Hydrological Response of the Geul Catchment to the Rainfall in July 2021

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SWECO

TU Delft

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by

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to obtain the degree of Master of Science in Water Management
at the Delft University of Technology,
to be defended publicly on July 8th, 2022 at 2pm.

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Project Duration:	December 2021 - July 2022	
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Cover Image: Impression of the Geul, photo taken May 2021

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Preface

Dear reader,

it is a coincidence that my thesis is finished almost exactly one year after the flash flood hit the cities and villages along the Geul and caused substantial damage in the whole valley. I hope that my research can contribute to all the ongoing projects about possible flood mitigation measures in the catchment, to ensure that the Geul is better prepared for possible events in the future.

This research taught me how many things are still unknown in hydrology and how much uncertainty there is in the scarce data we have, especially in the case of extreme events. I was able to apply many skills which I have learned during my studies, but I also acquired new skills. I know how to set up, run and adjust a wflow-sbm model. My programming skills improved tremendously and I can appreciate much better how much work it takes to write a thesis.

This thesis would not have been possible without the support of all the people, who offered their time and knowledge to me. I greatly enjoyed all the discussions, excursions and technical advice I got from various sides. In particular, I would like to thank my thesis committee for guiding me on my journey. I thank Martine for her weekly questions and advice always making sure I keep track of my research objective and my schedule. I thank Remko for guiding me to the applicable research papers and the detailed feedback on my reports and presentation. Also, I thank Roel for our regular chats and discussions, and Koen for answering all my questions about groundwater data.

A great thank you also for the colleagues from Deltares. Mark, Laurene, Albrecht, Klaas-Jan and Ruben without your support on the model and on general catchment related questions, the final thesis would have looked much different.

It was great to have regular meetings with other students and researchers via the Limburg Flood Group of the Deltas Futures Lab. I learned much about all the different research topics and about different approaches and methodologies, which also greatly benefitted my own research.

Finally, I would like to thank my family and friends who supported me in these last two years and made sure that my work-life balance kept healthy.

Enjoy reading!

Angela C. Klein
Rotterdam, July 2022

Abstract

Flash floods are a major concern in hydrology and natural hazard science due to their high potential of causing fatalities and damages. They are caused by short, high-intensity rainfall and characterized by a flood event happening within six hours of the onset of precipitation.
In July 2021 an extremely large rainfall event took place in the mid mountain area of Belgium (Ardennes), Germany (Eifel), Luxembourg and the Netherlands (South Limburg). Precipitation amounts of up to 250 mm in 48 hours were recorded in the core of the rainfall area in Belgium. In the Netherlands the Geul catchment was affected the most as the high precipitation resulted in a flash flood hitting the villages and cities along the rivers.

This research is aimed at understanding the hydrological response of the Geul catchment to this extreme rainfall event. To begin with, the catchment and its hydrological behaviour is studied in detail, followed by an event analysis including rainfall, discharge and groundwater data. Furthermore, the antecedent wetness conditions prior to the event are assessed. Next to the data analysis, a wflow model was set up and adjusted to reproduce the event, to evaluate the event contributions of the different tributaries, and to test the impact of different antecedent conditions, rainfall amounts and infiltration capacities on the discharge response. By adjusting three parameters in the model (soil thickness, maximum leakage and a horizontal conductivity parameter), the model was able to reproduce the floods and the different responses of the subcatchments.

In July 2021 the Geul catchment received on average 128 mm precipitation in 48 hours. The highest rainfall sums were recorded in the Belgian part of the catchment and around Ubachsberg. The high rainfall quantities led to high discharges in the catchment. Based on model results, the peak discharge in the central part of the catchment at Gulpen was approximately 124 m^3/s. The discharge response of the catchment differed strongly between the subcatchments, especially between the tributaries and the Belgian upstream part of the catchment. The Belgian part contributed about 60% to the flow in Gulpen, although its contributing area is only 45%. The event run-off coefficient in the Belgian area was approximately 41%, while the event runoff coefficients of the tributaries Gulp and Eyserbeek were 21 and 23%, respectively. The differences in hydrologic responses within the catchment can be linked back to the geology. While the upstream part is characterized by thin soils and impermeable carboniferous rocks at the riverbed, the central and lower part of the catchment consist of a thick unsaturated chalk layer acting as major storage areas. In general, the overall run-off coefficient of 32% is fairly small for such an extreme event. The floodplains and the thick unsaturated zone at the chalk plateaus stored much water, and considerably delayed and dampened the peak. Based on the simulation approximately 75 mm of water was stored in the catchment area upstream of Gulpen.
30-days prior to the event the catchment received 50% more rain than the long-term average. Assuming average July wetness conditions, according to the simulation the event peak and cumulative discharges would have been 20-35% lower, and an additional 4.8 x 10^6 m^3 water could have been stored in the catchment upstream of Valkenburg. Consequently, the wetter-than-usual antecedent wetness conditions increased the severity of the flood from being minor (under normal conditions) to the major flooding which was experienced in the downstream catchment areas. However due to climate change, wetter summers are projected to become more frequent in the future and consequently the role of antecedent wetness will become even more important.

In the Geul catchment the geology is a dominant control on the runoff response of the (sub)catchments. The impact of flood mitigation measures can be maximized by taking the role of geology and its interaction with the effect of land-use changes into account in the selection process. Flood mitigation measures are especially required in the Belgian upstream part of the catchment. Retaining water already there, will attenuate and delay peak discharges at the villages and cities downstream.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Antecedent Conditions
ADCP	Acoustic Doppler Current Profiler
API	Antecedent Precipitation Index
CSO	Combined Sewer Overflow
DWD	Deutscher Wetterdienst
ECMWF	European Center for Medium-range Weather Forecasts
FEWS	Flood Early Warning System
G2G	Grid to Grid
genRE	generalized REgionalisierte Niederschlaege
GEV	Generalized Extreme Value Theory
HBV	Hydrologiska Byråns Vattenbalansavdelning
IC	Infiltration Capacity
IHMS	Integrated Hydrological Modelling Systems
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological Institute
KSHF	horizontal saturated conductivity fraction
NASA	National Aeronautics and Space Administration
PTF	Pedo Transfer Function
Q-H	Discharge and Stage
RC	Runoff Coefficient
REGNIE	REgionalisierte NIEderschlaege
RWZI	Rioolwaterzuiveringsinstallatie
SBM	Simple Bucket Model
SPW	Service Publique Du Wallonie
STOWA	Stichting Toegepast Onderzoek Water
TOPKAPI	TOPographic Kinematic APproximation and Integration
TOPOG	Topography
UTC	Coordinated Universal Time
WOW	Weather Observation Website
WWA	World Weather Attribution

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1 Introduction

1.1. Flash Floods

Flash floods are a major concern in hydrology and natural hazard science due to their high potential of causing fatalities and damages (Marchi et al., 2010). Flash floods are caused by short, high-intensity rainfall and characterized by a flood event happening within six hours of the onset of precipitation. As such they usually impact basins less than 1000 km^2 in size (Marchi et al., 2010, Blöschl et al., 2015). The extremely rapid response times of a flash flood pose a major challenge to water management and early warning systems (Brauer et al., 2011). This rapid response, the moment at which overland flow is initiated, is usually aggravated by steep slopes, saturated soils and/or impermeable surfaces (Norbiato et al., 2008). Hence, these floods are not only the result of high-intensity rainfall in small basins, but also topography, antecedent conditions and geology are major factors.

The topographic relief promotes fast stream flow concentration and determines the susceptibility to flooding by slope and relative channel length (Marchi et al., 2010). The importance of the initial hydrological state for the flood response and the impact of the initial wetness on the event runoff coefficients has been shown in many papers (Brauer et al., 2011, Marchi et al., 2010, Norbiato et al., 2008, Borga et al., 2008, Blöschl et al., 2015). Even in extreme flash flood events the initial soil moisture conditions still influence the response (Marchi et al., 2010).

Next to climate and landscape controls, often geology is an additional factor determining the catchment response dynamics (Vannier et al., 2016, Merz and Bárdossy, 1998, Bloomfield et al., 2011, Norbiato et al., 2009). The development of preferential flows governs the rapid response and the bedrock permeability is directly linked to the water storage capacity of the catchment and by that influences the antecedent wetness conditions (Vannier et al., 2016). Especially in small catchments heterogeneity in soil properties is more important than heterogeneity in rainfall for the hydrological response (Nicótina et al., 2008).

Monitoring flash flood events gives the unique opportunity to observe catchment behaviour when most surface and subsurface hydrologic flow paths are active (Borga et al., 2008). Additionally, peak runoff is an important quantity representing the flood magnitude (Blöschl et al., 2015). However, flash floods are typically poorly observed as peak water levels often exceed the range of the measurement devices (uncertainty in rating curves) and/or measurement devices are damaged or destroyed during the flood (Amponsah et al., 2016). A hydrological model using indirect peak flow estimates from post flood surveys can constrain the large uncertainty of the data and by that provides a tool to examine key hypotheses on the flood response in regards to:

- role of antecedent soil moisture conditions on flood response
- role of land-use and catchment properties on runoff generation (Borga et al., 2008)

The understanding of the mechanisms driving the hydrological response of a system, cannot only enhance the understanding of the catchment dynamics, but also provides valuable insights for flood response and mitigation measures and their dependency on catchment characteristics (Marchi et al., 2010).

1.2. Limburg 2021 Floods

In July 2021 an extremely large rainfall event took place in the mid mountain area of Belgium (Ardennes), Germany (Eifel), Luxembourg and the Netherlands (South Limburg). Precipitation amounts of 250 mm in 48 hours were recorded in the core of the rainfall area in Belgium. The event was not only characterized by large 48-hour precipitation sums, but also by the large extent. As can be seen in figure 1.1 an area about the size of the Netherlands received more than 110 mm in 48 hours.
The event was triggered by a slowly moving low pressure system which continuously provided moist air to a wide region. Due to the relief the air was forced to move upwards and caused heavy precipitation in these mid mountain areas (Kreienkamp et al., 2021).

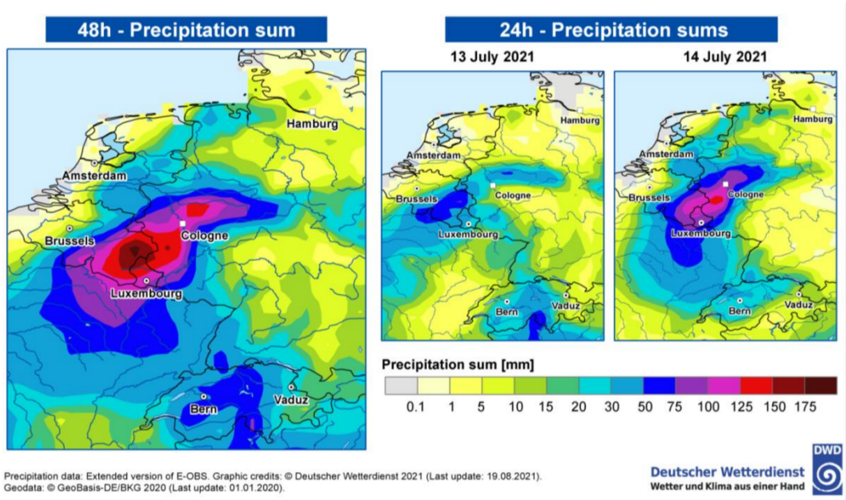

Figure 1.1: 48-hour (13 July 00:00 UTC - 15 July 00:00 UTC) and 24-hour precipitation sums over Central Europe for the extreme precipitation event. The figure is based on an E-OBS data set extended by station data. (Taken from Kreienkamp et al., 2021)

The combination of extreme precipitation, wet antecedent conditions and topography led to severe flooding, high death tolls and damages in the entire region. In Germany and Belgium 239 people died, several villages were demolished and critical infrastructure such as power supply and transport networks were interrupted. The damages for Germany alone are estimated to be about 40 billion Euros (MunichRe, 2022).
In the Netherlands the extreme precipitation as well as the fact that the regional rivers received much water from Belgium and Germany led to high discharges, especially in the river Maas and its main tributaries Geul, Geleenbeek and Rur. The Geul catchment was affected the most as the high precipitation resulted in a flash flood hitting the villages and cities in the valley. Extensive flooding occurred especially in Valkenburg and Meerssen. Shortly after the event, the damages for the Geul catchment were estimated between 100 million and 400 million euros (ENW, 2021). Currently, the damage estimation for Valkenburg alone is 400m€ (Metsemakers, 2021).

According to a study from the World Weather Attribution (WWA) initiative the event was likely influenced by climate change (Kreienkamp et al., 2021). The intensity of summer rainfall in Western Europe has increased 3 - 19% since 1900. The 6th IPCC (International Panel Climate Change) assessment report projects a further increase in extreme precipitation, pluvial and fluvial flooding for Western and Central Europe with high confidence for a 2°C increase scenario (Allan et al., 2021). According to the Royal Meteorological Institute (KNMI), climate change will result in the Netherlands becoming wetter. Rainfall will become more intense, especially in summer months, as a warmer atmosphere can hold more moisture (KNMI, 2021). Therefore it is expected that the frequency, magnitude and impacts of (flash) floods in Europe are increasing in the future (Kreienkamp et al., 2021). This increase is expected to affect especially small catchments (less than 1000 km^2) (Sharma et al., 2018). Furthermore, the Geul river is vulnerable to flooding and erosion (de Moor and Verstraeten, 2008) and climate change effects have already been detected in the main river system and its tributaries (Bouaziz, 2021, Driessen et al., 2010, Tsiokanos, 2022).

1.3. Problem Statement and Research Objective

The Netherlands have a long history of flood protection due to their geographical location in a river delta. The main river systems are well understood and recent improvements in flood protection (e.g. the Grensmaas project) have shown positive effects at the recent flood event in July 2021 (ENW, 2021). However, local river systems (subcatchments of less than 500 km^2 in size) are less well studied and understood so far, and especially in South Limburg the characteristics of these catchments - steeper gradients and a complex hydrogeological system - differ from the typical lowland catchment. Although flash floods can also occur in lowland catchments (Brauer et al., 2011), the majority of flash floods takes place in small hilly or mountainous catchments (Marchi et al., 2010).
The heavy rainfall event in July demonstrated the substantial damage which flash floods can cause in these subcatchments. In Germany (Ahr, Erft) and Belgium (Vesdre) major damage and fatalities have been caused by flash floods in relatively small hilly subcatchments (Kreienkamp et al., 2021). Also in the Netherlands more than 50% of the overall damage caused by the floods can be attributed to the flash flood in the (relatively small) Geul catchment (ENW, 2021).
However, there exists no hydrological model of the Geul catchment which has the capability to project the hydrologic response of the catchment to extreme precipitation events reasonably well (K.-J. van Heeringen, personal communication, 11/2021). This research aims to close this knowledge gap.

The main objective is to gain a better understanding of the catchment hydrology and in particular to investigate the hydrologic response of the catchment to the rainfall event from July 2021. The term hydrologic response refers to the rainfall-runoff relationship as well as to the groundwater response. As part of the research several sub-questions have been formulated.

1. What are the spatial and temporal characteristics of the rainfall and flash flood at the Geul catchment in July 2021?
2. Is it possible to reproduce the hydrologic response of the Geul catchment with any of the existing models? What improvements / changes are necessary to reproduce the event?
3. What role did the antecedent wetness conditions play on the floods in July 2021?
4. What were the individual contributions from the different brooks in the catchment? Are there notable differences in rainfall – runoff relationships between the brooks?
5. What hydrological information can be used to support the decision-making in regard to flood mitigation measures and early warning?
6. Is it possible to determine the effect of land use change on the impact of the flood?

This research aims to contribute to a better understanding of flash floods in South Limburg and especially the Geul catchment itself through a combined approach of data analysis and modelling. A better understanding of the hydrologic response of the catchment together with a fit-for-purpose hydrological model is important to support the decision-making for efficient flood mitigation measures as well as to improve early warning systems for these type of events. From this point of view the outcome of the thesis can be seen as a starting point for a hydraulic analysis of the flood and an impact assessment for the city of Valkenburg.

1.4. Readers Guide

The thesis is structured into six chapters. To begin, in chapter 2 the study area is introduced by describing the topography and climatic conditions. This is followed by a detailed description of the geology and hydrogeology, as these aspects differ from most catchments in the Netherlands. Finally, the subcatchments and the land-use of the catchment is presented. The materials and methods of the research are introduced in chapter 3. To start, the data are explained, followed by a description of the analysis methods used for examining the data sets. In this chapter the choice of the hydrological model is highlighted, and the model itself is presented. At the end, the adjustment methodology and the scenario selection are explained.
In chapter 4 the results of the data analysis and the modelling exercise are presented. First, the rainfall, discharge and groundwater data analyses are shown to gain a better understanding of the catchment

and the characteristics of the (flash) flood. Then, the results of the adjusted model and the reproduced flood event are presented. Finally, the impact of different scenarios on the event is described. Chapter 5 discusses the implications from the data analysis and the modelling study. Additionally, the limitations of the wflow model are reviewed. In the final chapter, the key findings are summarized and the research questions as presented in the introduction are answered. Recommendations for further research are given.

2
Study Area

The river Geul is an important tributary of the river Maas with a catchment size of 340 km^2. The catchment is partly located in Belgium (Walloon Region - 42%), where the Geul originates in Lichtenbusch, the Netherlands (South Limburg - 52%) and Germany (6%). After 56 km the Geul joins the Maas north of Maastricht (de Moor et al., 2008).

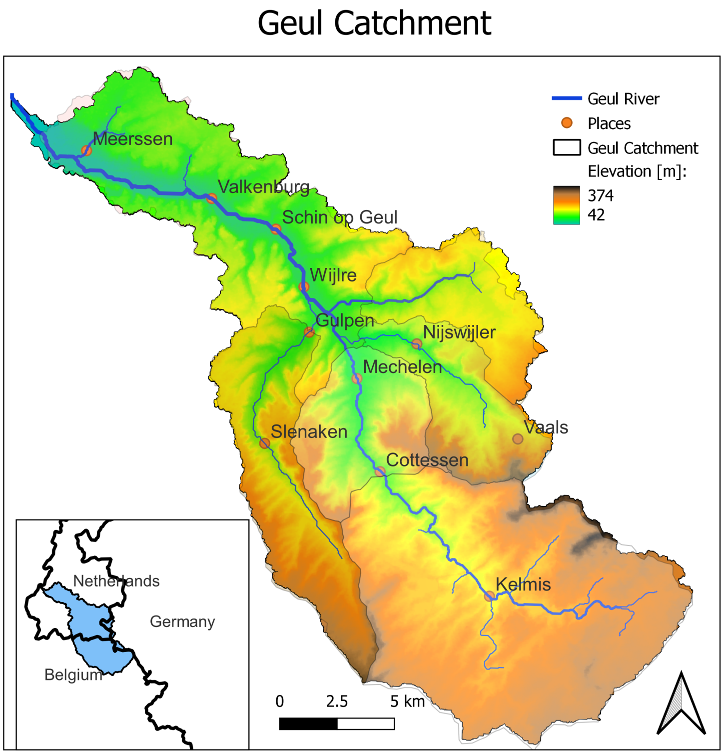

Figure 2.1: Elevation map of the Geul Catchment

2.1. Topography

Figure 2.1 shows the extent and topography of the catchment. The landscape in South Limburg can be characterized as a typical hilly landscape with altitudes ranging from 50 - 400 metres (de Moor and Verstraeten, 2008). In the Dutch part of the catchment, the Geul valley is deeply incised into the surrounding plateaus and has an asymmetric shape with steep slopes on the eastern and more gentle slopes on the western side. In the Belgian upstream area, the catchment is situated on a plateau and slopes are less steep. The slope in the upstream area is 0.2 m/m and 0.0015 m/m at the outlet (van den Munckhof, 2020). With an average slope of 3% the Geul river is a fast-flowing river by Dutch standards and is one of the few rivers without a stabilized riverbed which is able to meander through the landscape (Westeringh, 1980, van Heeringen et al., 2022). The river is fed by more than hundred small streams along its trajectory.

2.2. Climate and Hydrology

The average discharge of the Geul is approx. 2.8 m^3/s, however as the Geul is a rain-fed river the discharge is highly variable ranging from 1 m^3/s during dry periods to more than 40 m^3/s after a storm event (1/5 years return period). Based on the Koeppen-Geiger climate system the catchment is situated in the temperate oceanic climate (cfb) which is characterized by no significant differences in rainfall between the seasons. The annual average rainfall is ranging from 720 mm (Meerssen) to 940 mm (Vaals), with the highest values recorded in August (90 mm/month) and the lowest in April (45 mm/month). The annual average precipitation is 620 mm (2000 - 2020) based on Maastricht-Beek station and the annual discharge is 260 mm. The average seasonal cycles of precipitation, potential evaporation and discharge are visualized in figure 2.2. While the rainfall intensity is the highest in the summer months, the winter is the usual flood season, when the discharge of the Geul is the highest. These high discharges are caused by any combination of (relatively) high precipitation, wet antecedent conditions, snow melt and low evapotranspiration. The runoff is more or less evenly distributed throughout most of the year due to the groundwater storage provided by the extensive chalk aquifers in the catchment (Tu, 2006).

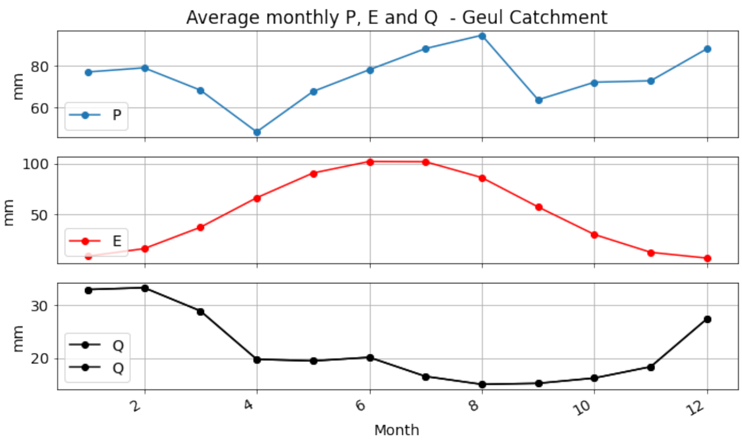

Figure 2.2: Top: Average monthly precipitation in the central part of the catchment (based on KMNI rain gauge 980 in Epen). Middle: Average monthly potential evaporation (Makkink) from Maastricht-Beek weather station. Below: Average monthly discharge measured near the catchment outlet in Meerssen. All data is based on average values from 2000 - 2020.

Figure 2.3 shows the location of the Geul catchment on the Budyko plot with a runoff ratio of 0.32 and an evaporative index of 0.6. The Geul catchment plots in the framework as an energy-limited catchment meaning that the evapotranspiration is limited by energy and not by water.

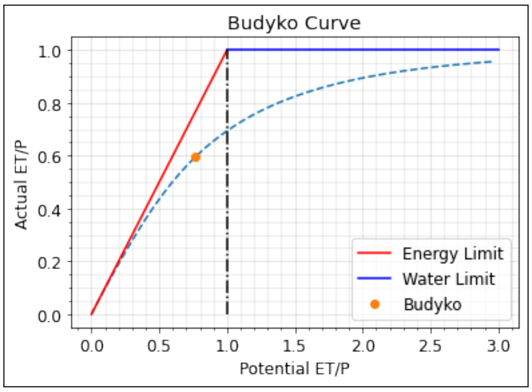

Figure 2.3: The position of the Geul catchment on the Budyko plot based on average catchment rain and discharge (Meerssen) data from 2000 - 2020

2.3. Geology

The geology of South Limburg differs greatly from the geology of the rest of the Netherlands and plays a major role in the runoff generation process of the Geul catchment. Geologically the area belongs to the northern extensions of the Ardennes and Eifel mid mountain range, and consists of rock deposits from the periods visualized in figure 5.1. The oldest rock deposits date from the Carboniferous and are nearly impermeable layers of sand- and claystone and coal. The Perm, Trias and Jura deposits are completely eroded (Hendrix and Meinardi, 2004). When during the Upper Cretaceous the sea-level was rising, first the shallow marine deposits of the Aken (coastal swamp, clay and sand) and Vaals Formation (shallow marine fine sand and clay) and later deep marine chalk of the Gulpen and Maastricht Formation were deposited. In the Quaternary, the river eroded deeply into the deposits and formed the deep valleys which characterize South Limburg today. During the last two ice-ages, aeolian loess was deposited with a thickness ranging from 1 m to 15 m (Hendrix and Meinardi, 2004). The existence of numerous faults in the area ensures a high vertical permeability between the different layers (Schaminée et al., 2009).

Era	Period	Millions of years ago
Cenozoic	Quaternary	0 – 1.6
	Tertiary	1.6 - 66.4
Mesozoic	Cretaceous	66.4 - 144
	Jurassic	144 – 208
	Triassic	208 - 245
Palaeozoic	Permian	245 – 286
	Carboniferous	286 – 320
		360 – 320
	Devonian	408 - 360

→

Era	Period	Formation
Mesozoic	Cretaceous	Maastricht
		Gulpen
		Vaals
		Aken
	Jurassic	eroded
	Triassic	eroded

Figure 2.4: Geological timescale including eras, periods, ages and formations present in the Geul catchment

2.4. Hydrogeology

Like the geology the hydrogeology is also different compared to a typical Dutch catchment in the lowlands. The whole catchment has impermeable carboniferous rocks at its base and three main water bearing aquifers: Aken, Vaals and Gulpen formation. These formations can be described as dual porosity and dual hydraulic conductivity media. The flow through the fractures shows a quick response to precipitation, while the porous flow shows a slow response (Hendrix and Meinardi, 2004). The topsoil in the catchment can be defined as fine clay soil (aeolian loess), which is quickly saturated. The infiltration capacity at the soil has been determined to be 18 mm/hour at agricultural land, 42 mm/hour

at grassland and 2-5 mm/hour at loess grounds (Wageningen, 1988). Hortonian overland flow is not common in the Geul catchment. It has been observed on arable land, but not much in forests and grass land as most of the water infiltrates. The unsaturated zone consists of the loess on top, clay and sand layers of the Quaternary and chalks below (Hendrix and Meinardi, 2004). It is more than 40 metres thick in some areas.
In terms of hydrogeology, the catchment can be divided in four different zones (zone 3-6) based on the Dutch Groundwater Model (Schaminée et al., 2009). The different zones are visualized in figure 2.5 and will be explained in more detail below. The geohydrology of the Belgian part of the catchment will be discussed thereafter.

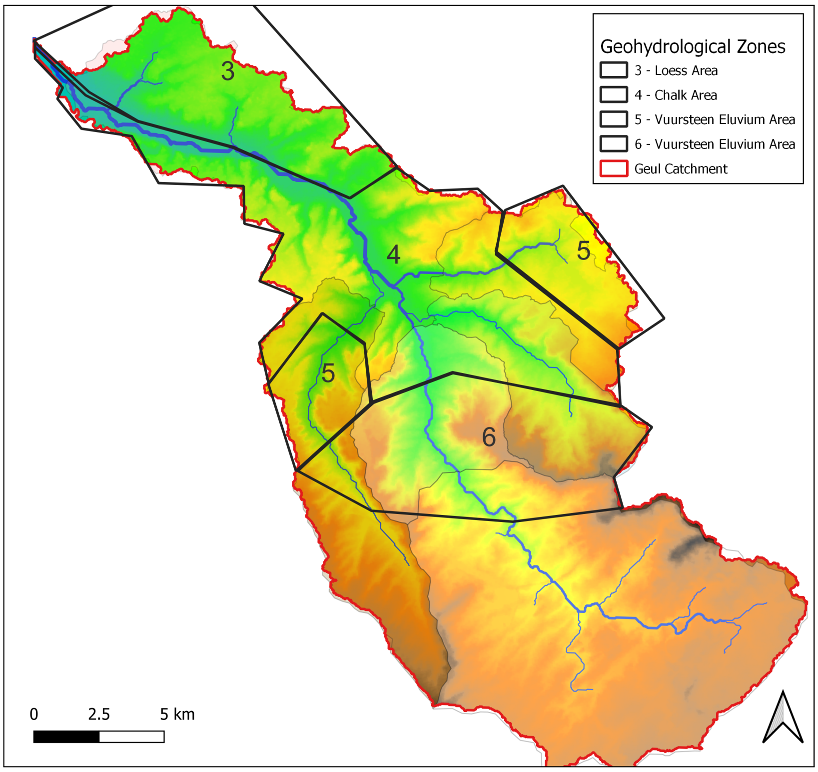

Figure 2.5: Geul catchment map visualizing the distribution of the geohydrological zones present in the catchment. Geohydrological zones are based on the Dutch Underground Model REGIS (Schaminée et al., 2009).

The differentiation of the zones is based on the different deposits which the river cut into at the valley beds and flanks as these determine the geohydrological characteristics of the area [24].

- **Zone 3:** Loess Area: Oligocene and Miocene deposits at the flanks of the valley
- **Zone 4:** Chalk Area: Chalk deposits at the flanks and under the river bed of deep valleys
- **Zone 5:** Vuursteen (Flint) Eluvium Area: Vaals Formation is cut into at the valley
- **Zone 6:** Vuursteen (Flint) Eluvium Area: Aken and Vaals Formation at the flanks of deep valleys

Zone 3: This zone is characterized by medium to low permeability deposits from the late Cretaceous, which act as a thick unconfined aquifer. The groundwater flow is very slowly moving laterally through the sand layers, and only slowly entering the clay layers. Most groundwater comes to surface at the hill slopes, sourcing the numerous springs in the area. Only a small amount of water reaches the underlying chalk aquifer (Schaminée et al., 2009). This zone is found at the lower eastern part of the Geul valley.

Zone 4: Zone 4 is characterized by a thick chalk layer, which is cut through by the river in the valley as shown in the cross-section of figure 2.6. The chalk formations can be considered as one water bearing zone which is very heterogeneous with high and low permeability zones. The flow velocity of the groundwater is large, because of preferential flow through the karst system (Schaminée et al., 2009).

This area functions as an infiltration area. The storage capacity of these chalk plateaus is high, because of the large thickness of the chalk layers indicated in figure 2.6 with orange (Maastricht Formation) and red (Gulpen Formation). This zone can be found in the western part of the Geul valley, as well as in the Eyserbeek and Selzerbeek tributaries.

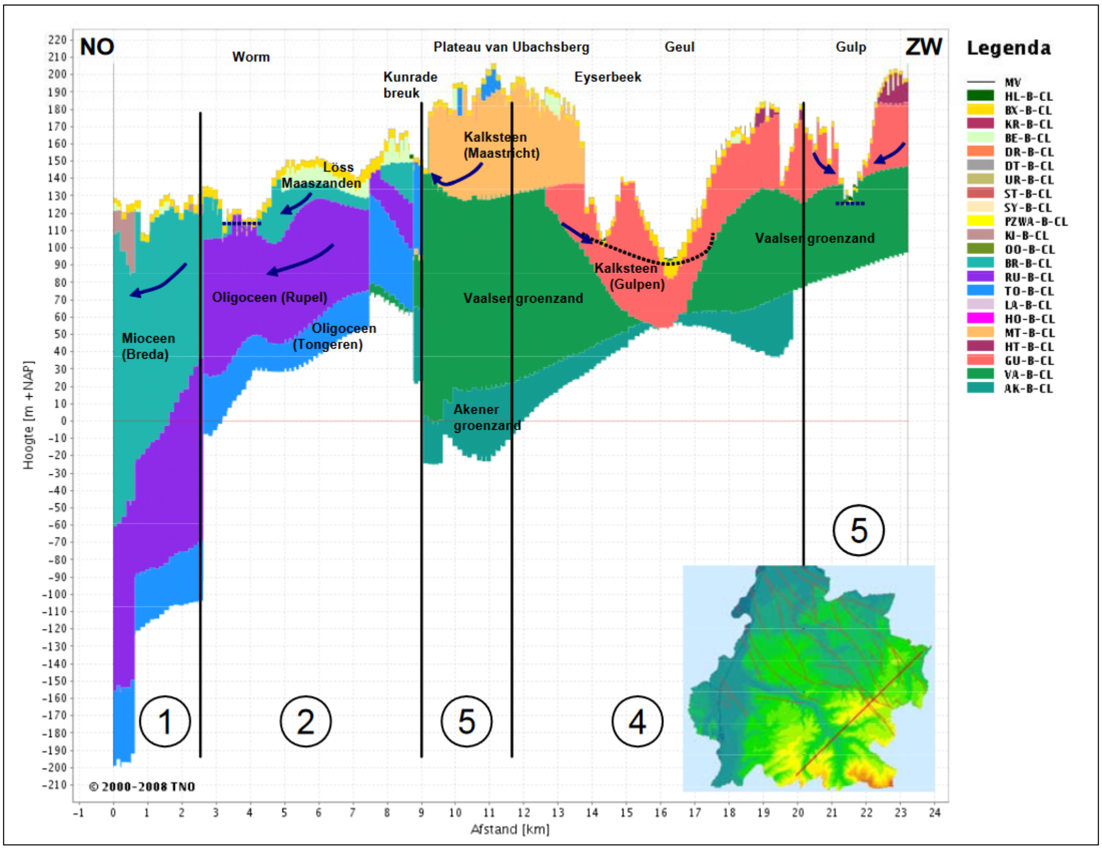

Figure 2.6: Cross Section depicting several geohydrological zones based on the Dutch Underground Model REGIS in South Limburg. The Eyserbeek, Geul and Gulp catchments are shown by a NE-SW cross section upstream of Gulpen representing Zone 4 and 5. Zones 1 and 2 are not present in the Geul catchment. (Taken from Schaminée et al., 2009.)

Zone 5: The riverbed lies in the low to medium permeability Vaals Formation and the slopes cut into the chalk formations. The groundwater at the chalk plateaus, which is about 30 - 50 m below surface, is recharged by precipitation. As visualized by the cross-section in figure 2.6, the water from the chalk plateaus is drained laterally on top of the Vaals Formation into the valley. These areas are characterized by many springs and provide a constant flow to the river, especially in dry periods (van Heeringen et al., 2012, van Lanen et al., 1996). The Gulp valley and the upstream part of the Eyserbeek belong to zone 5.

Zone 6: In this zone the Aken and Vaals Formations are located so close to surface that they are cut into by the flanks of the valley. Both formations are characterized by low permeability. However, due to the high heterogeneity of the permeability the groundwater velocity varies from low to very high. As there is a much thinner chalk layer on top, the storage capacity is much lower and consequently, the system reacts stronger to rainfall (Schaminée et al., 2009). Zone 6 can be found in the upper part of the Dutch Geul, between Epen and the border, as well as at side tributaries of the Selzerbeek.

Belgian Upstream Area: On the Belgian side of the catchment the geohydrological system is similar to zone 6 of the Dutch part. The cross section of figure 2.7 visualizes that the river Geul cuts into the impermeable carboniferous base rock (light blue), resulting in no storage capacity in the river valley and limited storage at the slopes. The system consists of three water bearing aquifers: the formations of Aken, Vaals and Gulpen. Due to its low permeability in the order of 0.1 - 0.9 m/day the Vaals Formation is often not considered as an aquifer and is seen as a barrier between the other two; which have a permeability ranging from 1 - 20 m/day. On the plateaus, karstic phenomena are observed, which act as preferential infiltration points into the aquifer (Ruthy and Dassargues, 2009).

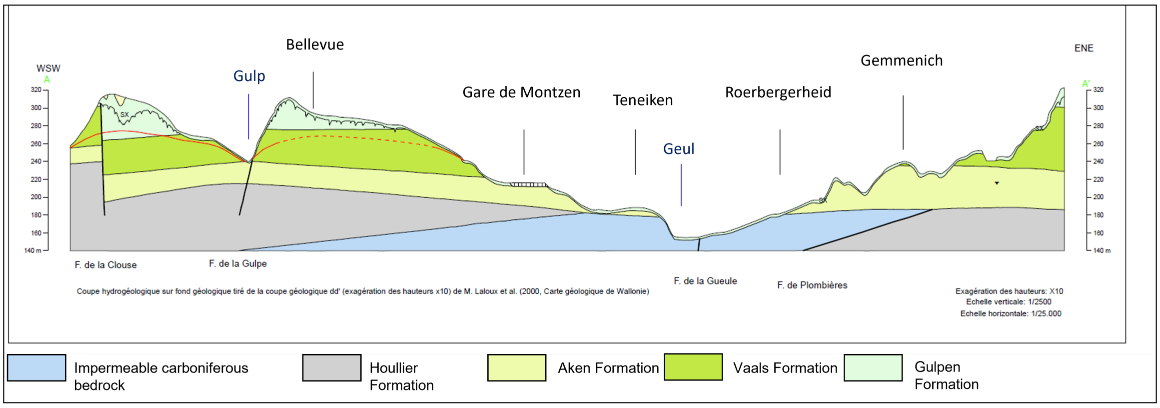

Figure 2.7: Geological Cross Section from west-southwest (WSW) to east-northeast (ENE) through the Belgian part of the catchment showing the Gulp and Geul. (Taken from Ruthy and Dassargues, 2009)

Figure 2.8 shows the average groundwater levels in the catchment. The groundwater table differs greatly within the catchment. At the chalk plateaus it is between 30 - 60 m below surface, while in the valleys it ranges from a few meters to a few decimeters below surface (Ruthy and Dassargues, 2009). The groundwater table at the slopes is somewhere in between. Especially at the chalk plateaus the groundwater table fluctuates strongly during the year (up to 5 - 10 m), with high water levels in the winter-spring time and low water levels in summer - autumn. Groundwater extraction in the catchment is limited due to the deep groundwater level and is only permitted for agricultural purposes at eight places within in the catchment. (No permit is needed is for groundwater extractions with a maximum of 10 m^3/hour.) Additionally, groundwater is extracted at the beer brewery in Gulpen (B.V. Gulpener Bierbrouwerij - 136800 m^3/year) and at a sport field in Vaals (2500 m^3/year).
The catchment boundaries do not fully coincide with the groundwater flow system. Groundwater leaving the catchment to use a more direct flow path to the Maas has been observed in the western part of the catchment (Gulp tributary), and is suspected on the eastern part of the catchment (Selzerbeek and Eyserbeek tributaries) as well (van de Westeringh, 1979, van Lanen et al., 1996, Ruthy and Dassargues, 2009, Agor, 2003, Dautrebande et al., 2000).

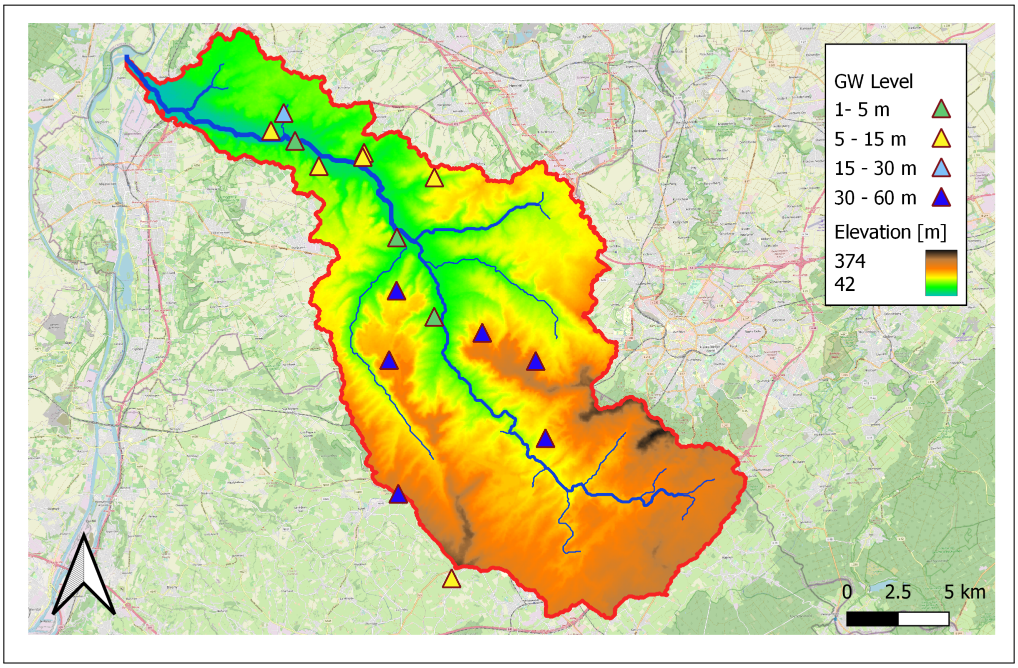

Figure 2.8: Average groundwater levels in metre below surface

The different geohydrological zones with their different abilities to store water can be seen back in the drainage pattern of the Geul valley (see figure A.2). The drainage pattern is well developed in the upstream part of the catchment, with a drainage density of about 13.5 m/ha (Winden, 2022), indicating a quick hydrological response with high peak discharges (Pallard et al., 2009). On the contrary, the drainage pattern of the lower Geul catchment as well as of the Eyserbeek, Selzerbeek and Gulp tributary are poorly developed. The rivers consist of only the main branch and consequently the areas have an average drainage density between 4 m/ha and 5.6 m/ha (Winden, 2022). The pattern indicates that there is limited overland flow, but a good infiltration and storage capacity (Pallard et al., 2009). This is also confirmed by a study which determined the hydraulic conductivity of the upper 50 cm to be around 0.5 - 4 m/d in that area (Wageningen, 1988). The drainage density can be seen as an index of geology (Pallard et al., 2009, Bloomfield et al., 2011). In this case the low drainage density can be linked to the karstic area, which implies large storage volumes and response times and hence small flood peaks and volumes (Pallard et al., 2009).

2.5. Subcatchments

The catchment is commonly divided into six subcatchments based on the discharge stations by the Waterboard Limburg (excluding Schin op Geul). This division will also be used for this research. The six subcatchments consist of the three main tributaries of the Geul: the Gulp, Selzerbeek and Eyserbeek, as well as three sections along the Geul: Sippenaeken, Hommerich and Meerssen. Figure 2.9 shows the location and extent of the six subcatchments and illustrates that the three tributaries all join the Geul in relative proximity to each other at Gulpen.

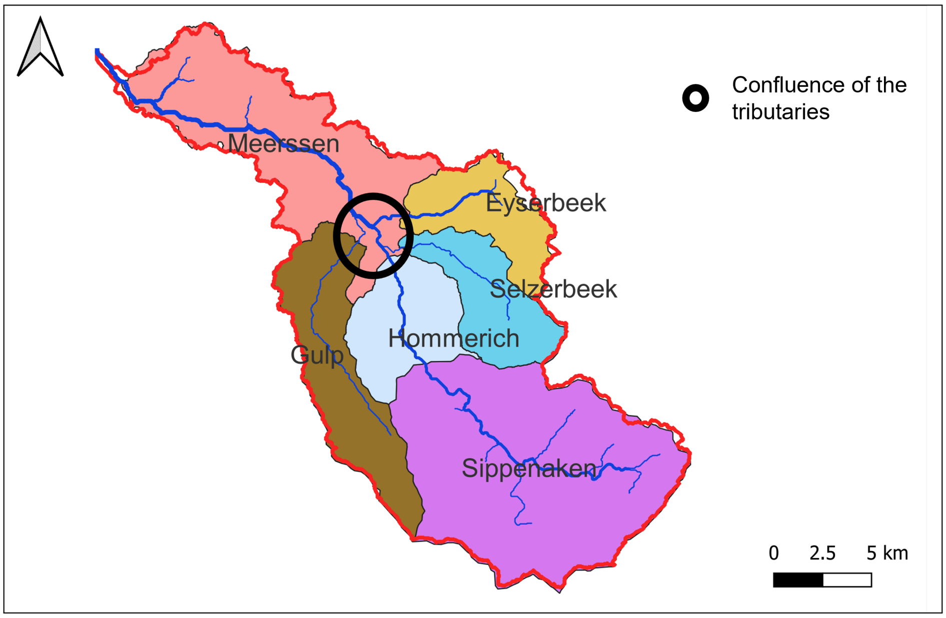

Figure 2.9: Subcatchments of the Geul catchment

Table 2.1 gives a first overview on the different characteristics of the subcatchments. The slope of the Geul and its tributaries are visualized in figure A.1.

Table 2.1: Overview of the characteristics of the subcatchments of the Geul. Response times based on van Heeringen et al., 2012, Dautrebande et al., 2000. Groundwater thickness based on Schaminée et al., 2009, Wageningen, 1988, Ruthy and Dassargues, 2009.

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

The travel time of the water along the Geul during high discharges is 2-3 hours from Kelmis to Cottessen, 5-7 hours from Cottessen to Valkenburg and 5-7 hours from Valkenburg to Meerssen (H. Pavelkova, personal communication, Jun/2022).

Gulp
The Gulp is the largest tributary of the Geul and can be characterized as a typical chalk catchment. The catchment has an elongated shape of 46 km^2. While the river is of 18 km length, the maximum width of the catchment is only 4 km. The Gulp originates at Henri-Chapelle in Belgium and joins the Geul at Gulpen after having dropped about 200 m in elevation (285 m - 88m), which translates to an average slope of 12 m/km. Like the Geul also the Gulp has a very asymmetric valley shape. The slope in the east is 17%, whereas it is 5% in the west. 45% of the catchment is in the Netherlands.
The Gulp catchment belongs to Zone 5 and 4 as described in section 2.4 and is therefore characterized by a high water storage capacity in its thick groundwater aquifers (40 - 100 m) and a high base flow of

up to 85% (Wageningen, 1988). The soil in the Gulp valley has a good infiltration capacity; experimental research confirmed that surface runoff and inter flow rarely occur (van Lanen et al., 1996, Nota and Weerd, 1978). Loess is the main soil cover, but it is very thin occasionally (Notebaert and Verstraeten, 2008). Groundwater is lost to the neighbouring Voer and Vuers catchment (van Lanen et al., 1996).

Eyserbeek
The Eyserbeek can be considered as a small mountain stream with a length of approx. 12 km and an average slope of 5.9 m/km. The catchment has a size of 27 km^2 from which 83% are situated in the Netherlands. Hydrogeologically the most upstream part belongs to zone 5 where the Eyserbeek cuts into the Vaals formation, while the majority of the subcatchment can be counted to zone 4. The high storage capacity of the unsaturated zone (40 - 100 m) and soil is contrasted by the high urbanization in the subcatchment. The Eyserbeek originates in an urban environment in the city of Bocholtz. It is canalized in the upstream part and flows through a densely populated region. Downstream the river becomes more natural.
Due to the high amount of paved surface area in the upstream part of the catchment, the river shows a flashy behaviour with short response times and high peak discharges. Discharges have high fluctuations between 0.026 m^3/s and 10 m^3/s. The average discharge is 0.11 m^3/s.

Selzerbeek
The Selzerbeek is another important tributary. It originates in Germany and after 14.5 km and an average slope of 10 m/km it joins the Geul at Partij. The catchment has a size of 27 km^2 of which 82% is situated in the Netherlands. Upstream the river cuts into the Aken Formation and hence can be described as zone 6. Downstream it cuts into the Vaals Formation and is characterized by zone 4 and a thick unsaturated zone (40 - 100 m) (Wageningen, 1988). The low storage capacity (10 - 20 m) in the upstream parts leads to a flashy response with short response times and high peaks, although less pronounced compared to the Eyserbeek. The discharge can vary between 0.02 m^3/s and 6 m^3/s. The average discharge is 0.15 m^3/s.

Sippenaeken
The Belgian part of the catchment has a size of 123 km^2 and has two discharge stations along the Geul - Sippenaeken (123 km^2 upstream area) at the border to the Netherlands and Kelmis (80 km^2 upstream area) in the interior of the catchment. The whole area is characterized by thin soils and low storage capacity (0 - 20m) and a flashy discharge behaviour with response times between 2-4 hours to rainfall. In contrast to the central part of the Geul valley which is deeply cut into the chalk plateaus, the upper part of the catchment is more flat and urbanized.

Hommerich
The most central section of the Geul is from the Belgian border until Hommerich. Although the smallest section only covers 12 km of the Geul and has a catchment size of 31 km^3, it is characterized by the change in geology and geohydrology. At Mechelen the Geul starts to cut into the chalk area, which represents the change from the hydrogeological zone 6 to zone 4. This results in a different drainage pattern and a much higher storage coefficient compared to the area upstream of Mechelen (Paarlberg, 1990).

Meerssen
The lower Geul valley ranges from Hommerich to Meerssen, covering a long stretch of the river of 24.5 km. The downstream Geul is geohydrologically represented by zone 4 in the western and zone 3 in the eastern part of the catchment. Due to its high infiltration capacity, the area downstream of Valkenburg until Meerssen hardly contributes to the flow of the Geul, only 0.2 - 0.3 m^3/s on average (van Heeringen et al., 2008). Furthermore, in the most downstream part of the catchment (from the Maas confluence up to Meerssen) the Geul is influenced by the water level of the Maas.

2.6. Land-use

The catchment changed substantially in the 20th century (Dautrebande et al., 2000). As the population increased, the originally meandering river courses were straightened and the land-use changed from grasslands to more farmland. The agriculture was intensified and new crops such as maize were introduced (Tu, 2006). At the beginning of the 21st century, as a reaction to the major floods in the Maas 1993 and 1995, the river was given more space again and is nowadays meandering more freely outside of the cities and villages again (de Moor et al., 2008). Due to the fertile loess grounds, the catchment has always been an area for agricultural activities and is relatively densely populated (de Moor et al., 2008). Based on the Corine Land cover Map from 2018 (see figure A.4) the greatest catchment area is used for agriculture (41.5%), followed by pastures (27.5%), urban areas (17%) and forests (13%). The land-use is strongly determined by the slope. It is mainly grassland in the river valley, a mixture of grass and arable land on the gentle slopes (0 - 20°), forest on steep slopes (>20°) and predominantly arable land on plateaus (de Moor and Verstraeten, 2008). Urban areas of greater extent are situated around Kelmis, in the Eyserbeek tributary, as well as around Valkenburg and Meerssen.

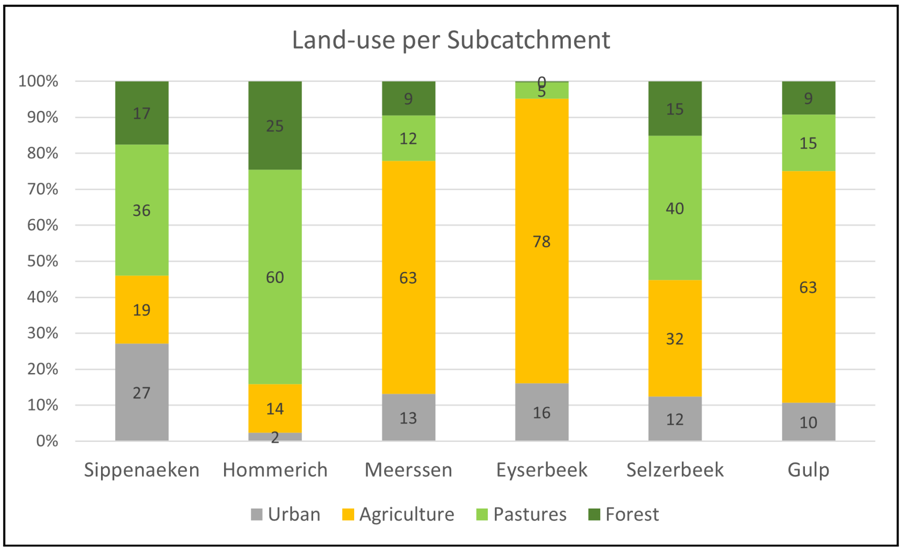

Figure 2.10: Distribution of urban, nature, pastures and agriculture areas in the subcatchments based on an aggregated Corine Land Cover Map of 2018 (see table A.1)

From figure 2.10 it can be seen that the overall percentage of urban, nature, agriculture and grassland area varies quite substantially between the subcatchments. Comparing Sippenaeken to the other sub-catchments, the Belgian part is much more densely populated than the Dutch part of the catchment. However the Belgian part also consists of a considerable amount of forest which is only topped by the Hommerich subcatchment in the Netherlands. The Eyserbeek catchment on the other hand, has no natural areas. It is also the most urbanised catchment in the Dutch part. Agriculture and pastures are the dominant land-use type in all subcatchments varying from 55 to 83%. Pastures are dominant in the upstream catchment (Sippenaeken, Hommerich and Selzerbeek), whereas arable land is dominant downstream.

As typical for a medium scale river catchment, the Geul catchment serves several functions, such as providing ecological environments, local drinking water reservoirs and flood retention areas (de Moor et al., 2008). Tourism plays a major role for the cities and villages in the valley, especially for Valkenburg.

2.7. Water Retention Basins

More than 400 water retention basins have been built in the past years, and more are planned by the Watershap Limburg to protect urban areas against flash floods caused by local short heavy rainfall events (van Heeringen et al., 2022). Most basins have been built in the tributaries, dry valleys (valleys without a stream) and on the slopes in higher areas of the catchment (van Heeringen et al., 2022). Older basins were designed based on a 20-minute rainfall with intensity of 90 mm/h, whereas newer basins are designed for a 2-hour rainfall with intensity of 47 mm/h.This translates to a 1/25 years return period. The standard, without any automated control systems, can discharge the retained water within a day (van Heeringen et al., 2022). Only the large water retention basins such as in Nijswijler (62,550m^3) and

Rolduckerweg (84,000m^3) are automatically controlled. Besides protecting the houses a secondary benefit is the slowing down of the water before entering the stream.
However, the role of the retention basis for longer rainfall events has not been analysed in detail. They might cause disadvantageous effects in case they are full and spill over at the wrong moment.

Table 2.2: Overview of water retention volumes and percentages per subcatchment

Subcatchment	water retention volume [m^3]	Percentage of total volume [%]
Eyserbeek	239,253	30%
Meerssen	305,633	38%
Gulp	56,131	7%
Selzerbeek	154,184	19%
Hommerich	45,844	6%
Sippenaeken	0	0%
Total	**801,045**	**100%**

Table 2.2 shows that the water retention basins are not evenly distributed throughout the catchment. While Meerssen has exactly the storage volume in relation to its relative size (38%), Eyserbeek and Selzerbeek have much more retention volumes compared to the Gulp and Hommerich, which is linked to the fact that the last two are less densely populated and therefore less neighbourhoods are in danger of flooding. In the Belgian part of the catchment no water retention infrastructure exists (N. Feltz, personal communication, Jun/2022).
On top of the retention water basins also the extensive floodplains function as buffers, especially upstream and downstream of Valkenburg . These flood plains are 200 - 400 m wide, and are a very dynamic natural storage. When the floodplains upstream are full, the floodplains downstream are not flooded yet and when the downstream ones start flooding, the upstream parts are empty again (H. Pavelkova, personal communication, Apr/2022).

3

Materials and Methods

The research of this paper is two-fold. First, the hydrologic response of the catchment is assessed by analyzing the observations made before, during and after the flood. Secondly, the hypotheses drawn from the data analysis are assessed with a hydrological model of the catchment. In section 3.1 the data used for the analysis will be introduced. In section 3.2 the methods are described and in section 3.3 the model concept, forcing data, adjustments and scenarios are introduced.

3.1. Data Analysis

3.1.1. Rainfall Data

Station Data

Rainfall data from 13 stations has been used. The Dutch part of the catchment is covered by five manual rain gauges from KNMI (Ubachsberg, Epen, Vaals, Valkenburg and Noorbeek, which is just outside the catchment boundaries) as well as the weather station in Maastricht. The KNMI rainfall stations only record daily values, therefore hourly data from the WOW station in Mechelen and from four stations of the Waterboard Limburg (Ransdall, Maastricht, Vaals, Noorbeek) have been used for the precipitation analysis of the July 2021 event. Additionally, hourly data was used from the SPW rainfall station in Gemmenich (Belgium) and from the DWD station in Aachen-Orsbach (Germany).
All stations are displayed in figure 3.1. The downstream part has a better coverage of rain stations, compared to the upstream part. For more information on the location, data frequency, data availability refer to table B.1.

Radar Data

KNMI published a re-analysis product for the event, which used the data from numerous rain gauges in Germany, Belgium and Netherlands for the adjustment of the radar rainfall data. This reanalysis was necessary as the real time radar underestimated the rainfall amount by a factor 2 - 3, due to a number of effects, such as the orographic enhancement effect (Overeem and Leijnse, 2021). The final reanalysis product is used complementary to the rainfall stations in the data analysis. The full description and methodology is described in their report (Overeem and Leijnse, 2021). For the Geul catchment all rain gauges, with the exception of the Mechelen station, have been used to adjust the real-time radar to (Overeem and Leijnse, 2021).

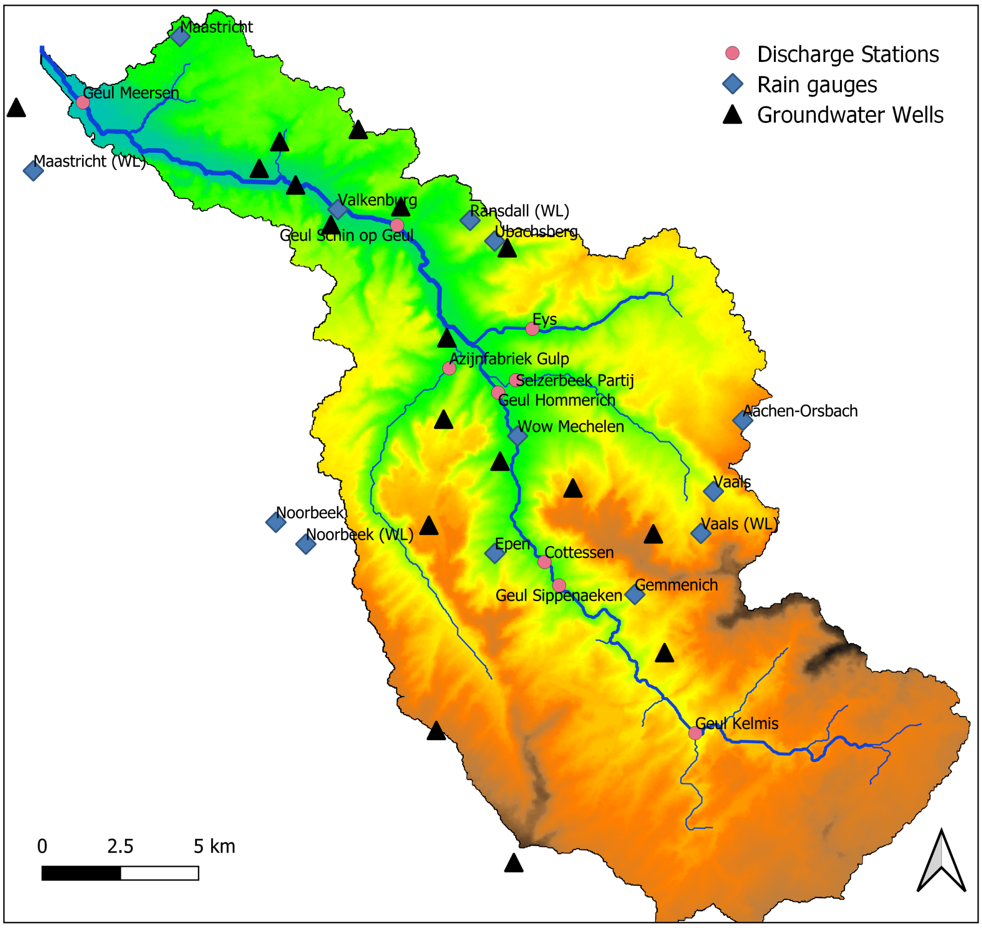

Figure 3.1: Spatial distribution of rainfall, discharge and groundwater measurements in the Geul catchment

3.1.2. Discharge Data

Data from 10 discharge stations has been used and analysed. Six stations measure discharge along the Geul (two in Belgium and four in the Netherlands) and four stations are situated at the three main tributaries the Gulp, Selzerbeek (two stations) and Eyserbeek. The locations of the discharge stations are indicated on figure 3.1.

An overview of the discharge stations is presented in table 3.1. Discharges are measured by three principles: ADCP (Acoustic Doppler Current Profiler), measurement weirs and rating curves. The measurement uncertainty is between 5% and 30% depending on the measurement type and range. In general, the measurement error increases with increasing discharges. This is the case especially for the stations with a stage-discharge relationship. As these relationships have been established based on control measurements which take place by low and medium flows, the established curves are extrapolated for flood events. Furthermore, unsteady flow conditions and seasonal changes in roughness increase the uncertainty (Di Baldassarre and Montanari, 2009, Le Coz, 2012).

Table 3.1: Overview of discharge data of the Geul catchment (Ogink, 2009, de Graaf and Hagedooren, 2021, van der Stappen, 2016)

Station Name	Station ID	Frequency	Type	Data start	Measurement Range
Kelmis		hourly	Q-H relationship	01.01.2002	no data available
Sippenaeken	L6660	hourly	Q-H relationship	13.06.1996	0.165 - 25 m^3/s with 10% uncertainty
Cottessen	10.Q.29	15 min.	measurement weir (meetstuw)	01.08.1991	0.5 - 20 m^3/s with 5 - 15% uncertainty; 20 - 25 m^3/s with 15 - 20% uncertainty
Hommerich	10.Q.30	15 min.	Q-H relationship	01.01.1970	1 - 60 m^3/s with 10 - 30% uncertainty
Schin op Geul	10.Q.63	15 min.	ADCP	17.02.2016	no data available
Meerssen	10.Q.36	15 min.	ADCP	03.09.1969	1 - 55 m^3/s with 5 - 25% uncertainty
Eyserbeek	11.Q.32	15 min.	measurement weir (meetstuw)	01.07.1991	0.01 - 0.08 m^3/s with 10 - 25% uncertainty; <0.08 m^3/s - 7.75 m^3/s with 5 - 15% uncertainty
Selzerbeek	12.Q.31	15 min.	measurement weir (meetstuw)	31.07.1991	0 - 6.5 m^3/s with 10 - 20% uncertainty
Selzerbeek Molentak	12.Q.46	hourly	measurement weir (meetstuw)	01.10.1994	0.1 - 1.0 m^3/s with 5 - 10% uncertainty
Gulp	13.Q.34	15 min.	Q-H relationship	15.04.1972	0.2 - 12 m^3/s with 15 - 25% uncertainty

The discharge measurement in the Eyserbeek is downstream of the discharge of the waste water treatment plant (RWZI), which depends on the water usage in the rural areas and fluctuates between 0 - 0.2 m^3/s (H. Pavelkova, personal communication, Apr/2022). During dry periods, the discharge can be strongly influenced by the wastewater flow. However during high discharge events the flow is negligible and therefore is not shown separately in the analysis. During peak discharges several combined sewer overflows (CSO) discharge into the Eyserbeek and Selzerbeek adding to the flashy behaviour.
The discharge station in Selzerbeek is just downstream of the split off the Selzerbeek Molentak, where periodically water flows through the Molentak (0 - 0.6 m^3/s). For simplicity, the discharge of the Molentak was added to the Selzerbeek discharge station. This way it is ensured that the water balance for the subcatchment is taking all discharges from the valley into account. Therefore, in the remainder of the report, the analysis refers to nine discharge stations. The locations (x and y coordinates) of the discharge stations can be found table B.2.

3.1.3. Other Data

In total 17 groundwater wells have been analysed in the whole catchment. Figure 3.1 shows that similarly to the rain gauges, also the majority of the available groundwater wells is situated in the Dutch part of the catchment. All groundwater data has been available from 2016 until 2021. For a few wells also longer time series were used. The overview can be seen in table B.3. Evaporation data from the Maastricht-Beek weather station has been used. Additionally, evaporation data has been used from the ERA5 reanalysis product (Hersbach et al., 2018). In both cases the Makkink formula has been used (De Bruin and Lablans, 1998).

3.2. Methods

The data analysis begins with a general analysis of the hydrological behaviour of the catchment to better understand the hydrologic response of the catchment to the rainfall in July 2021. The analysis is sketched out in figure 3.2.

Analysis	Methods	Data
Flow Characteristics	Flow Duration Curves Flow Indices Flow Contributions	Discharge
Rainfall – Runoff Relationship	Mean Runoff Coefficient	Discharge Rainfall

Figure 3.2: Overview of the methods and data used for the general analysis of the hydrologic behaviour of the catchment

The flow characteristics are determined based on the average hourly discharge from 2000 - 2020. The methods are explained further in table 3.2.

Table 3.2: Applied methods for the determination of flow characteristics for the subcatchments

Methods	Description
Flow Duration Curve	Cumulative curve that shows the percent of time specified discharges were equaled or exceeded during a given period. It combines in one curve the flow characteristics of a stream throughout the range of discharges, without regard to the sequence of occurrence (Searcy, 1959).
Flow Indices Q90/Q50	The base flow variability index, which describes the relation between low flows (Q90) and the mean base flow (Q50). The greater the value, the greater is the variability of the base flows (Pyrce, 2004).
Q10/Q95	This index describes the relation between the low flow index (Q95) and the high flow index (Q10). Base flow (groundwater) dominated streams have values ranging from 2.5 to 6.5 (Pyrce, 2004).
Flow Variability Index	Also called annual daily flow coefficient of variation. It is calculated as the standard deviation of all daily flow values divided by the mean annual flow. It is a measure for the intra-day variability of a flow (Pyrce, 2004).

Long-term Runoff Coefficients: For the analysis of the rainfall-runoff relationship, the long-term runoff coefficient has been determined for each subcatchment. The coefficient has been calculated by taking

the average of the ratio of the yearly discharge to the yearly precipitation of the last 20 years.
Long-term Flow Contributions: Long-term flow contributions have been evaluated near Gulpen where the three main tributaries join the Geul. Flow contributions have been calculated as monthly averages to show the seasonal differences based on discharge data from 2000 - 2020.

The event of July 2021 is analysed using rainfall, discharge and groundwater data. An overview of the analyses and methods applied is given in figure 3.3.

Analysis	Methods	Data
Rainfall	Time Series Analysis	Rainfall (station and radar)
Flow	Time Series Analysis Gumbel and GEV	Discharge
Rainfall – Runoff Relationship	Event Runoff Coefficients Response Times	Discharge Rainfall
Groundwater	Time Series Analysis Response Times	Groundwater Rainfall
Antecedent Conditions	Time Series Analysis Antecedent Precipitation Index	Rainfall Groundwater

Figure 3.3: Overview of the methods and data used for the event analysis

Return Periods - Precipitation: The return periods have been determined based on the precipitation statistics for water management 2019 from the foundation for applied water research (STOWA) (STOWA, 2019). Based on the location of Geul catchment, the high precipitation regime table is applicable, see figure C.2. Return periods have been determined based on the 48-hour sums (13.7.2021 00:00 UTC - 15.7.2021 00:00 UTC, for KNMI stations values 13.7.2021 8:00 - 15.7.2021 8:00).
Generalized Extreme Value distribution: The discharge return periods have been determined using Generalized Extreme Value (GEV) theory. The GEV distribution is a family of continuous probability distributions and consists of the Gumbel, Fréchet and Weibull distribution, also known as type I, II and III extreme value distributions. The GEV distribution has three parameters: shape, location and scale. The shape parameter defines the type: equal to 0 is Gumbel, larger than 0 is Fréchet and smaller than 0 is Weibull (Gellens, 2002). Extreme value theory is used to estimate the probability of very rare events and has been applied to estimate the return periods of the discharges for all stations with a minimum time series length of 25 years. The return periods are calculated based on the event peak discharges.
Event Runoff: The catchment response is analysed using the event runoff coefficient. It has been determined for the subcatchments, which either had an (almost) full discharge time series of the event, or a reconstructed discharge time series was available. The coefficient is computed by dividing the cumulative discharge from July 13 to July 18, with the areal precipitation of the subcatchment based on the KNMI reanalysis from July 13 to July 15.
Antecedent Precipitation Index: The antecedent precipitation index determines the impact of initial soil moisture condition on the runoff (Marchi et al., 2010). The index is calculated as the ratio of the precipitation 30 days ahead of the event to the long-term 30 days average (year 2000 - 2020) for the same period. The index classifies the initial soil moisture conditions in three classes: dry (<= 0.5), normal (0.5 - 1.5) and wet (>1.5).

3.3. Hydrological Model

3.3.1. Model Selection

A hydrological model can be described as a simplified representation of the complex interactions of hydrological processes in a heterogeneous landscape (Bouaziz, 2021). In this study it is evaluated if a

model, which incorporates the understanding gained through a detailed catchment analysis, is able to reproduce the event of July 2021. In a second step the model is then used to assess how the system would have reacted under different conditions.
As there is a vast number of hydrological models available, the model selection process has been narrowed down by the following criteria:

- lumped / semi-distributed vs. fully distributed model
- model availability
- model support

Although the Geul catchment is a fairly small catchment of 340 km^2, chapter 2 showed that the subcatchments display substantially different characteristics. The hydrological model used by the waterboard Limburg is a semi-distributed HBV-96 (Hydrologiska Byråns Vattenbalansavdelning) model using the software package from IHMS (5.10.1). The current model set up has difficulties to reproduce the distinct characteristics of the subcatchments and does not allow to evaluate the effect of land-use changes, therefore it is considered to replace the semi-distributed HBV model with a fully distributed model (M. Hegnauer, personal communication, Nov/2021).
Following these thoughts a spatially distributed model was selected for this study, as it offers several advantages (Pokhrel and Gupta, 2011, Yu et al., 2014, Schellekens, 2022):

- being able to evaluate the hydrological behaviour of the interior of the catchment
- high resolution data to allow investigation of vegetation and land- use changes
- easiness to link spatially distributed data to the model

Deltares offers a completely distributed modelling platform, called wflow, which aims to maximize the use of physical parameters and meteorological input data. The framework consists of several modelling concepts. For this study the wflow-sbm (simple bucket model) concept was chosen. The wflow-sbm is a conceptual bucket model loosely based on the topog-sbm model by Vertessy (Vertessy and Elsenbeer, 1999). It can be seen as an intermediate model which fits in between low-resolution/ low-complexity and high-resolution/ high-complexity hydrological models. As most of the parameters have a clear physical meaning and represent physical characteristics such as rooting depth and infiltration capacity, the model needs limited calibration in theory. This set up also allows to link the observations from the catchment analysis more easily to model parameters, and adjust them if required.

3.3.2. Model Structure and Set Up

The wflow-sbm model is based on the assumption that topography mostly controls water flow, which limits its use to steep catchments. The kinematic wave approach is used for lateral subsurface and overland and river flow processes similar to TOPKAPI (Benning, 1995, Ciarapica and Todini, 2002) and G2G (Bell et al., 2007, Imhoff et al., 2020). In figure 3.4 the different processes and fluxes of the model are described. Contrary to the original topog-sbm model by Vertessy, several processes have been added: Evapotranspiration and interception losses, a root water uptake reduction function and capillary rise. From the process sketch it can be seen that the vertical processes of the model are split up in different buckets. The model allows to define multiple soil layers, and makes a distinction between the saturated and undersaturated zone. Groundwater processes are represented through the saturated store and the kinematic subsurface flow.

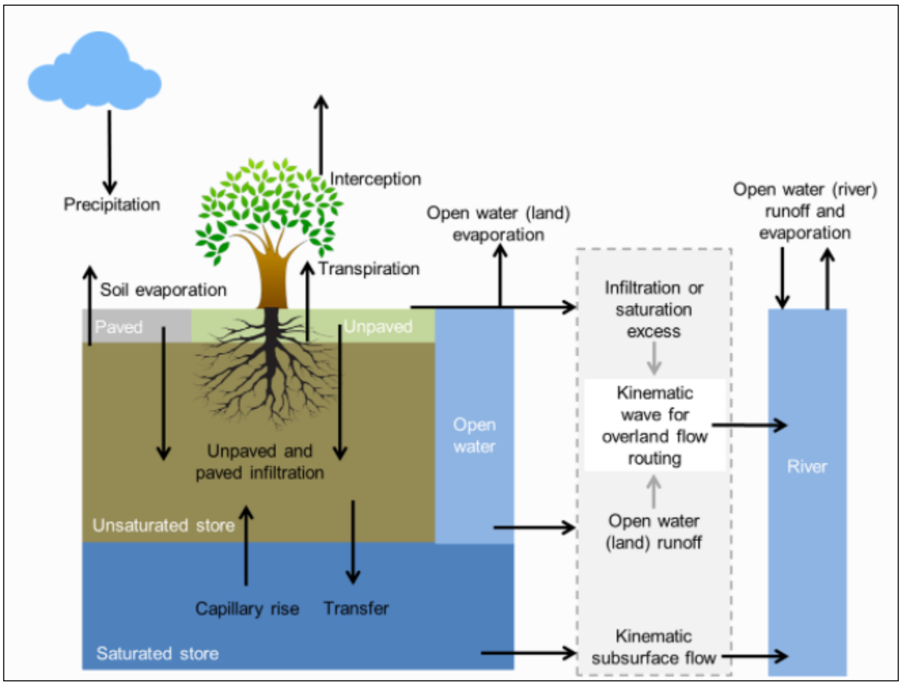

Figure 3.4: Overview of the different processes and fluxes in the wflow sbm model (Schellekens, 2022)

The Geul model has been created from an existing Maas model which is based on the date sets described in table 3.3. HydroMt-wflow, a python package that facilitates building and analysing spatial geoscientific models (Bouaziz, 2020, Eilander and Boisgontier, 2022) has been used for the model set up. The model has been developed for steep catchments and relatively thin soils. Additionally, lateral groundwater flow follows the topography instead of the true hydraulic head. This results in the following limitations of the model:

- channel flow (and to a lesser degree overland flow,) may be unrealistic in flat terrain and in situations where pressure forces and inertial momentum is important
- lateral movement of groundwater may be wrong in flat terrain
- results for deep soils > 2m maybe unrealistic (Schellekens, 2022, Eilander and Boisgontier, 2022)

Many wflow-sbm parameters are derived from the gridded input using point-scale (pedo)transfer functions (PTFs) as described by Imhoff et al. (2020). The remaining parameters are used with a uniform value in the model. All parameters and their values are documented in table B.4.

Table 3.3: Data sets used to set up the wflow-sbm model of the Geul catchment

Category	Data Sets	Resolution [m]	Reference
Soil	Soil Grids	250	(Hengl et al., 2017)
	Depth to impermeable layers for Europe	-	(European Commission, 2015)
Land cover	Corine Landcover Map 2018	300	
LAI	MODIS LAI	500	
Hydrography	MERIT Hydro	90	(Yamazaki et al., 2019)
	Discharge Data from Global Runoff Data Center (GRDC)	-	
	CHELSEA dataset	1000	(Nikolaus Karger et al., 2016)
	Koeppen - Geiger climate zone map	-	(Kottek et al., 2006)

The model of the Geul catchment has been set up with a resolution of 0.00833° (or approximately 600 m x 925 m). The base map of the model is visualized in figure 3.5. The nine discharge stations (Kelmis, Sippenaeken, Cottessen, Hommerich, Gulp, Selzerbeek, Eyserbeek, Schin op Geul, Meerssen) of the Geul catchment have been added to the model. The locations of the discharge stations had to be slightly adjusted to make sure each station is linked to the right tributary (see table B.6). Based on the location of the discharge station, the model determined nine subcatchments based on the digital elevation data.
It runs in hourly time steps to be able to analyse the temporal variations of the discharge during the July 2021 flood.

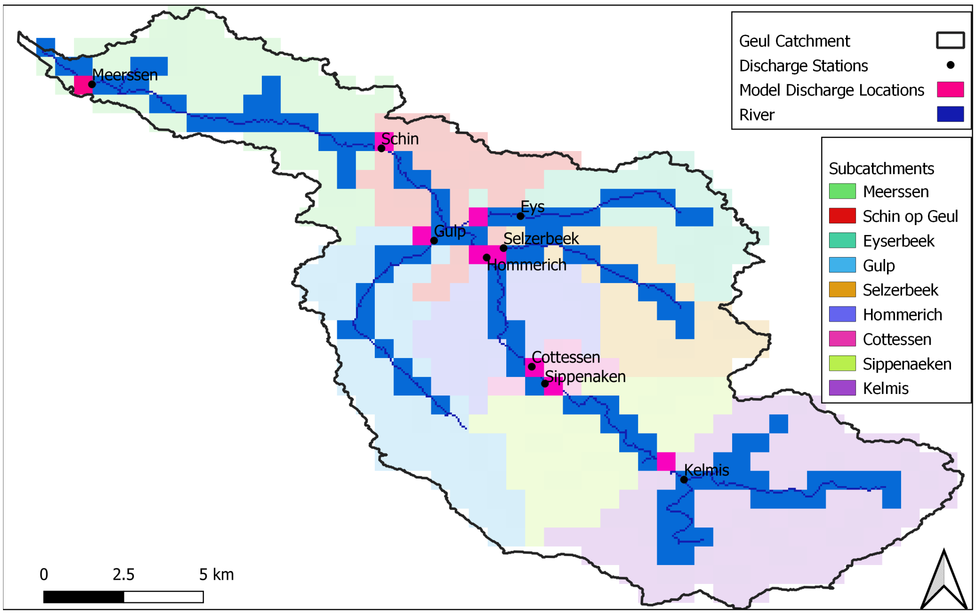

Figure 3.5: Catchment map of the wflow-sbm model showing the river cells, the model discharge locations (pink) and the subcatchments

3.3.3. Forcing Data

The model requires gridded precipitation, temperature and potential evaporation data as input forcing. Since the main objective of the model is to analyse the event in July 2021, the precipitation data is the most critical forcing parameter. For comparison, the model was set up with three different sets of precipitation forcing data.

- **REGNIE Deltares**: The REGNIE Deltares is a gridded precipitation data set using the generalized REGNIE (genRE) interpolation method (van Osnabrugge et al., 2017). The precipitation heights are measured at the stations and are interpolated through the genRe method to a regular grid. The data set has been created through the FEWS (Flood Early Warning System) platform from Deltares.

- **ERA5**: ERA5 is the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis for global climate and weather. The original 0.25° x 0.25° (about 31 km^2) hourly data set has been up-scaled to match the 1 km^2 grid size of the model. The full name of the used data set is *ERA5 hourly data on pressure levels from 1979 to present* (Hersbach et al., 2018).

- **KNMI Reanalysis**: The KNMI reanalysis was created for the event and covers 48 hours from July 13th 8am, because the real time data underestimated the average rainfall amount by 56% (Overeem and Leijnse, 2021). It is a hourly data set with a 100 x 100 m resolution. For the reanalysis the radar data has been adjusted using hourly data from in total 77 automated + manual rain stations. The detailed procedure is described by Overeem et al. (2021).

The data sets have been compared in regard to their temporal and spatial distribution of the rain to ensure the runoff is modelled with a good representation of the rainfall organisation.

3.3.4. Model Adjustments and Calibration

As most of the parameters are based on physical observations, the model only requires limited adjustments and calibration. The objective is to minimize the number of calibrated parameters. However, some calibration is needed for optimal performance. The calibration is performed manually and focuses on a set of parameters which can be linked to the characteristics of the catchment explored in chapter 2. For this reason, the main parameters linked to soil, groundwater and geology were selected to be investigated in more detail. Table 3.4 describes these parameters.

Table 3.4: Description of the selected calibration parameters linked to soil, groundwater and geology (Schellekens, 2022, Eilander and Boisgontier, 2022)

Parameter	Description
Soil Thickness	Soil thickness defines the depth of the entire soil layer and therewith defines the size of the soil storage. Increasing the soil depth will increase the storage capacity and attenuate and delay streamflow peaks.
KsatVer	KsatVer is the vertical saturated hydraulic conductivity. Increasing KsatVer will lower the base flow and flatten the peaks.
f parameter	The f-parameter determines the decay of KsatVer with depth. It controls the base flow recession and parts of the storm flow curve.
KsatHorfrac	KsatHorFrac links KsatVer to the horizontal conductivity and therewith defines the lateral connectivity between the grid cells. The higher KsatHorfrac, the higher the base flow and the lower the peak discharges.
max. leakage	The maximum leakage parameter defines how much water is leaving the saturated zone and therewith is not accounted in the model anymore.

For the calibration and validation a time frame of two years before the event was chosen (01.07.2019 - 30.6.2021), the six months ahead of the period are used as the warm-up period of the model. The calibration was performed on the 6-month period from January to June 2020, as discharge data was available for all stations. It has been performed on a subcatchment level with two main objectives:

- decrease the difference between observed and modelled cumulative discharge for the calibration period
- reproduce the signature of the hydrograph

To estimate the goodness of the fit of the hydrograph, the Nash-Sutcliffe efficiency (NSE) was chosen as the main parameter (Nash and Sutcliffe, 1970). Since the focus is on the flood event in 2021, the representation of high flows is more important than of low flows. Prior to the final calibration, the sensitivity of the chosen parameters has been investigated to understand the effect of each parameter on the cumulative discharge as well as on the hydrograph.

3.3.5. Modelling of the Contributions at Gulpen

The adjusted model was used to reproduce the event of July 2021. The results will be compared to the observations and estimations. The contributions of the main branch (the Geul) and the tributaries for the event at Gulpen will be investigated and compared to the long-term contributions. Contributions are calculated based on the cumulative discharges from July 13 - July 18, 2021. Two scenarios were developed to evaluate the effect of the different event rainfall sums at the tributaries (Gulp, Eyserbeek and Selzerbeek) and the main branch of the Geul:

- **Scenario 1:** The upstream area of Hommerich will receive the same rainfall amount than the tributaries
- **Scenario 2:** The tributaries will receive the same rainfall amount as the upstream area of Hommerich

3.3.6. Model Scenarios

To get a better understanding of the hydrologic response of the Geul and its tributaries to extreme rainfall, the adjusted model was used to investigate several scenarios. Scenarios were developed to analyse antecedent wetness conditions, rainfall volumes and infiltration capacities.

Antecedent Conditions Scenarios:
The role of antecedent wetness conditions on the severity of flash floods has been analyzed in many papers, but the individual response of a catchment is based on its unique characteristics. Three scenarios based on different APIs have been developed to analyze the response of the catchment to antecedent wetness conditions.

- **AC1a**: Rainfall 4 weeks prior to the event is increased by 100% (API = 3)
- **AC1**: Rainfall 4 weeks prior to the event is increased by 50%
- **AC2**: Rainfall 4 weeks prior to the event is decreased by 50% (API = 1)

Rainfall Scenarios:
The spatial and temporal rainfall distribution excites a strong influence on the catchment response (Saharia et al., 2021, Zoccatelli et al., 2011, Nicótina et al., 2008). The extreme precipitation in July 2021 was characterized by a core area with rainfall quantities above 250 mm/48-hours and an extensive surrounding area with more than 100 mm/48 hours. If the rainfall center would have been shifted to the North or South, the Geul catchment would have received much more or much less rain.

- **Precip 1**: average catchment rain of 128 mm spatially and temporally evenly distributed throughout the catchment
- **Precip 2**: actual rainfall of neighbouring Geleenbeek catchment is simulated for Geul catchment (rainfall scaled with a factor 0.7)
- **Precip 3**: actual rainfall quantities received 50 km North of the catchment in the Ardennes are simulated for the Geul catchment (rainfall scaled with a factor 1.3)

Infiltration Capacity Scenarios
The infiltration capacity of the model has been varied to simulate the effect of land-use change in the model. This can be seen as a first estimate and needs to be evaluated further, as land-use changes do not only result in a reduced infiltration capacity, but also in lower soil porosity, and vegetation loss leading to changes in evapotranspiration (Tollan, 2002).

- **IC1**: Infiltration capacity is reduced to 50% (from 600 mm/d to 300 mm/d)
- **IC2**: Infiltration capacity is reduced to 10% (from 600 mm/d to 60 mm/d), equal to the infiltration capacity of loess soil
- **IC3**: Infiltration capacity is increased to 150% (from 600 mm/d to 900 mm/d)
- **IC4**: Catchment is completely covered with paved surfaces (from 600 mm/d to 5 mm/d everywhere)

Each of the scenarios are compared to the base case of the July 2021 event and the effect of these changes is quantified and discussed regarding:

- cumulative and peak discharges
- timing
- contribution of the tributaries
- runoff coefficients

4

Results

In this chapter, the results of the data analysis and the wflow-sbm model are presented. In section 4.1 the long-term hydrological behaviour of the catchment is assessed. Subsequently, in section 4.2 the July 2021 event is analysed using rainfall, discharge and groundwater data. Finally, in section 4.3 the model results of the flood event are presented.

4.1. Hydrological Behaviour

4.1.1. Flow Duration Curve

To gain a better understanding of the hydrological behaviour, normalized flow duration curves were calculated for the stations along the Geul and for the main tributaries. From figure 4.1 it can be seen that all flow duration curves along the Geul have a similar shape. The curve for the outlet Meerssen has the lowest slope, which can be attributed to the dampening and averaging effect of greater catchment areas.

However, the normalized flow duration curves for the main tributaries show greater variations. It can clearly be seen that the Eyserbeek and Selzerbeek based on their catchment areas have lower flows over the full range of possible flows compared to the Geul (Hommerich) and Gulp. Also, the curves of the Geul (Hommerich) and Gulp differ. The Hommerich curve has a higher slope, indicating a flashier behaviour compared to the Gulp, which shows a much more constant flow regime.

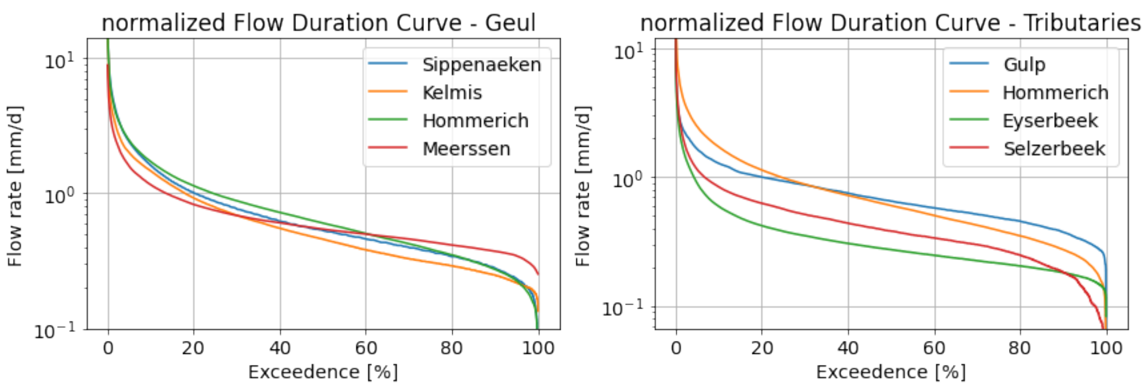

Figure 4.1: Normalized flow duration curves along the Geul (right) and its tributaries (left) based on hourly discharge data from 2000 - 2020

4.1.2. Flow Indices

The minimum and maximum discharges per catchment show the high range of discharges. During dry periods the discharges can become very low, especially in the Eyserbeek and Selzerbeek. However, in a flood event the discharges can be more than a factor 100 higher.

Table 4.1: Measured minimum and maximum discharges and flow indices per subcatchment based on hourly discharge measurements from 2000 - 2020

Station	min. discharge m^3/s	max. discharge m^3/s	Q10/Q95	Q50/Q90	Flow Variability Index
Kelmis	0.125	50	6.7	1.8	1.2
Sippenaeken	0.2	53	6.9	1.9	1.4
Hommerich	0.21	40.5	7.6	2.2	0.9
Meerssen	1	35	3.35	1.5	0.8
Eyserbeek	0.026	10.1	3.6	1.5	1.1
Selzerbeek	0.022	6.2	6.3	2.1	1
Gulp	0.1	14.3	4	1.7	0.6

Table 4.1 shows that the highest flow variability is in the upstream part of the catchment (Kelmis and Sippenaeken). The further down the discharge station is situated along the Geul, the lower the flow variability becomes. Also, the Eyserbeek and to a lesser extent the Selzerbeek show high variability in flow. The high flow variability in the upstream part can be linked to the geohydrological setting. Thin soils and an impermeable bed rock limit the infiltration and storage capacity. The Eyserbeek has very permeable soils, but the high amount of paved surfaces causes the flashy behaviour. As expected the Gulp shows the least variability in flow and has a Q10/Q95 value of four, indicating high base flows. Also, Eyserbeek and Meerssen have high base flow indices. As many springs in these areas feed the rivers during dry periods, suggesting that the groundwater is a major contributor to low flows during dry periods. In contrast to that, the upper catchment area has low groundwater support.

4.1.3. Long-term contributions at Gulpen

Downstream of Hommerich the main tributaries (Gulp, Eyserbeek and Selzerbeek) join the Geul river at Gulpen. At this point the average contributions of the tributaries have been calculated and compared to their size. Table 4.2 shows that the Geul and Gulp have higher discharge contributions compared to their size, while the Selzerbeek and Eyserbeek have lower contributions in relation to their size.

Table 4.2: Average long-term contributions (based on daily discharges from 2000-2020) of the tributaries and the main branch at Gulpen compared to the contributions expected by the size of the catchment.

Subcatchment	Size [km^2]	Size [%]	Discharge Contribution [%]
Geul Hommerich	154	60	66.5
Gulp	46	18	20
Eyserbeek	27	11	5.5
Selzerbeek	29	11	8
Sum	256	100	100

In figure 4.2 the average daily contributions of the tributaries are shown in a stacked bar plot. The graph shows that the contributions differ through the seasons. In winter, when discharges are high (above 2 m^3/s at Hommerich), the contribution of the Geul increases relative to the tributaries from 62% to 72%. In spring and summer the trend is opposite and the tributaries increase their contribution, especially the contribution of the Gulp increases strongly in springtime, from 15% to 24%. This effect is based on the higher storage capacity in the Gulp catchment compared to the Geul catchment upstream of Hommerich. Especially, in dry times the Gulp discharge is sustained by groundwater. The contributions of the Selzerbeek and Eyserbeek to the total discharge are low, while the Selzerbeek constantly contributes more to the flow than the Eyserbeek. However, in case of heavy precipitation events the Eyserbeek even contributes more than the Gulp, showing a very dynamic discharge behaviour due to its high fraction of urbanized areas.

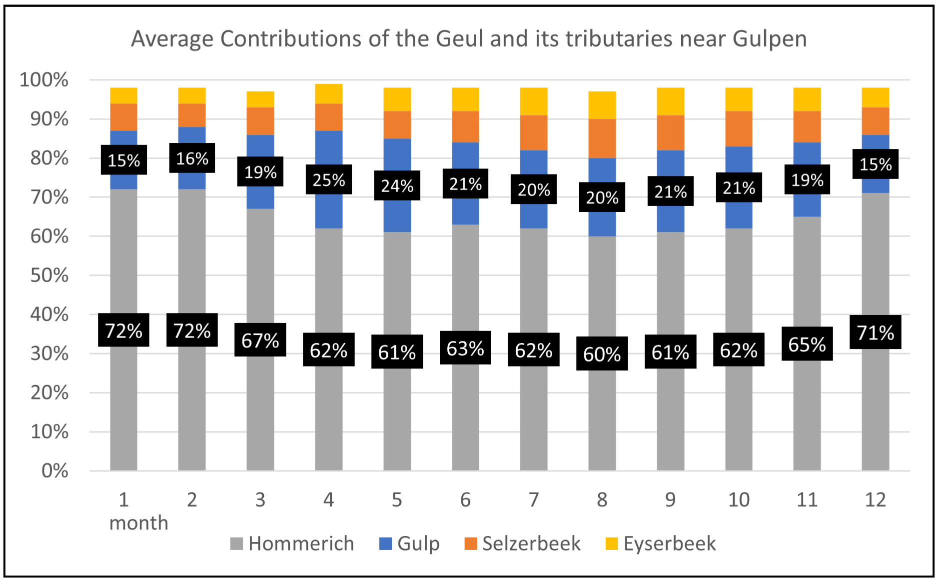

Figure 4.2: Seasonal change in contributions of the Geul catchment and its tributaries near Gulpen based on discharges from 2000 - 2020

4.1.4. Long-term Mean Runoff Coefficient

The long-term mean runoff coefficient has been calculated for the different subcatchments based on discharges from 2000 - 2020. The mean annual runoff coefficient for the whole catchment is relatively small with 32% at the outlet in Meerssen. Table 4.3 shows that the mean runoff coefficient differs strongly within the catchment. While the runoff along the Geul is 39%, the runoff coefficient in the Eyserbeek and Selzerbeek catchments are only 15% and 20% respectively. Taking into account the land-use of the Eyserbeek catchment (see figure 2.10), the expectation would be that the runoff coefficient would be higher due to the high amount of paved surfaces in the catchment. There are several explanations for the differences in runoff coefficients. One is that the boundaries of the groundwater system do not coincide with the catchment boundaries as was discussed in section 2.4. Groundwater is leaving the system to the neighboring catchments and to the Maas (van de Westeringh, 1979, van Lanen et al., 1996, Ruthy and Dassargues, 2009, Agor, 2003, Dautrebande et al., 2000). Most water is lost in the three main tributaries Gulp, Eyserbeek and Selzerbeek. Further research is required to address the cause and magnitude of these losses.

Table 4.3: Long-term mean runoff coefficients calculated per subcatchment based on rainfall and discharge data from 2000 - 2020

Subcatchment	Mean RC [%]
Kelmis	39
Sippenaeken	39
Hommerich	39
Meerssen	32
Eyserbeek	18
Selzerbeek	20
Gulp	32

4.2. Data Analysis: July 2021 Event

4.2.1. Rainfall

The spatial and temporal distribution of the event precipitation has been analysed using adjusted radar and hourly rain gauge data as discussed in 3.1.1.

Figure 4.3 visualizes the extent and magnitude of the rainfall which occurred from July 13th to July 15th, 2021 in Central Europe by showing the 48-hour precipitation sums. The average catchment rainfall based on the data set is 128 mm in 48-hours: 58 mm fell on July 13th and 70 mm on July 14th. Two areas - the most upstream part in Belgium as well as the area around Ubachsberg - even received rainfall amounts above 160 mm. The highest rainfall amount was measured at the rainfall station in Ubachsberg with 182 mm in 48 hours.

The radar data shows that the Geul catchment was at the edge of the high precipitation amounts. In case of a shift of event 50 km to the North, 48-hour sums of 250 mm, which were seen at the higher elevation areas in the Ardennes, could have occurred in the catchment areas. Also, the orientation of the rainfall (SW - NE) compared to the orientation of the Geul catchment (SE - NW) reduced the impact of the rain (van Heeringen et al., 2022).

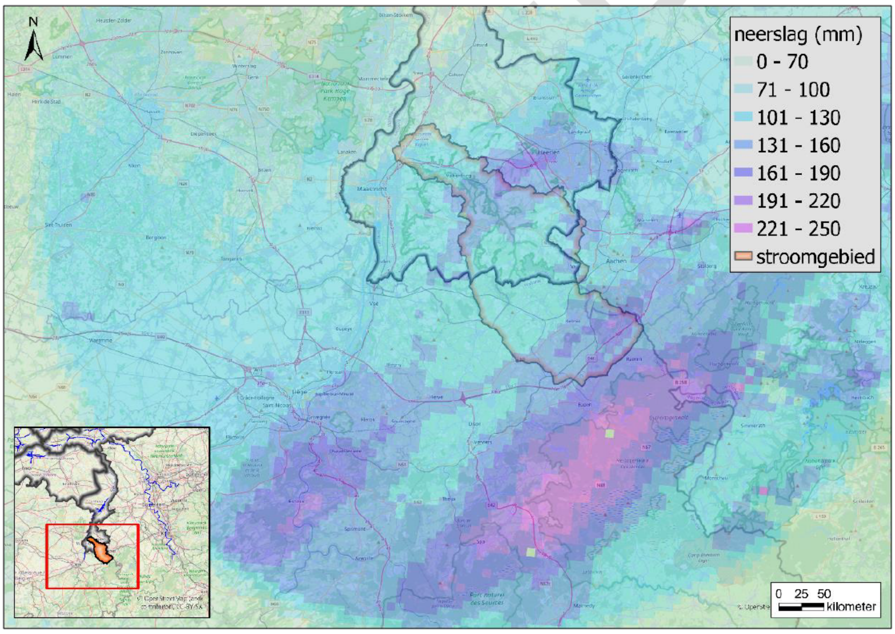

Figure 4.3: Spatial distribution of the rainfall in the Geul catchment based on 48-hour rainfall sums (July 13 10:00 UTC - July 15 10:00) of the KNMI Final Reanalysis. (Taken from van Heeringen et al., 2022)

Figure 4.4 shows the hourly station data in the Geul catchment for the duration of the event; three distinct peaks have been recorded in the majority of the stations.
The first peak took place on July 13th around 5pm - 7pm and was the strongest in the lower part of the Geul catchment. At Ubachsberg a max. rainfall intensity of 40 mm/h was measured. Also in Maastricht, Aachen and Mechelen rainfall intensities of approx. 20 mm/h were recorded. The second and third peaks happened on July 14th 8am and 1pm, which resulted in rainfall intensities above 15 mm/h at several stations in the catchment (Noorbeek, Vaals, Gemmenich, Mechelen). During the 48-hour rain event individual stations recorded between 1 - 5 hours of rainfall intensities above 10 mm/h. This is much higher than the infiltration capacity of loess grounds of 2-5mm/h (Wageningen, 1988) and probably resulted in Hortonian overland flow in these areas. Also, the infiltration capacity of the arable land of 18 mm/h (Wageningen, 1988) was exceeded in some cases, leading to Hortonian overland flow and erosion from the fields.

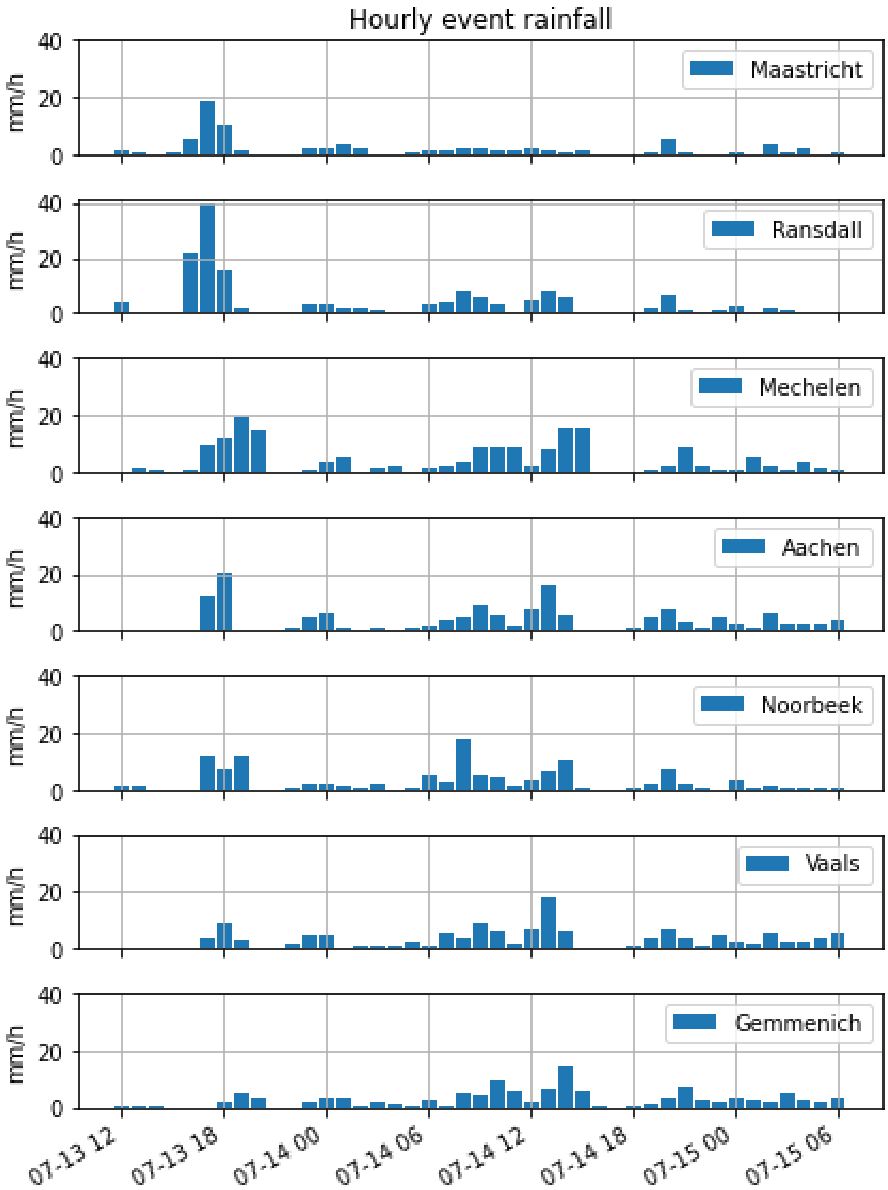

Figure 4.4: Temporal distribution of the event rain as recorded by hourly rain gauge data. Stations are ordered based on their location in the catchment from North (Maastricht) to South (Gemmenich).

Figure 4.4 also emphasizes the high heterogeneity of the rainfall and the general distinction which can be made between the downstream and upstream part of the catchment. The downstream part of the catchment, where the stations Ransdall and Maastricht are located, received the most intense rain during the first peak, whereas the upstream part of the catchment had a less intensive first peak, followed by more intense rain during the second and third peak as can be seen by Vaals and Gemmenich stations.

Comparing, the 48-hour rainfall sums to the average July and yearly rainfall (2000 - 2020) per station in table 4.4 highlights the exceptionally high precipitation amounts of the event. The average July rainfall was exceeded for all stations except Maastricht. Ubachsberg (182 mm) and Aachen-Orsbach (150 mm) received more than double of their monthly averages of 88 mm and 70 mm. Translated to a yearly scale this means that within two days depending on the location 9% to 22% of the average yearly rainfall fell in the catchment.

Table 4.4: Comparison of the event rain to the average July and average yearly rainfall. Averages are calculated from 2000 - 2020.

Station	**48 hour sum [mm]**	**Average July Rainfall [mm]**	**Yearly Average Rainfall [mm]**	**Ratio of event rain to yearly rainfall [%]**
Gemmenich (SPW)	126	88	890	14
Maastricht (KNMI)	65	73	722	9
Ubachsberg (KNMI)	182	88	818	22
Epen (KNMI)	110	89	899	12
Vaals (KNMI	125	92	942	13
Valkenburg (KNMI)	134	93	877	15
Noorbeek (KNMI)	133	90	850	17
Aachen - Orsbach (DWD)	150	70	763	17

To quantify how extreme these rainfall amounts were, the return periods of the 48-hour sums have been determined based on the precipitation statistics from STOWA, as explained in section 3.2. Figure 4.8 shows that the return periods vary between 1/5 years at Maastricht to 1/1000 years at Ubachsberg, the majority of the stations received rain amounts between a 1/50 and 1/250 year return period. The return period for the average event rainfall of the whole catchment (128mm in 48hours) is estimated to be approx. 1/900 years (van Heeringen et al., 2022). This estimate is based on the current climate and taking into account an aerial reduction factor based on the catchment size of 340 km^2 (van Heeringen et al., 2022, STOWA, 2019). These return periods confirm on the one hand the extraordinary amount of total rain from the event and on the other hand the heterogeneity in rainfall amounts within the catchment.

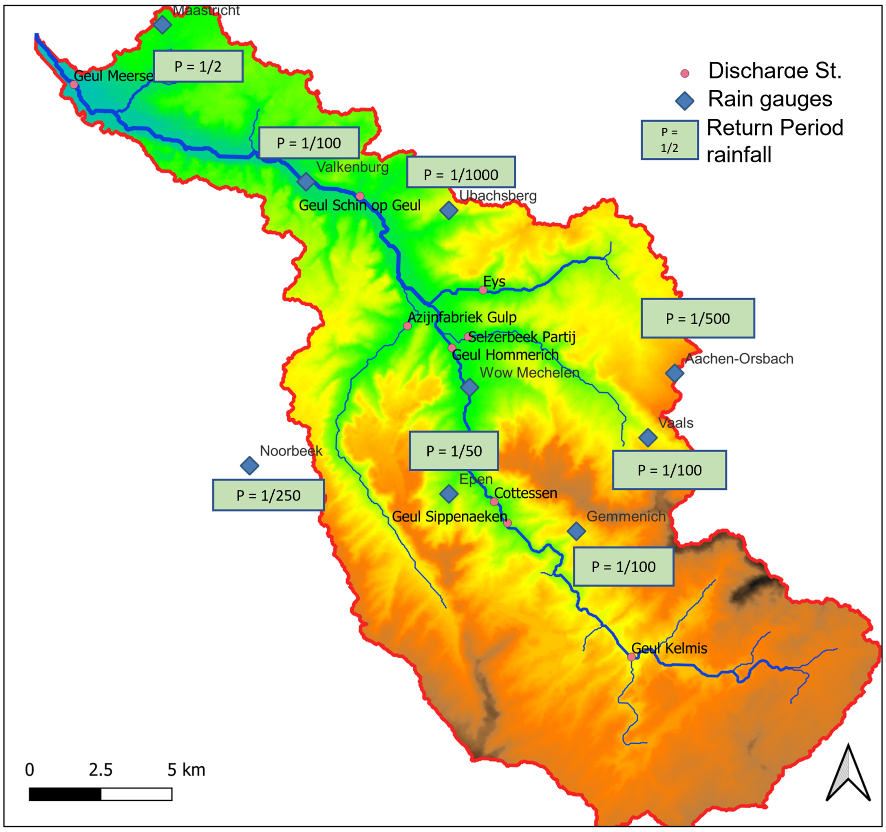

Figure 4.5: Map of the Geul catchment showing return periods of rainfall 48-hour sums (July 13 08:00 UTC - July 15 08:00) based on STOWA precipitation extremes for a 2-day duration (see table C.1).

4.2.2. Discharge

Discharge is next to the water level the most important variable for the analysis of a flood event. However, there is limited discharge data of the event (ENW, 2021). From figure 4.6 it can be seen that only 3 (Kelmis, Sippenaeken, Gulp) out of the 9 discharge stations in the Geul catchment were able to provide data over the whole 48-hour time period of the event.

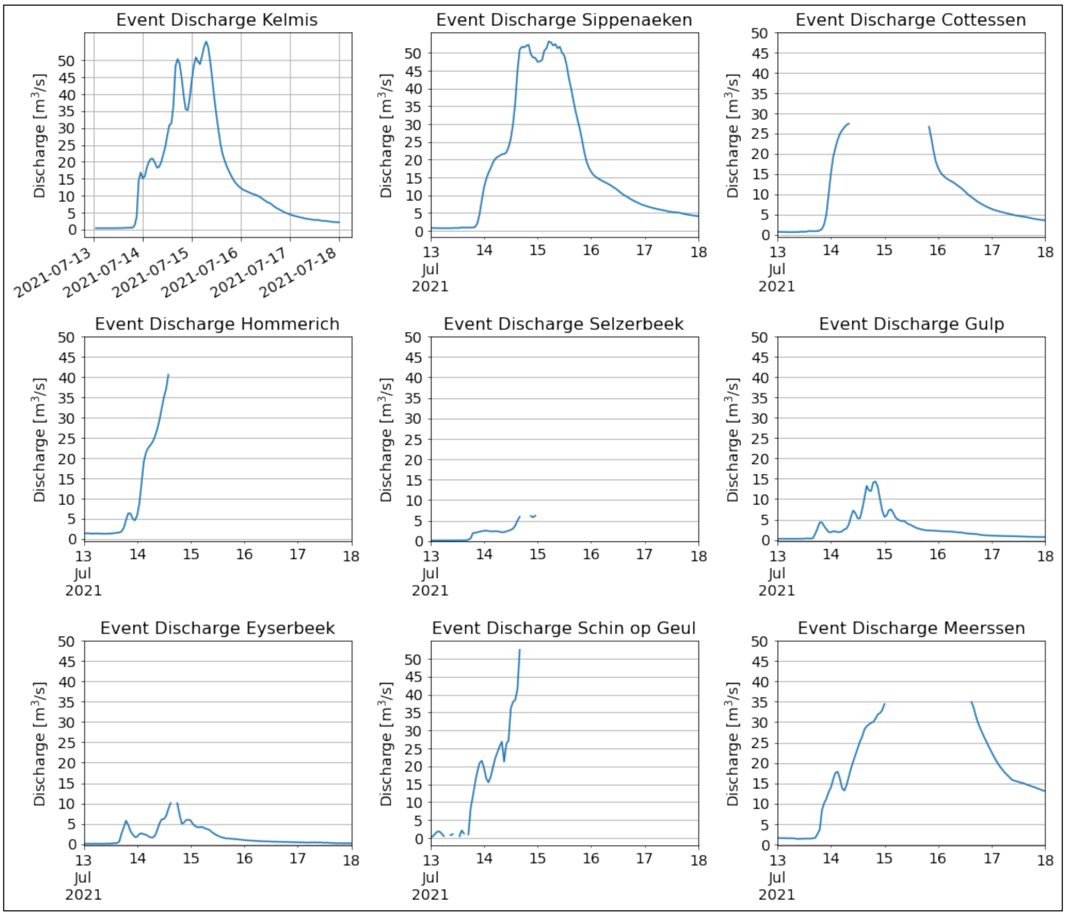

Figure 4.6: Overview of the existing data from all discharge station during the July 2021 event (July 13 - July 18)

In table 4.5, the measured peak and cumulative discharges, peak timing and unit peak discharges are shown for the discharge stations with an (almost) complete discharge record of the event. From the unit peak discharges, the difference in response between the subcatchments can be seen. The response of the most upstream part in Kelmis was much stronger than the response of the Gulp. Also, the Eyserbeek reacted stronger compared to the Gulp. Furthermore, the peaks of the tributaries are earlier compared to the peak discharges in the upstream catchment. In appendix C.2 more information can be found about the timing of the discharges.

Table 4.5: Overview of observed peak discharges, timing and cumulative discharges (13.7.21 - 18.7.21) for all discharge stations with data. For Eyserbeek the peak discharge is estimated as there is a data gap of 3 hours at the peak.

Subcatchment	Observations			
	peak discharge [m^3/s]	peak timing	cum discharge [10^6 m^3]	unit peak discharges [$m^3/s/km^2$]
Eyserbeek	12*	14.7.2021 17:00	0.77	0.44
Gulp	14	14.7.2021 20:00	1.16	0.30
Sippenaeken	53	15.7.2021 07:00	7.43	0.42
Kelmis	56	15.7.2021 07:00	6.41	0.7

Especially the discharge measurements along the Dutch part of the Geul (Cottessen, Hommerich, Schin op Geul and Meerssen) were interrupted at an early stage of the event and provided limited data. Due to erosion and consequent sedimentation along the riverbed, the cross section of the river changed during the flood, which increased the uncertainty in the measured data. It is a common approach to perform post-flood surveys after major flood events to get more information about water levels and river discharges, as the gauging stations are often destroyed. There has been no official post-flood survey executed by the waterboard of Limburg, but several studies have been performed to get an estimation of the discharges at various points in the catchment, particularly in Valkenburg and Meerssen where most flooding occurred. The results are summarized in table 4.6.

Table 4.6: Discharge estimations from different sources for Meerssen, Valkenburg and Hommerich

Report / Locations	**Peak Discharge Estimation (m^3/s)**		
	Meerssen	Valkenburg	Hommerich
Fact Finding (ENW, 2021)	100	84	-
Rura Arnhem (RuraArnhem, 2021)	87.5	-	-
Deltares (van Heeringen et al., 2022)	-	120	100
Waterschap Limburg (van Heeringen et al., 2022)	85 - 90	-	80

All discharges are in a similar order of magnitude. The estimations of the waterboard and from the fact finding are early estimates, whereas the discharges of Deltares and Rura Arnhem are based on modelling studies. In the subsequent data analysis, the discharge at the outlet in Meerssen based on the Rura Arnhem report has been used (RuraArnhem, 2021). The reconstructed hydrograph can be seen in figure C.3. The estimated peak discharge for Meerssen is 87.5 m^3/s, which translates to an unit peak discharge of 0.26 $m^3/s/km^2$.

Normalized Discharges

To compare the discharges along the Geul and between the main tributaries, the event discharges have been related to the catchment area. In figure 4.7 the normalized discharges are presented. By far the highest normalized discharges are calculated for the Belgian catchment area upstream of Kelmis. The discharge at the border to the Netherlands in Sippenaeken is already a bit dampened, but it is still considerably higher than the outlet in Meerssen. The normalized discharges also indicate that the spatial heterogeneity in discharge (factor 3 between Kelmis and Meerssen) is more pronounced than the spatial heterogeneity of the rainfall (factor 1.7 between Kelmis and Meerssen).

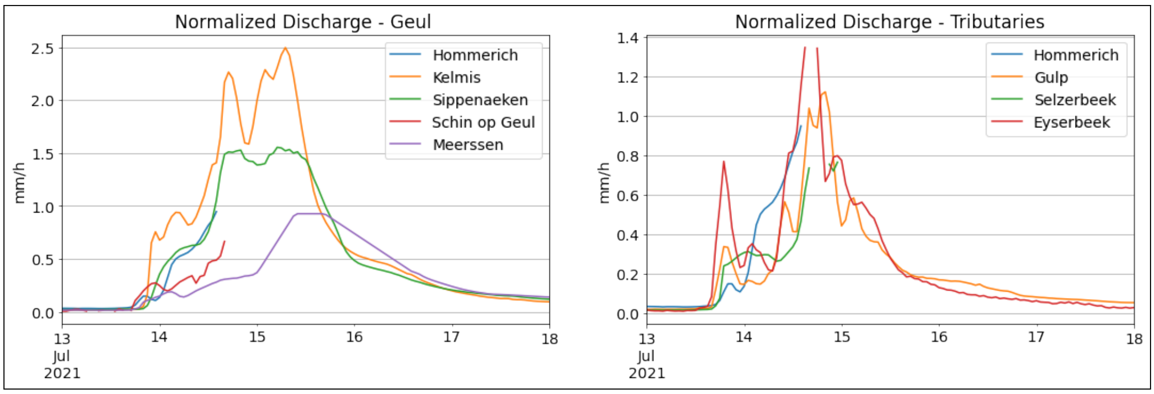

Figure 4.7: Normalized discharges of measured (all except Meerssen) and estimated (Meerssen) discharge data for the July 2021 event. Left: normalized discharges along the Geul, right: normalized discharges of the tributaries

The contrasts in the normalized event discharges of the main tributaries confirm the difference in hydrological behaviour discussed in the catchment characteristics section. The response of the Eyserbeek is very quick and flashy, showing high peaks in relation to its catchment size. The strong first rainfall peak around Ubachsberg can be clearly seen on the hydrograph. The Gulp response follows the rainfall peaks; however the system strongly attenuates the peaks and shows a much weaker response to the event. Both subcatchments can store much water, but the Gulp is less urbanised (10% vs. 16%) than the Eyserbeek.

Event Runoff

The event runoff coefficients (RC) have been determined for the discharge stations where sufficient data was available. An overview of all these event runoff coefficients is presented in table 4.7. While in Kelmis almost 45% of the precipitation ended up in the river, the average event runoff coefficient for the whole catchment is around 32%. The lowest coefficients are calculated for the tributaries Gulp and Eyserbeek. In general the event runoff coefficients are in line with the long-term runoff coefficients discussed in section 4.1.4, which are also the highest for Kelmis and Sippenaeken and are considerably lower for the tributaries. However, the difference between upstream and downstream is more pronounced. The relatively low event runoff coefficient for the whole catchment indicates that the catchment buffered much water in the ground and in the flood plains, which upstream and downstream of Valkenburg have a width of several hundred meters. It was estimated that about 5.5 million m^3 have been stored in the flood plains (Winden, 2022). Part of the buffered water probably also infiltrated. At Meerssen the discharge was still considerably higher the first week after the event as all the water buffered in the system was released. In Kelmis on the other hand the discharge was already back to normal after a few days after the event (Winden, 2022).

Table 4.7: Overview of cumulative discharges, rain and runoff coefficients for subcatchments with measured or estimated (Meerssen) discharges. Cumulative discharge is the sum off all discharges from July 13 - July 18. Rainfall amounts are based on the KNMI final reanalysis. For reference longterm runoff coefficients from table 4.3 are added.

Subcatchment	Event July 2021				Long-term
	cum. discharge [10^6 m^3]	cum. discharge [mm]	rain [mm]	RC [%]	RC [%]
Kelmis	6.41	85	176	48	39
Sippenaeken	7.43	65	160	41	39
Eyserbeek	0.77	32	130	25	15
Gulp	1.16	27	128	21	31
Meerssen	12.37	41	128	32	32

By comparing the cumulative discharges from the different discharge stations presented in table 4.7 the high amount of discharge originating of the Belgian part of the catchment can be deducted. While only 42% of the catchment belongs to Belgium, 60% of the cumulative discharge estimated in Meerssen originates from the Belgium part. In the Deltares flood report it was estimated that 75% of the water which entered the city of Valkenburg originated in the Belgian part of the catchment (van Heeringen et al., 2022). Although they cannot compared to each other directly, both numbers show that the upstream part of the catchment played an important role in the event.

Since most discharge stations failed during the floods, it is not possible to estimate the contributions of the different tributaries based on the observation data. However, the response times have been estimated based on the available data and can be found in appendix C.2.

Return Periods

After the event, the return periods were estimated to be between 1:100 - 1:1000 per year for the Geul catchment. Due to the limited measurement points, there is a large uncertainty concerning these values (ENW, 2021). The return periods based on GEV are visualized in figure 4.8, together with the return periods of the precipitation. On the map the values range from 1/50 years (Gulp) to more than 1/500 years (Hommerich, Meerssen), which confirms the estimation from the fact finding and the extremity of the discharges. However, it has to be taken into account that the discharge stations often fail during flood events, so high discharge values are underrepresented in the time series. This further increases the uncertainty of the calculated return periods.

When comparing the return periods of the precipitation and discharge to each other, one can see that high precipitation amounts (long return periods) do not directly translate to high discharges (long return periods). This is because the discharge response is also influenced by other factors, such as geology and land-use. The discharge at Hommerich (1/500) is more extreme than the discharges at the tributaries, which can be linked back to the limited storage capacity in the upstream part.

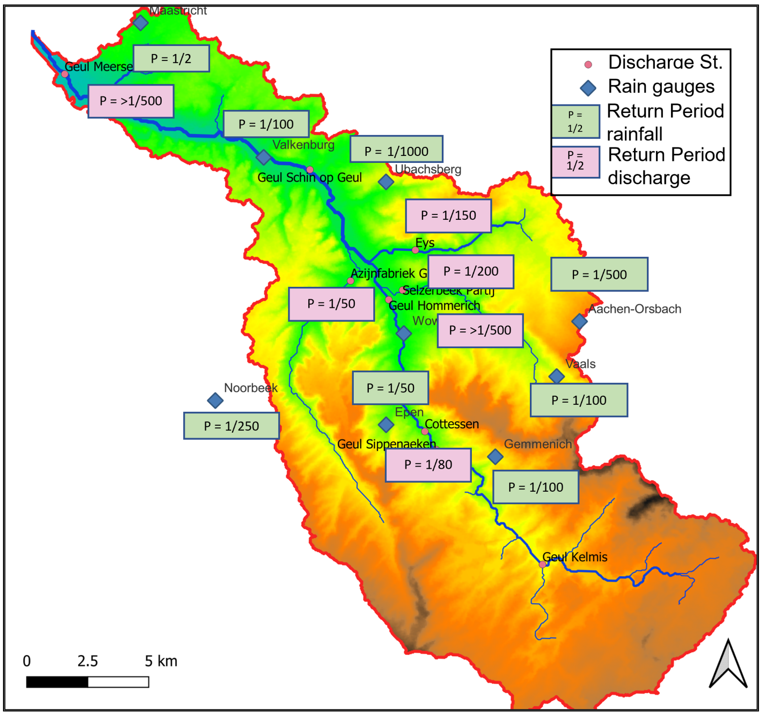

Figure 4.8: Map of the Geul catchment showing return periods of rainfall based on 48-hour precipitation sums (see fig 4.8) and of peak discharges (based on GEV)

More details about the calculation can be found in table C.4.

Comparison to earlier flood events

Earlier flood events have been recorded for the Geul and the Gulp. Based on a local newspaper search, 29 flood events have been identified: one in the 17th century, 27 in the 20th century, 1 in the 21st century (see table C.6) (Delpher, 2022) . All floods have in common that inundations occurred, however there is limited information on the magnitude of the flooding. Figure 4.9 shows the seasonal distribution of the floods throughout the year. The majority of the flood events (20 out of 29) took place in the winter season from December to February. Only four floods happened between June and September, of which two were local flash floods in the Gulp. A major flood during summer has not been observed since the beginning of the 20th century.

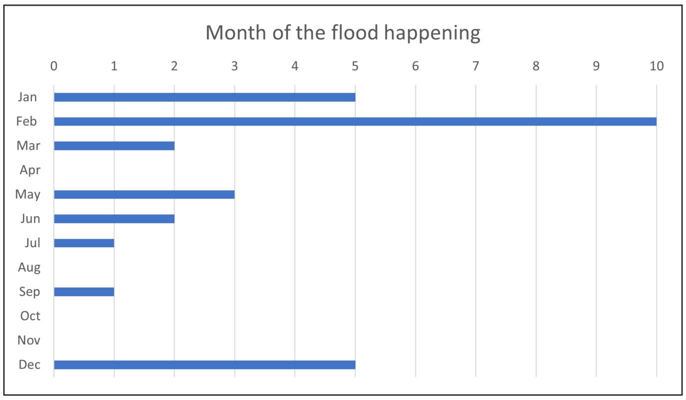

Figure 4.9: Monthly count of historical flood events of the Geul. Flood events were identified based on a local news paper search and include events from the 17th century up to today (Delpher, 2022).

The last major floods in the Geul happened in September 1987 and 1998. Both events resulted in the flooding of the city centre of Valkenburg. In 1998 a discharge of 38 m^3/s was measured in Sippenaeken and 57.6 m^3/s in Hommerich as can be seen on the upper two plots of Figure 4.10. This contrasts to the July event in 2021 where the discharge in Sippenaeken was 53 m^3/s. This may indicate a lower contribution from the Belgian part of the catchment. As the Kelmis station further upstream in Belgium has only been in place since 2002, it is difficult to compare the contributions of the most upstream part to the previous flood events. What can be concluded from existing data is that the July event 2021 showed record high discharges from all tributaries while in the previous floods not all tributaries showed high discharges, as can be seen by the relatively low discharge of the Eyserbeek in 1998.

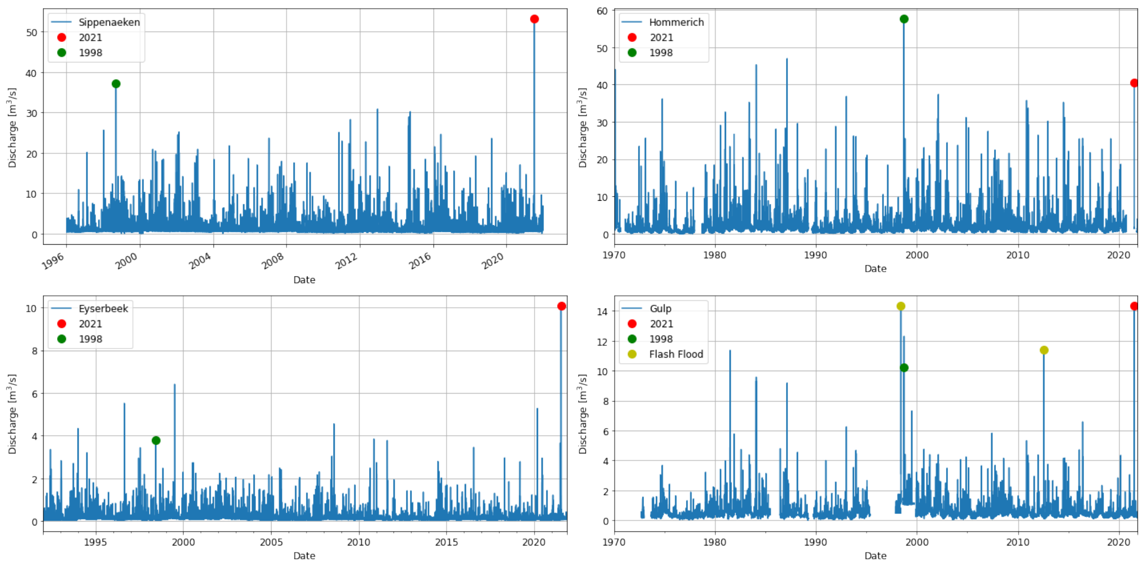

Figure 4.10: Plots of the discharges at station Sippenaeken (upper left), Hommerich (upper right), Eyserbeek (lower left) and Gulp (lower right). Discharges of the flood in September 1998 (indicated with a green dot) are compared to July 2021 discharges (red dot). Bright green dots indicate flash flood events of the Gulp.

The event in July 2021 was the first recorded major flash flood in the summer which extended over the whole catchment. However, in the Gulp valley two local flash flood events occurred in the last 25 years. Both events took place in July as well (1998 and 2012) and were characterized by high-rainfall intensities. The discharge in July 1998 was the same as recorded for the July 2021 event. Due to the high storage capacity in the catchment, surface runoff is only generated when rainfall intensities exceed the infiltration capacity of the ground. These rainfall intensities are predominantly reached in summer storm events.

Comparison to other Flash Floods in Europe
Marchi et al. (2010) characterized and compared 25 extreme flash floods in Europe with each other. In figure 4.11 the data of the Geul catchment for Kelmis and Meerssen were added to two of these plots. When relating the watershed area to the unit peak discharge for Kelmis and Meerssen, it can be seen that the unit peak discharges are relatively low compared to unit peak discharges recorded especially for the Mediterranean catchments, but similar to unit peak discharges for alpine and continental catchments. The second figure relates the runoff coefficient to the accumulated event rainfall. In general it can be seen that the Mediterranean flash floods are characterized by much higher cumulated event rainfall than the Geul catchment. However, the cumulated rainfall of the Geul is relatively high compared to the majority of the continental flash floods on the plot. The runoff coefficient in relation to the event rain is relatively high for Kelmis and average for Meerssen.

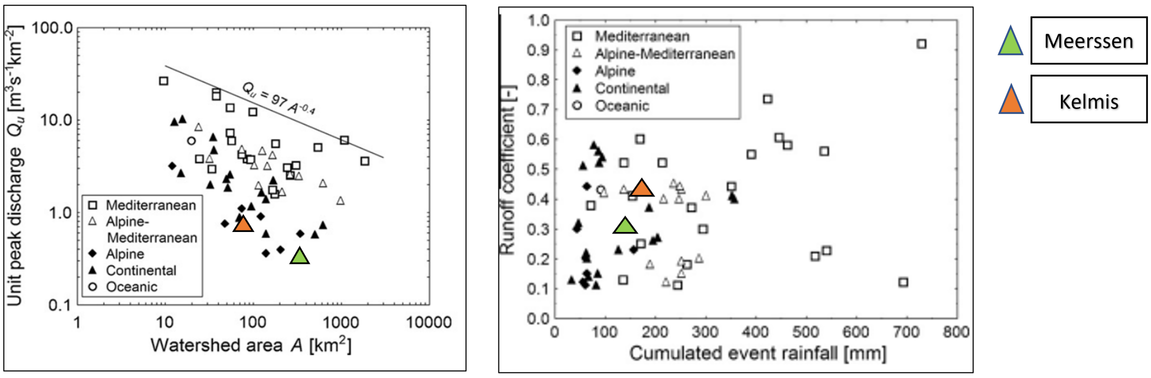

Figure 4.11: Left plot: Relation of the watershed area to the unit peak discharge for 25 extreme flash floods in Europe. Right plot: Relation of the cumulated event rainfall to the runoff coefficient for same 25 extreme flash floods as in left plot. Data for Meerssen (green) and Kelmis (orange) have been added. (Plots are taken from Marchi et al., 2010. Envelope curve in left plot based on Gaume et al., 2009).

4.2.3. Groundwater

Next to the discharge, also the groundwater response to the event has been analysed. In chapter 2.4 the seasonal groundwater level variations and the different groundwater levels at the chalk plateaus, flanks and valleys were discussed. Figure 4.12 relates the increase of the groundwater level during the event to the average groundwater depth. First, the high heterogeneity in response can be seen. The increase in groundwater level varies between 0.1 and 6 metres. The strongest increases have been observed at the wells located on the plateaus. These plateaus are characterized by a thick chalk layer, which can vary greatly in porosity and hydraulic conductivity. Preferential flow paths are very common, and if present can result in a strong and quick response of the groundwater (as can be seen in Figure 4.13). Groundwater levels also increased in the slopes and at the river valley. The relatively strong increase at the valley is linked to the fact that the flood plains were flooded.

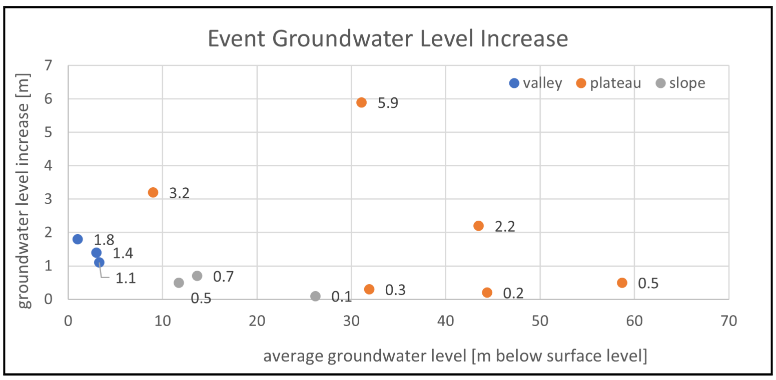

Figure 4.12: Groundwater level increase (in metres from July 13 - 18) is plotted against the average groundwater level of the wells (in metres from 2016 - 2021). Colours indicate the location: valley (blue), slope (grey) or plateau (orange).

Figure 4.13 shows the recorded daily precipitation values and the daily groundwater level for three wells in the Geul catchment. Independently from the location of the wells on the plateaus, flanks or river valley, all wells recorded an increase in groundwater level within a day after the rain started. Especially at the plateaus, this quick response indicates a good vertical hydraulic conductivity of the unsaturated zone, as the water had to travel more than 30 metres to reach the groundwater.
The first well in figure 4.13 also shows a declining trend of the groundwater within a few days after the rain has stopped, suggesting a quick drainage of the groundwater. This quick drainage is facilitated through preferential flow paths (e.g., along the surface of low permeability layers such as the Vaals Formation). The other two wells show a different behaviour, where even 10 days after the event the groundwater level is still rising, displaying a dual porosity / dual permeability matrix behaviour. The fast response indicates that there are preferential flow paths / fractures in the aquifer which facilitate the water flow through the aquifer. The slow increase indicates that the water is eventually stored in the matrix, which has a low hydraulic conductivity, but a high storage coefficient. A few wells only showed minor reactions to the rainfall. These variations in response underline the complex geohydrology of the catchment.

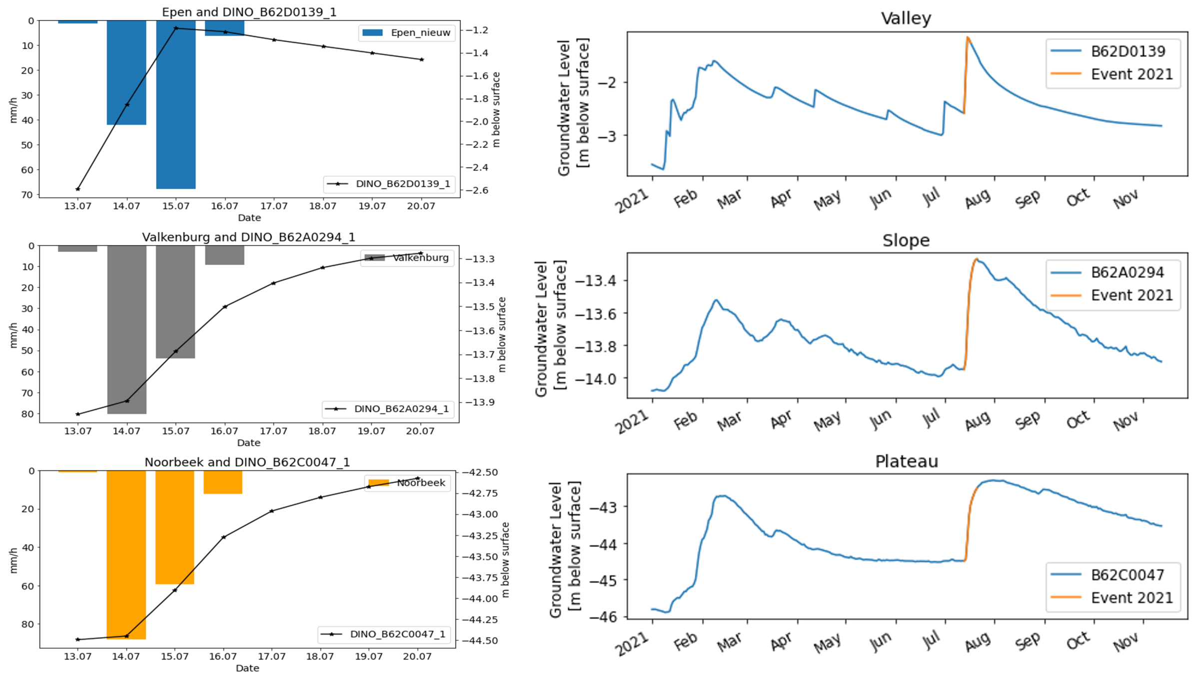

Figure 4.13: Left side: Daily Precipitation (mm) and groundwater level (m below surface) plotted from July 13 - July 19, 2021. Right side: Groundwater level (m below surface) plotted for the same three groundwater wells for the year 2021; in orange the increase due to the event in July 2021 is indicated.

Also the long-term effect of the event on the groundwater differs within the catchment. While the wells with the highest fluctuations in the Belgian part of the catchment (e.g. Plombieres) came back to their pre-flood groundwater levels within a month, the other wells showed a different behaviour, as can be seen in Figure 4.13. In these wells (regardless of their location at the valley, slope or plateau) the groundwater level did not drop to the pre-event level until the winter season. This indicates that water from the event in July is still stored in the groundwater system months later, and reconfirms the significant role of groundwater storage in the catchment.

4.2.4. Antecedent Catchment Conditions

In addition to the precipitation amount, the antecedent conditions play an important role for the severity of the catchment response. Wet soils limit the infiltration capacity and result in more surface runoff (Zehe and Blöschl, 2004). The antecedent precipitation index has been used to analyse the wetness of the catchment at various locations. In figure 4.14 it can be seen that the majority of the points are right at the threshold of normal and wet. This means that 50% more rain has fallen in the 30-days prior to the event compared to the average. The antecedent wetness indices for shorter time periods (e.g.

7-days, 14-days) show the same order of magnitude with the majority classifying between an API of 1.3 - 2.4 (see table C.8). Maastricht is an outlier, as the city experienced another heavy rain event on June 29th with 90 mm on a single day.

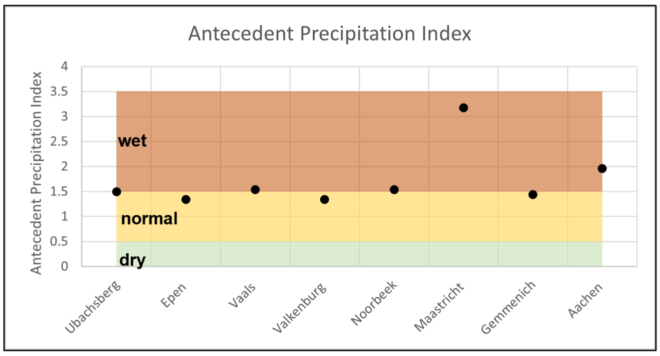

Figure 4.14: Antecedent Precipitation Index (Ratio of 30-day pre-event rain to long-term average for the same period). The index classifies the initial soil moisture conditions in three classes: dry (<= 0.5), normal (0.5 - 1.5) and wet (>1.5). (Marchi et al., 2010)

The wetter-than-usual antecedent conditions can also be seen back in the groundwater data. In figure 4.15 the groundwater levels of three different wells are visualized for the last five years from June 15 - July 30. The groundwater level varies between the years. The groundwater table in 2021 was low compared to previous years (since the last years have been very dry) (Huang et al., 2021). However, the groundwater trend the weeks before the event was different. Whereas usually the groundwater level is decreasing, the groundwater level was stable and in some cases even increasing in the weeks before the event. Hence the higher-than-average precipitation is also reflected in the groundwater level development. The increase in groundwater level was limited however, as the actual evaporation and transpiration is high in the summer and consequently limits the amount of water reaching groundwater.

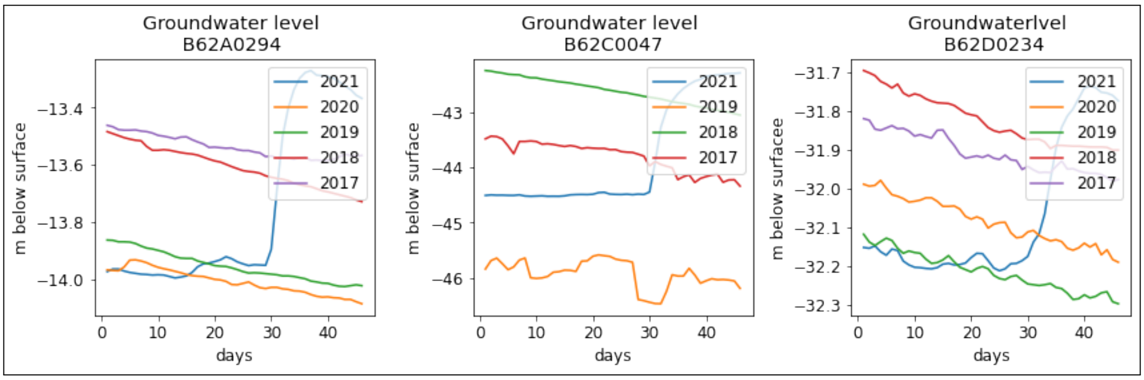

Figure 4.15: Comparison of the daily groundwater levels (m below surface) at three groundwater wells of the last five years for the period from June 15 to July 30

4.3. Model Results of the July 2021 Event

4.3.1. Comparison of Forcing Data Sets

The wflow-sbm model requires gridded precipitation, temperature and evapotranspiration data as forcing input. Three different data sets covering the event have been compared with each other. There are no differences between the temperature and evapotranspiration data, but the data sets differ significantly in their precipitation values.

Figure 4.16 shows the 24-hour precipitation sums of the three days for the event for all three data sets. By comparison to the rainfall analysis (section 4.2.1) several things can be concluded from these maps. In general, the heterogeneity of the rainfall is captured by the REGNIE Deltares and KNMI data set, but not by the ERA5 precipitation data as it is too coarse. On July 13th, the downstream and eastern part of the catchment were exposed to high intensity rain. However this rainfall is not captured by the

REGNIE Deltares data set. The ERA5 data set on the other hand shows high precipitation sums for the south-eastern part of the catchment. Both the KNMI and REGNIE data show the rainfall on July 15th, which occurred mainly in the Belgian part of the catchment. The rainfall cannot be seen back in the ERA5 data set.

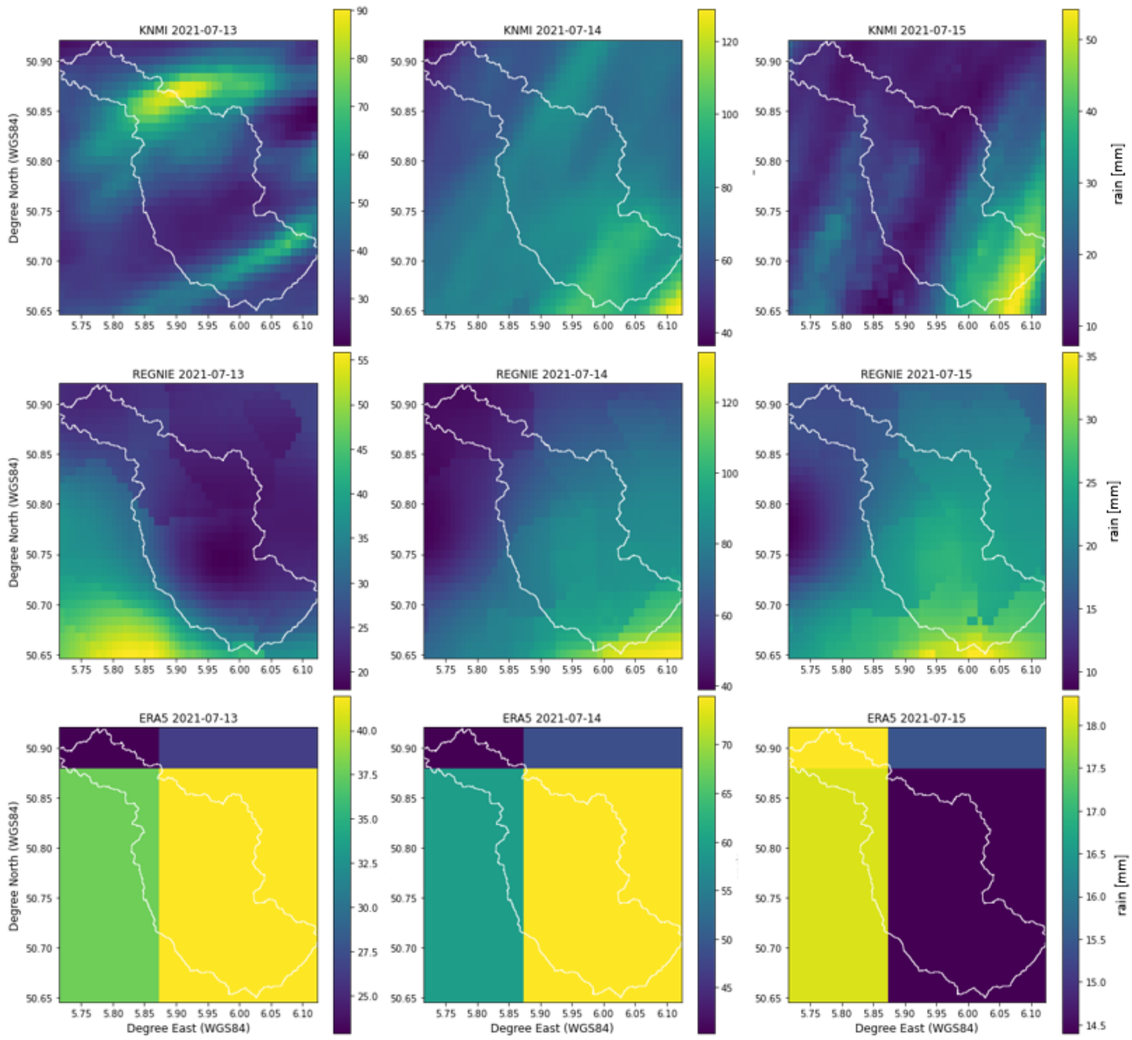

Figure 4.16: Comparison three different precipitation data sets covering the event in July 2021. From left to right the 24-hour precipitation sums in mm are visualized for July 13, July 14 and July 15, 2021. First row: KNMI final reanalysis, second row: ERA5 reanalysis, third row: Deltares REGNIE.

Next to the spatial distribution, also the temporal distribution of the rainfall differs between the data sets. In figure 4.17 the hourly rainfall data at Aachen-Orsbach is compared to the gridded precipitation data at the same grid cell from all three data sets. The conclusions from this station are exemplary for the temporal differences in the rainfall forcing of the different data sets. The cumulative discharges of all three data sets are similar (KNMI: 134.6 mm, REGNIE: 124.6 mm, ERA5: 131.3 mm), but the ERA5 data does not follow the discharge peaks, and more evenly distributes the rain during the event period. Due to this, the data set also shows rain at the location in the morning of the July 13th, when the station was not recording any rain yet. The REGNIE data shows a much better representation of the different rain peaks during the event, but the first peak is not captured. The KNMI data set is correct in timing and magnitude and therefore was chosen to be used as the forcing for the event.

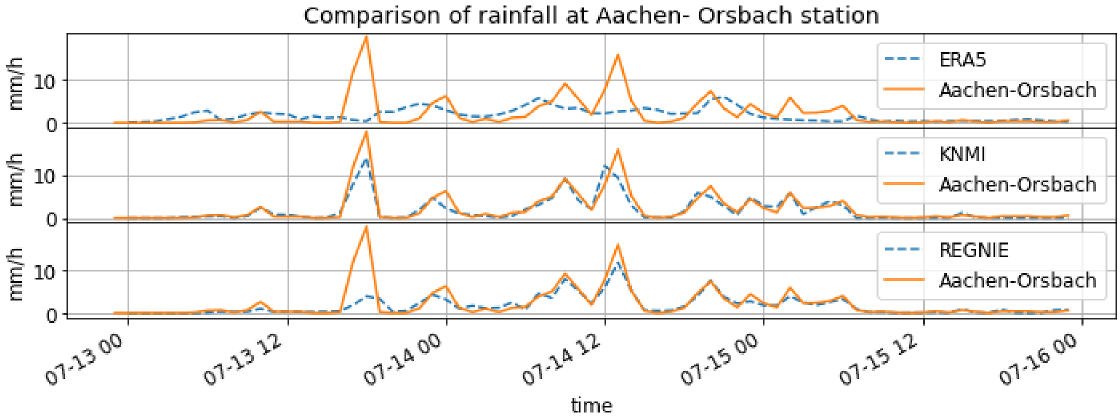

Figure 4.17: Hourly rainfall in mm/h recorded at Aachen-Orsbach station (DWD) compared to the precipitation in the corresponding grid cell of all three data sets

4.3.2. Model Results without Adjustments

The performance of the model has been analysed by running the wflow-sbm model with the original parameter set without any adjustment and calibration. In figure 4.18 the cumulative discharge for 2020 as well as the hydrograph for the start of year 2020 is shown exemplary for three subcatchments: Meerssen, Kelmis and Eyserbeek. The model overestimates the cumulative discharges at all three stations. The biggest difference is at the Eyserbeek tributary, where the model overestimates the measured cumulative discharge by a factor of 2.3.

The simulated cumulative discharges show the same trend for all subcatchments: during the summer period the discharge is only slightly overestimated, whereas in the wet period the gap between simulated and observed cumulative discharge is great. This indicates that the model storage in the unsaturated zone is too small. Therefore during wet conditions the storage is full too quickly.

Similar behaviour can also be seen in the plotted hydrographs, especially for Meerssen and Eyserbeek. The low and high flows are overestimated, and consequently the computed NSE values are low. For Kelmis the NSE value is slightly better, as the high flows are in the right order of magnitude and only the low flows need adjustment.

The model seems to better represent the upstream area, which is characterized by shallow impermeable bedrock, thin soils and little storage capacity. Without adjustments the model cannot reproduce the hydrologic behaviour of the catchment areas, which are characterized by high storage capacity and high base flows.

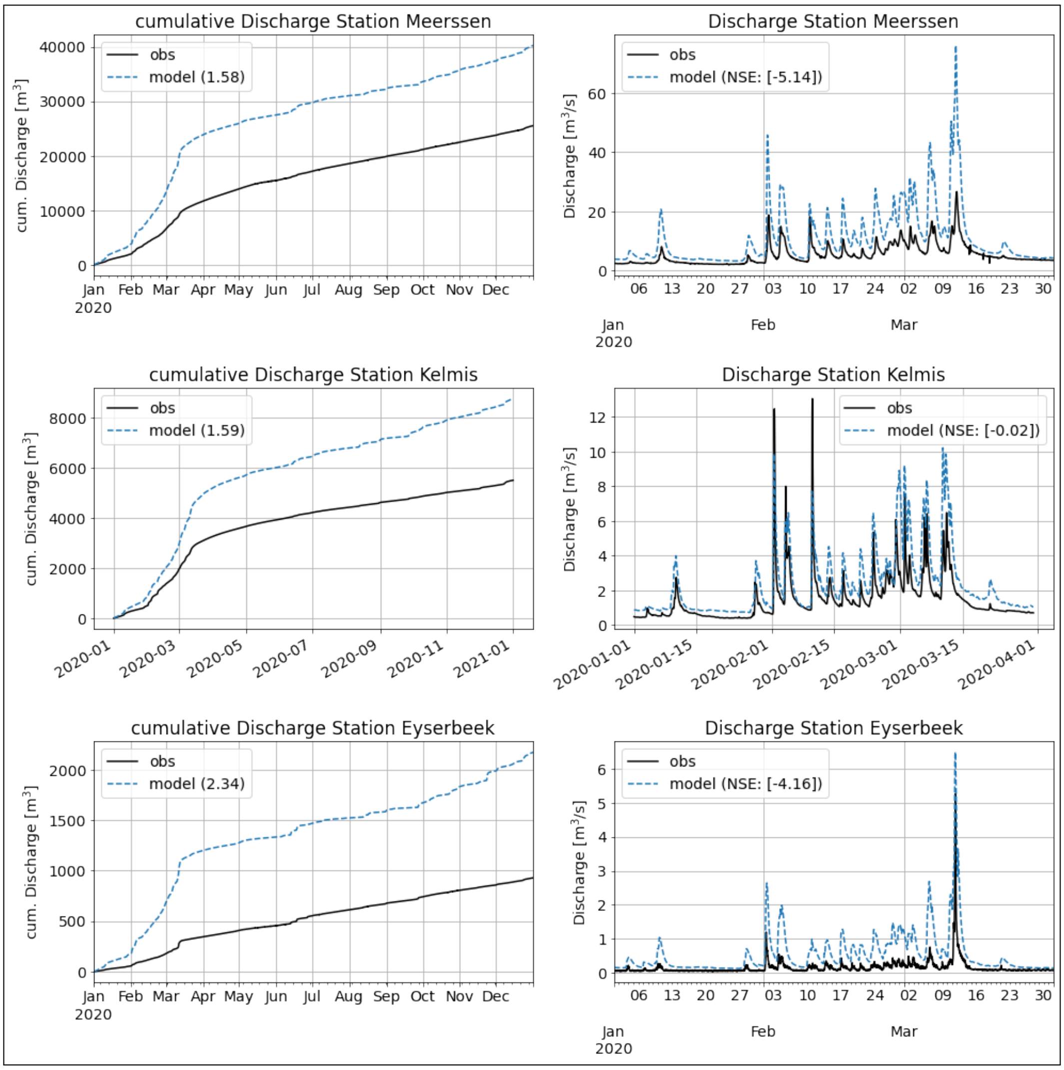

Figure 4.18: Cumulative Discharge (01.01.2020 - 31.12.2020) and hourly discharge (01.01.2020 - 31.03.2020) in m^3/s of three discharge stations: Meerssen (top), Kelmis (middle) and Eyserbeek (botton); observations are shown in black and original model results shown in blue.

4.3.3. Model Adjustments and Calibration

From the catchment understanding and the original model results, it can be concluded that the parameters linked to the soil and geology are crucial to be able to reproduce the discharge signature of the catchment. This is especially true for the parameters which are linked to the storage capacity of the model. These six parameters described in section 3.3.4 have been varied to understand their influence on the model results. For the parameters which are distributed through the model, a scaling parameter has been used. This way the original distribution of the parameter is not changed (see table D.1). Through these parameter variations (see figure D.2), the sensitivity of each parameter on the cumulative discharge has been analysed, and the three most important parameters have been determined:

- Soil Thickness
- Maximum Leakage
- KsatHorFrac

These three parameters will be used to improve the model.

Soil Thickness

The soil thickness determines the size of the soil bucket and therewith the unsaturated zone. One of the reasons for the overestimation of the discharge in the model could be linked to an underestimation of the storage capacity in the soil.

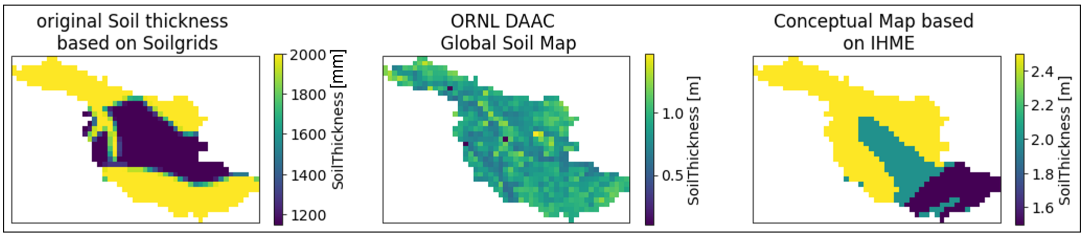

Figure 4.19: Figure depicting three different soil thickness distributions. On the left: original soil thickness distribution in the sbm model derived from pedotransfer functions using soil grids. The detailed explanation and code can be found on the wflow documentation (Schellekens, 2022). In the middle: Soil thickness based ORNL DAAC global soil map (Pelletier et al., 2016) On the right: Conceptual soil map based on IHME (IHME, 2022) (see figure D.3)

The left map in figure 4.19 shows the original distribution of the soil thickness in the wflow-sbm model. It can be seen that the soil thickness in the model varies between 1200 and 2000 mm, which seems a small variation taking into account the great differences in geology and hydrogeology of the different subcatchments. Moreover, the distribution of the thickness does not reflect the increase in thickness (of the unsaturated zone) from upstream to downstream as described in section 2.4. The soil thickness is not only high in the lower part of the catchment, which fits to the geological map of the catchment, but there is also a high soil thickness in the upstream part. This is contrary to the fact that the upstream part has shallow bedrock and thinner soils compared to the downstream part. Additionally, in the model the lowest soil thickness values are found in the centre of the catchment at the tributaries Eyserbeek and Selzerbeek, which in reality have thick unsaturated chalk layers as described in section 2.4.
This mismatch of the soil distribution to the conceptual understanding has also been seen in other chalk catchments (e.g., in England) (A. Weerts, personal communication, Apr/2022). The soil thickness in the input maps is limited to the soil on top of the rock. However in chalk catchments the chalk layer beneath the soil acts also as a unsaturated storage zone. This effect is not accounted for in the model.

Therefore, the impact of alternative soil thickness distributions based on the NASA soil map and the conceptual map has been tested. In figure 4.19 the different distributions are visualized. Additionally, the model has been run with a uniform soil thickness distribution of 2000 mm.
From figure 4.19 it can be seen that also the NASA soil map is not reflecting the different geological zones within the catchment. Therefore as a third option a new soil map has been created based on the international Hydrogeological Map of Europe (IHME) (IHME, 2022), which splits up the catchment in different zones based on the lithology. The new soil thickness has been distributed throughout the model based on these zones using three different soil thickness values of 1.5 m, 2 m and 2.5 m (see figure D.3).
Figure 4.20 shows the effect of different soil distributions on the cumulative discharge. It can be seen that a uniform soil distribution and the conceptual distribution are closer to the observed discharges of the catchment than the original soil map. Overall, the conceptual distribution achieved the best results and will be used as the new base distribution.

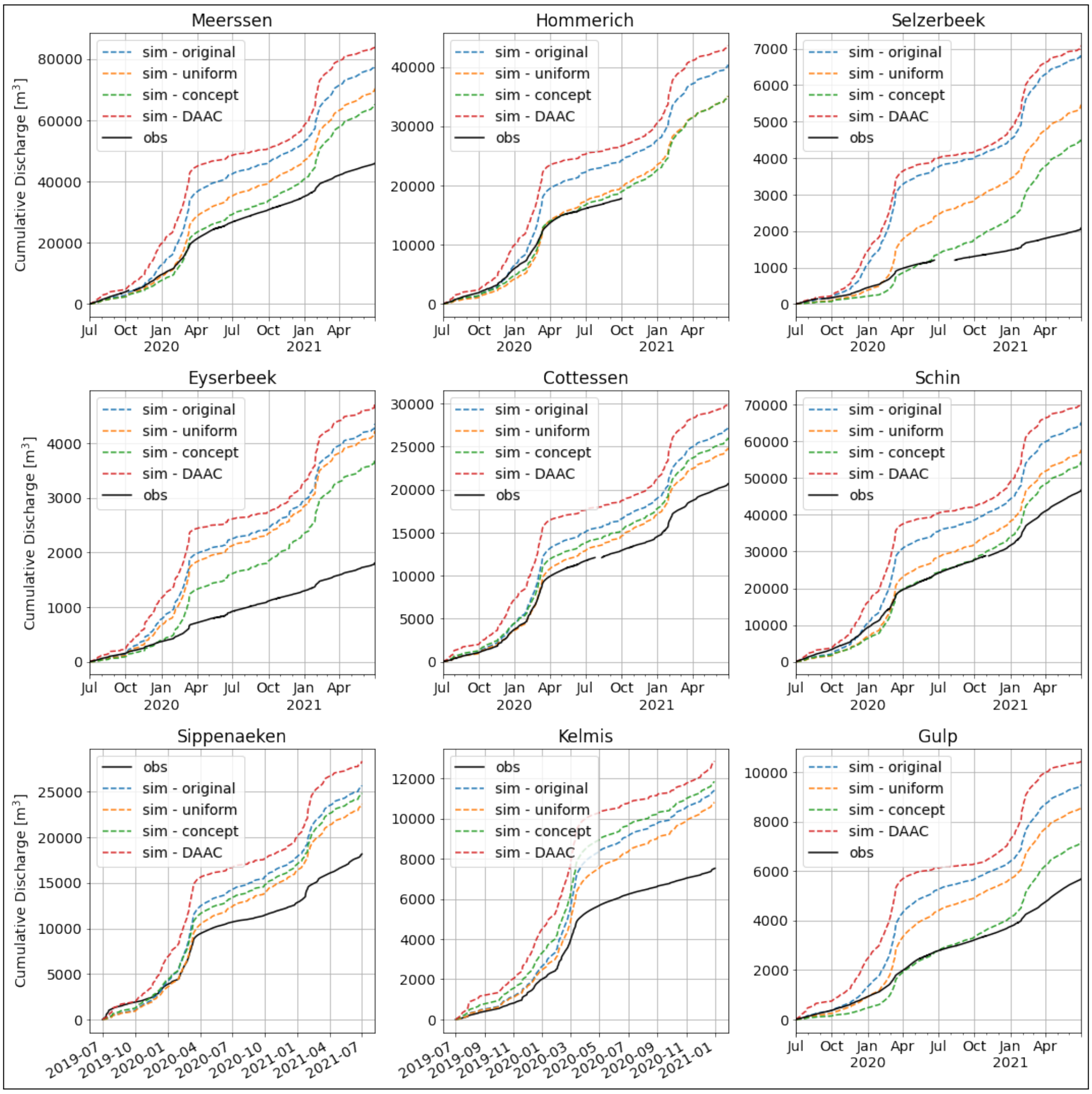

Figure 4.20: Effect of different soil thickness distributions on the cumulative discharge (1.7.2019 - 1.7.2021) in comparison to the observed data. In blue the original soil map based on soil grids (Schellekens, 2022), in orange a uniform soil thickness of 2 m is used, in green the conceptual soil map based on IHME (see figure D.3) and in red the soil map based on NASA ORNL DAAC (Pelletier et al., 2016)

However, it can also be seen that only adjusting the soil thickness is not sufficient to achieve a good match in all catchments.

Maximum Leakage

The original model does not take any leakage into account. However leakage is an important parameter in the catchment. Groundwater leakage is documented for some areas and also the variation in mean runoff coefficients within the catchment (see section 4.1.4) indicates that there is leakage and that it differs within the catchment. To represent this leakage in the model, a leakage factor has been determined per subcatchment using a simple water balance calculation.

$$Storagechange(ds) = 0 = Precipitation(P) - Evaporation(E) - Discharge(Q) \tag{4.1}$$

Where:

- P in mm based on KNMI radar data
- E in mm based on potential evaporation ERA5 radar data

- Q in mm based on observations

As the water balance is taken over full years it is assumed that the change in storage is negligible over the period and is zero. Hence a different number than zero indicates that there is leakage in the system. The potential evaporation has been converted to actual evaporation using an uniform factor of 0.9 (R. Imhoff, personal communication, Apr/2022). As the actual evaporation depends also on the type of land-use and soil, this is a big simplification. However, for the purpose of getting an indication of the leakage, the error margin within the evaporation assessment is deemed acceptable. The individual values of the water balance are shown in table 4.8.

Table 4.8: Water balance calculation per subcatchment from 01.07.2019 - 30.6.2021. Precipitation (P) based on KNMI gauge adjusted radar data, evaporation (E) based on ERA5 reanalysis and discharge (Q) based on observations. Based on the water balance value a leakage factor of 0 (WB=-0.1 to 0.1), 0.2 (WB= >0.1 to <0.4) or 1 (WB= >0.4) has been assigned to a subcatchment

Subcatchment	P [mm/d]	EPOT * 0.9 [mm/d]	Q [mm/d]	WB [mm/d]	Max Leakage [mm/d]
Meerssen	2.35	1.72	0.69	-0.06	0
Schin	2.49	1.72	0.83	-0.06	0
Eyserbeek	2.56	1.72	0.33	0.51	1
Gulp	2.45	1.71	0.62	0.12	0.2
Selzerbeek	2.51	1.71	0.40	0.40	1
Hommerich	2.56	1.72	0.92	-0.08	0
Sippenaeken	2.48	1.71	0.73	0.04	0
Kelmis	2.50	1.70	0.68	0.12	0.2

Based on the water balance value, a leakage factor of 0 (WB=-0.1 to 0.1), 0.2 (WB= >0.1 to <0.4) or 1 (WB= >0.4) has been assigned to a subcatchment. The resulting map is visualized in figure 4.21. The maximum leakage parameter has been adjusted in four subcatchments. The highest adjustment has been made for the Eyserbeek and Selzerbeek tributary and is in line with expert judgement (A. Weerts, personal communication, Apr/2022). Leakage from the Gulp to the Maas terraces has been documented in literature (van Lanen et al., 1996). The leakage in Kelmis can be accounted to the karstic phenomena, especially in the area around Kelmis (Ruthy and Dassargues, 2009).

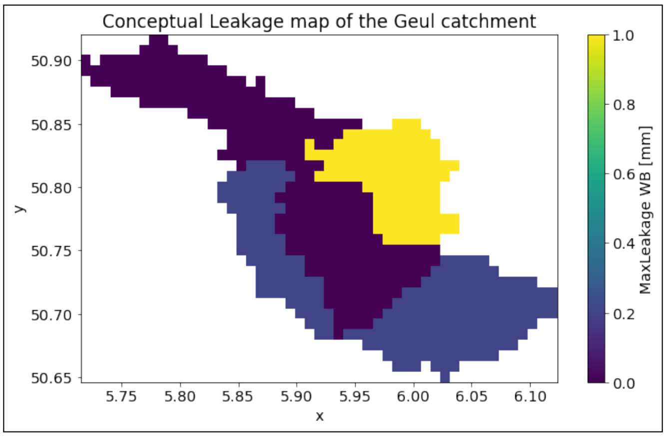

Figure 4.21: Distribution of the maximum leakage parameter in the adjusted wflow-sbm model

KsatHorFrac

After these two parameters (soil thickness and maximum leakage), the best relation between base flow and storm flow has been determined by variation of the KsatHorFrac (KSHF) parameter. As a performance indicator the NSE value was used to evaluate the ability of the model to reproduce the hydrograph from January 2020 - June 2020 for all discharge stations. The range of KSHF is linked to the vertical saturated hydraulic conductivity (KsatVer) in the model and consequently to the soil type. In the hydrogeology section 2.4 it was discussed that the groundwater flow can be large as a result of preferential flow through the chalk system (Schaminée et al., 2009). The KSHF parameter has been distributed through the catchment based on the existence of highly productive aquifers (Bouaziz, 2020). From table 4.9 it can be seen that the model performs better when increasing the KSHF values.

Table 4.9: Overview of NSE values for different simulations run with scaling the KSHF parameter from 1 to 2.5. NSE values are shown per subcatchment. Green values indicate the highest NSE value for that subcatchment.

	NSE					
Station	uncal. sim	KSHF 1	KSHF 1.5	KSHF 2.0	KSHF 2.5	Final
Meerssen	-3.74	0.27	0.46	0.54	0.58	0.54
Schin	-2.35	0.5	0.6	0.64	0.64	0.64
Eyserbeek	-3.11	0.56	0.59	0.6	0.59	0.6
Gulp	-12.99	-0.07	0.13	0.18	0.17	0.16
Selzerbeek	-14.66	-0.39	-0.39	-0.39	-0.39	-0.39
Hommerich	-1.54	0.39	0.53	0.6	0.63	0.55
Cottessen	0.43	0.76	0.79	0.79	0.76	0.79
Sippenaeken	-2.22	-1.33	-1.11	-1	-0.94	-1.14
Kelmis	-1.92	-0.9	-1.59	-2.33	-2.91	-0.99

Based on the overall performance, a scaling parameter of 2 has been chosen. However, as this resulted in a strong overestimation of the flow in Kelmis, the KSHF parameter has been adjusted for the upstream catchment. The adjustments and the final KSHF distribution can be found in table D.4.

Model Performance

In figure 4.22 the performance of the adjusted model is shown for the same three subcatchments as in section 4.3.2. For Meerssen and Eyserbeek the model performs much better. The cumulative discharges are within 15% of the measured discharges and the model can reproduce the hydrograph. Low flows and high flows are both similar to the observed values. For Kelmis however the adjusted model only performs slightly better than the original model. The cumulative discharges are still overestimated. The signature of the hydrograph is reproduced, but both low and high flows are too high.

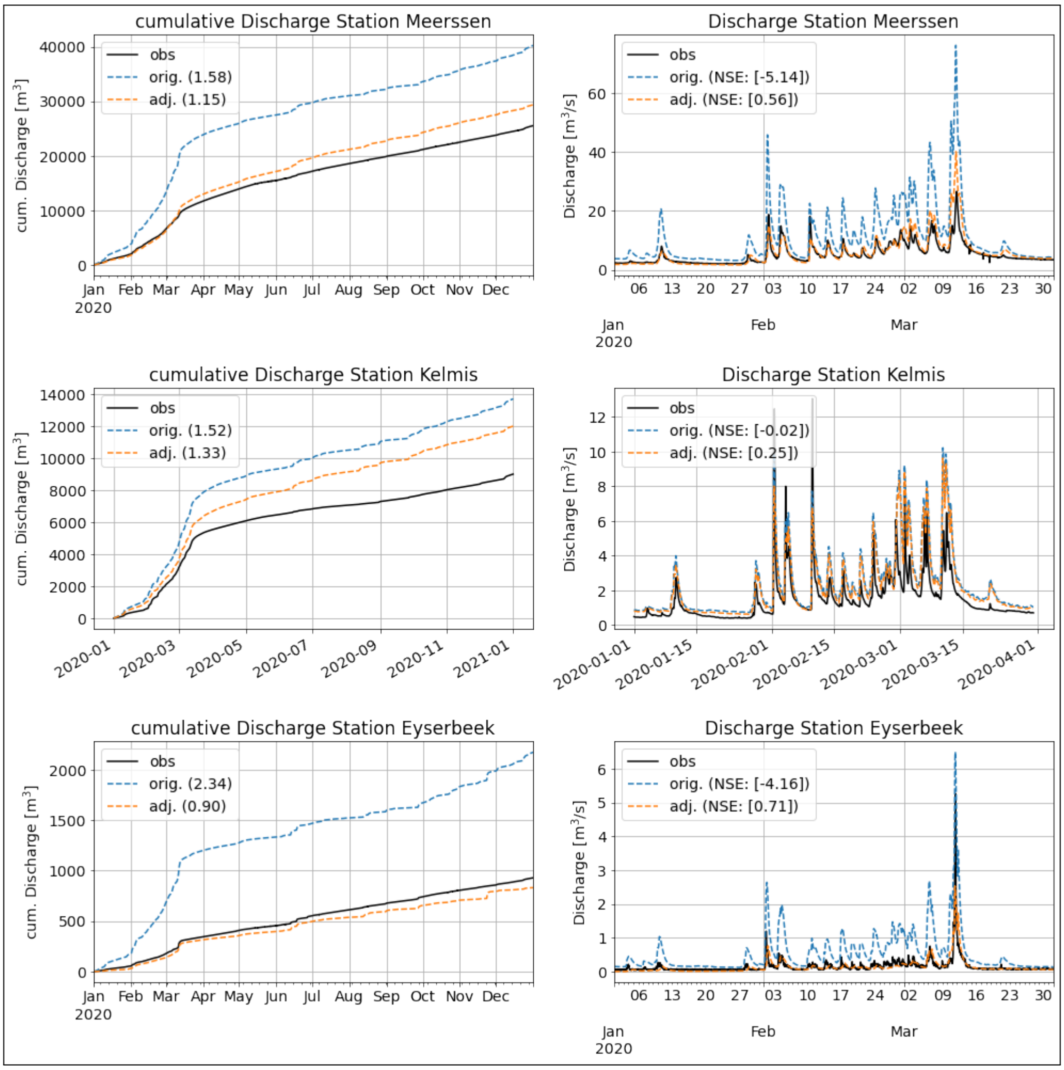

Figure 4.22: Cumulative discharge (01.01.2020 - 31.12.2020) and hourly discharge (01.01.2020 - 31.03.2020) of three discharge stations: Meerssen (top), Kelmis (middle) and Eyserbeek (botton); observations are shown in black, original model results in blue and adjusted model results in orange.

Appendix, figure D.5 and D.6 show the model performance for all discharge stations for the calibration period as well as for a validation period.

4.3.4. Reproduction of the 2021 Event

The adjusted model has been run to simulate the 2021 event. Figure 4.23 shows the result for all stations, for reference the results of the original model are shown as well. The adjusted model produces lower peak discharges along the Geul compared to the original model (5 - 10% lower in the upstream stations Cottessen, Sippenaeken and Kelmis, 25 - 30% lower in the downstream stations Meerssen, Schin, Hommerich). The shape of the hydrograph is similar for both models for these stations.
For the three main tributaries the adjusted model does not only show lower peak discharges in the order of 25 - 35%, also the shape of the hydrograph changed. In general, the model results are in good agreement with the estimations from the waterboard and the limited observation data which exists. The difference between the observed and simulated discharges is less than 20% (see table D.3). Based on the simulation data, return periods based on the peak discharges have been calculated and can be seen in table D.5.

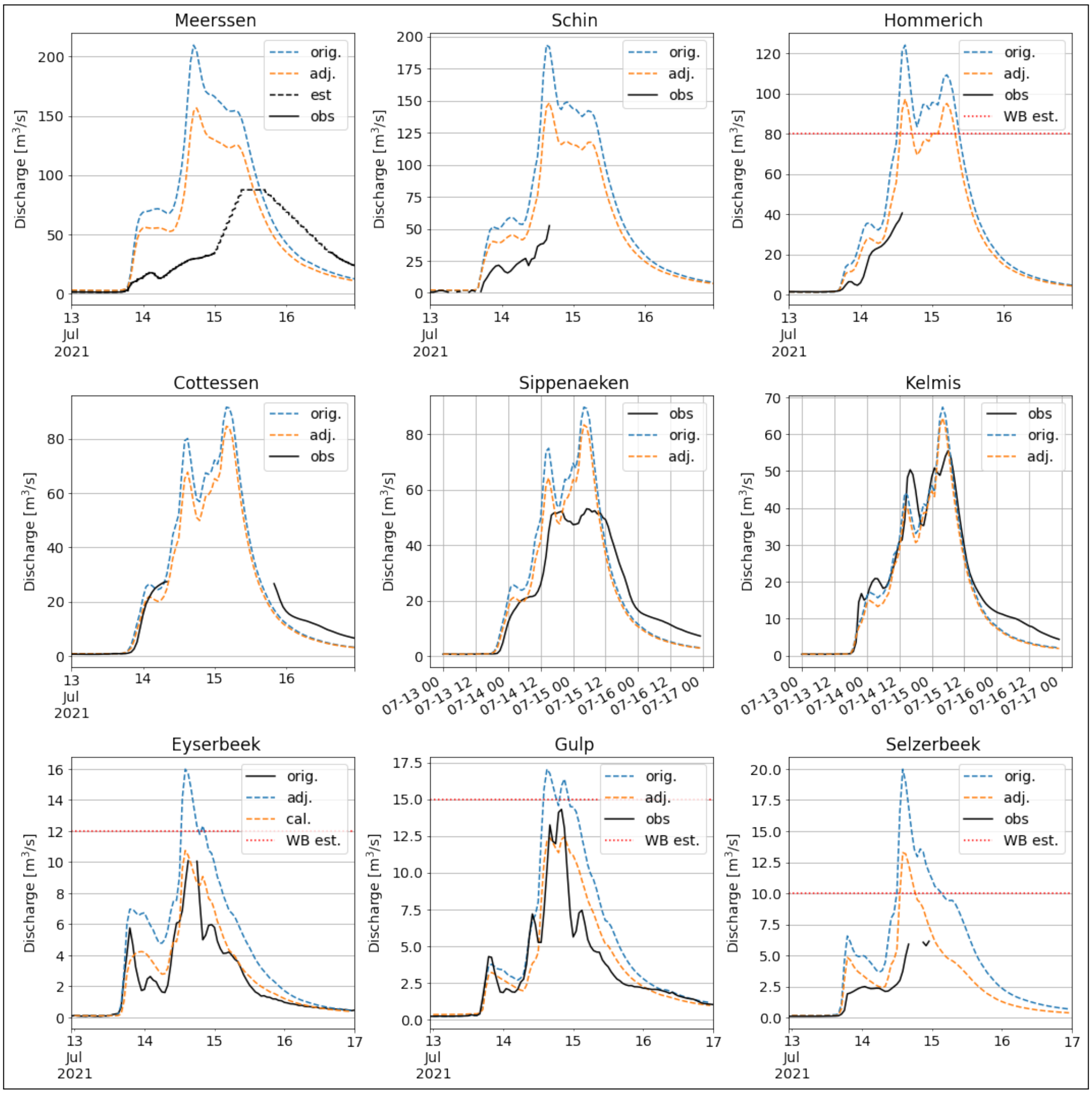

Figure 4.23: Discharge observations (black), original (blue) and adjusted (orange) model results are shown per subcatchment for the July 2021 event. Peak discharge estimations from the water board are indicated as a dashed red line.

Event Runoff Coefficients

The event runoff coefficients of the model and the observations show good alignment as can be seen in figure 4.24. The graphs visualize that the first 50 mm of rainfall were absorbed by the catchment and the discharge response remains low. However after that the discharge reacted stronger. Whereas the runoff coefficients in the upstream catchment reached about 40%, the runoff coefficients of the tributaries are much lower. The event runoff coefficients for all catchments based on the model results can be found in table D.4.

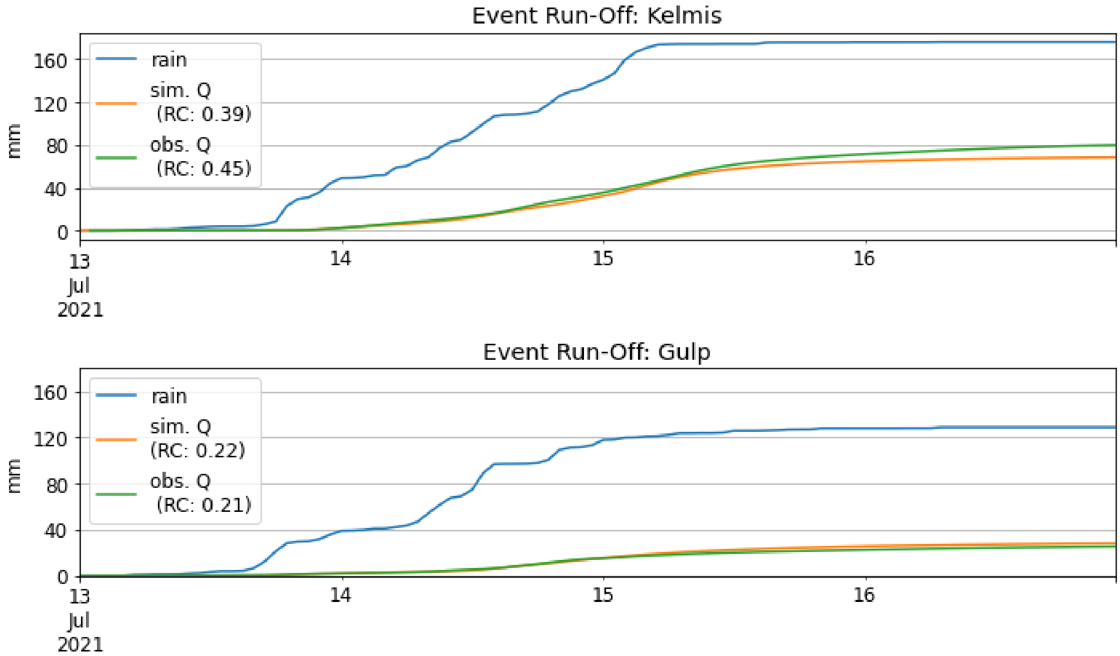

Figure 4.24: Rain (blue), observed (green) and simulated (orange) discharges are shown for Kelmis (top) and Gulp (below) for the event (July 13 - July 17, 2021)

4.3.5. Event Contributions at Gulpen

The contributions of the three tributaries and the main branch of the Geul (Hommerich) have been modelled and are shown in figure 4.25 for the confluence near Gulpen. The stacked discharges show two distinct peaks: the first peak on July 14 at 3pm and the second peak on July 15 at 5am.

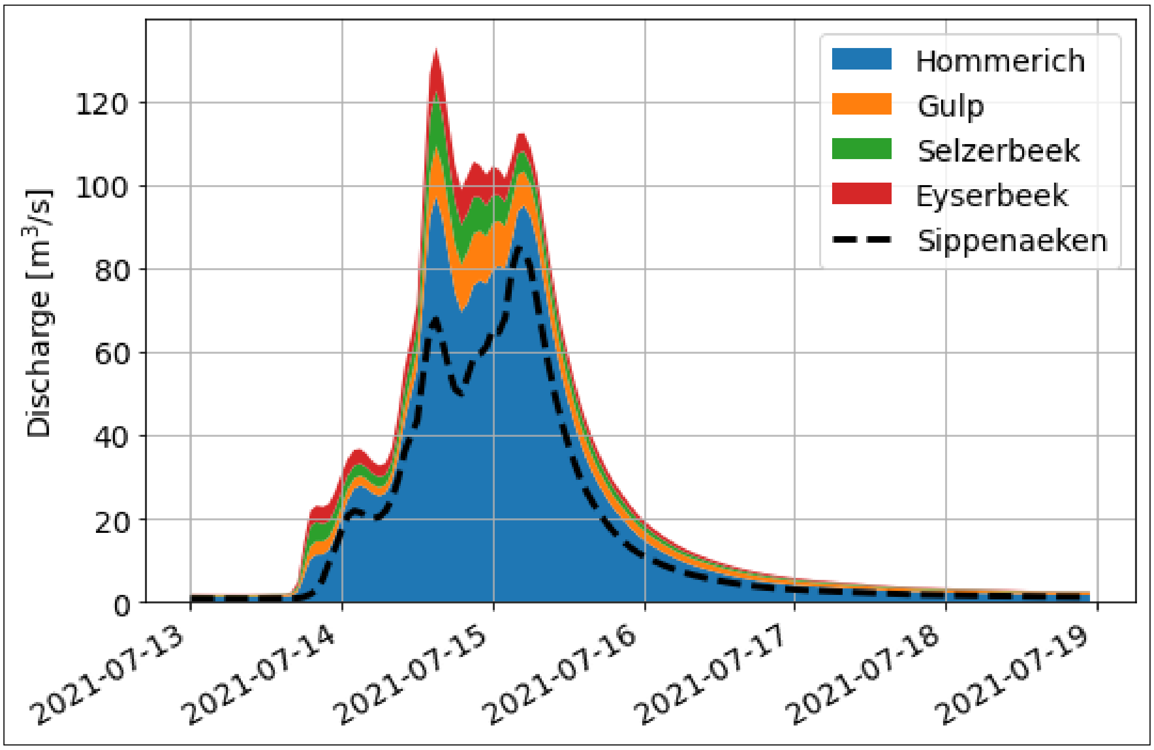

Figure 4.25: Discharge contributions at the confluence close to Gulpen from the three tributaries and the main branch of the Geul for the July 2021 event

The contributions based on the cumulative discharges per subcatchment are shown in table 4.10. Comparing these contributions to the average long-term contributions calculated in section 4.1.3, one can see that the contribution of Geul is much higher (75.6% vs. 66.5%) and of the Gulp is much lower (10% vs. 20%) than the long-term average. The event contributions are in alignment with the observation that in high discharge scenarios, the contribution from the Geul increases compared to the tributaries. Relating the flood contribution to the related area, the tributaries account for 40% of the contributing area at Gulpen, although only 24.4% of the cumulative discharge originated from there. Looking at the spatial distribution of the rainfall per subcatchment (based on the KNMI final reanalysis) it can be seen that the cumulative rainfall amount along the Geul was higher than at the tributaries.

Table 4.10: Flood contributions based on cumulative discharges (July 13 - 18, 2021) at the confluence near Gulpen in comparison to contributing area and long-term contributions

Subcatchment	Contributing Area [%]	Long-term Contribution [%]	Event Contribution [%]	Event Rain [mm]
Hommerich (Geul)	60	66.5	75.6	154
Gulp	18	20	9.9	128
Eyserbeek	11	5.5	7	130
Selzerbeek	11	8	7.5	129

The discharge from Sippenaeken is shown as a black dashed line in figure 4.25 to visualize the amount of water which originated from the Belgian catchment area. It can be seen that, while during the first peak the tributaries contributed strongly to the discharge (more than 25%), the second peak on July 15th consisted to 75% from water originating from Belgium. In total 60% of the water in Gulpen originated from Belgium although it is only 45% of the total size.
To better understand the role of the geology in the difference in contributions of the tributaries and the Geul, the contributions have been calculated assuming that the tributaries received the same rainfall amount as the upstream area of Hommerich (scenario 1: 130 mm/48-hours, scenario 2: 154 mm/48-hours). Table 4.11 shows that in both scenarios the contributions from the Geul decreased (-5 - 7%) and the contributions from the tributaries increased. However the discharge from the Geul is still higher than its long-term contribution and the contribution based on its contributing area (+8 - 10%). In both scenarios approximately 55% of the water in Gulpen originated from Sippenaeken.
Hence, the difference in contributions is not purely linked to the spatial heterogeneity of the rainfall sums, but also to the different (hydro)geological characteristics. The corresponding runoff coefficients for scenario 1 and 2 can be found in table D.6.

Table 4.11: Comparison of flood contributions at the confluence near Gulpen based on two scenarios. Scenario 1: The upstream area of Hommerich received the same rainfall amount as the tributaries (130 mm/48-hours), Scenario 2: The tributaries received the same rainfall amount as the upstream area of Hommerich (160 mm/48-hours)

Subcatchment	Contributions		
	Event [%]	Scenario 1 [%]	Scenario 2 [%]
Hommerich (Geul)	75.6	68	70
Gulp	9.9	12.9	13.5
Eyserbeek	7	9.2	8
Selzerbeek	7.5	9.9	8.8

4.3.6. Effect of Antecedent Conditions

The data analysis showed that, although the weeks prior to the event were wetter-than-usual, the catchment was not completely saturated at the onset of the floods. To test this hypothesis, several scenarios were run to investigate the effect of antecedent conditions (AC) in the catchment as described in section 3.3.6.

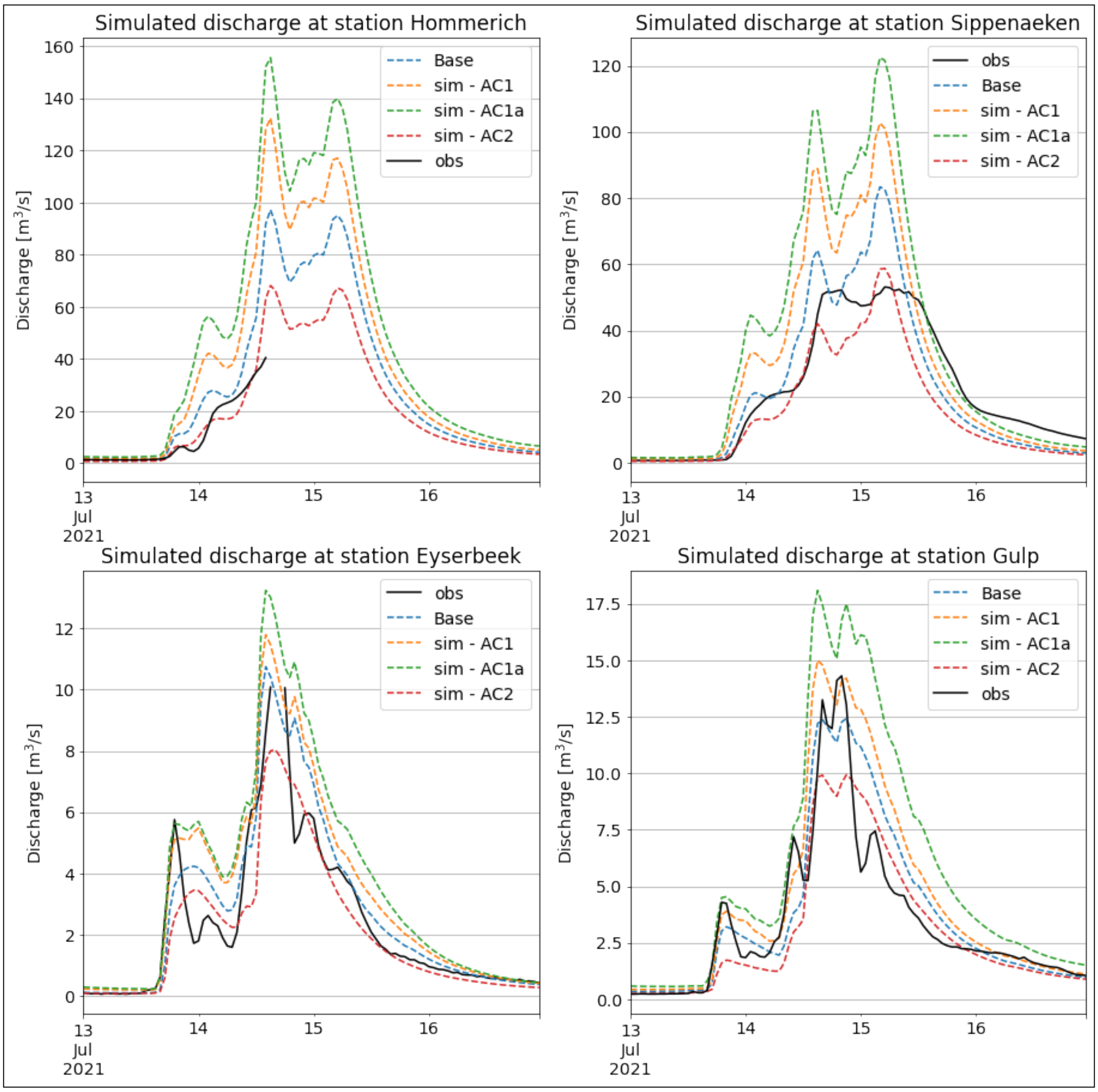

Figure 4.26: Effect of antecedent wetness conditions on the discharges of the event in July 2021 for Hommerich, Sippenaeken, Eyserbeek and Gulp. Different scenarios: AC1a - 100% more pre-event rain, AC1 - 50% more pre-event rain, AC2 - 50% less pre-event rain, Base: adjusted model, obs: discharge observations

In figure 4.26 the simulated runs are shown exemplary for a few points in the catchment. It can be seen that an 100% increase in the rainfall quantities during the four weeks prior to the event (*run AC1a*) would lead to an increase of the peak discharges of approx. 50 %. As the discharges would increase quicker combined with a slower recession, the increase in cumulative discharge is significant (30% and 65% for the different subcatchments) (see table D.7). The highest increases are simulated for Sippenaeken and Kelmis which links back to the limited storage in that area.
In figure 4.26 it can also be seen that the tributaries react differently to a change in wetness conditions. While the cumulative discharge of the Eyserbeek increased by 85% between run AC1a and run AC2, the cumulative discharge of the Gulp increased by a 100%. Since the Gulp is situated in a different geohydrological zone (Zone 5/4 vs. Zone 4) than the Eyserbeek and Selzerbeek, it reaches its storage

capacity earlier.
Decreasing the rain prior to the event (*run AC2*) illustrates that a dry catchment would have been able to dampen the peak discharge stronger. In that case an additional 4.8 $x10^6 m^3$ water could have been stored in the system.
The different wetness conditions have a profound impact on the runoff coefficients. The runoff coefficients along the Geul increase much stronger due to a change in wetness conditions than the runoff coefficients of the tributaries (see table D.9). The wetter the catchment, the stronger is the response from the upstream catchment and consequently the higher the contribution on the overall flow as visualized in figure 4.27. Even in the wettest scenario, the tributaries are still able to store additional water.

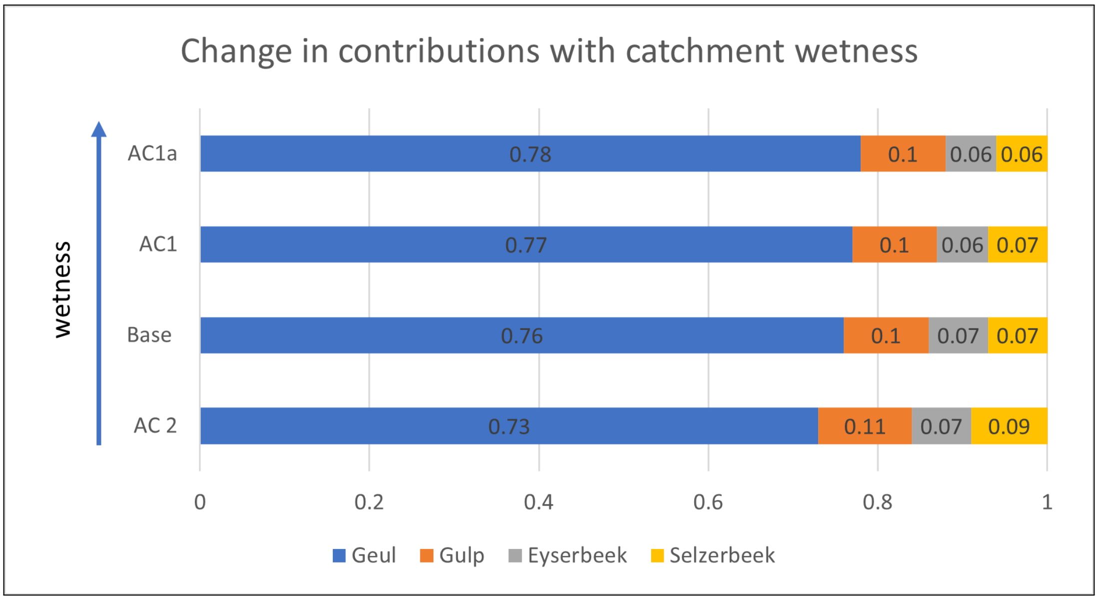

Figure 4.27: Contributions of the tributaries and the Geul based on cumulative discharges (July 13 - July 18) shown for the different wetness scenarios. Different scenarios: AC1a - 100% more pre-event rain, AC1 - 50% more pre-event rain, AC2 - 50% less pre-event rain.

4.3.7. Effect of different Rainfall Volumes

The 48-hour event rainfall sums of the neighbouring catchments show great differences. While 50km north of the Geul catchment (in the Ardennes) 30% more rain was measured, the neighbouring Geleenbeek catchment received 30% less rain. The impact of this variation in rainfall was investigated. Figure 4.28 visualizes the strong impact of the rainfall amount on the event discharges. Decreasing the rainfall amount by 30% (*Precip2*) leads to a reduction of the peak discharges by 45-70% for the subcatchment. The cumulative discharge would be reduced by 5.2 $x10^6 m^3$, which is similar to the discharge simulated for a dry catchment.

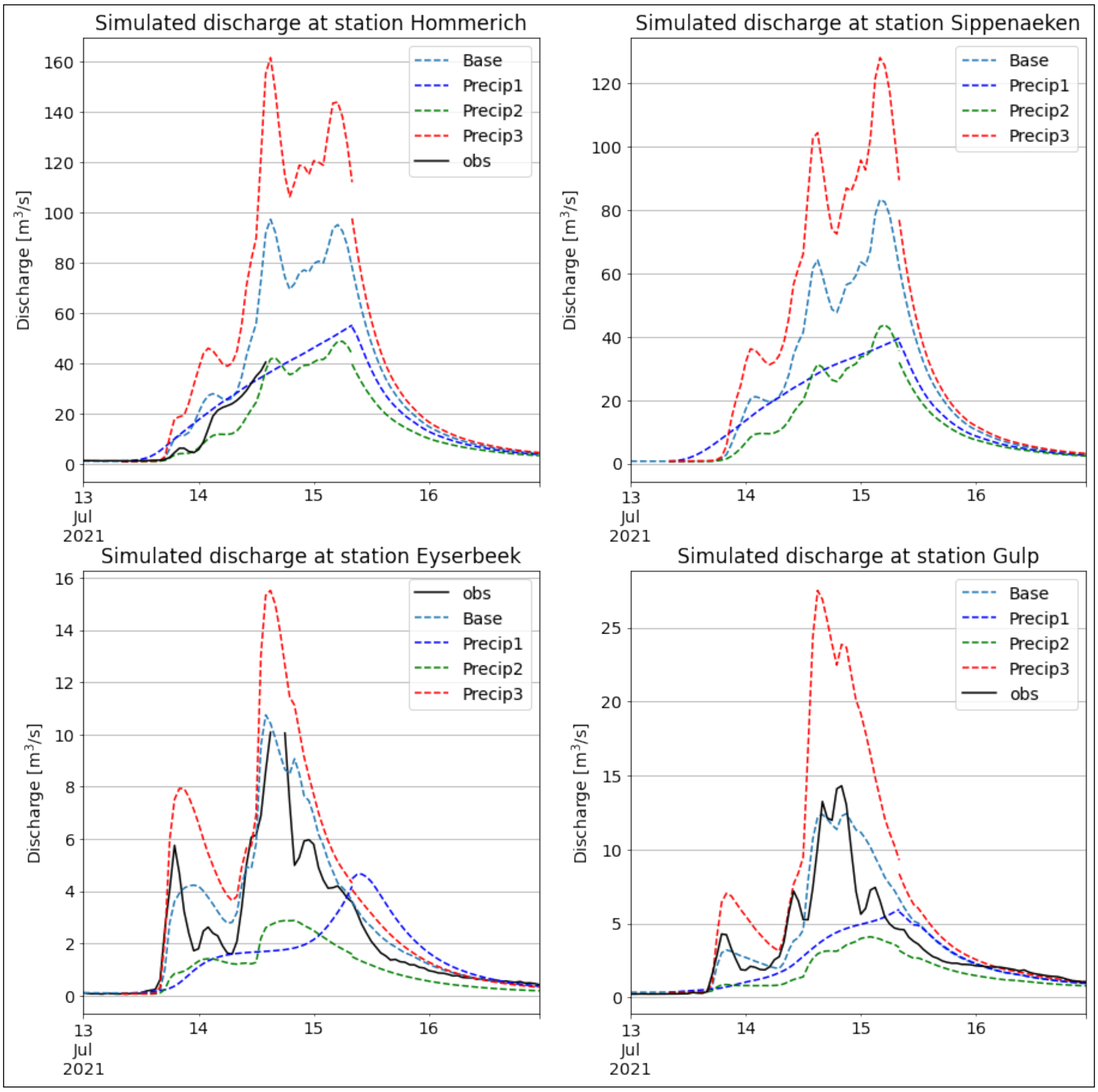

Figure 4.28: Effect of rainfall volume on the discharges of the event in July 2021 for Hommerich, Sippenaeken, Eyserbeek and Gulp. Different scenarios: Precip1: average rain, Precip2: 30% less rain, Precip3: 30% more rain, Base: adjusted model, obs: discharge observations

Increasing the rain (*Precip3*) resulted in a strong response of the catchment. The peak discharges would on average increase by 70% and the cumulative discharges would double. At figure 4.28it can be seen that especially the Gulp catchment reacts very strongly to the increase in rain (peak discharge 2.3 x base), while the upstream catchments (Sippenaeken - peak discharge 1.5 x base) reacts less strong. With increasing rain the catchment characteristics become less important and mainly the precipitation amount determines the discharge. Hence with increasing rain, the contribution of the Geul decreases compared to the tributaries. This can be seen in figure 4.29.

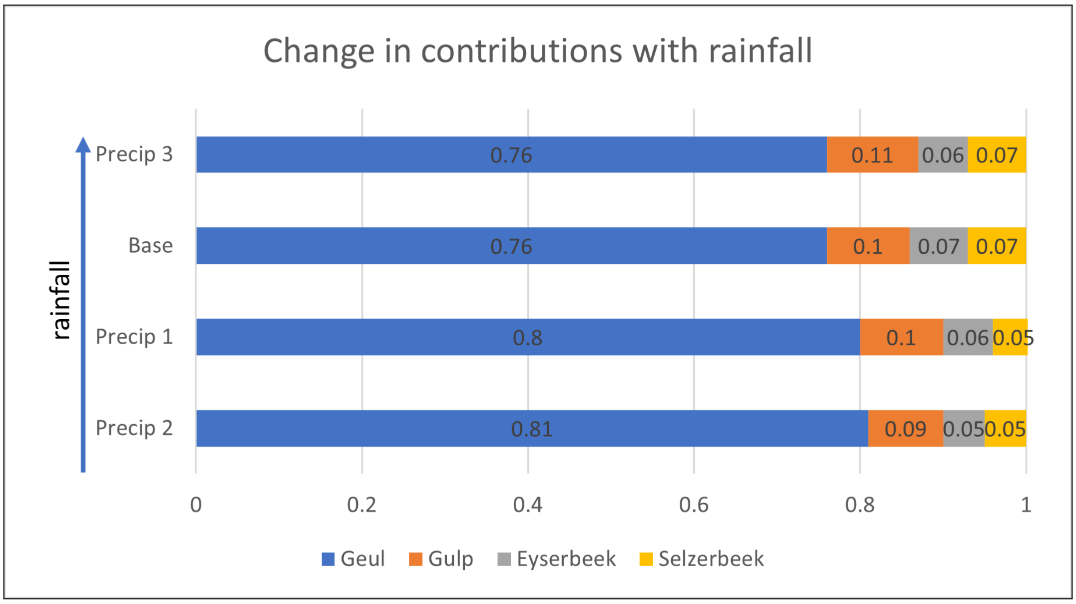

Figure 4.29: Contributions of the tributaries and the Geul based on cumulative discharges (July 13 - July 18) shown for the different rainfall scenarios. Different scenarios: Precip1: average rain, Precip2: 30% less rain, Precip3: 30% more rain.

Assuming an average distribution of the original rain amounts (*Precip1*), has a similar effect on the peak discharge as a reduction of the rainfall by 30%. In this case the discharge increases with a delay and shows only one peak. Looking at the contributions, it can be seen that a spatially uniform rain distribution also results in a high contribution of the Geul compared to the tributaries.

4.3.8. Effect of different Infiltration Capacities

Changes in the infiltration capacity can be used as a proxy to simulate the effect of land-use changes in the model. From figure 4.30it can be seen that the current infiltration capacity in the model is set so high (600 mm/day), that a variation of +/- 50% (*IC3 / IC1*) has no influence on the discharge, and consequently no hortonian overland flow takes place in the model. When lowering the infiltration capacity to 60 mm/d (*IC2*), the peak and cumulative discharges increase by 60% and 40%, respectively. The increase is much stronger in the Gulp catchment than in the Eyserbeek, as it is less urbanized and the decrease in infiltration capacity would have a stronger effect on the current infiltration capacity. The effect is very limited, however, on the upstream catchment (see Sippenaeken on fig 4.30) as the storage capacity there is already the limiting factor. 60 mm/day is equivalent to the infiltration capacity determined for loess ground (see section 2.4). However based on the discharge behaviour the infiltration capacity of the loess grounds must be higher in reality.

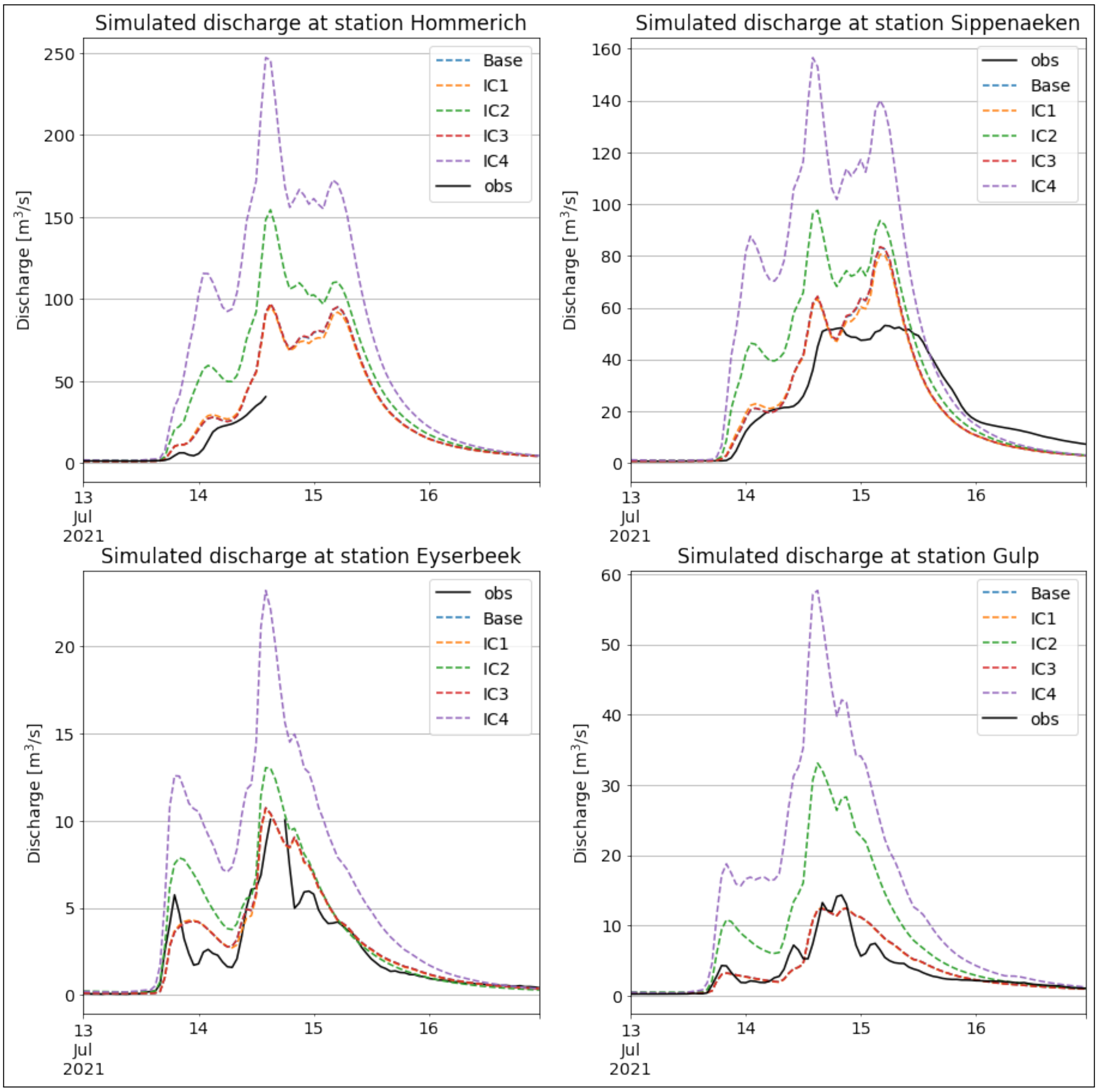

Figure 4.30: Effect of infiltration capacity on the discharges of the event in July 2021 for Hommerich, Sippenaeken, Eyserbeek and Gulp. Different scenarios: IC1 - infiltration capacity is reduced by 50%, IC2 - reduced to 10%, IC3 - increased to 150%, IC4 - reduced to 5 mm/d in the whole catchment, Base: adjusted model, obs: discharge observations

The decrease of infiltration capacity leads to a quicker and flashier response. Lowering the infiltration capacity even stronger to 5mm/day (*IC4*), pretending that the whole catchment consists of paved surfaces, resulted in a strong increase of peak and cumulative discharges by a factor of 2.3. This scenario illustrates the difference between the Geul catchment with a high infiltration and storage capacity and a catchment which lacks this capacity.

5 Discussion

In this chapter, first the implications of the key findings will be discussed and compared to other studies. Secondly, the assumptions and limitations of the wflow-sbm model are examined.

5.1. Implications

The role of Geology

The catchment analysis showed that the hydrologic response differs among the subcatchments of the Geul. Due to its geological setting the Belgian upstream area of the catchment is characterized by thin soils and low storage capacity, whereas the downstream areas consist of a thick unsaturated zone. Thus, the long-term contribution of the Geul (66.5%) compared to the tributaries at the confluence near Gulpen is higher than its relative size (60%). The results of the event analysis showed that the geology also played an important role in the catchment response of the event. The contribution of the Geul at Gulpen for the event was 76%. Model runs assuming equal rainfall over the catchment, suggested that without the difference in event rainfall sums (approx. 160 mm in the Belgian catchment and approx. 130 mm in the tributaries) the contribution of the Geul would have been approximately 68 - 70%. That geology provides a control on runoff response and can lead to pronounced contrasts in flood response between nearby basins had also been observed in other flash floods, such as in West Slovenia 2007 (Zanon et al., 2010), where karstified limestones in some of the basins attenuated discharges significantly. In the Geul catchment 60% of the cumulative discharge at Gulpen originated from the Belgian area, although the Belgian part of the catchment covers only 45% of the catchment area. This contrast in flood responses between the subcatchments is important to consider in the discussion about flood protection measures for the cities and villages downstream in the catchment, especially for the city of Valkenburg. The city is flooded in these high discharge scenarios when over-proportionally much water originates from the Belgian part of the catchment. Measures aimed at keeping the water upstream of Valkenburg, will have the greatest impact when implemented in the Belgian part of the catchment. A possible measure could be to increase the inundation areas between Kelmis and Sippenaeken.

Land-use Effects

Nature organisations claim that land-use changes have amplified the response to the extreme rainfall in South Limburg and therefore it is essential to provide more space to the river, to increase inundations areas, and to replace arable land with forests (Meertens, 2021, Klip, 2021, Haas, 2021). However, the exact role of land-use changes in modifying river floods is still elusive (Hall et al., 2014). The difference in hydrological response of the tributaries and the main river can be linked to the differences in (hydro)geology, but the effect of land-use on the hydrological response is more difficult to capture from the analysis of the flood event. Comparable results have been observed for other flash floods (Gaume et al., 2004). The effect of land-use changes on the peak discharges of flash floods in the Geul catchment has been investigated by Dautrebande et al. (2010) in a pilot project. However, the proposed land-related measures were not able to decrease the peak discharge by more than 10%.
The urbanized areas, especially in the upstream areas of Sippenaeken, Eyserbeek and Selzerbeek,

lead to a quick and flashy response of the catchments. This is aggravated by the fact that urban run-off is often directly routed to the river. Consequently, the unit peak discharge of the Eyserbeek (0.44 $m^3/s/km^2$) is higher than of the Gulp (0.30 $m^3/s/km^2$), which is less urbanized (10% vs. 16%) and has more forests and grasslands (26% vs. 6%). Measures to slow down urban-runoff and to allow for infiltration, could reduce the flashiness.

Infiltration Capacity

The results from the groundwater analysis, event runoff coefficients and model scenarios contradict the common connotation that the infiltration capacity of the catchment is small due to its loess soil cover. The infiltration capacity might vary greatly within the catchment, but the flow characteristics of the subcatchments indicate that there must be areas which act as major infiltration zones. Especially the tributaries Eyserbeek and Gulp are characterized by high base flows (Q10/Q95 index of 3.6 and 4), which in dry times leads to higher contributions of the tributaries than in wet periods. While the Gulp only contributes approximately 15% to the flow during the winter season, the contribution in late spring can increase to 25% to the total flow at Gulpen. The ability to store the water long-term can also be seen in many of the groundwater wells, which had a higher groundwater level after the summer than before the event. Based on the simulation, more than 75 mm of water was stored in the catchment area upstream of Gulpen. This supports the results from the data analysis on the high storage capacity of the catchment. The high storage capacity has also been analysed by a recent study by stroming (Winden, 2022) about the water buffering capacities of the Geul catchment during the event. Based on the study 80 - 85% of the precipitation in the central Geul catchment and 50 - 65% in the Belgian catchment area did not contribute to the discharge. These numbers are in agreement with the runoff coefficients obtained by the data analysis and the model, which suggested that 72-79% (tributaries) and 59-61% (Belgian catchment area) of the water was not discharged.

Antecedent Conditions

TU (2006) showed in his research about the effects of climate variability and land use change on the hydrology of the Maas river basin that in the Geul catchment the antecedent k-day precipitation of up to 30 days is correlated with peak discharges (Tu, 2006). The wflow-sbm model also showed that antecedent wetness conditions impact the severity of the discharge response in the catchment. The 30 days prior to the event have been wetter-than-usual. Based on the antecedent precipitation index most areas in the catchment are classified at the threshold between normal and wet. This translates to 50% more rain recorded in the catchment compared to the long term average. Drier soil moisture conditions (50% less rain), would have led to a reduction of the peak discharges by 20 - 30% and the cumulative discharge would have been reduced by approximately 4.2 x 10^6 m^3 upstream of Valkenburg. This is already 70% of the volume necessary to be additionally stored upstream in order to avoid any flooding in Valkenburg as estimated by Deltares (van Heeringen et al., 2022). The model also illustrated the effect of what would have happened if the catchment would have been wetter. Increasing the antecedent rainfall by 50%, peak and cumulative discharges would have been increased between 20 - 40%, and an extra 4 x 10^6 m^3 water would have needed to pass through the city of Valkenburg. Furthermore, with increasing wetness also the contribution of the upstream catchment compared to the tributaries increases, intensifying the need for water retention measures in Belgium to keep Valkenburg dry.
Due to climate change, wetter summers and an increase in rainfall extremes in the summer are predicted for Europe and the Netherlands (KNMI, 2021, Allan et al., 2021). Tsiokanos (2022) showed that from 1980 on all extreme precipitation indices show statistically significant, strong and stable increasing trends for the summer in the Geul catchment. The frequency of very heavy (>30mm/d) and severe (>40mm/d) precipitation days increased, as well as the magnitude and duration of precipitation events (Tsiokanos, 2022). Consequently, the expectation of the winter season as the usual flood season (20 out of 24 four floods happened in the winter) needs to be revised and the impact of heavy rainfall in summer in combination with wet antecedent conditions has to be accounted for.

Post-Flood Surveys

As mentioned in the introduction, extreme events offer the opportunity to observe catchment behaviour when most flow paths are active (Borga et al., 2008). However, similar to most flash floods data scarcity is a challenge also for the Geul (ENW, 2021, Amponsah et al., 2016). Only 3 out of 9 discharge stations were able to measure the event discharges. Especially in the Dutch part along the Geul no discharge station captured peak discharges. A structured post-flood survey as explained by Gaume et al. (2008) with the objective to gather information on peak discharges, timing and sediment transfer processes covering the whole catchment can close this data gap. For the Geul catchment such a survey has not been performed (Gaume and Borga, 2008). For this reason, most observations have been made in places where most damages were observed (e.g. Valkenburg, Schin op Geul and Meerssen/Bunde) and information is limited on processes (such as erosion, landslides) in the upstream areas of the catchment, where the water originated. The missing data limited the ability to constraint the model based on post-flood observations as it is usually done for models reproducing flash flood events (Borga et al., 2008). A catchment wide survey should be included in the post-flood activities. The data will be a great support when evaluating flood mitigation measures later.

5.2. Wflow-sbm Model

5.2.1. Reflections on the Model Set up

Due to its high heterogeneity and complex geohydrology, the Geul catchment has been challenging to model. Nevertheless, it is promising that the wflow-sbm model is capable of reproducing the heterogeneity of the catchment and the different hydrologic behaviours of its subcatchments. As a physically-based model, it also allows further analyses of the effect of land-use change. The model adjustments showed that an in-depth study of the catchment characteristics was a great benefit for setting up the model and allowed to focus on the parameters - soil thickness, maximum leakage and KSHF - which are dominant factors for the runoff generation in the Geul catchment. Using pedotransfer functions to distribute parameters in the model based on input maps, ensured a fast and physically-based set up of the model parameters.

However, the process of distributing the soil thickness throughout the model based on soil maps does not work well for catchments with a thick chalk layer underneath. For this reason, the unsaturated zone in the model is too small and the flow is overestimated. The same behaviour has been observed for other chalk catchments as well, such as in England (A. Weerts, personal communication, April/2022). The limitation is not only on integrating the chalk properties into the model, but also on the knowledge of the chalk properties itself. Bell et al. (2009) used a adjusted G2G model (similar to wflow-sbm) and a detailed soil data set to improve the streamflow simulation for the UK catchments, where geology plays an important control on the runoff response (Bell et al., 2009). To apply a similar approach to the Geul catchment also detailed information on the hydraulic conductivity and the decay of the hydraulic conductivity with depth is required, next to the thickness of the unsaturated zone. Further research is needed in order to better understand the physical properties of the chalk in the Geul catchment and to apply them meaningful in a model.

Model Forcing

A model can only be as good as the quality of its input data. As part of this research different precipitation forcing data sets have been compared to each other. As real time radar underestimated the rainfall amounts by a factor 2 to 3 in places (Overeem and Leijnse, 2021), only reanalysis products were compared. The tested data sets differed strongly in precipitation amounts and in regard to the event 10% less or more rain can have a great effect on the peak (-30% and +15%) and cumulative discharges (-16% and +20%). The KNMI data set was the only available data set which spatial and temporal distribution was in agreement with the measured station data for the Geul catchment. Due to the high sensitivity of the discharges to rainfall, a comparison of the available precipitation products minimized the uncertainty of the forcing data. However, no research has been done to estimate the uncertainty of the KNMI reanalysis. In general the quality of the gauge-adjusted radar rainfall estimates is linked to the distribution of gauges over the catchment. Consequently, parts with a lower gauge density network are likely to have a lower quality of rainfall estimates. In the Geul catchment the density of used automatic and manual gauges is a bit lower in the Belgian part of the catchment than in the Netherlands (A. Overeem, personal communication June/2022).

KSHF

The calibration results illustrated that the KSHF parameter has a great impact on the relation between base flow and storm flow and with that strongly influences the model results. Ranging the KSHF distribution with a factor from 0.5 to 2.5 leads to a range in peak discharges at Hommerich from 80 m^3/s to 140 m^3/s for the event.

By translating the vertical into a horizontal conductivity, the KSHF parameter links the vertical to the horizontal flow. Since the vertical processes are much more detailed and refined in the model, the KSHF parameter also compensates for lateral processes which are not explicitly modelled such as preferential flow paths and groundwater flow. In contrast to other model parameters, the KSHF cannot easily be linked to physical observations and is often calibrated based on the discharge observations. However, this method poses an elevated risk of equifinality (Kirchner, 2006), so the parameter range must be constrained to the physical catchment conditions. In this study the KSHF parameter has been distributed through the catchment based on the existence of highly productive aquifers (Bouaziz, 2020), but calibration was still required.

5.2.2. Model Limitations

In this section the limitations of the model structure, adjustments and calibration are discussed. The items are numbered for clarity and do not indicate a prioritization. Recommendations are given where applicable.

1. **Bias to high flows:**
   As the model was used as a tool to reproduce the flood event in July 2021, the model has been calibrated with the NSE as the main performance indicator which focuses on the accuracy of the high flows.
2. **Balancing of overall catchment performance:**
   The calibration was aimed at achieving an overall good performance for all subcatchments, therefore not each subcatchment is calibrated equally well. With the calibration NSE values, above 0.5 were achieved for 5 out of the 9 subcatchments.
3. **Observation Quality:**
   The quality of the observations differed per station. Especially the Belgian data contained some artifacts which decreased the NSE value of the fit as can be seen in fig 5.1.

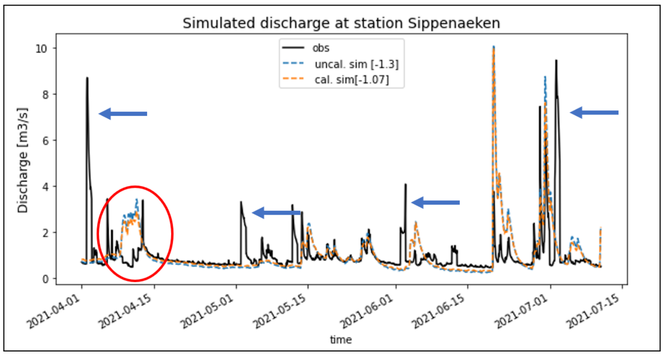

Figure 5.1: Comparison of discharge observation and model observations for Sippenaeken from 1.4.2021 with 15.7.2021. Blue arrows indicate artifacts in the discharge data, red circle indicates artifacts from rainfall data

   Additionally, some stations have long periods of missing data in the last years (e.g. Hommerich and Meerssen), so that only limited data was available.
4. **Calibration quality:**
   The KSHF parameter has been calibrated on a six month period in 2020, when observations for all catchments were available. However, when running the model for 2021 the performance is reduced and flows again tend to be overestimated (see figure D.6). Calibrating the KSHF on a longer period could further increase the model performance.
5. **No Hortonian overland flow:**
   The infiltration scenarios showed that the infiltration capacity of the soil is set so high in the model (600 mm/d) that no Hortonian overland flow on soil takes place in the model. As Hortonian overland flow outside of urbanized areas is not common in the catchment (see section 2.4), the impact on the reproduction of the floods is limited. However, overland flow may play a greater role with increasing wetness and rainfall.

6. **No downstream simulation:**
The model has not been linked to a hydraulic model and therefore cannot be used to estimate the discharges in the downstream part of the catchment. Due to the extensive flooding of the cities of Valkenburg and Meerssen, combined with the backwater effect from the Maas (Geertsema et al., 2018), the conditions are too different from a natural flowing river to be correctly simulated by a hydrological model.
7. **Groundwater Storage:**
The wflow-sbm model does not include a separate groundwater bucket. Groundwater flow in deeper aquifers is treated as leakage and the water is leaving the model. A coupling between wflow-sbm and a groundwater model (e.g. MODFLOW) would allow to model the groundwater impact on the July 2021 event. A groundwater model could better represent the complexity and heterogeneity of the geohydrology.
8. **Global Data Sets:**
The model is set up based on global/European data sets. Local data sets, especially related to soil and geology parameters can further improve the parameter distributions.
9. **Model Resolution:**
The model used for this study had a grid size of 0.00833° (or approximately 600 m x 925 m), also a more refined model of a grid size of 0.000833° (or approximately 60 m x 92.5 m) has been tested. By comparing both resolutions, the fine model did not improve the model performance (see E.1). However a calibrated model with fine resolution might be necessary, especially for the study of land-use effects.

6

Conclusions and Recommendations

6.1. Conclusions

The aim of this study was to investigate the hydrologic response of the Geul catchment to the extreme rainfall event in July 2021. This was achieved by a combined approach of data analysis and modelling. The wflow-sbm model was set up and adjusted by integrating the knowledge from the analysis of the catchment characteristics. The model was used to reproduce and to investigate the effect of changing conditions on the event. To conclude this thesis the research questions as presented in section 1.3 are answered.

1. *What are the characteristics of the rainfall and (flash) flood at the Geul catchment in July 2021?*

   The entire Geul catchment received high rainfall amounts during the event. On average the catchment received approximately 128 mm in a 48-hour period (based on the KNMI final reanalysis). The rainfall amount was not homogeneously distributed over the catchment. While in the Belgian part of the catchment and around Ubachsberg 48-hour sums were above 160 mm, at the outlet 48-hour sums were approximately 100 mm. The event rain was characterized by three distinct peaks in the rainfall pattern, a signature which can also be seen back in the discharge observations.

   The overall event runoff coefficient of 32% is fairly small for such an extreme event. The floodplains as well as the thick unsaturated zone at the chalk plateaus stored much water and considerably attenuated and delayed the peak. The rapid response of the groundwater wells to the precipitation and their increase in groundwater level of several meters in the chalk areas gives an indication of the high infiltration and storage capacity, especially at the chalk plateaus. The catchment can store water long-term as groundwater levels were still increased after the summer compared to pre-event levels.

   The discharge response of the catchment differed strongly between its subcatchments, especially between the tributaries and Sippenaeken, the Belgian upstream part of the catchment. While the event runoff coefficient for the Belgian part is 41%, the runoff coefficients for the tributaries Gulp and Eyserbeek are 21% and 25% respectively. Consequently, the Belgian part contributed about 60% to the flow in Gulpen, although its contributing area is only 45%. The differences in hydrologic response can be partly linked to the different rainfall accumulations and partly to the geology. While the tributaries are situated in areas with thick unsaturated chalk layers beneath (40 - 100 metres at the chalk plateaus), the Belgian upstream area is characterized by thin soils and impermeable bed rocks at the river bed which strongly limit the storage capacity (0 - 20 metres of unsaturated chalk layers).

2. *Is it possible to reproduce the hydrologic response of the Geul catchment with any of the existing models? What improvements / changes are necessary to reproduce the event?*

   A wflow-sbm model originally set up for the Maas was used to reproduce the event and to assess different scenarios in regard to antecedent wetness conditions, rainfall patterns and infiltration capacities. As the KNMI (final reanalysis) data set showed the best agreement with the temporal and spatial rainfall distribution of the event, as recorded by the local rain gauges, it was used as precipitation forcing for the model. The original model overestimated the discharges in the catchment strongly (by a factor 1.4 - 3.4 of observed yearly cumulative discharges), as the model did not account for the thick unsaturated chalk zone in the catchment. However, the model was able to reproduce the signatures of the hydrographs more closely during drier periods and in the Belgian upstream part of the catchment (by a factor 1.4 - 1.6), characterized by thin soils and low storage capacity. Three adjustments to the model were made to improve the performance:

- Adjusting the soil thickness distribution
- Adding a maximum leakage parameter
- Calibrating the KsatHorFrac Parameter (Parameter which links the vertical flow to the horizontal flow)

The model has been calibrated and validated on discharge data from 2020 - 2021 and is able to reproduce the distinct discharge patterns of the subcatchments. However the quality of the calibration varies between the subcatchments and between different time periods applied. The adjustments corrected the overestimation of the discharges, the simulated cumulative yearly discharges are within a range of 0.6 to 1.4 compared to the observations. Also, the simulated event discharges are in good agreement with the (limited) observations and estimations in terms of absolute values (>20% difference) and signature characteristics.

3. *What role did the antecedent wetness conditions play on the floods in July 2021?*

   The month before the event on average 50% more rainfall was recorded in the Geul catchment than the long-term average. Accordingly, based on the antecedent precipitation index (API), the catchment lies on the threshold between normal and wet conditions. Assuming average July wetness conditions, the event peak and cumulative discharges would have been 20-35% lower (depending on the subcatchment), as an additional 4.8 x 10^6 m^3 water could have been stored in the catchment upstream of Valkenburg. Consequently, the wetter-than-usual antecedent wetness conditions increased the severity of the flood from being minor (under normal conditions) to the major flooding which was experienced in the downstream catchment areas. However, as discussed in chapter 5, due to climate change wetter summers might become more frequent and therefore the role of antecedent wetness will become even more important.

4. *What were the individual contributions from the different brooks in the catchment? Are there notable differences in rainfall – runoff relationships between the brooks?*

   The contributions of the three main tributaries - Gulp, Selzerbeek and Eyserbeek - and the main branch (Geul) have been evaluated at the confluence near Gulpen. The long-term average contributions (from 2000 - 2020) of the tributaries showed seasonal changes. The contribution of the Geul was usually highest in winter (65% - 72%). In spring/summer the contributions of the tributaries increased, reducing the contribution of the Geul to 60 - 63%, whereas the Gulp showed the largest increase (5 - 10%). During the event, the Geul contributed even 76% to the total cumulative event discharge, which was driven by the high discharge from the Belgian upstream catchment.

   From the model scenarios it can be seen that the contributions change with catchment wetness and rainfall amount. With increasing the API from 1 to 3 for a similar rain event, the contribution of the Geul will increase to up to 78%. However, by increasing the rainfall amounts even further compared to the actual event rainfall, the different catchment characteristics become less important. The contribution of the Geul compared to the tributaries will not increase further in that case.

   There are notable differences in the rainfall - runoff relationships between the different brooks, which are visible in the long-term as well as for the event. These differences are therefore not only linked to differences in rainfall patterns, but also to the different hydrogeological zones the tributaries and the main branch are located in.

5. *What hydrological information can be used to aid the decision-making in regards to flood mitigation measures and early warning?*

The hydrological information from this study can be used to take short-term measures to improve the early warning system and long-term measures about the planning and design of flood mitigation measures.
In case of a heavy rainfall event, discharge and water level measurements are critical to estimate the severity of the flood wave. However, currently the first reliable Dutch discharge measurement along the Geul is near Hommerich which is in the central part of the catchment (as the measurement weir at Cottessen has a limit of 27 m^3/s). A flood wave from Hommerich takes only approximately 4.5 hours to reach Valkenburg. There are two discharge stations in the Belgian upstream part of the catchment in Kelmis and Sippenaeken, which kept working even in July 2021. These can give an early indication of the severity of the situation. Connecting these data points into the early warning system will increase the lead time by approximately 6 hours as well as the accuracy of the system. Especially with the understanding that the contribution of the upstream catchment is over-proportionally high in extreme situations, a permanent data transfer is of high value.
Additionally, the robustness and bandwidth of the existing discharge measurements should be improved. During the event, no discharge measurement along the Dutch part of the Geul kept working. Furthermore, the installation of additional discharge stations (e.g., at the Dutch/Belgian border of the Gulp) should be evaluated.
The understanding of the catchment characteristics and the interaction of different processes on runoff generation can support the choice of flood mitigation measures. This research showed that the geology is a dominant control on the response of the catchment. The impact of flood mitigation measures can be maximized by taking the role of geology and its interaction with the effect of land-use changes for the Geul catchment into account in the selection process. Flood mitigation measures are especially required in the Belgian upstream part of the catchment. Retaining water there already will attenuate and delay peak discharges at the villages and cities downstream.

6. *Is it possible to determine the effect of land-use change on the impact of the flood?*

   The effect of land-use changes on the impact of the flood is difficult to quantify. In general, it can be seen that urbanization in the upstream catchment areas, like in Kelmis, Eyserbeek and Selzerbeek catchment increases the flashiness in response compared to catchment which are less urbanized, like the Gulp. The high event unit peak discharges of the Eyserbeek compared to the Gulp (0.44 vs. 0.3 $m^3/s/km^2$) can be linked to the rapid response of urban runoff, as both catchments received the same rainfall and have similar storage capacities. The effect of land-use was simulated in the wflow-sbm model by adjusting the infiltration capacity. On a subcatchment level, the sensitivity of the response to changes in the infiltration capacity differs. While the Gulp catchment reacts strongly to a reduced infiltration capacity of 60 mm/d (peak discharge increased by 160%), the peak discharge of the Belgian upstream catchment only increases by 20%. This emphasizes the link between land-use change effects and geology in the catchment.

6.2. Recommendations for further research

Understanding of the regional water system
The event in July 2021 showed that the understanding of the regional water system (e.g. tributaries to the Maas) in the Netherlands was limited compared to the main river systems (e.g. Maas). This research aimed to contribute to closing this gap. Consequently, as a next step the interaction of the regional systems with the major river systems (Geul with the Maas) could be evaluated for such an event. The simultaneous occurrence of discharge peaks in the Maas and the Geul resulted in extensive flooding at the confluence in Bunde and Meerssen (ENW, 2021, de Jong and Asselmann, 2022). To understand the mechanisms behind simultaneous peak discharges at the confluence the methodology as explained in Geertsema et al. (2018) could be applied (Geertsema et al., 2018).

Water Retention Basins
Due to the rainfall pattern the downstream part of the catchment (downstream of Gulpen) received high rainfall amounts earlier (during the first rainfall peak on July 13th at 5pm), while the upstream catchment received stronger second and third rainfall peaks on July 14th at 8am and 1pm. For this

reason, the water from the lower Geul catchment was discharged to the Maas (first peak), before the high water amounts from the upstream part of the catchment arrived (second and third peak) 20 hours later. Increasing water retention in the central and lower part of the catchment (downstream of Hommerich) and therewith delaying the flood wave, might result in coinciding flood waves and increasing peak discharges.
More than 400 water retention basins have been built in the catchment so far and as a result of the flood event many more are planned. With increasing water being buffered in these basins, the timing effect of these buffers needs to be evaluated. Automation of the water retention areas could be a feasible way to avoid retaining water at the wrong moment and at the same time could increase the efficiency of the system greatly (Hall et al., 2014).

Hydraulic Analysis
As an outcome of this study, a wflow-sbm model of the Geul catchment has been set up which is able to simulate the different hydrological responses on a subcatchment level. Coupling the model to a hydraulic model (e.g. D-Hydro) of the Geul will allow to model the discharges and water levels in Valkenburg and other flooded areas. Such a combined model would allow to gain more insights about the impact of different flood mitigation methods on peak flows. Results could be compared to recent studies using a coupled HBV/SOBEK model for flood forecasting and the evaluation of flood mitigation measures (van Heeringen et al., 2022, Godlewski, 2022).

Climate Change Effect
Kreienkamp et al. (2021) estimated that the intensity of the event in July 2021 has been increased by climate change by approx. 3 - 19%. Also, due to climate change, the probability of occurrence of a similar event has increased by a factor of 1.2 to 9 in a larger area (Northern Alps to Netherlands) in comparison to the past (Kreienkamp et al., 2021). In a recent study the effect of climate change and land-use changes were analyzed in the Geul catchment based on time series trend analysis (Tsiokanos, 2022). One main finding was that climate variability affects to a great extent the runoff patterns in the Geul catchment. The wflow-sbm model in combination with future climate scenarios for the Geul catchment could help to achieve a better understanding of the effect of climate change on the catchment runoff in regard to high flows and low flows.

Land-use changes
In this research the effects of land-use change have been touched upon by using the change in infiltration capacity as a proxy for land-use changes in the model. However, as a distributed physically-based model, the wflow-sbm model allows to study effects of land-use change in more depths by varying the parameters in the model which are linked to land-use change (rooting depth, 3 interception parameters, roughness and Leaf Area Index) (Hassaballah et al., 2017). Further research on the interaction between geology and land-use effects in the subcatchment and the impact of these changes on the discharge response would give valuable guidance on choosing the best location for flood retention measures.

Water losses
The Geul catchment has a complex geology and hydrogeology. The low long-term runoff coefficients of a few subcatchments, such as the Eyserbeek and Selzerbeek and to a lesser extent the Gulp indicate that water is leaving the subcatchments or even the catchment. Studies have indicated these water losses, however, knowledge of the underground preferential flow paths, especially in the karstic systems is limited (van Lanen et al., 1996, van de Westeringh, 1979, Ruthy and Dassargues, 2009, Dautrebande et al., 2000). A better understanding of the subsurface flow paths and the magnitude of water leaving the catchment, would help to get a full picture of the water balance in the catchment and to account for that in the catchment models. A combination of tracer tests with stochastic simulation as done by Assari et al. (2017) could be applied in the Geul catchment to increase the understanding of the flow through the karstic systems (Assari and Mohammadi, 2017).

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A

Study Area

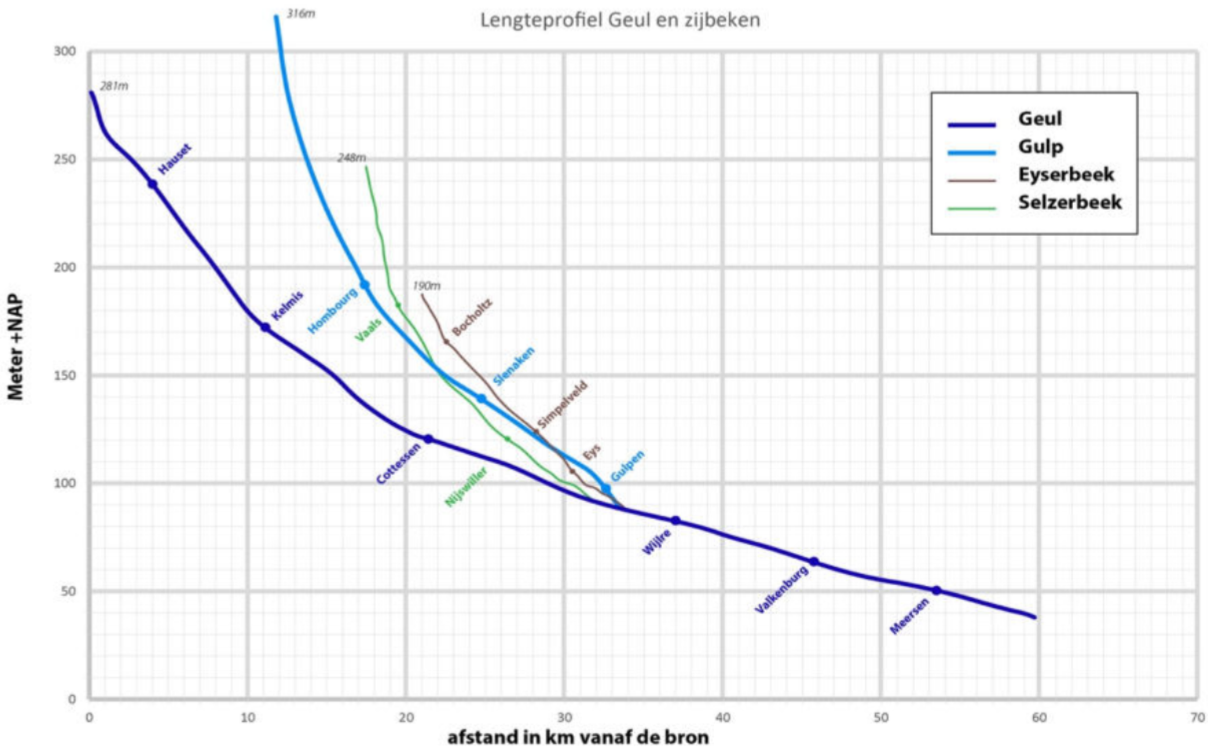

Figure A.1: Length and height profile of the Geul and its main tributaries: Gulp, Eyserbeek and Selzerbeek. (Taken from Winden, 2022)

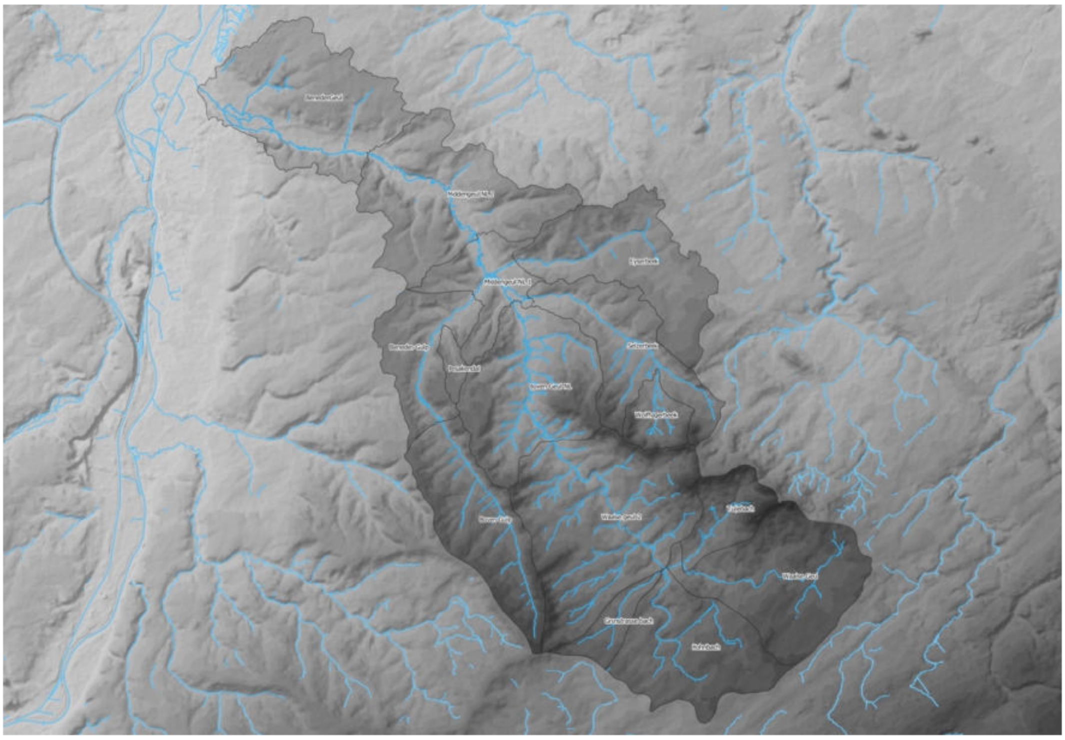

Figure A.2: Hydrographic network of the Geul catchment. The difference between drainage density in the upstream part compared to the downstream part can be seen clearly. (Taken from Winden, 2022)

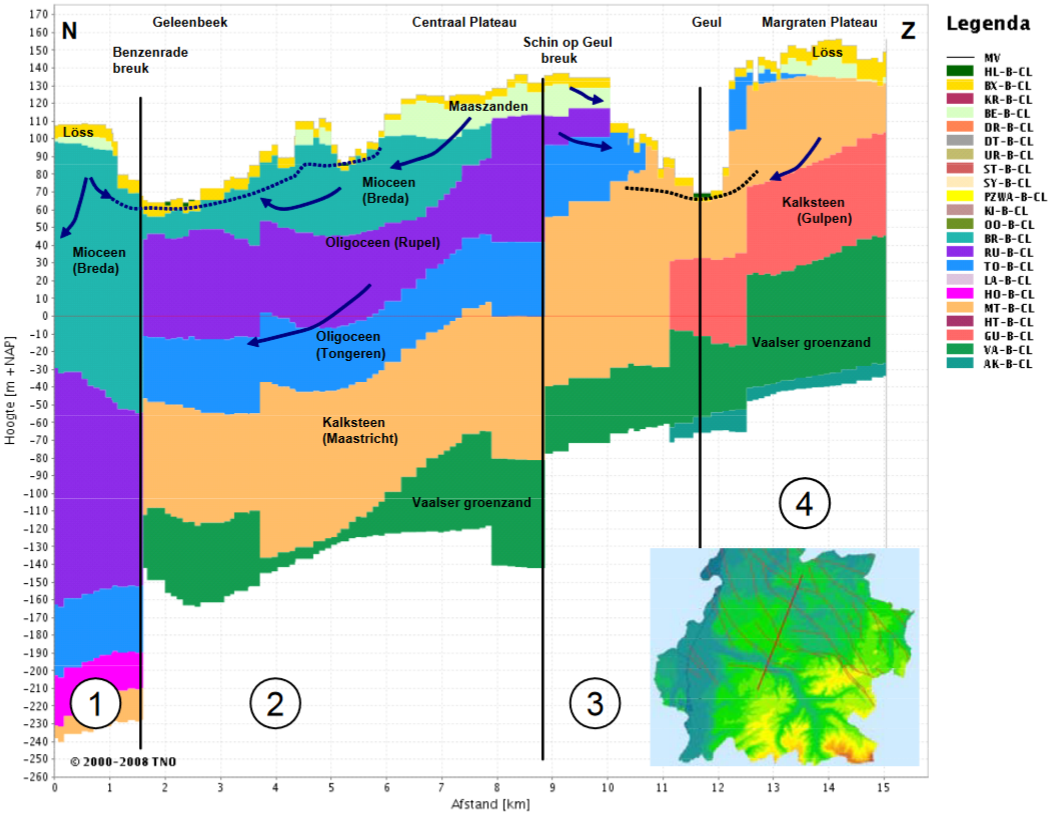

Figure A.3: Cross Section depicting several geohydrological zones based on the Dutch Underground Model REGIS in South Limburg. Zone 3 and 4 are represented by a NE-SW cross section upstream of Schin op Geul. (Taken from Schaminée et al., 2009)

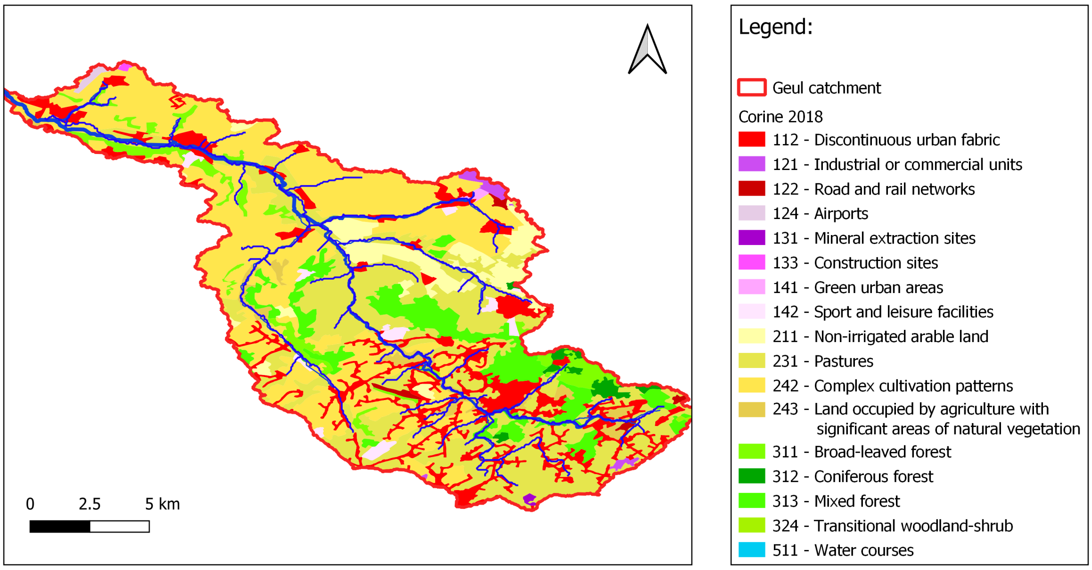

Figure A.4: Corine Landcover Map of the Geul catchment (Copernicus, 2022)

Table A.1: Initial and reclassified land-use categories. Reclassification based on similar run-off coefficients.

Initial Landcover	Code	Reclassfied Landcover	Code
Urban Fabric	112	Urban	112
Industrial Units	121		
Road & Rail Network	122		
Airports	124		
Mineral extraction sites	131		
Construction sites	133		
Green urban areas	141		
Sport facilities	142		
Arable Land	211	Agriculture	211
Complex cultivation pattern	242		
Agriculture with natural vegetation	243		
Pastures	231	Pastures	231
Broad Leaved Forests	311	Forest	311
Coniferous Forests	312		
Mixed Forests	313		

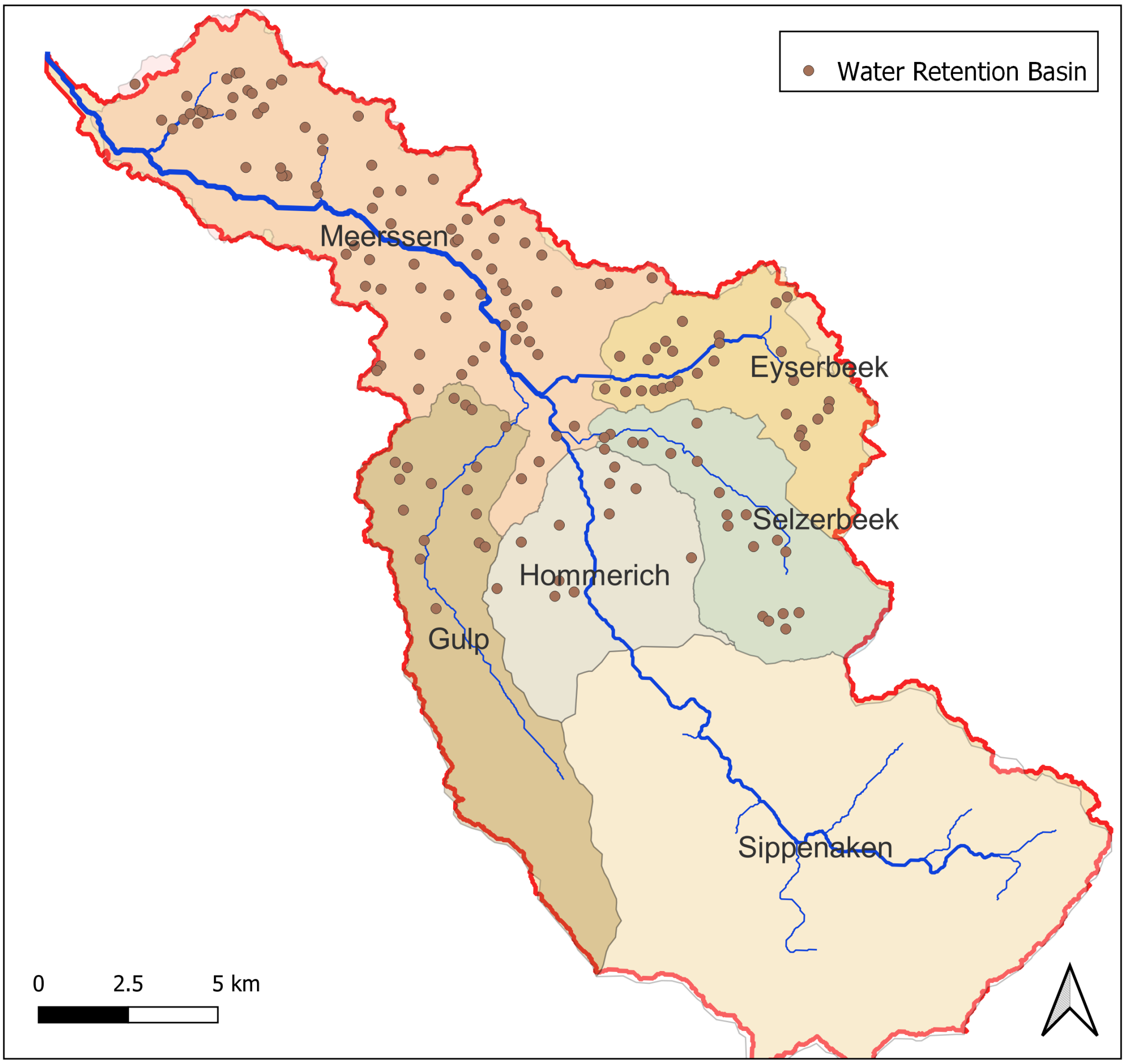

Figure A.5: Map of the spatial distribution of the water retention basins in the catchment

B

Methodology

Table B.1: Overview of rainfall gauges used for the research

Station Name	Station ID	Station Owner	Frequency	Data Start	X coord	Y coord
Maastricht Station	380	KMNI	hourly	01.01.1951	182834	325325
Maastricht	10.P.36	Waterboard Limburg	10 min	13.07.2021	177314	320266
Epen	980	KMNI	daily	01.01.1951	192000	308000
Vaals	968	KMNI	daily	01.01.1951	199000	310000
Vaals	12.P.25	Waterboard Limburg	10 min	13.07.2021	198559	308595
Noorbeek	971	KMNI	daily	01.01.1944	185000	309000
Noorbeek	15.P.41	Waterboard Limburg	10 min	13.07.2021	185950	308371
Ubachsberg	962	KMNI	daily	01.01.1884	192000	318000
Raansdaal	10.P.30	Waterboard Limburg	10 min	13.07.2021	191269	318617
Valkenburg	963	KMNI	daily	01.01.1904	187000	319000
Mechelen	9257	WOW	10 min	10.07.2021	192854	311729
Gemmenich	52840015	SPW	hourly	01.01.2002	196479	306686
Aachen - Orsbach	1500	DWD	hourly	01.04.2011	203230	316485

Table B.2: Overview of discharge stations used for the research

Station Name	Station ID	Station Owner	X coord	Y coord
Kelmis	52911002	SPW	185613	295310
Sippenaeken	L6660	SPW	194069	306871
Cottessen	10.Q.29	Waterboard Limburg	193606	307729
Hommerich	10.Q.30	Waterboard Limburg	192107	313156
Schin op Geul	10.Q.63	Waterboard Limburg	188938	318437
Meerssen	10.Q.36	Waterboard Limburg	178825	322436
Eyserbeek	11.Q.32	Waterboard Limburg	193204	315193
Selzerbeek	12.Q.46	Waterboard Limburg	192668	313548
Selzerbeek Molentaak	10.Q.53	Waterboard Limburg	192009	313973
Gulp	13.Q.34	Waterboard Limburg	190544	313923

Table B.3: Overview of groundwater data for the Geul catchment

Groundwater Well	Well ID	Station Owner	X coord (WGS 84)	Y coord (WGS 84)	Data Freqeuncy	Data Start
Plombiere	PZ34932	SPW	5.988148	50.73193	daily	28.09.2010
Aubel	PZ1829	SPW	5.884548	50.71003	daily	01.01.2011
Henri	PZ6809	SPW	5.919209	50.67186	daily	05.10.2010
Schin op Geul	B62A0309	Waterboard Limburg	5.8688	50.8583	daily	01.01.2016
Houthem	B62A0449	Waterboard Limburg	5.805818	50.87206	daily	01.01.2016
Kruitmolen 1-6		Waterboard Limburg	5.822279	50.86723	daily	01.01.2016
Walem	B62A0306	Waterboard Limburg	5.869977	50.86078	daily	01.01.2016
BeekStraat	B62A0235	Waterboard Limburg	5.815146	50.87971	daily	01.01.2016
Raren	B62D0234	Waterboard Limburg	5.983541	50.76612	daily	01.01.2016
Crapoel	B62D0233	Waterboard Limburg	5.888816	50.79956	daily	01.01.2016
Groeneweg	B62D0232	Waterboard Limburg	5.947227	50.77951	daily	01.01.2016
Schaeberg	B62D0139	Waterboard Limburg	5.91428	50.78737	daily	01.01.2016
Heijenrath	B62C0047	Waterboard Limburg	5.881782	50.76908	daily	01.01.2016
Elkenrade	B62B0912	Waterboard Limburg	5.91822	50.84875	daily	01.01.2016
Gracht Burggraf	B62B0748	Waterboard Limburg	5.890524	50.82295	daily	01.01.2016
Borgharen	B61F0174	Waterboard Limburg	5.695529	50.88995	daily	01.01.2016
Valkenburg	B62A0294	Waterboard Limburg	5.838194	50.85573	daily	01.01.2016
Hulsberg	B62A0440	Waterboard Limburg	5.850916	50.8831	daily	01.01.2016

Table B.4: Overview of the wflow model parameters (1/2). Default values are given in comparison to the values used in the Geul model. The fine model is briefly discussed in chapter 5.

Parameter	Description	Unit	Default	Distributed	Original Model (min)	Original Model (max)	Fine Model (min)	Fine Model (max)
cfmax	degree-day factor	mm °C/day	3.756		3.8	3.8	3.8	3.8
tt	threshold temperature for snowfall	° C	0		1.3	1.3	1.3	1.3
tti	threshold temperature interval length	°C	1		2	2	2	2
ttm	threshold temperature for snowmelt	°C	0		1.3	1.3	1.3	1.3
whc	water holding capacity as fraction of current snow pack	-	0.1		0.1	0.1	0.1	0.1
cf_soil	controls soil infiltration reduction factor when soil is frozen	-	0.038		0.038	0.038	0.038	0.038
g_tt	threshold temperature for snowfall above glacier	°C	0		1.3	1.3	1.3	1.3
g_cfmax	Degree-day factor for glacier	mm °C/day	3		5.3	5.3	5.3	5.3
g_sifrac	fraction of the snowpack on top of the glacier converted into ice	-	0.001		0.002	0.002	0.002	0.002
θ_s (theta_s)	saturated water content (porosity)	-	0.6	x	0.4	0.5	0.4	0.5
θ_r (theta_r)	residual water content	-	0.01	x	0.1	0.3	0.1	0.3
kv_0 (kv_0)	Vertical hydraulic conductivity at soil surface	mm/ Δt	3000	x	48.9	552.7	30	810
f	scaling parameter	1/mm	0.001	x	0.0005	0.006	0.0005	0.006
soilthickness	soil thickness	mm	2000	x	1150	2000	1150	2000
SoilMIn Thickness	Minimum soil depth	mm		x	1150	2000	1150	2000
infiltcappath	infiltration capacity of the compacted areas	mm/ Δt	10		5	5	5	5
infiltcapsoil	soil infiltration capacity	mm/ Δt	100		600	600	600	600
M	decrease of vertical saturated conductivity with depth.	mm	20 - 2000	x	60.3	352.1	44	592
M_		mm	20 - 2000	x	155.9	502.6	74	750
maxleakage	maximum leakage from saturated zone	mm/ Δt	mm/ Δt		0	0	0	0
c	Brooks-Corey power coefficient for each soil layer	-	10	x	8.5	9.5	8.7	9.5
KsathorFrac	multiplication factor applied to kv_z	-	1		250	1000	250	1000
waterfrac	fraction of open water (excluding rivers)	-	0	x	0	0.3	0	1
pathfrac	fraction of compacted area	-	0.01	x	0	1	0	1
rootingdepth	rooting depth	mm	750	x	0.8	427.9	0	432

Table B.5: Overview of the wflow model parameters (2/2). Default values are given in comparison to the values used in the Geul model. The fine model is briefly discussed in chapter 5.

Parameter	Description	Unit	Default	Distributed	Original		Fine	
					Model (min)	Model (max)	Model (min)	Model (max)
rootdistpar	controls how roots are linked to water table	-	-500		-500	-500	-500	-500
sl (specific_leaf)	specific leaf storage	mm	-		0	0.1	0	0.127
swood (storage_wood)	storage woody part of vegetation	mm	-		0	0.5	0	0.5
kext	extinction coefficient	-	-	x	0.6	0.8	0.6	0.8
e_r (eoverr)	Gash interception model parameter	-	0.1		0.1	0.1	0.11	0.11
N	Manning N parameter for the kinematic wave function for overland and river flow.				0.01	0.6	0.01	0.6
N_river	Manning N parameter for the kinematic wave function for overland and river flow.				0.03	0.05	0.03	0.05
leaf_area_index	leaf area index	m/m	-	x	0	2.4	0	2.2

Table B.6: Overview of x and y coordinates (WGS - 84) of the discharge stations and locations in the model. X and y coordinates in bold have been adjusted to be located in the correct grid cell of the model.

	Original Location		Adjusted Location	
	x	y	x	y
Meerssen	5.739583	50.88375	**5.71865**	**50.898**
Schin	5.868311	50.855417	5.868311	50.855417
Eyserbeek	5.929581	50.825425	**5.910532259**	**50.82482296**
Gulp	5.89096	50.814334	**5.886030185**	**50.81633214**
Selzerbeek	5.921759	50.811238	5.921759	50.811238
Hommerich	5.914498	50.807203	5.914498	50.807203
Cottessen	5.934967	50.75838	5.934967	50.75838
Sippenaeken	5.94029	50.751388	5.94029	50.751388
Kelmis	6.002012	50.708827	**5.993742271**	**50.7158979**

C

Event - Data Analysis

C.1. Rainfall Analysis

Looking at the cumulative event rainfall (48-hour sum) visualized in Figure C.1 one can see that the event was not only characterized by high-intensity rainfall peaks, but also and maybe even more by the high total amount of precipitation. More than 150 mm of rain has been recorded for the stations in Ransdall, Mechelen and Aachen - Orsbach. Only Maastricht Beek received less than 100 mm of rain, since the second and third peak did not extend to that station.

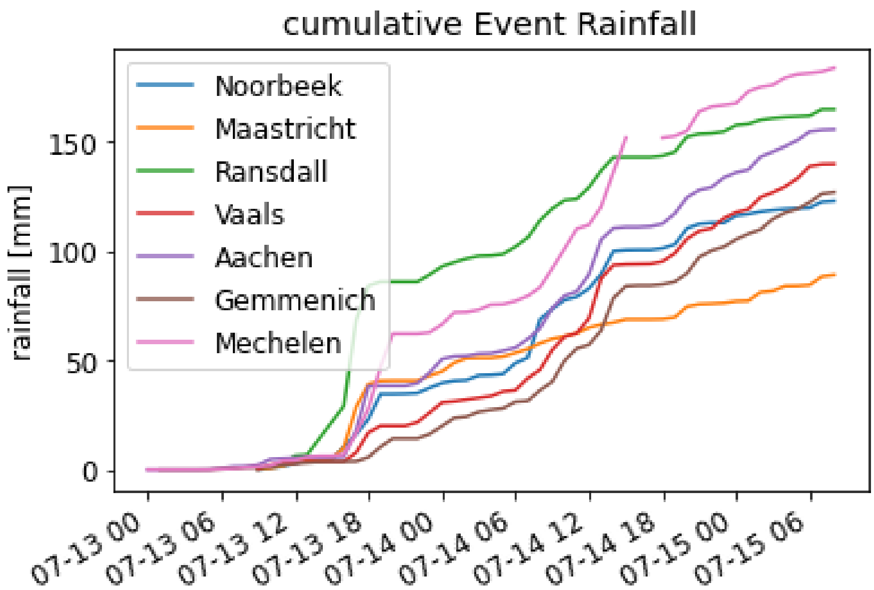

Figure C.1: Temporal distribution of the cumulative rainfall from rain gauges with hourly rainfall data. There is a 3-hour gap in the record of Mechelen station.

L

Gehele jaar	Dagen 1	2	4	8	9
2× per jaar	28.1	35.6	46.6	63.1	66.8
1× per jaar	34.0	42.5	54.8	73.4	77.5
1× per 2 jaar	40.5	49.9	63.4	83.6	88.1
1× per 5 jaar	50.1	60.6	75.3	97.1	101.9
1× per 10 jaar	58.2	69.3	84.7	107.3	112.2
1× per 20 jaar	67.1	78.6	94.4	117.4	122.4
1× per 25 jaar	70.2	81.8	97.6	120.7	125.7
1× per 50 jaar	80.3	92.0	107.8	130.8	135.8
1× per 100 jaar	91.4	103.0	118.4	140.8	145.7
1× per 200 jaar	103.7	114.8	129.4	150.9	155.6
1× per 250 jaar	107.9	118.8	133.0	154.1	158.7
1× per 500 jaar	121.8	131.7	144.6	164.1	168.5
1× per 1000 jaar	137.0	145.5	156.6	174.0	178.1

R

Gehele jaar	Dagen 1	2	4	8	9
2× per jaar	30.4	38.6	50.4	68.3	72.3
1× per jaar	36.8	46.0	59.3	79.4	83.8
1× per 2 jaar	43.8	54.0	68.6	90.5	95.3
1× per 5 jaar	54.2	65.5	81.4	105.1	110.2
1× per 10 jaar	63.0	74.9	91.6	116.1	121.4
1× per 20 jaar	72.6	85.0	102.1	127.0	132.4
1× per 25 jaar	75.9	88.5	105.6	130.5	136.0
1× per 50 jaar	86.9	99.5	116.6	141.5	146.9
1× per 100 jaar	98.9	111.4	128.1	152.3	157.6
1× per 200 jaar	112.1	124.2	140.0	163.2	168.3
1× per 250 jaar	116.7	128.5	143.9	166.7	171.7
1× per 500 jaar	131.7	142.5	156.4	177.5	182.2
1× per 1000 jaar	148.2	157.5	169.4	188.3	192.7

H

Gehele jaar	Dagen 1	2	4	8	9
2× per jaar	33.2	42.1	55.0	74.5	78.9
1× per jaar	40.1	50.2	64.7	86.7	91.5
1× per 2 jaar	47.8	59.0	74.9	98.7	104.0
1× per 5 jaar	59.1	71.5	88.9	114.7	120.3
1× per 10 jaar	68.7	81.8	99.9	126.7	132.5
1× per 20 jaar	79.2	92.8	111.4	138.6	144.5
1× per 25 jaar	82.8	96.5	115.2	142.5	148.4
1× per 50 jaar	94.8	108.6	127.3	154.4	160.3
1× per 100 jaar	107.9	121.6	139.8	166.3	172.0
1× per 200 jaar	122.4	135.5	152.8	178.1	183.7
1× per 250 jaar	127.3	140.2	157.1	181.9	187.4
1× per 500 jaar	143.7	155.5	170.7	193.7	198.9
1× per 1000 jaar	161.8	171.8	184.8	205.5	210.3

Figure C.2: Precipitation extremes (mm) for the full year for the duration of 1,2,4,8 and 9 days for events which occur on average 2 times per year up to 1/1000 years. For Limburg the high precipitation regime (H) is applicable. (Taken from STOWA, 2019).

Table C.1: Overview of the hourly rainfall stations in the Geul catchment showing precipitation sums, return periods and maximum rainfall intensities. Return periods are based on STOWA (STOWA, 2019).

Station	48-hour sum [mm]	Return period [1/y]	hours of rainfall intensity above 10 mm	max. rainfall intensity [mm]	Time of max. rainfall intensity
Mechelen (WOW)	182	<1 / 1000	5	19.1	13/07/2021 19:00
Gemmenich (SPW)	125.9	<1 / 100	1	14.7	14/07/2021 14:00
Maastricht (WL)	88.9	<1 /10	2	18.7	13/07/2021 17:00
Maastricht (KNMI)	65	<1/ 2	0	5.3	13/07/2021 22:00
Aachen-Orsbach (DWD)	153.8	1/ 500	3	20.2	13/07/2021 18:00
Noorbeek (WL)	122.7	1/100	4	17.6	14/07/2021 08:00
Ransdall (WL)	164.6	1/500	3	39.4	13/07/2021 17:00
Vaals (WL)	139.6	1/200	1	18.2	14/07/2021 13:00

Table C.2: Overview of 48-hour sum and return period for daily precipitation data

Station	48-hour sum [mm]	Return period [1/year]
Gemmenich (SPW)	125.9	<1 / 100
Maastricht (KNMI)	65	<1/ 2
Ubachsberg (KNMI)	182.4	<1 / 1000
Epen (KNMI)	109.8	<1 / 50
Vaals (KNMI)	124.6	<1 / 100
Valkenburg (KNMI)	134	<1 / 100
Noorbeek (KNMI)	147.3	<1/250
Aachen-Orsbach (DWD)	133.4	<1 / 100

C.2. Discharge Analysis

Table C.3: Overview of observed peak discharges, timing and cumulative discharges (13.7.21 - 18.7.21) for all discharge stations, which recorded data. For Eyserbeek the peak discharge is estimated as there is a data gap of 3 hours at the peak.

Subcatchment	Observations		
	peak discharge [m3/s]	peak timing	cum discharge [10^6 m3]
Meerssen	-	-	-
Schin	-	-	-
Eyserbeek	12*	14.7.2021 17:00	0.77
Gulp	14	14.7.2021 20:00	1.16
Selzerbeek	-	-	-
Hommerich	-	-	-
Sippenaeken	52	14.7.2021 20:00	7.43
Kelmis	50	14.7.2021 17:00	6.41

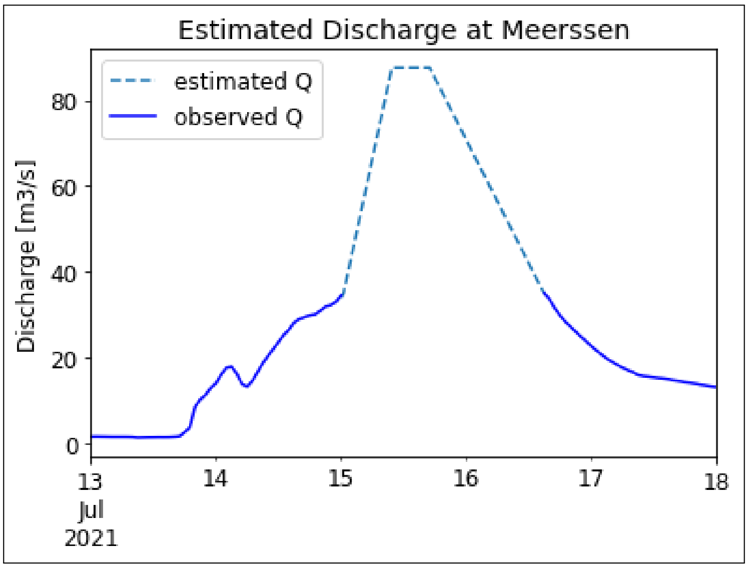

Figure C.3: Estimated event discharge for Meerssen based on Rura Arnhem (RuraArnhem, 2021)

Timing
In figure C.4 the measured event discharges have been plotted together. The discharge development shows that at the time (July 14th 2pm) the measurement at Schin op Geul stopped at a discharge of 53 m^3/s, the discharge peaked as well in the upstream catchment at Sippenaeken. The high discharge in Schin op Geul was caused by the first intense rainfall peak which hit the downstream part of the catchment and at that point the three main tributaries contributed their peak discharges. The water originating from the Belgian part contributed especially on July 15th to the high discharges. Consequently, due to the spatial and temporal variation of the rainfall, the peak discharges at the downstream part of the catchment did not coincide with the peak discharges in the upstream part of the catchment.

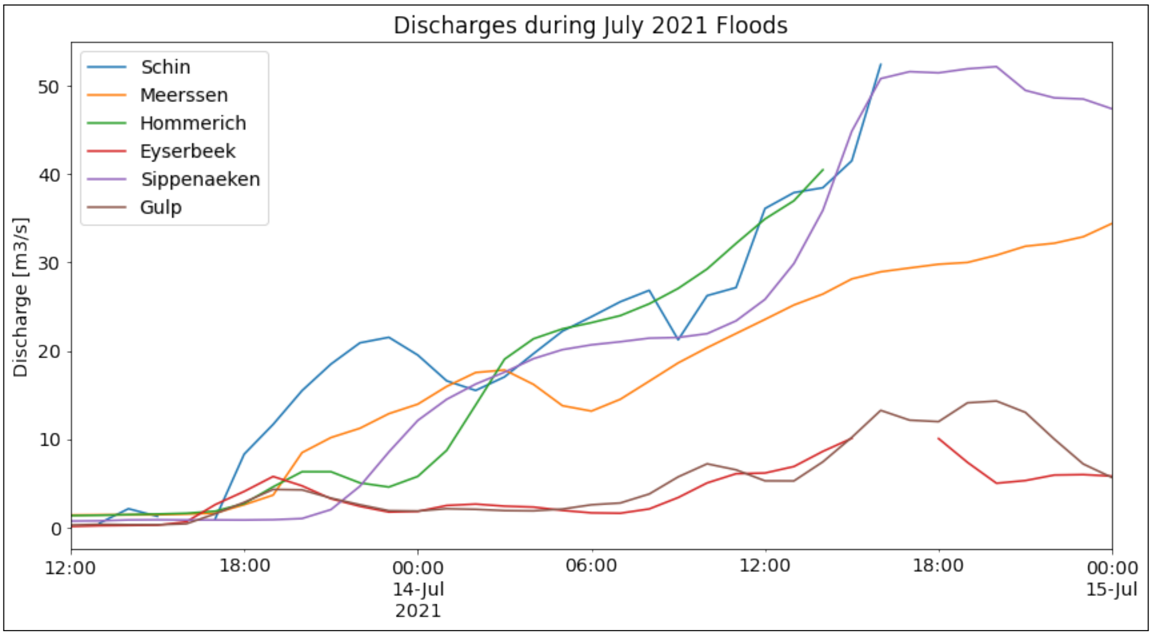

Figure C.4: All discharges measured during the first 18 hours of the event (July 13 12:00 - July 15 00:00) illustrating the early discharge of the downstream catchment (Schin) compared to the discharge from Sippenaeken.

Response Times
Response times for the Geul have been analysed by Dautrebande to be 2-4 hours in the central and upstream part and 4-10 hours at the outlet (Dautrebande et al., 2000). Figure C.5 visualizes by plotting

the precipitation and discharge data, that the event response time at Kelmis was approx. 3 hours and matches with the estimation from Dautrebande. In Meerssen the peak discharge occurred about 20 hours after the peak rainfall. This long time is influenced by two factors. First the flood plains as well as the flooding of the cities of Valkenburg and Meerssen delayed the peak, secondly the peak discharge of the Geul coincided with the peak discharge of the Meuse river and hence, the high water level at the Meuse caused a backwater effect at the Geul outlet reaching back up to upstream of Meerssen.
For the tributaries the lag time between the peak rainfall and peak discharge is short: 1 hour for Eyserbeek and 2 hours for the Gulp.

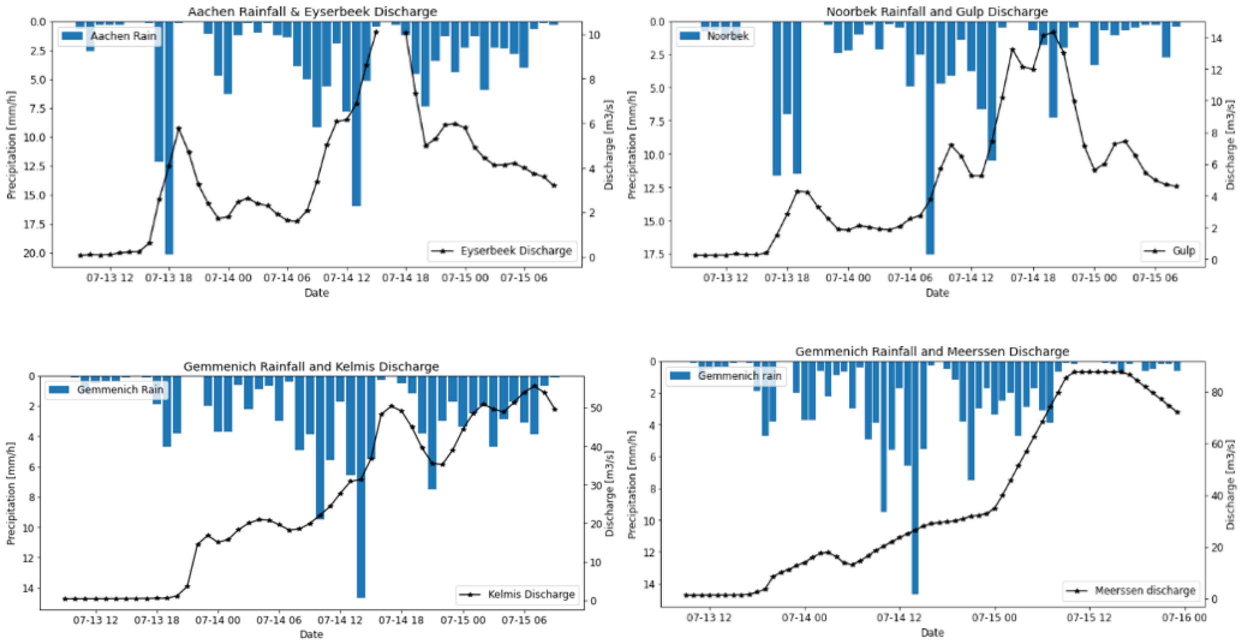

Figure C.5: Event precipitation (blue) and event discharge (black) plotted for Eyserbeek, Gulp, Kelmis and Meerssen station with corresponding rainfall gauges at Aachen, Noorbeek and Gemmenich.

Table C.4: Return periods calculated based on GEV and Gumbel calculated for all stations with more than 25 years of discharge data. Return periods calculated based on peak discharges. Discharges written in italics are estimations by the waterboard Limburg.

Station	**Peak Discharge m^3/s**	**Peak Timing**	**Return Period 1/y GEV**	**Return Period 1/y Gumbel**	**Comment**
Kelmis	56	July 15, 7 am	-	-	time series to short
Sippenaeken	53	July 15, 7am	1/80	1/700	
Cottessen	-	-	-	-	measurement limit at 27 m^3/s
Hommerich	*80*	-	>1/500	>1/500	WL estimation
Schin op Geul	53	July 14, 2pm	-	-	time series to short, peak not captured
Meerssen	*87.5*	July 15, 12pm	>1/500	>1/500	WL estimation
Eyserbeek	*12*	July 14, 3pm	1/150	>1/500	WL estimation
Selzerbeek	*10*	July 14, 11pm	1/200	>1/500	WL estimation
Gulp	14	July 14, 8pm	1/50	1/350	

Table C.5: Return periods for stations in the Geul catchment with a time series of 25 years or longer. Return periods are calculated with the GEV distribution.

GEV Method	**Discharge stations in the Geul catchment**					
Return Period [years]	**Meerssen [m^3/s]**	**Hommerich [m^3/s]**	**Gulp [m^3/s]**	**Selzerbeek [m^3/s]**	**Eyserbeek [m^3/s]**	**Sippenaeken [m^3/s]**
1	25.8	21.1	3.0	2.2	2.3	18.5
2	31.1	27.4	4.3	2.7	3.1	22.1
5	37.7	34.9	6.4	3.5	4.3	27.7
10	42.5	40.2	8.3	4.3	5.4	32.8
35	50.5	48.6	12.7	6.1	7.8	44.2
50	52.6	50.8	14.2	6.8	8.7	48.1
100	56.6	54.8	17.6	8.3	10.6	56.7
200	60.5	58.5	21.6	10.1	12.8	66.4
500	65.3	63.0	28.2	13.1	16.3	82.4
1000	68.9	66.1	34.3	16.1	19.5	96.8

Table C.6: Overview of all floods identified through a newspaper search based on Delpher (Delpher, 2022)

Year	Month	Day	Newspaper	Datum	Source
1643	1		Limburgs Dagblad	01/10/1963	https://resolver.kb.nl/resolve?urn=ddd:010526077:mpeg21:p002
1909	2		De Maasbode	11/01/1914	https://resolver.kb.nl/resolve?urn=MMKB04:000189036:mpeg21:p002
1914	1	11	De Maasbode	12/01/1914	https://resolver.kb.nl/resolve?urn=MMKB04:000189036:mpeg21:p002
1917	2	6	De grondwet	06/02/1917	https://resolver.kb.nl/resolve?urn=ddd:110621570:mpeg21:p010
1926	5	20	Overijsselsch dagblad	20/05/1926	https://resolver.kb.nl/resolve?urn=MMKB23:001317095:mpeg21:p00001
1926	2		Nieuwe Tilburgsche Courant	22/02/1926	https://resolver.kb.nl/resolve?urn=ddd:010234720:mpeg21:p005
1939	1	4	De Maasbode	04/01/1939	https://resolver.kb.nl/resolve?urn=MMKB04:000195388:mpeg21:p009
1940	2	6	Limburger koerier: provinciaal dagblad	06/02/1940	https://resolver.kb.nl/resolve?urn=ddd:010327230:mpeg21:p005
1947	3	5	Gazet van Limburg	07/03/1947	https://resolver.kb.nl/resolve?urn=MMCC01:048011041:mpeg21:p00001
1952	12	20	Eindhovensch Dagblad	23/12/1952	https://resolver.kb.nl/resolve?urn=MMRHCE02:163606071:mpeg21:p00001
1956	3	6	Provinciale Overijsselsche en Zwolsche courant	05/03/1956	https://resolver.kb.nl/resolve?urn=MMHCO02:163872055:mpeg21:p00001
1958	2	28	Nieuwsblad voor de Hoeksche Waard en Ijselmonde	28/02/1958	https://resolver.kb.nl/resolve?urn=MMMHW01:001115025:mpeg21:p00001
1960	12	6	Limburgs Dagblad	06/12/1960	https://resolver.kb.nl/resolve?urn=MMKB23:001934056:mpeg21:p00009
1960	5		De Volkskrant	14/05/1960	https://resolver.kb.nl/resolve?urn=ABCDDD:010875559:mpeg21:p001
1962	2	12	Limburgs Dagblad	15/02/1962	https://resolver.kb.nl/resolve?urn=ddd:011028049:mpeg21:p019
1965	1	10	Limburgs Dagblad	14/01/1965	https://resolver.kb.nl/resolve?urn=ddd:010526167:mpeg21:p023
1966	12	1	De Tijd De Maasbode	27/12/1996	https://resolver.kb.nl/resolve?urn=ddd:011237786:mpeg21:p005
1970	2	22	Limburgsch Dagblad	12/05/1970	https://resolver.kb.nl/resolve?urn=ddd:010541164:mpeg21:p013
1973	2	23	Limburgsch Dagblad	23/02/1973	https://resolver.kb.nl/resolve?urn=ddd:010556266:mpeg21:p015
1978	5	7	Limburgsch Dagblad	08/05/1978	https://resolver.kb.nl/resolve?urn=ddd:010563255:mpeg21:p005
1980	7	20	Limburgs Dagblad	21/07/1980	https://resolver.kb.nl/resolve?urn=ddd:010570822:mpeg21:p007
1981	6	30	Limburgs Dagblad	30/06/1981	https://resolver.kb.nl/resolve?urn=ddd:010570374:mpeg21:p011
1984	2	7	Limburgs Dagblad	09/02/1984	https://resolver.kb.nl/resolve?urn=ddd:010593217:mpeg21:p001
1987	2	31	Limburgsch Dagblad	02/03/1987	https://resolver.kb.nl/resolve?urn=ddd:010611204:mpeg21:p001
1987	1	3	Nederlands dagblad: gereformeerd gezinsblad	03/01/1987	https://resolver.kb.nl/resolve?urn=ddd:010562334:mpeg21:p003
1990	12	31	Limburgsch Dagblad	31/12/1990	https://resolver.kb.nl/resolve?urn=ddd:010624173:mpeg21:p011
1994	12	30	NRC Handelsblad	30/12/1994	https://resolver.kb.nl/resolve?urn=KBNRC01:000030833:mpeg21:p002
1998	9				
2012	7		Limburg 1	29/07/2012	https://l1.nl/hoogste-piek-rivier-de-gulp-is-gulpen-gepasseerd-50813

C.3. Groundwater Analysis

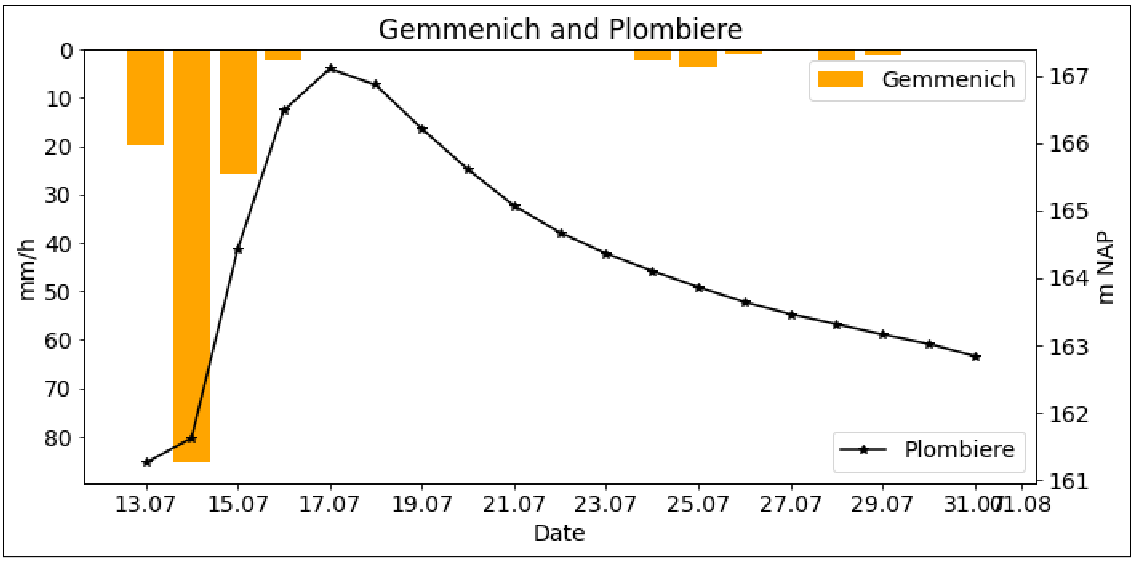

Figure C.6: Groundwater Level Development at Plombieres from July 13th - July 31th. Daily precipitation values based on Gemmenich rain gauge.

C.4. Antecedent Conditions

Table C.7: Precipitation Index per station based on Marchi et al (2010) (Marchi et al., 2010); The index classifies the initial soil moisture in three categories: <0.5 dry, 0.5 - 1.5 normal, >1.5 wet.

Station	precipitation 30 days before event		**Index**
	2021 [mm]	**2000 - 2020 [mm]**	**[-]**
Ubachsberg	125.4	83.7	1.50
Epen	121.9	90.9	1.34
Vaals	143.4	93.4	1.54
Valkenburg	116.8	87.1	1.34
Noorbeek	128.4	83.7	1.53
Maastricht	181.6	57.2	3.18
Gemmenich	125.3	87.2	1.44
Aachen	170.2	87.0	1.96

Table C.8: Antecedent Precipitation Index calculated for several rain gauges in the Geul catchment for different pre-event time periods: 30-days, 21-days, 14-days and 7-days.

Station	30-day API	21-day API	14-day API	7-day API
Ubachsberg	1.50	2.01	2.05	1.42
Epen	1.34	1.79	2.05	1.78
Vaals	1.54	2.06	2.33	2.32
Valkenburg	1.34	1.76	1.86	1.09
Noorbeek	1.53	1.98	2.13	1.82
Maastricht	3.18	4.62	5.29	0.75
Gemmenich	1.44	1.81	1.80	1.75
Aachen	1.96	2.31	3.15	5.6

D

Model Results

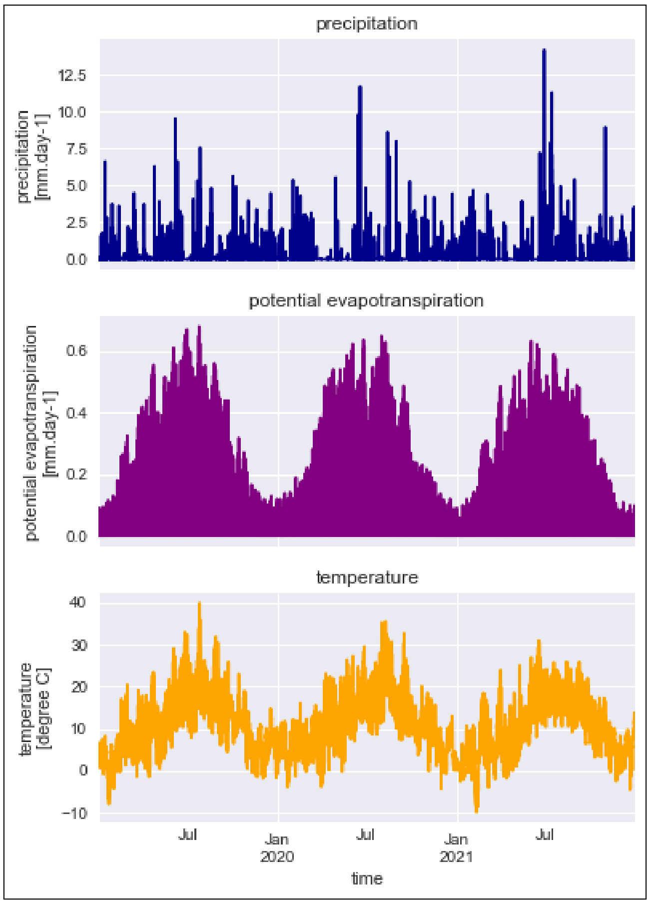

Figure D.1: Average precipitation, potential evaporation and temperature forcing in the model from 1.1.2019 - 31.12.2021. Precipitation: KNMI radar data + final Reanalysis (13.7.2021 - 15.7.2021), Temperature: ERA5, Evapotranspiration: ERA5

Table D.1: Overview of parameters, their model values and scaling factors used in the sensitivity analysis. For the max. leakage factor fixed values have been tested.

Parameter	Unit	Model Value	Scale Factor	New Value
Soil Thickness	mm	1250 - 2000	1 - 2	-
KsatVer	mm / d	48 - 552	0.5 - 2	-
f parameter	-	0.0008 - 0.004	0.5 - 2	-
KsatHorfrac	-	250 - 1000	0.5 - 2	-
max leakage	mm/d	0	-	0.2 -0.3

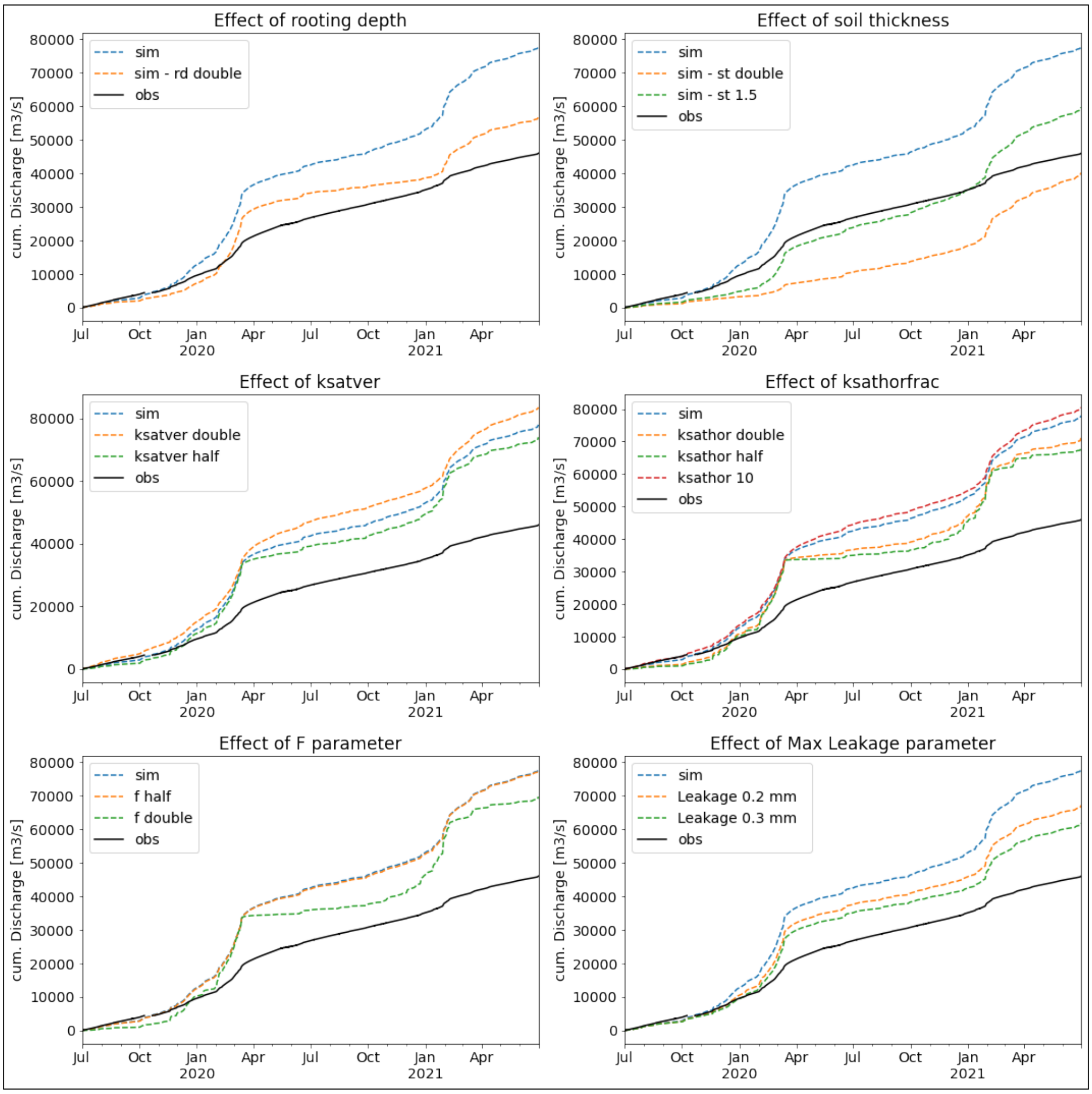

Figure D.2: Effect of changing parameter values on the cumulative discharge of Meerssen station in comparison to the observations (obs.).

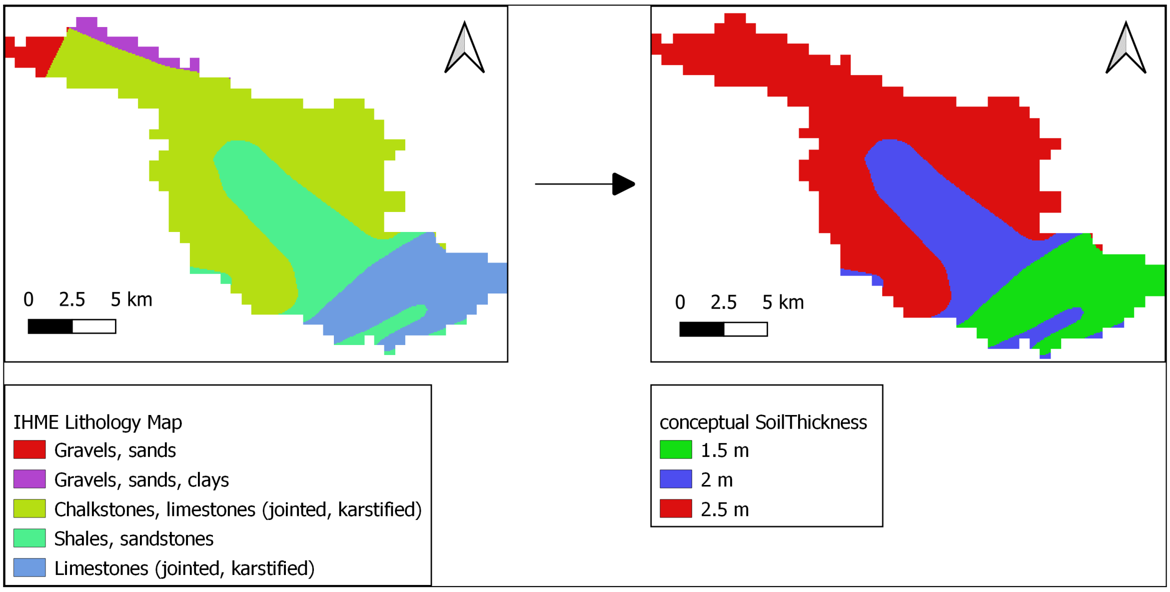

Figure D.3: Conceptual soil thickness map (right) derived from IHME lithology map (left) (IHME, 2022). The five different lithologies from the IHME map have been translated to three different soil thicknesses.

KSHF Derivation

The KSHF parameter is distributed in the model based on the IHME map, the process is explained in detail by Bouaziz (2020). A KSHF value of 250 has been used in the model and for areas which a high productivity aquifer, the value has been increased to 1000. This value has been adjusted in the most upstream part of the catchment as the aquifers there have a lower conductivity compared to the chalk aquifers downstream (Ruthy and Dassargues, 2009, Schaminée et al., 2009, Hendrix and Meinardi, 2004).

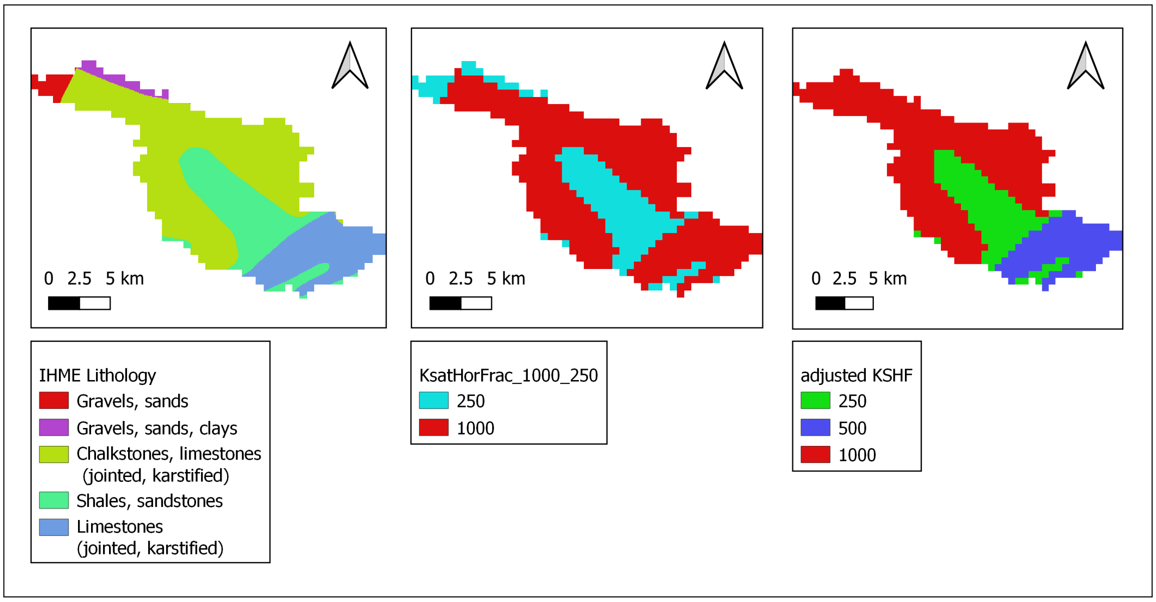

Figure D.4: Left: IHME lithology map, middle: KSHF map derived from IHME lithology map, right: adjusted KSHF map.

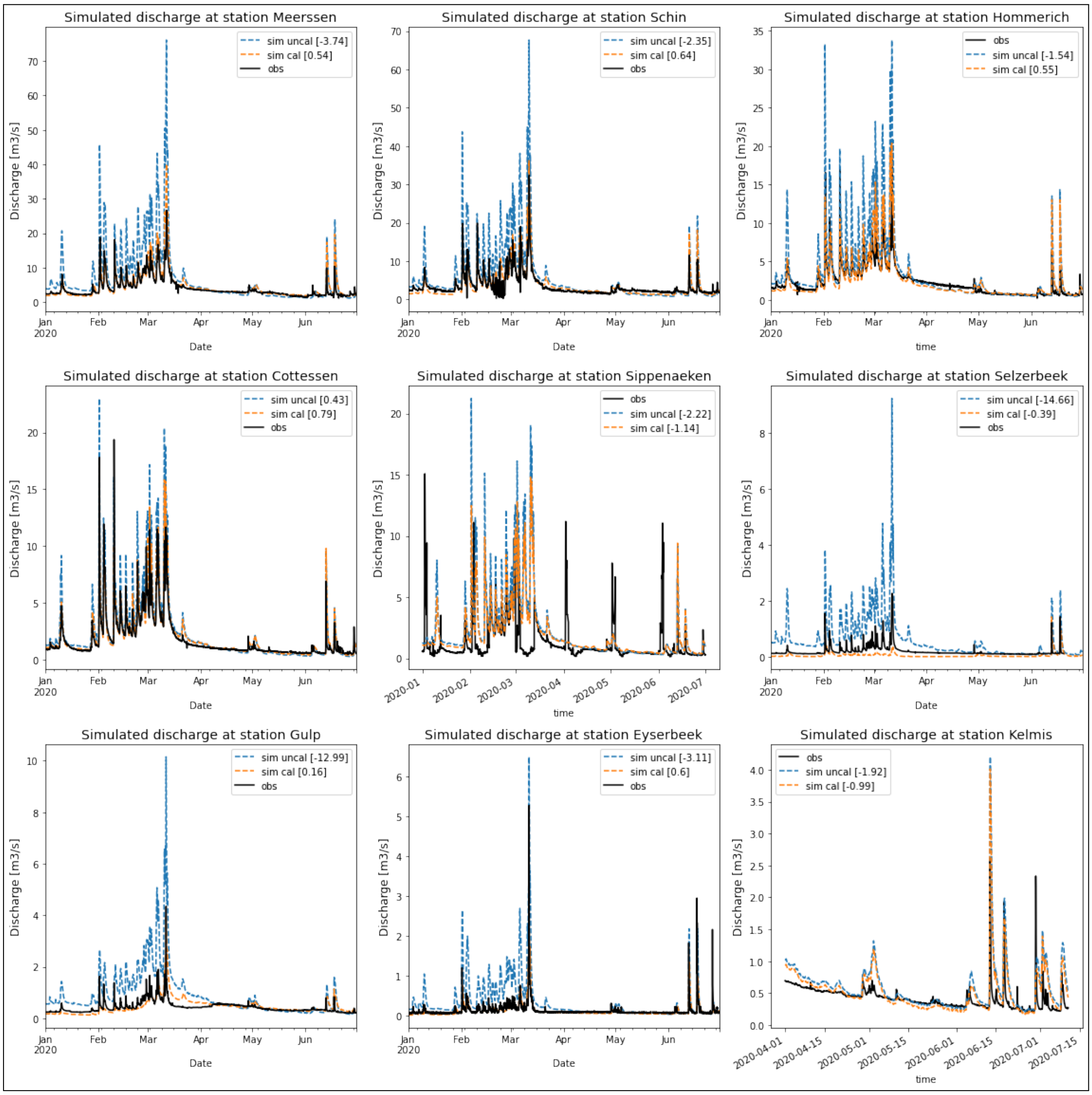

Figure D.5: Comparison of simulated discharge of the original model (sim uncal.) compared to the adjusted model (sim cal.) and the observations. Model results shown for calibration period from 01.01. - 30.06.2020

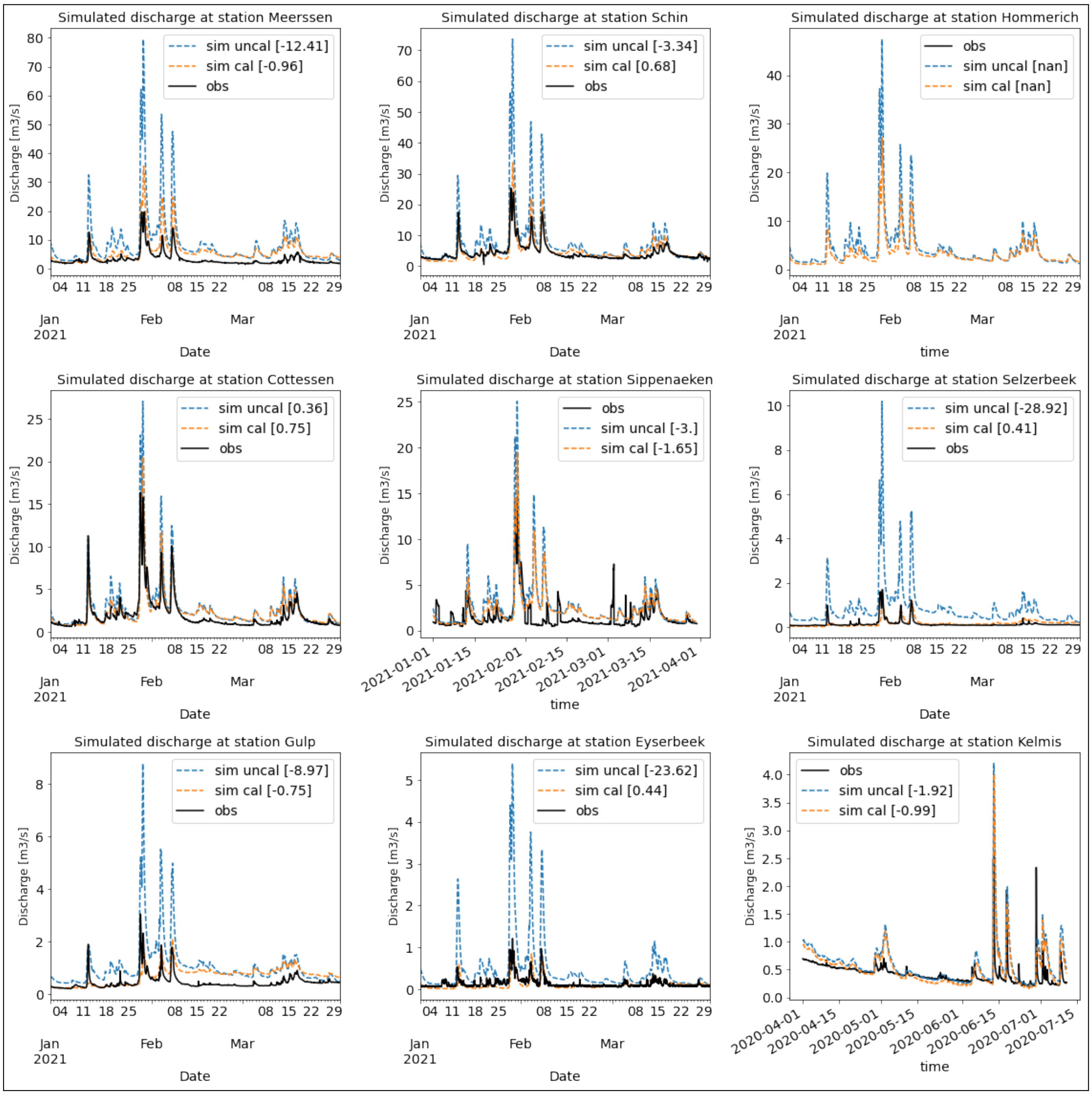

Figure D.6: Comparison of simulated discharge of the original model (sim uncal.) compared to the adjusted model (sim cal.) and the observations. Model results shown for validation period from 01.01. - 30.06.2021

Table D.2: Comparison of the original and adjusted models of the ratio of the cumulative discharges to the observed discharges (1.1.2020 - 31.12.2020) as well as of the NSE values from 1.1.2020 - 30.3.2020 for all subcatchments.

Subcatchment	original model		adjusted model	
	cum discharge model / cum discharge obs [-]	NSE	cum discharge model / cum discharge obs [-]	NSE
Meerssen	1.6	-5.14	1.2	0.56
Schin	1.5	-3.16	1.0	0.63
Eyserbeek	2.3	-4.16	0.9	0.71
Gulp	1.8	-15.19	1.1	0.16
Selzerbeek	3.3	-17.07	0.6	-0.43
Hommerich	1.8	-2.9	1.3	0.46
Cottessen	1.4	0.28	1.2	0.77
Sippenaeken	1.5	-4.81	1.3	-2.74
Kelmis	1.6	-0.02	1.4	0.25

Table D.3: Comparison of model cumulative discharges with observed cumulative discharges for the event (13.7.2021 - 18.7.2021).

Subcatchment	Model cum discharge [10^6 m^3]	Obs cum discharge [10^6 m^3]
Meerssen	18.2	-
Schin	15.9	-
Eyserbeek	1	0.77
Gulp	1.3	1.16
Selzerbeek	1	-
Hommerich	10.4	-
Sippenaeken	7.8	7.43
Kelmis	5.5	6.41

Table D.4: Calculation of the runoff coefficients for all subcatchments based on the model results. Rain per upstream area of the subcatchment is based on the KNMI reanalysis. Results for Meerssen and Schin are greyed out as model results of the downstream catchment are highly questionable since the model is not coupled to a hydraulic model.

Subcatchment	**cum. discharge [10^6 m^3]**	**cum. discharge [mm]**	**rain [mm]**	**RC [%]**
Meerssen	18.2	53	128	42
Schin	15.9	55	145	38
Eyserbeek	1	36	130	28
Gulp	1.3	28	128	22
Selzerbeek	1	36	129	28
Hommerich	10.4	64	154	42
Cottessen	8.1	62	160	39
Sippenaeken	7.8	63	160	39
Kelmis	5.5	69	176	39

Return Periods

The return periods for the discharges in the upstream and central part of the catchments have been estimated using the same GEV distribution as in section 4.2.2. The return periods for the modelled discharges are higher than 1/500 along the Geul and between 1/35 and 1/500 for the tributaries and therewith in line with the values from the observations.

Table D.5: Comparison of return periods from simulation and observations. Return periods are based on event peak discharges and GEV.

	Simulation		**Observations**	
	Peak Discharge [m^3/s]	Return Period GEV [1/years]	Peak Discharge [m^3/s]	Return Period GEV [1/years]
Hommerich	97.1	>1/500	80 *	>1/500
Eyserbeek	10.8	1/100	12	1/150
Gulp	12.4	1/35	14	1/50
Selzerbeek	13.3	1/500	10	1/200
Sippenaeken	83.4	>1/500	52	1/80

Table D.6: Comparison of runoff coefficients at the confluence near Gulpen of the event for two scenarios. Scenario 1: The upstream area of Hommerich received the same rainfall amount as the tributaries (130 mm/48-hours), Scenario 2: The tributaries received the same rainfall amount as the upstream area of Hommerich (160 mm/48-hours)

Subcatchment	Runoff Coefficients		
	Event [%]	Scenario 1 [%]	Scenario 2 [%]
Hommerich (Geul)	42	30	42
Gulp	22	22	34
Eyserbeek	28	28	34
Selzerbeek	28	28	36

Table D.7: Overview of peak discharges and cumulative discharges (13.7 - 17.7) for all antecedent conditions scenarios

	Peak Discharges [m^3/s]				cum. Discharges [10^6 m^3]			
	AC 1a	AC 1	Sim	AC 2	AC 1a	AC 1	Sim	AC 2
Meerssen	239.6	201.9	156.6	115.1	27.4	22.7	18.2	13.4
Schin	223.8	190.4	148.4	109.9	24	20	15.9	11.7
Eyserbeek	13.2	11.8	10.8	8	1.3	1.1	1	0.7
Gulp	18.1	15	12.4	9.9	2	1.5	1.3	1
Selzerbeek	15.8	14.8	13.3	12.3	1.4	1.2	1	0.9
Hommerich	155.6	132.4	97.3	68.1	16.5	13.5	10.4	7.3
Cottessen	124.5	104.5	84.7	59.8	13.1	10.6	8.1	5.6
Sippenaeken	122.4	102.7	83.4	58.7	12.6	10.3	7.8	5.4
Kelmis	96.4	80	64.4	45	9.1	7.3	5.5	3.7

Table D.8: Ratio of the peak discharges and cum. discharges of all antecedent conditions scenarios to the base case

	Peak Discharges				cum Discharges			
	AC 1a	AC 1	Sim	AC 2	AC 1a	AC 1	Sim	AC 2
Meerssen	1.53	1.29	1.00	0.73	1.51	1.25	1.00	0.74
Schin	1.51	1.28	1.00	0.74	1.51	1.26	1.00	0.74
Eyserbeek	1.22	1.09	1.00	0.74	1.30	1.10	1.00	0.70
Gulp	1.46	1.21	1.00	0.80	1.54	1.15	1.00	0.77
Selzerbeek	1.19	1.11	1.00	0.92	1.40	1.20	1.00	0.90
Hommerich	1.60	1.36	1.00	0.70	1.59	1.30	1.00	0.70
Cottessen	1.47	1.23	1.00	0.71	1.62	1.31	1.00	0.69
Sippenaeken	1.47	1.23	1.00	0.70	1.62	1.32	1.00	0.69
Kelmis	1.50	1.24	1.00	0.70	1.65	1.33	1.00	0.67

Table D.9: Runoff coefficients per catchment for all antecedent condition scenarios. Runoff coefficients calculated based on event cumulative discharge (13.7.-17.7) and event rainfall based on KNMI final reanalysis.

	Runoff Coefficients			
	AC 2	Base	AC 1	AC 1a
Meerssen	0.31	0.42	0.52	0.62
Schin	0.28	0.38	0.48	0.57
Eyserbeek	0.21	0.28	0.32	0.36
Gulp	0.18	0.22	0.26	0.33
Selzerbeek	0.24	0.28	0.32	0.37
Hommerich	0.3	0.42	0.55	0.67
Cottessen	0.27	0.39	0.55	0.63
Sippenaeken	0.27	0.39	0.52	0.64
Kelmis	0.26	0.39	0.52	0.64

Table D.10: Overview of peak discharges and cumulative discharges (13.7 - 17.7) for all rainfall scenarios.

	Peak Discharges [m^3/s]				**cum. Discharges [10^6 m^3]**			
	P1	P2	P3	Sim	P1	P2	P3	sim
Meerssen	86	63	265	156.6	13	10.3	38.9	18.2
Schin	77	60	246	148.4	9.5	10.2	36	15.9
Eyserbeek	5	3	15	10.8	0.6	0.5	2.1	1
Gulp	6	4	28	12.4	0.9	0.6	3.5	1.3
Selzerbeek	4	3	23	13.3	0.5	0.5	2.4	1
Hommerich	55	49	162	97.3	5.6	7.3	23.8	10.4
Cottessen	41	45	130	84.7	4	6.1	18.6	8.1
Sippenaeken	38	44	128	83.4	3.8	5.9	18	7.8
Kelmis	25	34	100	64.4	2.5	4.2	12.8	5.5

Table D.11: Runoff coefficients per catchment for all rainfall scenarios. Runoff coefficients calculated based on event cumulative discharge (13.7.-17.7) and event rainfall based on KNMI final reanalysis.

	Run-off Coefficients			
	P2	P1	Base	P3
Meerssen	0.22	0.29	0.42	0.64
Schin	0.2	0.26	0.38	0.58
Eyserbeek	0.1	0.16	0.28	0.37
Gulp	0.1	0.15	0.22	0.38
Selzerbeek	0.09	0.12	0.28	0.41
Hommerich	0.23	0.31	0.42	0.65
Cottessen	0.23	0.28	0.39	0.59
Sippenaeken	0.23	0.28	0.39	0.6
Kelmis	0.23	0.25	0.39	0.6

Table D.12: Overview of peak discharges and cumulative discharges (13.7 - 17.7) for all infiltration capacity scenarios.

	Peak Discharges [m^3/s]				**cum. Discharges [10^6 m^3]**			
	IC 2	IC 4	IC 5	Base	IC 2	IC 4	IC 5	Base
Meerssen	249	425	152	156.6	25.9	42.3	17.6	18.2
Schin	231	387	146	148.4	22.5	36.2	15.6	15.9
Eyserbeek	13	23	10	10.8	1.2	2	0.9	1
Gulp	33	58	11	12.4	2.8	4.8	1.2	1.3
Selzerbeek	22	41	12	13.3	1.8	3.3	0.9	1
Hommerich	155	247	97	97.3	14.8	23.5	10.2	10.4
Cottessen	105	168	85	84.7	11.1	17.2	8.1	8.1
Sippenaeken	98	157	84	83.4	10.6	16.4	7.8	7.8
Kelmis	71	104	66	64.4	7.3	11.1	5.6	5.5

Table D.13: Runoff coefficients per catchment for all infiltration capacity scenarios. Runoff coefficients calculated based on event cumulative discharge (13.7.-17.7) and event rainfall based on KNMI final reanalysis.

	Runoff Coefficients			
	IC4	IC2	Base	IC5
Meerssen	0.97	0.6	0.42	0.4
Schin	0.86	0.54	0.38	0.37
Eyserbeek	0.56	0.33	0.28	0.26
Gulp	0.81	0.47	0.22	0.21
Selzerbeek	0.88	0.49	0.28	0.25
Hommerich	0.96	0.6	0.42	0.42
Cottessen	0.82	0.53	0.39	0.38
Sippenaeken	0.83	0.54	0.39	0.39
Kelmis	0.79	0.52	0.39	0.4

E
Discussion

Comparison fine and coarse model
In Figure E.1 the model results are shown for simulating the event in 2021 with the sbm model using the global parameter set without any calibration. The results of the finer model (60 m * 92.5 m) as well as of the original (600 m * 925 m) model are visualized for all nine discharge stations in the catchment.

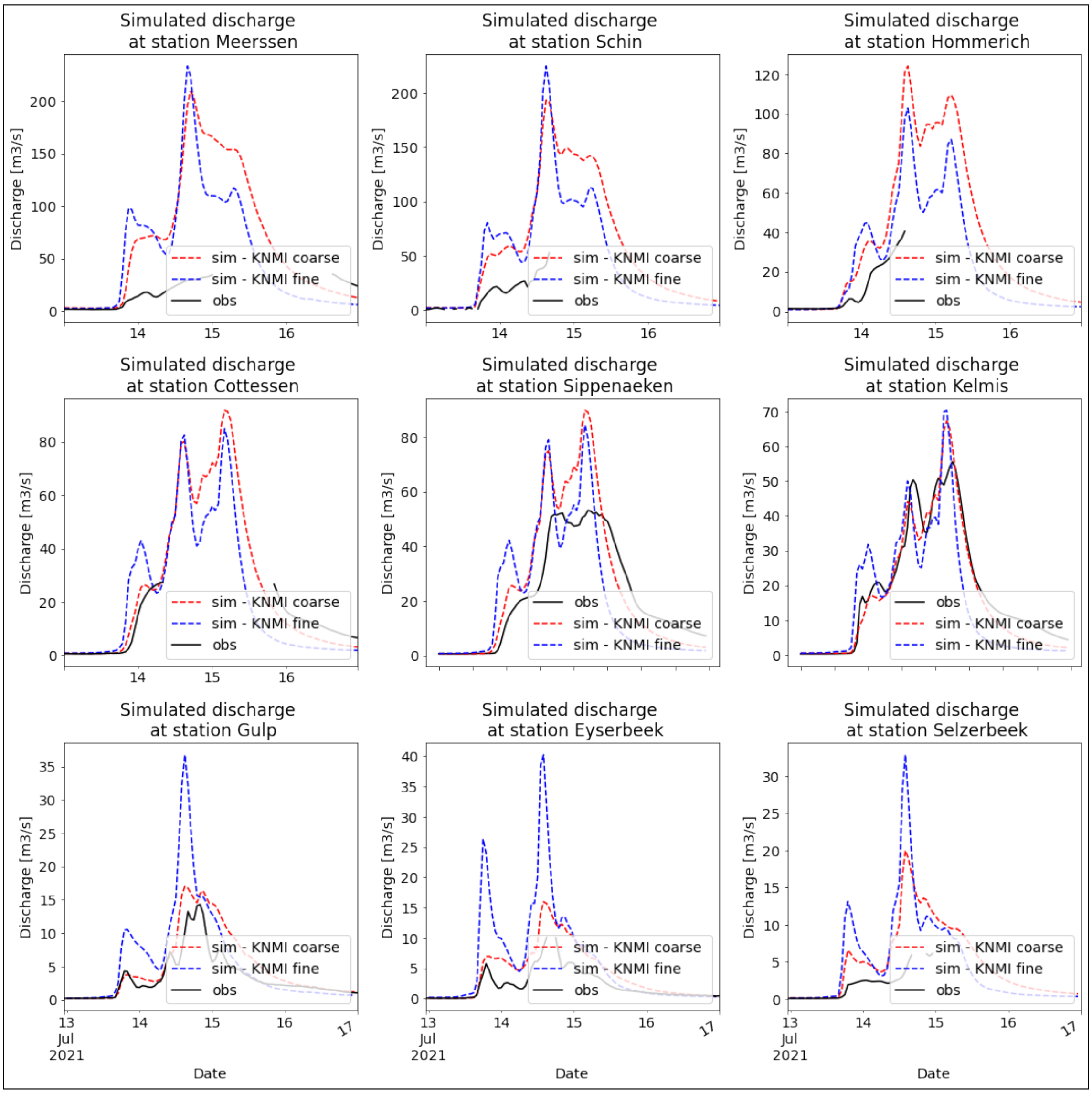

Figure E.1: Fine and Coarse Model compared to observed discharges

By first taking a look at the most upstream station in Kelmis it can be seen that the timing as well as the magnitude of the discharge is representative of the measured values. However, the further downstream the discharge station is situated in the catchment, the greater is the overestimation of the discharge. For the station in Schin op Geul upstream of Valkenburg the model predicts a discharge of 200 m^3/s, which is almost a factor 2 above the estimations. In general the fine and coarse model results are similar. For the stations along the Geul, the only difference is that the recession is quicker for the fine model. However, when looking at the simulation results of the three tributaries major differences can be seen between the models. The fine model is showing much higher peak discharges than the course model.

This difference is caused by the different thresholds defined in the fine and coarse model for a river cell (fine: 10 km^2, coarse: 25 km^2). In the fine model the rivers are much longer compared to the coarse model. As the roughness of a river cell is much lower compared to the roughness for a land cell (the hydrographs take a different shape (flashy and quick vs. dampened and slow). In reality all three rivers are very narrow (less than a metre bed width), heavily vegetated in summer and over bank flow occurred, therefore the coarse model captured the response of the tributaries more accurately.