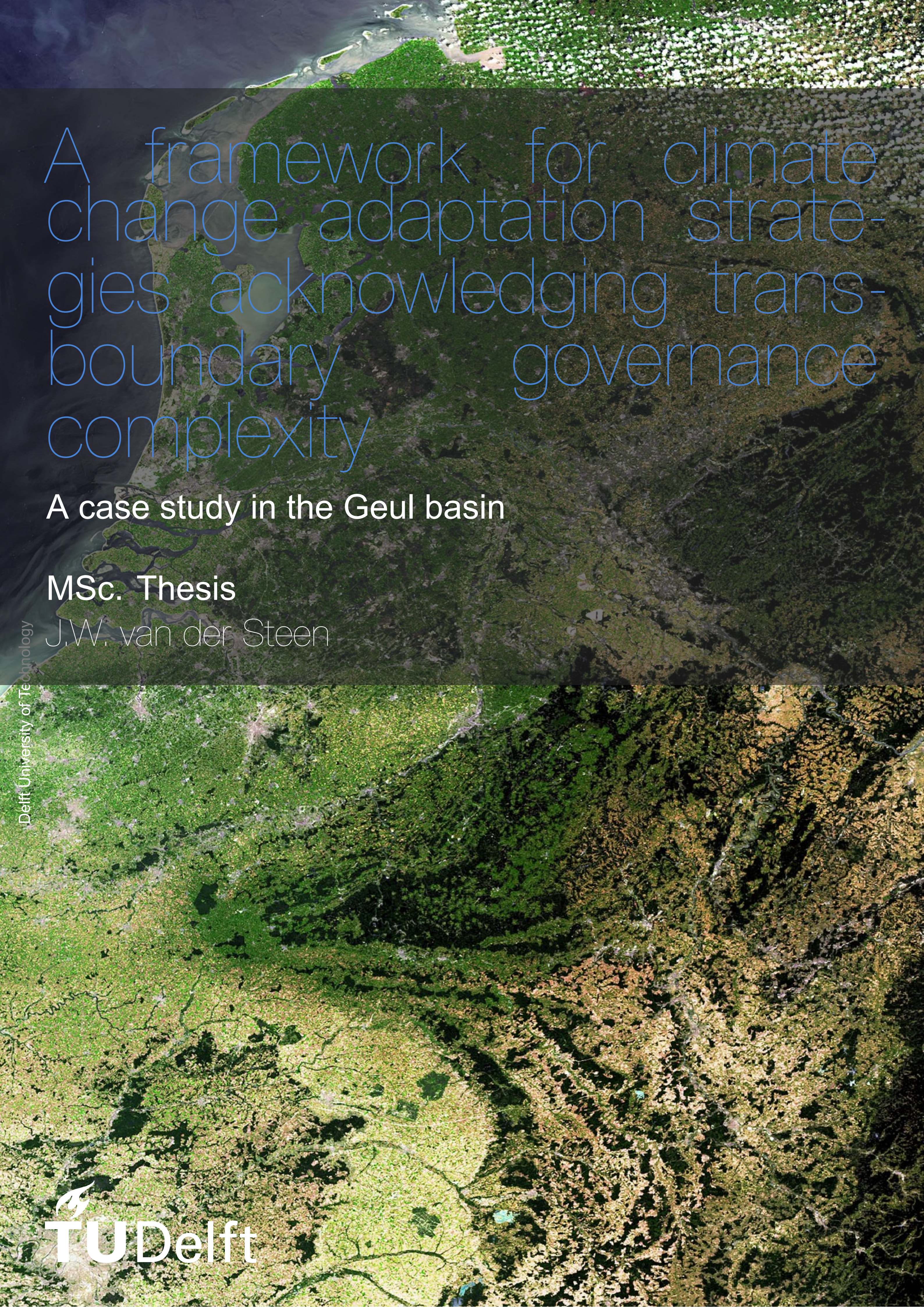

A framework for climate change adaptation strategies acknowledging transboundary governance complexity

A case study in the Geul basin

MSc. Thesis

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TUDelft

A framework for climate change adaptation strategies acknowledging transboundary governance complexity

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by

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Cover: 14 July 2003 image of the Benelux by Envisat's Medium Resolution Imaging Spectrometer (MERIS) (Modified)

TU Delft

Abstract

On the 13th and 14th of July 2021 a cold pit caused extreme precipitation along with record discharges in tributaries of the Meuse. These discharges caused floods in Belgium, Germany and the Netherlands. Extreme precipitation occurrence and its intensity are expected to increase in the area due to climate change this can lead to an increase in fluvial flood risk. This underlines the need for climate change adaptation efforts to combat increases in flood risk. Flood risk is the product of hazard, exposure and vulnerability. Research indicates all three are equally important drivers. Planned adaptation, however, has focused on mitigating flood hazard and reducing flood vulnerability. Planning of adaptation measures has been done with Decision Making in Deep Uncertainty (DMDU) methods to account for deep uncertainty. These methods lack natural and institutional context. The methods also implicate systems it governs are complicated rather than complex as DMDU methods lean on pre-determined actions and triggers. Literature suggests both the natural system and the system governing it are complex. Therefore there is a need for a method providing climate change adaptation strategies with regard for the context and the notion that these systems are complex.

To address the research gap, a Framework is developed that combines natural and institutional aspects of climate change adaptation. A systems approach is used to find leverage points for wider systemic change. This can be used to spark autonomous adaptation, thereby also targeting exposure and vulnerability. The Framework provides a solution space of possible adaptation combinations and maps of spatial cooperation difficulty. By combining these possible combinations and locations are proposed. Systemic leverage points determine preferential strategies and additional policies. The Framework is tested in a case study in the Geul, a transboundary tributary of the Meuse. Flood risk in the Geul is mostly situated in the downstream city of Valkenburg. Adaptation measures are therefore aimed at reducing flood risk there. This is done by evaluating their performance on achieving the storage equivalent of the excess discharge volume of the 2021 flood event; 6,000,000 m^3. Measures are recalculated to this millimeter equivalent for comparability. Methods used are expert judgment, literature review, social network analysis and using open-source information.

Of the 13,227 combinations, none can achieve the adaptation goal by 2050. This is when the Dutch government wants to fully adapted to climate change. Of these combinations, 10 can be implemented fully upstream and 29 can be implemented fully downstream. Any preference thus severely limits the number of combinations available. There are no combinations that only make use of natural solutions. The adaptive capacity is roughly 20 millimeters equivalent (6,680,000 m^3) upstream of Valkenburg and 23.6 millimeters equivalent (7,882,400 m^3) in the city itself. Two alternative options would suffice by themselves. These are raising quay walls in Valkenburg by 2.5 meters or constructing a giant reservoir in one of the dry-valleys.

The network governing flood risk is dense and polycentric. Cooperation quality is likely not sufficient between many actors to implement very intrusive adaptation measures that would be needed according to the solution space. When a certain cooperation is required, Flanders and the Netherlands are central players in the network. Germany and France are isolated in the network, causing the national governments of those nations to hold brokerage positions. Cooperation is the hardest in transboundary subcatchments especially when multiple nations are involved.

Depending on the preferences in the network, several adaptation strategies are possible in the Geul. In terms of cooperation difficulty, downstream solutions located in the Netherlands are preferential. Natural solutions would be preferable to harness self-organizational capacities of nature. Strategies that would cause secondary effects by intervening deeper into the systems should be highly visible. In addition, adaptation strategies should be accompanied by policies aimed at restoring the flow of information to citizens, restore or create financial incentives for autonomous adaptation of inhabitants and alter the paradigm of manageability of nature. Delays in planned adaptation response could be shortened by network interventions such as creating a central operational role in the network, implementing binding adaptation goals using the common European legislation or improving regional cooperation.

Preface

Before you lies the thesis I have written in partial fulfilment of the degree of Master of Science. I hope this work contributes to translating engineering solutions to real life. I value placing engineering solutions into a real world context. Humans shape how engineered solutions function: No matter how well thought off, engineering solutions are ineffective if the human aspect is not taken into account. People are intertwined with engineering.

During my student years, I have discovered taking a step back, being humble about what you understand (and what you don't) and observing might a better way to understand the world than trying to explain everything by something else. The systems approach I discovered during the writing of this thesis is an extremely interesting way to do this. I hold the theory in high regard and think there is a lot of truth in it. Hopefully the fields of climate adaptation and water management will benefit the coming years by more systemic views of their challenges. The task at hand is in any case significant. Hopefully this thesis inspires more people to have a broader view on engineering.

I also want to express some gratitude. I am grateful to my friends and family for their support during the last few years. My time as a student has been one of ups and downs, discovering myself and my motivations and acknowledging my limitations. The support of people around me allowed me to enjoy a wide range of experiences which have helped me become who I am now. I always felt the possibility to explore new things even though this is not a given. During my masters, I rediscovered the joy of learning. I want to thank the department and my fellow students for making this time so enjoyable and enriching.

In the end, an MSc. thesis is 'just' an educational activity. Any student writing their thesis will agree with me that this feels very different. Your thesis, at some point, becomes your life and vice versa. I feel that, in this thesis, I was able to bring my experiences from outside engineering and combine it with the knowledge I gained during my masters. I have enjoyed writing it and feel there is more to be discovered. I am proud with my work and my journey.

Lastly I want to thank my supervisors. I have enjoyed working with you! I want to thank you for your time and availability. I appreciate how you guided my abstract ideas into this thesis.

J.W. van der Steen
Delft, December 2022

Contents

1 Introduction

This thesis focuses on flood risk. It describes the development, use and testing of a Framework that can be used to gain insight in the adaptive capacity, solution space and the network of administrative entities involved in climate change adaptation (CCA). From this, it is able to propose adaptation strategies acknowledging transboundary governance complexity. This is done to identify suited CCA strategies to reduce flood risk. In this context, the solution space are the combinations of measures that would be able to achieve an adaptation goal. It is constrained by the locations that would be suited for the measure and the implementation time. The governance complexity in the area is quantified using expert judgment. By connecting these to the locations of administrative entities using their borders, maps can be created on cooperation difficulty per subcathcment. Combining these things, preferential adaptation strategies and locations can be suggested. Political and natural systems are regarded as complex. Adaptation strategies are therefore also assessed on their systemic effect.

Case Study

The Framework is tested in the Geul, a transboundary tributary of the Meuse. Its basin is shared by the Netherlands, Germany and Belgium (both Flanders and Wallonia). Due to its transboundary nature, the political context is hypothesized to be especially complex. During the 2021 European floods, an amount of 6,000,000 m^3 of water exceeded the discharge capacity and flooded several locations along the Geul. Valkenburg is the location where most damages occurred. This is because it is an hydraulic bottleneck. Due to the inhabitants and economic activity, the city also has high exposure.

In this Framework, measures are compared by recalculating them to a storage equivalent. Combinations are formed that are able to store the excess volume of the 2021 flood event. Together with the analysis of spatial governance difficulty and systemic properties, preferential strategies and locations are proposed. Lastly, the Framework is assessed on its broader applicability in other river basins.

Research Goal & Questions

The research goal is to find adaptation combinations and suitable locations for the Geul when acknowledging transboundary governance complexity. To find these adaptation combinations, the Framework is developed and used. The research goal can be achieved by answering the following questions:

1. Which combinations of measures can help adapt to fluvial flooding risk in the Geul?
2. In implementing these measures, which administrative actors are involved, and how is the quality of their cooperation?
3. Which adaptation combinations are suited and would be preferential for the Geul catchment?
4. How does the Framework developed in this thesis perform and can it be applied broader?

Research Context

Climate change is hard to manage because the effects of change and their extent are unknown. This means that planned adaptation is subject to deep uncertainty; both the effect and the degree to which adaptation is required are unknown. Management approaches have been developed for dealing with uncertainty in policy planning.[1] These are called Decision Making under Deep Uncertainty (DMDU) methods. DMDU methods can be either reactive or dynamic: One can design a robust plan that will do the job or iterate continuously.

DMDU methods are pre-defined. This implies the methods are based on the notion that natural- and governing systems are complicated rather than complex. Although able to cope with deep uncertainty, the management approaches might struggle with unexpected, self-organising and emergent characteristic for complex systems. Moreover, literature suggests DMDU methods do not take natural or human context into account.[2]

Research Gap

DMDU methods thus lack natural and political context.[2] In addition, DMDU methods do not suggest locations of measures based on this context. The pathways posed by DMDU methods fail to provide a systemic view. DMDU methods have been applied to situations where one parameter could be related to a timeframe. This enables DMDU methods to pose a high and low-end scenario and suggest strategies based on the parameter that is increasing or decreasing, for example sea level rise. In this subject, an amount of rise can be a trigger for additional action. In a situation where this link cannot be described by one parameter, such as changing precipitation patterns, these triggers are not useful. In fluvial flood risk, the intensity and duration of precipitation that is hazardous depends on the saturation of the soil, vegetation and spatial distribution of the precipitation. Over time, the natural context will self-organize and have a higher or lower runoff coefficient, a different retention time, different flow paths and so on. There is thus a need for a method to make the solution space insightful while taking into account natural and political context.

Climate change causes changes in precipitation patterns. In general, wet areas will become wetter and dry areas will become dryer.[3] Because landscapes have co-evolved with the climate [4], any change in the pattern will affect the discharge in streams. In smaller streams, such as tributaries, the change in discharge can be especially relevant. It might lead to increased flood- or drought risk by an increased occurrence probability. In the Geul this is especially relevant due to the strong correlation between precipitation and discharge.[5] This emphasizes the need to adapt to this new situation. Adaptation involves governments, people and nature. Together, they form the adaptive capacity; the ability to adapt. This is further complicated if a catchment spans multiple countries.

2021 European Floods

The 2021 European floods occurred after heavy precipitation events during July 13th and 14th in the area between the Alps and the Netherlands: Southern (Dutch) Limburg, among with the Ardennes and the Eiffel areas. In the area, a so-called cold pit occurred. This meteorological phenomenon is a low pressure area with a cold air bubble in its higher strata.[6] It is estimated that the associated discharges in the Rhine and Meuse tributaries were the highest ever recorded. This might partially be due to the wet period prior to the precipitation event.[7] The event caused flooding in Belgium, the Netherlands, Luxembourg and Germany. In total, at least 180 people lost their lives and damages are estimated to add up to 7 billion euros.[8]

Climate Change Adaptation (CCA)

The 2021 floods pose a need for adapting to a situation where extreme precipitation events occur more frequently. This has an effect on fluvial flood risk. In this context risk can be defined as the product of vulnerability, exposure and hazard. Where hazard is the event that can cause damage and its associated probability, exposure are the resources and infrastructure exposed to the event and vulnerability is the extent to which the assets are affected.[9]

Climate change causes changes precipitation patterns to which landscapes need to adapt to. Adapting to a new reality can either be autonomous or planned. It is the most effective when both occur at the same time.[10] Adapting to risk can be focused on hazard, exposure and vulnerability. Hazard mitigation can be increasing safety levels (e.g. by heightening dikes) thereby decreasing the occurrence probability. Exposure and vulnerability can be targeted by influencing the people and property at risk (e.g. via spatial planning or early-warning systems) or by making the people and property at risk more resilient to flooding (e.g. flood-proofing). Literature suggests all three factors in risk are equally important drivers for increases in flood risk.[11] This underlines the importance to have a broader scope than hazard mitigation alone in Climate change adaptation.

2
Setting the stage

Transboundary river basin management and climate change adaptation are typically subjects that involve a lot of administrative actors. In the Meuse and the Geul, all the basin countries are member states of the European Union, providing them with a common, legally binding supranational organization with laws and strategies. Some of which targeted at climate change, water and climate change adaptation. This creates an interesting dynamic for climate change adaptation. As integrated action and coordinated sets of measures might be needed to cope with current and future flood risks, transboundary tributaries are of special interest.

The Meuse is the subject of this thesis because it is a larger river basin where multiple tributaries are transboundary, with one being the Geul. The Meuse was affected heavily by the 2021 European floods and has also experienced droughts in recent years. Therefore, the basin has become more present in the public attention. This chapter will cover the characteristics of the Meuse, the Geul and the 2021 floods. Additionally, expected climate change effects and governance are addressed. Lastly, an overview of possible climate change adaptation measures from literature will be provided.

2.1. The Meuse

The Meuse is a rain fed river and is therefore quick in reaction to precipitation events.[12][13] Normally, 25 % of the discharge of the Meuse in the Netherlands originates from France, 40-50% of the discharge is from confluences in Belgium. 15% originates from tributaries in the Netherlands and the rest originates from smaller streams. The Meuse typically has wide valleys in France, but these become narrow and deep roughly from the French-Belgian border. Some sections of the Meuse might be especially vulnerable to fluvial flooding due to its steep valleys, relatively high slopes, rain fed nature and quick discharge trough narrow valleys.[13]

The Meuse can be characterized in three different zones. An image is provided in figure 2.1. The most upstream part is characterized by a relatively low slope, variable permeability and relatively low population density. The second zone is where the Ardennes are situated. It typically is low in permeability, has steep slopes and low population density. In the last, downstream zone, population density is higher. The area is flat and permeable.[12]

2.2. The Geul

The Geul is located on the border of the second and third zone. The sketched differences in geology are very present, with the upstream part being hilly, relatively impermeable and sparsely populated. The downstream part is flatter, has high storage capacity in the soil and is permeable. A lot of people are situated in the downstream part, with Valkenburg being the major settlement in the area.

The whole catchment changed when the population density increased in the 20th century[14]; meandering rivers were straightened and agriculture intensified. In addition, maize was introduced as a crop.[15] After the 1993 and 1995 floods, more space was reserved for the river again.[16] In terms of land use, the Geul basin consists of 5% maize, 40% pasture, 2% as impermeable built-up area and

Figure 2.1: Zones of the Meuse [12]

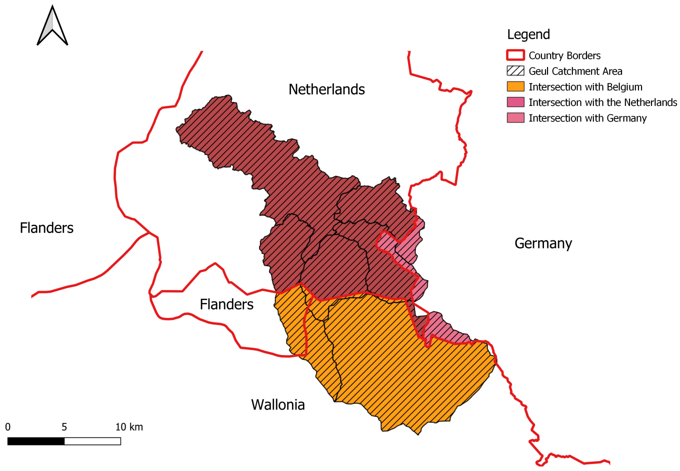


Figure 2.2: The intersection of the Geul catchment with different countries

20% deciduous forest.[17] Subcatchments Eyserbeek, Hommerich and Meerssen have relatively much built-up area.

2.2.1. Subcatchments

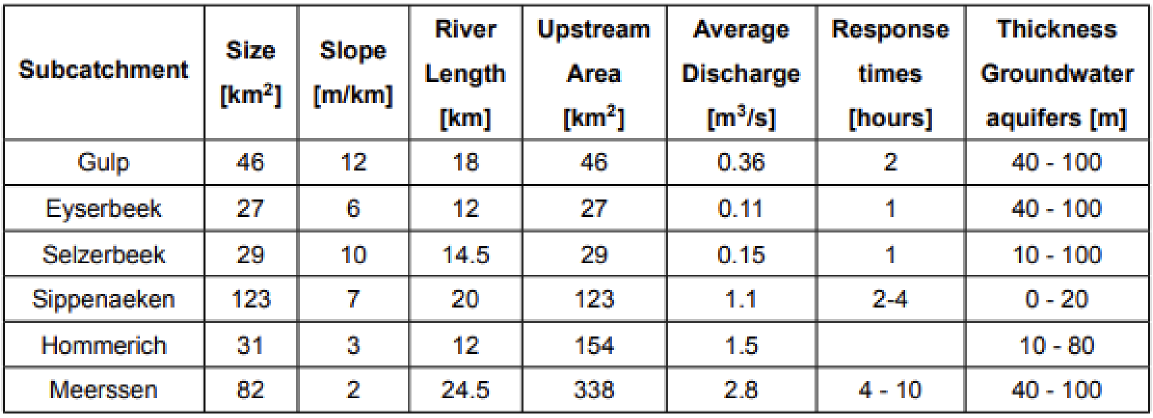
The Geul catchment is in this thesis referred to as a catchment consisting of six subcatchments; the Gulp, the Eyserbeek, the Selzerbeek, Sippenaeken, Hommerich and Meerssen. This follows the subcatchments as defined by Klein (2022).[7]

The Geul has two large hills which separate the Gulp (located to the west) and the Selzer and Eyserbeek (located to the east) from the subcatchments in the middle (Hommerich and more upstream Sippenaeken). The valley of the Geul is deeply incised in the surrounding plateaus and has an asymmetric form with steeper slopes in the east and less steep slopes in the west.[7]. The upstream area in Belgium is situated on a plateau. Slopes vary between 0.2 m/m in the most upstream area to 0.0015 m/m at the river mouth.[18]. In general, the valleys of the Geul are quick in hydrological response.[6] The Geul starts in Sippenaeken en flows through Hommerich as the 'kleine Geul'. Confluences are located near Gulpen with the Selzerbeek joining the Geul just upstream of Gulpen and the Gulp and Eyserbeek just downstream. The hills reach up to 250-300 meters.[17].

Characteristics of the sub basins are visualized by Klein (2022) in Figure 2.3.[7]

The tributaries are described by Klein (2022)[7] as;

- Gulp: Largest tributary with an area of 46 square kilometer. The elevation drop is almost 200 meters and the slope therefore is 12 m/km. It has high storage due to its thick groundwater aquifers. The soil has a very good infiltration capacity. Groundwater is lost to neighboring catchments.
- Eyserbeek: Has an average slope of 5.9 m/km. It has a high storage capacity due to the high unsaturated zone (40-100 m). It has a relatively large paved area.
- Selzerbeek: Slope of 0.01 m/m and with low storage capacity (10-20 meters of soil). Consequently, it has a flashy response to precipitation.
- Sippenaeken: Relatively large area with thin soils and low-storage (0-20 meters). It typically responds to precipitation between 2-4 hours.
- Hommerich: Characterized by a change in geology. Transitioning between a chalk (heterogeneous permeability) and a low permeability zone. This causes a higher storage capacity downstream.
- Meerssen: Hardly contributes to Geul discharge due to the high infiltration capacity.



Subcatchment	Size [km^2]	Slope [m/km]	River Length [km]	Upstream Area [km^2]	Average Discharge [m^3/s]	Response times [hours]	Thickness Groundwater aquifers [m]
Gulp	46	12	18	46	0.36	2	40 - 100
Eyserbeek	27	6	12	27	0.11	1	40 - 100
Selzerbeek	29	10	14.5	29	0.15	1	10 - 100
Sippenaeken	123	7	20	123	1.1	2-4	0 - 20
Hommerich	31	3	12	154	1.5		10 - 80
Meerssen	82	2	24.5	338	2.8	4 - 10	40 - 100

Figure 2.3: Overview of subcatchment characteristics from Klein (2022), extracted as a Figure.[7]

Transboundary element
The Geul is a transboundary catchment. It is a tributary of the Meuse and enters the Meuse just downstream of Maastricht, near Bunde in the Netherlands. The Geul spans Belgium (both Flanders and Wallonia), Germany and the Netherlands. The catchment is mostly located in the Netherlands and Belgium. Little sections in the east are German, the upstream and western parts are Belgian. An overview of the catchment and the country borders is provided in Figure 2.2.

German area
The response times of the catchments that are shared with Germany (Eyserbeek, Selzerbeek) is one hour. This is twice as low as any other catchment. Because of this, inflow from the Eyzerbeek and Selzerbeek can be flashy in nature.

Walloon area
Because of the thin soils and therefore low storage capacity, the area of the Geul in Wallonia is of specific interest. The area does, however, have no maize, relatively little agriculture and no steep hill slopes.[17] The Dutch area of the Geul has permeable and thick soil, causing the storage capacity to be large. Because of this, the Wallonian part contributed 2.5-3.5 as much to the peak discharge compared to the Netherlands.[17]

2.2.2. Geology
There is a clear distinction in geology between the upstream and the downstream parts of the Geul. The upstream section consists of Devonian and Carbonian (both Paleozoic era) depositions (slate, limestone, sandstone) while the plateaus and the flanks of the valley consists of aelion deposited löss that deposited in recent millennia. In the valleys, this is usually several meters thick.[17] Hendrix and Meinardi[19] state between 1 and 15 meters. Typically, upstream areas have an impermeable (e.g. slate or sandstone) or less permeable soil (e.g. clay) and flanks along the east and west of the Geul have permeable (e.g. sand and löss) or relatively permeable soils (e.g. limestone).[17]

Hydro-geological zones
Klein defines the area hydro-geologically in four different zones (3 through 6) based on the Dutch Groundwater Model.[7][20] An overview is provided in figure 2.4 Typically, zone 3 is low to medium permeable. Groundwater movement is slow laterally through sand and slow at the entrance of clay layers. Zone 4 is characterized by a thick chalk layer cut through by the river. Permeability is highly heterogeneous and ranges from high to low. There are preferential flow paths for groundwater, thus flow is generally quick.[20] Storage capacity of these plateaus is high because of the thickness of the soil. Zone 5 has medium to low permeability and groundwater is 30-50 meters below the surface and is recharged with precipitation. Zone 6 is low in permeability but has high heterogeneity such that the groundwater movement is low through very high. Storage capacity is limited.[7][20] The Belgian upstream area is characterized by impermeable carboniferous rock and therefore there is little to no storage capacity in plateaus or valleys and limited capacity on hill slopes.[7]

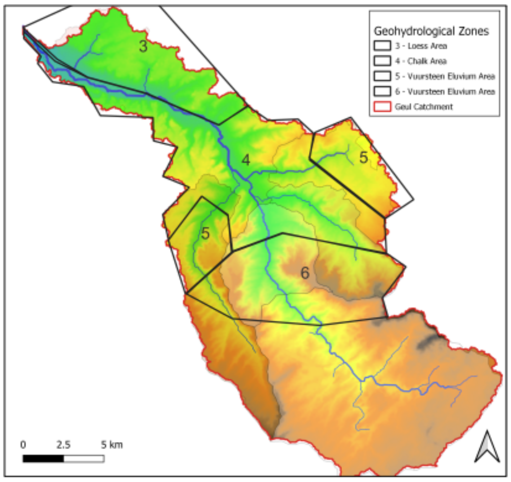


Figure 2.4: Different groundwater zones in the Geul according to the Dutch Groundwater Model from Klein (2022)[7]

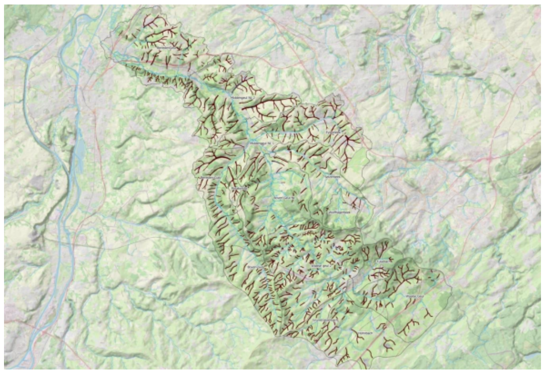


Figure 2.5: Dry-valley locations in the Geul.[17]

Aquifers
There are three main aquifers, namely the Aken, Vaals and Gulpen formation. These can be described as dual porous and hydraulic conductive. The flow typically shows quick response to precipitation.[7] The permeability of Vaals is 0.1-0.9 m/day, whilst the permeability of Aken and Gulpen is between 1-20 m/day. Therefore, Vaals is considered a barrier between the two others.[7].

2.2.3. Other features of interest
Underground culverts have been seen anecdotally. Stroming (2021) indicates it is not unlikely these are applied at large scale. Grassland typically retains water, but it does not when drained.[17]

There are also water storages in the basin area. Meerssen, Eyserbeek and Selzerbeek have relatively large storages. In the Belgian part, no retention basins are present[7]. In total, the storage is just over 800 thousand cubic metres. 38% of this storage is in Meerssen, 30% in Eyserbeek, 19% in Selzerbeek, 7% in Gulp, 6% in Hommerich and 0% in Sippenaeken.

The Geul has so-called dry-valleys. These valleys were formed during a different climatic era and are generally placed at locations with permeable soils. No stream exits these valleys, but water infiltrates. An overview of dry-valleys in the Geul is provided in figure 2.5[17]

2.2.4. Safety Levels
Downstream sections of the river can be very narrow and urbanized.[6] This causes water level to rise more sharply in times of high discharge. Because of this, and because of the high exposure in urban areas, such urbanized downstream sections can be potential bottlenecks. At these places the decimal value is higher and the water level rises more during high discharge than in rural areas. As a result, in these urban areas, retention of waterand discharge capacity can only be adjusted with costly measures.[6] Many places have therefore opted for a safety level of 25-year return periods instead of the usual 100 years for similar areas. This is a result of a Cost-Benefit Analysis.[6] This is also the case in Valkenburg.[21]

2.3. 2021 European Floods
On the 13th and 14th of July 2021, a cold pit caused an extreme precipitation event. In tributaries of the Meuse, record high discharges were recorded.[22] The hydrologic response of the Geul was highly heterogeneous and experienced higher runoff coefficients than usual, especially upstream. Antecedent moisture conditions might have aided this.[7] The event was in the range of accepted risk for Valkenburg even if Valkenburg had opted for a higher safety level. Given the high damages, there is a necessity to

decrease the flood risk for flood events, even if in the accepted risk range.

2.3.1. Cold pit

The high precipitation amounts were due to a slow moving low pressure area that originated from the North Atlantic and moved to Southern Europe. This sparked warm, moist air from the Baltic Sea to flow northeast. Baltic Sea temperatures were anomalously high, therefore it is possible that the northeast flow continued to supply moisture to the area. The slow moving low-pressure area was thus very saturated with warm and moist air and consecutively pushed up by the hilly Ardennes. This is visualized in figure 2.6. Due to this orographic rising, the air cooled down, causing the moisture capacity to fall and the precipitation to rain out. Due to the minimal movement of the low-pressure area, this caused unusual precipitation depths in the area. Combined with the saturated soils, this led to severe floods.

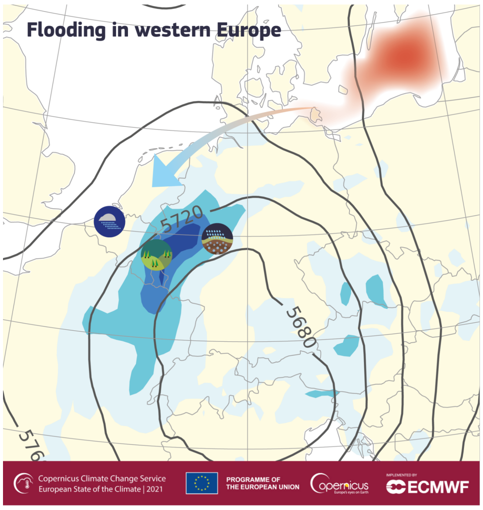


Figure 2.6: Origin of precipitation of the 2021 flood event.[22]

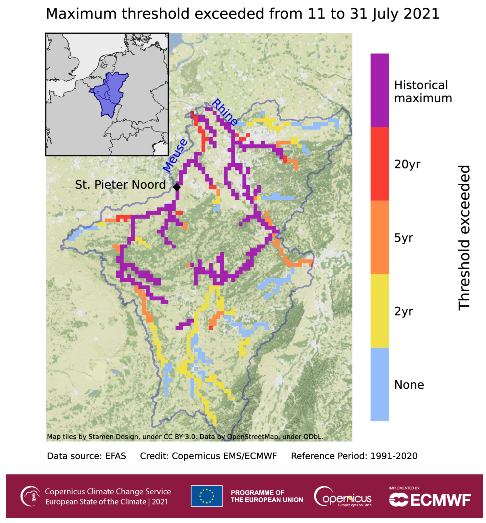


Figure 2.7: Discharge return periods.[22]

2.3.2. The floods in the Meuse

Precipitation

The most severe precipitation occurred between Liège and Bonn in the Vesdre and Ruhr subcatchments. The recorded precipitation daily maximum of 92.6 mm is the highest recorded in the region.[22] In Germany, local maxima reached up to 224 mm in 48 hours. This corresponds to a return period of between 100-1000 years.[6] Observed precipitation depth in the Ahr and the Belgian part of the Meuse subcatchment surpassed historical records significantly.[23] Figure 2.8 depicts daily precipitation depths.

Discharges

Copernicus estimated that the associated discharges in the Rhine and Meuse tributaries were the highest recorded in history.[22] Discharges in the Meuse are displayed in figure 2.7

Return period

For a location between the Alps and the Netherlands, a return period of 300 years is attributed to the event by the WWA.[23] In addition, the cumulative precipitation of the 12 days before the event was also extreme. The saturation of the soil potentially played a role in the flooding in the area.[22]

Damages

The most severe effects occurred in Belgium and Germany. These effects were more severe in those countries compared to the Netherlands and Luxembourg. Possibly this is due to the precipitation hotspots which were located near Liège and Bonn. Also, the narrow valley sections and steep slope might have created funnel-like effects.[23]

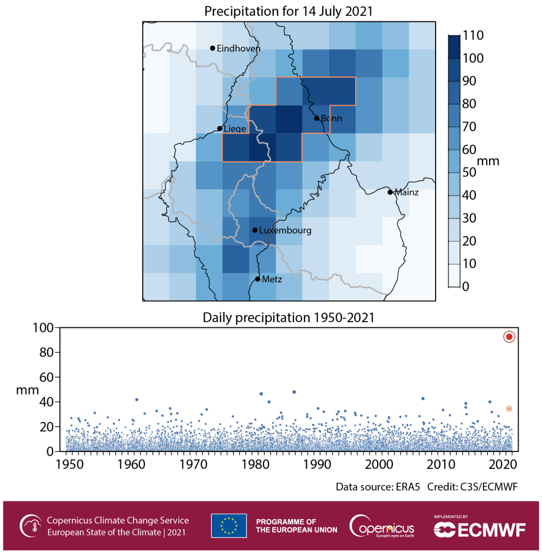


Figure 2.8: Precipitation on the 14th of July in the area between the Netherlands, Belgium, Germany and Luxembourg.(top) Precipitation records from the 1950s until now (roughly) of the area between Liège and Bonn. (bottom)[22]

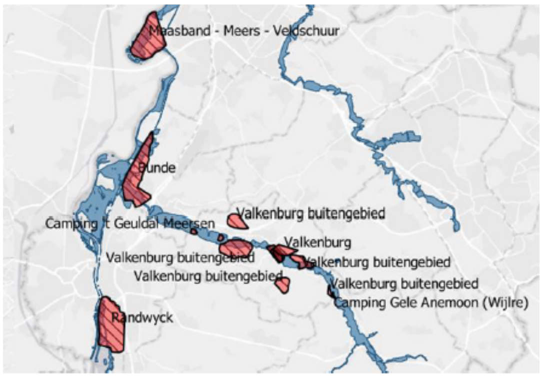


Figure 2.9: Overview of the inundated area (blue) and the areas that received emergency warnings (red)[6]

At least 180 people lost their lives and damages are estimated to add up to 7 billion euros.[8]. In Luxembourg, damage estimates are up to 120 million euros.[24] An overview of the 48-hour precipitation depth is provided in figure 2.8. In Belgium, at least 42 people lost their lives. Long term, flooding has been linked to psychological- and respiratory problems caused by mould.[25][26]

2.3.3. The floods in the Geul

Most damage claims originated from Valkenburg after the 2021 floods.[6] Valkenburg opted for a safety level of 25 years rather than the usual 100 years for similar locations.[21] In the valley of the Geul, water levels have surpassed the water level of the 100-year return period by a few decimeters to a meter. This leads to the conclusion that the return period of the discharge peak was somewhere between 100 and 1000 years.[6] Therefore, the event is seen as part of the accepted risk, even if the safety level had been 100 years.

Discharges

A precipitation event in the Geul with a cumulative rain depth of 160-180 mm is extremely rare, especially in summer.[6] The precipitation event was highly heterogeneous. Because of this, the return periods of the precipitation depths and discharges vary significantly; Discharge return periods range from 50 to 500 years and precipitation return periods from 2 to 1000 years.[7] There are three identifiable peaks; The 13th at 17:00 and the 14th at 08:00 and 13:00. The first peak in discharge most likely originated from the lower part of the catchment, and the latter two from the upper part.

Even as such a small subcatchment, the Geul displayed very heterogeneous hydrological behaviour. The most notable differences are between subcatchments and between the Belgian and Dutch sides. Large amounts of discharge originated from the Belgian part of the catchment. It is estimated that 60% of the discharge at Gulpen originated from the Belgian part of the catchment.[7] This is illustrated by the runoff coefficients of the subcatchments for the event and over a longer term. These are displayed in table 2.1

The saturation likely played a significant role in the hydrological response.[7]: In the weeks prior to the event, there was 50% more precipitation than usual.[7] This could have influenced the runoff as parts of the soil were likely to be close to saturation at the start of the event. Klein (2022) states that an unsaturated soil could have reduced the flood peak by 30% and stored an additional 4.2 million cubic meters of water.[7]

Table 2.1: Runoff coefficient of the precipitation event and normally. Table from Klein (2022)[7]

Subcatchment	Event RC [%]	Long term RC [%]
Kelmis	45	39
Sippenaeken	41	39
Eyserbeek	23	15
Gulp	21	31
Meerssen	31	32

Effects

Preliminary assessment estimates 350 million euros of damages in the Geul. During the event, 41,000 households were cut off power. No one lost their lives.[6] People along the Geul, with the exception of some holiday facilities and a nursing home, were not evacuated. In general, people have shown to be very self-reliant during the flooding of the Geul. Only a few people were in need of help. This is in line with literature, which states that 60-90% of people finds a safe location by themselves or with help of other affected citizens.[27][28]

2.4. Climate Change

Both in the Meuse and the Geul, summer extreme precipitation events are increasing in occurrence probability.[23] In the Geul, the link between discharge and precipitation is strong, causing changes in precipitation patterns to be especially relevant for flood risk. In this section, the link between climate change and precipitation and the effects in the Meuse and the Geul will be addressed.

2.4.1. Changing precipitation patterns

When air warms up, the moisture capacity increases. This is known as the Clausius-Clapeyron relation.[29] In climatic systems, this can lead to increased precipitation depths because the air simply can contain more water. When warm, moist air is pushed up either by elevation (orographic rising) or cold fronts (which are heavier), precipitation occurs. This amount can be especially significant at a single location if a front is slowly moving or not moving at all. Other lifting mechanisms can be convective or convergent rising. These are displayed in figure 2.10. Generally, climate change will cause wet areas to become wetter and dry areas to become dryer.[3]

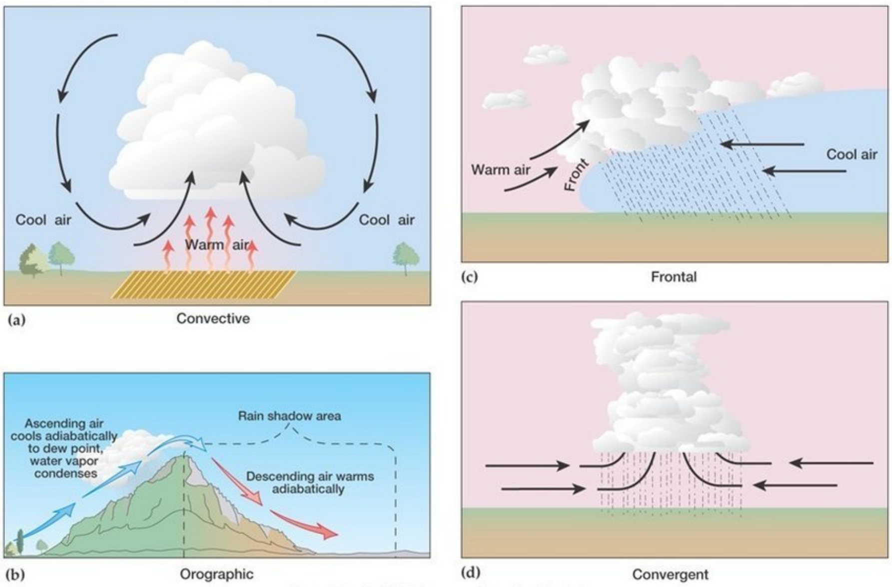


Figure 2.10: Different rising mechanisms.[30]

Precipitation patterns are dependent on many factors, such as moisture availability, evaporation, air flows and many other things. It can therefore not be directly linked with climate change, but should be assessed regionally.

2.4.2. Meuse - Precipitation

The World Weather Attribution initiative looked into the effect of climate change on the probability of events with similar characteristics. They compare the results to a baseline climate of 1.2 degrees ^oC colder than the current climate. The increased intensity of 1 or two day precipitation events is within the 3-19% range and its occurrence likelihood has increased by 1.2-9 times.[23] In a climate that is 2 ^{o} of pre-industrial times, there would be another increase in intensity of 0.8-6% and the probability of occurrence would be multiplied by 1.2 to 1.4.[23]

2.4.3. Geul - Precipitation and Discharges

Tsionakos (2022) investigated climate forcing present in the Geul and concludes that most discharge trends of the Geul and its tributaries are upward, but that most of these are not significant. Discharge in the Gulp seems to be increasing, but the Selzerbeek is significantly decreasing.[5]

Precipitation

Total precipitation shows a slightly upward trend, this is, however, not considerable. There is a statistically significant increase in wet days, this is however mainly in winter. Extreme summer precipitation show a relatively strong increase from the 1980s. The IPCC also reports an elevated probability of extreme precipitation in this climatic region.[31]

Correlation between precipitation and discharge

There are strong positive correlations between extreme precipitation and maximum discharge in the Geul.[5] Annual discharge maxima, therefore, change at the same rate as precipitation extremes in magnitude and timeframe. This indicates, according to Tsionakos (2022), that the variability of high flows is mainly a result of variability of extreme precipitation. Because of this, he suggests that the variability of extreme and mean flows is driven mainly by the variability of climate. This hypothesis is strengthened because land use changes are not visible in runoff patterns for 1970-2020.[5]

2.4.4. Droughts

Floods are not the only danger that lies in a changing precipitation pattern. Droughts are usually not as visible or acute as floods, but they can have severe (economic and ecological) consequences. According to Naumann et al. (2015), drought is seen as one of the most costly natural hazards due to its cascading effects in different economic sectors.[32] Effects of droughts are wide-reaching and span economic, social and environmental domains.[33] In the Meuse river basin, drought is expected to increase. Average deficit increases to 34 and 40 % respectively, while the average intensity increases by 27 and 22% respectively for hydrological droughts and extreme hydrological droughts.[34] In the Geul evaporation has shown a strong and stable trend in the catchment area between 1965 and 2020.[5] This trend adds up to about 100 mm extra evaporation increase over a full year since 1965. This thesis is focused on flood risk, but the effects of droughts and the expected increase in the Meuse and the Geul justify measures which have a positive effect on drought as well.

2.5. Governance in the Meuse and the Geul

Flood risk in the Meuse and the Geul is determined by the hydrological response of areas to precipitation. In turn, this is influenced by governments. For example, by spatial planning, agricultural policy or interventions in the river. The countries in the Geul basin are The Netherlands, Belgium and Germany. This has complicating implications for river basin management in transboundary river basins in both legal, governance and cooperative domains. Different countries also have different interest. Financial and technical resources might be different and there is a language barrier.[13]

A complicating matter is the fact that two Belgian regions with two different languages have areal in the basin; Flanders and Wallonia. The river basin countries of the Meuse have different governance structures. Most notable are the federal states of Belgium and Germany. A federal state consists of more or less autonomous states. Belgium consists of three regions or *gewesten*. For the Meuse and the Geul, Wallonia is the most relevant, as it contains the largest area of the river basin. In the next sections, water management in the basin countries as well as multilateral or supranational entities are described.

2.5.1. European Union

All the river basin countries are members of the European Union. This has implications for the governance of flood risk, as the European Union provides the basin countries with a common legal framework. The European Union has no operational competence in flood risk management and the governance structure is therefore not covered in this thesis.[35] The European Union also provides funding for development projects, climate adaptation and other relevant subjects in Flood risk management. The European Unions' legal framework regarding flood risk, however, is binding and agreed upon by basin countries.

European legislation

European legislation provides a basis for transboundary cooperation. The Water Framework Directive requires member states to make river basin management plans and relates international river commissions to EU legislation. The implementation of this legislation is, however, heterogeneous[36], climate change is not taken into account to the same extent [37], definitions are vague [38] and cascading events are not fully taken into account, causing flood risk to be estimated too low. [39] The Floods Directive also poses no time- or other quantitative and binding goals other than the periodic update of its required products.[40]

Water Framework Directive

The Water Framework Directive (WFD) is focused on pollution and water quality and is best known for the surface- and groundwater quality indications which member states much ensure do not decline further than their level when the WFD came into force. The WFD is thus not meant for or focused on mitigating negative effects of floods. However, it does lay a foundation for legislation that does. It requires river basins covering multiple member states to be assigned to an international river commission and that coordination is required, even if river basin countries are not member states.[41]

Floods Directive

The Floods Directive (FD) is specifically aimed at flood risk reduction. It requires several products regarding flood risk quantification and management. Some of these have to be coordinated in river basins, providing a legal requirement for cooperation. The Flood directive provides some tools for cooperation; Member states cannot implement measures that have a significant negative effect on downstream flood risk. Member states are also able to table issues they cannot fix themselves to the European Commission. Thereby, a legal role is created for the Commission in flood risk management.

The FD requires member states to provide several products. Preliminary flood risk assessments (PFRA), Flood Risk and Hazard Maps (FRM, FHM) and Flood Risk management plans (FRMP). These products are updated every six years. The most recent updates are 2018 (PFRA), 2019 (FRM, FHM) and 2021 (FRMP). Meaning the next cycles will be 2024, 2025 and 2026.[40] Member states must aim at producing a single FRMP and otherwise coordinate as much as possible. It also provides the possibility to report issues that cannot be solved within a member state to the Commission. Member states should, according to the Floods Directive, refrain from activities causing a significant increase in flood risk.[40]

Adaptation Strategy

The Commission wants to be fully adapted to climate change by 2050.[42] This will be done through accelerated spending from the EU, the before mentioned channelling of private funds into climate change adaptation, building asset capacity by doing research and making better models. In addition, there is special attention for local governance. The Commission sees the lack of actionable solutions as one of the main barriers to climate change adaptation.[42]

Issues with European legislation

The FD has improved aspects of flood risk management, but further efforts are needed to further strengthen awareness and strengthen coordinated flood prevention in line with climate change expectations.[43] Müller (2013) states how the FD plays a role in the gradual transition from a safety culture to a risk culture.[44] But the legislation is also flawed. From literature, issues can be identified that influence transboundary cooperation in the Meuse.

- Definitions in the FD are vague, causing the implementation of the FD to differ.[36][38] Sometimes even within member states. For example, in the return periods of extreme events, medium frequent events and frequent events.[36] or in watercourses the FD applies to.[44]
- Member states do not evenly consider climate change.[37] This conclusion might be especially relevant in transboundary river basin management such as the Meuse and the Geul: If managing member states do not agree on the objective of their climate change adaptation, this might pose a complicating factor in agreeing upon necessary measures.
- The FD tends to focus on small and localized impacts and might therefore underestimate effects of cascading effects during floods (e.g. electricity grids being impacted).[39]

2.5.2. International Meuse Committee (CIM)

The International Meuse Commission, CIM, is the coordinating body of the river basin countries. It was founded in 2002 with the Ghent treaty. Participating parties are Flanders, Wallonia, Germany, Luxembourg and the Netherlands. The CIM aims at reaching integral and sustainable water management in the Meuse river basin. The CIM consists of a Secretariat, a plenary assembly, delegation chairs and 5 working groups. The 5 working groups (Coordination (R), Pollution calamities (P), Hydrology (H), WFD (A) and Monitoring (M). In addition, there are some project groups where countries can share specific information and work on specific topics.[12]

One of the most important tasks of the CIM is to coordinate a River Basin Management Plans (RBMPs) of the Meuse. RBMPS are required by the European Floods Directive.[40] In this RBMP, the CIM states some measures and their expected effect on other countries in the basin.[12] The RBMP of the CIM is coordinated, not integral. The CIM has no operational role in water management or CCA.

2.5.3. Water Management in the Netherlands

In the Netherlands, Rijkswaterstaat is responsible for the primary flood defences such as the dikes along the major rivers (Rhine, Meuse), the Ijsselmeer and the coast. Rijkswaterstaat is an agency of the Dutch Ministry of Infrastructure and Water Management. Secondary flood defences, smaller streams and polder management is the responsibility of Water Authorities. This administrative layer is typical to the Netherlands and has a rich history of over 700 years of water management.[45] Provinces are the competent authority for, among other things, groundwater, infrastructure- and spatial planning.[46]

2.5.4. Water Management in Wallonia

Water Management is not the responsibility of the national Belgium government, while climate change adaptation is a shared responsibility between national and regional levels.[47] In Wallonia, public services are provided by the *Service public de Wallone*, abbreviated to SPW. Two relevant sections of the SPW are the entities responsible for agriculture, natural resources and the environment (SPW ARNE) and the mobility and infrastructure entity (SPW MI). The management of rivers is dependent on the category of the river. There are 5 categories; Navigable waterways which are the responsibility of the government of Wallonia (subfederal, more specifically the department of mobility and infrastructure, SPW-MI[13]), then, larger tributaries are the responsibility of the subfederal ministry of Agriculture and environment SPW ARNE, category two waterways are the responsibility of the provinces, category three waterways are the responsibility of municipalities and non-classified waterways are the responsibility of inhabitants.[13] The Geul and some of its tributaries are classified as third and second category.

SPW MI is the coordinating authority for FD implementation and drought issues, whereas SPW ARNE is concerned with ecology and hydraulics and therefore provides the FRMPs. Crisis response is done by the DCENN direction of SPW ARNE.The management of waterways is thus very fragmented in Wallonia. One interesting observation by Zeimetz et al. (2021) is that there is no legal directive for maintenance and safety level of dams.[48]

2.5.5. Water Management in Flanders

Governance in Flanders is organised in a similar matter with a lot of responsibilities at the Flamish Government.[49] The same characterization of river streams and responsibilities is the same as in Wallonia.[50] The Vlaamse Overheid is the Flemish counterpart of the SPW. Navigate-able waterways that are not coastal are managed by the Vlaamse Waterweg n.v.[51]

The first category of non navigate-able waterways are managed by the VMM (Vlaamse Milleu-maatschappij), an executive agency of policy domain Omgeving of the Vlaamse overheid.[52] Category two is managed by the provinces and category three by the municipalities. If waterways are in a polder, the agency managing the polder is responsible for category two and three waterways.[50]

2.5.6. Water Management in Germany

The water management policy in Germany is focused on ecology of waters, good quality of drinking- and industrial water and save guarding water to serve public interest.[53] The federal government has a competence to provide framework provisions and the responsibility to answer to the European Union. The Länder are responsible for implementation of these provisions and the enforcement of law.[53] With the Federal Water Act (Wasserhaushaltsgesetz or WHG) of 2020, the federal government provides subfederal governments with harmonization and uniform regulations on surface-, coastal- and groundwater. Additionally, there is a federal nature conservation program aimed at restoring flow and conservation of flood plains.[53]

Competences

The Federal government is the competent authority for water protection. Länder may deviate from federal provision, but this is rare. Länder have supplementary provisions to the federal provision to provide a complete legislative framework.[54] Districts have intermediate authority and do regional water management planning. Local entities mostly have technical authorities such as monitoring. Water management is coordinated in the working group on water issues of the Länder and the federal government.[54]

National Water Strategy

There is also a National Water Strategy by the federal government, which focuses on 10 domains.[55] One of the domains is adapting water infrastructure to climate change. It aims to adapt the infrastructure (sewers, waterways, dikes, basins) to the changing climate by 2050.[55]

2.6. Adaptation Measures from literature

There are different focuses possible in climate change adaptation. In general, downstream infrastructure and flood-proofing seem to be very effective in decreasing flood hazard and vulnerability respectively. Nature based solutions provide co-benefits, and upstream solutions spread the adaptation efforts over basin countries. Natural retention of water is, however, hard to realize in the upstream part due to the soil type and thickness.

In order to find suitable adaptation strategies, adaptation measures are needed. Due to the high public interest in the Geul, a lot of research has been done on potential adaptation measures in the Geul. This section summarizes the work of a Multidisciplinary group from the TU Delft, two master theses' at the same university and reports by Bureau Stroming and Natuurmonumenten, Deltares and Arcadis.[21][9][56][17][57][58] Later in this thesis, these measures will form a large portion of the solution space for the adaptation strategies.

2.6.1. Multidisciplenary Project Group TU Delft

The multidisciplinary group evaluated measures at the bottleneck; Valkenburg. These measures are all meant to increase the discharge capacity and include infrastructural adjustments and hydraulic interventions.[21] The multidisciplinary group included a disclaimer that these number were a result of work within a limited time with limited information and that their work is part of an educational program.[21] The resulting measures of the group are as follows;

- Flat bridge; Installing flat bridges would increase peak capacity from 65 to 80 m^3 per second. The cost of flat bridge would vary between 475 thousand and 2.8 million euros.

- Removable bridges; Fully removable bridges would provide for a discharge capacity 107 m^3 per second.
- Raising quay walls: By heightening quay walls by one meter, discharge capacity would increase to 103 m^3 per second.
- Water tunnel; Install a tunnel as emergency bypass for peak discharge. Diameters 2.5, 3.5 and 4 meters would cost 9-19, 12-27 and 14-30 million euros respectively. Safety level increases of the tunnel are of 100, 365 and 2580 years respectively. This can be related to a discharge capacity increase.

2.6.2. Bureau Stroming & Natuurmonumenten

Stroming (2022) investigated the area to specifically look for Nature-Based Solutions (NBS). Stroming looked for NBS for the following goals; make use of storage capacity, retain water in the soil as long as possible, slow overland flow to allow re-infiltration, slow overland flow to reduce coincidence and make space for the river to occupy floodplains.[17]

The measures are grouped in the mentioned goals and are as follows[17];

- Make use of storage capacity; Transform cultivated land to roughly vegetated pastures, Expand areal deciduous forests
- Retain water in the soil as long as possible; Remove culverts from pastures, Re-infiltrate intercepted groundwater
- Slow overland flow to allow re-infiltration; Restore natural edges of forests and pastures, Direct flow over pastures instead of roads
- Slow overland flow to reduce coincidence; Vegetate dry-valleys, Vegetate upstream floodplains
- Make space for the river; Make the river bed more shallow, Meander river, Do not clean up vegetation remains in the stream (e.g. dead trees) or let the floodplains be vegetated

Stroming proposes some interesting measures. Stroming, however, has a strong focus on Nature-based solutions and also state this in their report. This focus is useful for defining the solution space, but is obviously lacking in painting a full picture.

2.6.3. Arcadis & Vista Landscape architects

Engineering Consultant Arcadis, Landscape Architect Vista and Design firm Defacto have produced a booklet where they, among other things, sketch opportunities of landscape interventions possible in the Geul.[58] Measures include the increase in roughness, cultivation in strips and changing livestock farming to more roughly vegetated lands, such as forests.[58] By increasing the room for the river by 1.1 to 1.4 square kilometers, the consortium estimates the current buffer capacity can be increased five-fold. This would mean a lower water level of 0.1 to 1 meter for over 7 kilometers following the intervention.[58]

2.6.4. Deltares - Water System Evaluation

The analysis of the water system during the 2021 floods by Deltares focuses on the hydraulic properties of the system. It evaluates some of the measures that are also proposed by the MDP group and makes an analysis of the task at hand. Most importantly, the report concludes that 6 to 10 million m^3 of water must be retained or stored to prevent a similar event. This is due to the storage being not fully empty at all times during operational use. Raising quay walls to discharge the water safely in Valkenburg would require 2.5 meter high walls. It estimates that an effect in the order of magnitude of 10 mm is the maximum storage that can be reached by measures aimed at the source. The report defines this as measures aimed at reducing peak discharge by retaining water and releasing it gradually.[57].

Emergency Spillways

Deltares mentions that the increase of discharge capacity locally can lead to (bigger) problems more downstream. When assessing the effect of two tunnels with a diameter of 3.5 meters, a lot of flooding in the center of Valkenburg can be prevented. This is visualized in figure 2.12. The figure seems to

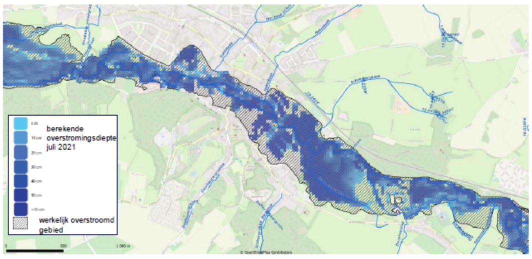


Figure 2.11: Inundation Valkenburg during the 2021 flood event [57]

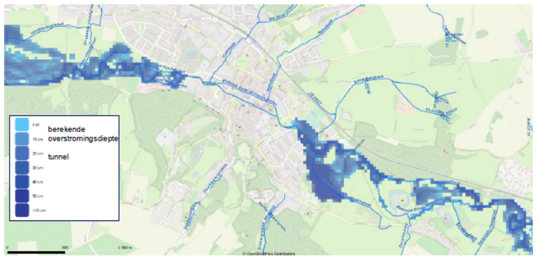


Figure 2.12: Inundation Valkenburg when two tunnels with a diameter of 3.5 meters are implemented [57]

nuance the picture painted by the MDP, but is shows the measure could be highly effective in terms of local flood risk reduction.

A more cost-effective option would be to use an existing sewer pipe that is 2.5 meters wide and 1.5 meters high as an emergency discharge tunnel. The effect of would be in the order of 5 m^3/s if managed effectively. Heightening the quay walls by 1 meters, as proposed by the MDP[21], would not be sufficient according to Deltares. To accommodate the water of the 2021 flood event, 2.5 meter high quay walls would be needed.[57] The 1-meter heightening of the walls would still be an option in combination with other measures.

Interventions in the river

Another measure suggested by Deltares is to change the profile of the river bed just upstream of the Valkenburg city center at the Walramstuw. This would entail widening the Geul from approximately 10 meters to 50 meters. This would lead to 1.3 meter lower water height locally.[57] This would mean that some buildings should be demolished and is therefore likely costly and possibly undesirable.

2.6.5. Deltares - Rapid Assessment

In the 2022 Rapid Assessment of the events in the Geul, Deltares estimates the peak discharge to be 130 m^3/s.[59] They analyse a number of measures and conclude that a total reduction of 30% of the flood peak would be feasible when all of their proposed measures are applied.[59] This flood peak would still cause inundation and damages in Valkenburg. One of the underlying assumptions is that 10 to 20% of the maximum land-use transformation would be plausible. This is still a very significant change of land use in the area. Deltares also notes that the implementation time is typically very long (10 to 30+ years).[59] An overview of all considered measures and their combined effect is provided in Figure 2.13.

Deltares state that the top layer and soil coverage above the bedrock is thin in the Belgian part of the catchment. This implicates that the potential increase in natural storage in that section of the basin is limited.[59] Creating artificial storage in Belgium similar to the storage in the Netherlands (0.7 million m^3) would reduce peak discharge by 8%.[59] If a large storage is realized in the Dutch part of the Geul, the discharge reduction could add up to 16%.[59] All measures investigated by Deltares are summarized in table 2.6.5.

Table 2.2: Quantified measures in the rapid assessment of Deltares [59]

	Reducing effect [%]	millimeter equivalent [mm]
Reforestation on hills and plateaus	1 to 2%	0.36
Urban rainwater diversion	1 to 2%	0.36
Retention at Belgian foothills	2 to 4%	0.72
Remeandering	Negligible	-
Reforestation of river valleys	16%	2.87
Large dam with reservoir	4 to 7%	12.57

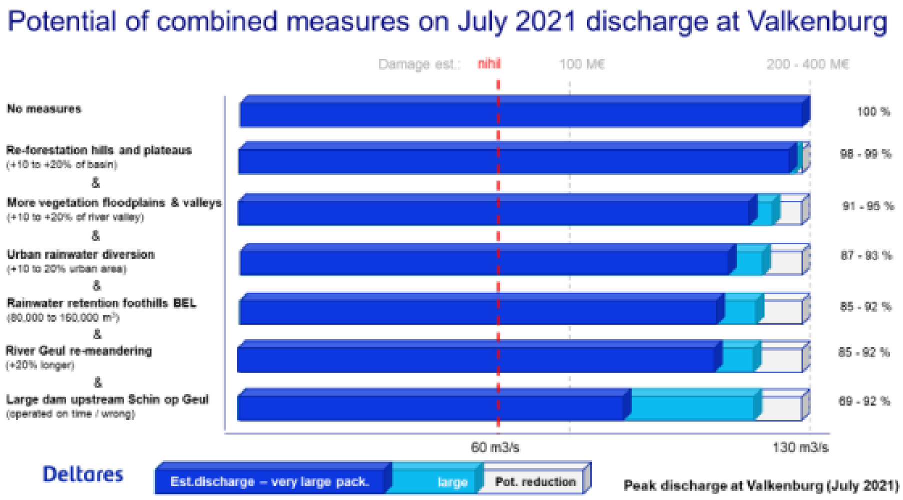


Figure 2.13: Effect of all investigated measures by Deltares in their rapid assessment.[59]

Deltares recommends flood-proofing or the implementation of FEWS. This because the implementation time of these measures is expected to be much lower.[59] In addition, they conclude that NBS are likely not able to prevent damages, but they are able to reduce the flood peak. Given that they provide ample co-benefits (ecosystem services), they should be implemented.[59]

2.6.6. Work on measures outside of the water system

Risk can be reduced by other means than increasing discharge- or retention capacity. Another interesting thesis has been written by Suijkens (2022) on wet- and dry-proofing of houses in Valkenburg. Dry-proofing refers to the prevention of inundation (e.g. by using panels or sandbags).[9] Wet-proofing refers to the reduction of vulnerability to inundation (e.g. by using waterproof materials in houses or moving up power plugs).[9] Suijkens (2022) showed that, when applied at the houses most at risk, dry- and wet-proofing can reduce flood risk by 30 to 40%.[9] Godlewski (2022) investigated the use of a Flood Early Warning System (FEWS hereafter). Currently, a flood warning could have been given 12 hours prior to the flood. This is, generally, not enough time to build up temporary flood defences or evacuate people. FEWS could potentially provide an additional two days in forecasting time.[56]

2.7. Chapter Synthesis

The Geul is an interesting catchment as there is a significant difference in permeability of the upstream and downstream soil. There are two large aquifers with high flow speeds. The geology of the area constrains the possibility of the expansion of natural retention of waterand storage in the upstream parts. Response times of upstream areas are between 2 and 4 hours, causing a flashy river and potentially hazardous river. The downstream safety level in Valkenburg is 25 years. This was decided upon because downstream measures are costly. Due to the characteristics of the catchment, it is not certain upstream measures are that easy to implement.

Summer extreme precipitation events will rise and show a strong correlation with extreme discharge.[5] In this thesis, the adaptation goal is set at the excess discharge during the 2021 floods. This is 6 million m^3 of water. Implementation times of adaptation measures are likely to range between ten and thirty years.[59] Deltares estimates 10 millimeters of additional natural storage is the maximum achievable.[57] The common legal framework of the European Union provides common legal instruments and legislation. These do, however, not always function desirably and are implemented heterogeneously in the catchment. Operational water management and spatial planning is organized within countries.

3
Theoretical Framework

3.1. Flood Risk

Flood risk is subject to a variety of definitions; It is a combination of the occurrence probability of an event and the associated effects. It operates across various societal domains and is considered in social, economic and physical terms and the interactions between them. Most often, risk is defined as the product of vulnerability, exposure and hazard.[9]

Hazard is the event that can cause damage and its associated probability, exposure are the resources and infrastructure exposed to the event and vulnerability is the extent to which the assets are affected.[9] The people at risk are generally considered as part of the exposure.

3.1.1. Drivers

Exposure has been identified as a primary driver of increased impacts by earlier studies, but Kreibich et al. show a positive and significant and roughly equal correlation with changes in hazard, exposure and vulnerability. This implies these factors are all equally important.[11] Changes in vulnerability, however, have been less successful in addressing drought compared to flood impacts.[11] Exposure can also vary per season, for example during summer when more people and property can be present in regions due to tourism. Secondary loss of income is also more significant in that case.[11]

3.1.2. Reduction strategies

The most effective flood risk reduction is accomplished when both planned and autonomous adaptation take place at the same time.[10] But flood risk management is mostly dominated by planned adaptation.[10] One could argue that autonomous adaptation in terms of hydrology also occurs due to self-organization and co-evolution. This would imply that interference with that by humans could be seen as maladaptive.

The management of risk generally has a reducing effect on risks of floods and droughts, but the discipline struggles with reducing impacts of events that are unprecedented.[11] When evaluating impacts of coupled events, Kreibich et al. found that whilst the risk is effectively reduced when the second event is less severe, the impact was bigger when the second event was more severe as well. Vulnerability and management shortcomings are often decreased in paired events.[11] Increases in flood risk in coupled events are thus likely the result of increased hazard and exposure.

3.2. Responses to Climate Change

Two fundamental societal responses to climate change are adaptation and mitigation. Whereas mitigation concerns limiting or reducing greenhouse gas emissions and increasing their sinks, adaptation to climate change is a term subject to multiple definitions. Füssel et al. state that it concerns actions targeted at the vulnerable system in response to actual or expected climate change.[60] According to Filatova, adaptation to climate change is improving the resilience of the socio-economic system to a new climate.[10] In either case, adaptation to climate change is a challenge that crosses multiple societal domains.[61]

Relating this to flood risk, one could pose that adaptation is the management of flood hazard, vulnerability or exposure to a change. In flood risk, this change is a changing precipitation pattern. In the case study area specifically this is an increase in occurrence probability and intensity of extreme precipitation.[23] Due to the strong coupling of precipitation and discharges in the Geul basin, this directly leads to a rise in probability and intensity of floods in the Geul, leading to an increase in flood hazard.

3.2.1. Climate Change Mitigation

Traditionally, mitigation has received more attention from both the scientific community as from policy-makers. One of the reasons for this, according to Füssel et al., is that the potential of adaptation is limited, the effectiveness of mitigation is more certain and because mitigation addresses the root cause of climate change.[60] But, both can be mutually beneficial in flood and drought management.[60][33]

3.2.2. Climate Change Adaptation

Adaptation can be very different depending on the local environment, economy and political and cultural conditions. It can either be autonomous or planned.[10] Autonomous adaptation can for example be self-organizing properties of ecosystems or human behaviour. Planned adaptation can be river basin management plans by administrative bodies. Adaptation efforts often spark after an extreme event has occurred[10] such as the 2021 European floods. It can include risk management, coastal management, resource management, spatial planning, urban planning, public health and agriculture.[10] The more information about future climate change is present, the more efficient adaptation efforts can be aimed. It can therefore reduce the costs of adaptation. For example, if one knows exactly how big a reservoir for water retention needs to be.[10] Sometimes, adaptation is seen as a strategy to prevent all impacts of current and future climate change. Underlying that definition is the assumption that the future climatic conditions are perfectly known and the resources for adaptation are unlimited.[10] As this is not the case, there are likely unavoidable impacts of climate change. Adaptation also concerns reducing exposure and increasing resilience. For example, by implementing early warning systems or flood-proofing houses. A factor that is frequently not seen as adaptation is migration.[62]

3.2.3. Challenges of Climate Change Adaptation

In adaptation efforts, hazard and vulnerability are generally targeted. For example, by heightening dikes or by the implementation of early warning systems. Vulnerability decrease has been shown to be effective in coupled events.[11] But when an event is more severe than the previous event, damages were also more severe.[11] This indicates that people tend to mitigate hazard to the extent of the event they experience but after that increase exposure again. If climate change continues to cause an increase in hazard, this creates a lock in. An effective flood risk reduction strategy should therefore also take into account exposure and unprecedented climate change effects.

When not executed correctly, adaptation can lead to lock-ins which require ever-increasing adaptation efforts. Financial burdens are not trivial, although autonomous adaptation through the creation of financial incentives or information flow might be a solution to this. The extent of adaptation efforts is limited by the adaptive capacity, which in turn is limited by finance, politics, maladaptation and lock-ins. Filatova states that it is not a question whether to pursue climate change adaptation, but rather to what extent and who pays for it.[10]

Path Dependency and Lock-ins

Path dependency and lock-ins limit the solution space available to a decision maker at any moment. Path dependency occurs when organizations fail to effectively adapt to changing circumstances. One example can be increased exposure in flood risk areas; by building in areas prone to flooding, one increases the exposure and creates a lock-in.[61] The cost of stopping adaptation effort increases, thereby creating a situation where one has to continue adaptation efforts for the area at risk, either due to economical or ethical reasons. Some argue that path dependency is a kind of inertia that results when precious decisions shape future decisions. This concept is also touched upon by Filatova et al.[10] Especially in climate change adaptation, it is hard to overcome path dependency. This is because a lot of the decision-making points for measures in climate change adaptation are cyclical (e.g. spatial plans that are revised every 5-10 years).[61]

Finance

Financing adaptation efforts is a challenge. Adaptation to extremes is costly, and the adaptation extent is uncertain. In climate change mitigation, the polluter pays principle can be applied. In adaptation, the link between cause and effect is less trivial. Issues with this are that, when paid for with public funds, all taxpayers pay for those who benefit.[10] Internationally, countries that have the biggest challenge are generally the ones that have not contributed as much to the emission of greenhouse gases historically.[60] Public funding for climate change adaptation is thus problematic.

Autonomous adaptation can pose a solution to this. Market based instruments such as flood insurance and specific taxes can incentivize private adaptation by providing price signals.[10] Filatova et al. argue that individual behaviour is rational and therefore people will continue to live in flood prone areas if the flood defences are publicly funded. But even this financial incentive was there, people are known not to respond rationally to intangible risks that are global and distant in time.[63] A need for information flow on current and future adaptation is needed to inform and incentivize autonomous adaption.

Maladaptation

Maladaptation are actions creating conditions that worsen the adaptation task at hand. In the context of climate change this is a process which caused people to become more vulnerable or exposed to changing conditions.[64] An example of maladaptation, path dependency and lock-in provided by Filatova et al. are the Dutch Delta works. These have sparked an unprecedented safety level in the flood prone western part of the Netherlands. As a result, unprecedented growth in population and economic activities took place in the area.[10] The exposure in the area is now so high that exiting the path of ever-increasing adaptation efforts is undesirable from an economic and ethical perspective.

Unprecedented Events

Flood risk management struggles with reducing impacts of events that are unprecedented.[11] In coupled events, vulnerability and management shortcomings are generally decreased.[11] This can be achieved with improvement in early warning systems, management, public awareness, investments in infrastructure and institutional planning.[11] But people tend to adapt to what they know and when measures are implemented, people rebuild and develop economically in the same area; exposure increases again. even to higher levels than before. Leading to even bigger damages in unprecedented events. This poses a challenge to climate change adaptation as precipitation events are expected to increase in occurrence probability and intensity in the case study area.[23] Potentially this will lead to unprecedented effects.

Adaptive capacity

The extent to which adaptation is possible depends firstly on the domain the adaptation is focused on, but also the extent the landscape, behaviour or system can be changed.[61] There are, for example, physical limits to how much additional storage can be realized to a soil. There are also limits to the ability of people to pay for and decide upon adaptation measures. These limits are called the adaptive capacity. The adaptive capacity is a finite solution space. This solution space can be limited by lock-ins or decision-making time. Due to the limited adaptive capacity, climate change has unavoidable impacts.

3.3. Decision Making Under Deep Uncertainty

The governance of changing conditions can be very challenging, depending on the uncertainty of the amount of change. Predictions about future conditions can be done by probabilistic predictions. However, these predictions tend to have high variances and 'fat tails'[65] and rely on historical data. Implicating a system behaves within the stationarity as defined by Kaufmann et al.[61] Due to climate change, this might not be the case in the future. CCA therefore deals with large or even deep uncertainty. Deep uncertainty is the domain where it is difficult to agree on key driving forcings or on probabilistic methods to quantify this.[2]. In the context of CCA, this means that it is uncertain to which effects and to what extent adaptation is needed.

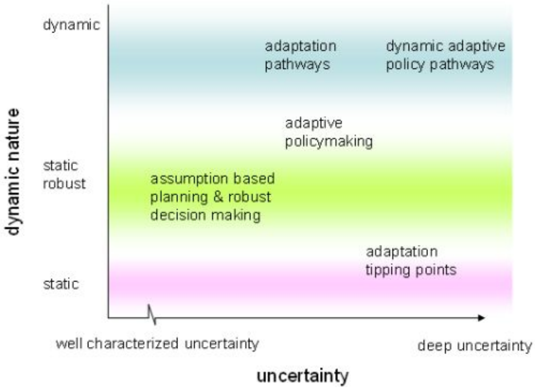


Figure 3.1: Different application domains of DMDU methods by Walker et al. (2013)[66]

Figure 3.2: Dynamic Adaptive Policy Pathways cycle [68]

To deal with the uncertainty in climate change adaptation, Decision Making under Deep Uncertainty (DMDU) methods are recognized to support robust and adaptable decision-making.[2] Examples of DMDU methods are Robust Decision Making (RDM), Adaptation tipping points, Adaptive Policymaking, Adaptation Pathways and Dynamic Adaptive Policy Pathways. These are visualized in Figure 3.1. (Static-) robust means that the adaptation is primarily anticipatory in character. Dynamic means that the adaptation can be anticipatory, concurrent, and reactive. The level of uncertainty specifies the degree of uncertainty. It can range from low, well characterized uncertainty, to deep uncertainty.[66] Methods are listed below;

- Robust Decision Making: a method that supports decision-making under deep uncertainty by producing a static but robust plan. The idea is that the plan performs 'well enough' under a broad variety of possibilities.
- Adaptive Policymaking: a stepwise method which develops a basic plan and provides contingency measures to adapt to new information.[67][1] Adaptive Policymaking makes use of triggers; when a certain condition is reached (the value of the trigger) a new, pre-defined action must be taken. Adaptation pathways are similar, but take into account the temporal and path dependent nature of tipping points.
- Dynamic Adaptive Policy Pathways: A dynamic method with elements of adaptation pathways and adaptive policymaking and combining them in a Dynamic Adaptive Policy Pathway framework, or DAPP-Framework. This framework first describes problems, objectives and uncertainties and develops a plan. This is implemented and through monitoring, the deployment of contingency actions is kept viable. A visualization of the cycle is provided in Figure 3.2.

DMDU methods shift the paradigm of 'predict and act' to 'monitor and adapt'.[2] But in the end, the solutions posed by the methods are still pre-defined. The ability of DMDU methods to fully reflect the context of decisions has been criticized. DMDU methods tend to overlook organizational and individual context.[2] This flaw is especially relevant for Infrastructure, as it is vulnerable to changing socio-economic and environmental changes. Additionally, decision-making happens in an organisational an institutional context. Adaptation measures targeting flood hazard are often infrastructural.[2] DMDU methods approach this complexity by using large scenario spaces for the deep uncertainty.[2] (e.g. RDM) But this scenario space is also built on aspects that are considered by the user. Social, cultural, political and location specific properties are not considered equally in the application of the method.[2] Complexity of infrastructure, due to the network of involved actors and assets, is rarely addressed in applications of the method.[2]

3.4. Classification and Archetypes

For the management of natural resources, insight into system behaviour is needed: Water resource managers must take decisions even if they do not completely understand a system.[69] For this, insight in a system is needed, even if that system cannot be completely defined by a characterization. Archetypes can be a solution for this. Three landscape Archetypes for landscapes in the Meuse river basin are proposed by Savenije (2010) and are based on self-organization and topography. They are proven to be effective in the case study area. Additionally, the archetypes can connect measure categories to landscape types, as they provide dominant runoff directions and mechanisms per landscape type.

3.4.1. Classification

Classification is the ordering or arrangement of objects based on the perception that these objects, in one or more aspects, have a relationship.[70] The classification of rivers and river sections provides the opportunity to extrapolate strategies, knowledge and information between different locations. By classifying aspects of rivers and river basins, such as hydrology, ecology and geomorphology, one enables knowledge to be generalized and applied to other rivers.[71] This implies that there is a relationship between the classes and that knowledge can be extrapolated to other cases within that class.

A pitfall of classifications is that they tend to add layers of complexity to correctly describe classes. This would lead to a higher level of equifinality and predictive uncertainty.[4] This is exactly contrary to the goal of classification, which, one could state, is predictive certainty. Classifications used for policymaking regarding environmental management are based on the assumption that the members of a class are equivalent and interchangeable.[71] But classes depend on the scale considered [72][73], the area defined and its deviation from the true context [72], fluidity of boundaries due to spatial and temporal variability [73], local context [74], the attributes considered [71] and the subjective perceptions of these attributes.[71] When a system is complex or complicated and not fully understood, classification is also problematic because behaviour of classes cannot be predicted or grouped, possibly leading to wrong classifications. Every river can fit in a classification scheme, but this does not mean that relations (formative or generative) hold.[71][75]

Classification relies on classes with clear definitions, which often can be defined by Boolean membership metrics (yes/no criteria) or candid boundaries (e.g. slope between 0.01 and 0.05).[73] This is needed because a class implies that any member of that class is representative of the entire class and shows similar behaviour.[73] In the light of the earlier mentioned class biases and limitations, Cullum et al. (2017) argue this is a negative aspect of classes rather than a positive.[73]

3.4.2. Archetypes

Some argue that class membership might also be graded in degree of similarity to a certain prototype or archetype of this class.[76] An archetype is a conceptualization of a class of categories of objects. Archetypes deviate from classifications, as classifications aim to explain behaviour of systems, whereas archetypes provide typical behaviour and a degree of similarity. Archetypes are deliberately vague, and therefore the membership can be in terms of more similarity rather than yes or no.[73] These might seem like two sides of the same coin, but this conceptual difference causes the use and management implications of classifications and archetypes to differ. Where classifications can be used to design management strategies to manage behaviour of a system, archetypes only allow for insights into the system.

3.4.3. Landscape Archetypes and hydrology in the Meuse

European landscape typically consists of forested hill slopes, plateaus and wetlands.[4] Settlements in river basins are usually placed on plateaus or in riparian zones and the roads cut through the hills. Savenije uses these archetypes because landscape morphology, groundwater, geology, ecology and hydrology self-organize in these landscapes.[4] The archetypes are displayed in Figure 3.3

Runoff generation

Hydrological processes in plateaus are mainly vertical: Water travels into the ground or evaporates. If the precipitation is not balanced by evaporation, plateaus recharge groundwater.[4] Plateaus have

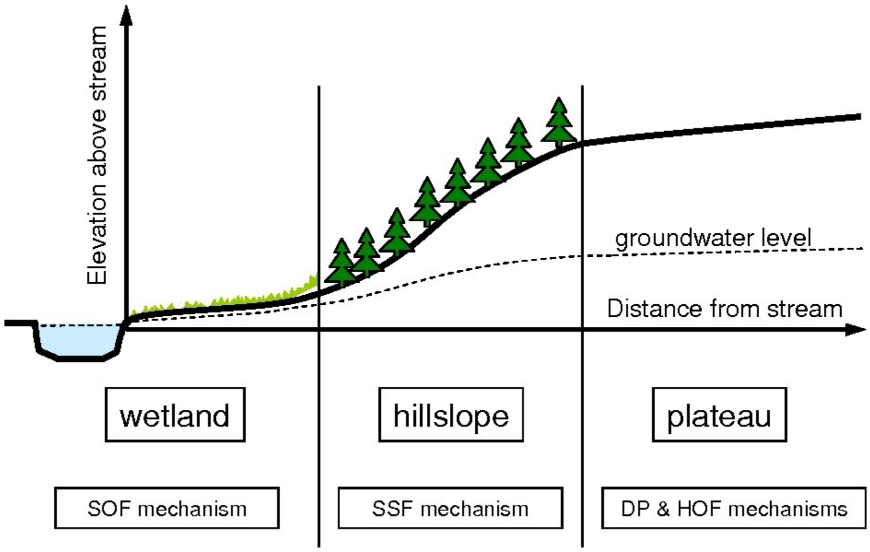


Figure 3.3: Landscape types and associated dominant runoff processes according to Savenije (2010) [4]

therefore mainly a role in retention. Usually, storage capacity is as big as the phreatic water table is deep and underlying rocks have lateral permeability.[4] The storage capacity is specifically big if there is deep-rooted vegetation on the plateaus. Savenije states that the contribution of plateaus to the base flow is probably small.[4] This is, however, dependent on the location and can differ in space and time. Contribution of wetlands and riparian zones to runoff generation are due to saturation overland flow and are also quite small.[4] This leaves hill slopes as a driving landscape for runoff generation.

Forested hill slopes have two very important properties; drainage and moisture retention. For trees to grow, water must be retained, but excess water needs to be drained. The water needs to be drained without causing a lot of erosion, otherwise the hill slope would not allow for vegetation either and would disappear due to this erosion. This leads to the suggestion that preferential pathways might play a big part in draining hill slopes. Fenicia (2010) showed that, even in catchments with very different geological properties, subsurface drainage could be evaluated by using the same model with the main dissimilarities being in parameters.[77] This suggests similarity in the role of subsurface flow. Ecosystems on hill slopes have likely created an environment where this sub-surface drainage is the dominant feature.[4]. Runoff generation therefore happens mainly on hill slopes despite different geological properties.

Justification of archetype definition
Differentiation of the different landscape types, as done by Savenije (2010), is justified as there are numerous studies in the area which indicate there are significant differences in hydrological function between these landscapes. Applications of topoflex are for example Gao et al., Gharari et al. (2014) and Euser et al. (2015).[78][79][80]

3.4.4. Adaptation measure categories and landscape archetypes

The archetypes by Savenije (2010) are based on dominant hydrological processes and are therefore suited as starting point for measure categories.[4] These categories are used to group measures and connect them to landscape types in the case study area. From this we can identify the direction of runoff is mostly lateral in hill slopes and in wetlands, but vertical on plateaus. Plateaus participate less dynamically in the hydrological cycle, as their runoff duration is much longer as the vertical process is much slower. The runoff water can be either stored, slowed or discharged. All can contribute to the smearing out of the flood peak and therefore be effective at preventing floods at bottlenecks. The store, slow and discharge categories are consistent with categories used in literature on the Geul (e.g. [59][58][57]) and encapsulates the dominant runoff mechanisms of landscape types in the Meuse.

Retention and storage of water are aimed at combating lateral runoff. Increased discharge capacity is not targeted at runoff, but at discharging the runoff when it is already in the stream. These types of measures can therefore be complementary. Relating this to the landscape types and associated dominant runoff mechanisms; retention and storage are useful for hill slopes and discharge increase is suited for downstream locations. In this thesis, measure categories are defined as;

- Room for the River (RR)
- Downstream infrastructure (DI)
- Upstream Infrastructure (UI)
- Upstream Natural Retention (UNR)

Room for the River, Upstream Infrastructure and Natural Retention are aimed at retaining and storing water, Downstream Infrastructure at disposing water. These are connected to the landscape archetypes through their dominant runoff directions. In wetlands and on hill slopes, the runoff direction is lateral, causing measures aimed at slowing or storing water to be effective. Despite not participating dominantly in runoff generation, plateaus can be useful for storing water. Discharge capacity enhancing measures are located downstream. An overview of the measure categories and associated landscape archetypes is provided in table 3.1

Table 3.1: Measure categories and their typical landscape archetype locations

	RR	DI	UI	UNR
Hill slope		x	x	x
Wetland		x	x	x
Plateau			x	
Downstream	x			

3.5. Network Theory

Network Theory can be used to explain the effects of observed connectivity patterns on elements in a network.[81] Networks in network theory consist of nodes, links and clusters. A node is the smallest unit that can be an agent or an institution. A link is the connection between two nodes.[82] Complex networks can be analysed using Social Network Analysis (SNA) by analysing social networks in terms of actors (nodes) and their interaction (edges).[83] Different properties have been assigned to the edges in order to provide more information on the network. SNA can therefore provide insights in the role of individual actors and can help identify central, coordinating and bridging actors.

3.5.1. Network Theory in (international & water) Governance

Governance networks are usually fragmented because responsibilities are divided but also shared between different organizations. This is also the case in the Meuse as sketched in the section on governance in the Meuse. From a network perspective, a governance system is structurally fragmented when it is highly modular at the community level but sparsely connected at the network level.[81] Fragments of networks are often based on regions or sectors, and they can be formed by international treaties or court systems.[81] Whether institutions contribute to fragmentation or defragmentation depends on the connections of these new elements; Institutions with a global focus exert ‘centripetal’ forces and defragment a network, regions or issue specific institutions are considered ‘centrifugal’ and contribute to the fragmentation of a network.[81] Shared membership across institutions has been a common proxy for inter-institutional relationships.[81] In the Meuse this is the case for the memberships of the CIM and the EU.

Network theory and analysis has been used in the field of Water Management and water governance. Applications range from classification of river systems based on network properties[84] to the analysis of actors governing and interacting with water.[83][85] These network analyses generally include the connection between multiple networks, such as networks governing nature and networks governing water. Governance of natural resources is recognized in scientific literature as complex.[86][87][85] Research proposes polycentric institutional arrangements for managing social-ecological systems rather than central government.[85] In reality, in River basin management, there is always a polycentric situation: Responsibilities are shared and divided between administrative layers. Their interaction is both formal and social, and is therefore not able to be described with responsibilities and legislation alone.

3.5.2. Social Network Analysis (SNA)

In a SNA, both the formal and the informal connections are relevant.[85] To capture both, SNA should be based on data such as cooperation quality or frequency. The application of a qualitative assessment for edges between nodes has been used in scientific literature.[83] In this thesis, this is done by asking cooperation quality between actors.

SNA starts with the modelling of a network consisting of nodes and links. By capturing only the basis, a lot of information about the interaction between nodes in a network is lost, but the method enables quantitative analysis. Models can be enriched by assigning values between links and nodes to assign an additional value or property to them.[81] SNA can also provide insights into the capacity for collaborative action and the cohesion of a network.[83] The structural properties of networks affect the qualities of cooperation and should therefore be handled as important factors in determining success of cooperation.[88] In the next sections the metrics used in this thesis will be explained.

Centrality

Nodes can act as bottlenecks [81]; Degree- and betweenness centrality can be used to identify central actors. Where a high betweenness centrality is a metric which might indicate brokerage actors.[85] A high degree of centralization may indicate that many edges are organized through a few actors that are central in the network.[85] Centrality can be measured as the degree of centrality or the betweenness of centrality. The first refers to the number of links connected to a certain node, whilst the latter refers to the central position of a node with regard to other nodes.[82] The fragmentation can be defined as the extent to which the network consists of clusters.[81]

Density

The higher the network density, the higher potential for collective actions. In addition, less dense networks are argued to have subgroups. This could have a negative effect for collaborative capacity, but can alternatively also induce diverse solutions, providing a wider solution space.[83] The high density improves the potential for collective action and collaboration. Well-connected networks facilitate communication, foster mutual trust and help prevent and manage conflicts. High tie density promotes joint action.[83]

Diameter and Clustering

The diameter of the network, the largest distance between two nodes, and the average path length, the average distance between two nodes, are also important measures of a network as they can provide information about the efficiency and transfer of information or ideas.[82] Another key indicator is clustering. This measures the degree to which nodes tend to cluster. Sometimes, clusters can indicate communities or subsystems.[81]

SNA metrics used in this thesis

The following metrics are used to analyse and describe the network of administrative actors in the Meuse and the Geul. The SNA is expected to provide insight into brokerage and central actors and identify clusters.

- The degree of centralization is the difference of the number of connections a certain node has, compared to the maximum number in the network. The centralization is then the ratio between the maximum possible number of edges and the actual number of edges.[83][85]
- Density is the number of edges present in a network divided by the maximum possible number of edges.[83]
- Degree is the number of edges a node has.[83]
- Betweenness is the number of shortest paths a node is on. Betweenness centrality is this number as a fraction of the total number of paths. A high betweenness centrality can therefore be a proxy to find a bridge node or a broker node for collaboration between other actors.[83]
- Clustering is the tendency of nodes to group together

3.6. Systems approach

Systems thinking is the analysis of the world based on relations and interactions between things, rather than the analysis of systems based on their individual parts. It is a systemic view rather than breaking down a problem into discrete issues that can be addressed separately.[89] This is in contrast with a reductionist approach which tries to analyse objects or networks by zooming in to the parts that make up bigger parts. The idea is that understanding the most fundamental parts and their interaction, one is able to explain the behaviour of bigger parts. System approaches are a way to analyse complex systems and recognize the emergent behaviour of parts interacting with each other and thereby forming more than the sum of their parts. In a systems approach, emphasis is placed on the (complex) context and interactions of an object, rather than trying to explain the object by its parts. A visualization of the difference between the two is provided in the Figures 3.4 and 3.5. In Figure 3.4 a reductionist approach is visualized by the analysis of a goose. In Figure 3.5 a reductionist analysis of a tree is next to the analysis of that same tree in its context.[90]

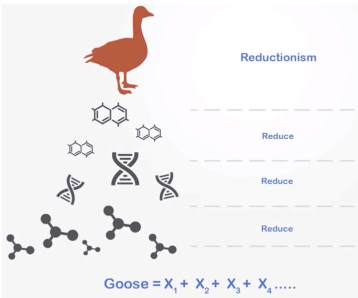


Figure 3.4: An example of the reductionist approach to understanding a Goose.[90]

Figure 3.5: A tree described by its parts (reductionist approach) or placed in context (systems approach)[90]

3.6.1. Complexity Theory

Approaching a system means one has to engage with the concept of complexity. Complexity theory is a theory that was originally developed in non-linear mathematics, thermodynamics and computational sciences. Implementations in social sciences quickly followed and the use of the theory was popularized in the 1990s in management.[91] It theorizes that complex systems are a collection of individual elements that form relationships with positive and negative feedbacks and therefore create system properties that emerge without central command and that exhibit a value more than the sum of its parts.[92] The concept of self-organization, emergence and feedback are at the heart of complexity theory.[92] Complexity helps explain how systems can evolve in unexpected ways and why they can exhibit unstable but also self-organising behaviour.[91]

Complex systems are known to have self-organising capacity without any central control.[92][91] Emergent properties are not predictable from other system characteristics and generally make the system behaviour more homogeneous.[91] In addition, complex systems are able to quickly undergo phase transitions. This is due to the fact that the systems have feedback loops that are able to cause tremendous change as a result of cascading effects.[92] These transitions are sparked by tipping points or triggering events are often hard to anticipate or prevent and are likely to be only the endpoint of an inertial path to a new paradigm. Additionally, complex systems are path dependent.[91] Meaning that previous actions will co-determine the eventual outcome.

3.6.2. Simple, Complicated and Complex systems

Systems can vary in degrees of complexity. Simple and complicated systems have linear relations and are deterministic; The same input will lead to the same output.[93] An overview is provided in Figure 3.6. In simple systems, a specific result can be reached via a single route, whereas a complicated system can be approached in many ways. A complex system, however, does not have linear relations, is dynamic, dependent on context and varies over time. A given input will not lead to the same output. When relating this to the subject of this thesis, a lot of connections can be made. Landscapes are known for self-organization.[4] Additionally, management approaches relying on pre-defined management actions are not able to predict management strategies.[2] In literature, systems approaches deem natural systems to be complex.[87][91][94] Political-administrative and governance settings are known to be complex.[92][81][95] DMDU methods have been shown to not fully account for the natural and political context. The management of natural resources should therefore be based on the notion that both the system it governs, and the governing process are complex. Stein et al. (2011) even state that the governance of water resources is just as complex and interconnected as the hydrological process it governs.[85]

Simple or Complicated Systems	Complex Systems
Homogeneous: identical / indistinguishable structural elements	**Heterogeneous**: large number of structural variations
Linear: a relationship with constant proportions	**Nonlinear**: cause does not produce a proportional effect
Deterministic: same result always occurs for a given set of circumstances; predictable	**Stochastic**: an element of randomness leads to a degree of uncertainty about the outcome
Static: nothing changes over time	**Dynamic**: changes over time; past has an impact on the future
Independent: subsystems are not influenced or controlled by other parts of the system	**Interdependent**: subsystems are interconnected or interwoven not just interacting
No feedback: open chain of cause and effect	**Feedback**: a closed chain of causal connections

Figure 3.6: Properties of simple or complicated- and complex systems extracted as a figure [93]

3.6.3. Managing Complex systems

In managing complex systems, focus should rather be on recognizing triggering events and harnessing emerging opportunities while limiting unwanted effects.[92] Changes in complex systems are path dependent, one might be able to achieve system-wide effects in their desired direction by triggering changes in their desired direction.[94] This is because of the positive or negative feedback properties of complex networks. Decision-makers can also try to set or alter the meta-rules of the game. This can only be done when decision-makers have a solid understanding of basic rules and relations of emergence within the system.[94] These aspects all miss in DMDU methods. Potentially this is the context which lacks in the approach.

Following the complex system properties, solutions will self-organise in the local context; a problem would over time solve itself. For example, by the creation of new flood paths and flooded areas as a response to changing precipitation patterns. The issue is, that climate change adaptation may be more aimed at preserving anthropogenic well-being and economic value rather than letting the complex system find a new equilibrium. This implicates that letting the self-organising properties of natural resources find a new equilibrium is not a suited management approach due to potential undesirable side effects. Levy et al. also acknowledge this and state that despite the limited degree of prediction, management is not only possible but also necessary to avoid the unwanted new equilibrium to form.[91]

However, in complex systems, managers that devise a policy that targets a single or small set of issues can sometimes think this solution is a complete and wider applicable method of management. This can limit flexibility and effectiveness, as complex systems do not behave following linear relations. Flexibility and feedback are necessary to manage a complex system.[92] For managing complex systems, sufficient pressure can be applied prior to a trigger event to push it in a favourable direction. [92]

Management actions in complex systems can be either physical as well as non-physical. Kim argues that network interventions can include forging new institutional links and rewiring existing counterproductive links. This is called a complexity-informed approach to networked global governance.[81] But, Bovaird states that even after large scale events, the policy landscape remains relatively intact. Only when policy subsystems break down and macro-political institutions divert their attention to the issue, major policy changes can occur.[94] The 2021 European floods and the dry summers of 2018, 2019 and 2022 might be such events where, for example, the European Commission might engage more actively in flood risk management.

3.6.4. Deeper systemic interventions

System interventions can also be more focused on deeper, less tangible system properties. Interventions in the hydrological system should be accompanied by deeper systemic interventions. Deeper leverage points in CCA can be useful as they can trigger wider systemic effects and harness self-organisational capacities of both natural and social systems. This way, autonomous adaptation can be initiated to reduce flood risk by decreasing exposure and vulnerability, whilst measures aimed at retention or extra discharge capacity reduce risk by reducing hazard.

In 1999 Donella Meadows published an article on the 12 leverage points for intervening in Systems. The 12 leverage points were ranked on their potential effects on systems. Typically, the lower the intervention number, the more profound the intervention intervenes in a system. Leverage points are placed in a complex system where a small shift can produce big changes in the whole and can be seen as points of power.[96] The 12 points are listed below in the table from Endreny (2020), which adapted it from Meadows (1999) and used it in a river basin setting[97]:

Reverse Rank	Leverage Points for Intervening in River Basin Systems
Lever 12	Constants, parameters, numbers (such as subsidies, water rates, standards).
Lever 11	The sizes of buffers and other stabilizing stocks, relative to their flows.
Lever 10	The structure of material stocks and flows (such as transport networks, population age structures).
Lever 9	The lengths of delays, relative to the rate of system change.
Lever 8	The strength of negative feedback loops, relative to the impacts they are trying to correct against.
Lever 7	The gain around driving positive feedback loops.
Lever 6	The structure of information flows (who does and does not have access to information).
Lever 5	The rules of the system (such as incentives, punishments, constraints).
Lever 4	The power to add, change, evolve, or self-organize system structure.
Lever 3	The goals of the system.
Lever 2	The mindset or paradigm that establishes the system goals, structure, rules, delays, parameters.
Lever 1	The power to transcend paradigms.

Figure 3.7: Leverage points as described by Endreny (2020)[97], adapted from Meadows (1999)[96]

The concept of leverage points have also been used in the domain of water and environmental management. Meadows (1999) states 90 to 95% of our time is invested in parameters of systems.[96] This is also described by Endreny (2020), who states river basins are complex spatio-temporal systems which consists of stocks (e.g. water volume), in- and outflows (e.g. precipitation and evaporation) and with feedbacks and delays in responsiveness that all function to stabilize the system.[97] This creates a tendency to focus on shallow leverage points, also described by Abson et al. (2017)[89]. Interventions in the solution space of this thesis are generally aimed at the flows, stocks and parameters of the system. In this section, potential deeper systemic interventions and examples in the case study are listed.

- Institutions: Institutions can be resistant to change, but crises can trigger institutional adaptation. A key leverage in the ability for an institution to change is openness to change. This might be aided by 'sunset legislation' which is designed to be revised after a given period of time.[89] This is, for example, the case in EU legislation of flood risk and water related legislation; The WFD is planned to be evaluated and potentially changed, and the FD requires periodic updates of flood risk maps and management plans. These moments can be used to intervene in the cooperation network.
- Interaction between Humans and Nature: Academics from different domains have noted the disconnection between people and nature and how this potentially has negative effects on nature.[89] A leverage point, thus, might lie in (re-)connecting people and nature (non-)materially.

Abson et al. note this as well; *How people perceive, value and interact with the natural world fundamentally shapes the goals and paradigms underpinning many systems of interest.*[89] An interesting example might be 'ecosystem services' which imply a certain production from nature for human consumption. It contrasts the human as a steward of nature and might shape the mindset of human interaction with nature. It might be very insightful to experience how little soil is on top of the impermeable layer in the Belgian upper part of the Geul. People might change their perception on the adaptive capacity to increased extreme precipitation via upstream measures and draw conclusions for downstream economic development.

- Buffers: The link to hydrology is very intuitive; Water systems generally consists of flows, retention and stocks. Increasing the stocks might cause a system to be more stable. An example of this might be building reservoirs. Leverage point 9 is about delays. In a water system, one might think of managing the route of this flow, for example by elongating it. Another example is to divert flow to another route. This might cause a flood peak to be smeared out and be more evenly spread. Examples of this can be remeandering rivers or creating spillways. By adding more buffer capacity relative to flow, a system can be stabilized.
- Delays: Delays in the governance of climate change adaptation are very decisive for eventual system outcomes. If a delay, for example in decision-making or implementation, is too long, the solution space will be limited. Potentially, streamlining the decision-making process would make the network better equipped to adapt.
- Mitigation: Without a countering feedback, adaptation efforts will be ever-increasing up to a point where the solution space no longer provides an option for the challenges at hand. Adaptation actions should be accompanied by mitigating efforts.
- Information on flood risk; In the Geul, not everyone is aware of the houses at risk of flooding and local governments provide little transparency.[9] As there is no information on flood risk channelled to the inhabitants of an area, they will not self-adapt, relocate or flood proof houses. In fact, they are more likely to continue economic development in the area, increasing exposure and therefore increasing flood risk. To harness the adaptive capacity of society, this information flow must be improved.
- Financial incentive: When the rules on compensation, insurance and the bearing of costs of flood risk are changed, system behaviour might also change. For example, is flood risk is not covered by disaster funds, banks might be less interested in funding houses in flood prone areas. Or if flood insurance is provided or even compulsory, the financial incentive might cause people to buy houses at other locations. Even if this is not the case, information flow about flood risk is restored this way. This has the ability to slow or even invert the increase in exposure and thus flood risk.
- The deepest leverage point is the mindset people have towards climate change adaptation and flood risk. The paradigm that has governed water management in previous decades is a paradigm of manageability, which is also embedded in Dutch culture. With increasing climatic pressures and sea-level rise, this paradigm is put under pressure. The paradigm that nature is manageable and that risk is mitigateable, should transition to living with risk.

3.7. Conclusions from literature

This section summarizes the conclusions drawn from literature. These are applied in the answering of the research questions.

3.7.1. Flood Risk and Climate Change Adaptation

Flood risk is the product of exposure, vulnerability and hazard. Exposure it the people and property exposed to risk, vulnerability is the effect a flood has on the people and property exposed and hazard is the occurrence probability of an event. Drivers of risk have been shown to be equally important.[11] Climate change adaptation efforts should therefore be aimed at all three, and are the most effective when both planned and autonomous adaptation occur.[10] Humans are, however, bad at estimating distant and abstract risks[63] and tend to adapt to events that are known. In coupled events, flood risk was only decreased when vulnerability and exposure were also decreased.[11] To trigger autonomous adaptation, leverage points can be applied to achieve systemic changes in the political-administrative and societal domain of climate change adaptation.

The adaptive capacity is finite. Therefore, it is necessary to not only adapt to climate change, but also to mitigate the source by climate change mitigation efforts. Adaptation is harder to finance due to the non-linearity in cause and effect, making it hard to apply the polluter pays principle.[10] But by reducing the hazard, inhabitants are not incentivized to autonomously adapt.[10] If only flood hazard is reduced, lock-ins and path dependency can be created.

3.7.2. Management Approach for Complex Systems

Decision Making under Deep Uncertainty (DMDU) methods have been used to deal with the uncertain nature of climate change extent and effects. These methods can either be reactive (e.g. Robust Decision Making or Adaptation tipping points) or dynamic (e.g. Dynamic Adaptive Policy Pathways). Application of DMDU methods is, however, often done with lack of organizational and physical context.[2] Due to the complexity of these systems DMDU methods are applied to, reactive methods are not suited.[2] Dynamic methods, however, also rely on pre-defined contingency actions and vulnerabilities. By nature, DMDU methods are therefore not suited to apply to complex systems due to the emergent and therefore unpredictable behaviour complex systems have.

The management of complex systems is different from complicated systems, as system behaviour can only be predicted to a limited extent. Managers of natural resources therefore join the game within its meta rules and should focus on the direction of the system and emergent opportunities rather than specific interventions. In this thesis, the proposed management method is therefore to provide a manager of natural resources with the solution space based on measures and the climatic pressure from literature. The manager can intervene in the natural system be intervening in 'shallow' leverage points by altering parameters, delays and flows (e.g. interception storage, reservoirs and emergency spillways). In addition, deeper leverage points can be used by the manager to steer the system in the desired direction, for example by triggering autonomous adaptation.

3.8. Framework developed in this thesis

From the theoretical Framework, it becomes clear there is a need for a different management approach to climate change adaptation strategies. This new approach should acknowledge institutional and natural context, complexity of the system and the relevance of all three factors of flood risk. The Framework proposed by the author is visualized in Figure 3.8. It takes the institutional and natural context into account by looking at a solution space for an area and combining it with the institutional context. By performing network analysis and spatially mapping cooperation complexity, locations for adaptation measures can be proposed not only based on landscape types, but also on difficulty of decision-making. As the Framework combines two domains, namely the adaptation solution space and the institutional context, it is based on two pillars which are in the end combined to provide adaptation strategies.

The Framework consists of analyses, inputs, products and results. Analyses provide the inputs, these are combined to form the products and based on the products results can be determined. The solution space is formed based on literature. Adaptation goals, possible measures and associated landscape types are from literature. This demands a high information level on a catchment the Framework is applied to. The solution space is formed by assessing all possible unique combinations of measures. Non-compatible combinations are removed, and a constraint is applied to filter combinations that do not provide the desirable performance.

The institutional context is analysed based cooperation quality between actors in the network, their territory based on maps of borders and network characteristics of the network these actors form. Methods for these inputs differ; Cooperation quality is quantified using expert judgment. This way, social and institutional links are combined. Maps of actors are based on Open-source information. These are the borders of the actors involved. By placing these on top of each other and evaluating the actors present in a subcatchment, maps can be made of involved actors at a given location. Social Network Analysis can be performed on the network formed based on the cooperation quality provided by the expert judgment. This gives insight into the central and brokerage players in the network and general network characteristics. These inputs are combined to form spatial maps of cooperation difficulty.

Based on the cooperation difficulty, network properties and the solution space, preferential strate-

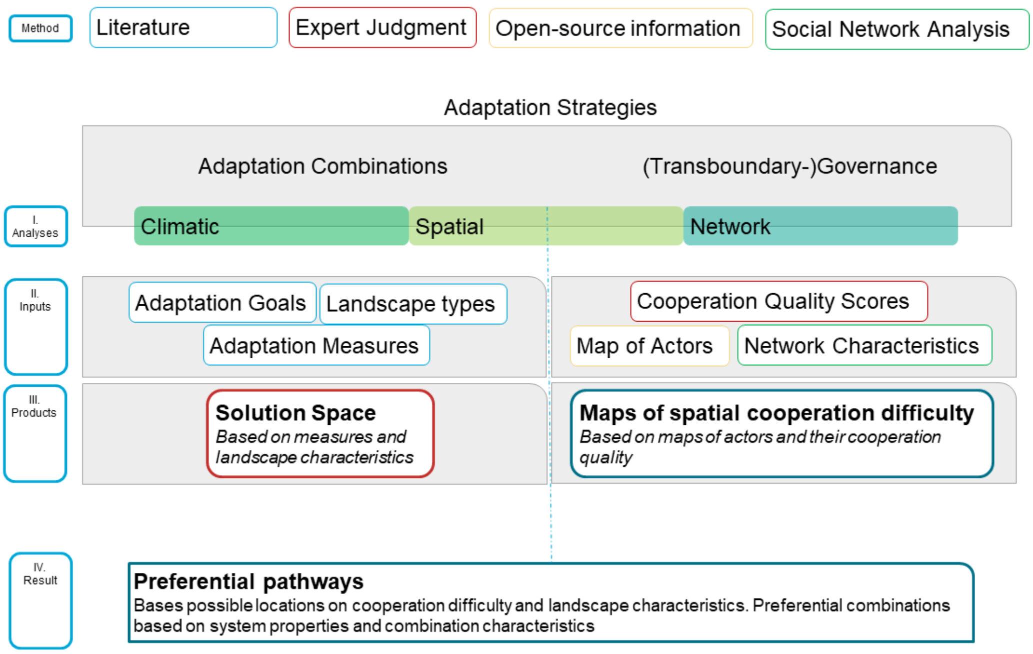


Figure 3.8: Framework proposed and tested in this thesis

gies and locations are determined. Preferential strategies can be based on their location fully upstream, downstream, being non-transboundary, being natural or on deeper systemic properties. In this thesis, this Framework is used and tested using a case study in the Geul. By applying this Framework in the Geul, strategies are proposed to manage the excess 6 million m^3 of water that flooded the area during the 2021 floods. The timeline for adaptation is determined to be 2050, but decision makers could determine otherwise. Therefore, 2050 is used in this thesis, but possible strategies are extrapolated to later moments. Methods used are literature review, expert judgment, open-source information gathering and social network analysis.

3.9. Scope and Assumptions

The case study is conducted in the Geul basin. Its scope is limited to floods and does not analyse the effects of climate change interventions on droughts. It is assumed, based on scientific literature, that the excess discharge volume of the 2021 European floods in the Geul is the adaptation goal, this is 6,000,000 m^3. All measures are also related to this volume in order to estimate their effects. The interaction of these measures and their combined effect is not in the scope of this thesis. Additionally, measures aimed at decreasing the vulnerability of people and property (e.g. flood proofing and FEWS) are not included in the solution space. The thesis assumes that the dominant runoff mechanisms and associated landscape archetypes in the Geul are the same as described by Savenije (2010).[4]

The scoping also excludes non-administrative actors in the social network analysis and the cooperation quality maps. The cooperation quality is calculated from the perspective of the Netherlands. Adaptation strategies are aimed at reducing flood risk in Valkenburg. This is because Valkenburg is the biggest city downstream in the Geul and because of this, flood risk is concentrated there. This approach is similar to the approach of literature on the area. (e.g. [59][57]) Both the natural system and the institutional network governing it are deemed complex.

4 Methods

The Framework used in this thesis consists of four different steps. The end product are suggestions for preferential strategies and locations based on a solution space and spatial cooperation difficulty maps. The Framework requires inputs that are drawn from three different analyses; climatic-, spatial and network. To construct these inputs, Literature review, Expert judgment, Open-source information and Social Network Analysis are used. From the inputs, products are formed and combining the products results in the preferential adaptation strategies. Some conclusions and discussion points were validated in two validation sessions with experts, one with four adaptation experts of engineering consultant Arcadis and one with an academic expert of the University of Liège.[98][47]

4.1. Step I: Analyses

Network Analysis

The network analysis should provide network characteristics and cooperation quality scores between the actors in the network. The analysis was done by using the Expert Judgment method, but can also be done using other metrics, such as the presence of contact and contact frequency (e.g. Fliervoet et al.[83]). When all actors and their quality of cooperation are known, the user might apply a threshold on cooperation quality to delete connections that are not meaningful. Social Network Analysis can then be applied to the network to find network characteristics. Metrics of relevance can be chosen by the user. In this thesis, degree, degree centrality, betweenness centrality, clustering and density were considered.

Spatial Analysis

Spatial analysis should provide two products: Landscape archetypes with associated measures categories and a map of administrative actors. The first can be used to find the mechanism that should be targeted by the adaptation measures. In case of this thesis, this is the dominant runoff mechanism and direction. These landscape archetypes can later serve as locations where measures could be located, as these measures target one or more properties of a landscape archetype. The map of administrative actors yield the actors present in a location of interest. This can combine any region of interest and the borders of governments. This way, one can look at a transboundary catchment and identify the actors present regardless of the location of nations or administrative entities. Archetypes can be identified by the user or be distilled from literature. Administrative borders were downloaded from GADM.org.[99]

Climatic Analysis

Climatic analysis can be done by analysing literature on the effects of climate change at the location of interest. This can for example be related to drought, precipitation patterns or other parameters or flows that are effected by the changing climate. This analysis provides an adaptation and time goal. Time goals can also be derived from policy goals posed by responsible governments.

Expert Judgment

Expert Judgment was conducted to provide inputs from experts on implementation times of measures and cooperation quality between administrative entities. The session was conducted on the 17th of

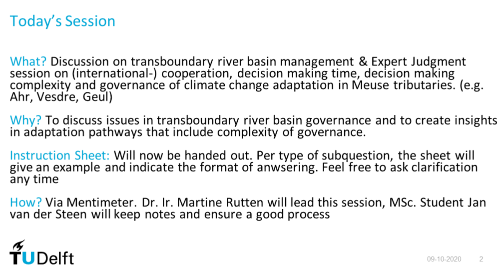


Figure 4.1: General instruction slides

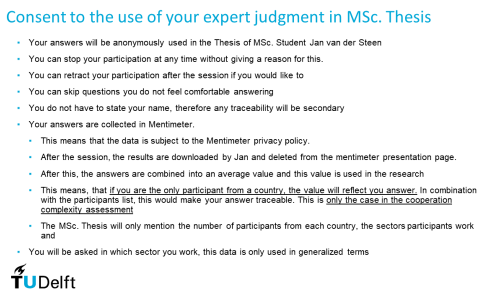


Figure 4.2: General instruction slides

October at the International Meuse symposium in Liège. The expert judgment method was based on the structured expert judgment as developed by Cooke.[100] 45 unique experts participated. The session was hosted in plenary using Mentimeter. 27 Participants provided scores on cooperation in the network. Participants were civil servants, technical consultants and academics. Experts originated from the Netherlands (16), Germany (3), France (3) and Belgium (5 of which 3 Walloon and 2 Flemish).

Participants were informed 15 minutes prior to the session that an expert judgment would be collected via Mentimeter and were provided with information and instruction form at exiting the conference room for the break of the congress. After that, the participants were plenary again informed on the experiment and their participation. Five participants retracted their participation from the session afterwards. Some participants only participated partially. The session with partially before and partially after presentations at the congress. Causing a difference in participant numbers. Not all entries were valid; some participants stopped answering questions or skipped almost (all) questions. These entries were removed along with the participants who retracted their consent for participation. This left, in general, about 33 valid entries for the cooperation quality on which the Social Network Analysis was based and 27 entries for the estimation of implementation times.

At the start of the experiment, participants were asked to join the Mentimeter environment with their own device while the researchers introduced each question. Questions were also visible on the plenary screen. Participants were able not to join but were, beforehand, also notified of the possibility to provide and retract consent at both the start and the end of the expert judgment. General instruction slides are displayed in Figures 4.1 and 4.2. Expert judgment and data handling was done using the guidelines of the TU Delft Human Research Ethics Committee. Data was gathered anonymously and was removed from the Mentimeter platform when the results were downloaded.

4.2. Step II: Inputs

Inputs were gathered from the analyses of the previous step. In this section, each input production of the Framework is described. The inputs can be seen in Figure 3.8.

4.2.1. Solution space

The solution space are the available adaptation combinations that could provide the desired level of adaptation. It was formed by first finding all unique combinations of all lengths and then constraining it by the adaptation goal. Lastly, combinations were grouped based on their characteristics. To form the solution space, adaptation goals, adaptation measures, landscape archetypes of the study area and implementation times are needed.

Adaptation Goals

The adaptation timeline in this thesis was derived from policies of the European Commission and of the country downstream, the Netherlands. Both administrative entities have the goal to be fully adapted to climate change by 2050.[101][42] The adaptation goal was determined using literature research of the area and was assumed to be equal to the excess volume of water, 6,000,000 m^3.[59][57] Policymakers might deviate from this goal for numerous reasons. For purposes of constructing a solution space, this one was used by the author.

Adaptation Measures

The 19 measures forming the solution space were drawn from literature and posed by the author. They were recalculated to the excess volume of the 2021 floods they could have managed. This volume was then recalculated to the metric *millimeters equivalent* which is the volume divided by the area of the subcatchment. This way, decision-makers could also estimate the effect of measures if they are implemented to a different area.

Measures

The solution space consists of 19 different measures. Of these, five were distilled from the Deltares report on the rapid assessment of the 2021 floods (2022) [59], three from the hydraulic analysis of Deltares (2021) [57], one from a report by Arcadis and Vista landscapes archetypes [58], four by the Multidisciplinary student research on hydraulic bottlenecks in Valkenburg [21]. In addition, five measures were reasoned in this thesis. Of this, two are maladaptive measures. These are not actually measures but rather negative impacts that humans might do. These were included to show the Framework is also able to deal with changing circumstances. In case these maladaptive measures (e.g. an increase in built-up area) take place, the solution space still provides suggestions on possible adaptation strategies while taking into account the negative effect of these maladaptive actions. An overview is provided in 5.1.

Measure categories

Measures were grouped in the categories Downstream Infrastructure (DI), Room for the River (RR), Upstream Infrastructure (UI), Upstream Natural Retention (UNR) and Maladaptation (M). Additionally, two alternative measures were added; 'Quay2.5' and 'Dryvalley'. These measures are 'out of the box' ideas which would provided the desired storage or discharge capacity by themselves.

Millimeter equivalent

The different metrics used in literature are peak reduction, discharge capacity increase and water level decrease. These metrics were all recalculated to a millimeter equivalent. This is a volume divided by the area of the Geul. Peak discharge during the 2021 flood event was 130 m^3/s [59] and the area of the Geul is 334 km^2.[7] With the excess volume of the 2021 floods being 6,000,000 m^3. The millimeter equivalent of the adaptation goal is 6,000,000 m^3 divided by 334,000,000 m^2. This is equal to 17.96 millimeter equivalent [mm]. The flood event is assumed to have lasted 0.7 days. This is equal to 16.8 hours or 60,480 seconds. Calculations were done using the following equations;

$$Additional\ discharge\ capacity\ [m^3/s] = 0.01 * Peak\ reduction\ [\%] * Peak\ Discharge\ [m^3/s] \tag{4.1}$$

$$Storage\ volume\ equivalent\ [m^3] = \frac{Additional\ discharge\ capacity\ [m^3/s]}{Duration\ of\ flood\ event\ [s]} \tag{4.2}$$

$$Millimeter\ Equivalent\ [mm] = \frac{Storage\ volume\ (equivalent)\ [m^3]}{1000\ *\ Area\ of\ the\ Geul\ [m^2]} \tag{4.3}$$

The area of the Geul is 334 km^2, the duration of the flood event was 0.7 days or 60,480 seconds.

Measures added

The solution space was widened by measures proposed by the author. They are listed and explained below. Two of the measures proposed by the author are maladaptive and meant to assess the strategies still available in case maladaptation occurs.

1. Aquifer storage (Aquifer)

   One possible way of dealing with excess discharge could be to actively pump water from the stream into an aquifer. Aquifer pumping is known for relatively high use of energy and would be sensitive to (temporary) losses of power. In addition, groundwater recharge might lead to extra discharge as groundwater normally discharges into base flow and a saturation of an aquifer might 'push out' water into the stream. Order of magnitude estimation related to Aquifer recharge and recovery research conducted in Belgium. Individual wells were able to recharge and recover roughly 260,000 to 396,000 m^3.[102]

By examining the thickness of aquifers, provided by Klein (2022) an estimation can be made on the average thickness and the related volume. Klein states that the aquifer at Sippenaeken is less than 20 meters thick, the aquifer at Hommerich is 10-80 meters thick and the other aquifer, closed off by the before mentioned ones, present is 40-100 meters thick.[7] Taking the average of these thicknesses and their area, one can estimate the total aquifer storage in the catchment is roughly 18,000,000 m^3. Assuming 10% of that is rechargeable, one can conclude that the number of 1,000,000 m^3 would be plausible; It is about 5% of total available aquifer storage in the catchment. A total storage capacity for the aquifer recharge measure assumed to be 1,000,000 m^3, this relates to 3 mm over the area of the catchment.

(a) Measure Category: Upstream Infrastructure (UI)
(b) Storage realized: 3 mm
(c) Code: Aquifer

2. 10 small reservoirs (Smallreser)

Ten small reservoirs of 8000 cubic meters storage each, in total providing 80,000 m^3 of storage. In total contributing to the equivalent of 0.26 mm storage when this volume is divided by the basin area. These are smaller and can therefore be more easily placed strategically.

(a) Measure Category: Upstream Infrastructure (UI)
(b) Storage realized: 0.26 mm
(c) Code: Smallreser

3. Several Big Reservoirs (BigRes)

Another solution might be to store the water in several big reservoirs. Three reservoirs of a little over 0.11 million cubic meters each, providing a total storage of 330,000 m^3 form the measure 'Several Big Reservoirs'. These reservoirs could then be located at the tributaries of the Geul and store an amount of water before the convolution. At a water depth of 15 meters, each reservoir would span 7300 m^2.

(a) Measure Category: Upstream Infrastructure (UI)
(b) Storage realized: 1 mm
(c) Code: BigRes

4. Built-Up area increases (BuiltupINC)

One of the maladaptation actions included was the increase of built-up area. This can possibly to increase the runoff and decrease the retention time. It was assumed built up increase, reduces storage capacity of soil by 40%. Currently 13,1% of the area is paved.[17] In this maladaptive action, it was assumed this increases to 20 %. As soil thicknesses vary between 0,2 and 15 meters, an average thickness of 1 meter was assumed. A decrease of 40% in storage of this additional 6.9% (a little over 23 km^2) would lead to a decreased storage capacity of 9,051,400 m^3 or 27.5 millimeter equivalent.

(a) Measure Category: Maladaptation (M)
(b) Storage realized: - 27.5 mm
(c) Code: BuiltupINC

5. Forest area decreases (ForestDEC)

This maladaptive action is the opposite of increasing the area of forest and is likely to have an opposite effect; quicker drainage and less storage. Currently roughly 59.5 of the 334 km^2 is forested, this is 17.8%.[17] In this maladaptive action, it was assumed forest cover decreases by 50% and this leads to a decline in storage capacity of 25 millimeters at the deforested locations. With area being decreased by 29.75 km^2, this would lead to a loss of storage capacity of 737.500 m^3. This would result in an equivalent storage loss of 2.2 mm.

(a) Measure Category: Maladaptation (M)
(b) Storage realized: -2.2 mm
(c) Code: ForestDEC

Landscape Archetypes

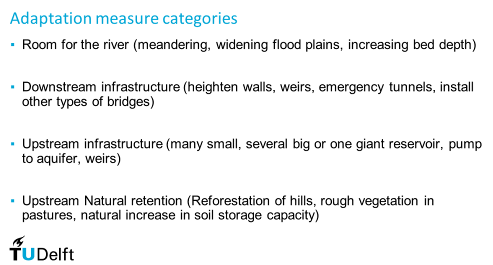
The landscape archetypes by Savenije (2010) were used to derive dominant runoff directions. An overview is provided in Figure 3.3 From this, measure categories were linked to landscape archetypes. This is displayed in table 3.1 Landscape archetypes are defined using Digital Elevation Models. Hill slopes were assumed to have a slope of 5% and a height above nearest drainage (HAND) of 30 meters. Wetlands and plateaus have a slope lower than 5%, but Plateaus have a HAND of 90 meters or higher.[103] The Geul was classified into Archetypes in WFlow topoflex.

Implementation Times

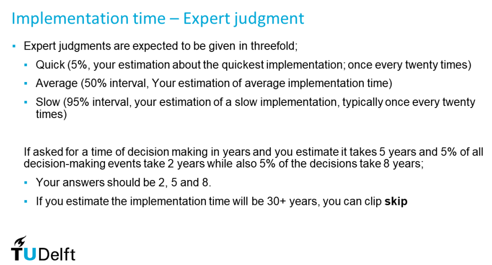
Implementation times estimation was done using expert judgment. Implementation times depend on a lot of variables and is therefore hard to quantify. For example the decision-makers involved, budget, location context, political situation and so on. By using expert judgment, estimates are based on the experiences of professionals that are familiar with these complex processes. The experts should have expertise in implementation of adaptation measures in the regional context. The mean estimation can be used for determining average implementation time of combinations in the solution space, and the spread can give insight into the uncertainty of this time. In this thesis, implementation time was defined as the combination of decision-making time and construction time.

Expert Judgment at the 8th International Meuse Congress

For estimating implementation time, Expert Judgment was used. Experts were asked to provide 5%, 50% and 95% estimates of implementation times of four measure categories (Room for the River, Downstream Infrastructure, Upstream Infrastructure and Upstream Natural Retention) and two categories that are transboundary in nature (Transboundary Measures and Integrated plans). The instruction slides were as displayed in Figures 4.3a and 4.3b.



(a) Instruction slides Implementation time



(b) Instruction slides Implementation time

(c) From left to right: Picture in the room for the river, downstream infrastructure, upstream infrastructure and upstream natural retention slides.

Figure 4.3: Impression of the expert judgment session at the International Meuse congress

Questions were:

1. What is the implementation time for 'Room for the river (meandering, widening flood plains, increasing bed depth)' measures?
2. What is the implementation time for 'Downstream infrastructure (heighten walls, weirs, emergency tunnels, install other types of bridges)' measures?

3. What is the implementation time for 'Upstream infrastructure (many small, several big or one giant reservoir, pump to aquifer, weirs)' measures?
4. What is the implementation time for 'Upstream Natural retention (Reforestation of hills, rough vegetation in pastures, soil storage etc.)' measures?
5. What is the decision-making time for transboundary adaptation measures in a tributary of the Meuse? (e.g. Geul)
6. What do you estimate the *decision* making time is for an integrated adaptation plan for a trans-boundary tributary? (e.g. Geul)

Answer possibilities were:

- Quick (5%, your estimation about the quickest implementation; once every twenty times)
- Average (50% interval, Your estimation of average implementation time)
- Slow (95% interval, your estimation of a slow implementation, typically once every twenty times)

The result are provided in a boxplot where the stripe indicates the mean and the wiskers the outliers. The box contains the 25th and 75th quartiles.

Context

This was done in the context of the Meuse and followed presentations of possible interventions in the Geul. These were on the Hydraulic Analysis [57] and the Rapid assessment[59] of the 2021 floods in the Geul. Measures proposed in these presentations constitute a significant portion of the measures included in the research (8 out of 17). The measures as mentioned by the Multidisciplinary student group of the TU Delft[21] were the basis for the 'Downstream Infrastructure' category and were also mentioned in the examples of the question. Other measures included in this research, such as a pump to an aquifer and small, big or giant reservoirs, were also mentioned in the question. The implementation slides were accompanied by the photo's in Figure 4.3c. The user experience of the question is displayed in Figure 4.4.

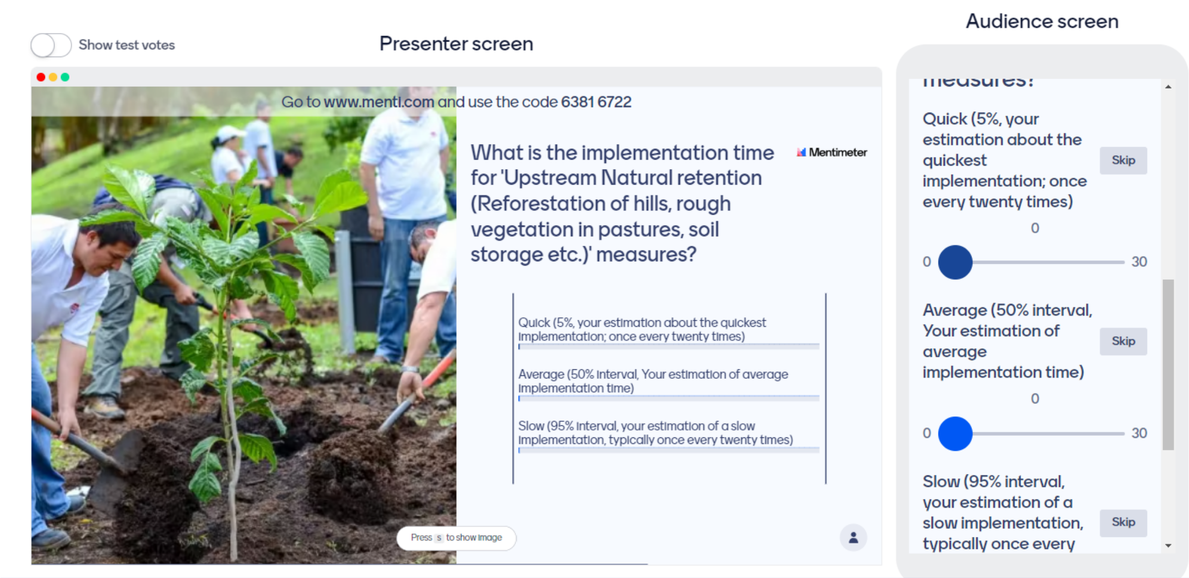


Figure 4.4: User experience of the expert judgment

Combination Analytics

Combinations were also analysed on their properties. This can give insights into the solution space, which is otherwise very abstract. Analytics were applied to the cumulative implementation time (TIS), transboundary combinations and measure categories prevalence in the solution space. Plots were generated in Excel and are bar charts, scatter plots and a pie chart.

Cumulative implementation time TIS

When constructing the solution space, options are assigned a time of implementation based on the assessment of experts, as visualized in Figure 5.1. Each measure was related to one of the categories. The estimation of implementation time was then used to construct a Cumulative Implementation Time of the strategy, TIS. TIS is later used as a proxy for the difficulty of implementing the strategy.

Latest Implementation time (LIT)

Due to the large quantities of Cumulative Implementation Time, it is necessary for the options to be implemented simultaneously. Therefore, a latest implementation time (LIT) was added to the strategies. This was based on the largest implementation time in the combination.

Measure categories in combinations

To analyse the combinations, the measures were replaced by their categories and counted. This is then visualized in bar and pie charts. In addition, an analysis was done on the occurrence of categories divided by the number of measures in that category. This gives an insight of the prevalence of the measure categories.

4.2.2. Governance

The transboundary governance difficulty was assessed based on spatial maps of actors, cooperation quality scores and network characteristics. Using expert judgment, cooperation quality scores within and between countries can be determined. By combining them, one is able to form a cooperation network. Using Social Network Analysis, network characteristics can be determined from this data. Maps of actors are maps where borders of national, regional and local administrative entities are combined. These were clipped for the subcatchment outlines in order to determine all actors in a subcatchment of interest.

Map of Actors

The maps with borders were constructed by downloading all administrative borders of the river basin countries (The Netherlands, Germany, France, Belgium and Luxembourg) in vector format from the GADM.org[99] and putting them together in QGIS. These maps included all the available administrative border maps for the basin countries. The maps are provided in WGS84 projection and version 4.1 was used. In the Netherlands, the maps included were the National border, provincial borders, municipal border and borders of waterschappen. In Belgium these were federal borders, borders of gewesten, provinces and arondissements. In France these concerned national borders, borders of provinces, regions, arondissements, cantons and communes. In Germany the maps included Federal borders, borders of Bündesländer, Kreise, Städte and Gemeinde and Municipalities. In Luxembourg, National borders are accompanied by borders of districts, cantons and communes. The entities were grouped as;

- N: National or Federal entitites (Federal government, national government, Région (FRA)) but also Subfederal entities (Bundesländer, Gewesten)
- R: Regional (Provinces, Région, (Land-)Kreise, District, Departement, Arondissement) and Water focussed entities (Waterschappen, Wasser- und Bodenverbände)
- L: Municipal (Gemeinden/Kreisfreie Städte, Gemeenten, Communes)

When categorized, the layers were merged and intersection with the Geul was clipped. Yielding a map with all the administrative entities in the Geul. From this, entities were grouped per subcatchment. Entities that were included in a (sub-)catchment due to small differences in border definition were manually removed. Leaving a list of all entities of all countries categorized in either N, R or L per subcatchment of the Geul.

Cooperation Quality Scores

Experts were asked to rate cooperation between National, Regional and Local administrative entities in their native country and the typical cooperation of their native country with other basin countries. The instruction slides were as displayed in Figures 4.5 and 4.6.

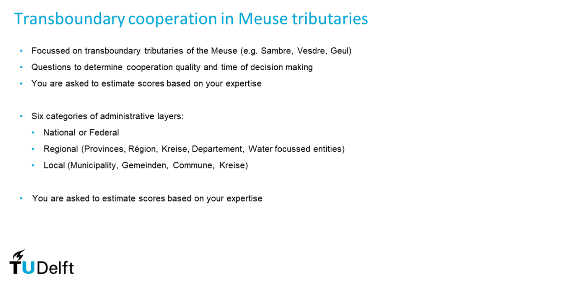


Figure 4.5: Instruction slides Cooperation score

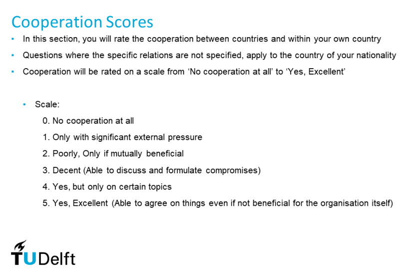


Figure 4.6: Instruction slides Cooperation score

As can be seen in the images 4.5 and 4.6, participants were asked to rate the cooperation based on a scale from 0 to 5. The user experienced the screen displayed in Figure 4.7. The scale was defined ad follows;

- 0. No cooperation at all
- 1. Only with significant external pressure
- 2. Poorly
- 3. Only if mutually beneficial
- 4 Yes, Well (Able to discuss and formulate compromises)
- 5. Yes, Excellent (Able to agree on things even if not beneficial for the organization itself)

The questions spanned:

- The typical cooperation of the native country with other basin countries
- The cooperation within their native country between national and regional and local entities
- The cooperation within their native country between regional and national and local entities
- The cooperation within their native country between local and regional and national entities
- Which of the entities (National, Regional, Local) works internationally within the basin

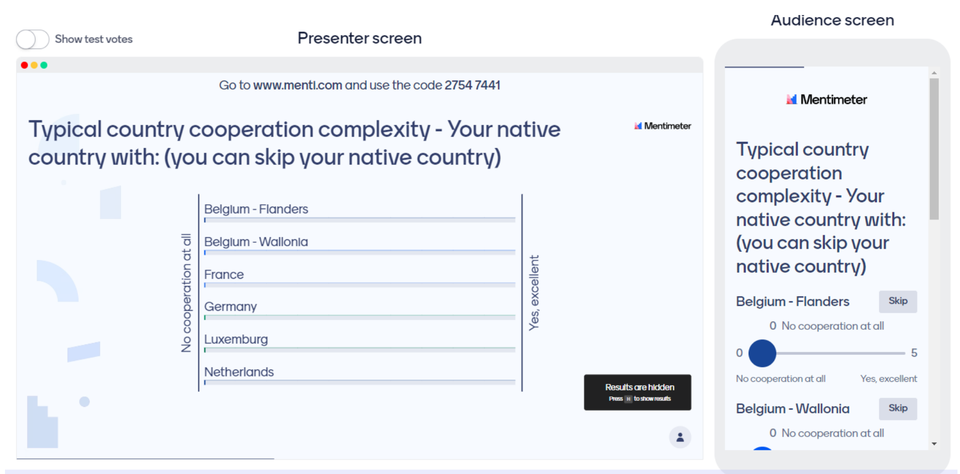


Figure 4.7: User experience of the expert judgment

The session included participants from every basin country except Luxembourg. Flanders and Wallonia were defined as separate countries. Participants were asked of their native country in order to attach their values to a certain country. All N's (The Netherlands: 18, Germany: 5, France: 3, Flanders: 2, Wallonia: 3) were bigger than one, making it not possible to identify the answers of anyone. Even with a list of participants and their nationalities. The questionnaire did not specify a difference between Flanders and Wallonia. However, participants were asked to answer skip at their native country, and it was specified Flanders and Wallonia are separate countries. From the skipped questions, all but one participant were possible to identify as either Flemish or Wallonian. This participant scored the cooperation with Flanders 5 and Wallonia 4, skipping none. Cooperation with France was scored 5 and the Netherlands 1. It was assumed this participant is Wallonian because literature [13] suggests there is a link in language and cooperation perceived by actors in the Netherlands and Wallonia and this difference is so extreme that the answer is very likely to be Wallonian.

Network Characteristics

From the cooperation quality scores, a matrix can be formed per country of the cooperation between administrative entities. The question of how National governments cooperate with regional and local governments provides the inputs N-R and N-L, Regional entities' cooperation with national and local entities provide inputs R-N, R-L and similarly local entities' cooperation provides L-N and L-R. A generic matrix to visualize this can be seen in table 4.1.

Table 4.1: Example of an internal cooperation matrix

	National	**Regional**	**Local**
National	NaN	R-N	L-N
Regional	N-R	NaN	L-R
Local	N-L	R-L	NaN

The International matrix was constructed using the national matrices and using the cooperation between that nation and a given other nation to extrapolate the whole matrix. This process is visualized in Figure 4.8. Here, the matrix on the right is the transposed version of the matrix on the bottom. This process was repeated for all countries and the matrix was averaged over the diagonal. This was done using the function *diagblockmatslicing*. This way, cooperation is averaged over the perception of both countries. Lastly, the cooperation between national entities was added in the matrix by placing the typical cooperation score of countries as the value of cooperation between two national governments.

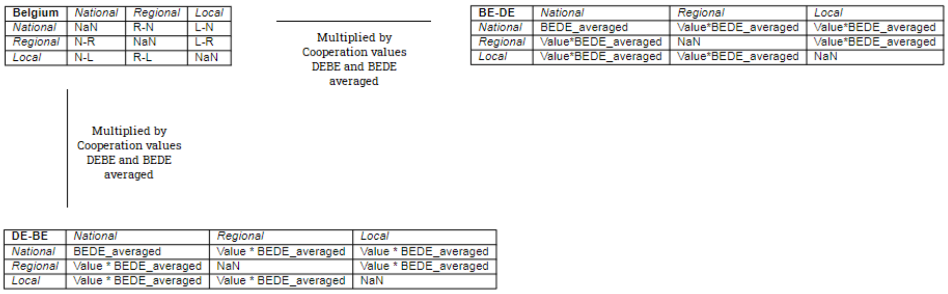


Figure 4.8: Construction of the matrix, including regional and local cooperation

Visualizing the Network

The network was visualized using the Networkx package in Python. A function, *colours* was written which first removes connections below the threshold provided by the user. Based on the cooperation quality, different line styles were applied: a black solid line at 0.5 or above, a purple dashed line for connections between 0.3 and 0.5, a cyan dashed line between 0.2 and 0.3 and a grey dashed line for connections lower than 0.2. Widths were decreasing, causing the visual effect of stronger connections catching the eye. A seed of 2000 was applied for the positioning of nodes. The function then calculates the network characteristics degree, clustering, degree- and betweenness centrality. Based on the betweenness centrality, the colour of the node was determined on the viridis colour scale. The higher the betweenness centrality, the lighter the node. Similarly, the degree compared to other nodes in the network determines the node size. These features cause broker- and central players to stand out visually. The function plots the edge value (the cooperation quality between the two nodes it connects). This can also be turned off to provide a network overview in the same function.

Network Characteristics

Network characteristics in the results of this thesis were calculated using the Networkx library. The library is designed for network analysis, therefore all calculations are present in the library by default. Calculations used were degree(), clustering(), degreecentrality(), betweennesscentrality(), connected-components(), singlesourceshortestpathlength(). These functionalities can be accessed using the function *stats* The function *colours* can also be provided with a threshold. The applied thresholds were 0.2, 0.4 and 0.6. These thresholds were used because they correspond to the cooperation quality scale. They stand for 'Only with significant external pressure', 'Poorly' and 'Only if mutually beneficial' respectively. This can give insight into which actors are able to meaningfully cooperate with regard to implementing climate change adaptation measures.

Other results

The international cooperation Matrix was visualized by setting the axes as the countries in the basin and plotting their cooperation in viridis colour scale. The degree was plotted against the rank, and the degree was plotted as a histogram.

4.3. Step III: Products

The products are the third level of the Framework. The products were made by combining the inputs generated at the previous step. There are two products, the solution space and spatial maps of cooperation difficulty. The products can, in turn, be used to produce the results, which are preferential climate change adaptation strategies.

4.3.1. Solution Space

The solution space was formed by evaluating all combinations of all lengths of the measures in the solution space. These were then constrained on performance with regard to the adaptation goal. In this thesis, the adaptation goal was set at 17.96 millimeter equivalent. Any combinations providing a lower storage equivalent were filtered. A constraint of 22 millimeter equivalent (20 % over the target) was also applied in order to filter combinations overshooting the adaptation goal; measures are very intrusive, therefore it was assumed it is undesirable to overshoot the adaptation goal.

Although possible, no time constraint was applied. This thesis proposes measures to be taken in parallel rather than in sequence. The method allows for filtering by latest decision-making time and cumulative decision-making time with regard to a desired moment to be adapted. This is, however, left for the decision maker. Timelines to 2050 and 2100 were provided to give insight into the adaptation solution space.

The combinations were created using the Itertools library in Python. The library has a function to create unique combinations of all lengths, *combinations()*. *Combinations()* provided a number lists equal to the number of measures that were used as input. These lists were converted to a single list with entries of all lengths using the function *flatten()*. A score on the storage realized was calculated by connecting the measures in the combinations to their performance by a loop. Constraints were applied to this score. The combinations were evaluated on the measure categories in each combination. Combining the implementation times as estimated by experts and these categories, the cumulative implementation time 'TIS' was calculated. A latest implementation time (LIT) was calculated based on the longest implementation time present in the combination. The end result is an Excel file with all combinations reaching the adaptation goal, their TIS, their LIT, their performance in the adaptation goal and the number of entries in each category.

4.3.2. Maps of spatial cooperation difficulty

Spatial Maps of cooperation difficulty were made by combining the Maps of Actors and the cooperation quality scores. The maps of actors provide the actors present in a subcatchment. A cooperation difficulty was assigned to a subcatchment by summing the cooperation difficulty of the actors present from the perspective of the downstream country or actor. In this thesis, this is the Netherlands. Cooperation difficulty was calculated as follows:

$$Cooperation\ difficulty = 1 - cooperation\ quality \tag{4.4}$$

$$Cumulative\ Cooperation\ Difficulty = \sum Cooperation\ Difficulty * Actors \tag{4.5}$$

The Cumulative Cooperation Difficulty per subcatchment was added in QGIS as a property of that subcatchment. The subcatchments were subsequently styled by applying a 'graduated' style based on an equal interval (quantile) of eleven classes. Classes range from 2 to 45, where the last one ranges 15 to 45.

Broader applicability

To evaluate the broader applicability of the method, the Maps of spatial cooperation difficulty were also applied to the basins of the Vesdre, Ourthe and the Sambre. Hybas provides Global watershed boundaries and sub-basin delineations derived from HydroSHEDS data at 15 second resolution.[104] The database divides areas into sub basins when two branches with a minimum upstream area of 100 km^2 meet. Smaller subcatchments can occur when basins are located between sub-branches. Coding is done using the 'Pfafstetter' method.[104] These are the codes assigned to the subcatchments. The Sambre and Ourthe catchments consist of second and third order subcatchments, the Vesdre of third and fourth order subcatchments. Second order branches flow directly into a main river of order one.[104] In the case of this thesis, the Meuse.

4.4. Step IV: Results

The adaptation combinations can be spatially mapped based on the Cumulative Cooperation Difficulty per subcatchment, landscape archetypes and the excluding properties as mentioned in Chapter 2 (e.g. aquifer presence for aquifer pumps).

4.4.1. Preferential Strategies

Five categories of preferential strategies were spatially mapped. They are listed with their description below:

- Most Effective: These combinations have the lowest Cumulative Implementation Time, TIS. TIS is used as a proxy for difficulty of combinations. These combinations might be the simplest to implement.
- Upstream: Combinations consisting of combinations without downstream infrastructure. These combinations are relevant because providing the desired storage upstream would not require expensive and possibly undesirable measures downstream.
- Downstream: Combinations consisting solely of Downstream Infrastructure measures. These combinations can address flood risk at the downstream bottleneck Valkenburg. These combinations might be relevant as upstream solutions tend to be very sizeable and intrusive in the landscape.
- With Maladaptation: Combinations that include a maladaptive action but still provide the desired storage equivalent. This is relevant as this provides insight to the decision maker of still the available strategies in case a maladaptive action takes place.
- Alternative Options: Two out-of-the-box solutions were also included in the preferential strategies due to the fact they provided the desired storage equivalent by themselves.

A few members per category along with the number of combinations in that category were provided in the results. Per category, two options were spatially mapped. Locations are suggestions based on Cumulative Cooperation Difficulty, landscape types and catchment characteristics. Other locations are therefore also possible.

4.4.2. Additional Results

The adaptive capacity and an example of Adaptation Pathways of four of the combinations were provided in the results. These results are additional and meant to provide insight into the abstract solution space.

Adaptive Capacity

The adaptive capacity is the total storage equivalent that can be realized using the measures in the solution space. The adaptive capacity is visualized by connecting the actions per category. The storage equivalent is on the horizontal axis. The length of lines associated to the actions is roughly equal to the equivalent storage that measure provides. A cycle indicates a point where two measures are sequenced. Adaptive capacity is visualized per measure category (background colours) and between upstream and downstream measures (connected paths). The two alternative options were also included.

Adaptation Pathway example

The solution space is very abstract. Four potential pathways to reach the desired storage equivalent were therefore visualized. Combinations with the indices 777, 928, 1100 and 1104, all upstream combinations, are used. The combinations reach the storage equivalent of 18.96. On the horizontal axes, indicative timelines for this adaptation goal were suggested based on the policy goals of the Dutch government.[101] Additionally, latest implementation times (LIT) of the measure categories are indicated on these axes.

Entities working internationally

The experts also indicated the entities from their native countries which work internationally. Results were displayed in a table.

Heterogenity of Cumulative Cooperation Difficulty

Cumulative Cooperation Difficulty can also be assessed within catchments. This was done in QGIS by sampling random points in the subcatchment and deriving Vonoroi polygons from these. QGIS can do this by default using the function random points in polygons in the Research tools tab and the Vonoroi Polygons tool found in the processing toolbox.

5 Results

5.1. Step I: Analyses

Spatial analysis yields the location of two aquifers at the east and west side of the basin. This limits the possible location of a measure making use of these aquifers to be at these locations. The aquifers are located at the Gulp and the Eyserbeek.[7] Both join the Geul in the area of Gulpen. A measure with a large amount of storage, or that is aimed at making room for the river, should therefore be located downstream of Gulpen. The upstream part has thin soils, limiting the storage capacity. Additionally, permeability is low.[59][7][57] This causes the adaptive capacity of increasing natural storage in the soil on the top half of the subcatchments Gulp and Sippenaeken to be limited. Deltares estimates maximally 10 millimeters at any location.[57] UNR measures are therefore more likely to be effective in other parts of the catchment. Lastly, the runoff coefficients in the subcatchments that Germany and the Netherlands share are relatively quick.[7] Measures aimed at retaining water might be especially effective there.

The climatic analysis indicates there is a strong and stable increase in evaporation in the Geul. Discharge and precipitation are also highly correlated, indicating extremes in precipitation will lead to extremes in discharge as well.[5] There is an expected increase in summer extreme precipitation occurrence and intensity in the area.[23] The Network analysis provided cooperation scores, of which a network could be formed where SNA is applied on.

5.2. Step II: Inputs

The inputs of the Framework are the quantified results of the analyses. In turn, they are used to form the products.

5.2.1. Solution space

Adaptation Goals form the constraints of the solution space and the measures to realize a certain storage realized. Measures are connected to landscape archetypes by their category. This can be seen in table 3.1.

Adaptation Goals

Return periods of the 2021 precipitation event that led to the floods is estimated to be between 100 and 1000 [6] and 300 years [105]. The event led to a volume of 6,000,000 m^3 over discharge capacity in the Geul.[59][57] This is used as the adaptation goal in this thesis. A decision-maker can decide otherwise.

Adaptation Measures

This results in the millimeter equivalent values displayed in table 5.1. Measures originate from Deltares [59][57], Arcadis and Vista [58], a multidisciplinary student group of the TU Delft.[21]

Table 5.1: All measures included in this thesis

Number	Code	**Category**	**Effect**	**millimeter equivalent [mm]**	**Source**
1	FlatBr	DI	Q: +15m^3	2.4	[21]
2	RemBr	DI	Q: +42m^3	6.7	[21]
3	QuayOne	DI	Q: +38m^3	6	[21]
4	Tunnel3.5	DI	Q: +29.6m^3	5.36	[21]
5	Sewer	DI	Q + 5m^3	1.44	[57]
6	Quay2.5	[-]	Q: 100%	17.96	[57]
7	Bedupstr	RR	H: maximum -1.3 m	assumed 6	[57]
8	R4R	RR	H: -1 m	6	[58]
9	ReforestHP	UNR	Q: -1 to 2%	0.47	[59]
10	Urbandiv	DI	Q: -1 to 2%	0.47	[59]
11	RainretBE	UNR	Q: -2 to 4%	0.94	[59]
12	SoGdam	DI	Q: -16%	3.64	[59]
13	ReforestV	UNR	Q: -4 to 8%	1.88	[59]
14	BuiltupINC	M	S: -27.5 mm/eq	-27.1	Own
15	ForestDEC	M	S: -2.2 mm/eq	-2.2	Own
16	Aquifer	UI	S: +3 mm/eq	3	Own
17	Smallreser	UI	S: +0.26 mm/eq	0.26	Own
18	BigRes	UI	S: +1 mm/eq	1	Own
19	MegaRes	[-]	S: +17.96 mm/eq	17.96	Own

Implementation times
Implementation time estimation of experts participating in the expert judgment session are provided in Figures 5.1 and 5.2. The spread in answering indicates that the implementation time of measures in a certain category is depends a lot on characteristics of the measure. The estimated implementation times are not the medians plotted in the boxplot in Figure 5.1, but the averages of the estimated scores.

The lowest implementation time is Downstream Infrastructure with 13.2 years on average. After that, Room for the River is implemented the quickest at 15.3 years on average. Room for the River is followed by Upstream Natural Retention at 16.3 years and Upstream Infrastructure at 17.9 years on average. Transboundary measures and integrated plans take longer, at an average of 20.2 years. This make sense as these require transboundary cooperation, making the decision-making process more complex. The additional time is, however, not that longer than 'simpler' measures of the previously mentioned categories.

Landscape Archetypes
The landscape archetypes are derived from the Wflow flextopo model and are based on the archetypes as sketched by Savenije (2010).[4][106] Poppelier (2022) classified the Geul using Wflow flextopo. Hill slopes are defined to be between 30 and 90 meters above the nearest drainage (HAND) and to have a slope of minimally 5%. Areas higher above drainage and with a lower slope are plateaus.[103] A visualization of the data points is displayed in 5.3 and the classification of the Geul is displayed in 5.4. The section downstream of Valkenburg is not classified because this was the limit of the DEM used for the input of the classification. No measures are implemented downstream of Valkenburg, therefore this does not matter for the usability in this Thesis.

Combination Analytics
Combination analytics is done by plotting certain characteristics of the adaptation combinations and assessing them on their properties. Figures a-d of Figure 5.5 are the plots used for this.

The TIS is plotted against the storage realized in Figure 5.5a. Although varying in performance on realized storage, TIS seems to be grouped in lines. This is likely because the storage is mostly dependent on the measure implemented and the TIS on the category of the measures. Combinations thus tend to group in implementation times, but range in realized storage. Some outliers can be identified, for example the most efficient combinations as described in table 5.5. The majority of measures has a TIS between 70 and 150 years as can be seen in Figure 5.5a.

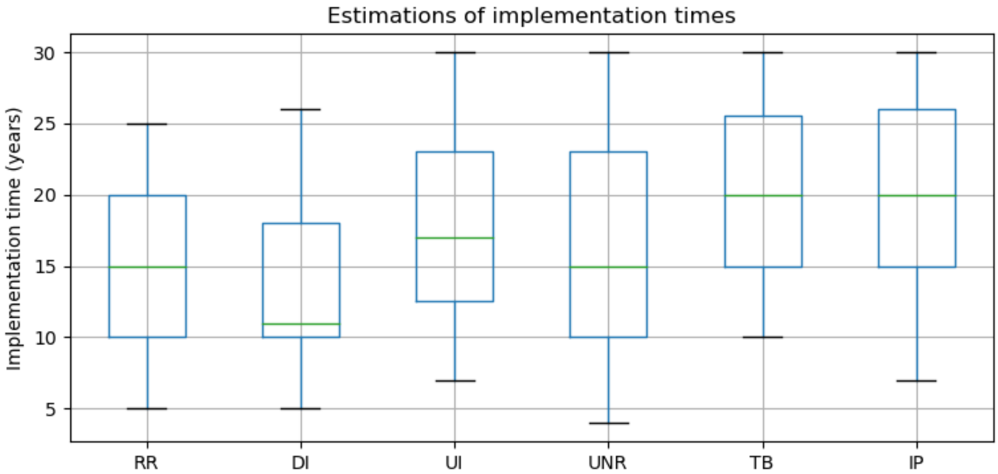
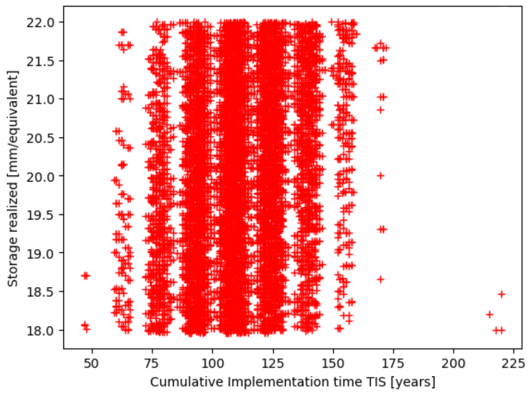


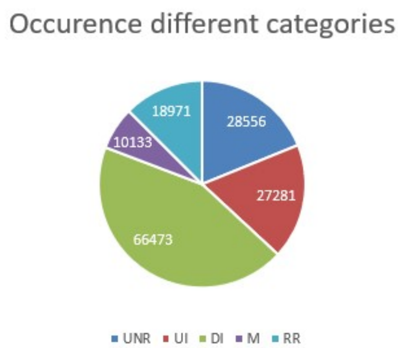
Figure 5.1: Boxplot of implementation time estimations of experts. Whiskers indicate outliers, the box is the first and third quantile and the green line is the average value. Estimation is done for measure categories 'RR' (Room for the River), 'DI' (Downstream Infrastructure), 'UI' (Upstream Infrastructure), 'UNR' (Upstream Natural Retention). Additionally expert estimated the implementation time of 'TB' (Transboundary Measures) and 'IP' (Integrated Plans)

Metric	RR	DI	UI	UNR	TB	IP
5% interval mean	8.5	7.2	10.7	9.9	13.1	14.0
Estimation mean	15.3	13.2	17.9	16.3	20.2	20.2
95% interval mean	23.9	18.5	25.0	22.5	26.9	28.0
Estimation median	15.0	11.0	17.0	15.0	20.0	20.0
N	26.0	24.0	26.0	26.0	17.0	20.0

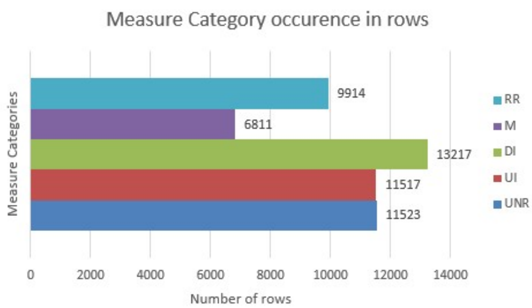
Figure 5.2: Provided scores of 5%, 50% (Estimate) and 95% intervals, minimum and maximum scores of the group and the number of experts per question (N)



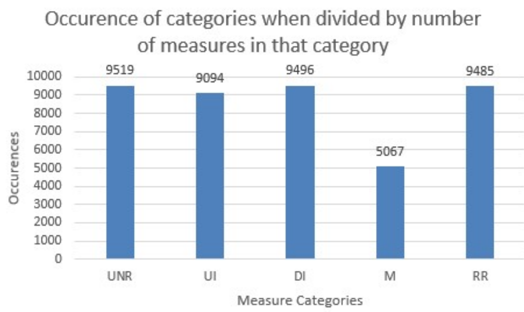
(a) Number of actions per category in the solution space



(b) Actions per category in the solution space divided by the number of measures in that category



(c) Number of actions per category in the solution space



(d) Actions per category in the solution space divided by the number of measures in that category

Figure 5.5: Combination analytics plots

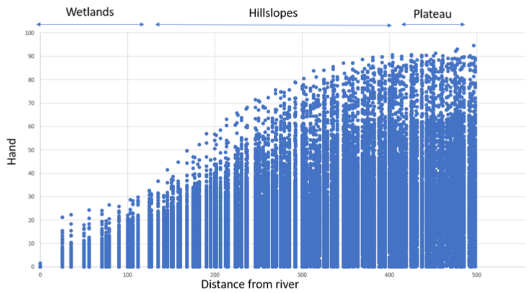


Figure 5.3: Classification and data points based on HAND and plotted against the distance to the river by Poppelier (2022)[103]

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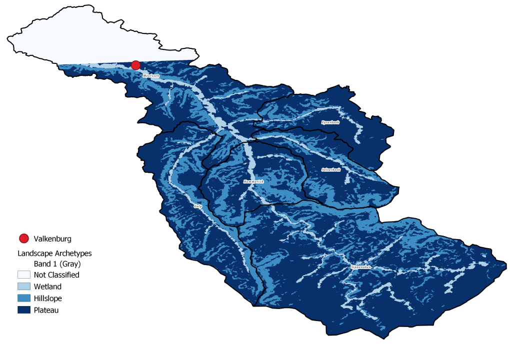


Figure 5.4: Classified map of the Geul by Poppelier (2022)[103]

Prevalence of measure categories in the solution space is assessed using Figures 5.5b, 5.5c and 5.5d. Downstream infrastructure is the most present in absolute numbers and in the combinations (rows) as can be seen in Figures 5.5b and 5.5c. When divided by the number of measures in each category, as done in Figure 5.5d, categories seems to be equally prevalent. Given the large spread in effectiveness of measures, this indicates a large quantity of the solution space is filled by combinations of measures that are not very effective, but are able to form a lot of unique combinations. This is confirmed by the Room for the River category: With two measures both achieving 6 millimeter equivalent, the category is highly effective. It occurs 18,971 times in total in the solution space over 9914 different rows. Almost all combinations consist of two Room for the River measures with one, two or three additional other measures. These measures might be interesting to start with as a decision maker; large parts of the solution space are still available if one or two of these measures are implemented. Possibly this buys time with regard to the adaptation goal.

5.2.2. Governance

Transboundary governance complexity is assessed by quantifying the cooperation between actors in the Meuse using Expert Judgment. This is connected to spatial cooperation difficulty by making maps of all actors present at a certain location. In addition, network characteristics can provide insight into the collaborative network. From this, network interventions could be designed.

Map of Actors

Actors of the categories National, Regional and Local are involved in the Geul from Germany, Flanders, Wallonia and the Netherlands. National entities present are The Netherlands, the Belgian state, Flanders, Wallonia, the German federal state and Nordrhein-Westphalia. Regional and local entities are not mentioned by name in this section. The quantity is listed per subcatchment below;

- In Sippenaeken there are four national entities from Belgium and Germany and four regional and seven regional entities from those countries. No Dutch actors are present.
- The Selzerbeek and Eyserbeek are shared by the Netherlands and Germany. In total there are two national, two regional and one local entity from the Germany and one national and two regional entities from the Netherlands. In Eyserbeek there is one more local Dutch entity compared to the Selzerbeek; three instead of two.
- Hommerich and the Gulp are both shared by the Netherlands, Flanders and Wallonia. The number of actors from Flanders and Wallonia is three of the category national, four of the category regional and two of the category local.
- Meerssen is a catchment that is in the Netherlands and therefore has only one national actor, two regional actors and seven local actors.

The actors per subcatchment are listed in table 5.2.2. A visualization is displayed in Figure 5.6. No differentiation is made between borders has been made in this map.

Table 5.2: Administrative entities per subcatchment of the Geul. 'BE' stands for Belgium, 'DE' for Germany and 'NL' for the Netherlands. 'N' indicates an entity of category 'National', 'R' a regional entity and 'L' a local entity. 'I' (Internal) indicates the Dutch entities and 'TB' (Transboundary) the non-Dutch

Sub-catchm	**Total Actors**	**I-N**	**I-L**	**I-R**	**T-N**	**T-R**	**T-L**	**Countries**
Sippenaeken	18	0	0	0	4	4	7	BE, DE
Selzerbeek	10	1	2	2	2	2	1	DE, NL
Meerssen	10	1	7	2	0	0	0	NL
Hommerich	14	1	2	2	3	4	2	BE, NL
Gulp	14	1	2	2	3	4	2	BE, NL
Eyserbeek	11	1	3	2	2	2	1	DE, NL

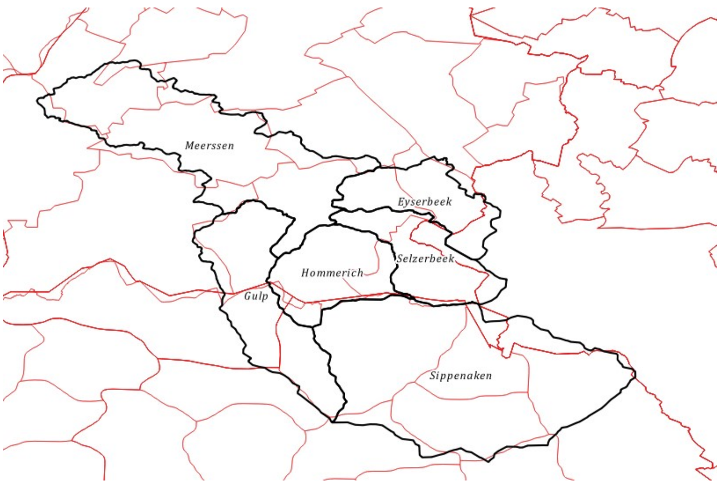


Figure 5.6: Map of Actors and their borders

Cooperation Quality Scores
Cooperation quality is assessed within and between countries. From this, different possible reasons and other things that stand out are addressed.

Cooperation within countries

Cooperation within countries is relevant to determine cooperation quality within countries and to construct the whole network. They are visualized in Figure 5.7. Cooperation is the best between the Flemish National and Regional governments (0.8). Cooperation is also relatively good between regional and local actors in France (0.7), Wallonian Local and Regional governments. Cooperation is generally relatively bas between National and Local governments and between Local and National governments. In Flanders, both categories are interesting, as the cooperation between National and Local governments is the lowest of all the countries (0.2) and cooperation between Local and National governments is the best (0.6).

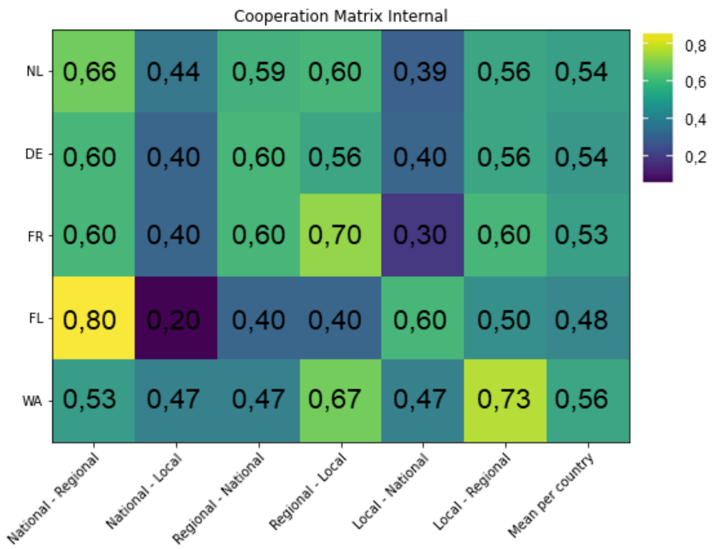


Figure 5.7: Internal cooperation quality visualized using a viridis colour scale. 'NL' is the Netherlands, 'DE' is Germany, 'FR' is France, 'FL' is Flanders, 'WA' is Wallonia and 'LX' is Luxembourg

Cooperation between basin countries

There are strong connections (>0.6) between Flanders and the Netherlands (0.9), Flanders and Wallonia (0.8), Germany and the Netherlands, Wallonia and Flanders (0.6) and France and Germany. These scores on cooperation quality are from the perspective of the first mentioned country. Cooperation is non-existent between Flanders and Germany and Flanders and Luxembourg. Cooperation is poor or below poor between Wallonia and Germany (0.1), The Netherlands and France (0.32), Flanders and France (0.30), France and Flanders and The Netherlands and Wallonia (0.3). All countries identify their cooperation with Luxembourg to be poor or lower.

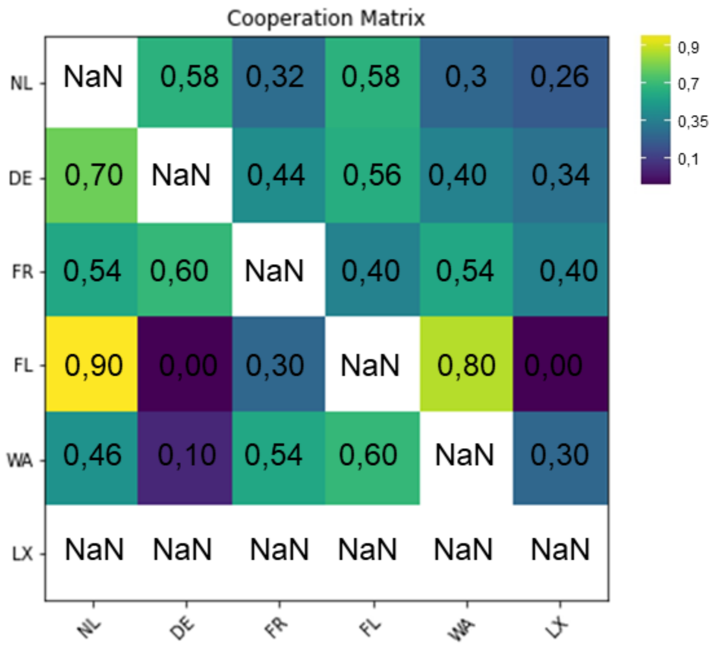


Figure 5.8: International cooperation quality visualized using a viridis colour scale. 'NL' is the Netherlands, 'DE' is Germany, 'FR' is France, 'FL' is Flanders, 'WA' is Wallonia and 'LX' is Luxembourg. From horizontal are the scores provided and vertical are the scores received

Cooperation of Flanders and international partners is skewered. Cooperation with Wallonia and the Netherlands is relatively well, but this is not the case with Germany and Luxembourg. Germany is percepted similarly with relatively well cooperation scores from France and Germany, but bad scores from Flanders and Wallonia. Overall, the Netherlands is percepted to be a good partner (with scores ranging from 0.46 to 0.7) with the worst scores being from French speaking actors France and Wallonia. France is not perceived as a good partner, but the best cooperation is with Wallonia. When not considering France, Flanders is also rated relatively well.Typical cooperation between Flanders and the Netherlands is rated 0.74, between Germany and the Netherlands cooperation is rated 0.64 and between Flanders and Germany to be 0.28. Cooperation of the Wallonia with the Netherlands is 0.38, with Flanders 0.7 and with Germany 0.25. This is visualized in Figure 5.8.

Language

Some of these strong and weak links seem to be between countries speaking different languages. Netherlands and Flanders indicate they have a stronger connection (0.9) than Flanders and Wallonia (0.6). At the same time, the connection between Wallonia and France is almost as strong as between Wallonia and Flanders. Wallonia and France have both French as official language, while the Netherlands and Flanders speak Dutch. People in Germany speak German, while people in Luxembourg have three official languages; French, German and Luxembourgish. In validation of these results, it is indicated the language barrier likely plays a role in cooperation quality.[98] This is in line with a sources on the cooperation between Wallonia and the Netherlands.[13][98]

Adjacency

Countries that are adjacent to one another might work more closely together. They are likely to have tributaries that are shared, causing cooperation to be necessary. From their own perspective, countries that play a central role in the Network (NL and FL) perceive the cooperation to be very centralized around the adjacent countries. This whilst countries that are not adjacent specifically identify them as relatively important partners. Difference in perception by other countries is less significant. Only in countries with one or no non-neighbours, differences in scores are significant. Results thus give little consensus on the importance of spatial adjacency in cooperation.

Differences in provided and perceived cooperation quality scores

Countries seem to have differences in perception of cooperation quality with international partners. For example France and Germany: whereas France indicates to cooperate relatively well with Germany, this is not the case from the German perspective. In general the Netherlands is perceived by others as a good partner, this is not reciprocal. The opposite is true for France and Germany. Flanders and Wallonia have negligible difference (>0.2 cumulative) in provided and perceived cooperation quality scores. The results indicate a potential difference in perception on what good cooperation is. Experts indicate this may be a result of cultural differences between countries in implementing measures. They state Germany is slow and conservative, whilst the Netherlands is quick and innovative. This potentially cause the Germans to see their cooperation with the Netherlands better than vice-versa: The Dutch might want more experimentation and implementation and want it sooner. This might frustrate them and cause them to rate their cooperation quality lower.[98]

Network Characteristics

Social Network Analysis is performed on the network constructed from the cooperation quality scores per country and the cooperation quality scores within a country. This creates international links between regional and local actors as well. The network is visualized in Figure 5.9.

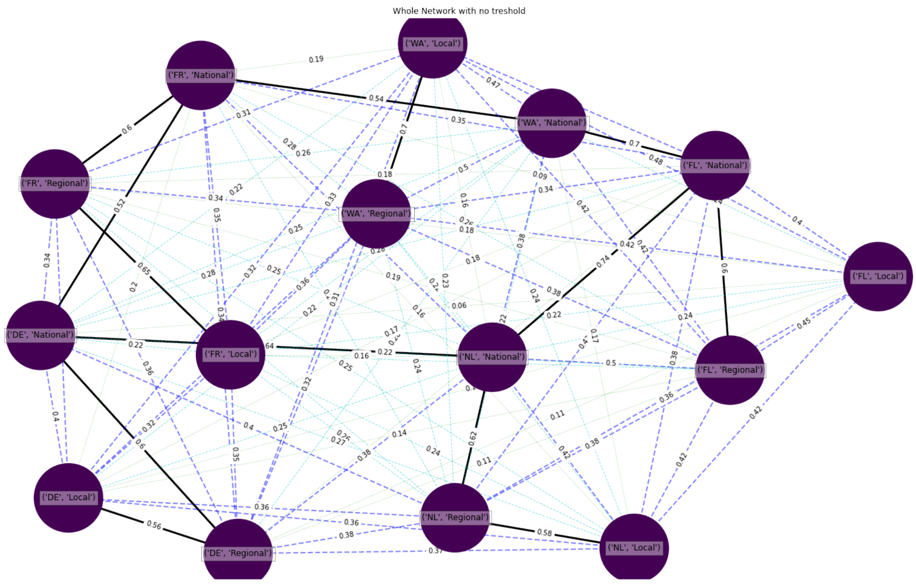


Figure 5.9: The Complete cooperation network in the Meuse. The lighter the colour, the higher the betweenness centrality in the network. The bigger the nodes, the higher the degree of the nodes

Given the scale, a score below 0.2 or 0.4 would mean that cooperation would be 'Only with significant pressure' or 'Poorly'. Below the 0.2 the cooperation would even be between 'Only with significant external pressure' and 'No cooperation at all'. Scores below 0.2 do not indicate a meaningful cooperation quality regarding climate change adaptation. A score of 0.4 only indicates a cooperation quality actors refer to as 'Poorly'. An overview of the scale can be seen in table 5.3.

Table 5.3: Cooperation quality scores normalized

Cooperation	Score
No cooperation at all	0
Only with significant external pressure	0.2
Poorly	0.4
Only if mutually beneficial	0.6
Yes, Well (Able to discuss and formulate compromises)	0.8
Yes, Excellent (Able to agree on things even if not beneficial for the organisation itself)	1

Thresholds

Social Network Analysis (SNA) relies on pathways that either exist or not. To provide a network analysis, a threshold range from 0 to 0.6 is applied, and network statistics are reviewed. This way, network analysis can be performed in cooperation that is well enough to be meaningful. When the threshold range is applied, one is able to see the 'evolution' of the network. When a higher threshold is applied and non-meaningful cooperation is deleted. The network becomes more and more reliant on some brokers that are needed to access a certain path.

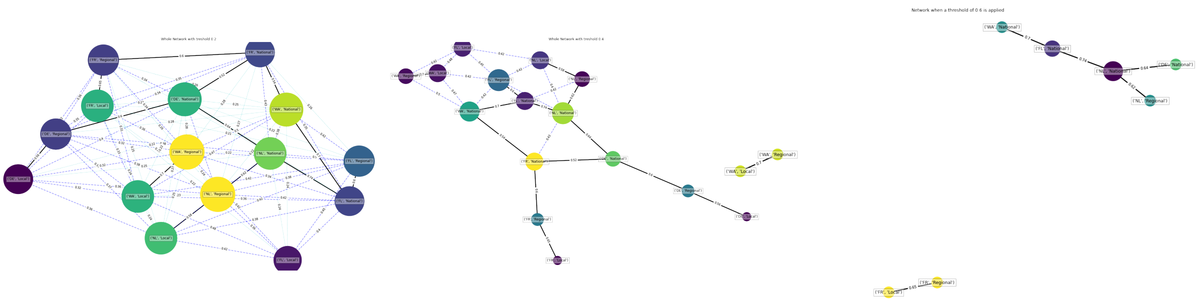


Figure 5.10: Evolution of the network when thresholds of 0.2, 0.4 and 0.6 are applied, from left to right. The lighter the colour, the higher the betweenness centrality in the network. The bigger the nodes, the higher the degree of the nodes

Threshold of 0.2

In figure 5.10 the network is visualized when no threshold is applied, and thresholds of 0.2 and 0.4 are applied. In the middle one (0.2 threshold) central players start to emerge. Dutch and Walloon regions emerge as the most in-between actors. This is likely due to the fact that they have strong connections to both the national and local domestic actors and have international contacts. Walloons have good contact with their Belgian counterparts, the Flemish, and have a relatively strong link with the French. Potentially this is due to the language. The Dutch are recognized by many international actors as central in the network. Due to their strong links with Flemish and German actors, they also play a central role. It is, however, notable that the links of 0.2 only represent a cooperation quality of 'Only under significant external pressure'. Degrees in the network range from 9 to 14. Betweenness centrality from 0.077 to 0.184. This means that the network is highly connected and the brokerage position of the central nodes is limited; even without them, pathways between actors are possible.

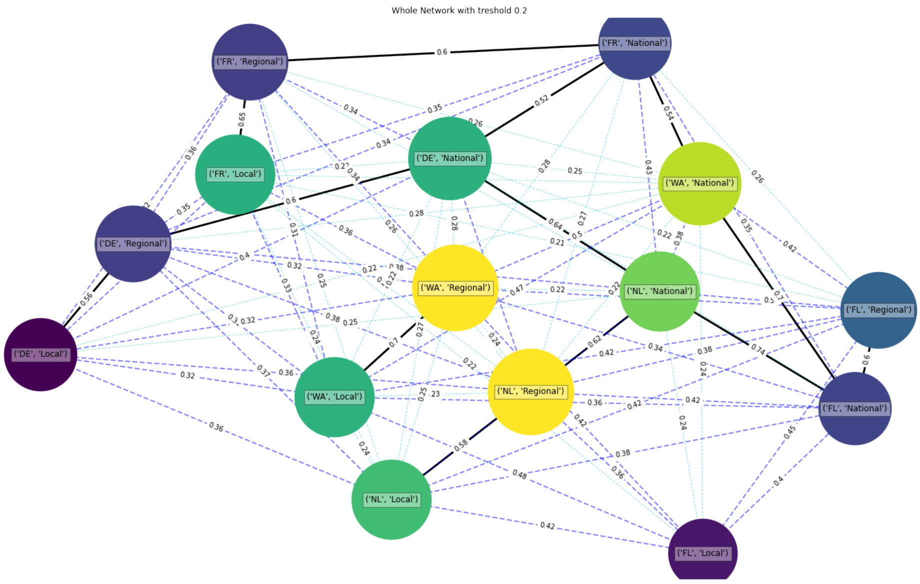
Threshold of 0.4

The network with a threshold of 0.4 differs a lot from that with a threshold of 0.2. French and German regional and local actors are isolated. Therefore, the role of the French and German national governments becomes more of a gatekeeper and brokerage one. For cooperation with a minimal level of 'Poorly', national actors are needed for regional and local entities from France and Germany to cooperate with others. The isolated French and German local entities, have a degree of 1. While more central players, such as Flemish regions and the Dutch nation, have a degree of six. This means that they have six connections with a higher score than 0.4. Brokerage roles are thus different from central actors. In this network, some actors are really the only connection to some other actors, causing power to be located at a few actors.

Dutch, Flemish and Walloon regional and local entities are still connected to their international counterparts, although it becomes clear that the links are not very strong. The cooperation score of 0.6 or ‘Only if mutually beneficial’ only occurs between and within nations. An exception to this are Walloon regional and local entities. These are also connected to their national government by a score of 0.5. This is comparable to Flemish local and regional entities. Experts indicate international cooperation in Wallonia is organized via the National government and is done regionally in the Netherlands.[98] In addition, experts state that cooperation between local and regional actors can be better than between national actors, but this depends on the problem and the people involved. For regional or local cooperation, actors need to be aware of their counterparts in the basin, this is not always the case.[98]

Threshold of 0.6

A threshold of 0.6 severely limits the network to three clusters: A French network of local and regional actors, a Walloon network of local and regional actors and the network that contains the national governments of Flanders, Wallonia and the national, regional and local Dutch governments. The threshold of 0.6 corresponds to a cooperation quality of ’Only if mutually beneficial’.

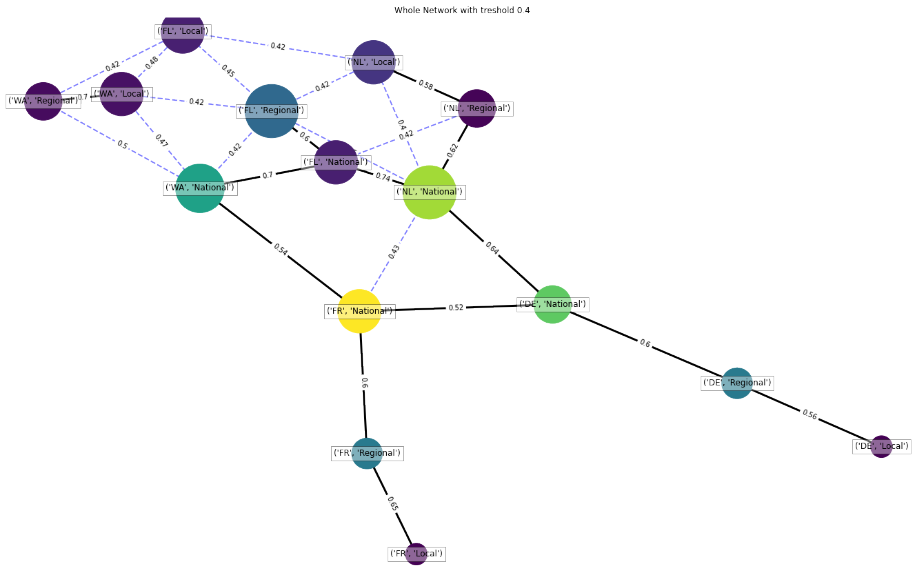


(a) Network when a threshold of 0.2 is applied. The lighter the colour, the higher the betweenness centrality in the network. The bigger the nodes, the higher the degree of the nodes

Actor	Degree	Clustering	Degree Centrality	Betweenness Centrality
('DE', 'Local')	10.0	0.933	0.714	0.166
('DE', 'National')	13.0	0.833	0.929	0.179
('DE', 'Regional')	11.0	0.891	0.786	0.077
('FL', 'Local')	9.0	0.889	0.643	0.168
('FL', 'National')	10.0	0.867	0.714	0.171
('FL', 'Regional')	11.0	0.855	0.786	0.174
('FR', 'Local')	12.0	0.818	0.857	0.181
('FR', 'National')	10.0	0.867	0.714	0.17
('FR', 'Regional')	11.0	0.891	0.786	0.077
('NL', 'Local')	12.0	0.803	0.857	0.179
('NL', 'National')	12.0	0.788	0.857	0.091
('NL', 'Regional')	14.0	0.802	1.0	0.094
('WA', 'Local')	12.0	0.818	0.857	0.087
('WA', 'National')	13.0	0.795	0.929	0.184
('WA', 'Regional')	14.0	0.802	1.0	0.187

(b) Metrics of the network when a threshold of 0.2 is applied

Figure 5.11: The network when a threshold of 0.2 is applied. In figure a, the network is visualized. The lighter the nodes, the higher the betweenness centrality, the bigger the nodes, the higher the degree. Both metrics supplemented by the clustering of the network and the degree of centrality are in figure b

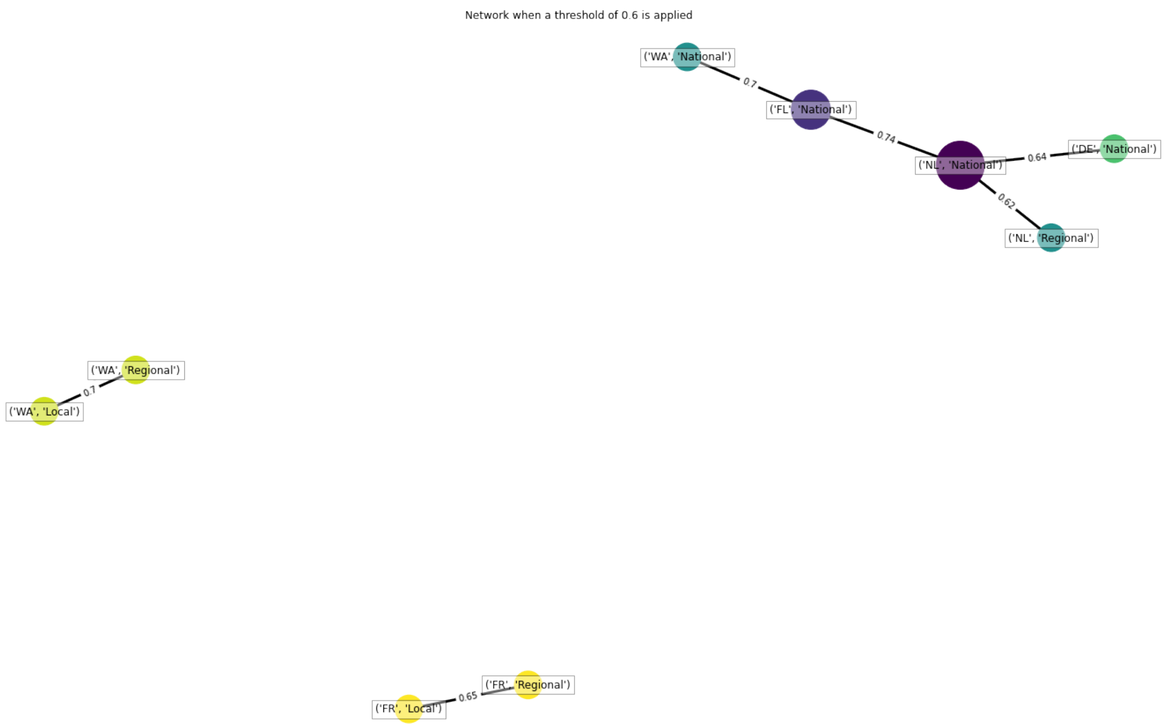


(a) Network when a threshold of 0.4 is applied. The lighter the colour, the higher the betweenness centrality in the network. The bigger the nodes, the higher the degree of the nodes

Actor	Degree	Clustering	Degree Centrality	Betweenness Centrality
('DE', 'Local')	1.0	0.0	0.071	0.164
('DE', 'National')	3.0	0.333	0.214	0.286
('DE', 'Regional')	2.0	0.0	0.143	0.229
('FL', 'Local')	4.0	0.5	0.286	0.193
('FL', 'National')	4.0	0.5	0.286	0.181
('FL', 'Regional')	6.0	0.4	0.429	0.254
('FR', 'Local')	1.0	0.0	0.071	0.164
('FR', 'National')	4.0	0.167	0.286	0.5
('FR', 'Regional')	2.0	0.0	0.143	0.314
('NL', 'Local')	4.0	0.5	0.286	0.205
('NL', 'National')	6.0	0.333	0.429	0.328
('NL', 'Regional')	3.0	0.667	0.214	0.076
('WA', 'Local')	4.0	0.667	0.286	0.091
('WA', 'National')	5.0	0.3	0.357	0.359
('WA', 'Regional')	3.0	0.667	0.214	0.178

(b) Metrics of the network when a threshold of 0.4 is applied

Figure 5.12: The network when a threshold of 0.4 is applied. In figure a, the network is visualized. The lighter the nodes, the higher the betweenness centrality, the bigger the nodes, the higher the degree. Both metrics supplemented by the clustering of the network and the degree of centrality are in figure b



(a) Network when a threshold of 0.6 is applied. The lighter the colour, the higher the betweenness centrality in the network. The bigger the nodes, the higher the degree of the nodes

Actor	Degree	Clustering	Degree Centrality	Betweenness Centrality
('DE', 'National')	1	0	0.125	0.062
('FL', 'National')	2	0	0.25	0.188
('FR', 'Local')	1	0	0.125	0.062
('FR', 'Regional')	1	0	0.125	0.062
('NL', 'National')	3	0	0.375	0.219
('NL', 'Regional')	1	0	0.125	0.062
('WA', 'Local')	1	0	0.125	0.0
('WA', 'National')	1	0	0.125	0.062
('WA', 'Regional')	1	0	0.125	0.0

(b) Metrics of the network when a threshold of 0.6 is applied

Figure 5.13: The network when a threshold of 0.6 is applied. In figure a, the network is visualized. The lighter the nodes, the higher the betweenness centrality, the bigger the nodes, the higher the degree. Both metrics supplemented by the clustering of the network and the degree centrality are in figure b

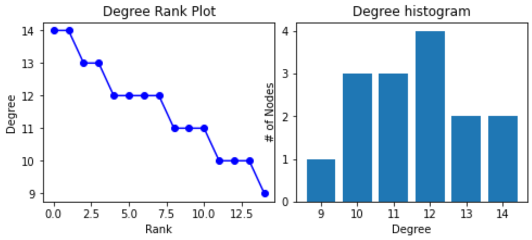


Figure 5.14: Degree distribution for threshold 0.2

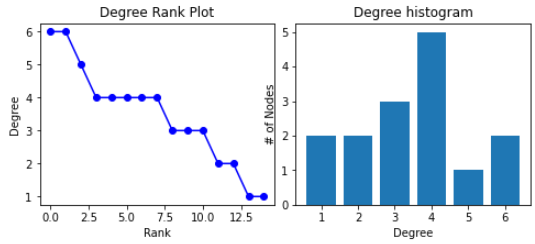


Figure 5.15: Degree distribution for threshold 0.4

Network Characteristics

Network characteristics of networks with 0.2 and 0.4 thresholds are analysed. Results are shown in 5.2.2. Characteristics of the network with threshold 0.6 not meaningful as only a few actors are still connected in that network.

Table 5.4: Metrics of networks when a threshold of 0.2 and 0.4 is applied. A threshold of 0.6 does not result in meaningful metrics as the network is fragmented

	Threshold 0.2	**Threshold 0.4**
Average shortest path	1.093	2.284
Radius	1	3
Diameter	2	5
Density	0.8286	0.2476
Giant component	15 nodes and 87 edges	15 nodes and 26 edges

Visualizing the distribution of degrees per rank in the network, the network seems to be relatively well-balanced at a threshold of 0.2, but when analysed at a threshold of 0.4 starts to show a distribution where only 3 actors hold a degree of 5 or more while 12 have a lower degree. Both are plotted in Figure 5.14 and 5.15 respectively. The degree distribution starts to show skewers and shows more of its true colours. It seems from this data that the network, when a certain level of cooperation is required, is run by a few actors. Possibly based on their location, interest, federal country and language. No cooperation in the network is of the quality Yes, Well (Able to discuss and formulate compromises). In general, the network is dense, with many links and polycentric with little fragmentation due to the absence of a single central actor. When a threshold of 0.6 is applied, a fragmented and monocentric network emerges. This indicates that, when a certain level of cooperation is necessary, the network functions like a monocentric network where French and non-national Wallonian and German actors are fully isolated. In this network, the national governments of the Netherlands and Flanders are the central players.

5.3. Step III: Products

The products are the solution space and the maps of spatial cooperation difficulty. These are formed from the inputs.

5.3.1. Solution Space

The solution space consists of 13,227 combinations. Combinations are grouped in the categories 'Most efficient', 'Upstream', 'Downstream' and 'With Maladaptation'. The number of combinations per category is 10 for 'Upstream', 29 for 'Downstream' and, 6812 'With Maladaptation'. Upstream combinations consist of UNR, RR and UI measures, Downstream combinations of DI and RR measures and combinations where maladaptation occur have a setback in millimeter equivalent due to this maladaptive action. Nevertheless, the combinations are able to still achieve the storage equivalent goal using measures from all categories. The options and their properties are listed in table 5.5.

Table 5.5: Adaptation Strategies of interest. The leftmost column contains the categories and the number of combinations (N) per category. The index is included to connect measure combinations to the solution space. The storage column contains the performance of that combination in millimeter equivalent. TIS is the cumulative implementation time in years of that combination and is a proxy for difficulty of implementation. LIT is the latest implementation time when implemented in parallel

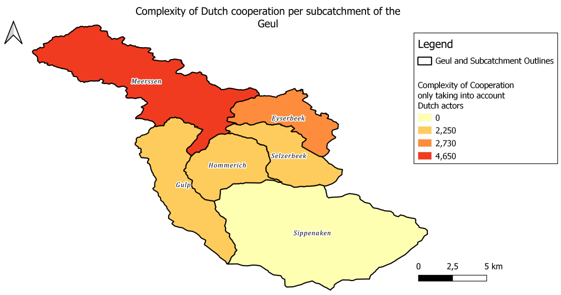
Category & N	Index	Measures	Storage	TIS	LIT
Most Efficient -	0	Removable Bridges, Quay walls raised with 1 meter, Bed adjustment	18.7	46.9	2035
	4	Removable Bridges, Room for the River, Bed adjustment	18.7	47.9	
	5	Room for the River, Quay walls raised with 1 meter, Bed adjustment	18	47.9	
Upstream 10	1474	Aquifer recharge, Bed adjustment, Rainwater retention upstream, Room for the River, Reforest Valleys, Reforest Hill slopes & Plateaus	18.29	92.8	2034
	1100	Aquifer recharge, Big reservoir, Bed adjustment, Room for the River, Reforest Valleys, Reforest Hill slopes & Plateaus	18.35	92.8	
Downstream 29	63	Removable Bridges, Quay walls raised with 1 meter, Emergency spillway of 3.5 meters diameter, Use of old sewer pipe as spillway	18.57	52.8	2037
	65	Removable Bridges, Quay walls raised with 1 meter, Emergency pipe spillway of 3.5 meters diameter, Dam at Schin-op-Geul	18.57	54.9	
	67	Removable Bridges, Quay walls raised with 1 meter, Emergency pipe spillway of 3.5 meters diameter, Diverting urban rainwater	20.7	52.8	
With Maladaptation 6812	496	Decrease in forest, Removable Bridges, Quay walls raised with 1 meter, Room for the River, Reforest Valleys	19.5	58	2034
	500	Decrease in forest, Removable Bridges, Quay walls raised with 1 meter, emergency pipe spillway of 3.5 meters diameter, Dam at Schin-op-Geul	18.38	54.9	2037
Alternative options	-	Quay walls of 2.5 meters	17.96	-	2
	-	Reservoir in a dry valley	17.96	-	

The category with the highest difficulty of implementation is 'Upstream'. With TIS values of over 90 years, measures are expected to be complex in decision-making. They are, however, more elegant than other solutions in the solution space as they do dodge very intrusive infrastructure measures. An occurrence of maladaptation in the form of decrease of forest is well manageable. The solution space is, however, quickly reduced and the decision-maker is no longer able to solve an issue fully upstream or downstream. The adaptive capacity is not able to achieve the adaptation goal if there is an increase in built-up area, as defined ad the maladaptive action 'BuiltUpINC'. No Cumulative- or latest implementation time is provided for the 'Alternative Options', as the implementation time estimation would not be meaningful for such intrusive solutions. With the passing of time, more and more combinations are not implementable. With LITs ranging from 2034 to 2037, the solution space starts to be limited in the 2030s. When measures are implemented transboundary, implementation time estimations suggest a decision-making process should be initiated by 2030.

5.3.2. Maps of spatial cooperation difficulty

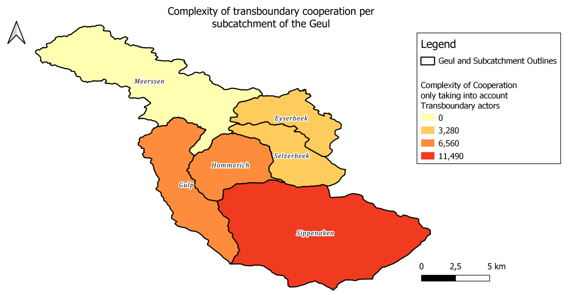
Using the Cumulative Cooperation Difficulty and the maps of actors, cooperation difficulty is mapped per subcatchment. This is done for the Dutch actors in Figure 5.16, for transboundary actors in 5.17 and both are combined in Figure 5.18.

Cumulative Cooperation Difficulty is higher in transboundary subcatchments. Although this seems logical from the method and literature, it is not that straightforward. Downstream subcatchments can also have a lot of local and regional actors and therefore have a high cooperation difficulty. This plays a secondary role, but is visible in the results.



Sub-catchm	Countries	Dutch N	Dutch R	Dutch L	Complexity of Dutch cooperation
Sippenaken	BE, DE	0	0	0	0
Hommerich	BE, NL	1	2	2	2,250
Meerssen	NL	1	2	7	4,650
Eyserbeek	DE, NL	1	2	3	2,730
Selzerbeek	DE, NL	1	2	2	2,250
Gulp	BE, NL	1	2	2	2,250

Figure 5.16: Difficulty of Cooperation within the Netherlands



Sub-catchm	Countries	Interrnational N	International R	International L	Transboundary Cooperation Complexity
Sippenaken	BE, DE	4	4	7	11,490
Hommerich	BE, NL	3	4	2	6,560
Meerssen	NL	0	0	0	0
Eyserbeek	DE, NL	2	2	1	3,280
Selzerbeek	DE, NL	2	2	1	3,280
Gulp	BE, NL	3	4	2	6,560

Figure 5.17: Transboundary Difficulty of Cooperation

Shared subcatchments by the Netherlands and Germany

In the Eyserbeek and Selzerbeek, the Netherlands and Germany share subcatchments. In the Selzerbeek, however, there is a local Dutch actor less. Therefore, the Selzerbeek would be more suited for deciding on (transboundary-) adaptation measures.

Shared subcatchments by the Netherlands and Belgium

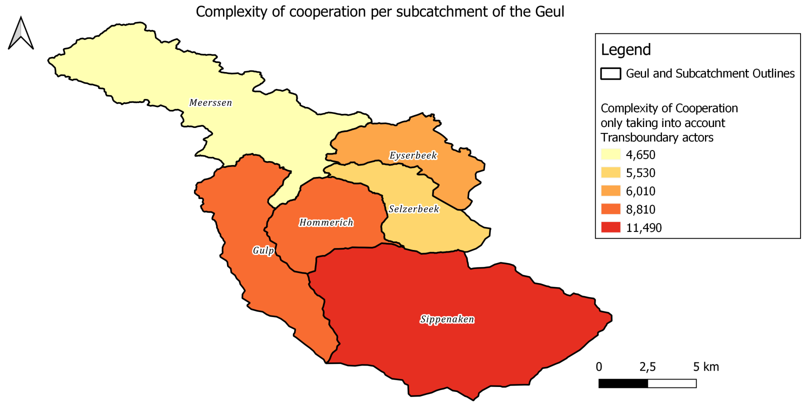
Another interesting observation is the cooperation with Germany compared to the cooperation with Belgium. Due to the presence of both Flanders and Wallonia in the Gulp and in Hommerich, cooperation difficulty is rather high in these areas. From a perspective of the Netherlands, three national actors (Flanders, Wallonia and federal Belgium) as well as four regional and seven local actors are required for cooperation in this subcatchment. Therefore, the difficulty is rather high.

Shared subcatchments by the Belgium and Germany

Flanders and Wallonia work together relatively well, causing cooperation in Gulp and Hommerich to be difficult. It is, however, not the most difficult in the catchment. In Sippenaeken, the most upstream subcatchment, Wallonia and Germany are present along with four regional and seven local actors. The cooperation thus involves a lot of actors. All of which have a different native language. Therefore, this location is complex in terms of decision-making. As described earlier, it is also complex in terms of storage capacity. Therefore, the location might only be suited for upstream infrastructure.

Cooperation difficulty for the whole catchment

When looking at the difficulty of cooperation per subcatchment, it is striking that the cooperation is very dependent on the presence of transboundary actors. In Figure 5.16 cooperation quality scores are displayed. The figures were constructed from the viewpoint of the Netherlands as this is the downstream country. Therefore, the Netherlands must cooperate with others to solve their issues in the bottleneck Valkenburg.



Sub-catchm	Countries	Interrnational N	International R	International L	Transboundary Cooperation Complexity
Sippenaken	BE, DE	4	4	7	11,490
Hommerich	BE, NL	3	4	2	6,560
Meerssen	NL	0	0	0	0
Eyserbeek	DE, NL	2	2	1	3,280
Selzerbeek	DE, NL	2	2	1	3,280
Gulp	BE, NL	3	4	2	6,560

Figure 5.18: Cumulative Cooperation Difficulty when transboundary cooperation and cooperation within the Netherlands are combined

5.4. Step IV: Results

In this section, preferential strategies are mapped based on the Cumulative Cooperation Difficulty per subcatchment and physical characteristics of the catchment. In the Discussion chapter of this thesis, a suited adaptation strategy is discussed when taking into account system properties. Additional policy possibilities are also discussed there.

5.4.1. Preferential Strategies & Locations

The solution space provides thousands of unique possibilities to achieve the adaptation goal. By categorizing these as done in Table 5.5, combinations with specific properties are identified. These can be very limited in number: there are 29 fully downstream solutions, 10 fully upstream and, 6812 combinations are able to achieve the adaptation goal if the forests are decreased by a third. None of the solutions, however, is able to deal with an additional adaptation goal of 27 millimeters due to increased built-up area. In Figure 5.19 measures are connected to icons. These icons are used in the maps in this section.

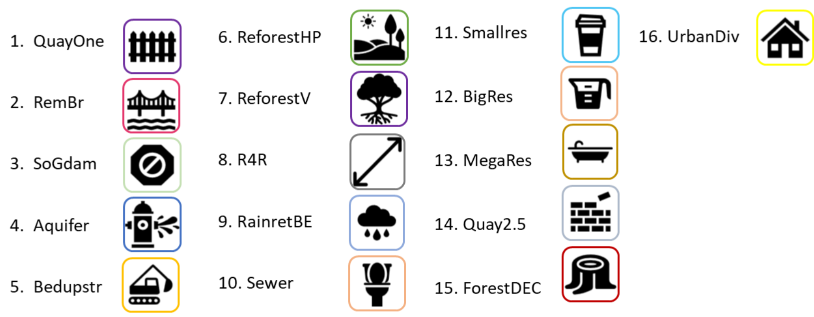


Figure 5.19: Connecting icons to measures

Most efficient Strategies

The most efficient strategies have the lowest TIS whilst achieving the adaptation goal. Combinations 0 and 4, shown in Figure 5.20 consist of three measures. Combination 0 has two Downstream Infrastructure and one Room for the River measure. Combination 4 is the other way around. The Room for the River measures are located below the confluence to be effective. All measures are implemented in the Meerssen subcatchment. At the latest, these measures should be implemented by 2035.

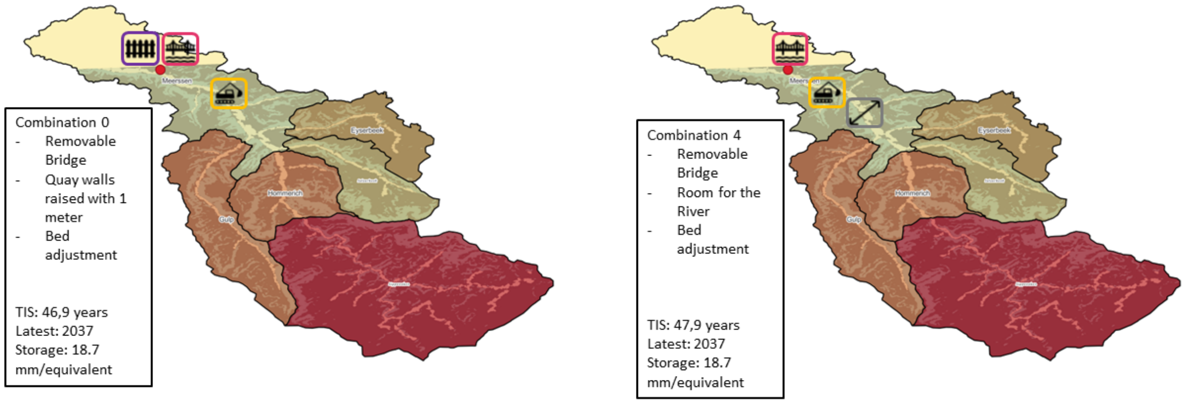


Figure 5.20: Spatial map of a potential placement of the most efficient combinations, 0 and 1

Upstream Strategies

Combinations 1100 and 1474 are examples of fully upstream solutions. The consists of measures of the categories Upstream Infrastructure, Upstream Natural Retention and Room for the River. Both consists of 6 measures. A pump to an aquifer is located at the Selzerbeek, limiting the necessary measures in the other catchments. The aquifer pump is located at the Vaals aquifer. Hill slopes in the Gulp, Eyserbeek and Selzerbeek should be reforested to an extent. By proposing multiple locations, this measure is less intrusive and possibly more effective. A Big reservoir (combination 1100) or Rainwater Retention (Combination 1474) complete the combinations. They are suggested to be placed in Hommerich rather than Sippenaeken due to the Cumulative Cooperation Difficulty in the subcatchments.

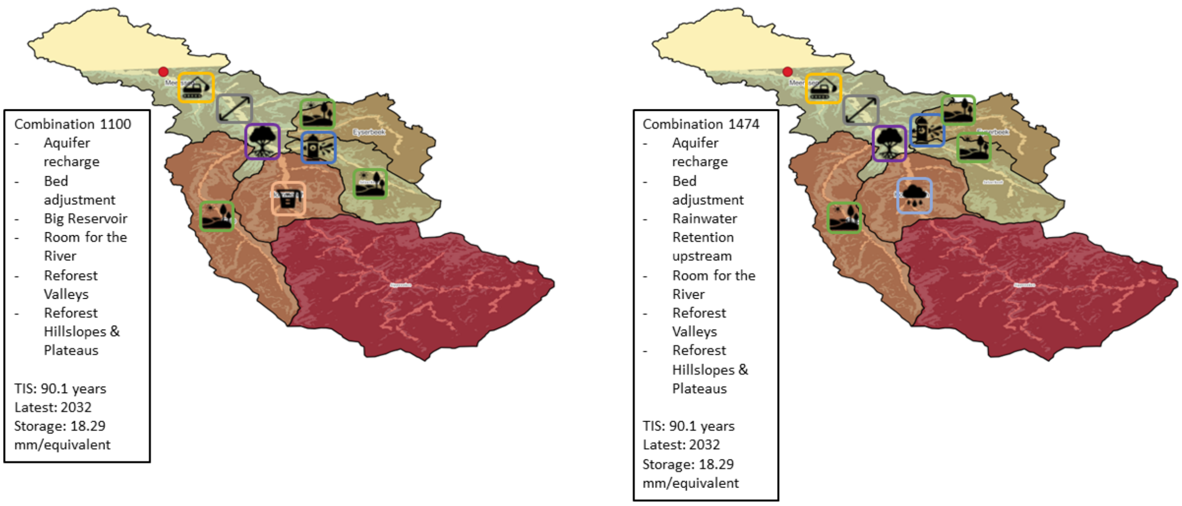


Figure 5.21: Spatial map of a potential placement of fully upstream combinations, 1100 and 1474

Downstream Strategies

Combinations 63 and 65 are fully downstream and consist of measures of the categories Downstream Infrastructure and Room for the River. All measures are implemented in Meerssen. Combination 65 consists of 4 Downstream Infrastructure measures. An emergency spillway has to be dug, and an old sewer pipe must be used as an emergency spillway as well. This can possibly cause flooding downstream.[57] In combination 65, the old sewer pipe is replaced by a dam at Schin-op-Geul, this measure is more intrusive, but possibly safer with regard to downstream flooding.

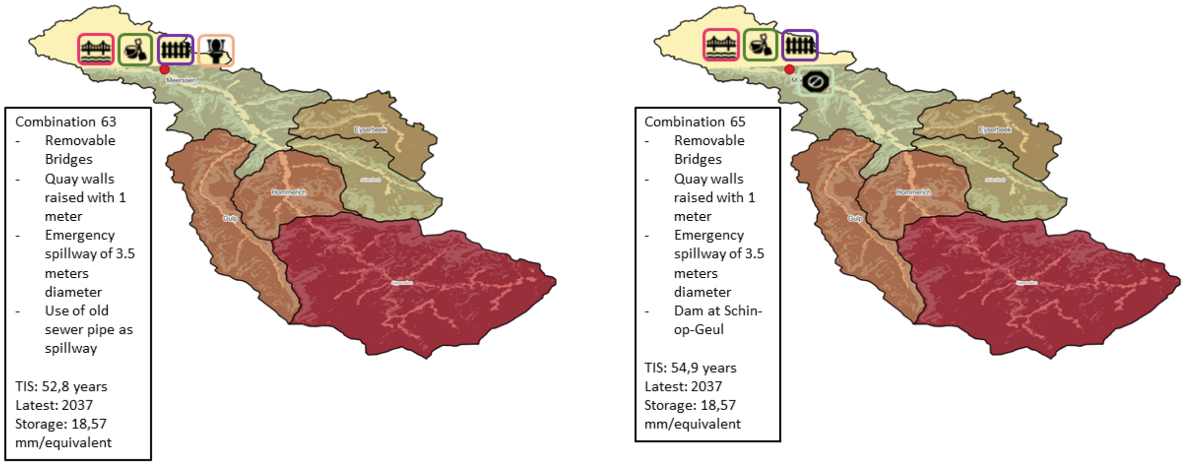


Figure 5.22: Spatial map of a potential placement of fully downstream combinations, 63 and 65

Strategies when maladaptation occurs

The solution space provides numerous options for reaching the adaptation goal if maladaptation occurs within the adaptive capacity. If the forests are decreased by a third, combinations 496 and 500 can still help achieve the adaptation goal. In combination 496 this is done with a combination of upstream and downstream measures and in combination 500, every measure is located in Meerssen. This makes it likely for combination 500 to be implemented easier. It is, however, less elegant as measures are intrusive and possibly costly.

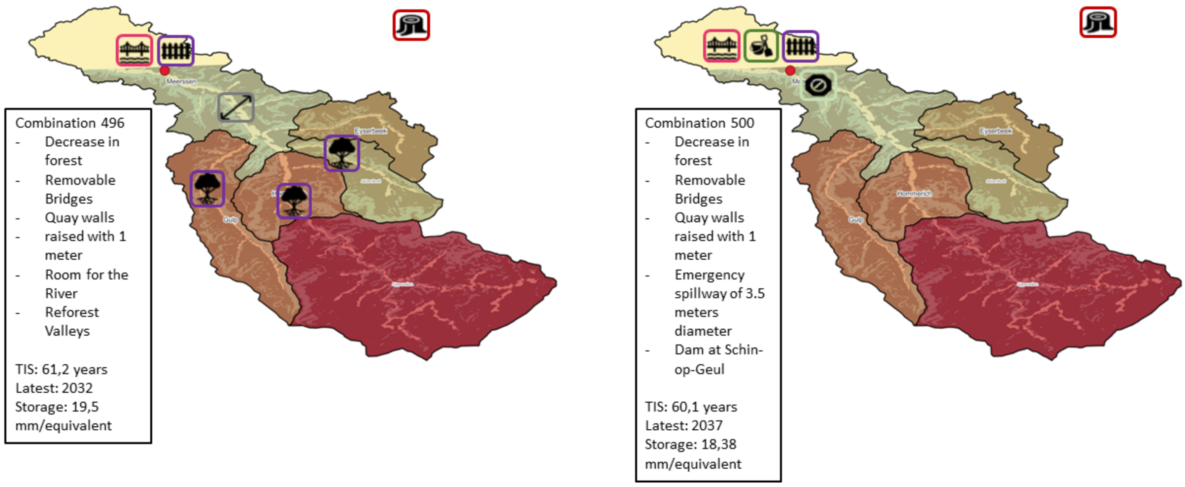


Figure 5.23: Spatial map of a potential placement of the combinations when maladaptation occurs, 496 and 500

Alternative Strategies

Two Alternative possibilities are the placement of an enormous reservoir at one of the dry valleys and the heightening of quay walls by 2.5 meters. The reservoir in the dry valley should be located below the confluence at Gulpen to be effective. At an area of 12 hectares, average depth would be 50 meters.

Logically, the location of the quay walls is in Valkenburg. This is because the measure is aimed at increasing discharge capacity, and therefore it should be located at the bottleneck.

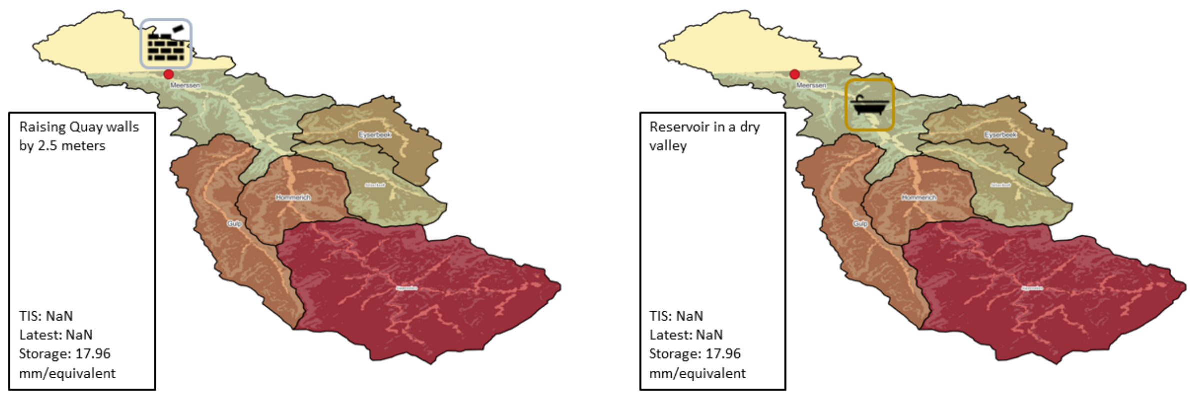


Figure 5.24: Spatial map of a potential placement of the alternative strategies

5.4.2. Additional Results

The additional results are not part of the Framework, but are results provided to give insight into the solution space and the adaptive capacity in the Geul.

Adaptive Capacity

The adaptive capacity of the water system is the maximum achievable storage equivalent in the system. In Figure 5.25, the adaptive capacity is visualized for upstream and downstream solutions. The measure categories RR, UNR, UI and DI are also given a colour to identify the solution space per category. Multiple categories are combined in the upstream adaptive capacity to sketch the image of the total upstream adaptive capacity. By itself, only downstream infrastructure and Alternative measures are able to provide the desired storage equivalent. Upstream categories UI, UNR and RR have to be combined to achieve the adaptation goal. All unique combinations from this figure form the solution space.

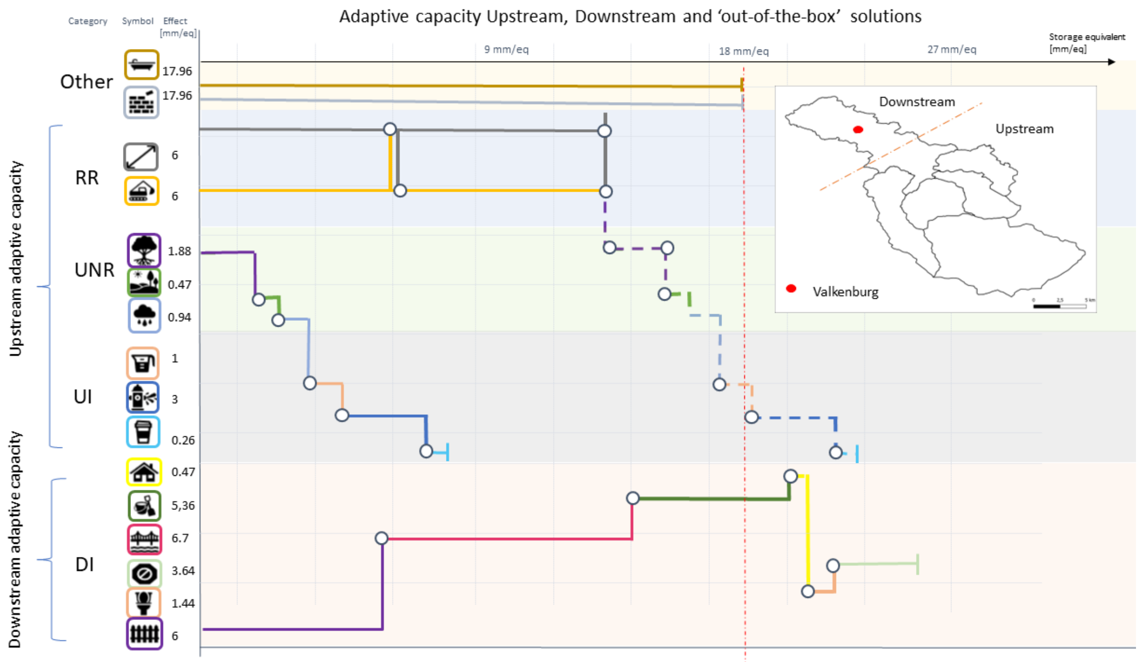


Figure 5.25: Adaptive capacity of the different categories of measures. The upstream and downstream adaptive capacity is visualized by sequencing the adaptive capacity of the categories. The adaptation goal is indicated using the red dotted line at 17.96 millimeter equivalent.

The adaptive capacity of Room for the River measures is 12 millimeter equivalent, Upstream Natural Retention 3.3, Upstream Infrastructure 4.26 and the downstream adaptive capacity is between 23 and

25.5 millimeters equivalent (depending if removable and flat bridges are deemed compatible with each other). The adaptive capacity of all categories, except Downstream Infrastructure, is insufficient to achieve the adaptation goal. In other words, the required storage equivalent cannot be achieved by only implementing upstream natural retention, upstream storage or room for the river solutions. In total, excluding the Alternative measures, adaptive capacity is roughly 43.6 millimeter equivalent. It should be noted that this number should be checked for its combined effect using more elaborate models. The 43.6 millimeter equivalent does make the limitations to climate change adaptation very concrete.

Room for the River measures should be implemented downstream of the confluence at Gulpen to be effective. This means that the adaptive capacity upstream of the confluence is just over 7.5 millimeters equivalent. This is not even half of the required storage equivalent. Downstream Infrastructure and Room for the River measures are all located in the downstream catchment of Meerssen, making the adaptive capacity of that catchment to equal 35.14-37.5 millimeters equivalent. Considering the limited upstream adaptive capacity and the complexity of cooperation in those subcatchment, it is likely that adaptation combinations that are implemented are concentrated downstream.

Adaptation Pathway example

The Dynamic Adaptive Policy Pathways depend on pre-defined tipping points, thereby limiting usefulness in complex systems. The method is, however, very effective in visualizing adaptation combinations in order for decision makers to have insight in their options. Adaptation Pathways are sketched for the combinations 777, 928, 1100 and 1104 to make the sequencing of actions insightful. In addition, timelines have been sketched to determine decision moments. These moments are moments where decision-making processes should be initiated in order to achieve adaptation goals in time. The adaptation goal of 17.96 is sketched for a high climate change extent scenario and a low climate change extent scenario. The figure assumes the adaptation required increases linearly over time: If an adaptation goal is equal to about 18 millimeter equivalent by 2050 or 2080, intermediate goals are 9 millimeters by 2036 or 2050. This is all displayed in Figure 5.26

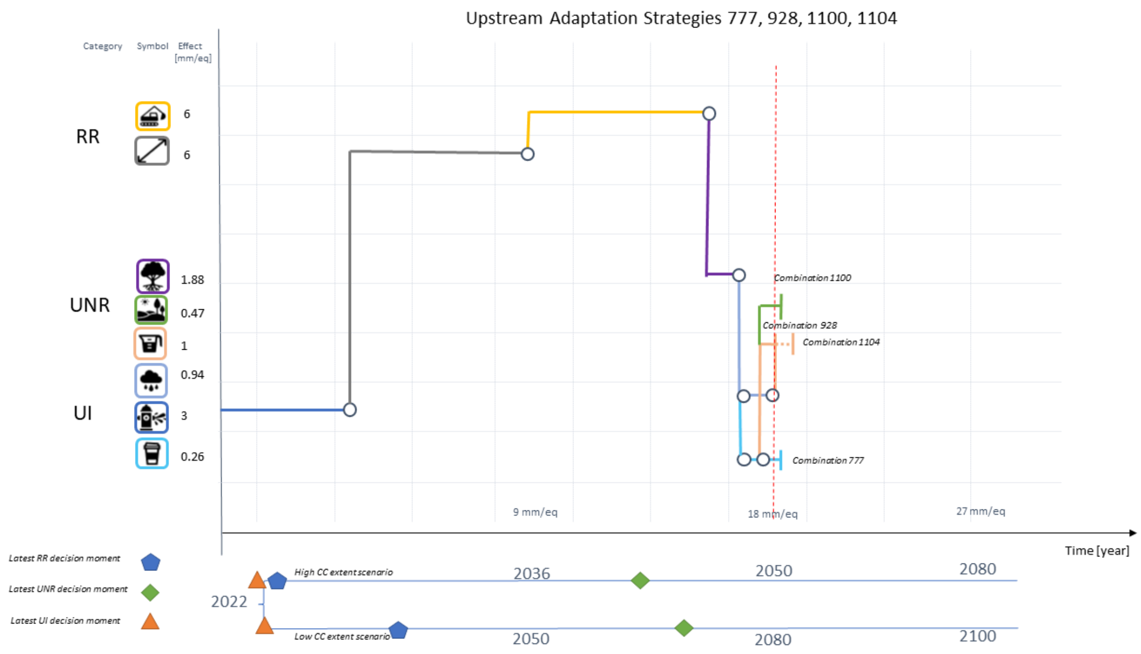


Figure 5.26: Adaptation pathways of four combinations, providing insight into the sequencing of actions and latest decision moments based on climate change extent scenarios. Measures are located on the vertical axis, the storage equivalent and associated timelines on the horizontal axis. Latest decision moments are sketched for both timelines using pentagon, diamond and triangular icons

Entities working internationally

Results on experts indicating entitites working internationally are shown in table 5.4.2 In the Netherlands and Germany this seems to be concentrated on national and regional actors while the French and

Belgians work internationally in regions, but not that much on the national level. No differentiation was made between Flanders and Wallonia. This data indicates a difference in organisation between countries. This difference also indicated by experts.[98]

Table 5.6: Entities that work internationally from different basin countries

	National	Regional	Local	*Number of entries*
The Netherlands	18	18	9	*19*
Germany	5	6	3	*6*
France	1	3	2	*3*
Belgium	1	5	2	*5*

Broader applicability

The broader applicability of the method for mapping spatial cooperation difficulty is assessed by applying the method to other (transboundary-) tributaries of the Meuse. The cooperation scores should be equally valid for these areas. Cooperation scores are again taken from the perspective of the downstream country, in this case Wallonia. Mapping is done for the Vesdre, Ourthe and Sambre. When the cooperation scores are known, it is relatively easy to use Hybas Global watershed boundaries and subbasin delineations derived from HydroSHEDS[104] to find tributaries and subcatchments, The maps of actors also span the other basin countries and can therefore also be used similarly. The results are shown in Figure 5.27 They seem to indicate that the complexity in other catchments is also linked to the presence of transboundary actors. In addition, a link can be made with the area subbasins cover. Larger subbasins generally have a higher Cumulative Cooperation Complexity.

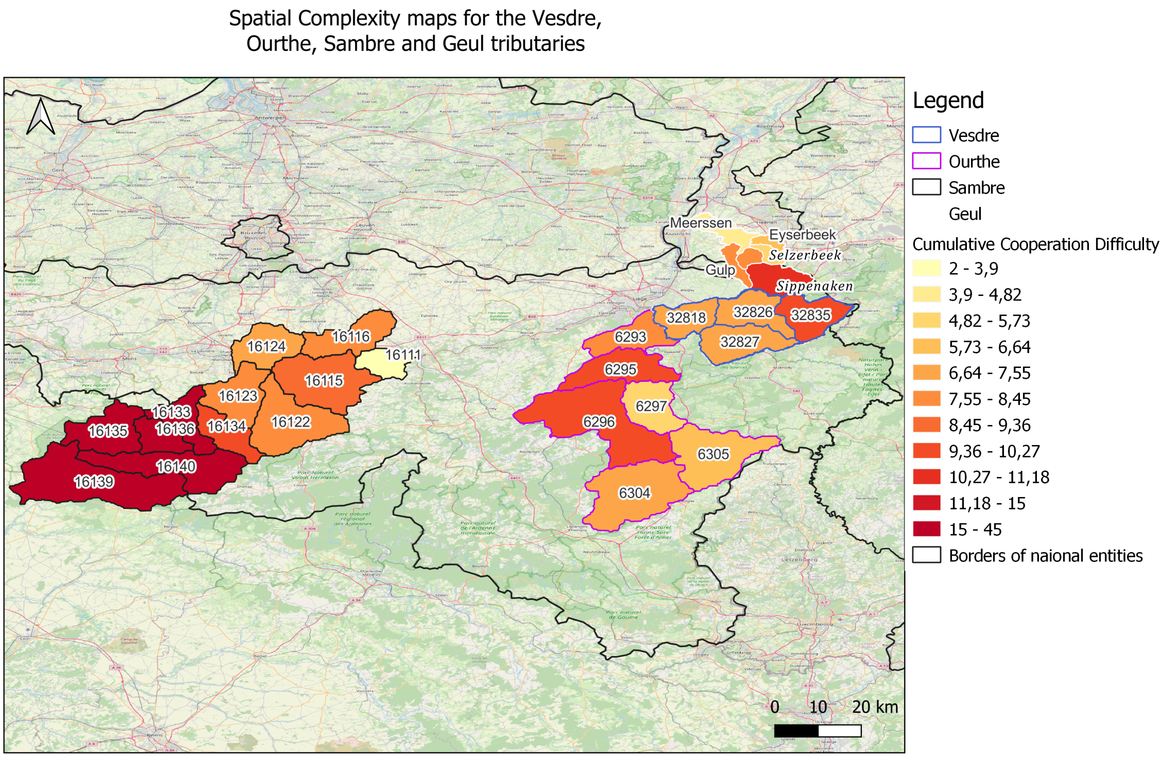


Figure 5.27: Cooperation difficulty in subcatchments of the Vesdre, Ourthe, Geul and Sambre

To evaluate the validity of mapping Cumulative Cooperation Cifficulty, a map is created using random points in the Meerssen, Hommerich and Sippennaken subcatchments. Using Vonoroi polygons, these are divided into random areas. This is visualized in Figure 5.28 This indicates the division per sub-catchment is coarse and heterogeneity exists of Cumulative Cooperation Difficulty within catchments.

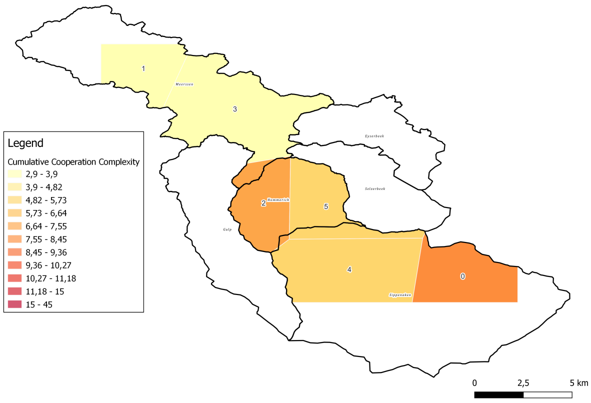


Figure 5.28: Cooperation difficulty in random sections of the Meerssen, Hommerich and Sippennaken subcatchments

6 Discussion

6.1. Methodological

This thesis connects the human domain to the natural domain. To do this, simplifications and assumptions are made. The study is more about connecting things that are usually not connected rather than studying a subject in great detail. The methodology is reflected upon in this section.

6.1.1. Archetypes

The use of archetypes can be contested. As described by Tadaki et al., classifications are not objective descriptions of reality. Archetypes, however, are examples of classes to which a landscape has a degree of similarity. No generalized management approached can be derived from archetypes, but only certain mechanisms. Archetypes are subject to similar issues as classifications. The metrics on which archetypes are defined are also subject to perception, possibly even to culture and geographical location. What in the northern Europe is called a hillslope might be called a plateau in hilly areas and vice versa. At the same time, the Archetypes as described by Savenije (2010)[4] have been used in the Topoflex model and have been proven effective in several studies, for example Gao et al., Gharari et al. (2014) and Euser et al.(2015).[78][79][80] The archetypes are the result of self-organizing behaviours of European landscapes. With similar boundary conditions, other landscapes in the area should show a degree of similarity to these archetypes because of this. In addition, studies have shown the relevance and effectiveness of topography based modelling.[78] Therefore the use for derivation of measure categories based on dominant runoff mechanisms is still justified.

6.1.2. Expert Judgment

The Social Network Analysis and the estimation of implementation time were based on data gathered using expert judgment. On itself, this method can be contested. The participants are possibly influenced by the setting, their peers and presentations before the expert judgment on cooperation. Being conducted at the International Meuse Symposium in Liège, the participants were in a location where they were to cooperate with each other and share knowledge. The event in itself might be seen by participants as part of the cooperation. This might cause a bias in their answers. Having a good or bad conversation with one of their (inter)national peers might cause them to view their cooperation differently than before that interaction. Being surprised by the high or low number of participants compared to what one expected might also alter ones view on cooperation. A lot more factors (e.g. mood, fatigue, stress, quality of the catering etc.) possibly influence the scores people provide. People might have misunderstood things as well. For example; Participants were supposed to skip their own country but some provided a score of zero of five. These things could be manually filtered, but other misunderstandings are likely not visible or correctable.

Expert judgment on implementation times

The expert judgment on implementation times was conducted at the end of the congress. People might have been tired and some people already left. Therefore the group of experts is a little smaller and not identical. The differences in participants and possibly their fatigue possibly influenced results. Additionally, the expert judgment was completed after presentations of Deltares on their rapid assessment [59] and hydraulic system analysis [57] and one on precipitation prediction. In the first two presentations, measures are proposed for adapting to climate change in the Geul. The proposed measures are also part of the solution space in this thesis. These presentations have likely influenced the idea of magnitude and complexity of climate change adaptation measures. Normally, this might be undesirable, but in this case it might aide the quality of the results. By providing people with the magnitude and types of measures, they might have a more common understanding of what they are estimating implementation time of. The effect of this is, however, unclear.bResults of implementation time are averaged over all countries, making it impossible to identify difference in implementation time. Implementation time was defined to be both decision-making time and construction time. This was communicated orally and plenary but it was not mentioned in the slides and instruction form. This might have influenced results.

Expert judgment on Cooperation Scores

The expert judgment of cooperation was on typical cooperation within a country and with other countries. A scale was provided, but no definition of cooperation was provided. Cooperation was asked about in the context of climate change adaptation measures. With participants being civil servants, academics and people from private entities, participants possibly have different understandings of cooperation. Academics might see this as sharing information whilst civil servants possibly see this as operational cooperation or forming joint (adaptation) plans.

In addition participitants possibly have experience with different administrative layers. There is no weighted scores taking into account the level of expertise. It is also not identifiable which administrative layers people have experience with. Cooperation might also be very different for different measure types. This is not asked in the expert judgment. It is, in any case, clear that cooperation will mean something different for all participants.

The expert judgment will be better with a larger sample size because the impact of people on the total result is less. Therefore individuals experiencing one or multiple of these factors will impact the overall result less. In case of this study, some groups had very small sample sizes (e.g. Wallonia, Flanders, Germany, France with two or three participants). The influence of circumstances on the cooperation scores for these countries might therefore be significant as the rating of an individual is half or one third of the total score. No people from Luxemburg participated.

The expert judgment deliberately focuses on administrative actors. In reality, private companies and citizens are also involved in adaptation. This can be because they also self-adapt or because their presence poses a complicating factor in implementing a measure. One can imagine it might be harder to displace a lot of people in the city center of Valkenburg compared to changing crop types at a farm or displacement of one household in a dry valley. It is also likely that measures on publicly owned land or in government managed forest are also more easy to implement. This complexity is disregarded in this thesis but is certainly present. Future work should also focus on this aspect.

Social Network Analysis

During expert judgment, experts do not indicate which administrative layer they have cooperated with, but indicate typical cooperation between different categories of entities. This is then extrapolated internationally. This is a rather coarse method: Extrapolation implicates that countries are organised in a certain manner (e.g. top down or with a prominent role for regions) and this works through in international cooperation. Cooperating with a country that is organised to down (thus with low cooperation between local and national actors) is hypothesized to also cooperate internationally in a similar manner. Because of this method, cooperation between regions cannot, by definition, be higher than between national governments. Validation indicates that cooperation regionally can be a lot better but also a lot worse. This is dependent on persons and organisations rather than institutions.[98]

This method also assumes that every connection between actors actually exists. In reality this is likely not true. Therefore thresholds are applied to find meaningful relationships. This method is different from literature (e.g. Fliervoet et al.[83]) where usually people are asked for relations or contact moments that are present. It might also influence system properties when analyzed this way. Possibly this can also influence conclusions on brokerage or central actors. For example, in the results of this thesis, brokerage roles are likely to be filled by national governments. But literature also indicates that cooperation is not only formal, but also social.[83] In the method applied in this thesis, both are encapsulated in the cooperation score. Additional results also provide an overview of which actors work internationally within the basin countries. This can help identify at which locations the local or regional actors are located which have better or worse connections then presumed by the method. Cooperation scores are averaged over the received and the provided cooperation scores between actors. This averages out differences in cooperation scores but disregards directed cooperation in the network analysis. In the spatial cooperation analysis, this is still implemented by using the cooperation difficulty as viewed by the downstream actor.

6.1.3. Solution space

The solution space is formed by all unique combinations of adaptation measures with all lengths to a maximum of the number of measures included. After this, scores on constraints are coupled to every combination and results are filtered. This causes the computational time to increase exponentially when additional measures are provided. With a few more measures in the solution space, millions of combinations have to be calculated. This is inefficient and limits the usefulness of the method.

Adaptation Goal

The adaptation goal is chosen to be equal to 17.96 millimeter equivalent as this is 6,000,000 m^3 divided by the area of the catchment (334 km^2). This is derived from the estimation of Deltares in their rapid assessment[59] and hydraulic analysis[57] and is based on the excess discharge at Valkenburg during the 2021 flood event. Measures are recalculated to this from different units. Discharge capacity increase is calculated to a volume by multiplying that extra capacity with the duration of the 2021 flood event. This amount of extra volume could have been discharged if the measure was implemented at the time of the flood. Measures that have an effect of lowering the water height in meters or the decrease of the flood peak in percentage are recalculated similarly.

Effect of adaptation measures

Some of the recalculations of measures require several steps and are assumed to be linearly recalculated. In reality, effects are less straightforward and might even have a negative effect on the flood risk. Measures that lower the flood peak could increase upstream water level because the water is 'slowed down'. Similarly, discharge capacity increasing measures can cause floods downstream.[57] A thorough hydraulic assessment must be done on the combinations the solution space provides and it is not unlikely that a lot of solutions do not provide the desired effect. The advantage of this method is that it narrows the amount of hydraulic calculations needed to assess the solution space. Decision makers now have insight in the possibilities. Based on their preferences, they can let some combinations be assessed in more depth.

It could also be that the effect of measures is estimated unrealistically. Deltares estimates the natural storage can be increased by 10 mm at its maximum.[57] Upstream Natural Retention measures add up to 1.32 millimeter equivalent. As they are assumed to be implemented at 10% or 20% of the catchment, a total of 13.2 to 6.6 mm is assumed to be stored using natural retention. This is in the same order as magnitude. Potentially, the effect of some of the other measures is overestimated, causing the combinations to have more effect in theory than they would have in reality. The estimations by the Multidisciplinary student group [21] and some of the estimations by Deltares and Arcadis have a very high effect. Possibly, these estimations are too high, causing the solution space to bigger than it is in reality.

The method does not evaluate combined effects of measures and is therefore vulnerable to measures that target the same issue and are therefore not effective combined. One example are flat- and removable bridges. Their effect is based on targeting the arches in the current bridges that limit the discharge capacity. Their combined effect is likely not the addition of both effects. Because of this, combinations containing both are not mentioned in the solution space.

Blindspots of the Solution space

The reduction of the adaptation goal to a water storage volume is very simplistic in multiple domains. Firstly, it does not take into account droughts. Droughts should be taken into account as their effects can even be more costly than the effects of floods.[33]

When droughts are taken into account, an operational aspect is added to the analyses of the adaptation requirements. For example; It is common practise to keep some water in retention reservoirs during summer to alleviate effects of droughts. And this has also proven to be effective combatting droughts.[11] But when reservoirs are not empty in summer, their full capacity cannot be used for retention of precipitation. Deltares states reservoirs should be able to store up to 4,000,000 m^3 of water more than the 6,000,000 m^3 adaptation goal.

The measures are also not evaluated on their cost. It can, however, be argued that this would not be meaningful as the specific spatial location of measures together with many other factors (e.g. buy-out cost of inhabitants, contractor availability and costs etc.) determining the cost of measures. The measures are focused on hydraulic interventions up- or downstream and natural solutions. Only the diversion of urban rainwater is included as an urban solution. This limits the solution space.

Additionally, measures are only rated on their effect at Valkenburg. This is because Valkenburg is one of the hydraulic bottlenecks and the location with the most flood risk due to both the high vulnerability and exposure. Other locations are also at risk for flooding and measures are not evaluated on the effect they have on other locations. Potentially, retaining water or creating emergency spillways can have negative effect on locations even further downstream or in the Meuse.

With an adaptation goal of 17.96 millimeter equivalent, an upper limit of 22 millimeter equivalent was applied. The upper threshold was applied because the measures in the solution space are very intrusive; It is assumed that a river basin manager would like to overshoot the adaptation goal by more than 20%. The number of feasible adaptation strategies is severely limited by the upper boundary: When maladaptive actions are removed from the solution space, the number of feasible combinations increases. This might indicate the maladaptive actions in a sense 'pull' more solutions into the range between 17.96 and 22 millimeter equivalent. It might also indicate that the number of combinations in a certain category is not a meaningful metric for measuring the solution space.

6.1.4. Cumulative- and Latest Implementation Times

The cumulative and latest implementation times (TIS and LIT) are derived from the implementation time estimation provided by experts. The TIS is the time all measures would take if implemented in sequence. As no combinations can be implemented in sequence given the goal to be fully adapted by 2050.[101] Therefore the TIS is used as a proxy of the difficulty of a measure combination; the lower the TIS, the easier it is to decide upon and implement these measures. In itself this seems like a logical proxy, but it provides a coarse and possibly not correct image of difficulty. For example, both 10 small reservoirs and 1 very big reservoir spanning several hectares are both in the category of upstream infra and are therefore assumed to be equally difficult to implement. This is not the case in reality and is also very dependent on the location of implementation. The LIT is the longest implementation time of measures in a combination. At this time, a decision making process on a certain measure must start in order to be adapted at the desired time. In reality, this decision making time is not equal for all measures in a single category. Additionally, increased public, political or climatic pressures might also influence decision making time at that point, potentially speeding up the process.

6.1.5. Spatial Mapping

The spatial mapping of governance difficulty is a simplified version of reality. In the mapping of difficulty in this thesis, cooperation difficulty from the perspective of the Netherlands was used. Therefore, the difficulty in subcatchments that are shared between Belgium and Germany is extremely high. This is because it is assumed that the downstream country needs something from the upstream countries.

Additionally, entities that span a large area of a subcatchment now count equally to entities that span less. There is also no analysis done on the land-use in these areas. A municipality spanning a little corner of a subcatchment that is covered by forest is likely to be a less relevant partner than a downstream located city. No differentiation has been made on the responsibility of different entities in an area. It is likely that there is a heterogeneity in Cumulative Cooperation Difficulty per subcatchment if this differentiation is made. In itself the subcatchments are heterogenous in Cumulative Cooperation

Complexity as shown by the additional results.

6.2. Results

6.2.1. Solution space

The downstream infrastructure measures seem to be very effective in achieving the adaptation goal. It could be the case this is because of the simplification of the adaptation goal or the calculation of their effect to millimeter equivalent. All the calculations are assessed on their effect on the bottleneck Valkenburg. It is therefore logical that measures aimed at increasing capacity at the bottleneck are very effective. However, the multidisciplenary group also indicated additional research was necessary to validate the numbers they posed.[21] Possibly the measures are less effective than assumed by the MDP and in this thesis. Downstream infrastructure measures investigated by Deltares (emergency spillway tunnels and raising of quay walls) seem to indicate the measures are indeed efffective in preventing flooding in Valkenburg. The tunnels, do however, have little positive effect just upstream of Valkenburg and a slight negative effect just downstream. Overall, the measures do seem to be very effective at preventing floods in Valkenburg, but not at other locations.

In the combinations analytics, measure categories seem to be prevalent equally well when taking into account the number of measures in their category. The meaningfulness of prevalence in the solution space is, however, questionable. Different measures with the same small effect can form many unique combinations. When this is regarded as an important metric, these measures seem to be very relevant.

Implementation time

The implementation time estimations have a very wide spread. One could question the meaningfulness of these estimations as experts possibly have different understandings of the measure categories. On the other hand, the wide spread could indicate that factors such as local context or decision making are so important that the implementation time varies a lot. This would mean that the timelines and the latest- and cumulative implementation time in the solution space are subject to considerable uncertainty.

The solution space provides numerous options to achieve the adaptation goal. If these are implemented in sequence, the year the quickest combinations achieve the goal is 2069. This is 19 years late of the 2050 goal.[101][42] To open up the solution space, decision-making time could be cut drastically. Currently this is a factor severly limiting the solution space. Of course measures could be implemented in parallel but implementing several measures at the same time is likely to be very intrusive and costly. It he public and political willingness to do this is not present, the decision-making time effectively rules out these options.

6.2.2. Network

Cooperation between National and Local entities is generally worse than other cooperation in the basin countries. This makes sense as regional entities are likely to act as a bridge between them. A surprisingly bad cooperation score between national and local actors might indicate a decentral organisation of a country. In Flanders the cooperation is especially bad when a national entity cooperates with a local entity. Interestingly enough, cooperation is relatively well the other way around. At the same time, cooperation of regions to national and local actors is the lowest of all countries. Possibly, regions do not play a bridging role in Flanders. Cooperation between national and local entities is also relatively bad in France. In France, the cooperation between local and regional actors is relatively well, indicating France might indeed be organized decentrally. These differences might complicate international cooperation.

The Netherlands and Germany rate cooperation internally similarly. These countries might be organized in a similar matter. This seems to also be the case on the entities form these working internationally. In contrast to France and Belgium. International organisation is done by national and regional actors more than local actors. In France and Belgium, this is the other way around. Given the large differences in cooperation scores between countries and the inconclusiveness on the factors that determine this, it is likely that a lot of factors determine cooperation quality. Things as adjacency, culture, organisation of government and many other things likely play a role.

Factors determining cooperation quality
A lot of factors determine cooperation quality between countries. In the results, themes as language, culture, perception and adjacency were explored. It is hard to determine the degree to which they influence cooperation quality. The language aspect is especially interesting in the Meuse as both Flanders and Wallonia are in the basin area. Both are part of the Federal state of Belgium. At the same time, Flanders indicates cooperation with the Netherlands is significantly better than cooperation with Wallonia (0.9 and 0.6, respectively). At the same time, Wallonia indicates cooperation to be almost as good with France as with Flanders. This indicates this factor is relatively dominant.[13][98]

Adjacency is a less straightforward influence. Although one could expect cooperation to be well between adjacent countries due to the necessity, this is not always the case. Countries with a central role in the Network (the Netherlands and Flanders) indicate cooperation to be centralized around adjacent countries. Possibly this indicates adjacency only is a dominant factor in cooperation quality if you are an active participant. This could be hindered if two partners operate differently, for example with one being conservative and another being innovative.[98] Differences in provided and perceived cooperation scores indicate this as well. Partners non-adjacent to central actors also indicate their cooperation with these actors is relatively well. Possibly they view cooperation differently, for example as active participation in shared institutions or sharing information. Validation also indicates that cooperation quality is very dependent on the people involved. Local and regional cooperation can be better or worse than typical cooperation due to this.[98]

It is not unlikely culture, governmental organisation, availability of personnel, prioritisation, the lack or presence of issues and many other things influence cooperation. It is hard to identify relevant factors and more research into this topic is necessary. What one can conclude is that the factors described play a significant role. Therefore this should be taken into account. A network analysis based on common institutions or meeting frequency would not encapsulate these things into the SNA. This calls for analysis of cooperation networks using a similar method as used in this thesis. Cooperation is too dependent on social aspects to describe effectively using shared memberships or other institutional links.

6.3. Preferential Adaptation Strategies
Preferential Strategies should target flood risk by not only targeting flood hazard, but also by causing wider systemic changes affecting exposure and vulnerability. Additionally, it should be accompanied by measures targeting vulnerability which are not implemented in the water system. In this section, leverage points in the water- and human system are explored and additional policies are suggested.

6.3.1. Water System
The water system is less influenceable on a deeper level than a human system. Goals and paradigm of the system can, for example, not be altered. Still, a systems approach can yield valuable insights. Meadows (1999) stated that 90 to 95% of our attention is directed to parameters (leverage points 12 through 9).[96] Targeting deeper leverage points might make approaches more effective.

Sizes of buffers relative to flows are known to have the ability to stabilize systems.[96] By implementing storages (either natural or infrastructural) these buffers can be increased. But these additional storages can also delay flow of water. This is a stronger leverage point than altering flow paths or increasing parameters. This makes it desirable to opt for delaying and storing measures rather than those aimed at increasing discharge capacity by altering flow paths (Room for the River or emergency spillways) or increasing discharge capacity by removing bottlenecks downstream. This suggests opting for Upstream Infrastructure and Upstream Natural retention measures rather than Room for the River or Downstream Infrastructure measures.

Strategies can also make use of self-organizing properties and feedbacks in systems. Environmental systems are known for self organisation and this capacity can be harnessed if steered in the right direction. When allowing natural phenomena to occur and monitoring their effect, self-organisation in the desired direction can help alleviate adaptation needed. Examples can be allowing periodic inundation, planting vegetation under trees, releasing animal species that influence ecology for example as natural enemies of undesired vegetation or other animals that negatively effect vegetation or by creating macropores. Decision-makers can also try to make use of feedbacks by releasing water in a flow pattern that would benefit desirable vegetation or strategically placing certain types of vegetation in floodplains. These interventions should, however, be verified further as their effect is highly uncertain.

6.3.2. People

People influence the factors that determine flood risk greatly. Via planned adaptation, humans can decrease flood hazard. Exposure and vulnerability can also be decreased. This can be done via policies, but also by triggering autonomous adaptation. Autonomous adaptation can possibly be sparked by leverage points in the human system. Financial incentives and information are the most relevant tools to push people to adapt by themselves.[47] By providing information (leverage point 6) on how to decrease vulnerability. This has for example been done by the Walloon government after the 2021 floods.[47] Decreases in exposure can be triggered by providing information flow as well. This can be done by restoring or creating information flow.

Clear information on future climatic influence and very visible things that note the extent of the 2021 floods, for example flood marks throughout the city, information signs in the city or a monument to remember the floods. This makes the risk tangible and make people aware they are actually walking and living in a flood prone area. Other ideas are to opt for very visible adaptation measures. In terms of information flow, which is a rather deep systemic leverage point, it would be wise to opt for the most visible adaptation measures possible. Informing inhabitants of flood risk at their house might be a good starting point as not all people are aware there is flood risk at their house.[9] (Re-)Connecting people and nature is also identified as a powerful tool for increasing awareness. In the Geul, this could for example be done by showing people how thin the upstream soil is. This could create insight into the limits of (upstream-) adaptive capacity. Informing people or how to decrease vulnerability to floods is also a possible way to decrease flood vulnerability. This is for example done by the Walloon governments following the 2021 floods.[47]

The rules of the financial system are possibly also a leverage point where autonomous adaptation can be triggered. Currently, flood risk can feel far away from Dutch citizens.[10] Subsidies for flood hazard mitigating measures by the central government cause all people to pay for the hazard mitigating measures at a location. This in itself can be desirable and ethical, but the financial link is very far away for inhabitants. In combination with the deployment of national disaster relief funds and the absence of flood risk insurance (requirement or sometimes even availability), all financial incentives to self-adapt are taken away from citizens. This likely contributes to lock-ins. By making insurance mandatory, this financial information is restored and people might opt to live elsewhere. This poses many ethical challenges and considerations, but in terms of rules of the game, it would possibly be effective. Another possible measure is to require flood risk labels for houses. This can cause wider systemic effects as houses at risk are less profitable to build. Possibly this leads to development elsewhere.

The most important leverage point is the mindset of people. Nature is not fully manageable, risk is not fully mitigateable. Müller (2013) describes the role of the floods directive in transitioning from a safety to a risk culture.[44] If this paradigm prevails, adaptive capacity might be greater as people understand that living in some areas might be undesirable.

6.3.3. Additional Measures & Policies

Network Interventions

Network interventions are also possible in order to reduce the implementation time, opening up the solution space. The network is already polycentric at low thresholds. Introducing a central operational actor with a wider view could provide centripetal forces and facility cooperation between actors which are now not connected. This could, for example, be the European Union or the CIM. When given an operational role or binding adaptation targets, these institutions enter the network. Other network interventions could be strengthening regional cooperation. Potentially this can be facilitated by providing European subsidies or initiating platforms for cooperation. The denser a network, the more potential for collaborative actions. Subgroups can harm this collaborative potential.[83] Commissions, especially those reagrding low flows, could also improve cooperation/[47]

In terms of legislation, a lot can be won as well. The FD is loosely formulated and therefore heterogeneously implemented. [38] Additionally, countries do not evenly consider climate change extent and cascading events are not fully considered.[39] The Floods directive could be streamlined by tightening its formulation, introducing binding targets and including network interventions.

Measures outside of the water system
Flood Early Warning Systems (FEWS) can be effective in decreasing exposure and vulnerability at the time of a flood event by providing early information. This way, people can self-evacuate or prepare their houses or businesses for the flood. Operationally, streamlining cooperation can aide effective management. Examples of this are sharing information, data and using the same models. Combining these things, it is possibly interesting to look into a common early warning system for transboundary catchments. Flood proofing has also been shown to be effective, even if implemented on a relatively small percentage of residences in the area in Valkenburg prone to floods.[9] Possibly, this measure is more cost effective and easier in decision-making than other measures in this thesis. Literature suggests both might have a lower implementation time than others.[59]

6.3.4. Relating to combinations in the Solution Space

Climate change adaptation is an endless path if climate change mitigation is not applied as well. In order to harness self-organising capabilities of the environmental systems, one could start with adaptation combinations that provide room for the natural system to evolve and monitor its effects. In order to harness self-organizing properties of people and society, flood risk should be visible in Valkenburg and the surrounding area. One of the ways to do this is to have visible reminders in Valkenburg. Another might be to opt for adaptation combinations that are visible in the landscape rather than solutions that provide invisible flood risk reduction, such as pumps to aquifers or emergency spillways. Additionally, tools to change the (financial-) rules of the game might trigger cascading autonomous adaptation. Lastly, managers must acknowledge and signal limits to the adaptation solution space in order to speed up paradigm change from manageability of nature to living with risk.

The strategies with indices 0 and 4 are simple and visible. These could be preferential when cooperation difficulty is determined to be the biggest hurdle by decision-makers. Combination 65 is relatively simple and visible and also provides buffer capacity. Combination 1100 provides both buffers and delays. It is natural and therefore self-adaptive capacities of the environment can be harnessed. It is however not visible. If a decision-maker opts for this option due to their preference, it should be accompanied by measures outside of the water system aimed at making flood risk visible. For example monuments, flood marks in the area or information signs. Combinations 65 and 1100 possibly also have a positive effect on droughts. In terms of cooperation difficulty, the decision maker would likely opt for combination 65 over combination 1100.

The difficulty of decision-making and implementation time of the giant reservoir in a dry valley and raising quay walls by 2.5 meters are unknown. Given the difficulty and intrusiveness of other combinations, one has to wonder if these ideas are really infeasible. A giant reservoir is very visible, likely has positive effects on droughts, provides buffer capacity stabilizing the system and can be located in a dry-valley in Meerssen, limiting the cooperation difficulty. Dry-valleys in the area are usually not inhabited by many people. Quay walls could also be implemented flexibly. For example by raising the walls 1.5 meters and having an emergency extension of a meter available. This would also be very visible. Compared to combinations of adjusting the river bed, making flood plains available, installing emergency tunnels, reforesting large portions of the basin and so on, this option might not be so crazy after all.

Additionally, measures targeting vulnerability and exposure are possibly also very effective. Specifically in Valkenburg, research has proposed FEWS and wet-proofing of houses as solutions.[56][9] Lastly, network interventions and streamlining of the common European legislation could improve implementation times and cooperation.

In any case, complementary policies should be implemented aimed at creating financial incentives and creating or restoring information flow to citizens. Financial incentives can help decrease attractiveness to build in flood prone areas for contractors or banks. Potentially, it has the power to create ripple effects and cause economic development to move out of flood risk zones, decreasing lock-ins and path dependencies. In turn, this will also widen the solution space again. It also restores the financial information to inhabitants, which currently can feel far away due to nationally subsidized hazard mitigation measures, unavailability of insurance and disaster relief funds. Information flow can also be restored or created by informing people living in flood prone areas, visual reminders of the 2021 floods or information about the limits to adaptation. This might aide the transition from a safety to a risk culture.

6.4. Reflection and broader applicability

6.4.1. Broader applicability

The Framework simplifies climate change adaptation an cooperation. Due to this, it is able to give insights into the solution space and the collaborative network governing climate change adaptation with relatively little information. The Framework tries to find a midway between connecting elements and meaningfulness. Due to this, the quality of outputs very dependent on the quality of the inputs. To apply this broader, the availability of inputs is especially relevant.

The Framework requires information on effectivity of measures in the area. In the Geul, much of this information was available and of high quality. In a catchment where less research has been conducted, this information might not be available or might have questionable quality. This would limit the quality of the provided solution space. It is, however, still possible to get a sense of the solution space with estimations of effects as well. Possibly this can also be done with expert judgment on measure effectivity.

Mapping the administrative actors requires maps of administrative borers. These maps are openly available for the whole globe on GADM.[99] Therefore this can be applied broader. Network analysis depends on cooperation scores provided by experts. These are gathered using expert judgment but could also be based on metrics derived from literature or using desk study. Common proxies for networks are shared membership and meeting frequency. These do, however, not encapsulate non-formal cooperation. It should therefore be possible to create maps of spatial cooperation difficulty. Catchments and subcatchments can be derived from HydroBASINS maps.[104] These are logical subdivisions of examined catchments as they represent smaller tributaries of the examined river. Digital Elevation Models which can be used to construct archetypes are also available globally. Archetypes based on dominant runoff mechanisms should, however, be identified per location. This way, specific geological features can be taken into account as well. Inputs on climate change pressures, measures, location specific information such as geology and hydraulic bottlenecks must be found for the location of interest, limiting the broader applicability of the Framework to locations where these are known. The Framework is also able to suggest strategies without archetypes, but then, no locations are suggested.

Overall, if inputted with local information and validated using more complex models, the network can be applied broader. It is relatively simple in terms of operation and inputs, but provides valuable insights.

6.4.2. Reflection

It is likely that the system behaviours also change with the circumstances present at that moment. Political momentum can follow natural events; Where Valkenburg opted for a lower safety level than customary, funds have now been assigned. It was unlikely the same would have happened without the flood. The same is valid for the autonomous adaptation that inhabitants are now doing as well as many other complex effects. The same can happen in the future, making the estimations on cooperation difficulty and implementation time invalid. Possibly implementation times also become shorter when the adaptation time constraint is coming closer. In reality it is likely that these properties are very dynamic. In addition, it is not clear how effective the proposed interventions at leverage points are. As described by Meadows; people tend to correctly identify a leverage point, but push it the wrong way, creating undesirable results.[96]

A weakness of this approach is the adaptation goal that is based on the excess volume of water of the 2021 flood event. Kreibich et al. [11] have shown that coupled events can cause more damage if the second event is more hazardous. If measures reducing flood risk by reducing vulnerability or hazard are implemented, people tend to increase exposure again. This underlines the importance of coupling adaptation measures and deeper leverage points in the anthropogenic system; people also need to autonomously adapt to flood risk in order to prevent bigger damages in case of a coupled event. In addition, not every location where climate change adaptation is necessary has an event to which adaptation is desirable. Using flood hazard mitigation quantities and relating these to the effects of measures, flood risk can also be reduced without a storage equivalent.

Another weakness is the simplification of cooperation. Multiple actors are now addressed as a single category while cooperation likely differs a lot. Additionally, no analysis was done on the responsibilities of actors. Actors involved in implementing measures likely differ per category of measures. This will likely cause Cumulative Cooperation Difficulty to differ per type of measures. Lastly, the Cumulative Cooperation Difficulty depends heavily on the scale considered. Some subcatchments of the same order cover much more area, creating a distorted image with regard to other subcatchments and the cooperation difficulty in that area.

Overall, the Framework can be very useful in providing insights into the collaborative network and the solution space. Use of the network can provide decision-makers with possible strategies and locations for CCA measures. These possible strategies should also be evaluated on their cumulative effect. The method simplifies the adaptation goal to a single bottleneck but does not evaluate the effects up- or downstream of this location. Furthermore, it simplifies the cooperation network and assumes all administrative entities are needed for implementing measures. In reality, some things will require less cooperation between actors. Again, the Framework provides insights, but is not conclusive. A human decision-maker is always needed to decide on strategies and monitor systemic effects. When the Framework is used appropriately, it provides added value for decision-makers in CCA.

6.4.3. Ethical considerations

The combinations that are proposed as possible solutions in this thesis are not evaluated on the ethical implications of implementing them. For example the dislocation of people or the replacement of nature by upstream infrastructure. Although many things can be said on this topic, I argue that it is up to the managers of natural systems to decide upon ethical implementation of measures. The Framework only provides solutions that are technically feasible. In addition, preferences in combination types (e.g. no downstream infrastructure or only natural solutions) could be made to provide the flood risk manager with options that might be ethically preferable.

In case of the Geul, the administrative entities present are of democratic nature. Measures in this thesis, however, can be so intrusive that additional things should be done to ensure taking into account all stakeholders. Examples of this could be consultations or referenda. In addition, a thorough debate should be held on the ethics of influencing the flood risk culture in the Netherlands via financial incentives. There are many reasons why this might be unethical (e.g. punishing current inhabitants for spatial planning governance) and also reasons why it might be very ethical.(e.g. the beneficiary pays principle [10]).

This thesis poses strategies providing a storage equivalent. This narrow approach disregards many things such as individual rights and costs. The thesis is a utilitarian approach to climate change adaptation where flood risk is seen as the most important factor. In proposing intrusive and costly measures at locations, individual rights and interests are disregarded. The author values stating that these individual rights and interests are extremely important. Any decision-maker should hold these considerations at high regard and should evaluate possible adaptation strategies on these ethical issues. This is also valid for additional policies such as creating financial incentives. These are proposed in this thesis because of their potential systemic effects. These effects are, however, unclear and should be investigated further. If deemed effective a thorough debate should follow on the desirability of implementing such policies and whom these policies should concern.

6.5. Recommendations for Future Work

The current method is focused on realising a certain storage equivalent to decrease flood hazard and then opts for adaptation combinations on their wider systemic effects. Future work could focus on applying a broader scope, for example based on risk quantity. This way exposure and vulnerability can be included in the solution space quantitatively. Possibly this can be related to costs of measures as well. This would allow for a cost-benefit analysis on the measures implemented.

Cumulative Cooperation Difficulty can be differentiated for different subjects. This could be done by only taking into account actors needed for a certain measure category. This would make location suggestions more appropriate and precise. Implementation time should also be estimated better in a similar manner. The high spread indicates measure categories are currently too coarse to provide meaningful estimations. It begs the question if TIS is a meaningful proxy. This should be investigated.

Future work could also focus on the time component of the network more. In this thesis, this is the responsibility of the decision-maker. An example with a high climate change extent scenario and a low scenario is sketched in Figure 5.27. A finer estimation of implementation times and more strict adaptation goals could provide a better overview of the time aspect of the solution space.

Regarding the case study explicitly, Preferential Strategies should be tested for their performance using models and if implemented in reality, on their real world performance. The Framework provides insights but currently the exact effect of measure combinations remains unknown.

Lastly, the Framework needs to be evaluated better to draw conclusions on its functioning. In this discussion, some points about broader applicability are raised. But it remains unclear to what extent input quality influences output quality. Additionally, the use of the network should be evaluated with different sample sizes and types of experts. This influences results as well, it would be useful to know to what extent.

7 Conclusion

A Framework was developed in this thesis to answer these research questions and fulfil the research goal. The Framework was tested using a case study. Methodology consisted of literature review, expert judgment, QGIS analysis and Social Network Analysis and adaptation combinations in Python using the Networkx and Itertools packages. From the inputs of this Framework, products are created. From these Adaptation Strategies are formed based on suited locations, difficulty of cooperation and the effect on leverage points in the systems. By answering research question one, the Solution Space is formed, by answering question two, the Governance network and cooperation between actors is analyzed. Research question two combines both products and yields preferential solutions when system properties of the natural environment and the political-administrative environment are considered. Research question four reflects on the framework and the results.

The research goal is to find adaptation combinations and suitable locations in the Geul when taking into account transboundary governance complexity.

This can be done by answering the following questions:

1. Which combinations of measures can help adapt to fluvial flooding risk in the Geul?
2. In implementing these measures, which administrative actors are involved and how is the quality of their cooperation?
3. Which adaptation combinations are suited and would be preferential for the Geul catchment?
4. Can the answers to the previous questions be more widely applied to typical landscapes in the Meuse river basin?

The Framework has a broader scope than methods currently used for planned CCA. It is able to provide insight into the institutional context DMDU methods lack. Using a systems approach, leverage points can also be identified that could trigger wider systemic effects. These effects are, however, not quantified and could be more concrete. With relatively little information, adaptation strategies and network characteristics are analyzed. This suggests the Framework could be useful in quick-scanning the solution space while providing necessary context.

From the institutional context, this thesis derives that, in the case study area, implementing CCA measures in transboundary catchments is likely harder than in non-transboundary catchments. This is because international cooperation is significantly more difficult than cooperation within a nation. International cooperation on a regional and local scale is likely more skewered: It can either be better or worse than typical cooperation between countries. Cooperation between nations in climate change adaptation is dependent on many factors. It is likely adjacency, culture, language and governmental organisation play a part in this. Cooperation within nations provides insights in their organisation (e.g. top down, decentralized etc.) and allow to compare different countries. The common European legislative framework, despite its limitations, can serve as a starting point for interventions in the cooperation network. This could be done by binding targets, clarifying definitions, creating a more central role or means for regional and local entities or by operationalizing the role of international organizations such as the CIM or the European Union.

Preferences in adaptation strategies are likely to be different depending on whom is asked. The adaptive capacity allows for achieving the adaptation goal of the excess volume of the 2021 floods upstream of Valkenburg and in the city itself. Unprecedented events are not accounted for by using this adaptation goal but flood risk of such events is potentially reduced by the wider systemic effects on exposure and vulnerability. The goal is also simplified and disregards effects of measures outside of Valkenburg, their cumulative and wider effects and the cost of measures.

No fully natural solutions provide the required storage equivalent and all combinations require some intervention in the downstream subcatchment Meerssen. Two alternative measures are raising quay walls in Valkenburg by 2.5 meters and installing a giant reservoir in a dry valley. Given the intrusiveness and complexity of other solutions, these alternatives are potentially more interesting than they seem at first glance. Adaptation combinations should in any case be as visible as possible to spark autonomous adaptation. Storages stabilize the system and are therefore preferable over measures increasing discharge capacity.

Additional policies regarding financial incentives, information flow and paradigm change should be implemented to achieve wider systemic effects. Measures outside of the water system (e.g. floodproofing or FEWS) are logical and potentially effective additional interventions. But the adaptation goal and timeline are not trivial and should be decided on by decision-makers. The solution space is wide because much work has been done in scientific literature on the case study area. This might not be the case in other catchments. One also has to question the validity of estimation of these measures as the quality of sources vary. Maladaptation can be accounted for using the Framework.

There are also some caveats in the results. Implementation time estimation varies significantly. Meaningfulness of the metric and thus the validity of the cumulative implementation time TIS and the latest implementation time LIT should be questioned. The wide spread might indicate many factors determine the implementation times of different measure categories. It might also indicate heterogeneity in implementation time of measures within a category. Spatial maps of cooperation are useful but dependent on the area considered. Additionaly, no differentiation is made between actors involved in a certain category of measures compared to other categories. It is likely that despite a high Cumulative Cooperation Difficulty, measures might be implemented rather easily as only one or two actors govern that subject. Also no differentiation is made between actors with big or small areas in a subcatchment.

7.1. Research Question One

Which combinations of measures can help adapt to fluvial flooding risk in the Geul?

The solution space are the combinations of measures that would achieve the adaptation goal. It contains 13,227 combinations consisting of 19 different adaptation measures. When certain preferences are indicated, this number drastically reduces. In total 13,227 combinations achieve the adaptation goal. These combinations include combinations where maladaptation occurs. Combinations fully upstream of Valkenburg and in Valkenburg itself are able to achieve the adaptation goal. No fully natural combinations or combinations upstream of the confluence in Gulpen can achieve this goal.

7.2. Research Question Two

In implementing these measures, which administrative actors are involved and how is the quality of their cooperation?

Cooperation in the Meuse river basin is widespread. The cooperation of the majority of actors in the network is not of high quality. When a threshold of 0.4, which corresponds 'Poorly', is applied, a lot of connections between nodes dissapear. The cooperation quality is likely not sufficient between a lot of actors to take adaptation measures that are very intrusive, coordinate transboundary adaptation measures or create integrated flood risk plans. This should be further investigated.

Low cooperation quality between the Germans and the Belgians lead to the highest difficulty of cooperation in Sippenaeken. In the Eyser- and Selzerbeek, the Dutch and the Germans have the lowest transboundary cooperation difficulty. Although the Dutch work well together with the Flemish, presence of Wallonians causes cooperation to be difficult in the Gulp and Hommerich. Cooperation that is not transboundary is by far less complex.

7.3. Research Question Three

Which adaptation combinations are suited and would be preferential for the Geul catchment?

Locations where measures can be implemented are limited by the landscapes in an area, the discharge at that location and geological properties. When looking at governance complexity, preferential locations would be in the Meerssen (the downstream part in the Netherlands) or in the Selzerbeek (which is shared by Germany and the Netherlands). Other options with more actors and a higher cooperation difficulty are the Gulp, Hommerich and the Eyserbeek. Measures in Sippenaeken are likely to be the most dificult in terms of cooperation due to the presence of both Germany, Flanders and Wallonia.

Interventions such as the measures posed in the adaptation combinations target the parameters, flows and delays in the natural system. In order for adaptation to be the most effective autonomous adaptation aimed at exposure and vulnerability should also occur. This could be triggered by intervening in the political-administrative and societal system. To do this, information flow should be restored to people. In addition, the rules of the game could be changed. There is currently very little financial incentive for people to relocate or flood proof. Lastly, decision-makers should target the paradigm of manageability of nature. The adaptive capacity is limited due to physical, organisational, monetary and many other constraints. If society deems nature to be manageable, lock-ins might occur causing endless adaptation costs. Interventions could also target the cooperation network. By decreasing implementation times, the political-administrative and societal system is able to respond more rapidly to climate change. This will open up the solution space because more options would be possible in sequence. This decrease in implementation time could possibly be achieved by harmonizing implementation of the common legal framework, the European floods directive.

7.4. Research Question Four

How does the Framework developed in this thesis perform and can it be applied broader?

If supplied with the inputs, the Framework is able to provide the solution space, preferential locations, network analysis and spatial cooperation difficulty. All theses aspects, however, have their own strengths and weaknesses as addressed in the discussion chapter of this thesis. The framework is therefore in need of an integral assessment of how especially the weaknesses propagate through to the results.

In addition, the framework should be assessed on its operational use. It is designed to provide insights into combinations still feasible when a certain path is chosen or a quantity of time elapses. It is not clear, however, if the framework provided these insights during its use. For know, it seems to provide enough insight to more specifically select certain combinations and analyze these on their hydraulic effects. Broader applicability is discussed in the Discussion chapter of this thesis. When supplied with the right inputs, the Framework is not bound to a single location. Generally, inputs can be gathered relatively easy and information required is available in openly available sources. Availability of literature on the area of interest significantly influence quality of results. Improvements mentioned in the recommended future works and reduction of weaknesses could further improve broader useability of the Framework.

7.5. Concluding

The research goal is, to an extent, fulfilled. With the development of the Framework, a contribution has hopefully been made to connecting the engineering domain and the societal domain. Much work can and should be done in this subject. By no means this Framework is complete. Hopefully it can be a starting point for a wider engineering approach of climate change adaptation.

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