors outside the system and must therefore be detected in order to take the appropriate counteraction (if needed). A systemic disturbance is a disturbance of function, capability or capacity of the system. This can either be caused by an external disturbance which resulted in a systemic disturbance (an external systemic disturbance) or by an internal disturbance (an internal systemic disturbance). Every aspect of the system can potentially cause a systemic disturbance as well as be an essential part of the recovery from one (Madni & Jackson, 2009).



## 3.2. Resilience of river systems

As outlined many definitions for resilience exist but one specifically for river systems has not yet been formulated. In this section, the definition of resilience of rivers system as used in this study will be given.

A complicating factor in defining the resilience of a river system is the degree of connectivity in a river system. Since all external factors, characteristics and functions are connected, a change in conditions or a disturbance in one of them influences many others. This complicates defining and assessing the resilience of the system, since all these connections have an influence on the resilience and thus need to be captured in the definition of resilience of river systems.

In this study the resilience of a **river system** is defined as the ability of the system to **continue functioning** during a **disturbance**.

The river system consists of a river stretch and its different characteristics, such as water quality and vegetation and fauna, and its functions and their connections. These characteristics are system attributes that in themselves cannot be assessed to be good or bad or sufficient or insufficient. They can only be assessed with regard to a certain demand or goal. This demand is created by the functions. The functions are how people and society use the river system (such as shipping and agriculture). These functions demand certain quantity and quality of the characteristics.

All the functions have a certain goal: they either produce goods (such as drinking water or electricity) or provide a different service (such as shipping and recreation). As long as functions are able to achieve this goal they are considered to be functioning. In order to be or remain functioning the degree to which this goal is achieved may vary as long as it is still achieved: less goods may be produced as long as some goods are still produced. When no goods are produced the functioning ceases. As an example, when the discharge decreases a drinking water plant will produce less drinking water, but as long as it still produces some drinking water it is still considered to be functioning.

Since characteristics have no clear goal, when not linked to a function, it is difficult to assess whether this goal is achieved. Hence, the 'continuation of functioning' focusses on the river system functions only. Hence, the continued functioning, and thus the resilience, of the river system depends on the continued functioning of the river system functions.

Only the aspects of the function that use to the physical river stretch are considered to be part of the river system. It can be that a function is fulfilled by another system than the physical river system. For example, drinking water production may shift from surface water to groundwater when insufficient surface water is available. In this situation only the drinking water production using surface water is considered to be part of the river system. This exclusion of certain aspects of functions also partly defines the system boundaries.

Since no general definition of system boundaries was found, nor any suggestions on how to define them, a more practical approach was decided upon. For the purpose of this study the system boundaries are defined by defining the physical boundaries of the considered river stretch at the start and thereafter defining per function which part of that function forms part of the river system.

The physical boundaries are needed in order to determine what aspects and factors are external. The other boundaries determine which aspects of the functions are taken into account and can thus have an influence on the resilience of the river system.

Disturbances, which can impede the 'continuation of functioning', are defined as short-term shocks or stresses in the external factors. These shocks or stresses in the external factors have an influence on the characteristics of the system and can have a direct influence on the functions. The influence of shocks or stresses on the characteristics can in turn have an influence on the functions, hence, this influence can still be traced back to the shocks or stresses in the external factors. The focus of this study is on (low) discharge. This discharge is considered to be an external factor, hence, possible disturbances caused by internal factors are not considered. An example of a disturbance caused by an internal factor is an increase

in water temperature, and thus a decrease in water quality, caused by the discharge of too much cooling water.

The resilience of a river system is tested as soon as the impact of a disturbance is felt. Before this impact is felt, resistance occurs. During the resistance phase a disturbance occurs but the impact of this disturbance is not felt. As soon as the resistance is exceeded, the impact will be felt and the resilience phase starts.

The river system as defined in this study is a simplification used to identify and visualise all connections. This system will be used to classify and assess the resilience of the system. This simplification can be seen as an application of the first suggestion of de Bruijn et al. (2017).

The choice for a definition focussing on the continued functioning rather than on returning to a steady state can be seen as an application and extension of the third suggestion of de Bruijn et al. (2017). Additionally, it is more straightforward to define a goal for all functions than it is to define a steady state for all functions.

### 3.3. Assessing resilience

#### 3.3.1. Disturbance-impact graphs

Since the degree of resilience is determined by how a system (and thus the functions) respond to disturbances, this response will need to be assessed in order to assess resilience. This will be done using disturbance-impact graphs. These graphs are based on the idea of the stressor-response graphs of Mens (2015). These stressor-response graphs show the relevant response of the system or aspect against the degree of the relevant stressor. They contain a resistance threshold, before which no system response occurs, and a point of no recovery at the recovery threshold beyond which an alternate system state is more likely than recovery, see Figure 5.

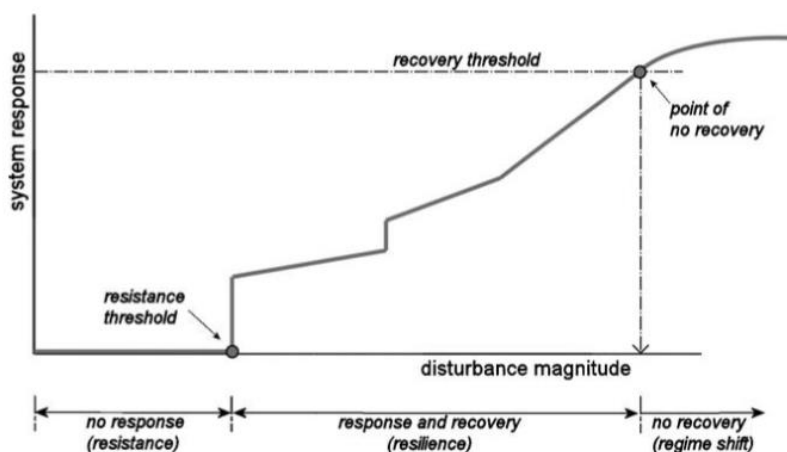


Figure 5 Stressor-response graph (Becker et al., 2020)

In the disturbance-impact graphs the magnitude of the disturbance is plotted against the impact the disturbance has on a specific function. The general graph can be found in Figure 6. In this graph several phases can be identified. At first the magnitude of the disturbance increases yet no impact is felt: the resistance phase. At some point, the disturbance magnitude exceeds the resistance and an impact can be observed. This impact will increase with the disturbance magnitude until, at a certain point, a demand can no longer be met, leading to an accelerated increase in impact. For example, for a decreasing discharge the impact will start when a user can no longer extract all the water he needs. When this discharge continues to decrease, at some point the user might not be able to extract any water at all. At this point the impact increases significantly since the user can no longer perform his business or task. After this point there might be buffers of some sort so the user can still partly continue his business. However, when these buffers are empty business will no longer be possible. The different points at which the impact starts or changes are referred to as thresholds.

In the stressor-response graphs of Mens (2015) the point of no recovery implies that a return to the old situation is no longer possible as in for example the deformation of steel. First, elastic deformation occurs

from which the steel can recover when the load disappears. When the elastic threshold is exceeded plastic deformation begins and the steel can no longer return to its original state (Abspoel et al., 2013). With regard to river system this works differently. When a disturbance causes a very low discharge, aspects or business sectors that are no longer able to perform their tasks will be able to do so again when the discharge increases. Hence, this is not really a point of no recovery. When this point is reached the function is, temporarily, unable to fulfil its function. When this occurs, society will look for other ways to obtain the product or service the river system can no longer provide. For example, shipping might use different routes where possible and some cargo might be shifted to another form of transportation. This could be seen as a temporary new system indicated in the disturbance-impact graphs with the arrow that starts at the point at which the current system ceases functioning.

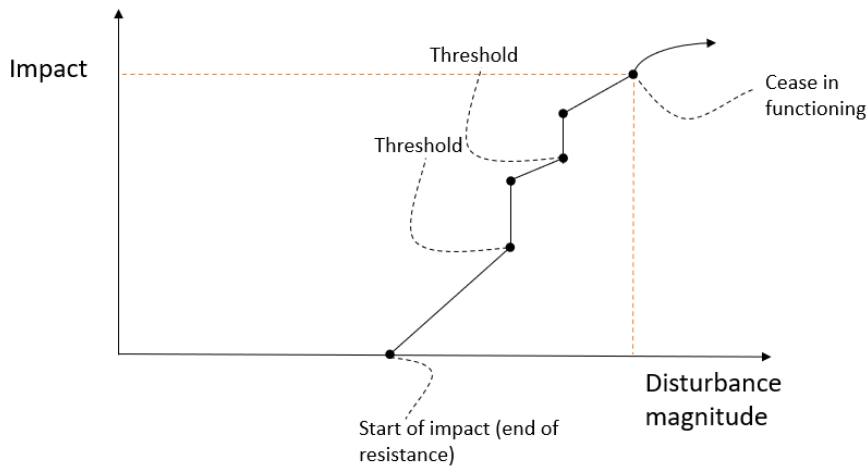


Figure 6 General format of a disturbance-impact graph

### 3.3.2. Resilience classification

#### Impact classification

As can be seen in the disturbance-impact graphs, the impact of disturbances is only felt when the first threshold has been exceeded. Beside this first threshold, the graphs contain other thresholds at which the increase in impact changes. The areas before the first threshold and between other thresholds could be seen as different phases. All these phases have their own impact magnitude and occur at a certain disturbance magnitude. Governments already use policies containing phases to indicate the magnitude of certain events and their consequences or impact. In the Netherlands the “Landelijk draaiboek watervdeling en droogte” (Ministerie van Infrastructuur en Waterstaat, 2020) is used for droughts. This script describes different phases with regard to droughts and water allocation and classifies them accordingly.

The script defines four stages or levels: level 0) business as usual, level 1) threat of water shortages, level 2) actual water shortages and level 3) (threat of) crisis water shortages. These levels are also indicated with the colours green, yellow, orange and red respectively. These levels are monitored using several indicators. When too many indicators are exceeded, the current level is increased.

Level 0 (green) represents business as usual. Enough water is available nationwide to supply the desired amount to every user. Few to no problems regarding droughts and water quality occur.

Level 1 (yellow) represents a threat of a water shortage. This happens once or twice a year and usually lasts a couple of weeks. Water quality problems are likely to occur and measures are taken to ensure all users receive the desired amount of water.

Level 2 (orange) is an actual water shortage. During a shortage not all users receive their desired amount of water and water quality problems occur. The available water is allocated according to an allocation scheme. These actual water shortages occur approximately once every five years.

Level 3 (red) is a nationwide water shortage. This occurs only once every ten to twenty years. This drought is felt across many sectors and exceptional measures need to be taken.

(Ministerie van Infrastructuur en Waterstaat, 2020)

### Resilience classification

A classification similar to the one explained before will be defined for resilience. This classification will be used to assess the resilience of river systems.

The levels and colours from the “Landelijk draaiboek waterverdeling en droogte” will also be used for the classification of resilience. However, they will be adapted to the perspective of the river system functions instead of the perspective of nationwide water availability.

Level 0 (green), business as usual from the perspective of a river system function means that the function can be fulfilled even though there might be an increasing disturbance magnitude. The disturbance has not yet exceeded the first threshold. This can be seen in Figure 7 as the green line in the graph.

Level 1 (yellow), at this level functions start to feel the impact of the disturbance and some thresholds have been exceeded. The function can still be fulfilled with a few limitations.

Level 2 (orange), at this level more thresholds will be exceeded due to an increasing disturbance magnitude. Hence the ability to provide the desired function is limited.

Level 3 (red), at this level fulfilment of the function is hardly possible. If the magnitude of the disturbance continues to increase fulfilment of the function will not be possible and a cease in functioning will occur.

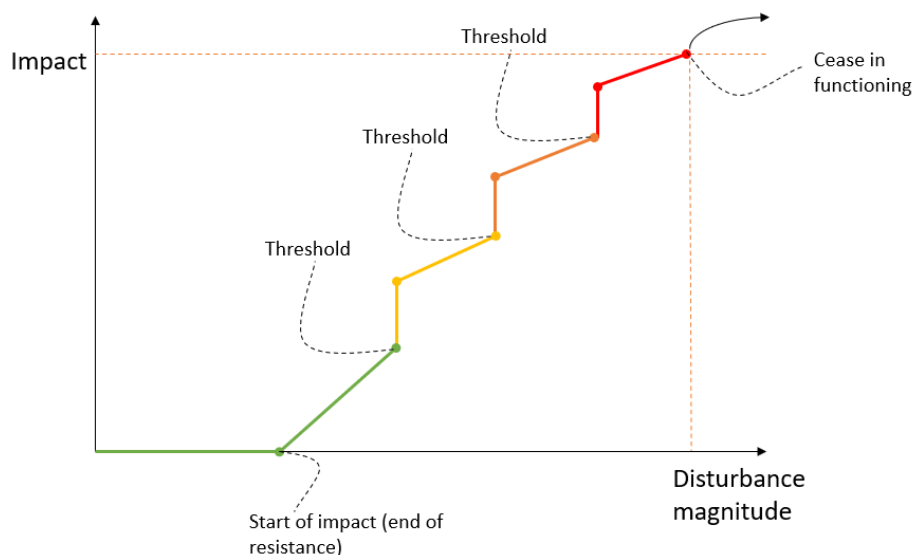


Figure 7 Resilience classification applied to disturbance-impact graph

# 4. The resilience assessment approach

This chapter contains an explanation of the method used to assess the resilience of river systems, the resilience assessment approach. First, the different steps and sub steps of the approach are explained. Then, the application to measures and future scenarios is presented. Finally, suggestions for additional stakeholder involvement and examples of disturbance-impact graphs are given.

## 4.1. The resilience assessment approach

The proposed resilience assessment approach consists of four steps. In the first step a system analysis is created. External factors that may affect the resilience of the system are identified as well as the system's characteristics, functions and their connections. The second step consists of the creation of disturbance-impact graphs for the different functions, containing disturbances caused by the external factors. The third and fourth step focus on the assessment of the resilience of the different functions and the river system. An overview of the different steps of the approach can be found in Figure 8.

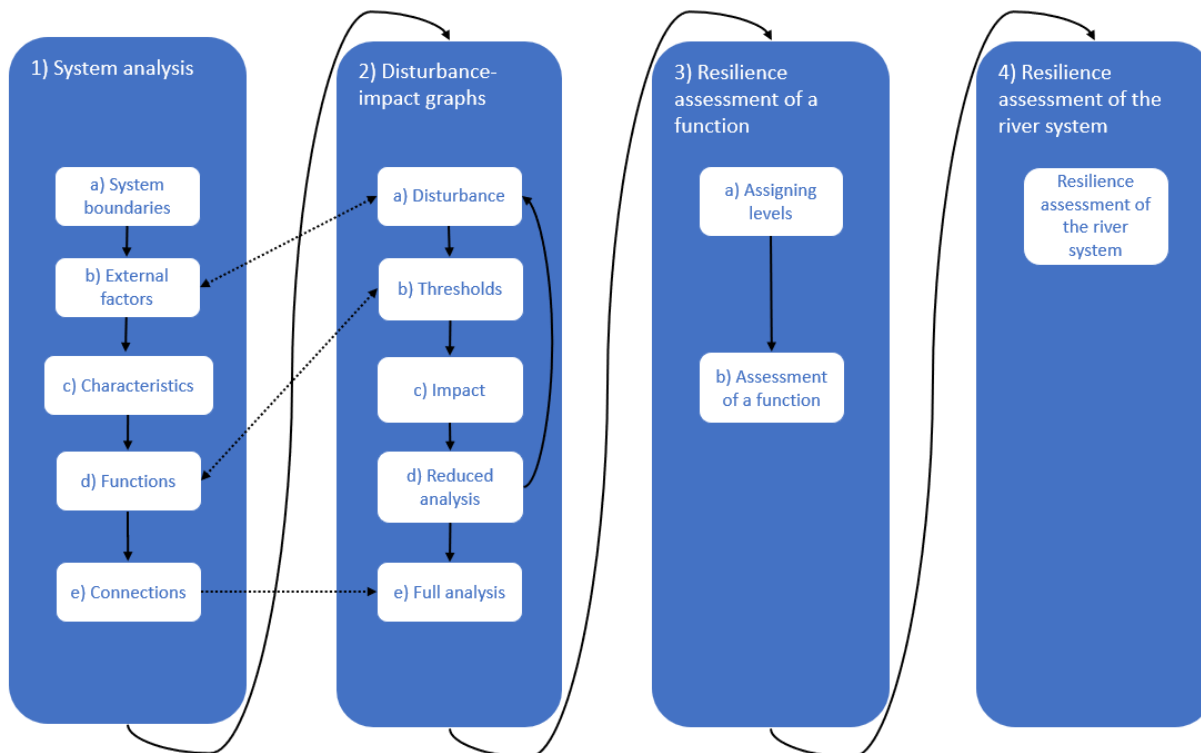


Figure 8 Flowchart of the resilience assessment approach (the dotted lines indicate a check)

This approach can be used to assess the current system operating under current conditions and show the effect of measures. It can also be used to assess how the current and possibly adapted system operates under different future conditions. The approach for the current situation will be explained first. Subsequently, the use of the approach for measures and future conditions will be explained.



### 4.1.1. Step 1: System analysis

#### A) System boundaries

First, the system boundaries need to be defined. It is important to ensure that the physical boundaries coincide with the area of interest. A regional policy only requires consideration of the river stretch within that region. However, external factors are needed to reflect the situation upstream, these will be identified in step 1b. In this step it is important to determine the topographical boundaries. However, these are not the only system boundaries. The other boundaries are defined through the definitions of the functions in step 1d. In this step it is decided which parts of a function are part of the river system.

#### B) External factors

The external factors act on the system boundaries and influence the characteristics and functions of the system. In case of a resilience analysis of a river stretch, external factors are the only way in which upstream occurrences can be incorporated in the system. The selection of external factors depends on the purpose of the analysis. For example, when focussing on flooding an important external factor is high discharges.

#### C) Characteristics

Characteristics are system attributes, such as water quality and vegetation and fauna. The characteristics of the river system are influenced by the external factors and have an influence on the functions.

#### D) Functions

The functions as defined for this approach are directly linked to demands from society. A function is the part of a system that pertains to the river. For instance, the function of electricity is that part of electricity production that pertains to the river i.e., cooling water. An overview of these function definitions should be made, since it is needed in step 2.

#### E) Connections

In the final part of the first step the connections between all the different external factors, characteristics and functions need to be identified and visualised. This is done by focussing on one external factor, characteristic or function and determining which others it is connected to. Finally, all the connection overviews are combined in one system overview. An example of such a system overview can be found in Figure 9.



Figure 9 Example of a simple system overview

### 4.1.2. Step 2: Disturbance-impact graphs

Disturbance-impact graphs are used to visualise the different phases a function experiences before it ceases to function due to a disturbance. These graphs contain a point at which the impact of the disturbance starts to be felt (the end of the resistance), several thresholds and a point at which a cease in functioning occurs. When a threshold is exceeded a function cannot continue to operate in its current manner. The change in operations required to continue functioning will cause a jump in impact. A general example of such a graph can be found in Figure 10.

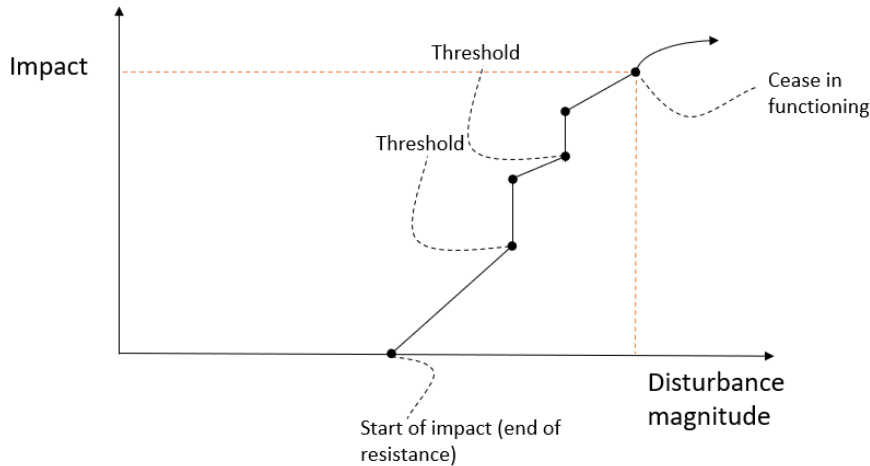


Figure 10 General example of a disturbance-impact graph

The disturbance-impact graphs are determined per function. Hence, this step will need to be performed multiple times. Examples of disturbance-impact graphs can be found in Section 4.4.

#### A) Disturbance

A disturbance occurs in one of the external factors or possibly in one of the characteristics caused by a disturbance in an external factor. A function can experience many disturbances. However, a disturbance-impact graph contains only one disturbance. Hence, a disturbance has to be selected. This can be done by estimating which disturbance is likely to have the largest impact. This decision can be based on expert opinion, or by choosing the one that corresponds to the overall disturbance or theme chosen for the analysis. For example, choosing to focus on low discharges since the overall focus is on droughts. Alternatively, one might realise early on that more than one disturbance is important. In this case separate disturbance-impact graphs need to be created for all disturbances. The units of the x-axis of the graph depend on the disturbance chosen. Discharge will have units of  $\text{m}^3/\text{s}$  or a similar unit, while water depth will have m.

*Only when redirected from step 2d:*

If step 2d showed that the selected disturbance has little to no impact on the function, a new disturbance needs to be selected. It should be possible to link this new disturbance to the external factors. If this is not possible either the wrong or too few external factors have been chosen in step 1a. In this case step 1 should be repeated.

#### B) Thresholds

Next, the thresholds for this disturbance need to be identified. These thresholds are based on technical information. They represent a (sudden) change in functioning, and thus a change in impact. When a threshold is exceeded, continuing to function or operate as before is impossible. For example, when the threshold for locking operation without actively reducing water losses is exceeded, pumping is needed to reduce water losses. The use of these pumps causes an increase in impact.

These thresholds are expressed in the unit of the disturbance under consideration. Thus, the threshold for pumping, which is expressed in  $\text{m}^3/\text{s}$ , is a threshold for the disturbance-impact graph considering a disturbance in discharge. A threshold with regard to the required draught for shipping, expressed in m, is a threshold for the disturbance-impact graph considering a disturbance in water depth.

It is important to realise that not all the function thresholds use the physical river stretch. As stated in Section 3.2 only these are considered to be part of the river system. However, in order to decide which thresholds pertain to the river system it might help to identify and visualise all function thresholds (see Figure 11, green system and associated thresholds). The next step is to determine which threshold(s) are part of the river system (Figure 11, blue area). Only these are important for the resilience of the river system (Figure 11, orange system).

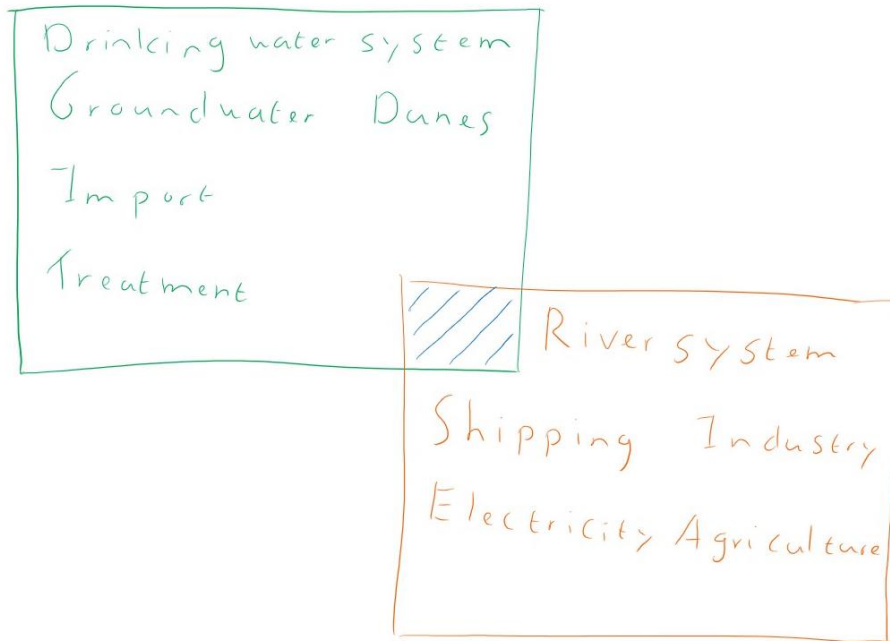


Figure 11 Overview systems and overlap

The thresholds that are considered to be part of the river system provide a check for the definition of the function as drawn up in step 1d. If the definition does not cover all these thresholds it is too narrow. If the definition included thresholds that are not a part of the river system it is too broad. In either case, the definition of 1d should be amended.

### C) Impact

A change in functioning causes a change in impact. This impact is measured using a proxy. An often-desired unit for this proxy is the local currency. For some functions it might be possible to express the impact in monetary value, while for other functions it is not yet known how to calculate this. In the latter case, another unit can be chosen, for example the loss in production.

The chosen proxy can be either quantitative or qualitative. However, a disturbance-impact graph should have either a quantitative or qualitative proxy. The impact should have a single unit per disturbance-impact graph, which is shown on the y-axis.

### D) Reduced analysis

Once the disturbance-impact graph is finished, a short analysis is done to check whether the right disturbance has been chosen and to evaluate the thresholds. This can be done with a simple historical analysis. One way to perform this analysis is by inquiring whether the identified thresholds have been exceeded in, for example, the past 10 years. The relevant timescale for this analysis depends on the function. If this information is unavailable, it is also possible to perform a short analysis based on historical data. For example, the discharge at which locking operations require pumping has been identified in the disturbance-impact graph. Discharge data, near the lock, of the last 10 years can quickly reveal whether this threshold has been exceeded. If the thresholds have not been exceeded or only a limited number of times, the disturbance currently under consideration might not be relevant. In this case, a new disturbance will have to be selected. This requires a return to step 2a.

Inquiries into past disturbances may reveal that a certain threshold had not yet been identified. In this case this new threshold needs to be added to graph and its associated impact has to be identified. Inquiries might also reveal that another disturbance is important as well. In this case, steps 2b and 2c need to be repeated for this new disturbance.

When many disturbances have been tested for a single function and a relevant disturbance has not been found it could be that the function is simply very resilient. In this case no return to step 2a is needed nor is the performance of step 2e. However, this should only be concluded when several disturbances have been tested and the reduced analysis does not suggest any other disturbances which might be relevant. While this shows the function is very resilient, other functions still have to be considered before an assessment of the resilience of the river system can be made.

Even when the reduced analysis shows no thresholds have been exceeded the disturbance-impact graphs for this function are still needed for the assessment of the system. This assessment, as explained in step 3, is then based on the analysis of step 2d not on that of step 2e for this particular function.

#### E) Full analysis

When the reduced analysis shows that the current disturbance is relevant, a full analysis needs to be done. This full analysis consists of an extended historical analysis. This analysis covers a large time period, for example 50 or 100 years, though this depends on the function, and aims to establish the number of times each threshold was exceeded. This analysis needs to consider the interconnectedness of the system. For example, many functions require extraction of river water. If little water is available most countries of regions have regulations for the allocation of this water. These regulations need to be taken into account. This means that according to the data the required water might be available, but that a threshold is still exceeded since regulations state that extraction of that water is not allowed for that function. This possible scenario needs to be included in the analysis to see how the system truly functions under the current situation.

#### 4.1.3. Step 3: Resilience assessment of a function

The assessment of the resilience of a function is based on a classification with associated scoring system. This resilience classification consists of four levels, level zero through level three, in which level zero represents business as usual and level three represents a situation in which continuing to function is hardly possible. A logarithmic scoring scale has been assigned to these levels, hence, level zero has zero points, level one has ten, level two has one hundred and level three one thousand points. These scores are used to assess the resilience of the function. This scoring system depends on a change in impact. Since the scoring system is logarithmic the change in impact between the levels should be (roughly) exponential. Since this is done per disturbance-impact graph this step will have to be repeated.

#### A) Assigning levels

First, the different levels of the classification need to be assigned to the different phases of the disturbance-impact graphs. The assignment should be based on the consequences of the exceedance of the thresholds rather than the number of times a threshold has been exceeded. The assignment should therefore be related to the impact of the disturbance. This requires experience with previous disturbances and detailed knowledge of the function. Therefore, experts will need to be consulted. Attention should be paid to how and why these experts are selected and to how the process of assignment is structured. Furthermore, it is important that the process is properly logged so that the process can be repeated in an identical manner.

The experts involved in the process should have a direct connection to the function. This means they should either be directly involved in the system of the function or should directly experience the impact of a disturbance in this function. For example, in the case of shipping locks a representative of the lock operators and lock policy makers is required as well as a representative of the skippers using the lock. Both are dependent on the functioning of the lock while a shipper can also use other means of transportation.

First, the disturbance-impact graphs should be explained. Most importantly it should be made clear that the thresholds in the graph are based on technical information and not on how the situation may be experienced. Then, the impact experienced when a threshold is exceeded needs to be determined. It is important to do this as accurately and objectively as possible. For example, when pumping is required to

reduce water losses during locking operations, the locking operations will require more electricity resulting in an increase in costs. The skippers on the other hand will likely not experience an impact since pumping does not increase waiting times. An overview of the consequences per threshold needs to be made. Once this has been done for all thresholds the different levels can be assigned.

The overview should form the basis for a discussion between the experts and analysts, resulting in the assignment of the different levels. First level zero, business as usual, needs to be assigned. The opinions of the different experts may vary somewhat and a compromise will need to be made. Once level zero has been assigned, the same needs to be done for levels one through three. All considerations and deliberations made during this process need to be logged.

During this process it is important to keep in mind that the changes in impact between the levels should be (roughly) exponential, due to the logarithmic scale of the scoring system. Consequently, two thresholds might belong to the same level when the change in impact between them is small. Furthermore, a disturbance-impact graph might not contain enough thresholds in order to assign all three levels of the resilience classification. A disturbance-impact graph containing only two thresholds will not have three levels, and a graph containing more thresholds could have levels containing several thresholds resulting in the assignment of only one or two levels.

### B) Assessment of a function

Once the levels of the classification have been assigned the score for the function can be calculated. This is done using the analysis of step 2e. All thresholds are now located in one of the four levels. A scoring system is used to assess the resilience based on these levels.

This scoring system is assigned to the resilience classification in order to assess resilience. The different levels are each given their own score. The higher levels have a higher score hence the higher the resilience score, the less resilient the function is.

A scoring system where a higher score indicates a worse performance might appear to be counterintuitive but if a high score is assigned to the levels where little to no problems occur while a low score is assigned to levels where problems do occur these problems would barely be visible when looking at the total score of a function or system.

A logarithmic scale has been chosen since the return periods as given in the “Landelijk draaiboek waterverdeling en droogte” for the different levels are roughly logarithmic. Furthermore, the change in impact when a function moves from level 0 to level 1 is much smaller than when it moves from level 2 to 3. The scoring system can be found in Table 4.

Table 4 Scoring system

Level	Score
Level 0	0
Level 1	10
Level 2	100
Level 3	1000

Based on the analysis of step 2e the number of times each level was reached has to be determined. This number should then be multiplied by the score of that level. The final scores of the four separate levels must then be added up leading to a total score of the graph. In the situation in which there is one disturbance this result constitutes the final score of the function. In the case of two or more disturbances the final scores of the graphs should be added to obtain the total score of the function. It is inevitable that a function which is vulnerable to more disturbances will have a higher total score. This higher total score is an accurate reflection of the reduced resilience.

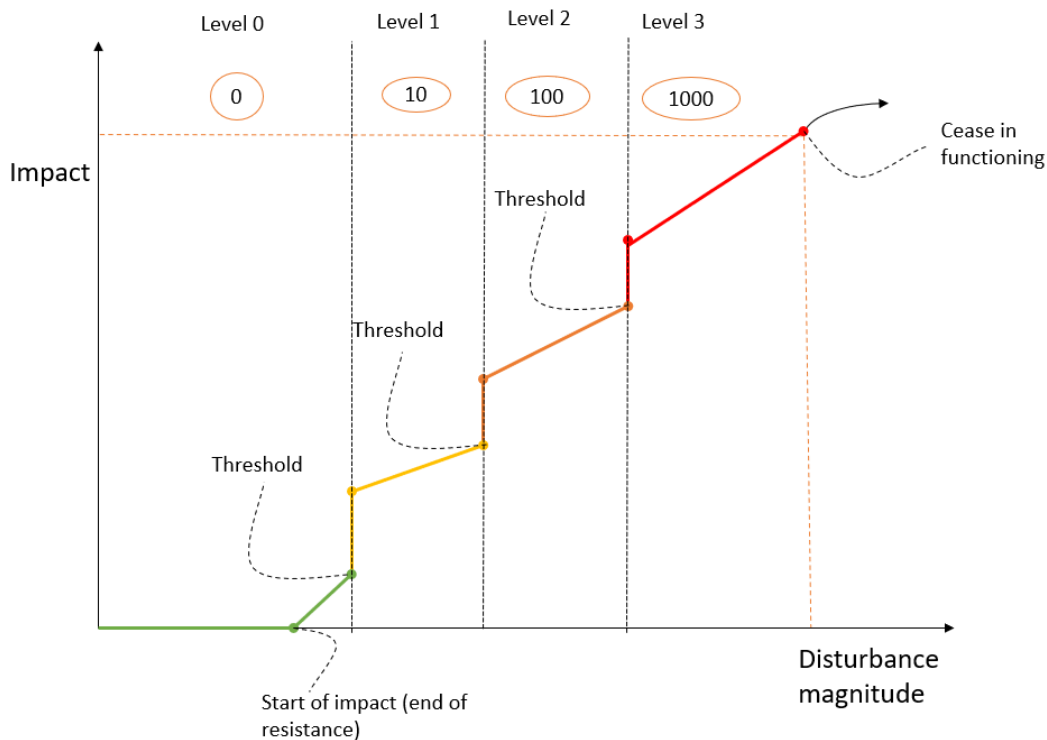


Figure 12 Example of a disturbance-impact graph with assigned levels

#### 4.1.4. Step 4: Resilience assessment of the river system

In the final step of the approach the resilience score of the river system is calculated. This is done by adding the scores of all the different functions. It is important to always consider both the score of the river system and the score of the individual functions. The latter contains information on the composition of the total score. It is therefore essential to present an overview of all scores as well as the total score.

### 4.2. Using the approach for measures and future scenarios

#### 4.2.1. Measures

In order to use the approach to investigate the effect of a prospective measure several steps of the approach need to be repeated: most of step 2 as well as step 3 and a part of step 4. When the measure is aimed at decreasing the impact of a specific disturbance on a function, step 2a (selecting a disturbance) should not be repeated. Step 2b will have to be repeated to determine the new thresholds. These can simply be the old thresholds which now occur for a different disturbance magnitude or entirely new thresholds. Depending on the outcome of step 2b, step 2c might need to be repeated. If only the disturbance magnitude of the thresholds has changed the impact will remain the same. However, if new thresholds have been identified, their impact needs to be determined as well. Since it has already been determined that the disturbance is important step 2d can be omitted. Step 2e will need to be repeated in order to determine how often these new thresholds are exceeded.

Step 3 will have to be repeated in its entirety. This also shows why it is important to properly log the discussion in which the levels of the resilience classification are assigned to the disturbance-impact graph. In order to be able to compare the scores of the old and the new situation, the levels have to be assigned in the same manner. The same considerations and deliberations will need to be made. It is possible that the occurrence of a new thresholds will lead to additional considerations and deliberations. Once this is done and step 3a has been completed the new score for the function can be calculated according step 3b.

Step 4 need only be altered to include any new scores. Since a measure might influence more than one function, it is important to check whether nothing changes in the disturbance-impact graphs of other functions as a consequence of the new measure. The connection overview created in step 1 might be helpful in determining which other functions might be affected.



It is important to realise that sometimes new policies are introduced. Such a new policy has to be used in the analysis of step 2e. If this new policy is the only change that is being introduced only steps 2e, 3b and 4 need to be repeated. If a new policy as well as a measure are introduced the entire procedure for a measure should followed complemented by the new policy in step 2e.

#### 4.2.2. Future scenarios

When future scenarios are considered, only two sub steps have to be repeated. Step 2e now consists of a historical analysis to determine how often thresholds have been exceeded. If, instead of historic data, a dataset representing the future is used, this step can be used to determine how often these thresholds are likely to be exceeded in the future. Step 3b will need to be repeated to calculate the new score corresponding to the new analysis of step 2e. This way one can see how the current system functions under future conditions.

One thing to consider is the effect of future conditions on the sensitivity to disturbance of different functions. A disturbance that was irrelevant before, as determined in step 2d, might become relevant under future conditions. Hence, it is advisable to check more disturbances than the ones deemed relevant for the current conditions.

A combination of measures and future conditions is also possible, then steps 2b, 2c, 2e, 3 and 4 need to be repeated with 2e consisting of analysis using a dataset representing the future.

#### 4.3. Additional stakeholder involvement

So far, only the essential stakeholder and expert involvement has been indicated in the different steps of the approach. Other steps of the approach allow for optional stakeholder involvement, though care should be taken that steps which should contain solely technical information are not influenced by stakeholder involvement. An example of this is step 2b in which the thresholds are identified. Stakeholders or experts can help identify these thresholds but the disturbance magnitude for which they occur should be based on solely technical information. Another example of optional stakeholder involvement is the end of step 1e. Once the system overview has been created it can be discussed with stakeholders and experts to help check whether no connection have been missed or made incorrectly.

#### 4.4. Examples of disturbance-impact graphs

Below, examples of general disturbance-impact graphs can be found. These graphs focus on a decreasing discharge. The detailed information given pertains to the case of the Meuse river system which will thoroughly introduced in Chapter 5. These graphs are meant as example to show what a disturbance-impact might look like and what possible thresholds can be.

##### Shipping

A disturbance-impact graph for shipping can be found in Figure 13. At certain discharges locking operations will be altered to save water. At first this is done using pumps but if discharges are low enough this is no longer sufficient and locks are operated less often. Instead of locking whenever a ship arrives the chamber will be filled up as much as possible with a maximum waiting time of 2 hours for the river Meuse (Rijkswaterstaat, 2017). This delay causes an increase in impact. This is not a gradual increase since the delay does not increase gradually but occurs as soon as locking operations are limited. If the discharge decreases even further locking operations will become even more limited until eventually locking is no longer possible. When locking is no longer possible shipping is no longer possible and a cease in functioning occurs.



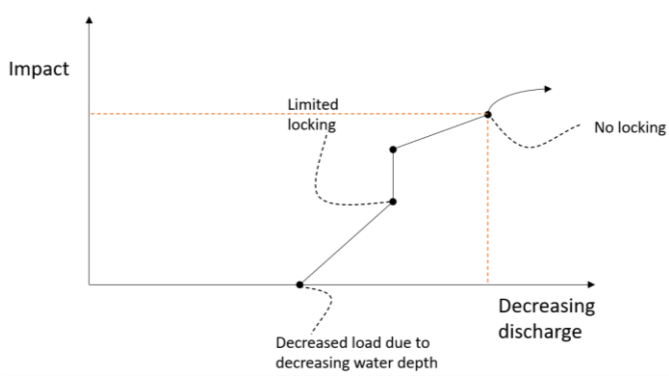


Figure 13 Disturbance-impact graph for shipping

### Drinking water production

Drinking water production depends on water quantity and is therefore influenced by a decreasing discharge. The disturbance-impact graph can be found in Figure 14. Drinking water plants depend on the intake of water to produce drinking water. When the discharge decreases the availability of water for intake decreases. At first there will be no consequence of the decreasing discharge but when a certain threshold is exceeded the drinking water plants will not be able or allowed to extract all the water require. The more the discharge decreases the more this effect increases until no extraction from the river is allowed or possible. At this point drinking water plant can still use their buffers to produce drinking water (Sjerps & Huiting, 2017). Once these buffers have been depleted production is no longer possible and a cease in functioning occurs.

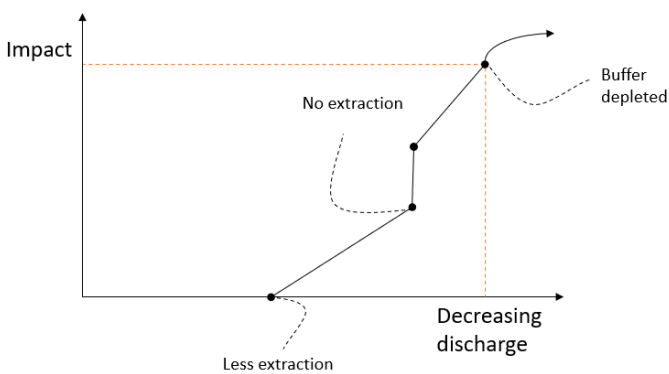


Figure 14 Disturbance-impact graph for drinking water production

### Industry

Industry extracts water from the river. This intake is mainly influenced by the discharge. The disturbance-impact graph can be found in Figure 15. When the discharge decreases the availability of water for intake decreases. At first this does not have an impact but when the discharge drops below a certain threshold the industry will not be able to extract all the water it would like to extract. The further this discharge decreases the less extraction is possible until no extraction is possible or allowed. At this point most industries will have their own buffers of water which they can use. When these buffers are depleted production will stop and a cease in functioning will occur.

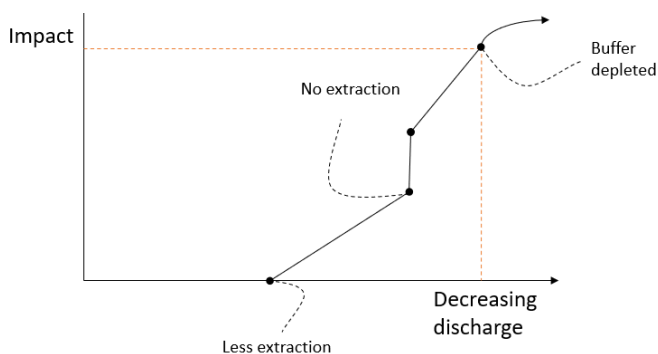


Figure 15 Disturbance-impact graph for industry

## Agriculture

Agriculture uses water for irrigation of crops. The disturbance-impact graph for agriculture can be found in Figure 16. When the discharge decreases it might eventually reach levels at which the agricultural sector is no longer able or allowed to extract the desired amount of water. If this continues eventually no extraction of water will be possible. At this point some agricultural companies might still have buffers which they can use for irrigation. When these buffers are depleted crops will no longer receive water (beside rain). For a short period of time this might not be too problematic but if crops do not receive water for too long, they will die. This loss of crops is the point at which the agricultural sector ceases functioning since it can no longer provide crops to society.

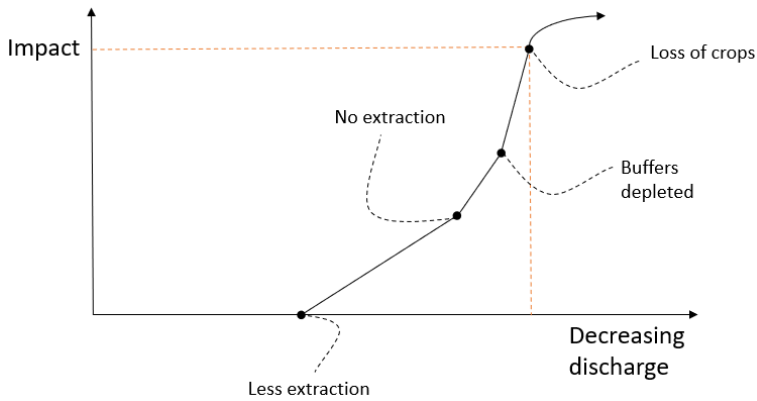


Figure 16 Disturbance-impact graph for agriculture

## Recreations

Recreation is influenced by low discharges. Depending on the type and location of recreation the requirements and thus the thresholds with regard to disturbances differ. In Figure 17 an example for recreational boating is given. Recreational boats have to give way to commercial shipping (Rijkswaterstaat, 2016). If the discharge decreases the water depth will decrease as well. This means that recreational boats will need to sail closer to the deeper parts of the river normally used by commercial shipping in order to have sufficient draught. Since they are closer to the commercial ships, they will need to give way more often. When the discharge decreases further locking operations will be limited. In these limited operation conditions recreational boats will no longer be allowed to use the locks (NH Nieuws, 2018).

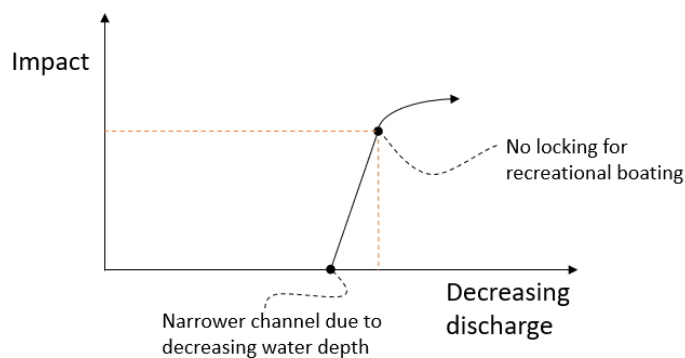


Figure 17 Disturbance-impact graph for recreation

## 5. River system analysis

*This chapter contains the application of the first step of the resilience assessment approach to the case study of the Meuse river system.*

### 5.1. System boundaries (step 1a)

The Meuse river system, as considered for the case study of this research, consists of the river stretch within the Netherlands. Hence, the physical boundaries of this river system are the upper and the lower boundaries of the river stretch: the upper boundary is located just below Eijsden and the lower boundary is located where the Meuse river enters the North Sea.

### 5.2. External factors (step 1b)

Since the focus of this research is on low discharges due to droughts the external factor of this analysis is discharge. In order to clearly see the effect of changes in this discharge it will be split into high and low discharge throughout the analysis.

### 5.3. Characteristics (step 1c)

The considered characteristics of the river system are: vegetation and fauna, water quality, water quantity and sediment.

Vegetation and fauna focusses on the different species that live in the river system as well as the number and age of specimen of those species. The species that live in a system or species that are missing have an influence on the other characteristics of the system and on the river functions.

Water quality is defined by the different aspects that influence it. Aspects such as temperature, oxygen content and nutrient concentration all have an influence on the water quality. Furthermore, rivers can be contaminated with toxic chemicals such as heavy metals and pesticides. The different aspects of water quality all influence one or more river functions since all river functions have specific demands for water quality (Ouyang, 2005).

Water quantity is used to determine whether sufficient water is available for the different river system functions. It is defined as the amount of water currently stored in the river system. However, this amount changes constantly since a discharge enters the system at one boundary and another discharge leaves the system at the opposite boundary. Furthermore, water is extracted from the river within the system.

Sediment is considered in both quantity and quality. Since both the amount of incoming and outgoing sediment has an influence on the system as well as the quality of said sediment. An excess in incoming or outgoing sediment would cause sedimentation and erosion respectively, influencing the water depth of the river. If the sediment entering the river system is contaminated, for example with heavy metals, it can have an influence on the water quality and vegetation and fauna (Duodo et al., 2016).

### 5.4. Functions (step 1d)

The functions that will be considered are: shipping, drinking water production, industry, electricity, agriculture, recreation and flood protection. The definitions of these functions, given below, determine the remaining system boundaries.

Shipping as an industry is influenced by supply and demand as well as the capacity of the waterways. Here shipping will be considered as solely the capacity of the river system. This capacity is influenced by locking operations and water levels. This has been chosen in order to see the effects of the characteristics and external factors on the shipping capacity of the river (Ligteringen, 2017; Verheij et. al, 2008).

Drinking water production depends on the intake of different sources of water: groundwater, surface water from rivers and lakes as well as surface water through soil aquifer recharge. Here only the intake of river water will be considered. This intake demands a certain water quality and a certain water quantity. Both

demands have to be met in order to provide sufficient intake for drinking water production. It will be determined whether the river system is able to meet this intake demand.

Industries take water from and return water to the river. Intake and return can be considered separately due to the possibly different water quality as well as the possible quantitative difference between the two. Regulations for the quantity and quality of the return of industry water to river systems can differ per country and area (De Nederlandse Overheid, 2020). It will be determined whether industries are allowed to discharge water to the river in the desired quantities. The intake can have a demand in both water quality and water quantity. It will be determined whether these can be met. Any other aspects of industries will not be considered, though any transport by water will be included in shipping.

Electricity is generated in power plants which need water for cooling. This cooling water is taken from the river and returned after use. The returned water will have a higher temperature often referred to in terms of energy. The amount of energy that can be discharged to rivers, through cooling water, is regulated (De Nederlandse Overheid, 2019). It will be determined whether power plants are able to discharge the desired quantity of cooling water.

Agriculture can require irrigation. While other sources of water for irrigation are available it is assumed that the required water is extracted from the river. Any water making its way to river from the agricultural areas might contain higher concentrations of nutrients (due to fertilisation) and pesticides which influence the characteristics of the river system. It will be determined whether the desired amount of water can be extracted from the river and what the influence of run-off from agricultural areas is on the water quality.

Recreation in and around rivers has many forms. River systems are used for recreational boating and sometimes they contain small beach like areas for recreational purposes. These have an influence on the characteristics of the river system and require certain characteristics. The possibilities and opportunities for recreation can either increase or decrease which will be determined.

Flood protection protects the surrounding areas from high water levels and high discharges. The extent of flood protection differs throughout the river system. It depends on the number of people and the amount of high value infrastructure in the surrounding area.

Society, which is not a river system function itself, is used to represent the people who use the functions the river system provides. Society is therefore influenced by the functions and the external factors and the characteristics that influence these functions. Internal dynamics can result in an increase or decrease in demand for a certain function. Through this society has an influence of the river system functions. The degree to which these demands can be met is how the river system functions have an influence on society.

## 5.5. Connections (step 1e)

All the external factors, characteristics and functions mentioned before are connected to one another. Hence, they are dependent on one of the external factors or characteristics or have an influence on one of the characteristics or functions. These connections are visualised in Figure 18 through Figure 31. The colours and patterns of the connections correspond to those in the system overview in Figure 32. Each external factor, characteristic or function has its own colour and pattern. For example, shipping has a continuous red arrow hence all the characteristics and external factors that influence shipping are connected to shipping using this continuous red arrow. In Figure 18 through Figure 31 one external factor, characteristic or function is moved to the left in order to show the connections to the other external factors, characteristics and functions.

### High discharges

High discharges increase the water quantity of the system. Furthermore, high discharges result in higher flow velocities. These higher flow velocities can cause problems for shipping since the velocity of the return flow around the ship will also increase.

When the increased discharge cannot be contained within the riverbanks and dikes it will cause flooding in the surrounding areas. The size of the area that will experience flooding depends on how large the discharge is.

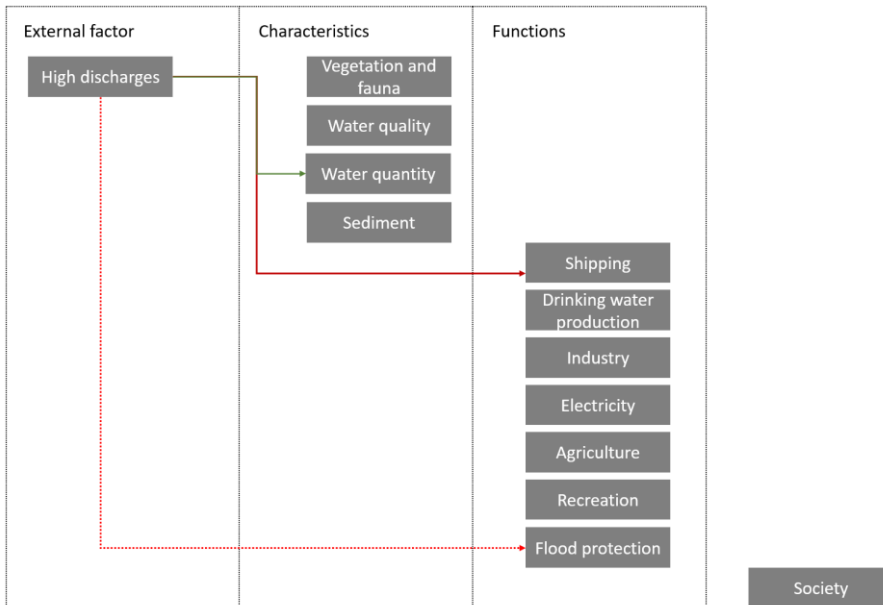


Figure 18 Connections high discharges

### Low discharges

Low discharges can cause problems for shipping since low discharges increase waiting times at shipping locks since they operate less frequently to decrease water losses during locking operations (Rijkswaterstaat, 2019).

Lower discharges can cause the water to heat up more quickly. Warmer water has a lower dissolved oxygen content. Furthermore, chemicals entering the river from industrial discharge and other pollutants will be less diluted. Hence, low discharges can be detrimental for the water quality.

Low discharges also have an influence on the water quantity. Since less water enters the system the water quantity in the system will decrease assuming all functions extract the usual amount of water.

Furthermore, low discharges can impede recreation since it could result in boats no longer being allowed to use the locks due to restrictions aimed to decrease water losses during the locking procedure.

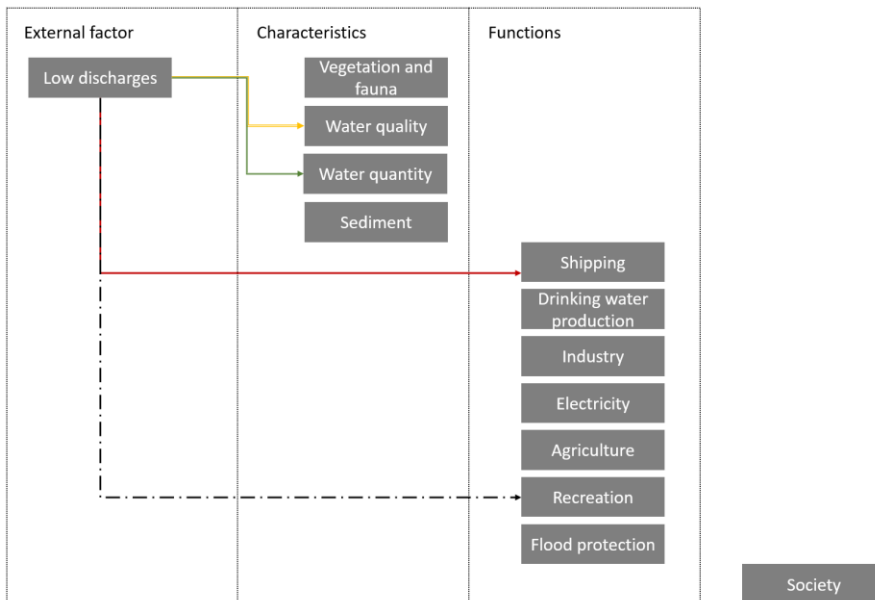


Figure 19 Connections low discharges

### Vegetation and fauna

Vegetation and fauna are influenced by water quantity since some species require a certain water depth or amount of light, which decreases with the water depth. Furthermore, they are influenced by the water quality. If the water quality deviates far enough from the normal values, of for example temperature or dissolved oxygen content, certain species will find it difficult to live in the river since current circumstances are outside their liveability range. If the deviation is temporary some losses might occur but they are unlikely to be significant. However, if these deviations persist for long periods of time some species might suffer heavy losses.

Some species (and therefore the vegetation and fauna) also have an influence on the water quality since they are able to convert substances. A river bed with a large number of plants can produce oxygen through photosynthesis and might decrease the negative effects of incoming water with low dissolved oxygen contents.

Since some species live in the river bed, sediment also has an influence on vegetation and fauna. A lack of sediment will decrease the living area of these species and over longer periods of time their numbers. Furthermore, if the incoming sediment is contaminated the living area of these species might become toxic.

Shipping influences the vegetation and fauna through human intervention. In order to increase the shipping capacity of river systems locks, weirs and other structures are built which disturbs the natural state of the river and the vegetation and fauna.

Vegetation and fauna influences recreation since it provides areas used for recreation and it has intrinsic value to people. However, recreation also influences vegetation and fauna since the natural state of the river can be altered in order to provide different or more opportunities for recreation.

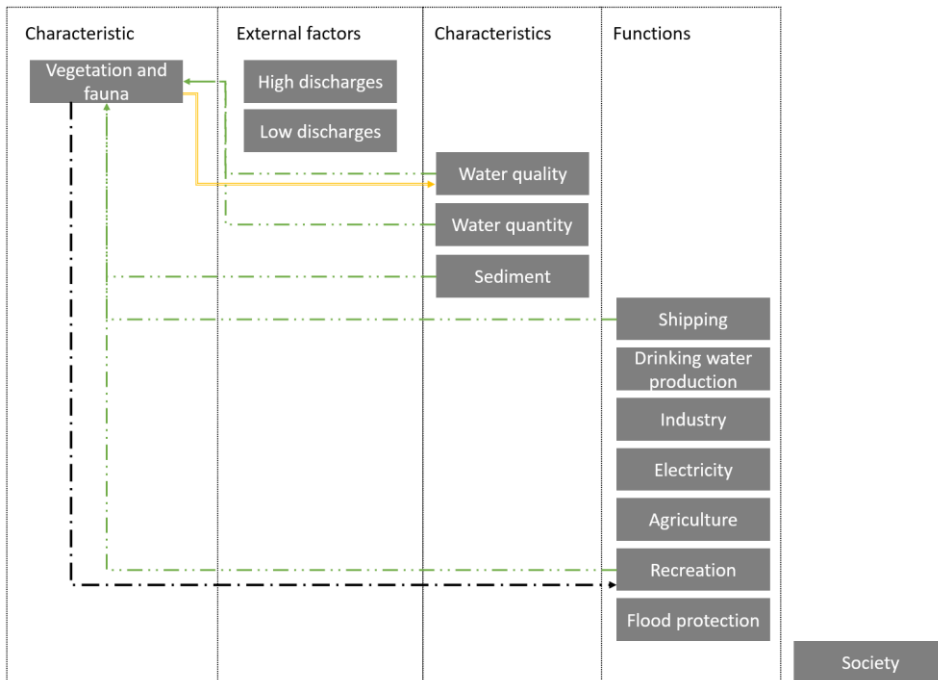


Figure 20 Connections vegetation and fauna

### Water quality

The water quality is influenced by the water quantity and low discharges. The smaller the water quantity the more easily the water temperature increases. An increased water temperature results in a lower dissolved oxygen content. Furthermore, potential pollution will be less diluted. Pollution can be flushed out of the system, however, when discharges are small this will take longer.

Vegetation and fauna are influenced by the water quality and have an influence on the water quality as well, as explained before. Sediment also has an influence on the water quality. If much sediment or particularly fine sediment enters the system the water can become turbid. Furthermore, if the incoming sediment is contaminated this contaminating compound can dissolve into the water decreasing the water quality.

The water quality determines if the water can be used for the production of drinking water. If the water is very polluted additional treatment steps might be needed and if these are not in place the river water can (temporarily) not be used.

Shipping can have a detrimental effect on the water quality since some oil or other fluids could leak from ships. Especially when there has been a collision (with another ship or with a structure) this risk is rather large.

The industry influences the water quality mainly through release of chemical substances. The water entering the river from industrial sites can have higher temperature as well. The cooling water returned from electricity plants (and some industrial plants) has a higher temperature than the river and thus causes an increase in water temperature.

Water from the river is used for irrigation in agriculture. If the water quality is too poor it cannot be used since it would have a detrimental effect on the crops. Run-off from the agricultural area can end up in the river. This run-off is likely to contain nutrients and possibly pesticides which influence the water quality. Too many nutrients entering the river can cause eutrophication.

If the water quality is too poor some of the recreational functions of the river system can no longer be fulfilled.



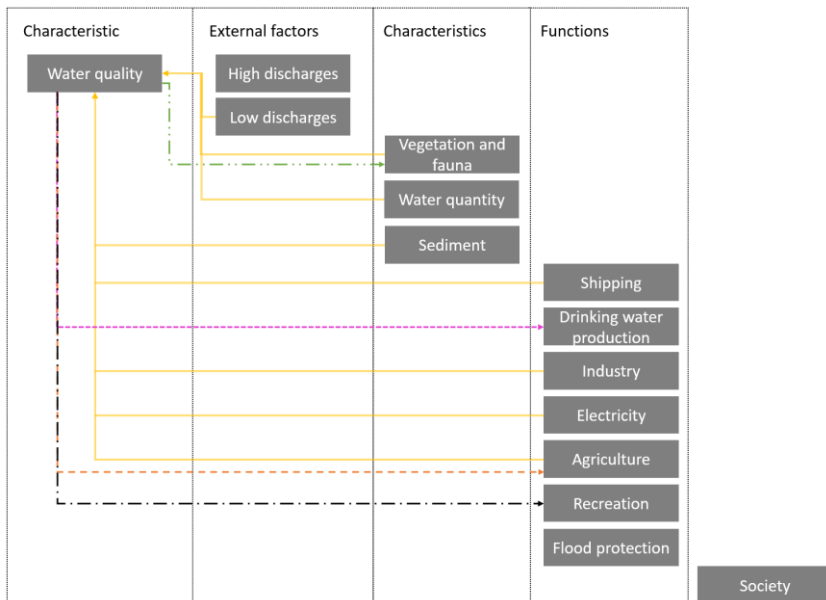


Figure 21 Connections water quality

### Water quantity

The water quantity is influenced by both high and low discharges and has influence on vegetation and fauna and the water quality. Furthermore, it has an influence on the drinking water production, industry, agriculture and flood protection. The first three extract water from the river system and the water quantity determines whether they are able to extract the desired amount. The larger the water quantity the more flood protection is needed to adequately protect the surrounding area.

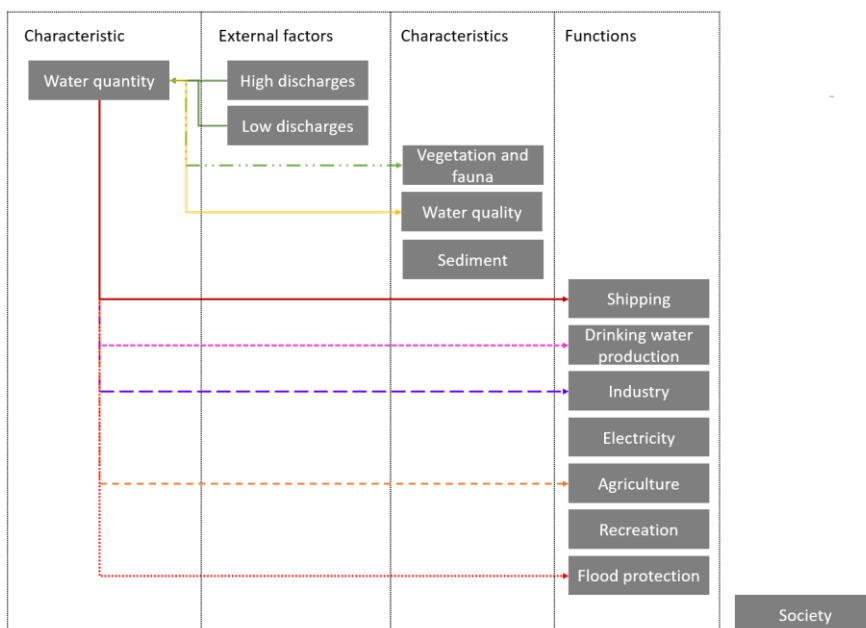


Figure 22 Connections water quantity

### Sediment

Sediment has an influence on both vegetation and fauna and the water quality. It also has an influence on shipping since ships require a certain draught. If too much sediment enters the river system sedimentation will occur. If too much sedimentation occurs this draught is no longer available impeding shipping operations.

Recreation is also influenced by sediment. If little sediment enters the system erosion occurs and certain recreational areas as for example small beach like areas will shrink. Furthermore, if the sediment that enters the river is contaminated recreational areas could be temporarily closed due to safety concerns.

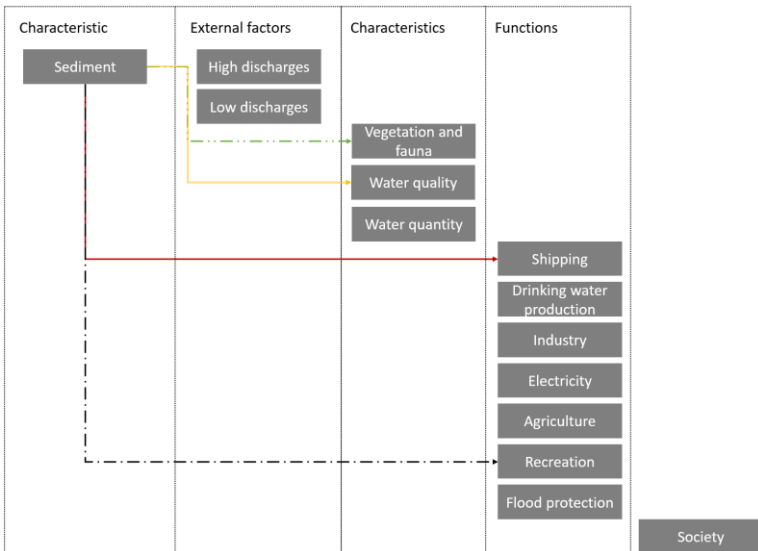


Figure 23 Connections sediment

### Shipping

The connections between shipping, high and low discharges, vegetation and fauna, water quality and sediment have already been mentioned. Shipping is also influenced by the water quantity. The smaller the water quantity the smaller the water depth will be. When the water depth no longer allows for sufficient draught shipping will be impeded.

Furthermore, shipping is influenced by society. Society demands a certain amount of goods to be shipped which can change overtime. This demand has to be met by the river system's shipping capacity. If this demand cannot be met shipping will influence society since shipping will be more costly and goods might arrive late.

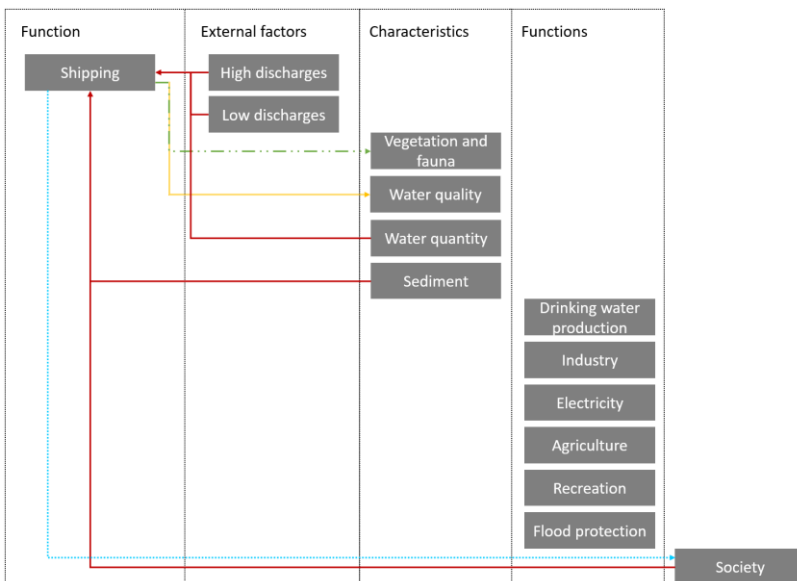


Figure 24 Connections shipping

## Drinking water production

Drinking water production is influenced by the water quantity and the water quality. If the drinking water production cannot meet the demands of society it will have an influence on society, since society will need to change the way it uses drinking water to accommodate the (temporarily) smaller production.

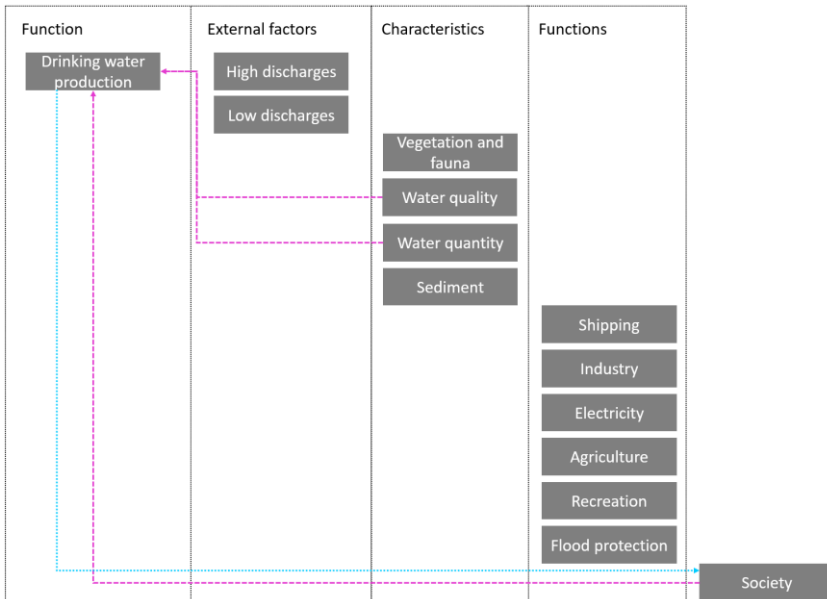


Figure 25 Connections drinking water production

## Industry

Industry is influenced by water quantity and has an influence on the water quality. Society has an influence on industry since it demands certain number of products to be produced, which in turn dictates how much water the industry will need. Industry influences society through output. If fewer goods are produced than demanded society will have to adapt to handle this deficit. This usually means an increase in price.

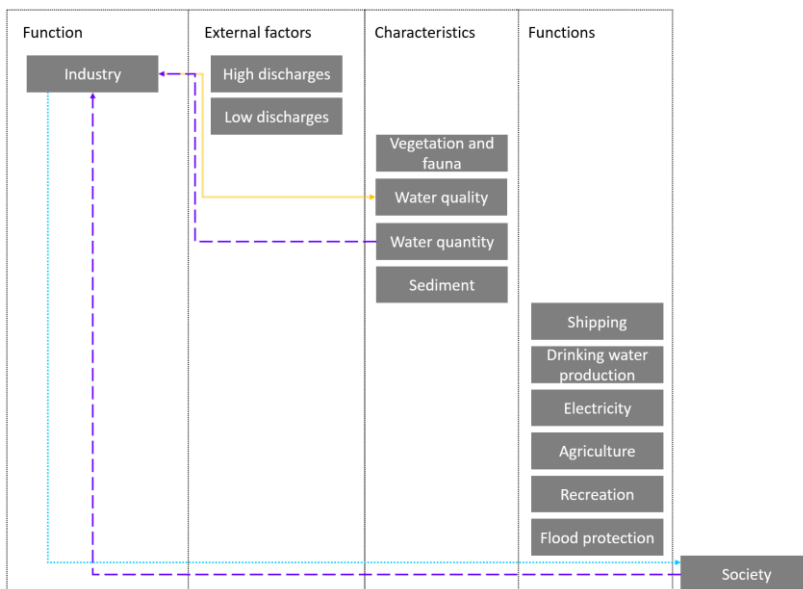


Figure 26 Connections industry

## Electricity

Electricity plants need cooling water and the discharge of this used cooling water has an influence on the water quality. Since the water extracted from the river system is returned to the river system (with some minor losses) electricity is not influenced by discharge or the water quantity.

Society has a certain electricity demand which influences the electricity production and the amount of cooling water needed. However, the amount of cooling water that can be returned to the river system depends on the water quality. Regulations determine how much the temperature is allowed to increase due to discharge of cooling water. Hence, electricity is also influenced by water quality. Finally, electricity has an influence of society should it not be able to meet the demands.

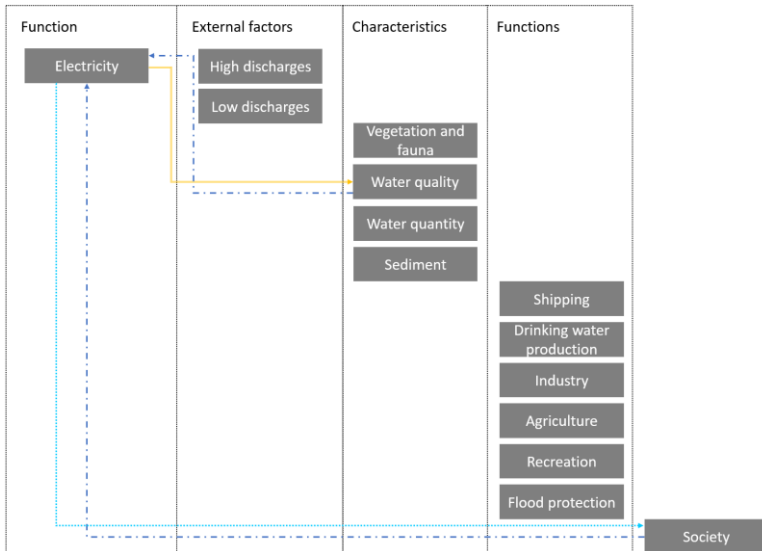


Figure 27 Connections electricity

## Agriculture

Agriculture is influenced by the water quantity and the water quality. Agriculture itself also has an influence on the water quality. Furthermore, agriculture is influenced by society. Society demands a certain number of total crops as well as certain numbers of certain crops. This demand influences the water demand of the agricultural sector. Whether agriculture can meet this demand influences society.

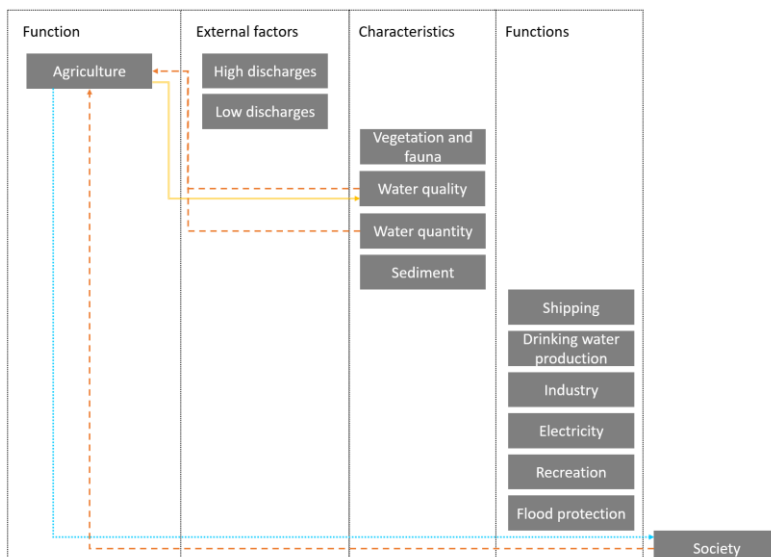


Figure 28 Connections agriculture

## Recreation

Recreation is connected to water quality, vegetation and fauna and sediment. Society demands recreation of certain types and whether these can be provided has an influence on society.

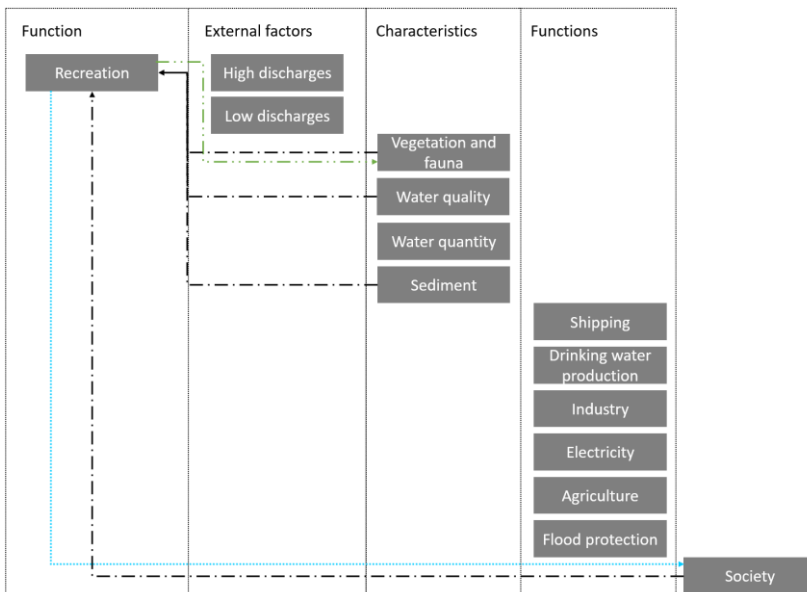


Figure 29 Connections recreation

## Flood protection

Flood protection is influenced by both high discharges and the water quantity. The impact on society depends on the number of people and the infrastructure in the surrounding area. The more people the larger the impact of possible flooding is. Flood protection has an influence on society by either succeeding or failing to deliver the required protection. Society has an influence on flood protection since the use of the surrounding area dictates the level of protection required.

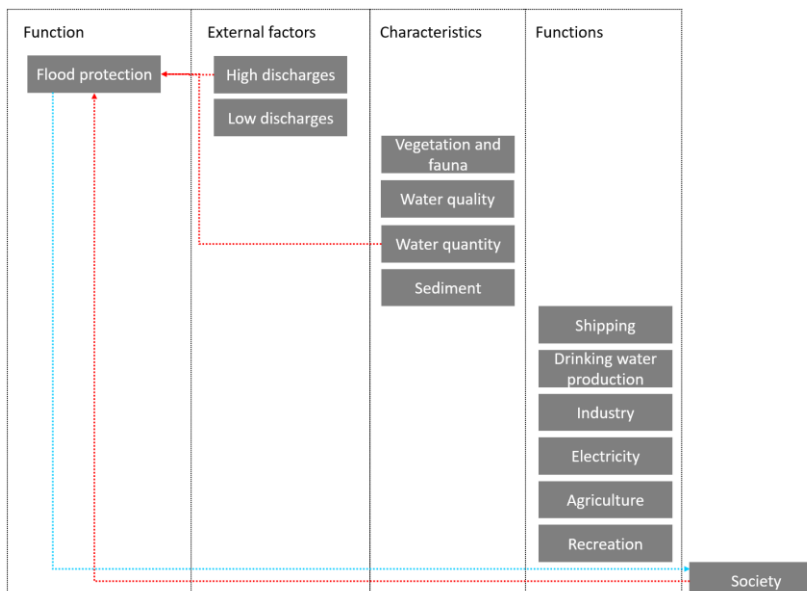


Figure 30 Connections flood protection

## Society

Society is connected to all river system functions since it demands a certain amount or capacity of these functions. It is then influenced by whether these demands can be met.

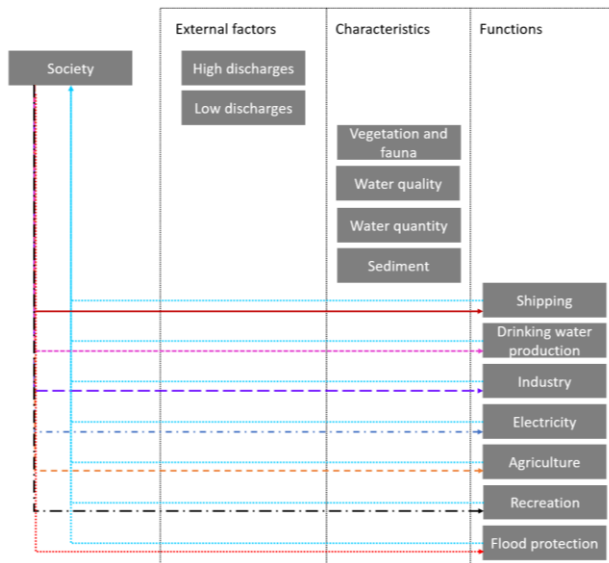


Figure 31 Connections society

## System overview

In Figure 32 (as well as in Appendix A) an overview of all connections is given. Here it can also be seen that when one external factor or characteristic changes, or is temporarily impaired, the impact will most likely be felt throughout almost the entire system. For example, if the water quantity is small for a longer period of time the water quality will decrease which has a negative effect on both the vegetation and fauna and the drinking water production. Additionally, a small water quantity can impair shipping, agriculture and industry. Society is consequently affected by the decrease in output from these functions.

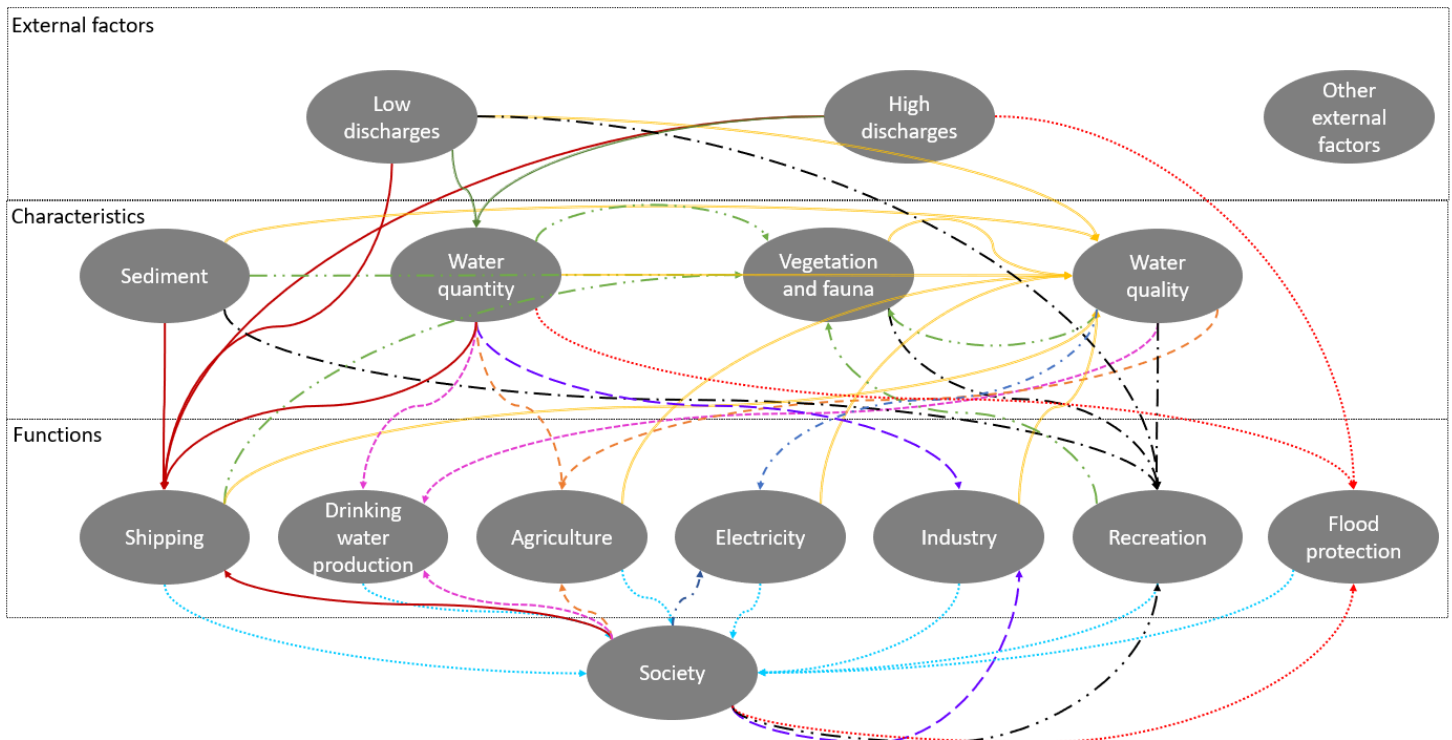


Figure 32 Overview of the system and connections



## 6. Shipping

This chapter contains the application of step 2a, 2b, 2c and 2e of the resilience assessment approach to the river system function shipping of the case study. Step 2d has not been performed since this step was not yet included in the approach when this analysis was done.

### 6.1. Shipping on the Meuse river system

The Meuse river system is used as part of a shipping route into Europe. Shipping on the Meuse river system is done partly on the river itself and partly on canals. Of the 196 km of this route located in the Netherlands 23% is also covered by canals. In the upper part of the river system, indicated with the green rectangle in Figure 33, ships use the Julianakanaal instead of the river itself. This canal splits off from the river at Borgharen and re-joins the river at Maasbracht. Just after Maasbracht part of the ships use the river itself while the others use the Lateraalkanaal (Asselman et al., 2018).

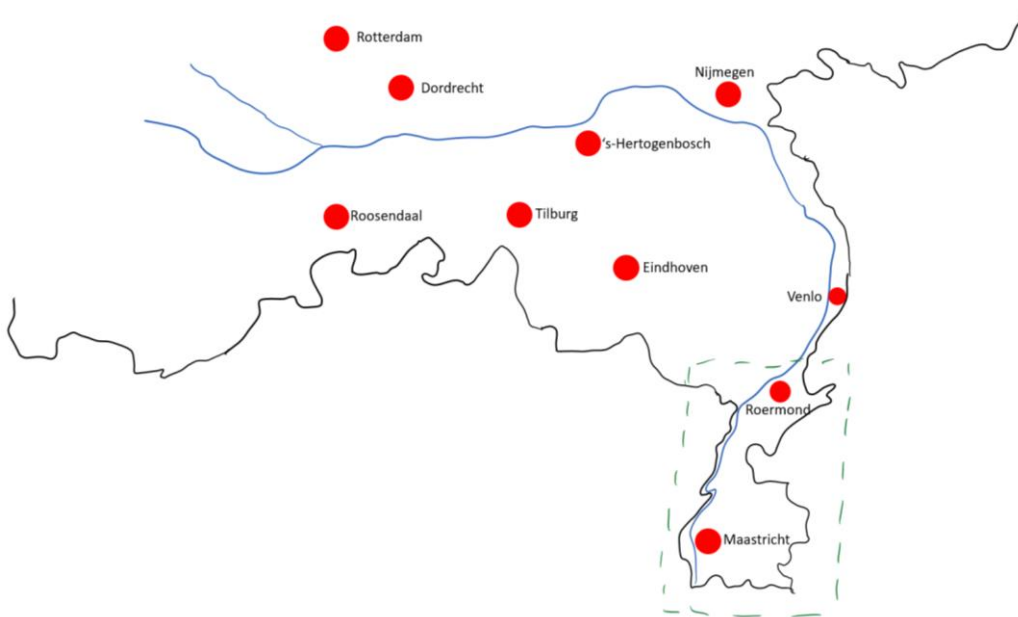


Figure 33 Map of the Meuse river in the Netherlands. The green rectangle indicates the upper part.

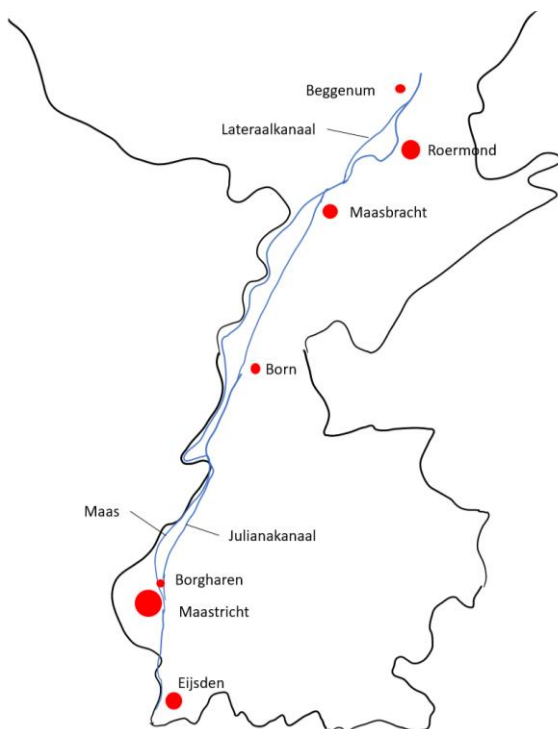


Figure 34 Map of the upper part of the Meuse river in the Netherlands

For the purpose of the analysis the capacity of the river system with regard to shipping focusses on the number of ships that can use it. Here mainly the Julianakanaal is important since ships need to use this canal for the river itself has an insufficient water depth in this part. The Lateraalkanaal is used as a shortcut but use of the river itself is possible. Since this analysis is done in order to illustrate the application of the resilience assessment approach it will focus solely on the Julianakanaal. The capacity of the canal is influenced by the weirs and locks in the canal, which in turn are influenced by the discharge and water level in the canal. Most ships use the entire canal, however, a few only have to reach one of the smaller harbours next to the Julianakanaal and therefore do not use all the locks. However, since the capacity is based on the number of ships that can use the canal the destination of these ships is not taken into account.

## 6.2. Julianakanaal shipping requirements (step 2a, 2b and 2c)

Ships use the Julianakanaal since this canal has a larger water depth than the river itself. Both discharge and water depth requirements need to be met for ships to be able to use it and for the canal to operate at the desired capacity. Both requirements are influenced by a disturbance in discharge. Since the focus of this research is on low discharge this low discharge is the considered disturbance (step 2a of the approach). Below the thresholds (step 2b) and the impact associated with the thresholds (step 2c) are identified.

### 6.2.1. Discharge requirements

Discharge requirements apply mainly to the locks next to the weirs that regulate the water level in the canal. The Julianakanaal has three locks: one near Maastricht (control lock Limmel), one near Born and one near Maasbracht which allow ships to use the canal. These locks influence the shipping capacity of the canal. Since the locks themselves have a certain chamber size they can only lock a limited number of ships at a time. This can cause waiting times when this locking capacity is insufficient. Ministerie van Infrastructuur en Milieu (2012) states that when operating under normal conditions waiting times cannot exceed 30 minutes. Locking times may increase to up to two hours when the discharge decreases (Rijkswaterstaat, 2017).

During locking operations water is lost. When the discharge is high enough this does not cause any problems. However, when the discharge decreases these losses start to have an influence on the water depth near the locks. Three different methods can be used to reduce these water losses: firstly, only locking once the lock is entirely full, secondly, using retention basins to store water from one locking operation to use it for the next and thirdly, using pumps to decrease the losses. The first two methods increase the time needed for locking and hence also the waiting time. When using pumps an effective locking discharge of 0 m<sup>3</sup>/s can be achieved when the pumping capacity is sufficient. This would eliminate discharge requirements for locking. All these methods increase the costs of locking. Where the first two methods cause an increase in cost through increased waiting times the option using pumping has additional electricity costs. An overview of the different methods can be found in Figure 35. Here the blue arrows represent the water used for locking. The dotted blue arrows in part c) indicate that some water from the river is still needed to fill the lock and some is still lost when emptying despite the use of a retention basin (de Jong, 2019).

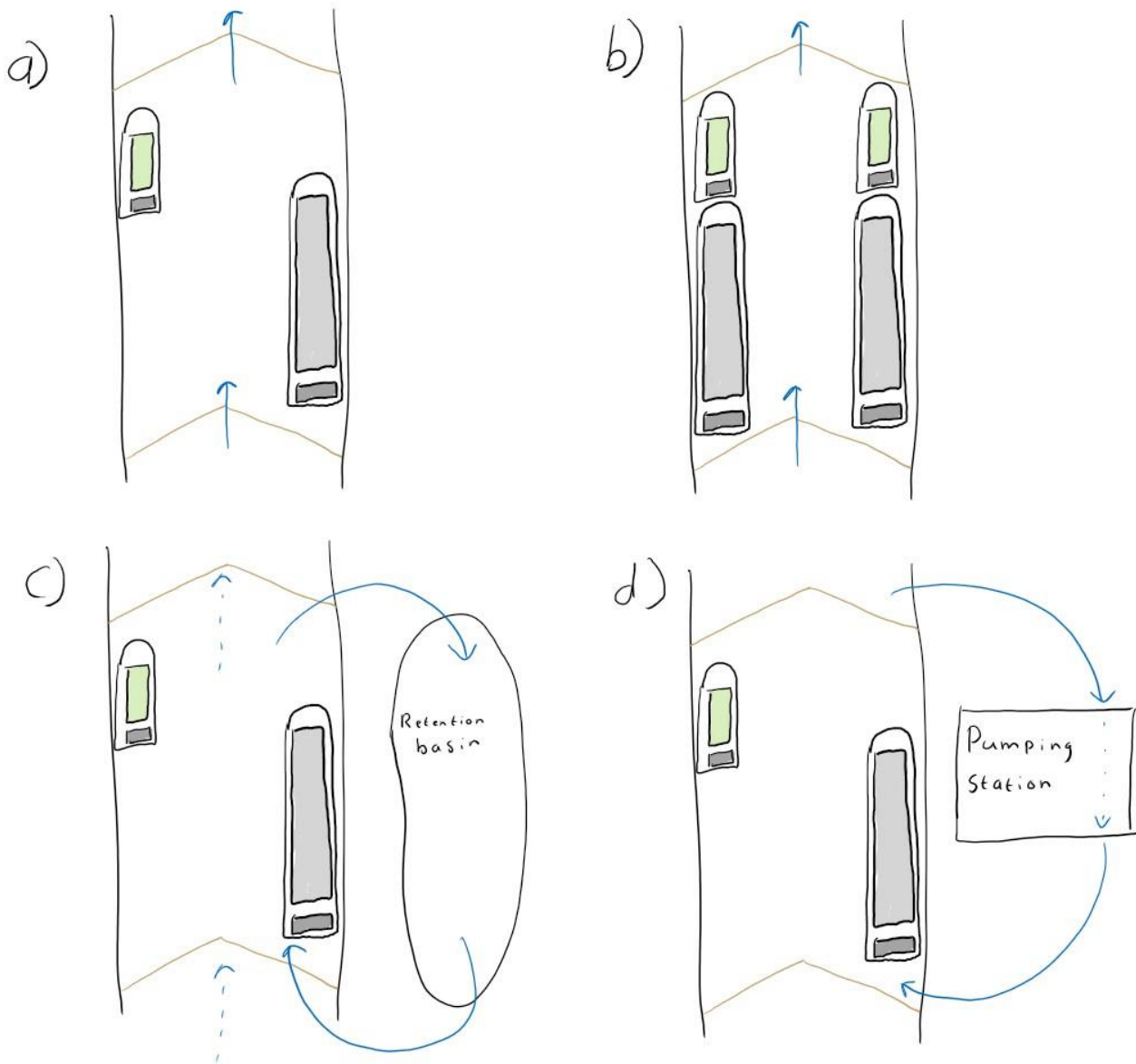


Figure 35 Overview locking methods: a) normal operation, b) full lock, c) using a retention basin and d) using pumps

Of the three locks in the Julianakanaal, the first one near Maastricht, control lock Limmel, is only used when discharge in the river Meuse exceeds  $1300 \text{ m}^3/\text{s}$  (Rijkswaterstaat, 2009). Since droughts are the area of interest this lock is not considered further. The lock near Born has three chambers. They were all built in 1960, however, only the second and third chamber have been upgraded and expanded in 2012. The first chamber is no longer in use, so effectively this lock has only two chambers. The dimensions of the chambers can be found in Table 5. The lock near Maasbracht has three chambers. It was built in 1964 and upgraded and expanded in 2012. The dimensions of these chambers can also be found in Table 5 (Breedebeld & Kramer, 2018). Since 2012 both locks can be used by  $V_B$  class ships. The maximum dimensions of these ships are a length of 190 m, a width of 11.4 m and a draught of 3.5 m (Rijkswaterstaat, n.d.).

Table 5 Lock characteristics

	Number of chambers	Length of chambers	Width of chambers	Maximum length of ships	Maximum width of ships	Maximum draught of ships
<b>Born</b>	3 (chamber 1 is no longer in use)	For chamber 2: 225 m For chamber 3: 142 m	16 m for all chambers	190 m	11.4 m	3.5 m
<b>Maasbracht</b>	3	For chamber 1 and 2: 142 m For chamber 3: 225 m	16 m for all chambers	190 m	11.4 m	3.5 m

Research with regard to the required discharge has been done for the locks at Born and Maasbracht. They require a discharge of 15.4 m<sup>3</sup>/s and 17.2 m<sup>3</sup>/s respectively to operate without the need to actively reduce water losses. The lock at Born has the option to reduce locking losses using pumps. The lock has a total pumping capacity of 12 m<sup>3</sup>/s. However, the lock at Born does not have a retention basin. When no retention basin is present it is possible to use the locking chamber for the opposite direction as a retention basin. However, this significantly increases waiting time since only one chamber can be used at a time. The lock at Maasbracht has a pumping capacity of 9 m<sup>3</sup>/s and does have a retention basin. Hence, both methods two and three and a combination of both are possible here. Both locks can use method one (only locking when the chamber is full) however the waiting times should not exceed two hours (de Jong, 2019).

The electricity costs, in euro, for pumping at the different locks are estimated to be  $C_{Born} = 44041 + V * 0.0042$  for Born and  $C_{Maasbracht} = 34868 + V * 0.0048$  for Maasbracht, where V is the volume of water pumped. The first part of the formulas are the fixed costs and the second part of the formulas are variable costs which depend on the pumped volume (de Jong, 2019).

An optimisation of locking with a full chamber and locking while using retention basins gives increased waiting times at the different locks. At Maasbracht it is possible to save up to 12 m<sup>3</sup>/s which corresponds to an increase in waiting time of 60 minutes. At Born it is possible to save up to 5 m<sup>3</sup>/s in this manner and this causes an increase in waiting time of 29 minutes. The waiting times and discharges are based on SIVAK simulations by Bolt in 2003 (de Jong, 2019; Bolt, 2003).

The costs caused by these increased waiting times consist of 25% shipping costs and 75% waiting costs. In 2018 the costs were estimated to be €200 per hour on average, for the entire fleet of ships that uses the Meuse river system. These costs, based on social economic costs, were determined by NEA in 1994 and have been adapted to the price level of 2018. The waiting costs were determined for different types of shipping: sand and gravel shipping, tankers and other cargo. An average of sand and gravel shipping and other cargo is used as the costs for freight shipping. Furthermore, 20% of all shipping is assumed to be tankers. This standard fleet was used to calculate the waiting costs for the Julianakanaal. These waiting costs only include the fixed and variable costs of the ship itself and its crew (de Jong, 2019; Bolt, 2003).

De Jong (2019) shows that, for the current system, the costs caused by the increased waiting times, caused by water loss reducing locking methods, are larger than the costs for reducing the water losses using pumps. Hence, locking facilities will use their pumping capacity before turning to other measures. Hence, for the lock at Born additional costs start to occur when the discharge drops below 15.4 m<sup>3</sup>/s. It is possible to operate up until a discharge of 3.4 m<sup>3</sup>/s before other measures are needed. For the lock at Maasbracht this means that locking using the retention basin starts when the discharge drops below 8.2 m<sup>3</sup>/s. The increase in costs starts at 17.2 m<sup>3</sup>/s when use of pumps is needed and when the discharge drops below 8.2 m<sup>3</sup>/s additional waiting costs will also occur in addition to the pumping costs. This can also be seen in the disturbance-impact graphs in Figure 36 and Figure 37 for Born and Maasbracht, respectively.

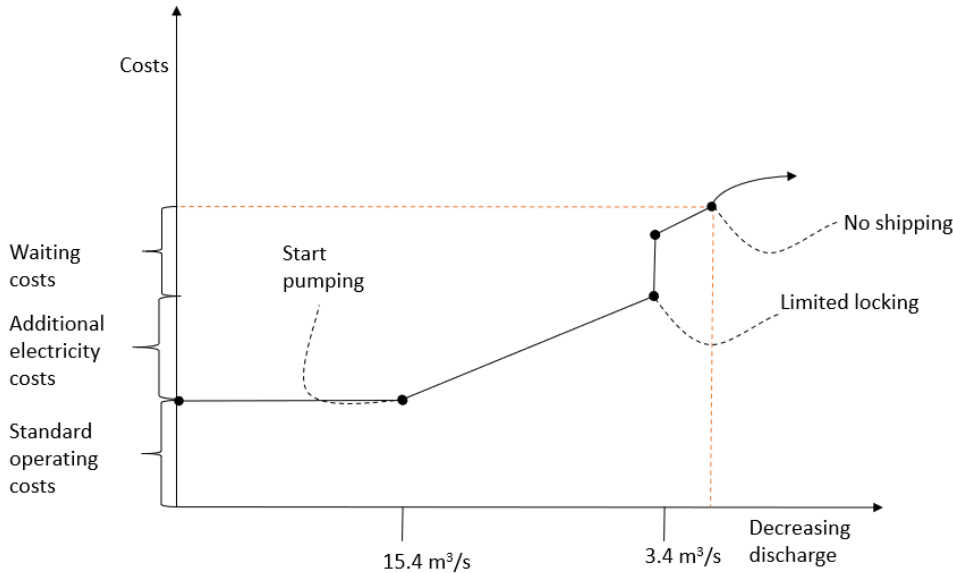


Figure 36 Disturbance-impact graph for the lock at Born

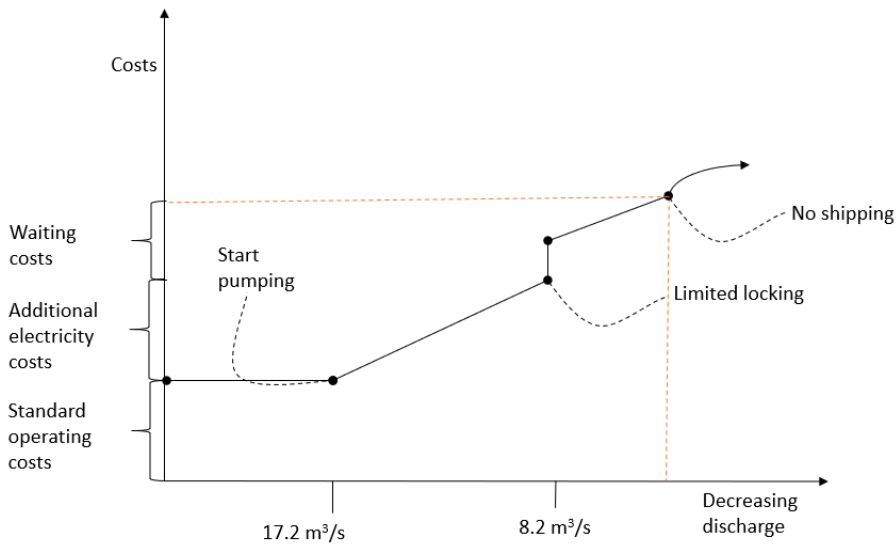


Figure 37 Disturbance-impact graph for the lock at Maasbracht

In both cases the capability to reduce water losses without pumping is larger than the discharge still required when pumping at full capacity. Hence, a cease in functioning for shipping does not occur due the locking operations, since they will always be able to be executed. This, however, can occur when ships can no longer reach locks. Hence, the point where shipping is no longer possible depends on the water depth in the canal.

Since ships using the Julianakanaal need to use both locks a graph containing both locks has also been created. It can be found in Figure 38.

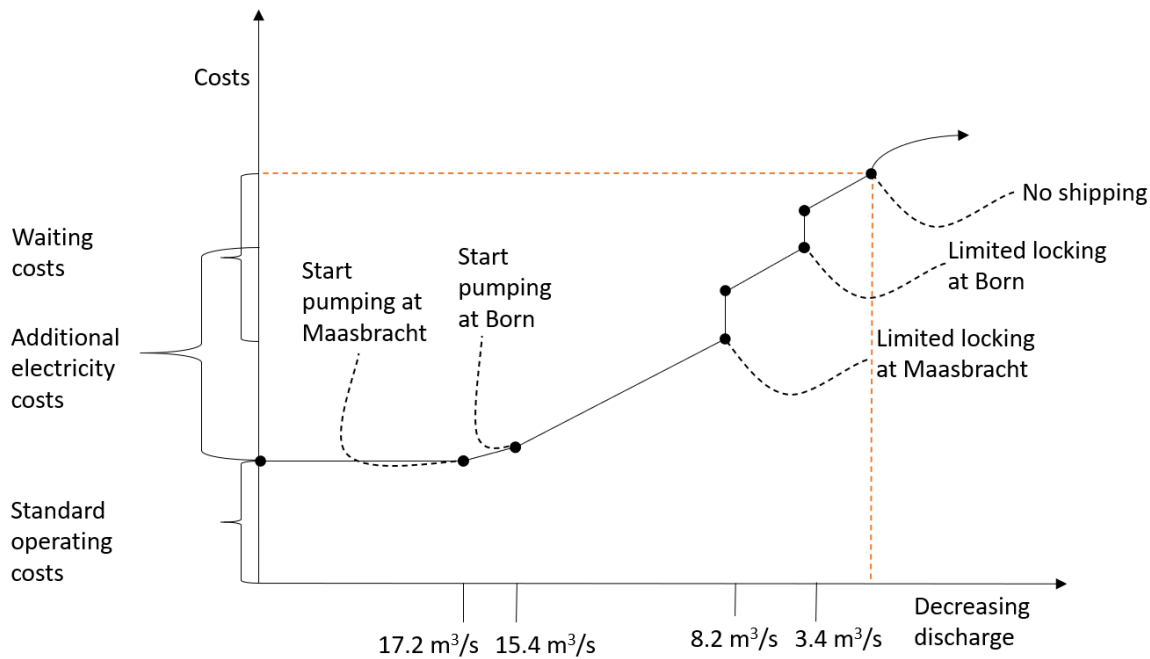


Figure 38 Disturbance-impact graph for both the lock at Born and Maasbracht

### 6.2.2. Water depth requirements

The shipping route in the Meuse river system will be suited for class  $V_B$  ships in 2024. Since this was supposed to happen in 2019 parts of the route are already suited for class  $V_B$  ships while work is still being done on other parts. In order to be suited for larger ships the Julianakanaal needed to be widened and the depth had to be increased (Rijkswaterstaat, 2020-b). The ships of the  $V_B$  class have a draught of 2.5 to 4.5 m and a width up to 11.4 m. However, the Meuse river system only has a guaranteed draught of 3.5 m. So, class  $V_B$  ships cannot be fully loaded (Wegman et al., 2018).

When the water depth decreases ships will need to decrease their load in order to decrease their draught and still be able to use the canal. At some point it might not be profitable to move cargo by river due to increased costs due to decreased loading. In order to determine whether and when this occurs insight from the local shipping industry is needed.

### 6.3. Discharge in the Julianakanaal (step 2e)

The discharge in the Julianakanaal is calculated from the discharge at Monsin. The data used ranges from October 1<sup>st</sup> 1935 to December 31<sup>st</sup> 2019. This dataset contains the daily averages. The allocation of the discharge at Monsin and at bifurcations after Monsin can be found in Table 6. Using this, the discharge in the Julianakanaal can be calculated. The first part of the table, the allocation between the Albertkanaal and the Meuse near St. Pieter, was taken from Prinsen (2008). This allocation is based on the Maasafvoerverdrag as signed in 1995 (De Nederlandse Overheid, 1995). The second part, the allocation at Borgharen, is based on discharge data of the different branches of the last ten years (2009-2019) as received from (Rijkswaterstaat, 2020-c). A map of the different canals and cities can be found in Figure 39.

Table 6 Allocation of discharge at Monsin and at St. Pieter/Borgharen

Discharge at Monsin (m <sup>3</sup> /s)	Q towards Albertkanaal (m <sup>3</sup> /s)	Q towards Meuse (at St. Pieter) (m <sup>3</sup> /s)	Q towards Julianakanaal (from St. Pieter)
Q>130	26	Q>104	12%
115<Q<130	21	94<Q<104	16%
100<Q<115	16	84<Q<94	19%
90<Q<100	16	74<Q<84	20%
80<Q<90	16	64<Q<74	25%
70<Q<80	16	54<Q<64	28%
60<Q<70	16	44<Q<54	35%
55<Q<60	13.5	41.5<Q<44	42%
50<Q<55	12	38<Q<41.5	48%
45<Q<50	11.4	33.6<Q<38	56%
40<Q<45	9.9	30.1<Q<33.6	56%
35<Q<40	7.4	27.6<Q<30.1	55%
30<Q<35	4.9	25.1<Q<27.6	46%
25<Q<30	4.3	20.7<Q<25.1	38%
30<Q<25	3.7	16.3<Q<20.7	33%
15<Q<20	3.1	11.9<Q<16.3	32%
10<Q<15	2.1	7.9<Q<11.9	30%

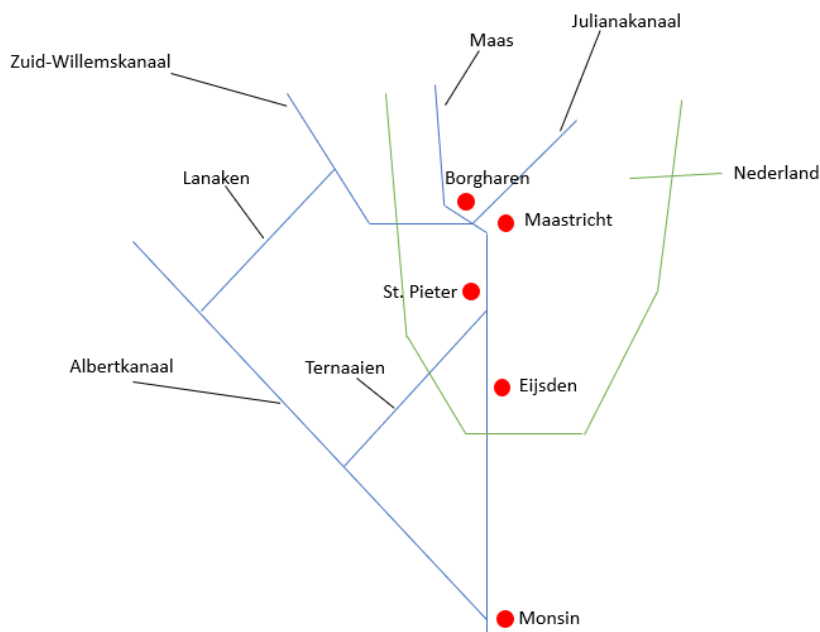


Figure 39 Overview Meuse river system near the border of the Netherlands

A discharge of 17.2 m<sup>3</sup>/s in the Julianakanaal, at which the lock at Maasbracht would need to start using pumps has occurred often during the last 84 years, see Figure 40. For the lock near Born the discharge at which pumping starts (15.2 m<sup>3</sup>/s) also occurred at least once every year in the past 84 years, see Figure 41. However, while this means additional costs were incurred no additional waiting times and hence no decrease in capacity occurred. This decrease in capacity occurs when the discharge drops below 8.2 m<sup>3</sup>/s since at this discharge the first additional waiting times due to locking operations occur. In the past 84 years this happened only 70 days, see Figure 42. A discharge below 3.4 m<sup>3</sup>/s has not occurred in the considered time period.



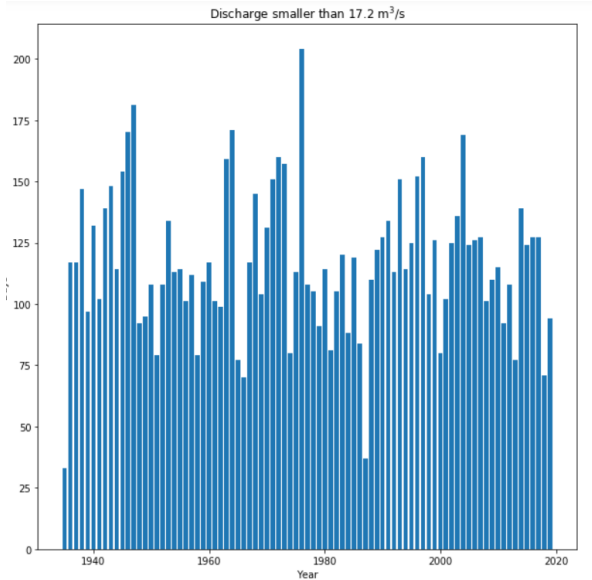


Figure 40 Number of days the discharge was smaller than 17.2 m³/s

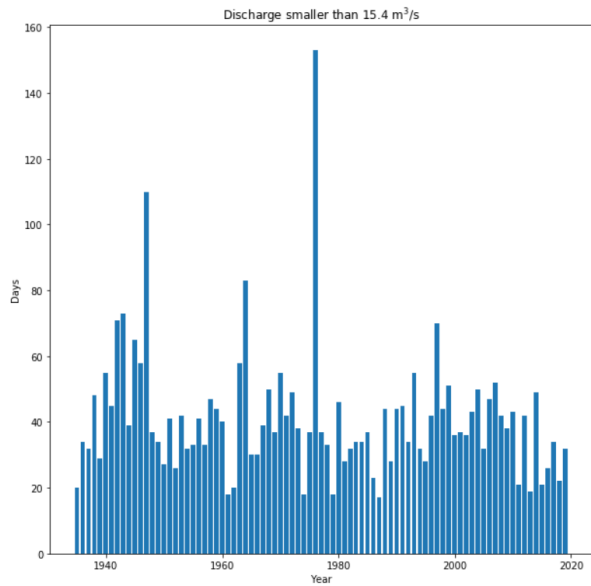


Figure 41 Number of days the discharge was smaller than 15.4 m³/s

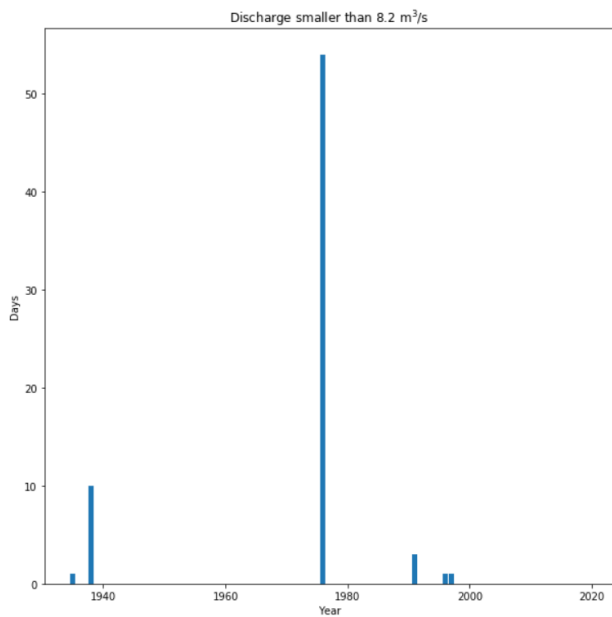


Figure 42 Number of days the discharge was smaller than 8.2 m³/s

## 6.4. Water depth in the Julianakanaal (step 2e)

As can be seen in Figure 43 the water level in the canal barely deviates, except for the end of 2010 and early 2011. The water level is given in m NAP. Given the fact that the water level hardly deviates it would seem that the influence of the discharge on the water level is small. This is expected since the water level in the canal is controlled by weirs. This implies that it is unlikely that the water levels will drop to a depth at which it is physically impossible for ships to reach the locks.

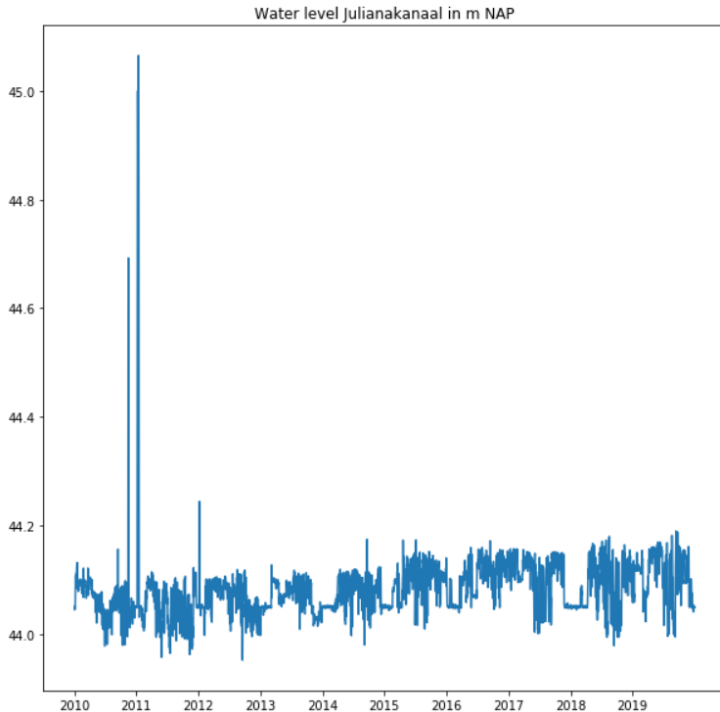


Figure 43 Water level in the Julianakanaal

A simple water balance is made in order to see whether this constant water level is likely to remain. For this water balance the evaporation is needed. The evaporation used is based on evaporation data for Beek from KNMI (2020). This dataset ranges from 2003 to 2019. The average evaporation in mm/day for the different months can be found in Figure 44. For simplicity interaction with the surrounding groundwater is ignored.

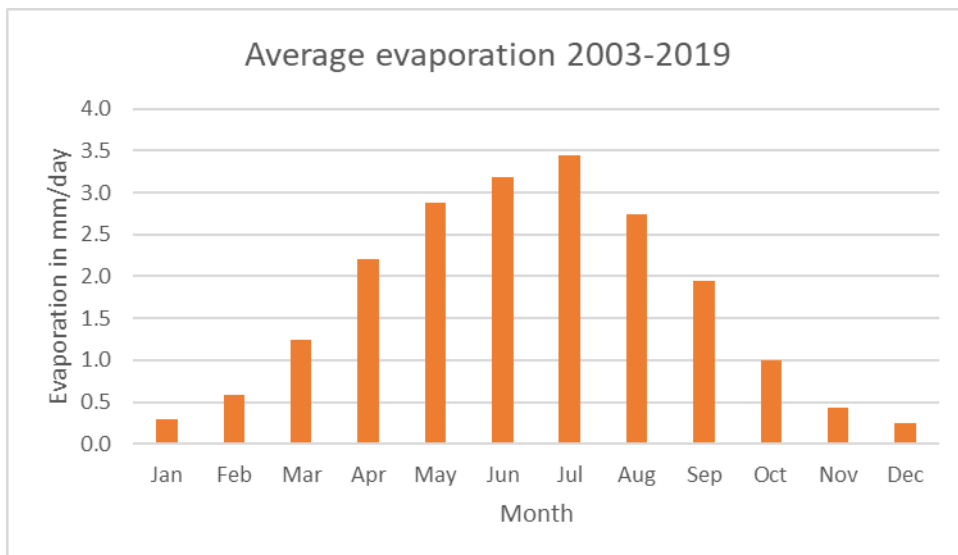


Figure 44 Average evaporation 2003-2009 in mm/day

Four cases are taken into account: the largest evaporation and the corresponding discharge, the lowest discharge with the corresponding evaporation, the average discharge and evaporation in July and finally the lowest discharge with the largest evaporation. The largest evaporation occurred in July 2010; this

evaporation was 5.0 mm/day. The lowest discharge in the time period that both discharge and evaporation were measured is 9.31 m<sup>3</sup>/s and it occurred in September 2018. The average discharge and evaporation in July are 18.4 m<sup>3</sup>/s and 3.4 mm/day respectively. An overview of the cases can be found in Table 7.

Table 7 Overview water balance cases

	Discharge (m <sup>3</sup> /s)	Evaporation (mm/day)
<b>Case 1: largest evaporation</b>	18.20	5.0
<b>Case 2: lowest discharge</b>	9.31	1.8
<b>Case 3: average for July</b>	18.40	3.4
<b>Case 4: lowest discharge and largest evaporation</b>	9.31	5.0

The canal has a total length of 36 km and an average width of 6 m. These dimensions are used to determine the evaporation in m<sup>3</sup>/s in the canal,  $E_c = L * W * E$ . Since the canal is simulated as one large basin only the lock near Maasbracht is taken into account. It is assumed that methods to reduce water losses are used to cover the difference between the minimum discharge for which this is not needed and the actual discharge. Hence, if the discharge is 14 m<sup>3</sup>/s the pumps are assumed to return 3.2 m<sup>3</sup>/s to the canal, since the minimum discharge without reducing losses at Maasbracht is 17.2 m<sup>3</sup>/s. A schematic overview of the simulation can be found in Figure 45.

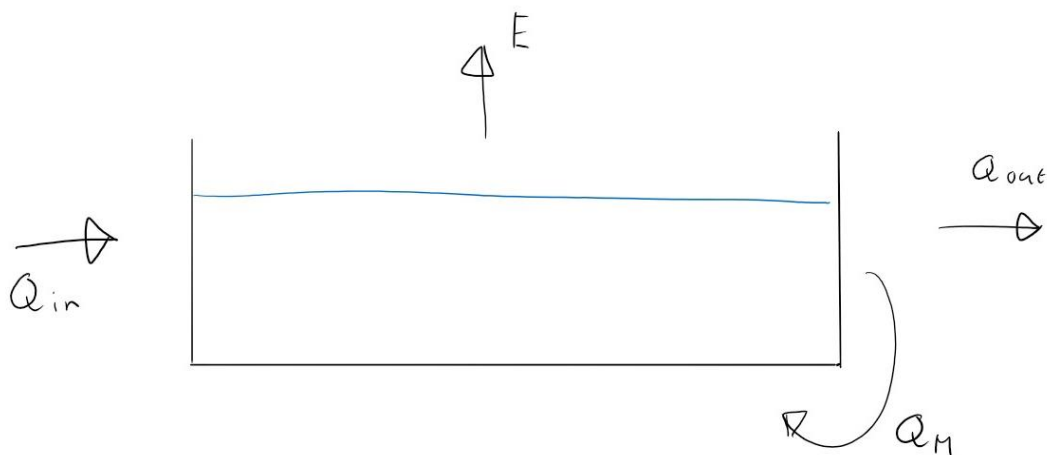


Figure 45 Schematisation of Julianakanaal for water balance

The results of the water balance can be found in Table 8. As can be seen the effect of evaporation is negligible. Furthermore, for all combinations the pumping capacity is sufficient using the single basin schematisation. Hence, it is likely that the water level as presented in Figure 43 can be maintained.

Table 8 Water balance results

	Q <sub>in</sub> (m <sup>3</sup> /s)	E <sub>c</sub> (m <sup>3</sup> /s)	Q <sub>M</sub> (m <sup>3</sup> /s)	Q <sub>out</sub> (m <sup>3</sup> /s)	Amount of water retained
<b>Case 1</b>	18.20	0.125	0.0	18.08	No water retained
<b>Case 2</b>	9.31	0.056	7.95	1.31	7.95 m <sup>3</sup> /s retained
<b>Case 3</b>	18.40	0.086	0.0	18.40	No water retained
<b>Case 4</b>	9.31	0.125	8.02	1.17	8.02 m <sup>3</sup> /s retained

## 6.5. Conclusions for shipping on the Julianakanaal

As shown above a cease in functioning due to decreasing discharge does not occur with the current external factors. Nor is it likely that this will occur due to a decreasing water depth. A decrease in functioning, due to a decrease in capacity, occurred only for 70 days during the last 84 years. This implies that the Julianakanaal is resilient with regards to shipping. In order to assess this resilience, the different levels of the resilience classification, as explained in Section 3.3.2, need to be assigned to the different phases that can be identified in the disturbance-impact graphs.

Time is an important factor in the assignment of the different levels. A discharge for which pumping at one lock is necessary is unlikely to have a large effect on overall costs or cause much nuisance for skippers when it only occurs for a day. If that same discharge occurs for a longer period of time this impact will start to be felt.

In order to properly assign the different levels, the duration and the extent of this impact need to be determined. Consultation with different stakeholders, as for example a representative of the skippers using the route and lock operators, is needed to do this. The system overview created in Chapter 5 can help decide who needs to be consulted for this specific function.

The disturbance-impact graphs can be used to show stakeholders when and where potential limitations occur. The knowledge of the stakeholders will then be used to help determine the timescale at which these limitations start to cause problems. With this knowledge of the timescales the different levels can be assigned. Once the levels have been assigned a resilience score for this function can be determined. Given the dataset used, this score would represent the past 84 years.

## 7. Drinking water production

*This chapter contains the application of step 2a, 2b, 2c and 2e of the resilience assessment approach to river function of drinking water production of the case study. Step 2d has not been performed since this step was not yet included in the approach when this analysis was done.*

### 7.1. Drinking water production in the Meuse river system

Drinking water companies extract water to produce drinking water and distribute it to households and companies. In 2017, approximately 1,199 million m<sup>3</sup> of water were extracted for the production of drinking water. This extraction was done by drinking water companies throughout the Netherlands. Of all this water 38% was extracted from rivers and lakes (van Hussen et al., 2019). Beside rivers and lakes water for drinking water production can also be extracted from groundwater using pumps. Many drinking water companies use a combination of both sources since extraction from rivers and lakes is more susceptible to droughts.

The extraction from rivers can be affected by droughts in two ways: through a decrease in water availability and a decrease in water quality. Furthermore, during droughts the demand for drinking water tends to increase. When the water availability does not allow the desired amount of water to be extracted, water from buffers can be used to temporarily bridge this gap.

Drinking water companies have both operational and non-operational buffers to be able to cope with unforeseen circumstances and unexpected growth (Tangena, 2014). When the water quality no longer meets the standards for extraction the intake of water from the river will be stopped. During this stop in intake water from the buffers will be used to produce drinking water.

The aforementioned buffers can only store water for a limited period of production. Hence, the duration of either a shortage of intake or a stop in intake should be short enough such that this capacity is not exceeded. This means that not simply the current discharge and water quality are important, the water quantity and water quality over a period of time are important as well.

Beside buffers drinking water companies have other options to ensure continuation of production during droughts: using alternative water sources and using additional water treatment allowing water of poorer quality to be used for production. The option of investing and using additional water treatment is seen a last resort (Sjerps & Huiting, 2017).

The Meuse river is also used as a source for water for drinking water production. Multiple drinking water companies use river water from the river Meuse. However, a few of those companies also use water from other river systems. The Waterleiding Maatschappij Limburg (WML) is used as an example for this analysis since it only uses river water from the Meuse river system.

### 7.2. Drinking water production by Waterleiding Maatschappij Limburg (step 2a, 2b and 2c)

The Waterleiding Maatschappij Limburg (WML) provides drinking water for over 500,000 household in the province of Limburg. They use up to 76 million m<sup>3</sup> of water per year for the production of drinking water. Up to 25% of this water is extracted from the river system. The other 75% is extracted from groundwater (Sjerps & Huiting, 2017; Waterleiding Maatschappij Limburg, n.d.).

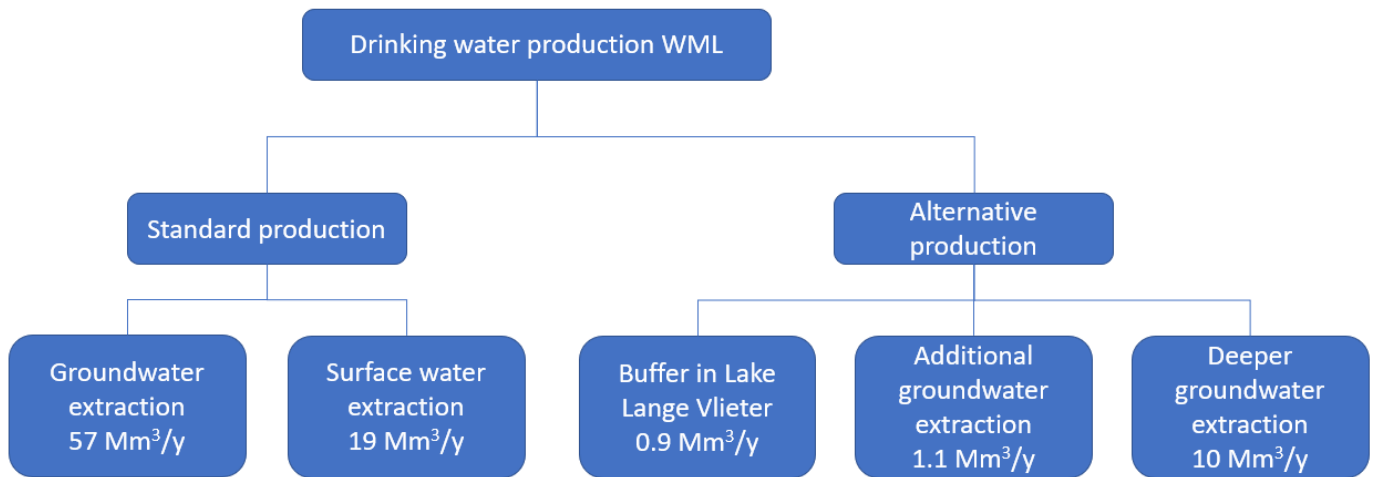


Figure 46 Overview drinking water production WML

WML extracts water from the Lateraalkanaal near Beegden and pumps it to Lake Lange Vlieter, see Figure 47. This water is later extracted from banks of the lake and pumped to water treatment plant Heel. After treatment the drinking water is mixed with drinking water from groundwater treatment plants and distributed to households throughout the province (Sjerps & Huiting, 2017).

The water pumped from the Lateraalkanaal to Lake Lange Vlieter stays in the lake for one and a half to two years. It is then pumped up through the infiltration area in the bank of the lake. Water remains in this infiltration area for at least 30 days. The water extracted from the bank of the lake is pumped to treatment plant Heel, see Figure 48. Lake Lange Vlieter and the infiltration area are used as both part of the treatment of drinking water and as a buffer (Sjerps & Huiting, 2017).

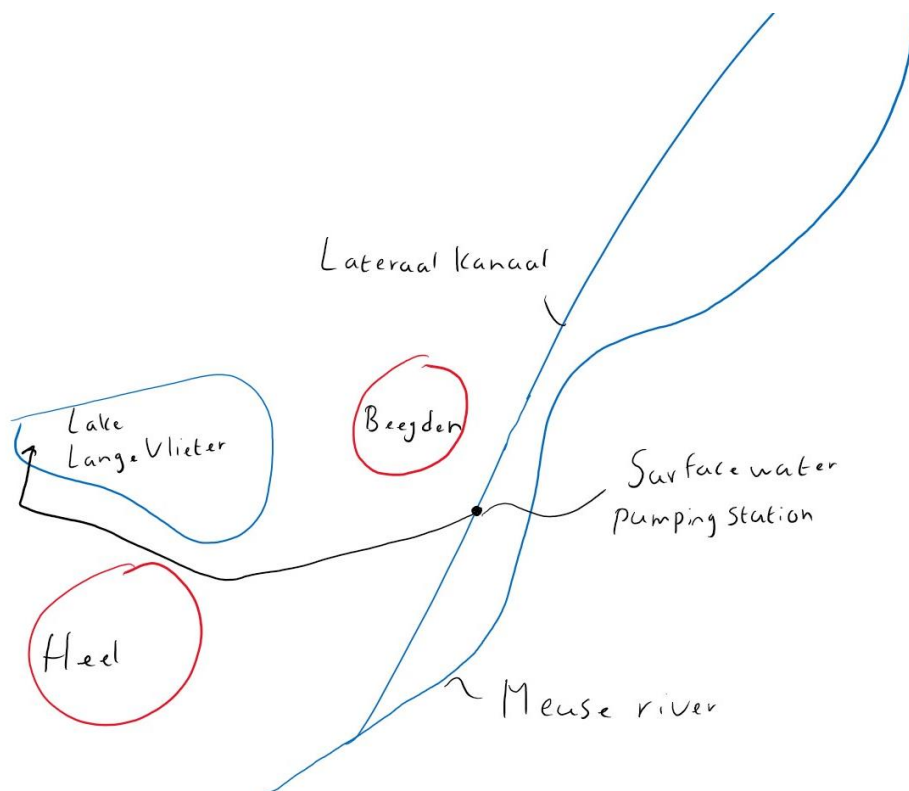


Figure 47 River water extraction WML

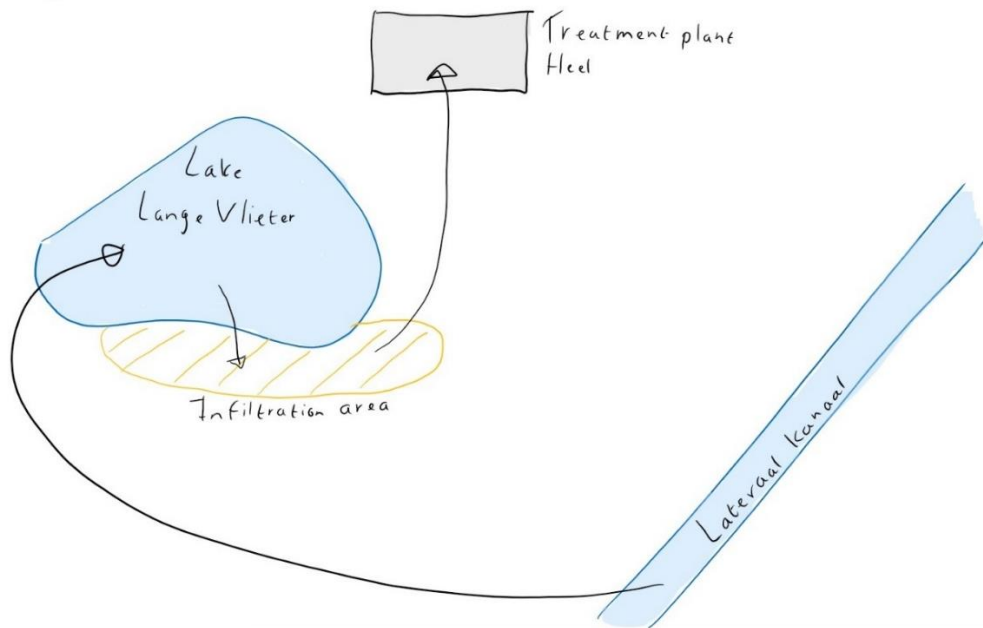


Figure 48 Treatment river water WML

When a stop in intake occurs WML uses the buffer of Lake Lange Vlieter and other measures to continue production. This stop in intake can be caused by both a lack of water availability or by a poor water quality. Since the focus of this study is on low discharges, caused by droughts, these low discharges, and thus a lack of water availability, are the disturbance considered.

The buffer of lake Lange Vlieter can supply water for production for two to three weeks. After three weeks additional water will have to be extracted through groundwater extraction. In addition to the regular groundwater extraction 1.1 million m<sup>3</sup> of water can be extracted per year. On average the groundwater is extracted at a rate of 1.81 m<sup>3</sup>/s. Assuming the additional extraction is done at the same rate it will take approximately one week to extract the additional groundwater. When this amount has been exceeded WML has one final option. They have several pumps that can reach deeper groundwater. These, however, are used as an emergency option since the quality of this deeper groundwater is poorer. It has a higher hardness and currently no treatment steps are in place to reduce this. Using all of these measures WML can cope with a stop in intake of maximal four to five months. When this timescale is exceeded a decrease in production occurs due to water shortages (Sjerps & Huiting, 2017). An overview of the thresholds and their impact can be found in Figure 49.



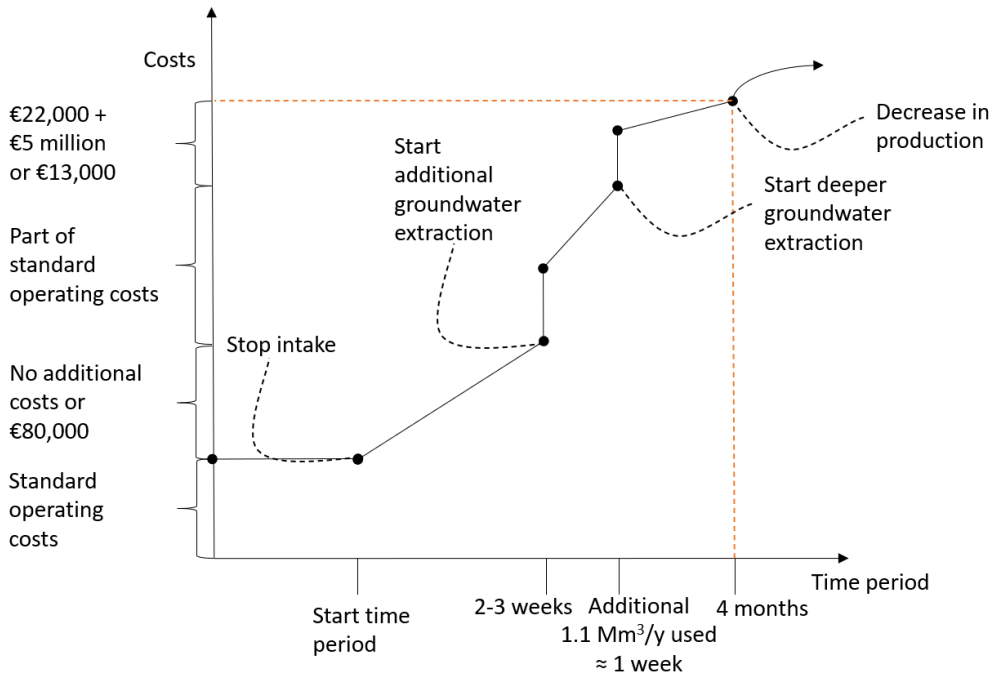


Figure 49 Disturbance-impact graph drinking water production WML

The additional costs for a stop in intake depend on the disturbance causing the stop in intake. If it is caused by a lack of water availability at first no additional costs will occur. If it is caused by pollution the identification and analysis of an unidentified substance can cost up to 80,000 euro. The costs for the pumping of the additional groundwater are part of the standard pumping operating costs. The costs for the extraction of deeper groundwater consist of two part. The first part contains the costs for the additional personnel and electricity. This will cost approximately 22,000 euro for a period of four months. The second part is either the investment in additional treatment for this poorer quality water or the costs for informing all users of the increased hardness of the water. The costs of informing all users are estimated to be 17,000 euro. The costs of the investment are estimated to be 5 million euro. This investment would allow 10 million m<sup>3</sup> of deeper groundwater to be treated every year (Sjerps & Huiting, 2017).

The timescale presented in Figure 49 represent a complete stop in intake. When less, but still some, intake is possible, due to a lack of water availability, the timescale up until the extraction of additional groundwater will be larger. The extraction of the additional groundwater is expected to have the same timescale. The extraction of the deeper groundwater can still be done for four months. Hence, the total timescale will be extended with the additional time the buffer of lake Lange Vlieter can supply the required water.

The overview as presented in Figure 49 represent the system of the drinking water production. It does not represent the river system with regard to drinking water production. The function of the river system with regard to drinking water production is to deliver sufficient water for production. The river system starts to fulfil its function to a less than desirable extent as soon as the desired intake is no longer possible. It stops functioning when alternative sources of water need to be used since the buffer of river water is no longer sufficient. At this point the river system no longer provides water to the drinking water production. The disturbance-impact graph of drinking water production with regard to the river system can be found in Figure 50.

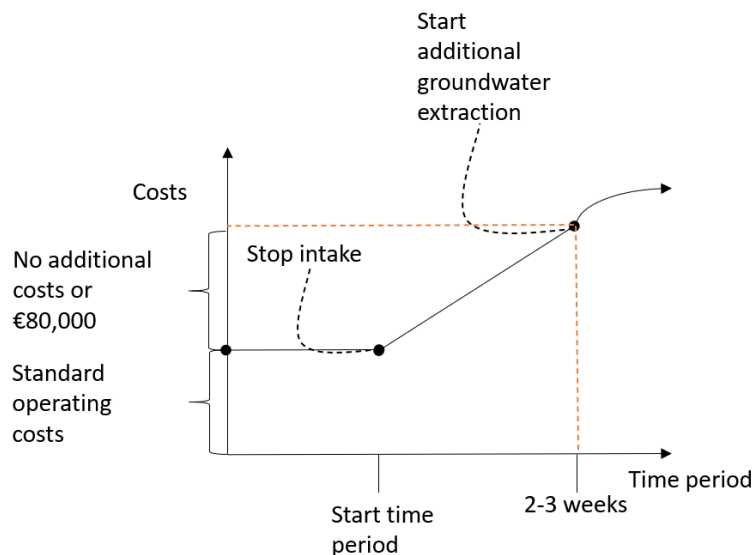


Figure 50 Disturbance-impact graph drinking water production river system

### 7.3. Disturbances in production (step 2e)

Research shows that drinking water production using river water from the Meuse river system is more susceptible to water quality issues than to a lack of water availability. In the past couple of years an average of 50 to 70 stops in intake occurred due to an insufficient water quality. Mainly the duration of the stops in intake has risen sharply since 2014. However, in 2018 this duration once more dropped below 200 days. The increase in 2013 and 2014 is likely due to the fact that the number of substances checked has increased. The fact that the duration dropped again in 2018 is partially due to a temporary exemption of water quality demands. Though the extend of this is unknown (RIWA-Maas, 2019).

According to Sjerps & Huiting (2017) the drinking water production of WML does not suffer from discharge shortages since the inlet is located in the Lateraalkanaal. The water level of this canal is regulated for both shipping and drinking water purposes. Figure 51 shows the water level just in front of the lock at the entrance of the canal near Heel. Figure 52 shows the water level behind the lock in the Lateraalkanaal. The water level in the canal fluctuates but hasn't dropped below 1.4 m NAP in the past 19 years. Assuming this minimum of 1.4 m NAP provides enough water for drinking production the production of WML does indeed not suffer from a lack of water availability. This implies, however, that the intake point of the surface water pumping station is still below the water surface when the water level is at 1.4 m NAP and that in maintaining this water level sufficient water for extraction enters the canal. Based on the average extraction of river water per year river water is extracted at a rate of 0.6 m<sup>3</sup>/s. The lowest discharge in the river Meuse (based on the analysis of Section 6.4) is 9.31 m<sup>3</sup>/s. This is not the discharge in the canal. However, given the fact that drinking water production has a high priority in the Netherlands, it is unlikely that the demand of 0.6 m<sup>3</sup>/s cannot be met.

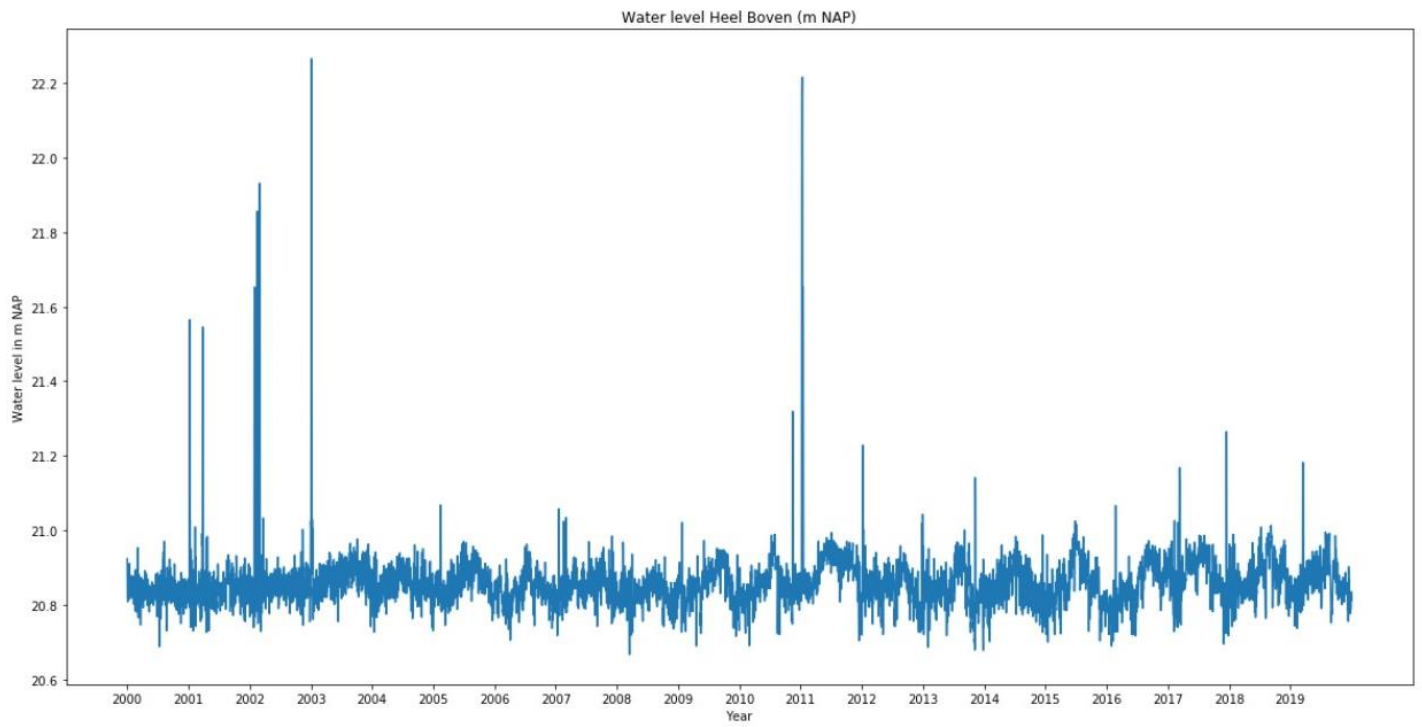


Figure 51 Water level Heel Boven (m NAP) in front of lock

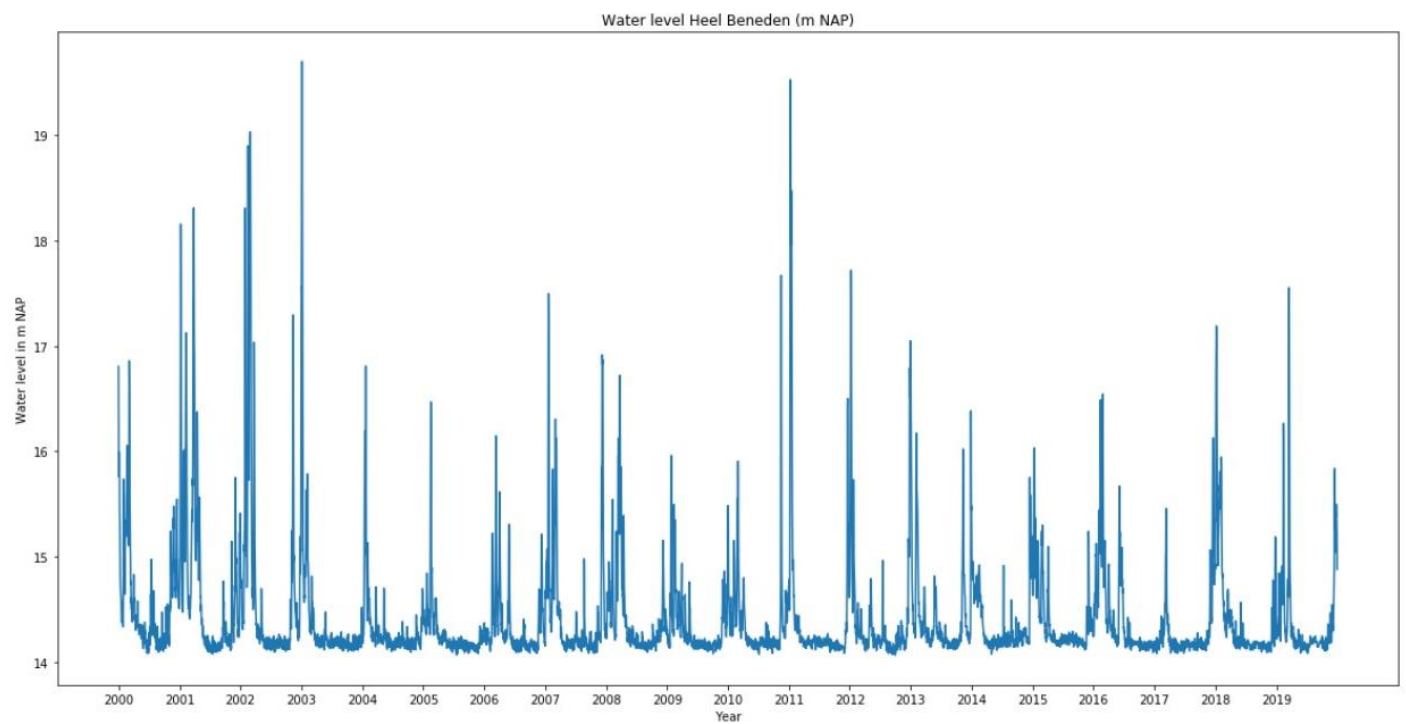


Figure 52 Water level Heel Beneden (m NAP) behind lock

## 7.4. Conclusions for drinking water production by WML

As explained above a cease in functioning, from the perspective of the river system, has occurred not occurred with regard the water quantity. This implies that the Meuse river system is resilient with regard to drinking water production for the considered disturbance.

The analysis showed that the drinking water production by WML is often impaired by a poor water quality. A disturbance in water quality has not been considered in this study. This however shows that an adaptation of the approach is needed in order to prevent performing a full analysis for an irrelevant disturbance. Therefore, an additional step (step 2d) has been added to the approach.

The analysis also showed that the system boundaries of the river system should be clearly defined in order to determine which parts of a function are part of the river system. The approach has been adapted to reflect this.

In order to assess the resilience of drinking water production, the different levels from Section 3.3.2 need to be assigned to the different phases in the disturbance impact graph of Figure 50. Consultation with stakeholders is needed to assign the different levels. As shown, the timescale of the disturbance is very important. This timescale also has an influence on the timescale of recovery. For example, if a lack of water availability lasts only four days it will take less time to refill the buffer of lake Lange Vlieter than when the disturbance lasts the full three weeks. Knowledge from the stakeholders is needed to take both these timescales into account in order to properly assign the different levels. In this case it would make sense to involve the drinking water company WML and the organisation in charge of maintaining the water level in the Lateraalkanaal as well as experts to help determine to origin and extend of possible pollution.

Once the different levels have been assigned a score for the Meuse river system with regard to drinking water production by WML can be determined. In order to determine the score for drinking water production for the entire Meuse river system all intake points along the river need to be taken into account. These intake points provide water to several different drinking water companies. This means that a disturbance-impact graph will need to be created for all these different companies. Furthermore, the levels need to be assigned to all these different disturbance-impact graphs. Since step 3 of the approach has not been performed due to time constraints a score for drinking water production cannot be given.

## 8. Discussion

*This chapter contains a discussion on the resilience assessment approach and its application to the case study.*

### 8.1. Resilience of river systems

The goal of the literature study on resilience was to create a definition of resilience of river systems which could be used to assess this resilience. The definition as given, focussing on the continuation of functioning, has allowed this assessment. It focusses only on the system functions and does not take into account the resilience of the characteristics. The characteristics do not have a clear goal (against which to measure the continuation of functioning) unless linked to a function. Hence, the resilience of the characteristics is indirectly assessed through the functions.

The assessment focusses on disturbances caused by external factors. Changes within the system can also cause disturbances. Since these are not taken into account the resilience score assigned using the resilience assessment approach does not reflect these possible internal disturbances. If it is desired to take these into account the definition has to be amended to include these.

The system boundaries as defined in the definition of resilience of river systems depend on the physical river stretch and the different functions. At the start of the system analysis, it is important to accurately define the boundaries of the physical river stretch. The boundaries of the different functions should be defined at the start as well, however, these might have to be amended after the completion of the disturbance-impact graphs when they turn out to be too stringent or too broad.

### 8.2. Shipping

The analysis of shipping on the Julianakanaal shows that this function appears to be very resilient. A cease in functioning has not occurred in the 84 years considered. For both locks the thresholds for the need of pumping has been exceeded every year. Alternative locking methods have never been necessary for the lock at Born. They have been necessary for the lock at Maasbracht for but only for 70 days in 84 years. Since the use of pumps does not decrease the capacity of the canal, a decrease in capacity occurred for only 70 days. This is likely due to the fact that the water level in the Julianakanaal is managed to ensure a continued shipping capacity.

It could perhaps be argued that canals are not part of a river system since they are not the physical river stretch under consideration. However, if they are considered implemented measures, as done in this research, they are a part of the river system since these measures are implemented to improve the functioning or resilience of a river system. To assess the effect of this measure a comparison using the scores of the situation with and without the canal can be made.

The Julianakanaal can be seen as an implemented measure. The water depth in the river stretch next to the canal does not provide sufficient draught and hence the canal has been constructed. If the canal is considered to be measure the analysis shows that the measure has had the desired effect given that a decrease in shipping capacity only occurred for 70 days since the canal has been opened.

The analysis used to assess the resilience of shipping requires several different types of data. An overview of the data requirements, and the alternative used when this data was unavailable, can be found in Table 9.

For shipping in the Julianakanaal the details of both the water depth throughout the canal and the details of the operating procedures of the locks were needed. The guaranteed water depth throughout the canal is 3.5 m. Data on the water depth is needed to investigate whether this guaranteed water depth is achieved. However, data on the water depth was unavailable. Data on the water level was available. This data was only available in m NAP. The height of the bed of the canal in m NAP could not be found. Hence, the water depth in the canal could not be calculated. The data found, however, could be used to investigate the fluctuation in the water level of the canal from 2010 to 2019. During this period the water level barely fluctuates except for late 2010 and early 2011. These fluctuations are due to a higher water level which

does not pose a problem for the draught for shipping. It has been assumed that the relatively constant water level of 44.1 m NAP provides sufficient draught.

For both locks (Born and Maasbracht) it needed to be determined which of the locking procedure mentioned in Section 6.1 could be used. Furthermore, the pumping capacity of both locks was needed. Both this data and the discharge below which reducing water losses is necessary have been obtained. What was not readily available, however, was data on how the pumps are operated during low discharges. If the first lock uses its full pumping capacity this has a large influence on the second lock since this will then receive an even smaller discharge. It might be best to optimise the usage of pumps at both locks to ensure the lowest operating costs. However, since data on this could not be found the canal has been schematised as a single reservoir in the water balance in Section 6.4. This water balance also required data on the evaporation, which has been acquired from KNMI (2020). Data on the interaction with the groundwater could not easily be found. It has therefore been assumed that no interaction with the groundwater occurs.

Table 9 Data requirements shipping

Required data	Alternative used
Required draught	
Water depth Julianakanaal	Water level Julianakanaal
Operating procedures locks	
Pumping capacity locks	
Start reducing water losses	
Discharge Julianakanaal	
Evaporation	
Interaction with the groundwater	No interaction assumed
Operating procedure pumping capacity both locks	Schematised as canal with only one lock at the end

### 8.3. Drinking water production

The drinking water production by WML appears to be resilient when focussing on low discharges as is done in this research. Few to no stops in intake occurred due to a lack of water availability. This likely due to the location of the intake point. The intake point is located in the Lateraalkanaal. The water level of this canal is managed for shipping and drinking water purposes. Furthermore, the desired intake is very small, only 0.6 m<sup>3</sup>/s.

However, when focussing on water quality stops in intake do occur. In 2013 and 2014 a stop in intake occurred for more than 200 days each year. The exact days on which this occurred are unknown, however, considering how many days this occurred it must have been for consecutive periods of two to three weeks. This means a cease in functioning has occurred multiple times. Hence, when the water quality is considered the resilience appears to be very poor.

The low discharge considered is not a relevant disturbance for the drinking water production, as no stops in intake have occurred. In order to obtain an accurate assessment of the resilience of drinking water production other relevant disturbances should be considered as well. An additional step has been added to the approach in order to assess the relevance of a disturbance before a full analysis is performed.

The analysis of the drinking water production shows the importance of the system boundaries. A cease in functioning of the entire drinking water production scheme of WML, which occur when no intake is possible for four to five months, has never occurred. However, a cease in functioning of the part of the scheme related to the physical river stretch (and thus the river system) has occurred. The system boundaries determine which part of the production scheme is considered to be part of this river system. Hence these boundaries have a large influence on the assessment of the resilience of the function. Step 1d and 2b of the approach have been adapted to reflect this.

An overview of the required data for the analysis of drinking water production by WML can be found in Table 10. This table also shows the alternative used when the required data was not readily available.



In order to check whether the required water for extraction for drinking water production is available the discharge in the Lateraalkanaal is needed. This was currently unavailable, however, it might be possible to obtain it from the discharge in the Meuse near the entrance and exit of the canal. It might also be possible to obtain it from the discharge near Maasbracht and the operating policy for the weirs and locks in the Lateraalkanaal. Neither of these options have been pursued due to time constraints.

In order to determine the requirements for the production of drinking water the production scheme of WML is needed. This as well as their scheme for alternative production, when insufficient water is available within the river system, has been obtained. The intake point for production using surface water is located near Beegden in the Lateraalkanaal. The required discharge at this intake point is needed in order to determine whether this condition can be met. However, this discharge could not be found. Therefore, an estimation has been made based on the total annual extraction. Data on the discharge near this intake point could not be found either. However, other research has stated that low discharges do not pose any problems for the drinking water production by WML since the intake point is located in the canal and the water level in the canal is managed for shipping and drinking water purposes. An analysis of the water level during 19 years shows that the water level in the canal does not drop below 1.4 m NAP. Based on this and the fact that the required discharge is very small (0.6 m<sup>3</sup>/s) it has been assumed that low discharges have indeed not caused any problems in the past.

Table 10 Data requirements drinking water production

Required data	Alternative used
Standard production scheme WML	
Possibilities for alternative production	
Required discharge at intake point	Estimation made based on annual extraction
Discharge near intake point	Water level Lateraalkanaal and other research

#### 8.4. The resilience assessment approach

In the first step of the resilience assessment approach a system overview is created which forces one to look at all the system's characteristics and functions and their connections. It is therefore less likely that the effect a measure has on other characteristics or functions is overlooked. The disturbance-impact graphs created in the next step give a graphical overview of all the technical information of a specific function. These graphical overviews can be used to show stakeholders and decisionmakers how the different parts of the system function and where problems might occur. Their knowledge of the use of the system and the impact they have experienced during previous disturbances is then used to assign the different levels of the resilience classification to the disturbance-impact graphs. This hybrid approach allows both the technical information and the experience of the stakeholders to be included in the determination of the resilience.

Both functions of the case study used to test the approach appear to be very resilient. This could either be because the approach is not yet applicable in its current form or because both functions simply are very resilient with regard to the considered disturbance. Since the considered disturbance, low discharge, is taken into account the operating procedures of both functions, as illustrated in the respective chapters and earlier in this discussion, it is assumed that both functions simply are resilient with regard to disturbance and that step 1 and 2 of the approach are thus applicable in their current form.

A challenge in using this approach is the definition of the system boundaries. As illustrated, these can have a large influence on the assessment of the resilience of the different functions. It is therefore not unlikely that the definitions created at the start have to be amended later.

Another challenge is the choice for the considered disturbance. As seen in Section 7.3 the disturbance chosen at first might not be the relevant disturbance for the considered function. In order to reduce the time needed to discover that the considered disturbance is irrelevant step 2d has been added to the approach. Using this reduced analysis allows the relevance of the disturbance to be investigated before performing the full analysis needed to determine how many times the thresholds have been exceeded.

The final result of the approach, the total score of the system, gives a general indication of the resilience, a score of 40 is significantly better than a score of 1000. However, the real value of the score is derived from



a comparison to the same system in a different scenario. In the example of Figure 53 the first score shows the score of the current system with an overall score of 40. Then measures are taken to improve the resilience of function five (score 2). When only looking at the resilience of function five these measures appear to be a success, the score for function five has dropped from ten to zero. However, the total score of the system has increased. The measures to improve the resilience of function five have deteriorated the resilience of function one and seven, both have increased from zero to ten. A different measure to improve the resilience of function five can also be found in Figure 53 (score 3). Here, it can be seen that the total score has dropped from 40 to 30 due to the increased resilience of function five while no other functions have deteriorated. All three scores, 40, 50 and 30 suggest a resilient system. However, when compared to the original score of 40 a score of 50 suddenly does not seem very resilient. So, an overall judgement can be passed on the resilience of a river system based on the total score. However, the true value of the score can only be seen when comparing different scenarios.

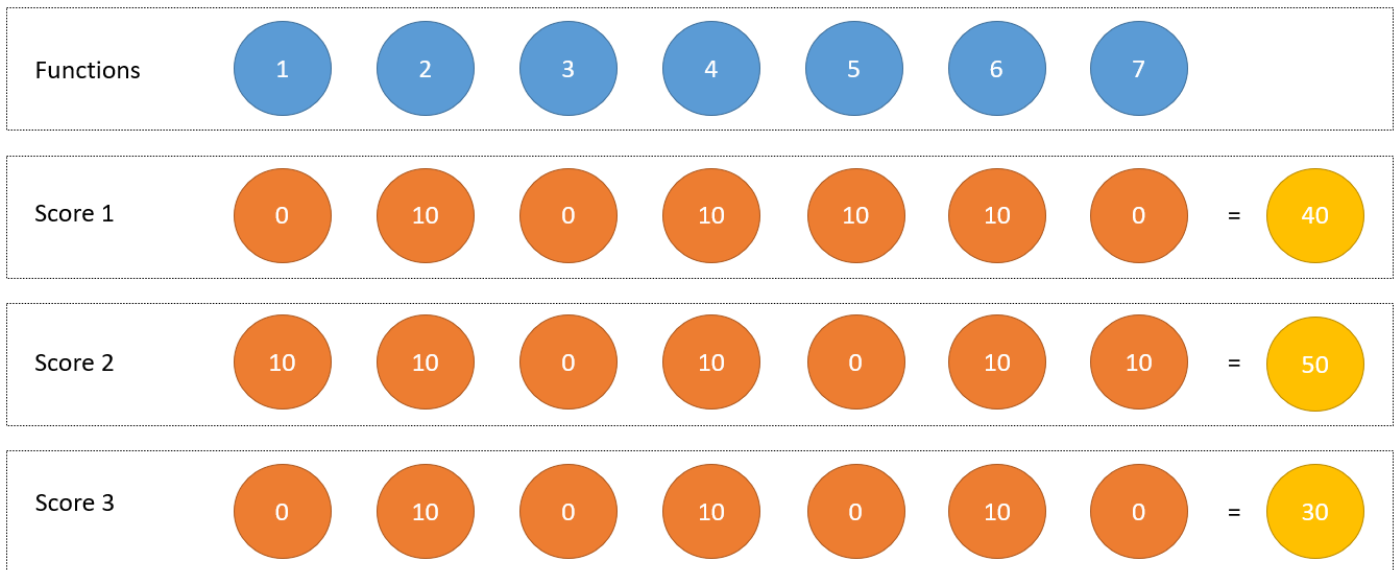


Figure 53 Example of score comparison

As can be seen in the example it is important to look at the individual scores and not just the total score. In the example the total score does show an overall increase or decrease in the resilience but not why this occurs. Looking at the individual scores shows how a measure aimed at one function influences the others. This can help answer the question whether something that is resilient for one function is also resilient for another.

It is important to properly log the discussion in which the different levels are assigned to the disturbance-impact graphs. When the approach is used to investigate the influence of measure on the resilience of the river system the levels need to be assigned to the new disturbance-impact graphs in the same manner as done for the original graphs in order to be able to properly compare them. This logging is also needed when the system has changed and analyses have to be redone in the future.

Currently, the approach is used to determine the resilience of the functions. However, it could also be used to assess the resilience of different characteristics. In order to do this a definition for the functioning of a characteristic is needed. Perhaps a desired state for the different characteristics can be defined. This would represent functioning under normal conditions. Disturbances will then alter this state and impede this functioning. However, defining thresholds with regard to this impeding of functioning will likely not be based on solely technical information as is done for functions. Hence, the assessment of this resilience will likely be more subjective.

In order to see how the resilience assessment approach fits in the development of a new project or policy decision the multi-objective analysis under (deep) uncertainty and the dynamic adaptive policy pathways are considered.

The multi-objective analysis focusses on a single project. The decision to intervene and where and how to intervene has already been made and specific demands for the performance of the project have been defined (Timmermans et al., 2020). The resilience assessment approach can be used to help determine where intervention is needed and what form this intervention should have.

The dynamic adaptive policy pathways can be used to ensure that a strategic vision for the future is reached. This strategic vision is defined at the start and possible events that can impede the achievement of this goal are identified as well as possible countermeasures (Haasnoot et al., 2012). The resilience assessment approach can be used to help determine which events can be impeding for different parts of the system.

Hence, the resilience assessment approach can be used support other methods and provides several insights on its own.

## 8.5. Resilience of the Meuse river system

Only two functions of the Meuse river system have been analysed in this research, hence, the assessment of the resilience of the river system is based solely on these two functions and is therefore likely only moderately representative.

Furthermore, both functions have not been considered in their entirety. In the case of shipping only shipping on the Julianakanaal has been considered and not shipping on the entire Meuse river within the Netherlands. The analysis of drinking water production only included drinking water production by WML and not any of the other drinking water companies that use water from the Meuse river system.

Since both analyses were performed at a later stage of the research stakeholder involvement, step 3 of the approach, has not been included due to time constraints. Hence, the analyses consist of only the first two steps of the resilience assessment approach. Consequently, no score has been assigned to the functions. The assessment of both functions is based solely on how many times the thresholds have been exceeded.

With regard to low discharges both functions seem to be resilient. However, when water quality is also taken into account drinking water production has a poor resilience. If it is assumed that these two functions adequately represent the system then it can be said that the Meuse river system is resilient with regard to droughts when drought are treated as solely a decrease in discharge.

However, both functions seem very resilient with regard to low discharges since low discharges appear to have been taken into account in their operating procedures. Shipping uses a canal with manually operated water levels and the intake point of the drinking water production is located in a different canal that also has manually operated water levels. Hence, if the resilience of the entire system is based on solely these two functions with regard to low discharges this resilience is not an accurate representation. This assessment will likely be too positive.

A more accurate assessment can be obtained when the water quality is also taken into account. While this water quality has no influence on shipping it does have a significant influence on drinking water production. The poor resilience of the drinking water production with regard to water quality has a larger influence on the resilience of the function than the good resilience with regard to low discharge due to the logarithmic scale of the scoring system. Hence, when both are taken into account the drinking water quality does not appear to be very resilient.

Now, if the two functions are used to assess the resilience of the entire river system, the resilience of the system appears to be merely average. Given that disturbances do cause quite an impact in some cases this is assumed to be a more accurate assessment of the resilience of the system.

## 9. Conclusions and recommendations

*This chapter contains the conclusions of the study presented in this report and gives recommendations for further research on the assessment of the resilience of river systems.*

### 9.1. Conclusions

River systems experience disturbances and handle all disturbances differently with regard to the different functions. The resilience of a river system can be used to determine how a river system responds to these disturbances. However, a method to assess the resilience of river systems is not yet available.

Using a literature study on resilience a definition for the resilience of river systems has been created. Using this definition and the literature study on the assessment of resilience a first version of the approach to assess resilience was created. The further development of this approach was an iterative process during which the approach was applied to the case study of the Meuse river system to see whether further amendment was needed.

The resilience assessment approach, as proposed in this study, can be used to assess the resilience of river systems. It is based on the resilience suggestions of de Bruijn et al. (2017) (adopt a system's approach, look at beyond-design events, build and prepare infrastructure according to the 'remain functioning' principle, increase recovery capacity by looking at social, institutional and economical capital and remain resilient into the future), the stressor-response graphs of Mens (2015) and the drought classification of Ministerie van Infrastructuur en Waterstaat (2020) (a script which describes the different phases with regard to droughts and water allocation, in the Netherlands, and classifies them accordingly). The approach consists of four steps, the creation of a system overview including the identification of external factors, characteristics and functions, the creation of disturbance-impact graphs for the different functions and disturbances, the assessment of the resilience of the different functions and the assessment of the resilience of the river system.

The resilience of a river system, as considered in the proposed approach, is defined as the ability of the system to continue functioning during a disturbance. The disturbances considered are short-term disturbances since the focus of the study is low discharges due to droughts. The continuation of functioning is applied to solely the functions of river systems since this continuation of functioning depends of the achievement of a certain goal and characteristics do not have a clear goal when they are not linked to a function.

The approach has been applied to shipping and drinking water production of the Meuse river system with regard to low discharge due to droughts. Both these functions appear to be very resilient with regard to this disturbance. For shipping this is likely largely due to the fact that the water level in the Julianakanaal is managed to ensure continued shipping possibilities during discharge fluctuations. Pumping facilities have been constructed in order to maintain water levels even when very small discharges occur. The large resilience of the drinking water production by Waterleiding Maatschappij Limburg is likely largely due to the fact that the intake point is located in the Lateraalkanaal. The water level of this canal is managed using weir and sluices for shipping and drinking water production. Furthermore, the required discharge is very small only 0.6 m<sup>3</sup>/s. The lowest discharge in the Meuse river (based on the analysis of Section 6.4) is 9.31 m<sup>3</sup>/s.

When the resilience of the Meuse river system is assessed based on the analyses of these two functions the system appears to be very resilient (in the current situation). However, the analysis of drinking water production showed that while production is very resilient with regard to the disturbance of low discharge, problems often occur due to water quality. Pollution plumes have a detrimental effect on the water quality and this disturbance should also be considered in order to assess the 'full' resilience of this function. When another disturbance is considered, and when more functions are considered, the result of the assessment of the Meuse river system is likely very different. In order to give an accurate assessment of the resilience of the Meuse river system with regard to droughts more functions should be considered. An accurate assessment of the 'full' resilience of the river system also requires consideration of more disturbances.

Only the first two steps of the approach have been tested using the case study. These steps have been adapted and the final version can be used in practice. The third and fourth step of the approach have not yet been tested and will likely need adaptation before they can be used in practice.

## 9.2. Recommendations

### 9.2.1. Steps 3 and 4 of the resilience assessment approach

Due to time constraints only steps one and two have been tested. Both steps three and four should be tested before the approach is used in practice. Especially step 3a (the assignment of the different levels of the resilience classification to the disturbance-impact graphs) might require additional adaptation. In the approach general instruction for stakeholder input session are given. An input session, even for only a few functions, can help determine whether these instructions are sufficient. Furthermore, this session can uncover possible challenges and complications that have not been considered yet.

### 9.2.2. Applicability to other river systems

The resilience assessment approach should be applicable to river systems in general. However, it has only been tested for the Meuse river system. It should be investigated whether the approach is indeed applicable to other river systems. Especially the system boundaries might pose some challenges. The instructions for the system boundaries given in the approach are largely based on the experience of the case study. They are therefore applicable to the case study but it has not been tested whether they are equally applicable to other river systems.

### 9.2.3. Applicability to characteristics

The resilience assessment approach focusses on the continuation of functioning of the river system functions. The resilience of the characteristics is indirectly assessed through the functions. A separate assessment of the characteristics could have an influence on the resilience score of the system. It should be investigated whether the resilience of the characteristics can be assessed separately and whether and how this influences the resilience score of the river system.

The continuation of functioning could perhaps be applied to characteristics by defining a desired state, as a goal, and looking at how disturbances impede the 'continuation of 'functioning' of this state. Research should be done to investigate this.

## References

- Abspoel, R., de Vries, P. A., & Bijlaard, F. S. (2013). *Staalconstructies*. Delft: TU Delft.
- Adger, N. W. (2000, September). Social and ecological resilience: are they related? *Progress in Human Geography*, pp. 347-364.
- Asselman, N., Barneveld, H., Klijn, F., & van Winden, A. (2018). *Het Verhaal van de Maas*. Retrieved from Rijksoverheid Helpdesk Water: <https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/rivierkennis/verhaal-maas/>
- Becker, A., van de Pas, B., Klijn, F., & Asselman, N. (2020). *Towards a resilient Meuse River Concept versie mei 2020*. Delft: Deltares.
- Binnenvaart Krant. (2020, February 5). *Hoogwater op de Maas*. Retrieved from Binnenvaart Krant: <https://binnenvaartkrant.nl/hoogwater-op-de-maas>
- Bolt, E. (2003). *Scheepvaartaspecten Laagwaterbeleid Julianakanaal en Lateraalkanaal*. Rotterdam: Ministerie van Verkeer en Waterstaat.
- Breedebeld, J., & Kramer, N. (2018). *Kennisprogramma Natte Kunstwerken*. Delft: Deltares.
- Chrzanowski, C. (2016). *Een natuurlijker Maas. Samenvattende rapportage van de monitoringsresultaten 2017 van het project Monitoring en evaluatie natuur(vriendelijk)oevers Maas; ecologie en morfologie*. Delft: Deltares.
- Davoudi, S. (2012, May 24). Resilience: A bridging concept or a dead end? *Planning Theory & Practice*, pp. 299-333.
- de Bruijn, K., Buurman, J., Mens, M., Dahm, R., & Klijn, F. (2017, April). Resilience in practice: Five principles to enable societies to cope with extreme weather events. *Environmental Science & Policy*, pp. 21-30.
- de Jong, J. (2019). *Toename van pomp- en vaarkosten door droogte bij Maasbracht en Born*. Delft: Deltares.
- De Nederlandse Overheid. (1995, January 17). *Verdrag tussen het Koninkrijk der Nederlanden van het Vlaams Gewest inzake de afvoer van het water van de Maas, Antwerpen, 17-01-1995*. Retrieved from Wettenbank: <https://wetten.overheid.nl/BWBV0001232/1996-07-01>
- De Nederlandse Overheid. (2019, October 1). *Activiteitenbesluit Milieubeheer*. Retrieved from Wettenbank Overheid: [https://wetten.overheid.nl/BWBR0022762/2019-10-01/#Hoofdstuk3\\_Afdeling3.1\\_Paragraaf3.1.5\\_Artikel3.6](https://wetten.overheid.nl/BWBR0022762/2019-10-01/#Hoofdstuk3_Afdeling3.1_Paragraaf3.1.5_Artikel3.6)
- De Nederlandse Overheid. (2020, January 1). *Waterwet*. Retrieved from Wettenbank Overheid: [https://wetten.overheid.nl/BWBR0025458/2020-01-01/#Hoofdstuk6\\_Paragraaf1\\_Artikel6.1](https://wetten.overheid.nl/BWBR0025458/2020-01-01/#Hoofdstuk6_Paragraaf1_Artikel6.1)
- Duodo, G. O., Goonetilleke, A., & Ayoko, G. A. (2016). Comparison of pollution indices for the assessment of heavy metal in Brisbane River sediment. *Environmental Pollution*, 1077-1091.
- Fünfgeld, H., & McEvoy, D. (2012). Resilience as a useful concept for climate change adaptation? *Planning Theory & Practice*, 324-328.

- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2012). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 485-498.
- Hoogheemraadschap van Delfland. (2019, July 18). *Delfland bestrijdt blauwalg Delfste Hout - Plas tijdelijk dicht*. Retrieved from Hoogheemraadschap van Delfland: <https://www.hhdelfland.nl/actueel/nieuws/delfland-bestrijdt-blauwalg-delftse-hout-plas-tijdelijk-dicht>
- Hussain, M. (2013, March 5). Resilience: meaningless jargon or development solution? *The Guardian*. Retrieved from <https://theguardian.com/global-development-professionals-network/2013/mar/05/resilience-development-buzzwords>
- KNMI. (2020). *Overzicht van de neerslag en verdamping in Nederland*. Retrieved from Koninklijk Nederlands Meteorologisch Instituut: <https://www.knmi.nl/nederland-nu/klimatologie/gegevens/monv>
- Knuth, K. (2019, May 7). *The term "Resilience" is everywhere - but what does it really mean?* Retrieved from Ensia: <https://ensia.com/articles/what-is-resilience/>
- Ligteringen, H. (2017). *Ports and Terminals*. Delft: Delft Academic Press.
- Madni, A. M., & Jackson, S. (2009, June). Toward a Conceptual Framework for Resilience Engineering. *IEEE Systems Journal*, pp. 181-191.
- Mens, M. J. (2015). *System Robustness Analysis in Support of Flood and Drought Risk Management*. Amsterdam: IOS Press BV.
- Ministerie van Infrastructuur en Milieu. (2012). *Structuurvisie Infrastructuur en Ruimte*. Ministerie van Infrastructuur en Milieu.
- Ministerie van Infrastructuur en Waterstaat. (2020). *Landelijk draaiboek waterverdeling en droogte*. Watermanagement centrum Nederland.
- Ministerie van Verkeer en Waterstaat. (1998). *Vierde Nota waterhuishouding Regeringsbeslissing*. Den Haag: Ministerie van Verkeer en Waterstaat.
- NH Nieuws. (2018, August 1). *Grote Sluis Spaarndam dicht door droogte: pleziervaart de dupe*. Retrieved from NH Nieuws: <https://www.nhnieuws.nl/nieuws/228995/grote-sluis-spaarndam-dicht-door-droogte-pleziervaart-de-dupe>
- Ouyang, Y. (2005). Evaluation of river water quality monitoring stations by principal component analysis. *Water Research*, 2621-2635.
- Pahl-Wostl, C. (2009, June 10). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environment Change*, pp. 354-365.
- Prinsen, G. (2008). *Maasafvoer en andere DM-invoer*. Delft: Deltares.
- Rijkswaterstaat. (2009). *Leggerdocument sluis Limmel*. Rijkswaterstaat.
- Rijkswaterstaat. (2016). *Vlot en veilig door een sluis*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/water/wetten-regels-en-vergunningen/recreatievaart/vlot-en-veilig-door-een-sluis.aspx>
- Rijkswaterstaat. (2017). *Maas*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/maas/index.aspx>

- Rijkswaterstaat. (2019, September 11). *Maatregelen vanwege lage waterafvoer Maas*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/nieuws/2019/09/maatregelen-vanwege-lage-waterafvoer-maas.aspx>
- Rijkswaterstaat. (2020-a, March 30). *Projectenoverzicht water*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/water/projectenoverzicht#water,1>,
- Rijkswaterstaat. (2020-b, April 3). *Rijkswaterstaat gunt verruiming traject Berg - Obbicht in het Julianakanaal aan Van den Herik Sliedrecht*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/nieuws/2020/04/rijkswaterstaat-gunt-verruiming-traject-berg-obbicht-in-het-julianakanaal-aan-van-den-herik-sliedrecht.aspx>
- Rijkswaterstaat. (2020-c, July). *Waterinfo*. Retrieved from Rijkswaterstaat: <https://waterinfo.rws.nl/#!/nav/index/>
- Rijkswaterstaat. (n.d.). *Maas: verruiming Julianakanaal*. Retrieved from Rijkswaterstaat: <https://www.rijkswaterstaat.nl/water/projectenoverzicht/maas-verruiming-julianakanaal/index.aspx>
- RIWA-Maas. (2019). *Jaarrapport 2018 De Maas*. Rotterdam: RIWA-Maas.
- Sjerps, R., & Huiting, H. (2017). *Gevolgen van zoetwatertekorten voor industrie en drinkwaterproductie*. Nieuwegein: KWR.
- Speksnijder, C. (2019, September 11). Raakt ons drinkwater op? Waterbedrijven slaan alarm over de Maas. *De Volkskrant*.
- Tangena, B. H. (2014). *Behoeftedekking Nederlandse drinkwatervoorziening 2015-2040*. Bilthoven: Rijksinstituut voor Volksgezondheid en Milieu.
- Timmermans, J., van Druuten, E., Wauben, M., & Kwakkel, J. (2020). Polder pumping-station for the future: designing and retrofitting infrastructure systems under structural uncertainty. *Sustainable and Resilient Infrastructure*.
- Transport Online. (2019, September 11). *Langere wachttijden scheepvaart vanwege lage waterafvoer Maas*. Retrieved from Transport Online: <https://www.transport-online.nl/site/107001/langere-wachttijden-scheepvaart-vanwege-lage-waterafvoer-maas/>
- van Heerder, J. (2019, September 11). Er dreigt een tekort aan drinkwater uit de Maas. *Trouw*.
- van Heugten, S., & Horrichs, S. (2019, November 2019). *Is ons drinkwater in gevaar door landbouwgif in de Maas?* Retrieved from 1 Limburg: <https://www.1limburg.nl/ons-drinkwater-gevaar-door-landbouwgif-de-maas>
- van Houdt, J. (2016, September 28). *Maas oevers projecten ID506367*. Retrieved from Rijkswaterstaat: <https://beeldbank.rws.nl/MediaObject/Details/506367>
- van Hussen, K., van de Velde, I., Läkamp, R., & van der Kooij, S. (2019). *Economische schade door droogte in 2018*. Rotterdam: Ecorys.
- van Liere, J. (2018, July 24). *Landbouw zucht onder extreem droge zomer*. Retrieved from Nieuwe Oogst: <https://www.nieuweoogst.nl/nieuws/2018/07/24/landbouw-zucht-onder-extreem-droge-zomer>
- Verheij, H. J., Stolker, C., & Groenveld, R. (2008). *Inland Waterways Ports, waterways and inland navigation*. Delft: Delft Academic Press.
- Waterleiding Maatschappij Limburg. (n.d.). *Over WML*. Retrieved from Waterleiding Maatschappij Limburg: <https://www.wml.nl/over-wml>



Wegman, C., Barneveld, H., & Vermeer, K. (2018). *Integraal Rivierbeheer Maas Functie Scheepvaart*. Lelystad: HKV.

Woods, D. D. (2015, April 3). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering and System Safety*, pp. 5-9.

# Appendix A Connections overview

