Evaluating spatial measures with a D-HYDRO model to reduce flood risk based on the Dutch flood safety standards

Master Thesis Civil Engineering & Management

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Preface

In front of you lies my master thesis '*Evaluating spatial measures with a D-HYDRO model to reduce flood risk based on the Dutch flood safety standards'*. This thesis is the final phase of my master studies Civil Engineering & Management at the University of Twente.

During my research I had the help and support of many people, for which I am very grateful. Firstly, I would like to thank my supervisors at Royal HaskoningDHV; Marcel van den Berg and Sam Westerhof. The feedback and guidance during my master thesis has been very helpful. I appreciate the time and effort that they put into guiding me through this research project. Furthermore, I would like to thank Ric Huting for helping me during the preparation phase of this research. Next to that, I want to thank all the other resilience and maritime colleagues for the nice working environment they provided.

Secondly, I want to thank my supervisors from the University of Twente; Martijn Booij and Fredrik Huthoff. Their feedback and insights both on the content and the reporting of this research have been valuable. Furthermore, I would like to thank Anouk Bomers for helping me during the preparation phase of this research.

Thirdly I want to thank Gert van Houten and Kees-Jan Leuvenink from water board Rijn & Ijssel for providing the D-HYDRO model used in this study and sparring about modelling choices.

Next to that I want to thank the experts in the field that I interviewed as part of this research for their cooperation and interesting insights. Furthermore, I want to thank Wouter Henk Kanger for the financial insights in the costs of spatial measures.

I hope you enjoy reading my report.

Isabelle Schippers, September 2023

Summary

All over the world flooding is experienced, which can have catastrophic results. Historic flooding has taken the lives of many and has resulted in large damages. The Netherlands is prone to flood risk from the larger rivers and the sea and has therefore adopted strict flood safety standards. In a recent policy shift a multi-layer safety approach was designed to minimize flood risk. Where, the first layer focuses on the primary flood defence, i.e. reducing flood risk by flood defences that protects the hinterland. The second layer focus on spatial measures to reduce the consequences of flooding. The third layer focuses on crisis management, such as evacuation of inhabitants. However, flood reduction using second- and third-layer options is often overlooked.

The mean research objective of this study is defined as; *Identify and evaluate spatial measures that can be implemented to reduce flood risk by evaluating the Dutch flood safety standards using D-HYDRO*.

To answer this research question different steps are performed. As a first step it is assessed what the influence of model complexity is on the derived safety standards, in order to make a comparison between effectiveness of calculated measures and model uncertainty. After that, the potential of spatial measures obtained from literature is ranked by means of semi-structured interviews with experts in the field. Lastly the most promising spatial measures were evaluated by recalculating the flood safety standards including those measures and comparing their investment costs with the added benefit of the measures. For this study, dike ring 48 is used as a case study.

Using a different flood simulation model has both an impact on the LIR criterion and on the SCBA criterion. For the LIR criterion the most important difference is the high differences in water depth, which mostly result from the different way breach flow is modelled. Line elements also play an important role, both for the magnitude and the spatial distribution of the mortality, because of the high ascent rates that they cause. For the monetary damages, most of the flood risk already occurs at a water depth of 1 m, therefore it is more important which parts inundate than the exact inundation depth. Because of the characteristics of the study large differences can already occur with small differences in inundation pattern, because the location of the highest economic value is in some flood scenarios shielded by the A12 till a certain water level. However, for the economic risk, the version of SSM and the discount rate used also play an important role in determining flood risk.

Two different spatial measures were evaluated, namely heightening a highway using a temporary flood defence and decompartmentation by removing a regional dike. The temporary flood defence measure showed to be effective to decrease the total amount of monetary damages and the total costs when including investment costs. However, north of the highway locally flood risk is increased because of the increased water depths. The decompartmentation measure is effective in reducing the local individual risk (LIR). However, it does increase monetary risk, as a result of the increased number of victims and monetary damage. Besides that, dike reinforcement was in all cases more cost efficient than the considered spatial measures.

Even though in some cases spatial measures seem promising, reduction in flood risk as a result of the spatial measures evaluated is in the same order of magnitude, or sometimes even smaller than the differences in derived safety standards using a different model. Therefore, more certainty in the model is required to fully draw conclusions on the effectiveness of the spatial measures evaluated in this research.

The most important reasons for that model uncertainty are the way breach flow is calculated and modelled and the representation of line elements in the model. It is recommended that more research

is performed into the way breach flow should be included in the model. Additionally, when performing flood simulations, it is recommended that line elements are included in the model, but that also underpasses and stability of those line elements are correctly modelled, since they have large impact on the ascent rates and thus resulting flood safety standards.

Next to the technical feasibility of the spatial measures, there are some limitations on a governance level. An important factor for the implementation of spatial measures pointed out in this research is the way in which measures to reduce flood risk are subsidised in the Netherlands. Currently only subsidies are provided for dike strengthening measures, which is considered a limitation for the implementation of spatial measures. Therefore, it is advised to reconsider the way funding for projects to reduce flood risk in the Netherlands is granted by *the Hoogwaterbeschermingsprogramma (HWBP)*.

Glossary

Table i – Glossary spatial categorisation of dikes and area characteristics

Term	Dutch translation	Explanation
Dike ring	Dijkring	An area that is protected from water outside this area by a primary flood defence or by higher elevated areas from flooding of the larger rivers, the sea, Lake IJssel and/or the Marker Lake.
Norm segment	Normtraject	Section of the dike ring for which the same flood safety standard is applied.
Primary flood defence	Primaire kering	All the flood defence structures, such as dikes and hydraulic structures, together form the flood defence system of a dike ring against outer water(s).
Ring section	Ringdeel	Primary flood defences are further divided into ring sections. Ring sections are defined in such a way that the inundation pattern within a ring section is more or less similar (so that the exact location of a breach within a ring section has no significant impact on the resulting flood pattern).
Dike segment	Dijkvak	Ring sections are further divided into dike segments. Dike segments are based on where the dike has similar characteristics (e.g. sub soil, geometry or other strength parameters).
Hinterland	Achterland	The area inland of the primary flood defence.
Secondary dike /Regional dike	Regionale keringen	Dikes which separate the hinterland in multiple smaller compartments but are not part of the primary flood defence.
Line elements	Lijnelementen	Long and narrow elements in the hinterland with increased bed level, such as elevated roads and railways.

Table ii – Glossary flood safety standards, flood processes and flood consequences

Term	Dutch translation	Explanation
Flood safety standard	Normering	The maximum allowed flood risk that is attributed to a certain norm segment.
Breach	Bres	A continuous hole in the primary flood defence cause by overload.
Normative discharge scenario	Toetspeil	The normative discharge scenario refers to the hydraulic conditions which the primary flood defence should be able to withstand without resulting in dike breach.
Above normative discharge scenario	Bovenmaatgevend scenario	The above normative discharge scenario refers to the hydraulic conditions which correspond with a 10 times higher reoccurrence probability than the normative discharge scenario.
Preventive evacuation	Preventieve evacuatie	The horizontal evacuation of people from somewhere in the potentially exposed area to a safe area outside of the dike ring before a dike breach occurs.
Acute evacuation	Acute evacuatie	The evacuation of people from somewhere in the potentially exposed area to a safe area outside of the dike

		ring, after a dike breach occurs, but before this area is inundated.
Vertical evacuation	Verticale evacuatie	The evacuation of people to higher floors or dry areas within the dike ring after dike breach occurred (and the area is inundated).
Evacuation fraction	Evacuatie fractie	The evacuation fraction is the estimated percentage of people that are able to successfully evacuate in case of flooding as a result of dike breach. In the evacuation fraction only preventive evacuation is taken into account.
Casualties	Slachtoffers	In the context of this report it refers to the of people that die from flooding
Victims	Getroffenen	In the context of this report it refers to the people whose residency is inundated.
Company downtime	Bedrijfsuitval	The discontinuity of business activities as a result of flooding.
Monetary damages	Schade	A combination between the total material damage that occurs from flooding and financial losses due to company downtime.
Economic risk	Economisch risico	The economic risk expressed the combination of the monetary damages and a monetization of the casualties and victims that result from flooding.
Mortality	Mortaliteit	The risk that an individual has to die from flooding at a specific location as result of dike breach.
Social cost-benefit analysis (SCBA)	Maatschappelijke kosten-baten analyse (MKBA)	The SCBA (social cost-benefit analysis) criterion expresses the balance between the economic risk and the required investment costs to reduce the annual probability of flooding.
Local individual risk (LIR)	Lokaal individueel risico (LIR)	the LIR criterium is defined as the yearly chance an individual has to pass away as a result of flooding, when preventive evacuation is taken into account.
Societal risk	Groepsrisico	Societal risk refers to the likelihood that a flood event will result in a large number of casualties.
Vital infrastructure	Vitale infrastructure	Vital infrastructure refers in this report to the flood risk criterion that aims to protect vital infrastructure, such as harbours, drinking water and nuclear power plants.
Normative criterion	Maatgevend criterium	The safety standard of a certain norm segment is determined based on four criteria; the local individual risk (LIR), the social cost-benefit analysis (SCBA), the societal risk and the risk to vital infrastructure. The strictest of those criteria is adopted to the safety standard and referred to as the normative criterion.
Alert value	Signaalwaarde	The flood probability at which management of the primary flood defence should start planning interventions in order to prevent that the toetspeil will be exceeded in the future.
Lower threshold	Ondergrenswaarde	The annual probability of flooding at which the primary flood defence of a certain norm segment marginally meets the normative flood risk criterium.
System effects	Systeem effecten	System effects in the context of flood risk refer to the interdependency of flood risk between different dike rings

Table iii - Glossary abbreviations

Abbreviation	Meaning	English translation/explanation
WRIJ	Waterschap Rijn & IJssel	Water board Rijn & IJssel
RWS	Rijkswaterstaat	Public service of the Ministry of Transport, Public Works and Water Management in the Netherlands
HWBP	Hoogwaterbeschermingsprogramma	Dutch alliance of water boards and Rijkswaterstaat responsible to strengthen the primary flood defence
SSM	Schade en slachtoffer methode	Tool to calculate damages and casualties
TP	Toetspeil	Normative discharge scenario
TPP	Toetspeil Plus	Above normative discharge scenario
TMR2006	Thermometer randvoorwaarden 2006	Specific set of discharge statistics for the Rhine
NAP	Normaal Amsterdams peil	The refence water/bed level used in the Netherlands

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1. Introduction

1.1. Research motivation

In many parts of the world flooding is experienced, which can have catastrophic results. Historic flooding has taken the lives of many and has cost lots of monetary damages. Around the world, different approaches are taken to limit the risk to flooding, either by minimizing the chance of flooding or reducing the impact of flooding.

Especially (densely populated) urban areas on riverbanks or near coastlines are prone to flood risk, because of their proximity to those water bodies and high economic value (Tempels & Hartmann, 2014). The Netherlands is as a low-lying delta, located within the Rhine, Meuse and Scheldt river basins and along the North Sea at large risk of flooding (Ritzema & Van Loon-Steensma, 2018). Historically prevention is considered the most important measure against flooding in the Netherlands. However, recently policy developments have taken place to also include risk reducing measures (Gilissen, et al., 2020).

As a policy instrument to design the Netherlands in such a way that it can adhere to the safety standards, the multi-layer safety approach was created. In this approach the protection against flooding is divided into three layers. The first layer focuses on prevention of flooding and the second and third layer on the reduction of flood consequences. In the first layer the focus lies on measures that strengthen the primary flood defence, reducing the hydraulic load on the dike and implementing building with nature measures on the dike itself. In the second layer the focus lies on spatial measures, such as; influencing inundation patterns using compartmentation dikes, adapted building, risk zoning and protecting critical infrastructure. The third layer focuses on crisis management, with measures such as; informing citizens, development adaptive evacuation strategy, providing sufficient emergency aids (National water plan 2016-2021, 2015).

Even though the Netherlands has a multi-layer approach regarding flood management, possibilities regarding alternatives for dike reinforcements remain mostly unused. Budgets are allocated to reduction of flood probabilities through flood defence improvement, however it is possible that this budget could be spent more efficiently for reduction of flood risk, if spatial measures to mitigate flood consequences were considered more. Besides that, in some dike segments there is limited room still available for broadening of dikes. Which limits the possibilities of improvement in first layer of flood safety.

1.2. State of the art

1.2.1. Influence model detail on flood simulation accuracy

The most important sources of uncertainty in the Dutch flood safety standards are identified by Westerhof, et al. (2022). The uncertainty in the LIR criterium mostly stems from evacuation percentages, whereas for the SCBA criterium uncertainty comes from multiple sources, with damage functions being the most substantial. The findings of this study are mostly relevant for Dutch dike rings which are at risk from river flooding.

When comparing flood simulations conducted with another spatial resolution, research shows that for a large spatial scale resulting flood characteristics are alike. However, when looking at smaller scales, such as areas close to waterways, tunnels and underpasses, important differences are observed. For example, when using coarser resolution this results in a slightly increased water depth and thus a higher number of fatalities (Brussee, et al., 2021). Mooijaart (2023) has concluded that a coarser grid resolution leads to higher peak and cumulative breach discharge, resulting from limited backwater effects when using a coarser grid.

According to Mooijaart (2023) model accuracy improves significantly when roads are added to the model as line elements, even for fine grid resolutions (20 by 20 m), since these roads are often small compared to the size of the grid cells. In case roads are not schematized correctly in the model, flood propagates quicker and the inundated area increases. Those findings correspond with Hardy et al. (1999), which state that spatial resolution directly influences inundation extent and the findings of Hesselink et al. (2003) and Aronica et al. (1998), which state that inundation patterns in Delft-FLS are very sensitive to obstructing elements.

1.2.2. Multi-layer safety

Literature shows multiple different spatial measures can be considered as an alternative to spatial planning. Some of those measures alter inundation patterns to reduce flood risk and others limit the damage in the areas that are inundated. The spatial measures obtained from literature can roughly be divided in the following categories: (de)compartmentation, temporary flood defences, risk zoning, flood proof building, drainage channels/retention areas and influencing hydraulic roughness. In most cases, efficiency of the spatial measure highly depends on characteristics of the study area.

Bakker (2022) already showed that adequate spatial planning can help to reduce flood risk. However, magnitude of this impact is largely dependent on characteristics of the current area, such as the current value of spatial assets. In this research it was mostly focused on relocation of housing. Even though it is addressed that other aspects of spatial planning such as densification of housing projects and the construction of higher apartment buildings can also be of influence. Suggestions for a spatial planning framework to limit flood risk have been proposed, based on damages and casualty rates. This is achieved by altering the resulting damage functions. Possible changes in inundation patterns are not considered.

Wolterink (2022) already made an overview of a selection of spatial measures that are implemented in Europe, that could be obtained from literature. From this selection only compartmentalization is evaluated, using a conceptual model. Conclusions of this research are that influencing flood patterns using (de)compartmentation can be effective for dike segments for which the LIR criterium is normative. However, the exact effect and required implementation differ per study area.

A first analysis of the possibilities of multi-layer safety in dike ring has been performed by Terpstra, et al., (2013). This research concluded that by taking measures to prevent flood risk (layer 1), the flood risk can be considerably reduced, while measures in the second layer have hardly any effect on the dike ring as a whole. Measures that were considered are compartmentalisation upstream of the city Rees and elevating new-build locations. An investment in crisis management of the order of 50 million over a period of 50 years would be cost-efficient, provided that the evacuation fraction increases substantially (from 75% to 95%).

1.3. Research gap

The new Dutch flood safety standards that were established in 2017 are mostly developed with a series of outdated flood calculations, often with a spatially coarse resolution and a large set of embedded uncertainties. Research in order to identify those uncertainties has already been performed by a number of parties (Westerhof, et al., 2022; Mooijaart, 2022; Brussee, et al., 2022). However, those studies are either performed with the same model that was applied or do not address the effect of those uncertainties on the Dutch flood safety standards. Therefore, it remains unknown to what extent the Dutch flood safety standards are sensitive to improved model accuracy.

Multiple case studies have been performed on the effectiveness of different spatial measures as an alternative to dike reinforcement. However, the effectiveness of those spatial measures is often case dependent, and it is unclear how effective specific spatial measures are compared to alternative spatial measures. Besides that, developments in model accuracy facilitate a broader range of measures that can be implemented in a model study.

1.4. Research framework

1.4.1. Research aim

Identify and evaluate spatial measures that can be implemented to reduce flood risk by evaluating the Dutch flood safety standards using D-HYDRO, with case study dike ring 48.

1.4.2. Research questions

1. To which extent are Dutch flood safety standards different when calculated using flood simulation performed with a different model?
2. Which spatial measures are most promising to be implemented in the study area to reduce flood risk?
3. Which spatial measures can be recommended based on their effectiveness in reducing flood risk and their cost efficiency?

1.4.3. Scope

Because of limited time available for this research, some restrictions are posed to what extent the research questions are elaborated and which matters are included.

In this research only fluvial flooding as a result from dike breach is considered. Other types of flooding and failure mechanisms of the primary flood defence that do not result in dike breach are out of the scope of this study.

Due to model availability only damages and casualties in the study area are considered. Cascade effects, i.e., flood risk in other dike rings as a result of a breach in the chosen dike ring, are thus not included in this research.

In the current flood safety standards calculation only preventive evacuation (compared to vertical evacuation) is considered, as well as in the evacuation plans of the safety region. Besides that, all aspects of evacuation are combined in just one evacuation fraction for the whole Upper Rhine Delta, which makes it difficult to properly assess the effectiveness of measures which are only aimed at improving evacuation. Therefore, spatial measures that affect the chances of evacuation are not considered in this research.

In the current procedure of determining flood safety standards, monetary values of current land use are used. Therefore, future possible scenarios which consider changes in land use type, such as housing development, are not considered.

1.5. Study area

In this study dike ring 48 is used as a case study. The choice for this study area is related to multiple aspects. Firstly, in order to assess spatial measures both on their potential to reduce the SCBA criterion and their potential to reduce the LIR criterion, a study area were both those criteria are normative is required. Dike ring 48 meets this criterion, since the LIR criterion in normative for norm segment 48-1 and the SCBA criterium is normative for norm segment 48-2 and 48-3 (Slootjes & Wagenaar, 2016b). Besides that, setting up a model to perform flood simulations can be a time-consuming process. For this study area a D-HYRDO model was already available, which saved time during the execution of this study.

Dike ring 48 is located partially in the Dutch part and partially in the German part (Figure 1) of the Rhine delta. Dike ring 48 is located on the northern side of the Rhine river, which enters the Netherlands at Lobith. The dike that protects dike ring 48 is also located along the Pannerdensch Kanaal, the IJssel and the Oude IJssel. The study area covers approximately 567 km^2. There are different land use types present in the study area, but the main land use allocation is agriculture. Most of the urban area is located along the (old) river branches. Especially the cities of Westervoort, Duiven and Zevenaar, located in the west of the study area (Figure 1) contain most of the population and economic value within the study area. Along the Old Rhine a natura2000 area is located, this area is called the Rijnstrangen and formerly served as overflow area.

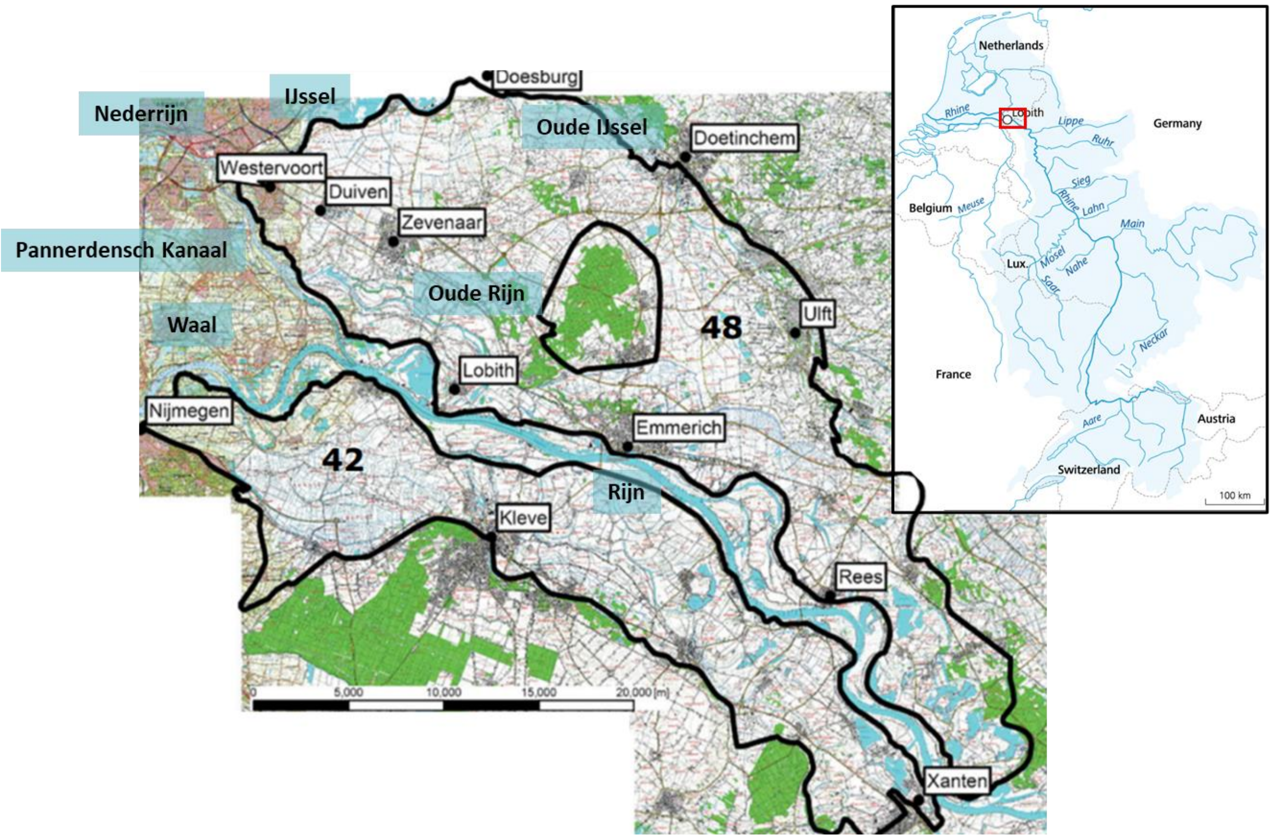

Figure 1 - Location of the study area (dike ring 48) within the Rhine river basin, including the different river branches and the largest cities in the study area (Maaskant, et al., 2019; Perk & Vilches, 2020)

The total length of the primary flood defence is 90.1 km, of which 46 km in Germany and 44.1 km in the Netherlands. The primary flood defence is divided into four different norm segments of which one lies in Germany and three in the Netherlands. Next to that, there are two regional dikes located in the study area (Figure 2), which previously were part of the primary flood defence to protect dike ring 48 from the Oude Rijn (Figure 1). The safety standards applicable for each of those norm segments is presented in Table 1.

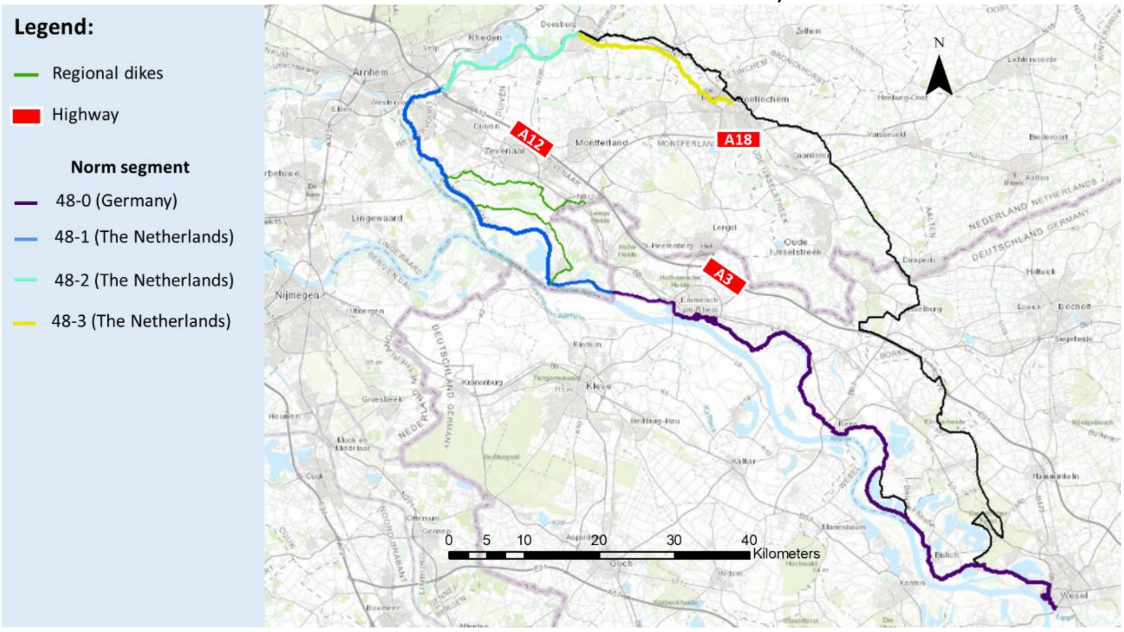

Figure 2 - Location of (regional) dikes and highways in dike ring 48

Table 1 - Classification flood safety standards for norm segments dike ring 48 (Slootjes & Wagenaar, 2016b)

Norm segment	Alert value	Lower threshold norm	Maatgevend
48-0	Not applicable		SCBA[1]
48-1	1/30.000	1/10.000	LIR
48-2	1/10.000	1/3.000	SCBA
48-3	1/10.000	1/3.000	SCBA

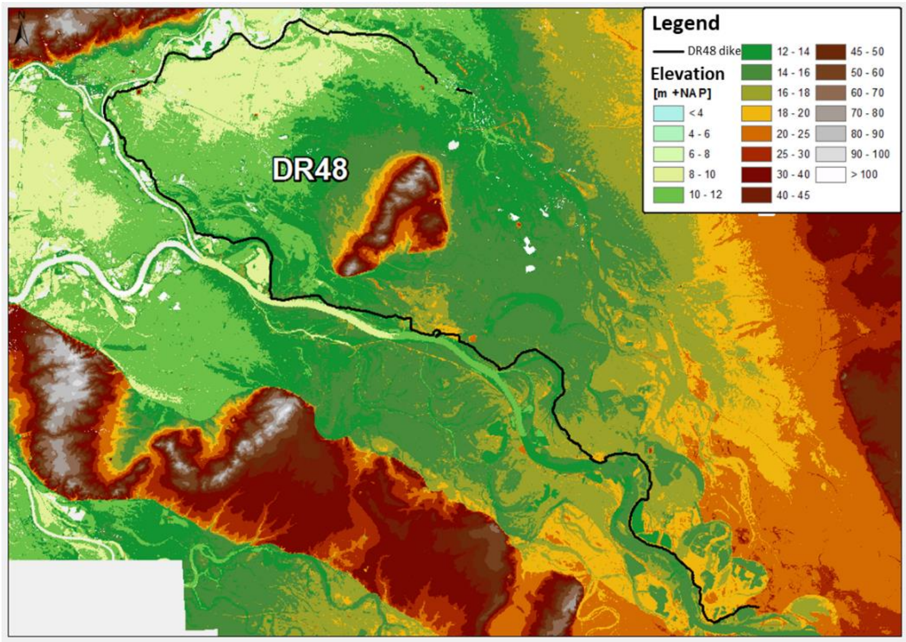

Figure 3 - Bed elevation [m +NAP] within dike ring 48 (RHDHV, 2019)

[1] In the Dutch safety standards the German part of the dike ring is not considered. However (RHDHV, 2019) showed that when the German part of the dike ring is considered as a piece of Dutch dike, the SCBA criterium is leading.

Compared to other areas in the Netherlands there are relatively high elevation differences in the study area (Figure 3). In the middle of the study area Montfoortland is located, which is characterised by the high bed elevation (25 till more than 100 meters). In the remainder of the study area the highest elevation is present in the north east, where bed levels vary between 18 and 25 meters. The lowest part of the study area is located in the north west, where bed levels vary between 6 and 8 meters.

In the evacuation plans of the dike ring for flooding, it is estimated that 80% of the inhabitants of the dike ring will try to evacuate in case the safety region gives the alert for evacuation. According to water board Rijn & IJssel & Veiligheids- en Gezondheidsregio Gelderland-Midden (2020) the whole dike ring can be evacuated within a day with control of traffic flow. Important evacuation roads are the A12 in the direction of Arnhem, the A18 in the direction of Varsseveld and the A3 in the direction of Oberhausen (Figure 2). Next to those highways, there are seven exit roads in the Netherlands and five in Germany. The self-reliant evacuees without own transportation will be led out of the area with busses to sports centre Papendal located in Arnhem which will also mainly use the A12.

1.6. Reading guide

This report starts with an explanation of the current Dutch flood safety standards, its derivation and flood models that can be used in order to derive those safety standards (Chapter 2). After that, the methodology used in this research to answer the research questions is explained (Chapter 3). Next, the answers to the research questions are presented (Chapter 4). Chapter 5 presents a discussion on the limitations of the study, as well as its potential and a generalization of the results. In Chapter 6 this research is finalized with its main conclusions and recommendations are provided for both management decisions and further research.

2. Theoretical framework

2.1. Current flood safety regulations in the Netherlands

The Netherlands has a long history of protecting itself against flooding. Large part of the Netherlands lies below sea level and are therefore prone to flood risk from the sea and the larger rivers. Those parts are divided in dike rings and norm segments, each with their own flood safety standard. A dike ring is a Dutch term which indicates an area that is protected from water outside this area by a primary flood defence or by higher elevated areas.

Since 2017 new flood safety standards have been established in the Netherlands. A novelty compared to the old safety standards is that the new safety standards consider flood risk instead of a probability of exceedance of the discharge. These standards therefore (still) determine the minimum height and strength of a flood defence system, but they also consider the characteristics of the area to be protected and the resulting impact of flooding.

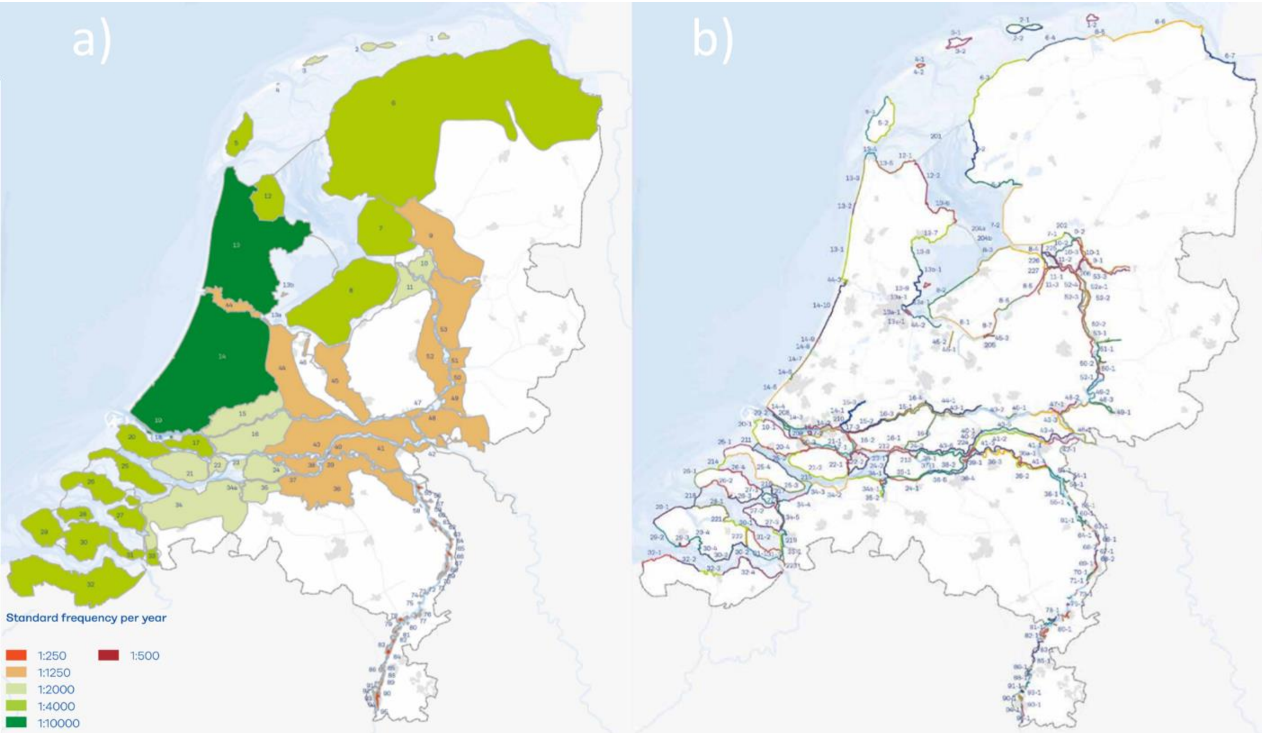

Figure 4 - (a) Old Dutch flood safety standards and (b) Current Dutch flood safety standards that were put into effect in 2017 (Kok, et al., 2017)

In the new flood safety standards the primary flood defences of the dike rings are divided in different norm segments over which the same safety standard is applied (Figure 4). These norm segments are further divided in ring sections and dike segments. The ring sections are defined in such a way that the inundation pattern within a ring section is more or less similar (so that the exact location of a breach within a ring section has no significant impact on the resulting flood pattern) and dike segments are based on where the dike has similar characteristics (e.g. sub soil, geometry or other strength parameters).

The safety standards are currently determined based on four risk criteria; a societal cost benefit analysis (SCBA), a local individual risk (LIR), a group risk and vital infrastructure. In most cases, the SCBA and/or LIR dictate the norm on a dike segment, however in areas with high population density and in areas with vital infrastructure, such as a nuclear power plants, additional criteria are set. In

Figure 5 an overview is given of the different steps taken to determine the flood safety standards, when group risk and vital infrastructure do not play a role.

A first step is to model different flood simulations based on different breach locations, for which currently flood model Delft-FLS is used for most dike rings. Arends (2014) identified a set of representative dike breach locations for each of the ring sections in the Netherlands. For the cross-border dike rings, only breach locations in the Netherlands were considered. For each of those breach locations a discharge curve which will determine breach flow is imposed, based on historic exceedance probabilities. Flood characteristics in the hinterland, such as inundation patterns, flow velocity and ascent rate are determined using an elevation and roughness map of the area, in combination with the flood model.

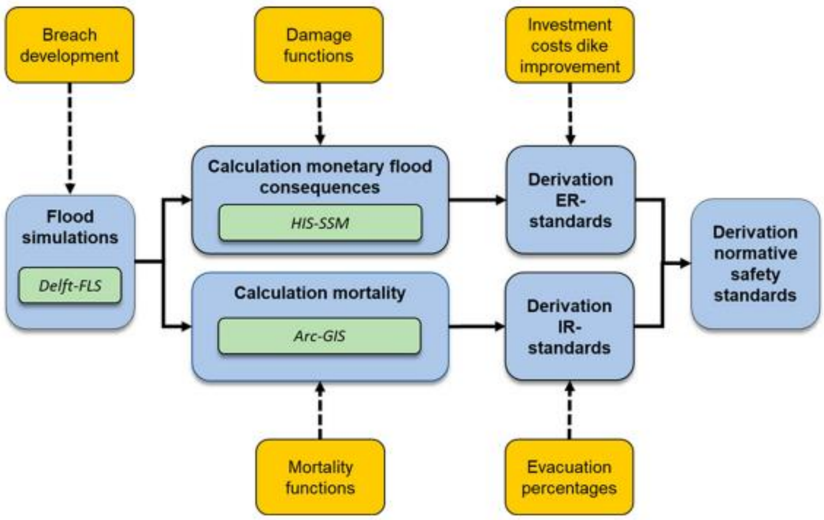

Figure 5 - Overview of steps taken in derivation of Dutch flood safety standards, including the five most important uncertainties (presented in yellow) (Westerhof, et al., 2022), ER denotes the economic risk (SCBA) and IR the individual risk (LIR)

Based on the inundation depths, ascent rate and flow velocity determined with the flood simulations, the individual risk and the monetary damages can be calculated. Those monetary damages include a monetization of the number of casualties. The number of casualties depends on the mortality and the fraction of the affected citizens that are able to evacuate. Monetary damage depends on inundation depth and the type of land use in that location. For each category of land use a monetary damage function is determined.

Afterwards, the LIR and SCBA criterium are calculated, using equation 1 and equation 2, respectively. In equation 1 LIR represents the maximum allowed LIR (1/100.000 years), E the evacuation fraction and M the mortality. In equation 2 I(h_{10}) represents the cost of investment for dike improvement [€] and D_{w2050} the projected total damage (Slootjes & Most, 2016a).

$$\text{Pf, LIR} = \frac{\text{LIR}}{(1-\text{E})*\text{M}} \qquad \text{Eq. 1}$$

$$\text{Pf, SCBA} = \frac{1\,I(h)}{38 D_w} \qquad \text{Eq. 2}$$

The criterium of the two that is the strictest is considered normative for that dike segment. After the safety standards are determined they are classified according to Table 2.

Table 2 - Classification flood safety standards (Slootjes & Wagenaar, 2016b)

Calculated flood safety standard [yr^{-1}]	Classification flood safety standard [yr]
0 - 550	1/300
550 – 1.700	1/1.000
1.700 – 5.500	1/3.000
5.500 – 17.000	1/10.000
17.000 – 55.000	1/30.000
55.000 – 170.000	1/100.000

2.2. Delft-FLS model

2.2.1. Delft-FLS

Delft-FLS is a numerical model developed by WL | Delft Hydraulics, currently named Deltares. The program is specifically designed to model flooding as a result of dike breaches (Duinmeijer, 2002).

Geometry is described by rectangular grid cells, each the same size. The bathymetry of those grid cells can be determined in several ways, using a Delft-FLS tool. This tool uses both elevation maps and line elements such as dikes and railroads to determine the bed level. Line elements, including dikes, are modelled as an elevated grid cell. Depending on the width of the dike breach it can be either modelled by the dambreak function or the culvert option. In the dambreak function the elevation is linearly lowered from its initial level to the final level. However, its limitation is that when the breach width is larger than the size of the grid cell, breach flow becomes discontinuous. A solution is using the culvert option, which uses the stage discharge relationship, presented in equation 3 (WL | Delft Hydraulics, 2001). The evolution of the breach width over time must be provided as an input in Delft-FLS.

$$q = mh_d\sqrt{2g(H_u - h_d)} \qquad \text{Eq. 3}$$

Where: q is the breach volume per meter breach width [m^2s^{-1}] m is the discharge coefficient, h_d is the water level in the breach [m], g is gravitational acceleration [m s^{-2}] and H_u is the water level in the hinterland [m]. Since in Delft-FLS flow velocity in the calculation of the energy head is neglected, this discharge coefficient (m) is always 1.

As output Delft-FLS presents several files. The incremental file can then be used to calculate water level ascent rates with the Delft-FLS ascent rate tool, which uses equation 4. This formula considers that in the Dutch safety standard calculation mortality is assumed zero until a waterdepth of 1.5m is reached, independent of ascent rate.

$$\frac{dh}{dt} = max_k\left(\frac{k - 0.02}{t_{h=k} - t_{h=0.02}}\right); k \in \{1.5, \ldots, maximum\ waterdepth\ class\} \qquad \text{Eq. 4}$$

Where; h denotes the waterdepth [m], t_h the time at which waterdepth h is reached and $t_{0.02}$ the time where a waterdepth of 0.02 m is reached.

2.2.2. Model set-up

The model set-up has a grid size of 100 by 100 meters. The elevation map that is used in the model is presented in Figure 6. Highways, railroads and (regional) dikes are implemented by elevating those grid cells in the elevation model. Since those grid cells have a dimension of 100 by 100 meters, in reality the width of those obstructing elements will be substantially smaller than in the elevation model. Underpasses of those line elements are not implemented in the model. In Delft-FLS it is assumed that the line elements will not fail in case of flooding. An exception is made for breach locations Gravenwaardsedam, Herwen and Kandiagemaal for the above normative scenario. In those cases multiple secondary breaches are modelled in the regional dikes in the Rijnstrangen area.

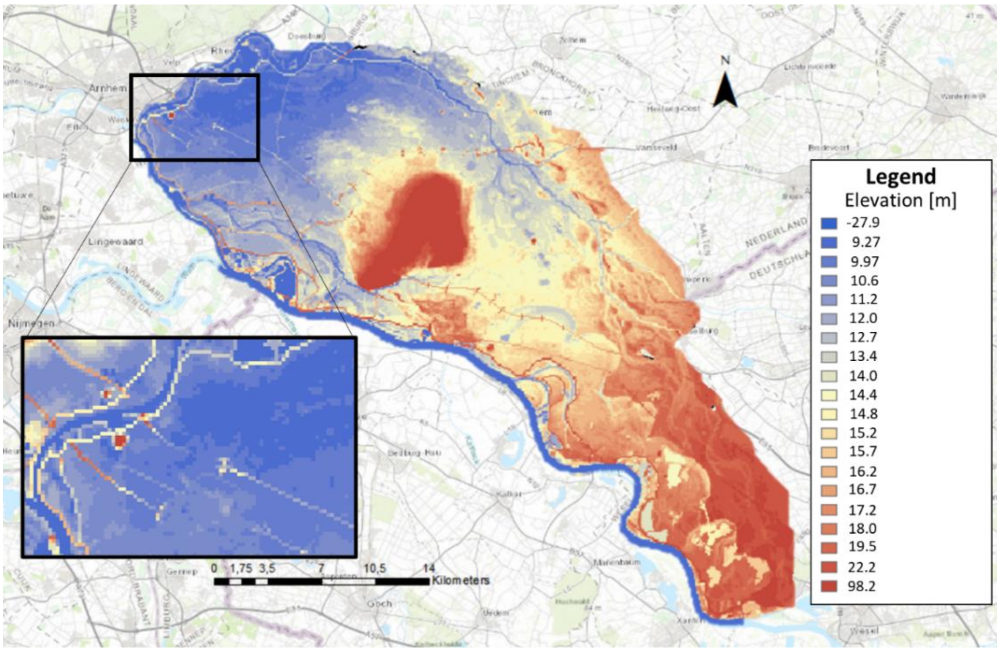

Figure 6 - Elevation map Delft-FLS dike ring 48

In Figure 7 the Nikuradse roughness values which are used in the model are presented.

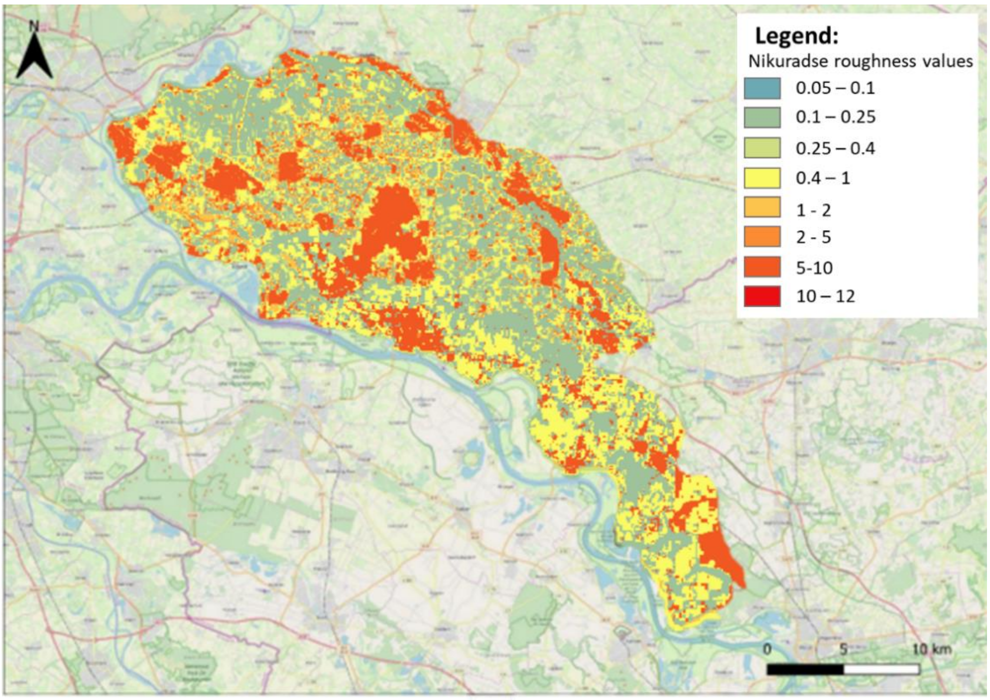

Figure 7 - Roughness map Delft-FLS dike ring 48

In the Delft-FLS model the discharge statistics corresponding with TMR2006 are used. In this scenario the normative discharge scenario corresponds with a discharge of 16,000 m^3s^{-1} at Lobith. Discharges for other return periods can be derived using equation 5. Note that, for this function climate change is not taken into account (Kuijper, et al., 2010).

$$Q = a_1 lnT + b_1 \qquad T \leq 25 \qquad \text{Eq. 5a}$$
$$Q = a_2 lnT + b_2 \qquad T > 25 \qquad \text{Eq. 5b}$$

Where; Q is the discharge [m^3s^{-1}], T the return period [$year^{-1}$], a_1 a parameter with value 1518, b_1 is a parameter with value 5965, a_2 a parameter with value 1316 and b_2 a parameter with value 6613. All parameter values are specifically for the Rhine at Lobith (Kuijper, et al., 2010).

2.3. D-HYDRO model

2.3.1. D-HYDRO

D-HYDRO, sometimes also referred to as Delft 3D – Flexible Mesh, is a process based numerical model developed by Deltares. The model is developed to simulate hydrodynamic processes, such as the shallow water equations, in 1D, 2D and 3D or 1D2D. It can be used for different types of applications, which includes river flow and flood simulation.

An important feature of the model is that it allows for using combinations of unstructured grids, such as hexagons. It also allows for using both curvilinear grid cells and triangular grid cells, as well as local refinement of the grid (Deltares, 2023). Line elements, such as dikes, roads and railways can be included in the model by either elevating the bed level or adding a fixed weir. Fixed weirs are obstructing line elements in the model which have a retaining height equal to the height of the fixed weir. The height of those fixed weirs can be varied over the length of the fixed weir to accurately match reality. D-HYDRO also allows for the inclusion of modelling waterways and structures within the hinterland. Those structures include culverts, bridges and weirs. Dike breach can be modelled by adding a breach to a fixed weir. There are different options to model breach development and breach volumes.

2.3.2. Model set-up

A model set-up of the study area has been developed by Prinsen, et al. (2020). A summary of the relevant aspects of the model set-up for this study is described in this section, further details can be obtained from Prinsen et al. (2020). The model set-up has been updated later as described in Prinsen et al. (2022).

The elevation map is created based on the most accurate elevation maps that were available for the Netherlands (2018) and Germany (2014), at the time the model set-up was created. The Dutch map has a resolution of 0.5 meter and the German map a resolution of 1 m. Those two maps are both cut off and merged at the border, an overview of the resulting elevation map is given in Figure 8.

Tunnels and underpasses were manually added to the model, based on area knowledge of the water board, elevation models and height elements. D-HYDRO uses one elevation level per calculation cell for its calculations. Some differentiations can be made in the way this height is calculated. In this model set-up there is opted to use the mean value of the different heights within one cell.

Since additional to elevation differences, obstructing elements such as barriers and higher elevation infrastructure also influence inundation patterns, those are added to the model set-up (Figure 6). The primary dike, selected roads and railways, barriers, quay surfaces and noise barriers are all implemented in the model as height line elements (fixed weirs). Besides that, local grid refinement has been applied around the higher-lying infrastructure. It is assumed that each of those line elements are stable. This means that in case of a flooding they stay in place, also in case water flows against or over it. An exception is made for the noise barriers along the 'Betuwelijn', which are assumed stable until a waterdepth of 1.5 m against the barriers.

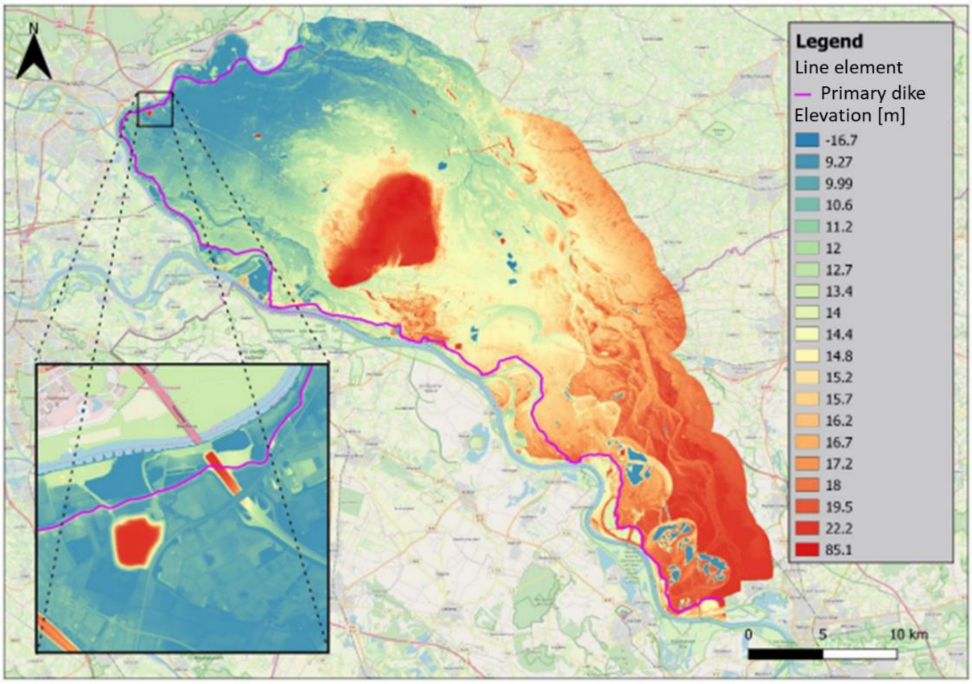

Figure 8 – Elevation map D-HYDRO (Prinsen, et al., 2020) dike ring 48 [m]

As recommended by de Bruijn et al. (2018) the roughness values in the model are based on land use type. For each land use type one fixed value for the hydraulic roughness is set (Figure 9).

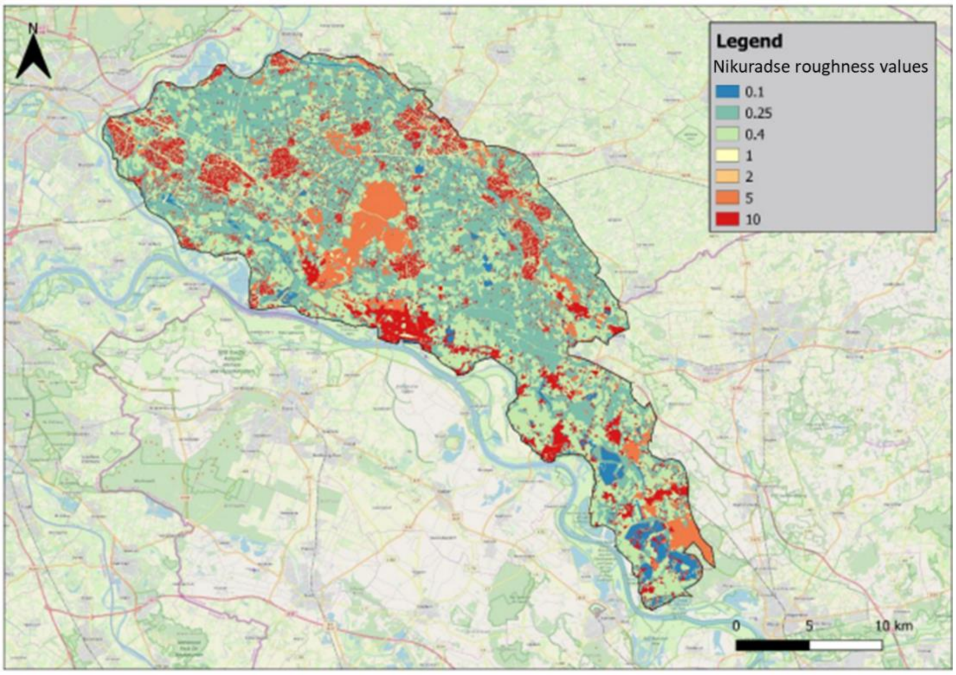

Figure 9 - Roughness values used in the D-HYDRO model (Prinsen, et al., 2020).

Since flooding propagates faster through water channels than over land, those are implemented in the model as well. All water channels with a width of 10 meters or more are included in the model (Figure A-2 Appendix A).

For the modelling of the Rhine branches in the model the 1D Rhine branches model is used for the Dutch part of the study area. This is a Sobek 3 model, based on baseline (Prinsen, et al., 2020). Baseline is an ArcGIS extension in which the summer bed and flood plains are defined, including elevation and roughness maps and cross sections (Informatiepunt leefomgeving, 2022). For this model set-up some alterations are made to this Rhine branches model. The historic timeseries at Lobith is replaced by a discharge curve obtained from the GRADE discharge statistics (Figure 4), for a specific return period. An overview of relevant return period is given in Table 2.

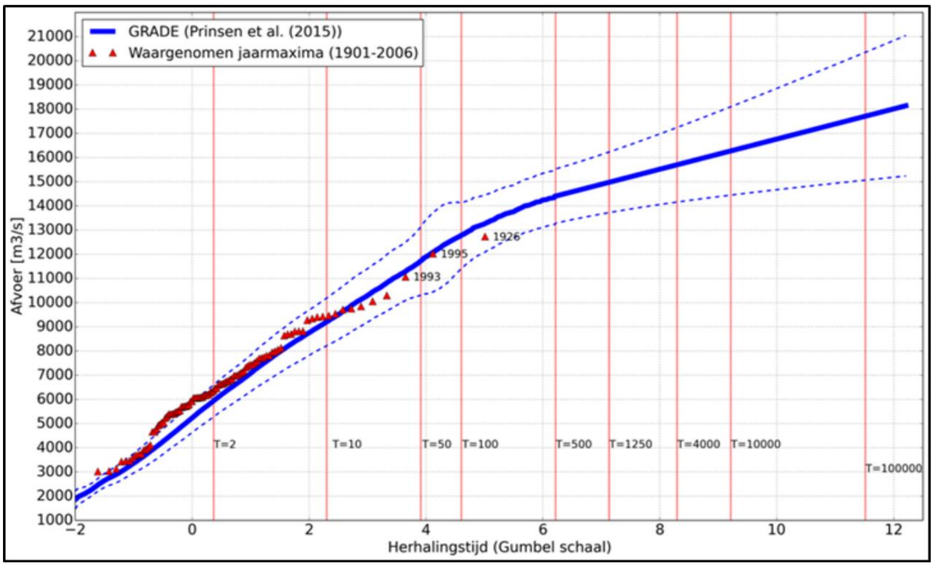

Figure 10 - GRADE discharge statistics at Lobith (Chbab, 2016; Prinsen, et al., 2015)

Table 3 - Extreme discharges for the river Rhine at Lobith for specific return periods (Chbab, 2016)

Return period [year^{-1}]	300	1,000	3,000	10,000	30,000	100,000
Discharge [m^{3}s^{-1}]	14,000	14,840	15,520	16,270	16,960	17,710

The flood wave with a certain repetition time and corresponding discharge can then be obtained by using the distribution as presented in Figure XX, for the Bovenrijn with parameter as presented in Table 4.

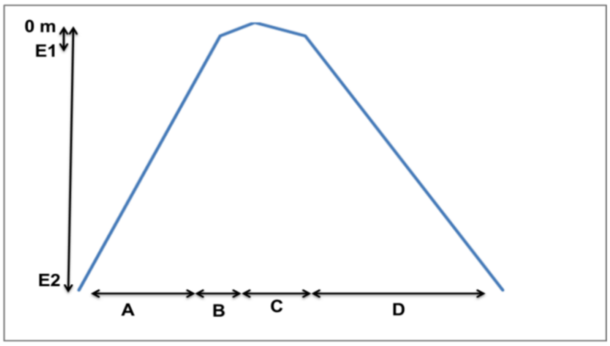

Figure 11 - Standard trapezoidal distribution for schematizing water level distribution (Chbab, 2016)

Table 4 - Parameters trapezoidal distribution for schematizing water level distribution Bovenrijn (Chbab, 2016)

Level E1 [m]	Level E2 [m]	Duration [hour]			
		A	B	C	D
-0.2	-6	200	46	52	305

Since the discharge boundary is located at Wesel, instead of Lobith, a correction factor of 0.75 % is applied to the discharge, so that the discharge curve from GRADE matches the discharge curve in the D-HYDRO model at Lobith (Prinsen, et al., 2020). For the German part a SOBEK3 1D – FM 2D model, developed for the GRADE project by Hegnauer, et al. (2014), is used from Wesel till Lobith. In this model the weir gates are fully open, which is the standard weir setting for high water.

In the model set-up there is opted to use the Verheij-Van der Knaap formula (Verheij, 2003) to determine breach growth, presented in equation 6.

$$Q = m \times B \times (h_{outside} - h_{breach}) \sqrt{2g(h_{outside} - h_{breach})} \qquad \text{Eq. 6}$$

Where; Q is the breach volume [m^3s^{-1}], m is a discharge coefficient [-], B is the breach width [m], g is the gravitational acceleration [m^2s^{-1}], $h_{outside}$ is the waterlevel in the hinterland [m] and h_{breach} is the waterlevel in the breach [m].

The breach flow (Q) changes over time depending on the breach width (B), calculated with equation 7.

$$B = 1.3 \frac{g^{0.5}(h_{outside} - h_{inside})^{1.5}}{u_c} \log\left(1 + \frac{0.04g}{u_c} t\right) \qquad \text{Eq. 7}$$

Where; u_c is the critical flow velocity [$m\ s^{-1}$] and t is the time [s].

3. Methods

In this chapter the methods used to conduct this study are explained.

In order to be able to research the possibilities of the implementation of spatial measures, a flood model with a higher level of detail than used in the current calculation of the flood safety standards is required. Therefore, in the first part of this research an existing D-HYDRO model is used to determine the flood safety standards within the study area, after which those are compared with the calculated safety standards using the previously used flood model (Delft-FLS). An assessment of the differences between the two models is performed in order to gain insight if the flood risk reduction as a result of implementation of spatial measures is substantial compared to model uncertainty. The second part of this research focuses on the identification and evaluation of spatial measures to reduce flood risk. A schematic overview of the used methodology is given in Figure 12.

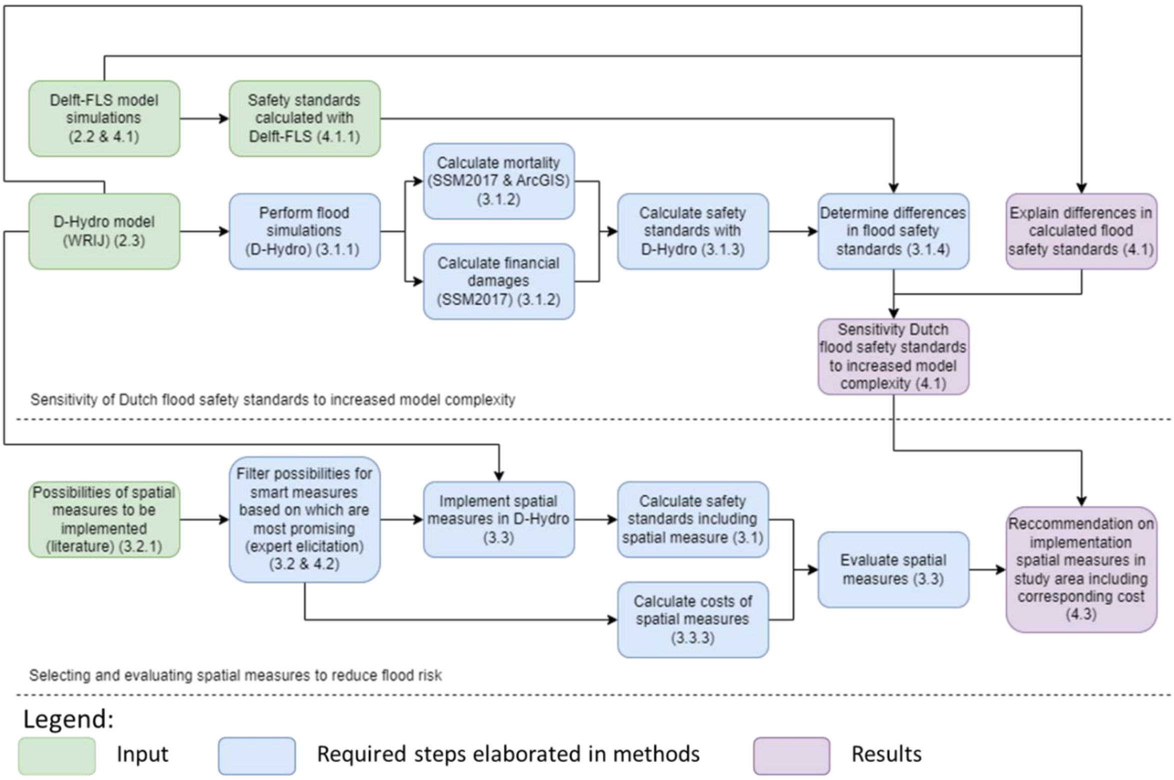

Figure 12 - An overview of the methodology used in this research (WRIJ refers to water board Rijn & IJssel)

In this study, to determine de flood safety standards using the flood simulations performed with D-HYDRO, there is tried to stick to the methodology used using the Delft-FLS flood simulations as much as possible. However, on a couple aspects deviations are made, corresponding to using the latest state-of-art insights. New discharge waves statistic corresponding to GRADE and the new flood safety standards are used (Section 2.3.2), as well as a newer version of the tool to calculate damages and mortality and corresponding factor for indirect costs (Section 3.1.2) and an updated discount rate (3.1.3).

3.1. Sensitivity flood safety standards to increased model complexity

For the different ring sections and their corresponding breach locations the outcomes of the model simulations of D-HYDRO and Delft-FLS and the resulting safety standards calculations are compared in order to gain insight in the influence of model complexity on the flood safety standards.

The calculation of the safety standards for dike ring 48 has already been performed using Delft-FLS (RHDHV, 2019). However, for D-HYDRO this process still needed to be executed, including performing flood simulations. The performed steps in the calculation of the safety standards using D-HYDRO flood simulations are elaborated in section 3.1.1 till section 3.1.4.

3.1.1. Flood simulations

In order to calculate the flood safety standards, maximum inundation depth, maximum flow velocity and maximum water level ascent rate are required, for each considered breach location. Those variables were obtained using the model set-up of D-HYDRO as explained in section 2.2. For the calculation of the safety standards a breach location is selected for each ring section (Table 5). Most of the breach locations have the same coordinates in the D-HYDRO simulations as in the Delft-FLS simulations, however there are some small differences (Figure 13).

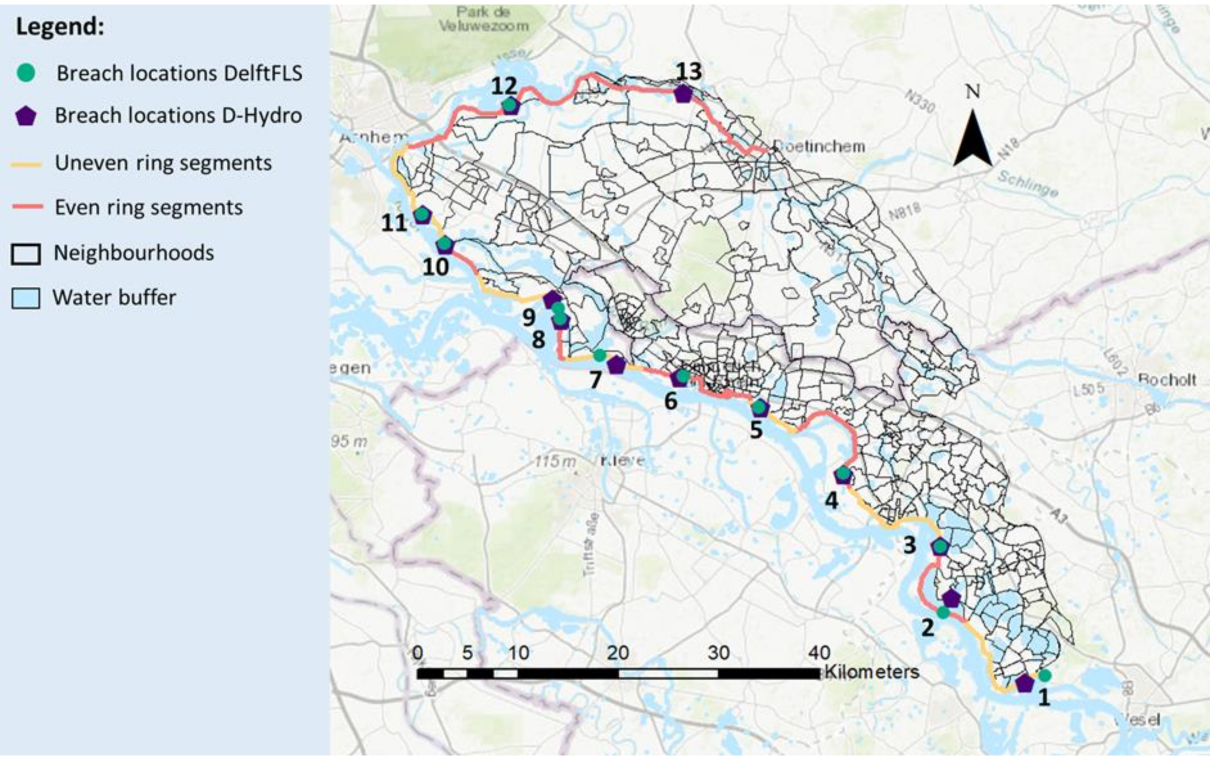

Figure 13 – Breach locations DelftFLS and D-HYDRO for all ring sections

Contrary to the calculation of the current safety standards (Slootjes & Wagenaar, 2016b), the German dike segment is also included in this research, since this has shown to have substantial influence on flood risk (Maaskant, et al., 2019). RHDHV (2019) calculated the safety standards for dike ring 48 both by considering German breach locations and without considering German breach locations. Therefore, an adequate comparison can still be made between the two models, also for the German breach locations.

For each breach location flood simulations are performed for the normative and above normative discharge scenario, corresponding with the flood safety standard that is in place for that norm segment. In correspondence with earlier research (RHDHV, 2017), it is assumed that regional dikes within the dike ring area withstand the normative discharge scenario scenario but fail at the above normative discharge scenario. In consultation with the water board, the secondary breaches[2] are

[2] i.e., a breach in the regional dike as a result of flooding after there has been a breach in the primary flood defence

assumed to occur at the section of the dike with the lowest crest level at the time that the water level reaches only 10 cm below crest level.

Table 5 - Breach locations considered in determining flood safety standards research question 1 (RHDHV, 2017)

Norm segment	Breach location	Ring section	Length ring section [km]	Respective contribution by ring section
48-0	Bislich	1	8.6	0.187
48-0	Haffen-Mehr Lohwardstrasse	2	6.7	0.145
48-0	Haffen Althrein	3	9.2	0.201
48-0	Rees Rosau	4	8.3	0.180
48-0	Emmerich Stadtweide	5	3.5	0.075
48-0	Emmerich West	6	9.7	0.212
48-1	Spijk	7	5.1	0.198
48-1	Gravenwaardse dam	8	2.9	0.112
48-1	Herwen	9	6.8	0.264
48-1	Kandiagemaal	10	2.9	0.113
48-1	Loo	11	8.1	0.313
48-2	Giesbeek	12	14.9	1.000
48-3	Eldrik	13	13.1	1.000

3.1.2. Calculation of mortality and monetary damages

For the calculation of mortality and monetary damages '*Schade en Slachtoffermodule 2017*' (SSM2017) is used. To calculate the mortality and monetary value of the area, SSM2017 uses the price level of 2011. Those monetary values from 2011 are scaled to the year 2050 by multiplying with a discount rate of 2.25% (Don, et al., 2020). Input for these calculations is the maximum inundation depth, maximum flow velocity and maximum ascent rate originating from the flood simulations (Deltares, 2020).

The general formula to calculate monetary damages is presented in equation 8 (Slager & Wagenaar, 2017).

$$S = \sum_{i=1}^{n} \propto_i n_i S_i \qquad \text{Eq. 8}$$

Where:

$\propto_i$	=	Damage function category i, dependent on the hydraulic conditions such as water depth
n_i	=	Number of units in category i
S_i	=	Maximum damage per unit in category i
n	=	Total amount of categories

The total damage is a combination of the direct damages and the damage resulting from company downtime (including the downtime of living facilities) (Equation 9). The damage factor ($\propto_i$) depends on the category and the hydraulic conditions, such as water depth (Slager & Wagenaar, 2017). An overview of the costs per category and the damage functions is displayed in Appendix B. Not all indirect costs are included in SSM2017 and to compensate for that, the monetary damages resulting from SSM2017 are multiplied with 1.42 (Heymen, 2020). A break down of this factor is presented in Appendix B.

$$S = \sum_{i=1}^{n}(\propto_i n_i SN_i + (1 - \propto_i) SB_i)\beta_i ID(1 - SF_i)M_i$$ Eq. 9

Where:

β_i	=	Damage function company downtime category i
SN_i	=	Maximum net damage per unit in category i
SB_i	=	Maximum gross damage per unit in category i
ID	=	1 year; maximum company downtime of damaged object
SF_i	=	Subsitution factor of category i
M_i	=	Multiplier for indirect damage for category i

The chance of mortality is dependent on water depth, ascent rate and flow velocity. Even for low water depths mortality can occur, because of rapid ascent rates (0.5 m hr^{-1} till a depth of 1.5 m) or high flow velocities (2 m s^{-1}) (Figure 14). In the Netherlands four different mortality functions are used (Equation B1-B4 in Appendix B), where flood characteristics determine which one should be used (Maaskant, et al, 2009; based on (Jonkman, 2007)).

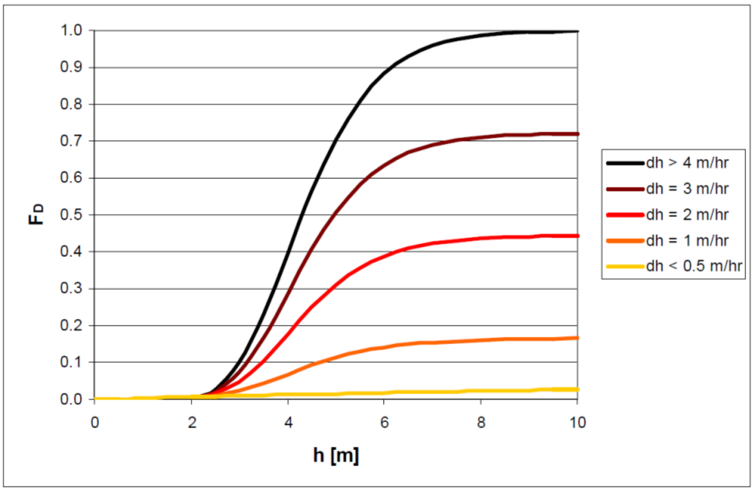

Figure 14 - Function victims depending on ascent rate (dh [m/hr]), where chance of dying (F_D [-]) is presented as a function of water depth (h [m]) (BRON memo SSM2017)

SSM2017 only supports grids that contain grid cells that all have the same size and are multiples of 5 m by 5 m. Since the model uses a flexible mesh, the grids of maximum water depth and maximum flow velocity need to be post-processed. The data is converted to a point map in ArcMap and after that the data of the grids cells is assigned to a new grid with the cell size of the largest grid cells (40 m by 40 m). When the grid cells are merged, the average value of the point data within a cell was calculated and assigned to that cell.

3.1.3. Calculation flood safety standards

After the mortality and monetary damage grids are obtained using SSM2017 (section 3.1.2) for each of the breach locations, the resulting data needs to be combined for each of the norm segments.

To calculate the LIR criterion, this is done by calculating a weighted average of the mortality maps for each breach location on that norm segment, based on the weight attributed to each breach location as presented in Table 5. After that, the normative and above normative discharge scenario are combined, using a weight of 0.6 and 0.4, respectively, in accordance with (Ministerie van Infrastructuur en Milieu, 2016).

Around surface water bodies the model results can be unrealistic, therefore all results within 100 m from any surface water are removed. This is done by combining locations in which initial water depths are higher than 0 in the model and locations in which the land use type is allocated to water into a map and adding a buffer of 100 meters. After filtering out mortality data within the waterways and surface water, the resulting data is converted to a mortality value per neighborhood, which is done by taking the median value within that neighbourhood. Locations in which the mortality is 0 are excluded from determining this median value. A shapefile of those neighborhoods is obtained from DPV.

The LIR criterion is then calculated using (equation 1) so that for each norm segment the normative neighbourhood does not exceed a local individual risk of 10^{-5}. After that, if the sum of all four norm segments of the risk that an individual has of dying from flooding within a specific neighbourhood then is still higher than 10^{-5}, the calculated LIR criterion for each of the norm segments is multiplied with the factor this sum deviates from 10^{-5}. Note that, this multiplication does not take into account which of the norm segments is most economically feasible to invest in.

For the SCBA criterion an economic risk is calculated, in which the monetary damages and a monetization of the number of casualties including evacuation and the number of victims are combined. This monetization is done by multiplying the number of casualties after evacuation with 6.7 million euros and the number of victims with 0.0125 million euros. After that, equation 2 is applied to obtain the alert value for the SCBA criterion. The lower threshold value of the flood safety standard is always one classification lower than the alert value, for the SCBA criterion.

The flood safety standards are then determined by which of the two criteria is the strictest, for that particular norm segment.

3.1.4. Analysing differences between safety standards calculated with different models

Since the flood safety standard classification has large jumps in safety standard (Table 2), the resulting flood safety standards before classification are used to compare the output of the two models. The differences have been explained based on differences in input, such as elevation maps, and model processes, such as the way dike breach flow is modelled and its influence on inundation patterns, flow velocities and arrival times.

3.2. Selecting spatial measures

3.2.1. General explanation

From literature research a list of possible spatial measures is obtained, of which an overview is given in Table 6.

Table 6 - Spatial measures obtained from literature

Spatial measure	Variations of spatial measure	Explanation	Source
Compartmentation	-Dike height of flood defence -Floodable dike -Heightening existing line elements	Dividing an area into smaller areas by adding a dike and/or altering inundation patterns by (temporarily) obstructing flood.	(Asselman, et al., 2008) (Geerse, et al., 2007) (Oost & Hoekstra, 2007)
Decompartmentation	-Removing dike -Lowering existing line elements	Removing or lowering of an existing dike/line element. This decreases local water levels and the rise rate that area.	(Asselman, et al., 2008) (Klein Wolterink, 2022)
Temporary flood defences	-Closing coupures -Inflatable tubes	Creating an obstructing element as crisis management. Works in similar manner	(Pötz, et al., 2014)

	-Movable panels	as compartmentation, however on a smaller scale and is sometimes movable to other locations.	
Risk zoning	Not applicable	Assigning the location of the different landuse types in the area based on the spatial division of flood risk in the area.	(Bakker, 2022)
Flood-minded construction	-Building on poles -Integral heightening of subsoil -Dry-proofing buildings	Adjusting the way of building to reduce the amount damage resulting from the inundated area. Influence on inundation patterns is limited.	(Asselman & Slager, 2013) (Linde, et al, 2018)
Influencing hydraulic roughness	-Adjusting vegetation type -Removing/lowering vegetation -Adding vegetation	By adjusting the hydraulic roughness, the flow velocity of the flood locally increases or decreases. This also result in locally lowering or increasing water levels, respectively.	(Calderón & Diez, 2015)
Water storage	- Increasing volume capacity current drainage channels - Adding new drainage channels - Creating retention areas	Water travels faster within drainage channels than over land. Besides that, it provides a storage for excess water (Prinsen, et al, 2020).	Literature regarding using drainage channels to reduce flood risk could only be found for pluvial flooding in urban areas, which is out of the scope of this research.

This list was shortened based on their potential to limit flood risk, estimated financial feasibility and the applicability in the study area based on the outcomes of expert elicitation. The experts were selected based on their knowledge of the Dutch flood safety standards and familiarity with the study area. The experts cover a wide range of organisations in which they operate, and each have a different expertise within the calculation process of the Dutch flood safety standards and flood risk in general. An overview of the experts is depicted in Table 7.

Table 7 - Overview of expert panel

Expert
Bas Kolen (HKV)
Geert Prinsen (Deltares)
Sander van Poorten (WRIJ)
Kees Jan Leuvenink (WRIJ)
Anouk te Nijenhuis (HWBP)
Durk Riedstra (RWS)
Martien Reniers (HWBP)

3.2.2. Set-up expert elicitation

During the interviews with the selected experts a fixed structure was followed. First, the expert is asked what her/his background is and to what extent they are familiar with the topic and the study area. This helped to identify if in the results there is a possible bias towards the expertise of the expert. Second, the case study is introduced, including an explanation about what the normative neighbourhoods are regarding flood safety criteria. After that, the list with spatial measures as obtained from literature is presented to the experts and it is asked to rank the different variations within the spatial measures based on their potential on a scale of 1-5. When the expert is of the opinion that the measure has no potential a 0 can be given. To gain insight at which location(s) the spatial measures should be implemented, the experts are asked at which locations they think the measures that they scored higher than 1 would be most promising. After that, the potential locations determined by the author that are based on the inundation patterns observed in the results from RQ1 are proposed to the expert and their opinion is asked. At the end, the experts will be asked if they have additional comments and if in their opinion a spatial measure is missing from the list presented to them. In case the expert suggests an additional spatial measure, this is also considered for implementation in research question 3.

3.2.3. Processing results expert elicitation

After each interview the discussion that took place during the interview is documented. This documentation is sent back to the concering expert, to check if the conversation is interpreted correctly. After all interviews are conducted, the average score for each of the variations of the spatial measures is calculated. The spatial measures are ranked based on their score and the most promising are selected as input for research question three.

3.3. Evaluation spatial measures

The ranking of spatial measures that resulted from research question 2 combined with expert insight on suitable locations within the study area are used as a starting point for this research question. In section 3.3.1 and 3.3.2 the implementation of the considered measures in the model is explained and in section 3.3.3 the assessment of those measures is described.

3.3.1. Implementation temporary flood defences

As implementation of the temporary flood defences measure the retaining capacities of the A12 are increased, in order to limit damages in the cities Westervoort, Duiven and Zevenaar. In practice this is executed by elevating the retention height using big bags and underpasses are closed. Besides that, culverts also need to be closed, for the highway to work fully obstructing. In the model this is implemented by increasing the height of the fixed weir that represents the A12 by 2 meters, elevating the bed level at underpasses to the bed level next to the underpasses and deleting the culverts in the model that connect the northern side of the A12 with the southern side of the A12. For all flood scenarios in which the flood propagates from the north of the A12 to the south of the A12 new simulations are performed.

3.3.2. Implementation decompartmentation

The decompartmentation measure considered is partial decompartmentation of the Rijnstrangen area, by removing the southern regional dike within this area (Figure 2).

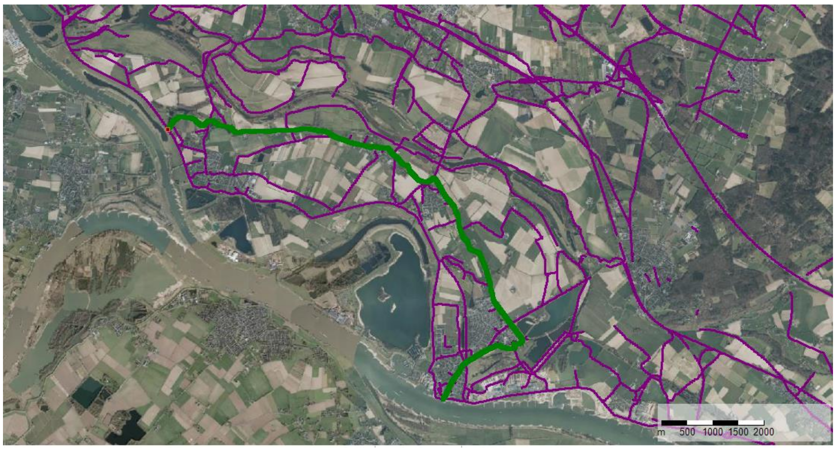

Figure 15 - Fixed weir to be removed in the model when the Rijnstrangen area is partially decompartmentalised

This measure is implemented in the model by removing the fixed weirs that represent this regional dike (Figure 15) and lowering the bed level on the old location of the dike to the bed level next to the dike. New flood simulations are performed for each of the flood scenarios in which at least one of the sides of the regional dike is inundated.

3.3.3. Evaluation spatial measures

The spatial measures are evaluated both based on their potential to reduce flood risk and their cost efficiency.

In order to assess their potential to reduce flood risk, calculated safety standards and underlying factors are compared with and without the implementation of spatial measures.

For each of the spatial measures the investment costs are compared to their reduction in monetary damages and local individual risk. Besides that, it is compared to the necessary investment costs of dike reinforcement, which yield the same results in terms of reduction of flood risk.

The investment costs of the different spatial measures are case specific and are estimated together with a cost estimator from Royal HaskoningDHV. Costs are estimated based on experience of the cost estimator. Because of the embedded uncertainty in this type of estimation, an uncertainty bandwidth of 30% was included.

For the estimation of the costs of the temporary flood defence measure costs are based on the following principles. The A12 is on one side temporarily elevated using standard Dutch big bags until a height of two meters is reached and underpasses are closed. Over the considered length of 9.8 km this results in a total required volume of those big bags of 48.510 m^3. Included in the costs are the supply of the big bags, including costs of big bags and the costs of supply, the filling of those big bags and manpower required to put them into place and the removal of the big bags. Furthermore, the costs of additional traffic control required to place the big bags is also included in the total cost of this measure.

For the estimation of the costs of the decompartmentation measure it is assumed that the regional dike which has a total length of 10.1 km consists of three parts, where the geometry along a certain part is approximately similar. An estimation is made that in order to remove those three sections combined a total of 595,600 m^3 of soil needs to be moved. The costs for the decompartmentation measure mostly consists of removing and application of the road paving, and the excavation and disposal of the soil. Additionally, the adjustment of dike entrances and required traffic measures are also included in the cost estimation.

For both measures, this total calculated cost is multiplied with additional factors to cover for general costs. Which includes 25% for indirect costs, 10% project management costs, 5% extra costs (such as permits), 10% risk and 21% tax.

4. Results

In this chapter the answers to the three main research questions are presented.

4.1. Sensitivity flood safety standards to increased model complexity

In section 4.1.1 the calculated safety standards using D-HYDRO flood simulations are compared to the safety standards reported in (Maaskant, et al., 2019; RHDHV, 2019). These are calculated using the same methodology as the safety standards incorporated in the Dutch law using Delft-FLS flood simulations. The underlying reasons for the differences are given in section 4.1.2.

4.1.1. Comparing calculated safety standards using D-HYDRO and DelftFLS

The calculated safety standards using D-HYDRO, computed as explained in section 3.1, are compared with the results from the study to the transboundary flood risk (Maaskant, et al., 2019; RHDHV, 2019). In that study an alternative approach is used to calculate the safety standards for norm segment 48-3[3] and model input for this norm segment is not available. Since a good comparison cannot be made for this norm segment, the focus in this analysis lies on the other three norm segments.

Table 8 shows that, for most of the norm segments both the calculated LIR criterion and the calculated SCBA criterion are substantially lower using the D-HYDRO flood simulations compared to the Delft-FLS flood simulations. This results for norm segments 48-0 and 48-1 in a norm classification one class lower in this study, compared to earlier results. For norm segment 48-3 the difference is even two classes and for norm segment 48-2 the same class is calculated. For norm segment 48-1 in this study the LIR criterium is not the only normative criterion anymore.

This can be attributed to different model characteristics, as explained in section 4.1.2. Note that, additionally to the differences in model characteristics, there is also a difference in the SCBA criterion resulting from a difference in the discount rate which is increased from 1.9% in Delft-FLS to 2.25% in D-HYDRO and a newer version of SSM.

Table 8 - Flood safety standards obtained by using Delft-FLS and by using D-HYDRO

	48-0	48-1	48-2	48-3
Safety standard Delft-FLS LIR	1/4,200	1/11,200	1/850	1/430
Alert value Delft-FLS SCBA[4]	1/8,700	1/17,200	1/10,900	1/7,000
Safety standard classification Delft-FLS	1/3,000	1/10,000	1/3,000	1/3,000
Normative criterium	LIR/SCBA	LIR	SCBA	SCBA
Safety standard D-HYDRO LIR	1/1,555	1/4,564	1/506	1/81
Alert value D-HYDRO SCBA	1/4,320	1/9,846	1/9,696	1/172
Safety standard classification D-HYDRO	1/1,000	1/3,000	1/3,000	1/300
Normative criterium	LIR/SCBA	LIR/SCBA	SCBA	LIR/SCBA

The SCBA criteria are the result of combining the damages from flooding (and by monetizing the expected number of casualties and victims) (Table 9) for the different scenarios (described in section 3.1.3) using SSM2017 (section 3.1.2). In most cases damages, casualties and victims are all higher for Delft-FLS than for D-HYDRO.

[3] For example, instead of using DelftFLS output to determine ascent rate and flow velocity, it is assumed that ascent rate and flow velocity both have a value of 0.5 everywhere in the study area.
[4] Classification for the SCBA is one safety standard class lower than the safety standard for the alert value.

When comparing the different components (damages, casualties and victims) it stands out that the largest differences occur for the number of casualties. This is partially the case since the number of casualties depends on the mortality, which is also lower in D-HYDRO. When comparing discharge scenario's, differences are generally larger for the normative discharge scenario than for the above normative discharge scenario, which can partially be attributed to the breach volumes (Section 4.1.2.1). The large difference between flood scenarios for Gravenwaardsedam can be explained by the additional modelling of two underpasses in D-HYDRO, which are not presented in the Delft-FLS model (section 4.1.2.2). When looking at individual breach locations, the highest differences are observed for Emmerich West in the normative discharge scenario and Kandiagemaal in the above normative discharge scenario. For Emmerich West this difference can be explained by the fact that in D-HYDRO flood propagation is limited by a specific line element whereas in Delft-FLS the water does flow over this line element (4.1.2.2). For Kandiagemaal this difference can be explained by the fact that in D-HYDRO the flood propagates outside of the Rijnstrangen area to the cities Westervoort, Duiven and Zevenaar and north of the A12, whereas in Delft-FLS the water stays within the regional dikes of the Rijnstrangen area (Table C-2 Appendix C).

Table 9 - Damage, casualties and victims for Delft-FLS and D-HYDRO for all breach locations at price level 2011[5], highlighted are the scenarios in which the largest differences between Delft-FLS and D-HYDRO occur

Norm segment	Breach location		Damages [million €]		Casualties without evacuation [-]		Victims [-]	
			DelftFLS	D-HYDRO	DelftFLS	D-HYDRO	DelftFLS	D-HYDRO
48-0	Bislich	TP	6,795	6,800 (+0.1%)	618	228 (-63%)	131,117	105,300 (-20%)
		TPP	10,447	10,000 (-4%)	950	556 (-41%)	146,976	127,100 (-14%)
48-0	Haffen-Mehr Lohwardstrasse	TP	7,740	4,200 (-46%)	749	98 (-87%)	140,099	49,490 (-65%)
		TPP	12,045	8,900 (-26%)	1,150	408 (-65%)	157,724	118,100 (-25%)
48-0	Haffen Althrein	TP	7,036	2,800 (-60%)	667	67 (-90%)	134,614	33,480 (-75%)
		TPP	10,953	7,700 (-30%)	1,017	294 (-71%)	149,323	111,400 (-25%)
48-0	Rees Rosau	TP	6,605	6,200 (-6%)	617	190 (-69%)	129,346	100,200 (-23%)
		TPP	10,450	10,000 (-4%)	952	539 (-43%)	146,201	125,900 (-14%)
48-0	Emmerich Stadtweide	TP	5,823	2,500 (-57%)	543	55 (-90%)	116,205	30,920 (-73%)
		TPP	9,179	5,400 (-41%)	850	151 (-82%)	131,972	93,760 (-29%)
48-0	Emmerich West	TP	6,844	1,000 (-85%)	816	56 (-93%)	123,666	10,660 (-91%)
		TPP	10,984	7,200 (-34%)	1,340	502 (-63%)	141,931	98,290 (-31%)
48-1	Spijk	TP	7,173	3,700 (-48%)	1,082	138 (-87%)	124,043	72,980 (-41%)
		TPP	7,889	6,800 (-14%)	1,399	431 (-69%)	128,539	96,020 (-25%)
48-1	Gravenwaardse dam	TP	306	450 (+47%)	335	294 (-12%)	4,110	6,316 (+54%)
		TPP	7,010	3,500 (-50%)	1,518	586 (-61%)	116,812	73,330 (-37%)
48-1	Herwen	TP	3,246	3,800 (+17%)	500	608 (+22%)	101,594	72,010 (-29%)
		TPP	6,861	7,300 (+6%)	1,012	1,124 (+11%)	114,089	98,740 (-13%)
48-1	Kandiagemaal	TP	207	240 (+16%)	16	3 (-81%)	3,504	2,277 (-35%)
		TPP	549	6,400 (+1066%)	75	387 (+416%)	8,909	93,810 (+953%)
48-1	Loo	TP	5,576	6,600 (+18%)	592	452 (-24%)	100,212	91,380 (-9%)
		TPP	5,703	7,000 (+23%)	613	477 (-22%)	100,540	92,260 (-8%)
48-2	Giesbeek	TP	3,536	3,200 (-10%)	325	111 (-66%)	83,955	63,040 (-25%)
		TPP	3,820	4,800 (+26%)	367	236 (-36%)	85,950	73,830 (-14%)
48-3	Eldrik	TP	990	26 (-97%)	40	0 (-100%)	46,290	89 (-100%)
		TPP	-	54	-	0	-	172

The LIR criterium is determined based on the mean mortality per neighbourhood (Section 3.1.3), of which results are presented in Figure 16 and Figure 17 for Delft-FLS and D-HYDRO, respectively. In general, mortality is higher for Delft-FLS, which can among others be attributed by the larger water

[5] Damages obtained for DelftFLS retrieved from (RHDHV, 2019) had price level 2015 and have been scaled down to 2011 using the discount rate used in that research (1.9%).

depths (Section 4.1.2.2). For norm segment 48-1 and 48-3 there is also a shift in the normative neighbourhood (Section 4.1.2.4).

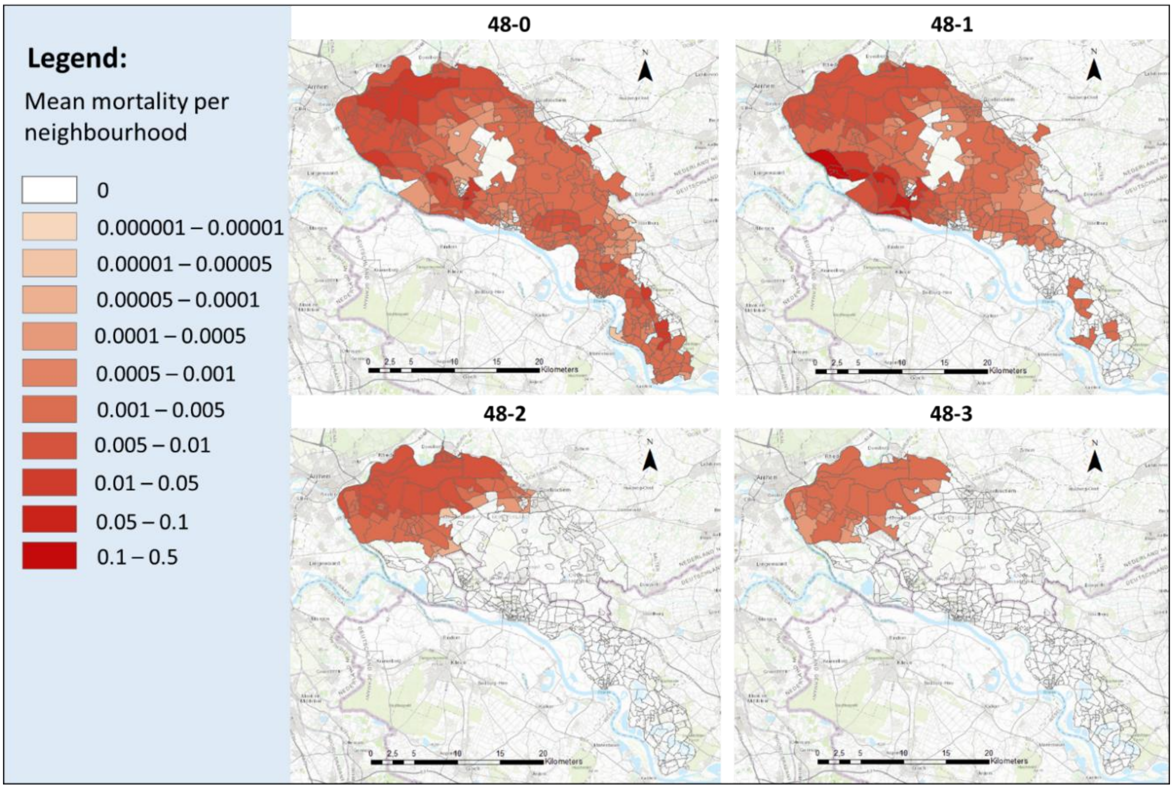

Figure 16 - Mean mortality per neighbourhood calculated using Delft-FLS flood simulations for the reference scenario (where the normative scenario contributes 60% and the above normative scenario 40%)

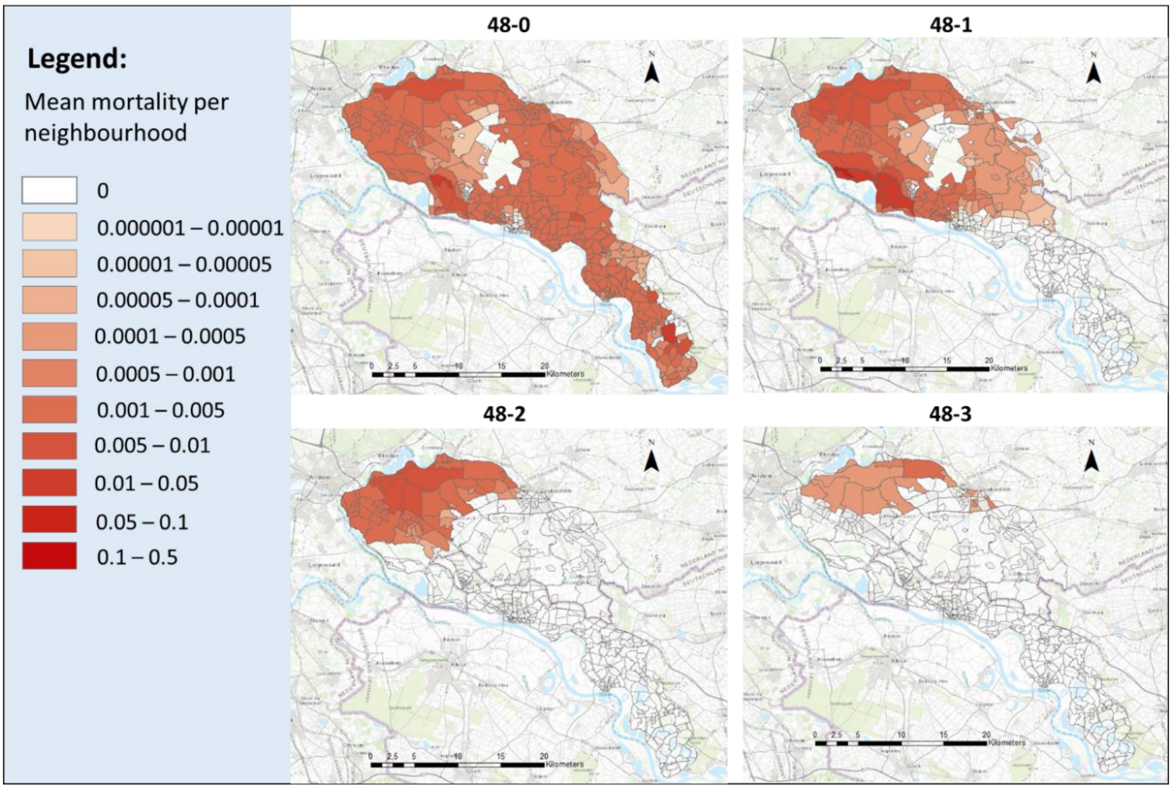

Figure 17 - Mean mortality per neighbourhood calculated using D-HYDRO flood simulations for the reference scenario (where the normative scenario contributes 60% and the above normative scenario 40%)

4.1.2. Underlying reasons for differences in safety standards

4.1.2.1. Differences in boundary conditions

The total breach flow is substantially different between the two models, even in cases that the discharge boundary conditions are similar (Table 10, Figure 18).

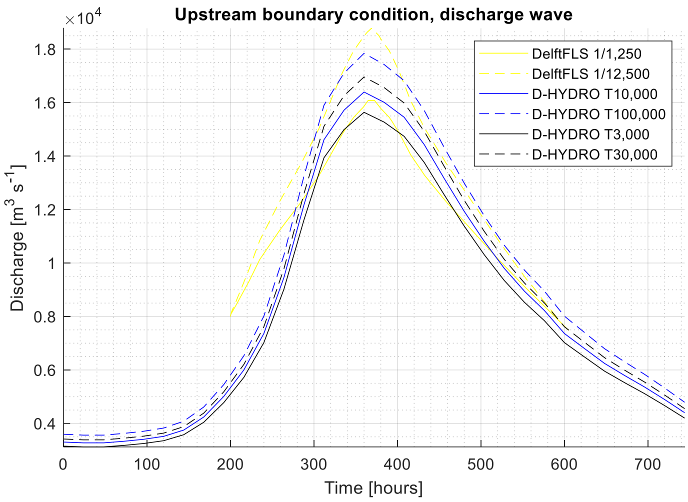

Figure 18 - Discharge waves at Wesel (the upstream boundary) for the normative and above normative discharge scenario for both Delft-FLS and D-Hydro. For D-Hydro the T3,000 and T30,000 discharge waves apply for norm segments 48-0, 48-2 and 48-3 and the T10,000 and T100,000 discharge waves apply for norm segment 48-1

The difference between the models can be explained in the way breach flow is modelled. In both models, it is assumed that the dike consists of sand, thus not resulting to any substantial differences in parameters. However, in Delft-FLS the expected breach flow is determined before the flood simulations and entered as a time series, including assumptions about the water levels during the breach. In D-HYDRO, water levels in the river are adjusted each timestep and resulting flow between the river and the hinterland is calculated based on this adjusting water level. In D-HYDRO this causes the breach flow to become lower, since the water levels in the river drop after a breach.

Table 10 - Comparison breach characteristics Delft-FLS and D-HYDRO for the normative scenario

Norm segment	Breach location	Total breach volume [10^8 m^3]		Peak breach flow [m^3s^{-1}]		Maximum width breach [m]	
		DelftFLS	D-HYDRO	DelftFLS	D-HYDRO	DelftFLS	D-HYDRO
48-0	Bislich	8.515	5.554	2443	1808	210	87
48-0	Haffen-Mehr Lohwardstrasse	5.956	3.759	2811	1309	210	136
48-0	Haffen Althrein	4.177	2.855	2113	1013	210	141
48-0	Rees Rosau	3.357	5.162	1802	1605	210	121
48-0	Emmerich Stadtweide	1.147	2.283	722	783	210	117
48-0	Emmerich West	2.296	2.279	1895	1058	210	149
48-1	Spijk	2.047	3.797	2690	954	210	71
48-1	Gravenwaardse dam	1.525	1.030	1672	861	210	53
48-1	Herwen	1.448	3.150	1510	1380	210	90
48-1	Kandiagemaal	0.565	1.073	1231	770	210	118
48-1	Loo	8.132	8.608	1640	1402	210	125
48-2	Giesbeek	2.019	1.781	919	506	210	103

48-3	Eldrik	-	0.060	-	35	-	28

Besides that, initial breach widths differ resulting in most cases in less total breach volume in D-HYDRO (Table 10). This difference in flood volume that enters the study area has consequences for the resulting flood characteristics (section 4.1.2.2.)

4.1.2.2. Differences in flood characteristics

In general, in most of the flood scenarios the area that is inundated and the maximum water depth are higher in Delft-FLS than in D-HYDRO (Table C-1 and Table C-2, Appendix C). Besides that, the minimum water depth at which mortality is calculated (1.5 m) is reached substantially more often in Delft-FLS than in D-HYDRO, especially in the normative scenario (Figure 19).

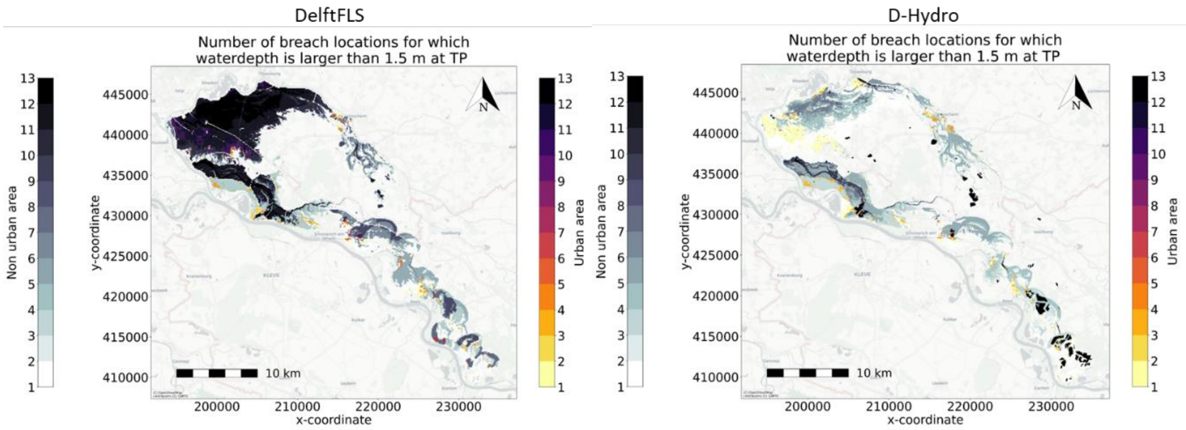

Figure 19 - Number of breach flow locations for which water depth exceeds 1.5 m (the threshold for mortality) at the normative scenario

This can partially be attributed by the differences in boundary conditions. For most of the breach locations in which breach discharge is the same order of magnitude (such as Rees Rosau) the differences in the eastern part of the study area are limited (Figure 20), resulting in less differences in damages and casualties in the German part of the study area. However, because of the gradient of the study area, there is still a large difference in water level in the northern part of the study area, where the bed levels are the lowest.

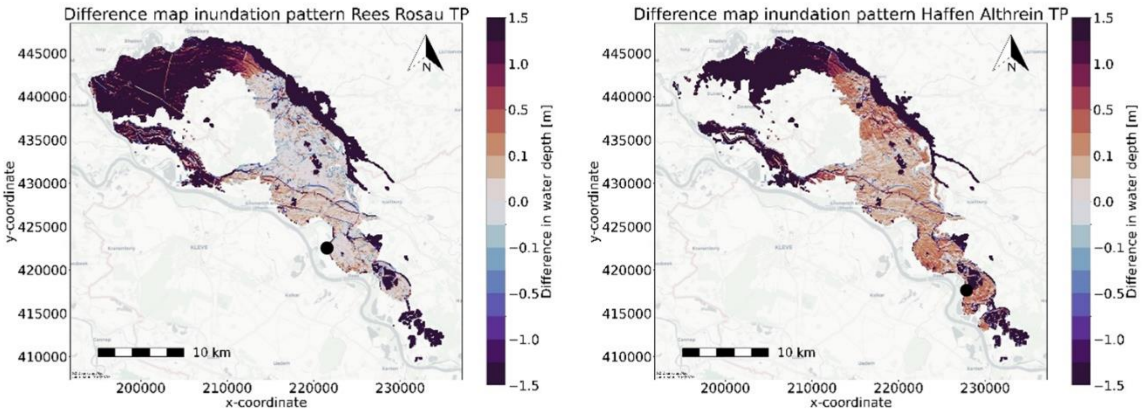

Figure 20 - Difference maps water depth [m], between Delft-FLS and D-HYDRO for the normative scenario, for breach locations Rees Rosau (left) and Haffen Althrein (right), where difference = Delft-FLS - D-HYDRO

In cases of rapid ascent rates, such as for breach location Herwen, D-HYDRO calculates higher ascents rates (Figure 21). This can be explained by the fact that the maximum ascent rate is limited by the magnitude of the timestep at which the waterdepth data is saved. In Delft-FLS this data is saved every hour and in D-HYDRO every 10 minutes, therefore the data is averaged over a larger time period in Delft-FLS. Because of that, mortality is higher in those neighbourhoods when using D-HYDRO simulations compared to Delft-FLS simulations, for those specific breach locations. The difference is especially large in the above normative scenario. In the above normative scenario, secondary dike breach in Delft-FLS occurs in multiple locations, compared to just one location in D-HYDRO, which results in faster flood propagation to the other parts of the study area in Delft-FLS. In the Delft-FLS model the ascent rate at other line elements is higher, such as against the Betuwe line and the A12. Which can be explained by the fact that underpasses are included in the D-HYDRO model, but not in the Delft-FLS model.

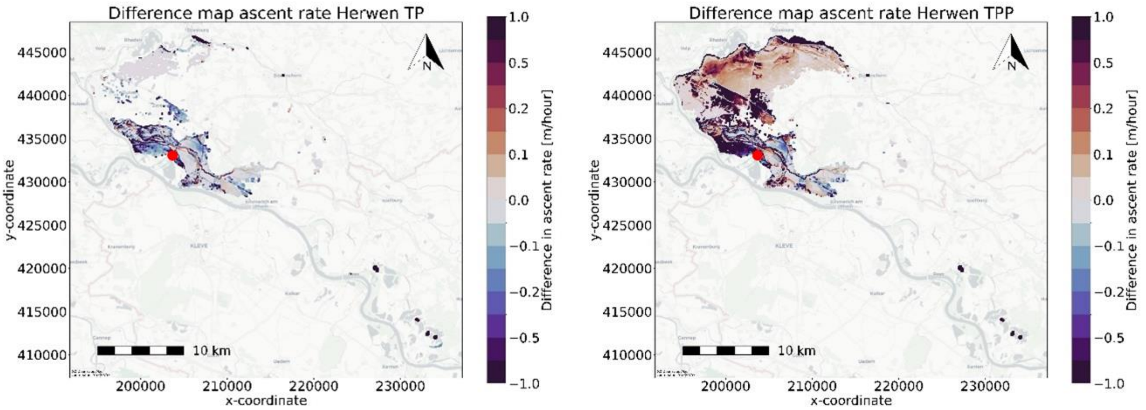

Figure 21 - Difference maps ascent rate Herwen for the normative scenario (left) and the above normative scenario (right), where difference = DelftFLS - D-HYDRO

In most cases, flow velocities are higher in Delft-FLS than in D-HYDRO. However, in the safety standard calculation flow velocities are only used to determine in which areas people have an increased chance of mortality as a result of the high flow velocities near the breach location. In the flood simulations made with both models the flow velocities only reach 2 m s^{-1} near a breach, which is the threshold for this mortality function. Therefore, this difference in flow velocity has minimal effects on the calculated safety standards. However, some breach locations are slightly shifted along the ring section, so therefore locally some differences in flow velocity occur (Figure 22)

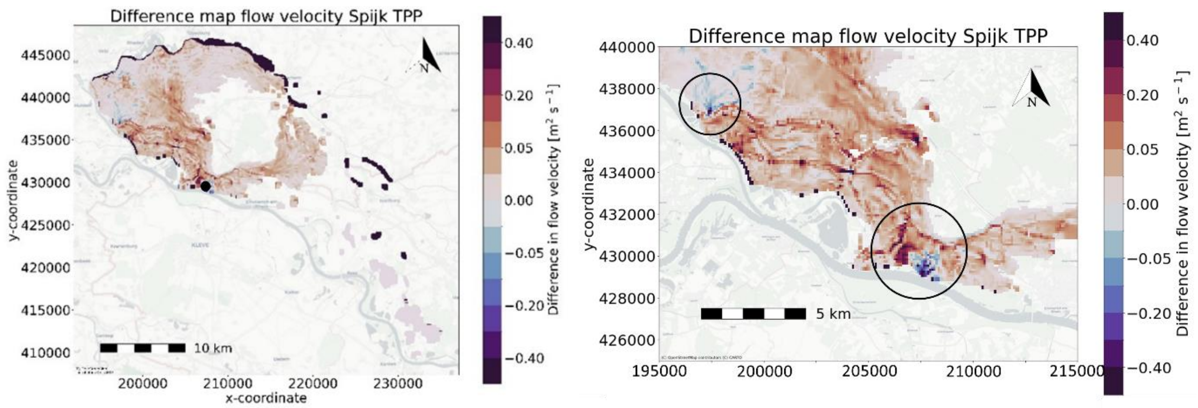

Figure 22 - Difference map maximum flow velocities [m^2s^{-1}] at above normative scenario for breach location Spijk, including zoom-in of the Rijnstrangen area (right)

The spatial resolution of the bed level has also influence on the flood characteristics. The introduction of modelling waterways in the hinterland showed to be of influence on the direction and speed in which the flood propagates. This resulted in slightly higher water depths and shorter arrival times around those water ways. Currently, arrival times are not included in the calculation of the flood safety standards. However, if that is included in the future, the extent to which waterways in the hinterland are included in the model could have more effect on the safety standard calculation. Besides that, in D-HYDRO mortality is locally substantially higher in areas with decreased bed level, such as underpasses. In general, this did not result in any deviations in the median mortality per neighbourhood, since it only concerns small surface areas.

4.1.2.3. Differences in monetary damages and SCBA

In the northern part of the study area waterdepths are so high that in large part of the scenarios the water depth reaches the threshold of maximum damages, especially in the above normative scenario. Therefore, the large differences in water depth in this part of the study area (Section 4.1.2.2), does not affect the amount of monetary damage substantially. However, large differences can be observed for cases in which the flood just reaches the cities of Westervoort, Duiven and Zevenaar in Delft-FLS, but does not reach those cities in D-HYDRO, or the other way around. The A12 forms an important barrier between the most northern part of the study area and the cities of Westervoort, Duiven and Zevenaar, which withstand the flood propagation till a certain water level. However, when this water level is surpassed, a large area with high economic value is suddenly also inundated, resulting in substantially larger economic damage.

Next to the differences in flood characteristics, some deviations in economic risk are caused by using a different version of SSM. In the version used in this study, land use maps are updated, some factors are included that were not previously (Table B-2 Appendix B) and economic value of land use types is adjusted. In the newest version of SSM (SSM2017), a lower estimate of the amount of housing is made, which results in a lower number of casualties and victims for the same flood characteristics (Table 11). On the other hand, monetary damages are larger in the newer version of SSM, which can mostly be attributed to larger economic values for the same land use type. Additionally, there are some shifts in land use type, such as a decrease in agriculture and an increase in urban area. Since urban area has a higher monetary value, this also results in higher damages calculated with SSM2017, compared to HIS-SSM. Since the economic risk directly influences the SCBA criterion, this means that the calculated differences in SCBA criterion between Delft-FLS and D-HYDRO (Table 8) using would be even larger if the same version of SSM was used.

*Table 11 - Comparison of the output of different versions of SSM, for breach locations Bislich, Herwen and Giesbeek, for which the damages include the multiplication factor for non-included costs (such as company downtime), of 1.42 for SSM2017 and 1.6 for HIS-SSM. Where difference = ((SSM2017 - HIS-SSM)/HIS-SSM) * 100%*

	D-Hydro		DelftFLS using SSM2017		DelftFLS using HIS-SSM		Difference DelftFLS different version SSM	
	TP	TPP	TP	TPP	TP	TPP	TP	TPP
Bislich (48-0)								
Damages [million €]	9,656	14,200	12,354	17,040	10,872	16,715	+14%	+1.9%
Casualties [-]	228	556	557	878	618	950	-9.9%	-7.8%
Victims [-]	105,300	127,100	115,400	128,600	131,117	146,976	-12%	-13%
Herwen (48-1)								
Damages [million €]	5,396	10,366	7,526	12,922	5,194	10,978	+44%	+18%
Casualties [-]	608	1,124	391	985	500	1,012	-22%	-2.7%
Victims [-]	72,010	98,740	98,560	112,800	101,594	114,089	-3.0%	-1.1%

Giesbeek (48-2)								
Damages [million €]	4,544	6,816	7,810	8,236	5,658	6,112	+38%	+35%
Casualties [-]	111	236	321	362	325	367	-1.2%	-1.4%
Victims [-]	63,040	73,830	82,040	84,180	83,955	85,950	-2.3%	-2.1%

The discount rate also plays a large role in the calculation of the monetary damages for 2050. Since the values are scaled over 39 years, half of damages is the result of interest. In accordance with national guidelines (Don, et al., 2020), a brief sensitivity analysis is performed with a lower bound of 1.85% and a higher bound of 2.65% (Table 12). In this case, none of the norm segment would fall in a different safety standard classification with a different discount rate within the prescribed range. However, the range in alert value is quite substantial, so when initial alert values are closer bounds of the classes, the discount rate might influence the safety standard classification.

Table 12 - Sensitivity alert value SCBA criterium to discount rate, where 2.25% is the prescribed default, which is used in the remainder of this study

	Alert value SCBA criterium			
	Discount rate 1.85%	**Discount rate 2.25%**	**Discount rate 2.65%**	**DelftFLS (discount rate 1.9%)**
48-0	1/3,853	1/4,320	1/5,031	1/8,700
48-1	1/8,451	1/9,846	1/11,466	1/17,200
48-2	1/8,322	1/9,696	1/11,291	1/10,900
48-3	1/148	1/172	1/201	1/7,000

4.1.2.4. Differences in (median) mortality (per neighbourhood)

In general, mortality is higher in the safety standard calculations for which Delft-FLS flood simulations are used, compared to D-Hydro flood simulations. This is mostly the result of the higher water depths calculated with Delft-FLS. However, there can also be some differences observed between the spatial distribution of the mortality.

An important difference between the derived median mortality per neighbourhood is the shift in normative neighbourhood for norm segment 48-1 (Figure 16 and Figure 17). This shift can be explained by the way the stability of regional dikes is modelled. In Delft-FLS secondary dike breaches occur at multiple locations along the regional dike, whereas in D-HYDRO this only happens in one specific location. This results in slower flood propagation in D-HYDRO, which in turn results in higher ascent rates against the regional dike. In Delft-FLS, water propagates faster to the remainder of the study area but is blocked by other line elements, such as the 'Betuwelijn', resulting in high ascent rates in those locations. For both models the normative neighbourhood is the neighbourhood with the highest ascent rate, however since those ascent rates are high in a different neighbourhood, the normative neighbourhood is also different.

As explained in section 4.1.2.2, the waterways in the hinterland influence the inundation pattern, in such a way that the area around those waterways is more likely to inundate and arrival times are shortened. Since those waterways where not included in the Delft-FLS calculations, there is a shift in in which neighbourhoods the median mortality is the highest.

4.1.2.5. Sensitivity of Dutch flood safety standards to increased model complexity

Using a different flood simulation model has both an impact on the LIR criterion and on the SCBA criterion. For the LIR criterion the most important difference is the high differences in water depth, which mostly result from the different manner in which breach flow is modelled. Line elements also play an important role, both for the magnitude and the spatial distribution of the mortality, because of the high ascent rates that they cause. For the monetary damages, most of the flood risk already occurs at a water depth of 1 m, therefore it is more important which parts inundate than the exact inundation depth. Because of the characteristics of the study large differences can already occur with small differences in inundation pattern, because the location of the highest economic value is in some flood scenarios shielded by the A12 till a certain water level. However, for the economic risk, the version of SSM and the discount rate used also play an important role in determining flood risk.

4.2. Selection spatial measures

In this section the conclusions of the performed expert elicitation are presented. Elaboration of individual interviews can be found in Appendix H.

4.2.1. Expert estimation feasibility of spatial measures

The interviewed experts have different opinions on the feasibility of spatial measures as an alternative or addition to dike reinforcement. Most of the experts have the opinion that spatial measures can be of added value in addition to dike reinforcement. Experts also indicate that the feasibility depends on the type of measure that is considered. Some experts indicate that an additional advantage of spatial measures is the protection against flooding from the lower than normative discharge scenarios and pluvial flooding. Besides that, in case dike breach does happen, spatial measures result in less impact. Some experts also indicated that in case flood risk is dependent on other factors than the Dutch primary flood defenses only, such as the dikes in Germany, spatial measures become more promising and that the Dutch safety standards might in some cases not be met by Dutch dikes only in the future.

Challenges lie mostly in the cost efficiency and the governance of those measures. Experts indicate that dike reinforcement needs to be done on only one segment and only once, whereas for spatial measures often large areas need to be adapted. This also addresses the issue of social equality; part of the population might address the question why the area in which they live the primary flood defence has a lower protection level than in other areas (which might be close by). Besides that, if spatial measures are used to reduce flood risk it may become unclear which party is responsible to arrange and/or maintain this measure. Furthermore, some experts also mentioned that if one relies on evacuation to reduce flood risk, it is important to consider that the available time to evacuate might in reality be shorter than currently assumed in evacuation plans. These considerations are taken into account in the evaluation of the spatial measures in the remainder of this chapter.

An important limitation specifically applicable for the Netherlands is the manner in which financing is arranged. Subsidies can only be allocated directly to dike strengthening projects and not to river widening and impact reducing measures. When effective, those measures can be funded from the same budget, however, this requires additional approval from the Ministry.

4.2.2. Suitable locations for spatial measures

In this section the findings of all experts, regarding the suitability of the spatial measures to be implemented in specific locations in the study area, are combined. In general, the guiding principle was to protect areas with high economic value and population density and to allow more water in areas with low economic value and population density, while taking the flood characteristics in consideration.

Most experts indicate that compartmentation and temporary flood defences would be most suitable in locations where they protect the cities Westervoort, Duiven and Zevenaar so that mortality and economic damage decrease or in locations where they delay the water coming from Germany so that evacuation times are increased. In practice, those cities can be protected by elevating the A12 and thus increasing its retaining height or building a compartmentation dike around those cities. The water from Germany that travels via the north of Montfoortland can be delayed by increasing the retaining height of the A18 and at the southern part by constructing a compartmentation dike between the south of Montfoortland and the primary flood defence. An advantage of those two locations is that they are relatively short in length and thus relatively cheap to implement. Note that, when roads are elevated, underpasses should also be closed and in case of permanent elevation of roads and railways, noise nuisance can increase. However, an additional advantage of elevating roads is that it takes longer till those roads are inundated and thus they are available longer for acute evacuation. A general challenge for compartmentation measures characteristic for the study area is the gradient in the bed level, which requires substantial retaining heights of flood defences in order to completely block the water.

Experts indicate that risk zoning and flood proof building are preferably combined and that they are especially efficient for new building. In general, from a flood perspective there should only be built in areas which are rarely inundated in case of flooding. One expert recommended that the old course of the Rhine is kept free from buildings, since water naturally prefers this path in case of flooding. Flood proofing current buildings can be beneficial in the sparsely populated areas within the study area and areas which are at the edges of the inundation pattern and inundation depths are minimal. However, in the north of the study area it is almost never feasible because of the high water depths. Additionally, multiple experts recommended to investigate the possibility to reduce damages of the power grid, water treatment plants and infrastructure in locations where this is applicable. Especially the Betuwe lijn was indicated to be an important asset to be protected, since it is an important route for freight transport.

In the areas with lower economic value more space can be provided for water. Almost all experts indicate that the Rijnstrangen area would be a suitable location to store water. Since the area previously already had a water-storage function, the area is already designed for that. Storing the water in this location reduces the flood risk in the remaining part of the study area. Some of the experts suggested the idea to bring back the inlet at Spijk, either using a fixed inlet or a controllable inlet. The trade-off to be considered here is that when opting for a controllable inlet a person is responsible to let the hinterland inundate, however the timing of opening the inlet can be altered to the shape of the discharge wave. When this inlet would be reimplemented it is important that the regional dikes are strengthened, to prevent that this stored water reaches Westervoort because of a breach in the regional dike, and that the town of Spijk is protected.

4.2.3. Ranking spatial measures

Each of the experts individually scored each of the spatial measures considered. The mean and the standard deviation of those scores are presented in Table 13, as well as an explanation of why the experts gave that score.

Table 13 - Ranking spatial measures based on expert elicitation

Spatial measure	Score	Standard deviation	Explanation score
Temporary flood defences	3.71	1.39	Both temporary flood defences and compartmentation dikes could protect the cities Westervoort, Duiven and Zevenaar, where the largest economic risk and most casualties occur. In case this measure is implemented by elevating roads, those roads also remain available longer for evacuation. However, this could result in an increase in daily noise nuisance. When comparing temporary flood defences and compartmentation, temporary flood defences are generally cheaper than compartmentation dikes, which is why most experts scored this measure higher than compartmentation. Besides that, it allows for strategic selection of the instances in which the measure should be applied. Permanent compartimentation measures could also negatively impact flood risk depending on the location where the breach happens. Temporary measures will not be used in that case and therefore, the extra risk that occurs for breach locations where the compartmentation measure is not designed for / feasible, is mitigated.
Compartmentation	3.14	0.64	
Risk zoning	3.00	1.51	Most of the experts acknowledge that currently a lot of buildings are built in areas which are not suitable from a flood risk perspective. Ideally, flood risk is taken into account when assigning land use types. Some experts do have concerns about the practical applicability of this measure, since it is quite challenging to change the land use type of urban areas. Therefore, this measure should especially be considered for new building.
Flood proof building	2.71	1.28	Most of the experts indicated that especially for new building this measure is very efficient. The largest part of the experts indicated that integral heightening of the subsoil is likely not feasible, however on very small scale it might be a suitable solution. Besides that, large part of the experts indicated that the protection of valuable elements, by for example locating them on a higher floor is very promising. One of the experts also indicated that the power grid is in need of replacement and that this could be combined with lowering the flood risk. Important to consider is the
Water storage	2.64	2.18	The large standard deviation in the score can be explained by the fact that retention areas and drainage channels were considered together as one type of measure. In general, the experts perceived retention areas as a promising measure, but were negative about the potential of drainage channels to reduce flood risk. The experts indicate that the storage capacity of the

			drainage channels or retention areas is important to consider in assessing the suitability of this measure. Most of the experts estimate that the storage capacity of drainage channels is too small compared to the breach flow to make a difference. Most of the experts do see possibilities in making the Rijnstrangen area a retention area. In general, creating large retention areas is not always desirable because you restrict a whole area for alternative land use types. However, this area is already designed for it and largely uninhabited.
Decompartmentation	2.57	1.06	Part of the experts indicated that this could be a useful measure to lower water depth and ascent rates in areas where the LIR is normative. Besides that, those experts indicated that it is a relative low-cost measure, since you only have to remove soil. The experts that did not score this spatial measure high have indicated that this is the result of a lack of a suitable location in the study area.
Preventive dike breach	1.14	0.64	Experts indicate that this spatial measure lacks a political support base. It is undesirable to put a person in the place to decide on this matter. In case of an emergency this measure might be considered, but a suitable location and timing are very case specific.
Influencing hydraulic roughness	1	0.93	Most experts indicate that this measure might locally influence transport of water but will not influence the flood course substantially. Experts do indicate that this measure might be effective in the flood plains, in order to reduce the hydraulic load on the dike, however this is out of the scope of this research.

From the interviews additional measures are obtained which might be promising in reducing flood risk, namely, vertical evacuation and shelters. Vertical evacuation and creating shelters are both aimed at increasing the evacuation fraction, without inhabitants having to leave the study area. Vertical evacuation is focused on the evacuation in buildings to a dry floor. Preferably this is a higher floor at home but could also be a public space that has multiple floors. Shelters could also be other dry spots within the area. Preferably every neighbourhood has sufficient heightened dry area in case of flooding. However, this might be harder to implement in areas with multiple meters inundation.

4.2.4. Most promising measures in the study area

Almost all experts considered temporary flood defences the most promising and most had little to no faith in influencing the hydraulic roughness in the hinterland and preventive dike breach. Therefore, it was decided to at least consider a temporary flood defence measure and exclude influencing the hydraulic roughness and preventive dike breach from further research. Most of the experts considered elevating the A12 (Figure 2) a suitable implementation of a (temporary) compartmentation measure, since it reduces the flood risk in the area with the highest economic value. Therefore, this measure will be evaluated. Since water depths in this area are high, the maximum height that is physically possible for a temporary flood defence (2 meters) is chosen, to block as much water as possible.

When looking more in depth in the justification for the scoring, it stands out that flood-proof building and risk zoning are considered especially useful new building, which is not included in the calculation of the flood safety standards and therefore left out of the scope of this research. Therefore, it is opted not to select those measures. Besides that, even though retention areas and decompartmentation score lower, a large share of the experts was positive about allocating space for water in the Rijnstrangen area. Therefore, this is selected as a second measure to be evaluated. Some of the experts indicated that attention should be paid to whether such a measure increases the flood risk in the cities Westervoort, Duiven and Zevenaar. Therefore, only the southern regional dike within the Rijnstrangen area (Figure 2) is removed, so that the northern regional dike still protects those cities from flood risk for the breach locations where that is the case without the implementation of measures.

4.3. Implementation and evaluation of spatial measures

In this section the spatial measures that are considered in this research are evaluated. First, each of the measures will be evaluated based on their possibility to reduce flood risk individually. After that, a comparison between the measures and their cost-efficiency is made.

4.3.1. Effectiveness temporary flood defences in reducing flood risk

In most cases the retaining height of the temporary flood defences is not sufficient to fully retain the water (Table I-1 Appendix I), which locally results in higher flood risk. However, in case the retaining height is sufficient to prevent the flood from propagating to the cities Westervoort, Duiven and Zevenaar, both damages and casualties can reduce substantially (Table 14).

Table 14 - Damages, casualties and victims when a temporary flood defence is implemented on the A12 (instances in which the water does not flow over the created barrier are highlighted in green)

Norm segment	Breach location		Damages [million €]		Casualties without evacuation [-]		Victims [-]	
			Reference	Temporary flood defences	Reference scenario	Temporary flood defences	Reference	Temporary flood defences
48-0	Bislich	TP	6,800	9,500	228	457	105,300	123,100
		TPP	10,000	11,000	556	623	127,100	133,200
48-0	Haffen-Mehr Lohwardstrasse	TP	4,200	4,100	98	109	49,490	46,320
		TPP	8,900	9,500	408	479	118,100	122,800
48-0	Haffen Althrein	TPP	7,700	8,400	294	358	111,400	116,100
48-0	Rees Rosau	TP	6,200	4,900	190	148	100,200	51,510
		TPP	10,000	10,000	539	551	128,100	126,900
48-0	Emmerich Stadtweide	TPP	5,400	6,000	151	180	93,760	98,550
48-2	Giesbeek	TP	3,200	1,300	111	32	63,500	9,584
		TPP	4,800	4,800	236	234	73,830	74,640

Besides that, even in cases that the reduction in flood risk is minimal, arrival times are increased substantially. Currently the largest share of the inhabitants of the cities Westervoort, Duiven and Zevenaar only have two to sixteen hours to evacuate after dike breach, which increases to at least three days when the temporary flood defence measure is implemented (Figure 23). Currently, arrival times are not included in the safety standard calculation, however, in practice, the percentage of the population that is able to evacuate could potentially increase substantially.

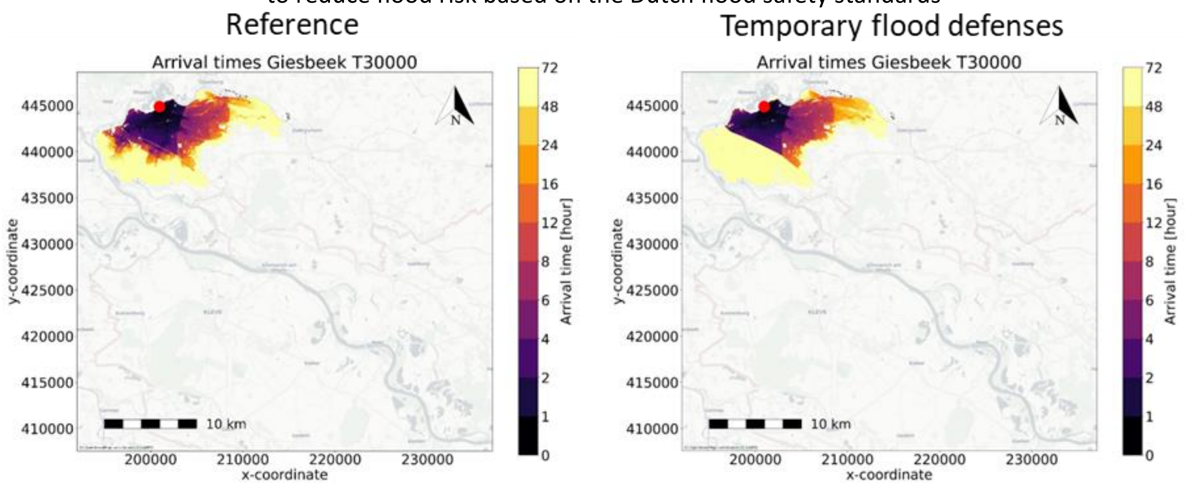

Figure 23 - Arrival times [hours] for breach location Giesbeek (indicated with a red dot) for the above normative scenario, with and without temporary flood defence measure

Since temporary flood defences are a temporary measure, they only need to be deployed when it is predicted that it is beneficial for flood risk. Therefore, only the scenarios in which the measure is beneficial (Table 14) are used to recalculate the mean mortality per neighbourhood (Figure 24) and the flood safety standards. The recalculated safety standards are presented in Table 15.

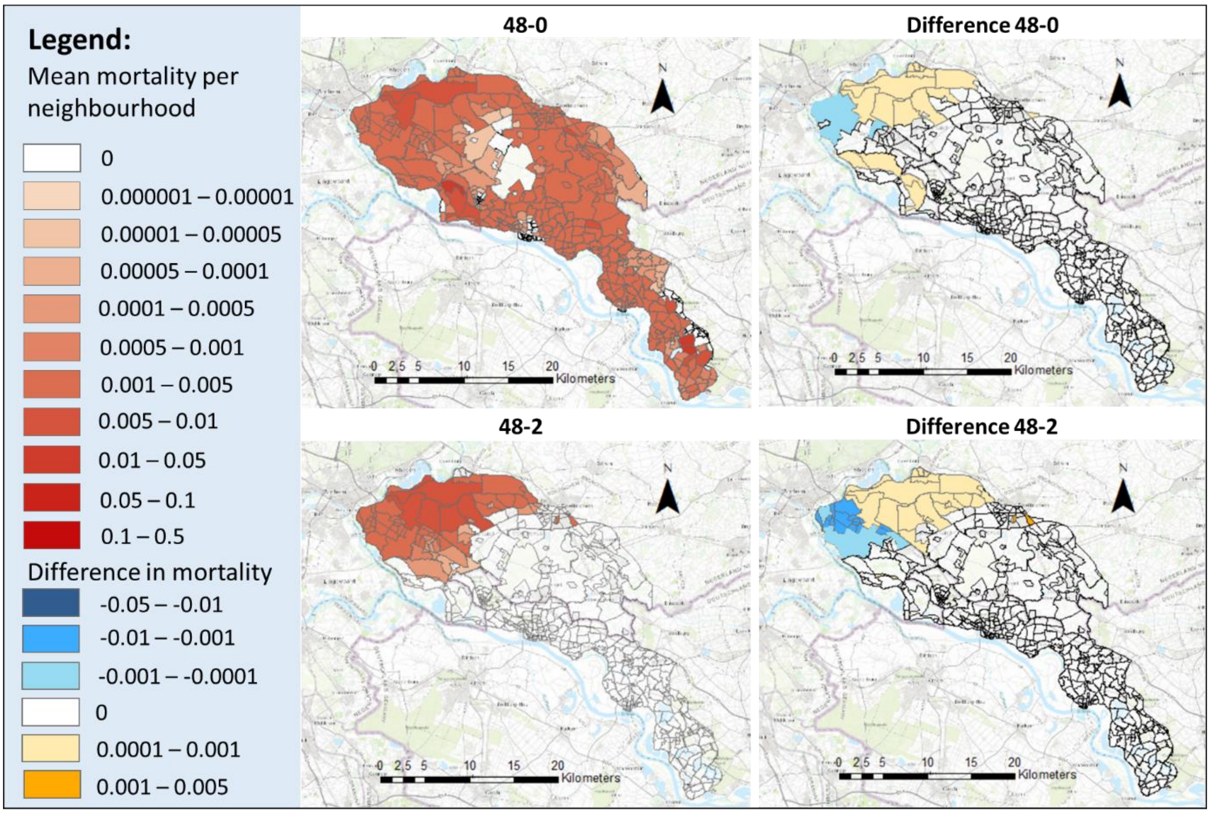

Figure 24 - Mean mortality per neighbourhood when a temporary flood defence measure is implemented, including the difference to the reference situation, where difference = mortality including measure - mortality reference situation

Because the water depth southern of the A12 is lower, this also results in lower mortality southern of the A12. However, on the northern side of the A12 water depths and thus mortality increases. Since for norm segment 48-0 the normative neighbourhood is located northern of the highway, the LIR criterion slightly increases for that norm segment when this measure is implemented.

The measure is effective in reducing the SCBA criterion on both norm segments, however differences are not large enough to obtain a lower safety standard classification (Table 15).

Table 15 - Comparison safety standards in the reference scenario and after implementation of a temporary flood defence

	48-0	48-1	48-2	48-3
Safety standard LIR reference	1/1,555	1/4,564	1/506	1/81
Alert value safety standard SCBA reference	1/4,320	1/9,846	1/9,696	1/172
Safety standard classification reference	1/1,000	1/3,000	1/3,000	1/300
Normative criterium	LIR/SCBA	LIR/SCBA	SCBA	LIR/SCBA
Safety standard temporary flood defences LIR	1/1,567	1/4,597	1/568	1/81
Alert value safety standard temporary flood defences SCBA	1/4,126	1/9,846	1/6,603	1/172
Safety standard classification temporary flood defences	1/1,000	1/3,000	1/3,000	1/300
Normative criterium	LIR/SCBA	LIR/SCBA	SCBA	LIR/SCBA

4.3.2. Effectiveness decompartmentation in reducing flood risk

The decompartmentation measure was designed to reduce the LIR criterion for norm segment 48-1, in which it is effective (Table 16), however the difference is not large enough to obtain a lower class in the safety standard classification. On the other hand, a slight increase in the LIR criterion for norm segment 48-0 can be observed. Because for this norm segment the criterion was very close to the boundary of the safety standard class, this results in a higher classification of the safety standards for norm segment 48-0.

Table 16 - Comparison safety standards in the reference scenario and after implementation of a decompartmentation measure

	48-0	48-1	48-2	48-3
Safety standard reference LIR	1/1,555	1/4,564	1/506	1/81
Alert value safety standard reference SCBA	1/4,320	1/9,846	1/9,696	1/172
Safety standard classification reference	1/1,000	1/3,000	1/3,000	1/300
Normative criterium	LIR/SCBA	LIR/SCBA	SCBA	LIR/SCBA
Safety standard decompartmentation LIR	1/1,741	1/2,016	1/566	1/90
Alert value safety standard decompartmentation SCBA	1/4,687	1/9,503	1/9,696	1/172
Safety standard classification decompartmentation	1/3,000	1/3,000	1/3,000	1/300
Normative criterium	LIR	LIR/SCBA	SCBA	LIR/SCBA

The reduction in LIR criterion for norm segment 48-1 can be attributed mostly to the decrease in ascent rates and thus in mortality for dike breaches at Herwen and Gravenwaardsedam. The basic safety requirement always stays lower than 10^{-5}, however the location in which the highest risk occurs is altered (Figure 25). For norm segment 48-1 this shift results in lower risk in the areas where people live and therefore a lower number of casualties (Table 17). For breaches along norm segment 48-0 some villages in the Rijnstrangen area are hit harder by flooding after implementation of the measure, since in the reference scenario the water would only reach those areas in case the regional dikes overflowed or secondary breaches in those regional dikes occurred.

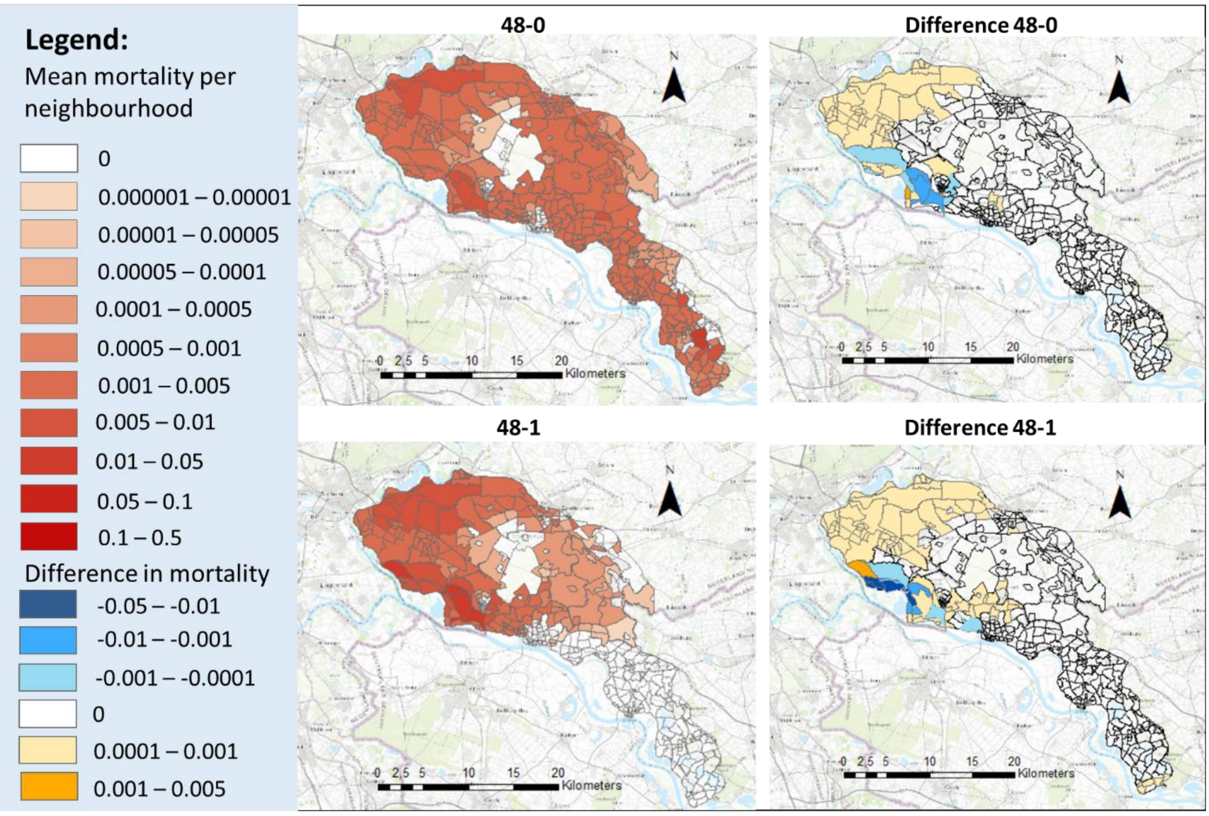

Figure 25 - Mean mortality per neighbourhood when a decompartmentation measure is implemented, including the difference to the reference situation, where difference = mortality including measure - mortality reference situation

Since the inundated area is greater after the implementation of the measure and most of the monetary damage already occurs at small water depths, the amount of damages increases. For most German breach locations, the effect of the decompartmentation measures is minimal, in line with expectation, since the inundation depths in those scenarios are relatively low in the area of the intervention. However, for breach locations Emmerich West and for breach location Kandiagemaal flood risk is increased substantially in the Rijnstrangen area (Table 17). However, because of the large reduction in number of casualties for some breach locations on norm segment 48-1, the SCBA criterion is still lowered for this norm segment. However, it should be noted that this reduction can largely be attributed to the fact that breach location Herwen is the worst case scenario and therefore this reduction in flood risk for that specific breach location contributes substantially to the difference in calculated SCBA criterion.

Table 17 - Damages, casualties and victims when one of the regional dikes in the Rijnstrangen area is lowered, compared to the reference scenario

Relative difference, ((reference-measure)/reference) * 100%)

> 10 % | 5-10 % | 2-5 % | 0-2 % | 0 - -2% | -2 - -5 % | -5 - -10 % | < -10 %

Norm segment	Breach location		Damages [million €]		Casualties without evacuation [-]		Victims [-]	
			Reference	Decompart-mentation	Reference	Decompart -mentation	Reference	Decompart -mentation
48-0	Bislich	TP	6,800	6,900	228	229	105,300	108,000
		TPP	10,000	10,000	556	557	127,100	129,100
48-0		TP	4,200	4,200	98	99	49,490	50,650

	Haffen-Mehr Lohwardstrasse	TPP	8,900	8,900	408	413	118,100	119,000
48-0	Haffen Althrein	TP	2,800	2,800	67	67	33,480	33,490
		TPP	7,700	7,700	294	291	111,400	112,600
48-0	Rees Rosau	TP	6,200	6,300	190	196	100,200	103,700
		TPP	10,000	10,000	539	540	125,900	128,700
48-0	Emmerich Stadtweide	TP	2,500	2,500	55	55	30,920	30,940
		TPP	5,400	5,400	151	147	93,760	93,630
48-0	Emmerich West	TP	1,000	4,900	56	246	10,660	82,610
		TPP	7,200	7,400	502	495	98,290	102,100
48-1	Spijk	TP	3,700	3,900	138	160	72,980	76,450
		TPP	6,800	6,900	431	440	96,020	99,630
48-1	Gravenwaardse dam	TP	450	2,100	294	108	6,316	41,250
		TPP	3,500	7,400	586	496	73,330	102,100
48-1	Herwen	TP	3,800	4,100	608	259	72,010	78,880
		TPP	7,300	7,500	1,124	561	98,740	102,800
48-1	Kandiagemaal	TP	240	680	3	49	2,277	10,890
		TPP	6,400	6,600	387	414	93,810	98,250

4.3.3. Cost efficiency spatial measures

In this section the cost efficiency of the spatial measures is assessed, this is done both based on the ratio between the investment costs and its respective reduction in flood risk and the costs required to decrease the mortality by a certain level. Since effects of the measures on norm segment 48-3 are minimal, this norm segment is not taken into consideration.

The determined investment costs for the temporary flood defence measure and the decompartmentation measure are estimated to be 3.3 million euros and 26.1 million euros, respectively. Since there is a large uncertainty embedded in the method at which those estimates are derived, an uncertainty bandwidth of 30% should be taken into account. For dike reinforcements the investment costs to reduce flood risk by a factor 10 are estimated to be 230 million euros, 94 million euros and 63 million euros for norm segments 48-0, 48-1 and 48-2, respectively.

4.3.3.1. Investment costs spatial measures compared to reduction in monetary damages

In Table 18 an overview of the total costs of the spatial measures is presented.

Table 18 - Costs comparison of the considered measures and dike reinforcement

	Economic flood risk [million €]	Investment costs [million €]	Total costs [million €]
Without measures	66,756	0	66,756
With temporary flood defence measure	61,107	3.3	61,110
With decompartmentation measure	68,127	26.1	68,153
With dike reinforcement	6,676	387	7,063

This shows that temporary flood defences can be cost efficient in terms of reduction of total costs. However, the economic flood risk reduction is much greater for dike reinforcement. For decompartmentation the total costs increase, even without the investment costs. Since the decompartmentation measure was mainly designed to bring down the LIR criterium, it does not necessarily mean that the measure is not effective. For some breach locations the monetization of the reduction in number of casualties brought down the total costs when the decompartmentation measure was implemented. However, this was overcompensated by the fact that both the number of victims and the amount of monetary damage increased for all breach locations.

4.3.3.2. Investment costs spatial measures compared to reduction in local individual risk

In Table 19 an overview is given of the different values for calculated LIR criterion. For the comparison between the spatial measures and dike reinforcement for the spatial measures the factor by which they bring down the LIR is considered, whereas for dike reinforcement, a factor 10 safer is considered.

Table 19 - Overview of the calculated LIR criterion with and without the implementation of spatial measures, for norm segments 48-0, 48-1 and 48-2

Norm segment	48-0	48-1	48-2
Safety standard LIR without measures	1/1,555	1/4,564	1/506
Safety standard LIR with temporary flood defence measure	1/1,567	1/4,597	1/568
Safety standard LIR including decompartmentation	1/1,741	1/2,016	1/566

When comparing measures based on how much flood risk is reduced based on the LIR criterion relative to the investment costs (Table 20), it stands out that dike reinforcement is for all norm segments the most cost-efficient measure. However, it should be noted that when the dike is strengthened, the resulting impact that occurs in case of dike breach is increased, which is not the case for the spatial measures.

Table 20 - Flood risk reduction per invested euro based on the LIR criterion (factor by which the LIR criterion is reduced / the investment costs)

Norm segment	48-0	48-1	48-2
Dike reinforcement	0.026	0.026	0.026
Temporary flood defence	-0.002	-0.002	-0.037
Decompartmentation	-0.005	0.02	-0.005

5. Discussion

5.1. Limitations of this study

5.1.1. Model uncertainty

In the current methodology required to calculate the safety standards, water depth and ascent rate play a large role in determining the flood risk in a certain location. The way the stability of line elements is modelled (in which cases it fails, when and in which location the line element fails, and if it fails in multiple locations) determines which areas are inundated and affects the ascent rates in the different neighbourhoods. This research showed that one of the implications of the differences in ascent rates between DelftFLS and D-HYDRO is a shift in the location of the normative neighbourhood in the mortality calculations. This has both influence on the calculated safety standards and the assessment of the effectiveness of the decompartmentation measure to reduce flood risk.

In the model it is assumed that the discharge partitioning of the Rhine is not affected by dike breach. Bomers (2019) showed that for extreme discharges flood risk increased for the river branch with the smallest discharge capacity, whereas flood risk for the other river branches reduced. Since at the Pannerdensche Kop the largest part of the discharge flows into the Waal and the smallest in the Pannerdensch Kanaal and at the Hondsbroeksche Pleij the largest discharge flow into the Nederrijn and the smallest into the IJssel, the discharge in the river branches which put the study area at risk (the Pannerdensch Kanaal and the IJssel) might in reality be higher than modelled in case of dike breach. In reality, calculated breach flows could thus be higher than calculated in this study for breach locations Kandiagemaal, Loo and Giesbeek and lower for the breach locations located upstream of Kandiagemaal (Figure XXBreslocaties H3).

5.1.2. Conducted methodolgy

In order to calculate the Dutch safety standards in this research the German part of the study area is also taken into consideration. However, in the current safety standard calculations the flood risk resulting from dike breaches in Germany are not considered. Since the spatial measures are also evaluated and partially designed on the consideration of flood risk resulting from dike breach in Germany, effects of the measures might be underestimated in regards to their potential to lower the current safety standards as defined in the Waterwet (Rijksoverheid, 2023). Since the designed measures and especially the decompartmentation measure have negative effects on the flood risk originating from German breach locations

As part of this research expert elicitation was performed in order to determine which spatial measures obtained from literature would be most effective in the study area. The standard deviation within the scoring of the different spatial measures was in some instances rather large. Increasing the number of experts interviewed might provide more certainty on which measures would be the most effective. However, in order to gain proper insights and scoring from those interviews the experts need both a certain degree of area knowledge and knowledge about flood characteristics, which limits the number of potential candidates substantially.

In this research, the GRADE discharge curves that were already implemented in the model (corresponding with the current safety standard on that norm segment as defined in the Waterwet (Rijksoverheid, 2023)) were used to perform the flood simulations. Because of the limited time available for this research there is no sensitivity analysis performed with different climate scenarios. Even though climate change is included in the GRADE discharge curves, the spread in uncertainty of different climate scenarios is not presented. Besides that, since the safety standards calculated in this study are lower than calculated in earlier studies, used discharges might still be too high. However, because of time limitations this iterative process is not performed.

In order to assess the influence of model complexity on the derivation of the Dutch flood safety standards, only two flood models were used (Delft-FLS and D-HYDRO), both developed by Deltares, formerly known as WL | Delft Hydraulics, however there are more models that are capable of fluvial flooding. The considered models do have some similarities. For example, both models use the shallow water equations to model the propagation of flooding. It is possible that the inclusion of other flood models and their possibilities in model representation of the study area and dike breach offer different insights in which model choices influence the derivation of the Dutch safety standards.

5.1.3. Interpretation results

When comparing the calculated safety standards of the reference scenario using the D-HYDRO with the reference scenario using Delft-FLS differences are larger than when comparing calculated safety standards with and without the implementation of spatial measures. Besides that, depending on the manner of modelling, a different neighbourhood is normative. This means that, the spatial measures might score differently when a different modelling method is applied.

This study aimed at giving insight in both the potential of spatial measures to reduce flood risk and their cost efficiency, compared to dike reinforcement. However, there remain challenges regarding the practical feasibility of the spatial measures.

5.2. Generalisation results

This study showed that the way line elements and their underpasses are included in the model have an impact on the inundation patterns and ascent rates, which is in correspondence with the findings of (Brussee, et al., 2022). Since this effect of an obstructing element is mostly independent of study area, those conclusions can be transferred to most other study areas, which have a similar bed level gradient. However, those high ascent rates are mostly only important for high water depths (above 1.5 meters).

Additionally, the way in which breach flow is modelled was identified as an important factor for the derived Dutch flood safety standards, which is in line with Westerhof, et al. (2022) which identified breach development as one of the biggest uncertainties in the derivation of the Dutch flood safety standards. This is of importance for at least the whole Dutch river area. For sea dikes, breaches develop in a different manner, therefore results cannot be adopted for dike rings which are at risk from flooding from sea.

As highlighted in this study, whether spatial measures are effective strongly depends on the flood characteristics of the area and the height of the current flood safety standard. The higher the current flood safety standard, the less effective spatial measures are. In this research only a limited number of spatial measures are considered, therefore, there can not be drawn any conclusions about the effectivity of the totality of spatial measures based on the results of this study.

6. Conclusion & Recommendations

In this chapter the main conclusions from this research are presented (Section 6.1), as well as some recommendations for management decisions (Section 6.2) and future research (Section 6.3).

6.1. Conclusion

Using a different flood simulation model has both an impact on the LIR criterion and on the SCBA criterion. For the LIR criterion the most important difference is the high differences in water depth, which mostly result from the different way breach flow is modelled. Line elements also play an important role, both for the magnitude and the spatial distribution of the mortality, because of the high ascent rates that they cause. For the monetary damages, most of the flood risk already occurs at a water depth of 1 m, therefore it is more important which parts inundate than the exact inundation depth. Because of the characteristics of the study large differences can already occur with small differences in inundation pattern, because the location of the highest economic value is in some flood scenarios shielded by the A12 till a certain water level. However, for the economic risk, the version of SSM and the discount rate used also play an important role in determining flood risk.

In this research two different spatial measures are evaluated. Namely, increasing the retaining height of the A12, using a temporary flood defence and a decompartmentation meausure inside of the Rijnstrangen area. Both these measures have advantages and drawbacks. The temporary flood defence measure showed to be effective to decrease the total amount of monetary damages and the total costs when including investment costs. However, north of the highway locally flood risk is increased because of the increased water depths. The decompartmentation measure effective in reducing the local individual risk (LIR). However, it does increase monetary risk, as a result from the increased number of victims and monetary damage.

However, reduction in flood risk as a result of the spatial measures evaluated is in the same order of magnitude, or sometimes even smaller than the differences in derived safety standards using a different model. Therefore, more certainty in the model is required to fully draw conclusions on the effectiveness of the spatial measures evaluated in this research.

6.2. Recommendations for management decisions

6.2.1. Recommendations for evaluation current Dutch safety standards

In 2024 the current method to calculate flood safety standards is evaluated. This research showed that certain model choices can have substantial impact on the calculated flood safety standards, which are addressed in this section, as well as limitations of the current method to calculate the safety standards.

Both this study and earlier research showed that large part of the flood risk in the Dutch part of the study area can be attributed to dike breaches in Germany. Especially when the German dikes will be reinforced at a lower rate than the Dutch dikes, the chance that dike breach occurs in the German part of the study area before the dike in the Netherlands fails will only increase. It is therefore recommended to consider using a transboundary approach in assessing the flood risk for dike rings that are not only dependent on the Dutch dikes and river system. As a result of the exclusion of the German breach locations in the safety standard calculation, those breach locations are also partially excluded in the evacuation strategies for the area. Even though the arrival times are generally large in the Netherlands for breach locations in Germany, in some locations in the Dutch part of the study area arrival times are only 4 hours. It is therefore also recommended to update evacuation plans in accordance with the inclusion of German breach locations in the safety standards.

This study showed that the way the retaining capacity of line elements in the hinterland is modelled can have substantial influence on both magnitude of flood risk and the location where this risk occurs. It is recommended that the way dike breaches in regional dikes in case of flooding should be modelled is incorporated in the documentation of methodology to calculate the Dutch safety standards. Important is to at least consider the threshold for failure of those regional dikes, the timing of secondary dike breaches and the location(s) at which a regional dike will fail.

The evacuation plans of the safety region state that in case of organised evacuation, the whole Dutch part of the study area can be evacuated. However, for some breach locations mortality values above 0 are calculated for areas in which arrival times are 1-3 days, even though those areas can be evacuated in time even after the breach occurs. It is therefore recommended to include arrival times in the evacuation fraction. Including arrival times in the safety standard calculation would also give a better view of the added value of spatial measures that increase arrival times and thus time to evacuate.

In the calculation of the local individual risk criterion the optimal safety standard for a norm segment is determined by multiplying the mortality (regarding evacuation) with the to be determined safety standard so that the LIR is 10^{-5}. The total sum of the risk LIR resulting from each norm segment is therefore larger the basic safety requirement. The standards are then multiplied with the factor between the total LIR and the basic safety requirement to achieve a maximum local individual risk of 10^{-5}. This is not the most optimal solution, and this does not allow for strategic choices on which norm segment would be the most financially feasible to reinforce. Allowing for strategic selection of the distribution of reduction of the sum of the risk along norm segments would also introduce more possibilities to combine dike reinforcement with spatial measures to achieve an acceptable flood risk, in case the LIR criterium is normative.

6.2.2. Recommendations implementation spatial measures

Even when spatial measures are cost efficient (compared to dike reinforcement), they might not always be financially feasible because of the way subsidies are currently provided. The organisation which provides those subsidies in the Netherlands is only authorised to finance dike reinforcement. Even for alternative measures in layer 1, such as river widening measures, they do not have the funding authority. Funding may be taken from the same provision as funding for dike reinforcement, provided it is efficient, but those projects must be arranged with the ministry. If a more integral scope of funding would be applied, consequence reducing measures could be more likely to be included by water boards as a measure to reduce flood risk. Therefore, it is advised to reconsider the way funding for projects to reduce flood risk in the Netherlands is granted by *the Hoogwaterbeschermingsprogramma (HWBP)*.

The considered spatial measures (temporary flood defences and decompartmentation) are mostly effective in reducing the criterion that they were designed for but have negative effects for other norm segments and/or the other safety standard criterion. Besides that, the calculated differences in calculated safety standard are larger when comparing models than when comparing the reference situation with the implementation of the spatial measures. Therefore, it is recommended to first gain more certainty in the flood analyses, before deciding whether to implement the spatial measures.

6.2.3. Recommendations for modellers

Different model choices are suitable depending on the topic of interest. For the use of calculating the Dutch flood safety standards it is recommended that the primary flood defence is not able to overflow in the model. In the calculation of the safety standards the effect of breach locations are considered individually, which is not possible if water flows over the primary flood defence at a certain location before dike breach occurs. For other purposes however, for example if one is interested in the location where the river overflows the primary flood defence, it is required that height of the primary flood defence in the model matches with reality.

For both breaches in the primary flood defence and in the regional dikes the manner in which the bed level of the dike is included in the model is of importance for proper calculation of the breach flow. For the primary flood defence it is recommended that the bed level of the primary defence is removed from the elevation map, since breach flow depends on the waterlevel in the hinterland. For regional dikes, it is recommended that at the locations of secondary breaches the bed level is locally adjusted to the bed level next to the regional dike, since otherwise the bed level still withholds the water after the structure which represents the dike has breached. For other purposes however, for example when one would like an indication of when a road on a regional dike will be inundated, it can be useful to include a higher bed level in the locations of those regional dikes.

This study showed that the importance of including more details in the hinterland for flood simulations and derived flood safety standards. Both including water ways in the hinterland and modelling underpasses in line elements in the model can have effect flood characteristics. It is therefore recommended to include those water ways and underpasses in the model, especially when arrival times are also of interest.

6.3. Recommendations for future research

In this study a qualitative indication is given of the impact of using a different flood simulation model (Delft-FLS compared to D-HYDRO) on the calculation of the Dutch flood safety standards. However, the qualitative relative contribution of the different modelling aspects remains unclear. Therefore, it is advised to perform more in-depth research to quantify the relative contribution of different model aspects to the differences between the calculated flood safety standards resulting from performing flood simulations using a different model. Additionally, other models capable to simulate fluvial flooding could be included in further research, to determine the influence on the Dutch flood safety standards of model aspects which are included in a similar manner in Delft-FLS and D-HYDRO.

The manner in which breach development is modelled is shown to be of importance to the derivation of the Dutch flood safety standards. It is therefore recommended to perform more research about the manner in which breachflow should be modelled. In addition to this uncertainty in breach development because of model uncertainty it remains unknown how dike breach will influence the discharge partitioning and its effect on water levels near the breach. Besides that, it is advised to perform more research into the calculation of breach development, including resulting breach width and realistic parameters (representing soil type) used in those calculations.

Arrival times are currently not included in the Dutch safety standard calculation. However, including arrival times could give better insight in the chances of successful evacuation. Currently, there is no method developed yet to include this in the safety standards. It is recommended to develop a method in which arrival times can be included into the Dutch flood safety standards. Note that, ongoing research is being performed by Hahn (2023) to investigate a manner in which arrival times could be included the calculation of flood risk. In that research the weighted mean arrival time per neighbourhood is converted to a recalculated evacuation fraction. Which is done using modelled traffic curves obtained from (Kolen, et al., 2008).

The number of spatial measures evaluated in this research is limited and combinations of different spatial measures were not considered. To gain a more complete overview of which spatial measures could be effective and what the effect of combining spatial measure is, it is recommended to extent this study. Besides that, most of the studies that are currently performed regarding the possibilities of spatial measures to reduce flood risk are set in Dutch context. In the Netherlands the current dikes are already of such a standard that the discharge when dike breach occurs is very high, the maximum water depths are therefore multiple meters. Multiple experts indicated that, when return periods would be lower, the potential of spatial measures would increase, since spatial measures are mostly not efficient when water depth reaches multiple meters. This research showed that temporary flood defences can be promising as long as the water level does not reach the level of the retaining height of the flood defence. In the study area, this required retaining height was often higher than is technically possible. Therefore, it is recommended that the effectiveness of temporary flood defences to reduce flood risk is re-evaluated in areas where protection against flooding which result in smaller water depths. Besides that, certain measures where not deemed efficient by experts because of the flood characteristics in the Netherlands. For example, influencing the hydraulic roughness was deemed ineffective because the threshold for which flow velocities become dangerous (2 m^2s^{-1}) is only reached near the breach, as a result of the relatively flat landscape. However, in an international context, in locations where bed level gradients are large, this measure could be reconsidered.

The focus of this study lies on the theoretical feasibility of spatial measures, in the form of reduction of flood risk and cost efficiency. This research already shortly addressed a couple of concerns regarding the feasibility of implementing spatial measures from a management perspective obtained from expert elicitation, such as the financing of spatial measures. However, it is recommended that additional research is performed to assess if the spatial measures are also feasible on governance level.

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Appendix A – Model set-up D-Hydro

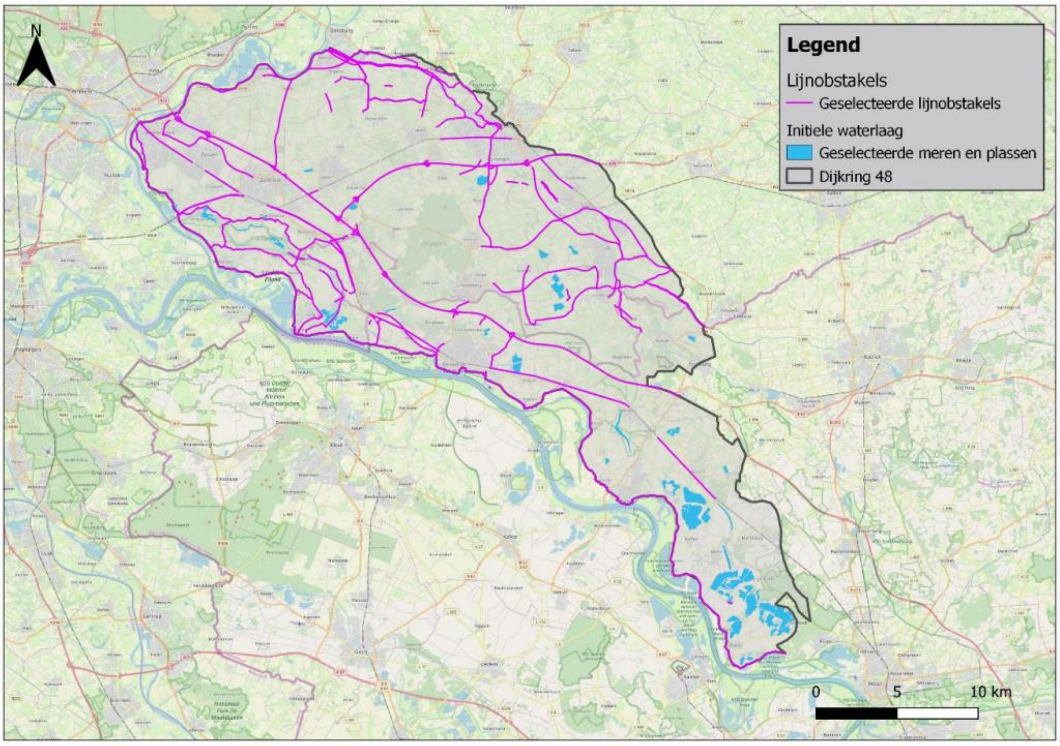


Figure A-1 - Line elements, lakes and retention areas included in the D-Hydro model (Prinsen, et al., 2020).

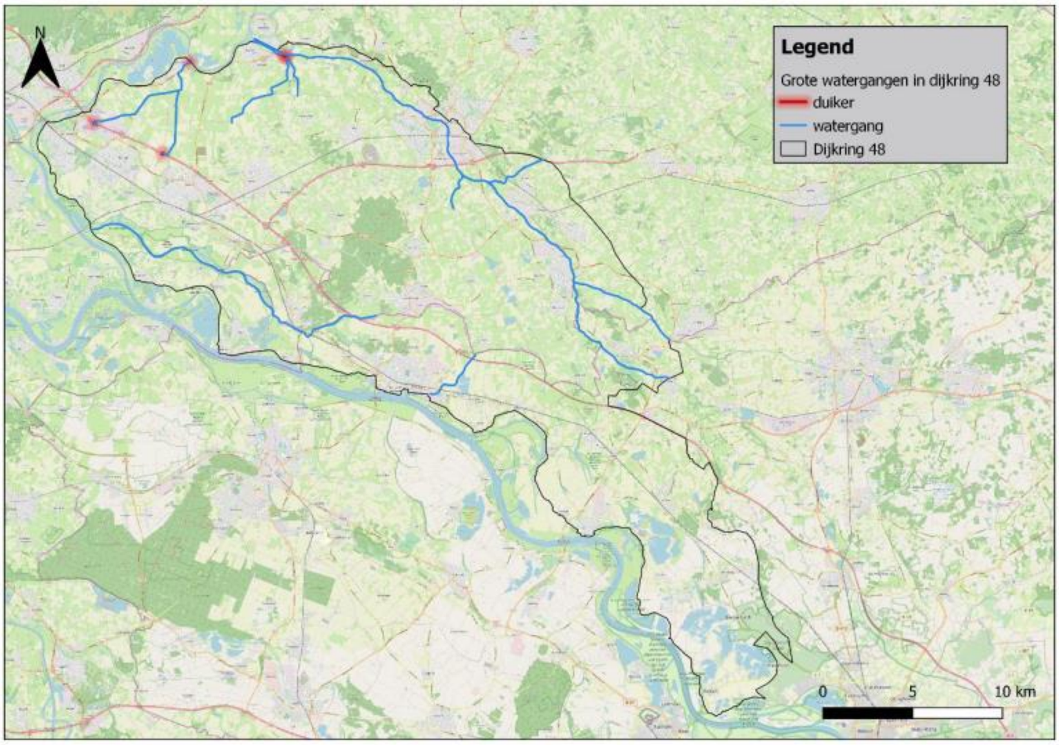


Figure A-2 - Water channels included in the D-Hydro model (width > 10m) (Prinsen, et al., 2020).

Table A-1 - Translation of landuse classification to roughness values (Bruijn & Slager, 2018)

Value	Landuse	Roughness value (winter) Nikuradse
1	Grassland	0.25
2	Corn	0.40
3	Potatoes	0.40
4	Beetroots	0.40
5	Grains	0.40
6	Other agriculture	0.40
8	Glasshouse horticulture	5.0
9	Orchard	5.0
10	Flower bulbs	0.40
11	Deciduous forest	5.0
12	Coniferous forest	5.0
16	Fresh water	0.10
17	Salt water	0.10
18	Urban built-up area	10.0
19	Buildings in the countryside	10.0
20	Deciduous forest in the built-up area	5.0
21	Coniferous forest in the built-up area	5.0
22	Forest with dense building	10.0
23	Grass in built-up area	0.40
24	Bare land in built-up area	0.40
25	Main roads and railways	1.0
26	Buildings in agricultural area	10.0
30	Salt marshes	1.0
31	Open sand in coastal area	1.0
32	Open dune vegetation	1.0
33	Closed dune vegetation	1.0
34	Dune heather	1.0
35	Open drifting sand	1.0
36	Heather	1.0
37	Moderate degraded heather	1.0
38	Strongly degraded heather	1.0
39	Bog	1.0
40	Forest in bog area	5.0
41	Other swamp vegetation	1.0
42	Reed vegetation	1.0
43	Forest in swamp area	5.0
44	Peatland	0.25
45	Other open vegetated nature area	1.0
46	Bare soil in nature area	0.40

Appendix B – Schade en slachtoffermodule (SSM 2017)

B-1 Monetary damages

Table B-1 - Maximum damage functions per damage category per unit (in euro's, excluding tax) (Slager & Wagenaar, 2017)

	Unit	Direct damage	Downtime bruto	Downtime netto
Companies				
Gathering	m^2	168	145	132
Health care	m^2	1,974	1,125	1,055
Industry	m^2	1,497	808	700
Office	m^2	1,283	1,107	942
Education	m^2	993	183	162
Sport	m^2	102	54	46
Shops	m^2	1,508	334	276
Housing				
Single-family houses - opstal	m^2	1,000		
Single-family houses - household contents	object	70,000	10,665	
Ground floor flats - opstal	m^2	1,000		
Ground floor flats – household contents	object	70,000	10,665	
First floor flats - opstal	m^2	1,000		
First floor flats – household contents	object	70,000	10,665	
Higher floor flats – opstal	m^2	1,000		
Higher floor flats – household contents	object	70,000	10,665	
Infrastructure				
Highways	m	1,770		
Motorways	m	1,200		
Other roads	m	327		
Railways – electric	m	5,400		
Railways – non-electric	m	1,350		
Other				
Agriculture	m^2	1.83		
Glasshouse horticulture	m^2	49		
Urban area	m^2	56.65		
Extensive recreation	m^2	10.79		
Intensive recreation	m^2	13.29		
Airports	m^2	146		
Modes of transport	object	7,942		
Gemalen	object	911,600		
Treatment plants	object	13,240,000		

Table B-2 - Factor for items not included as derived in Appendix D of the WV21 study for flood safety standards of primary flood defences (Heymen, 2020)

Posten die via een opslag meegenomen worden	Opslag op schade volgens WV21	Opgenomen in SSM2017	Nieuwe opslagfactor
Cost of aid extension, evacuation, clean-up and aftercare	10%	0%	10%
Damages from direct and indirect company downtime	9-19%	100%	0%
Indirect effects of intersecting infrastructure	2-14%	0%	2-14%
Other (handling costs, outages of housing services, intersection of utility lines and communication links, long-term impact on investor climate, LNC values, unknown damages)	17-19%	20%	14-15%
Risk premium	10%	0%	10%
Total – midpoint	60%		42%
Factor	1,6		1,42

B-2 Mortality functions

In the Netherlands four different mortality functions are used (Equation 7-11), where flood characteristics determine which should be used (Maaskant, et al, 2009; based on (Jonkman, 2007)). For the area close to the breach, where flow velocities exceed 2 m s^{-1} and the product of waterdepth and flow velocity exceeds 7 $m^2 s^{-1}$:

$$F_{D,B} = 1 \quad \text{Eq. B-1}$$

For areas with high ascent rate (larger than 4 m $hour^{-1}$) and a waterdepth higher than or equal to 2.1m:

$$F_{D,S} = \varphi_{N1}\left(\frac{\ln(h) - \mu_{m1}}{\sigma_{n1}}\right) \quad \text{Eq. B-2}$$

Where h represents waterdepth and φ_{N1} is a lognormal distribution with parameters μ_{m1}, σ_{n1}, which represent the mean and standard deviation of ln(h) and have in this equation a value of 1.46 and 0.28, respectively.

For areas with low ascent rate (smaller than 0.5 m $hour^{-1}$) or if the waterdepth is smaller than 2.1 m:

$$F_{D,0} = \varphi_{N2}\left(\frac{\ln(h) - \mu_{m2}}{\sigma_{n2}}\right) \quad \text{Eq. B-3}$$

Which is essentially equal to equation 8, but with a different lognormal distribution. In this instance its parameters μ_{m2} and σ_{n2} have a value of 7.60 and 2.75, respectively.

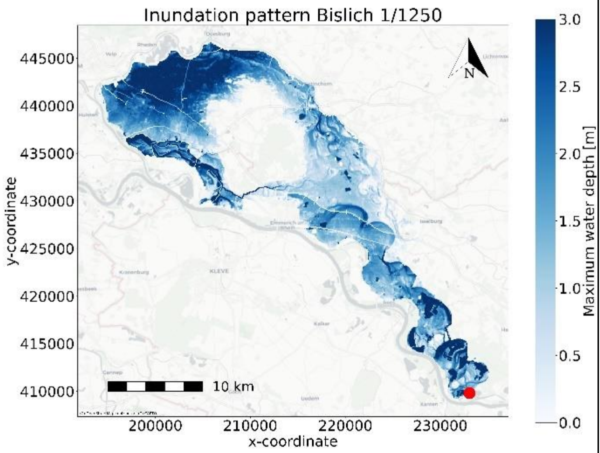
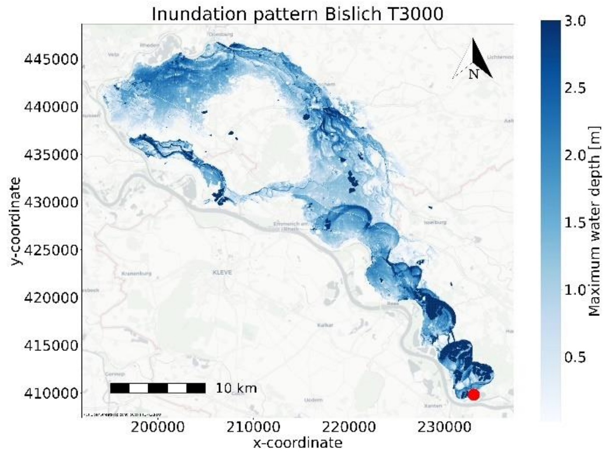
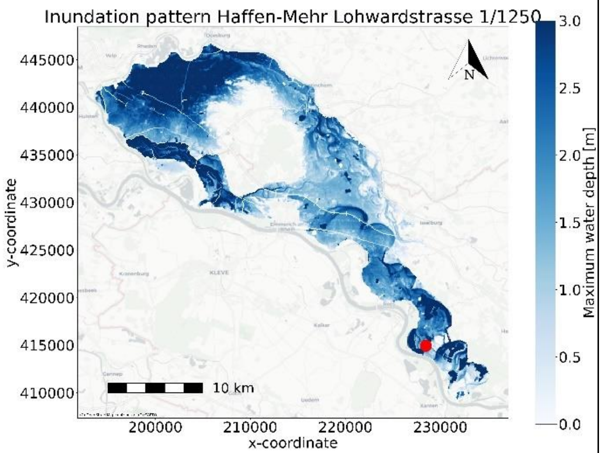
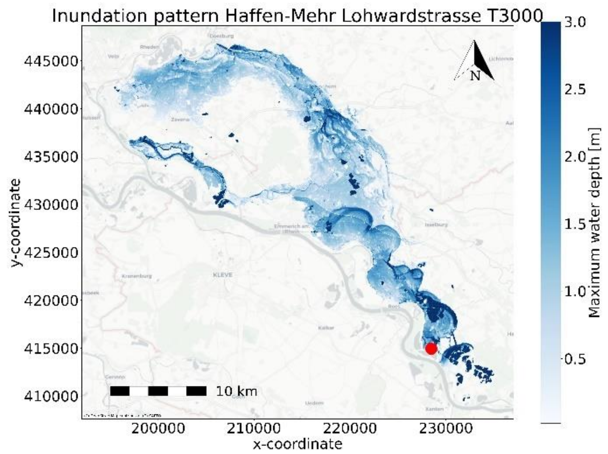
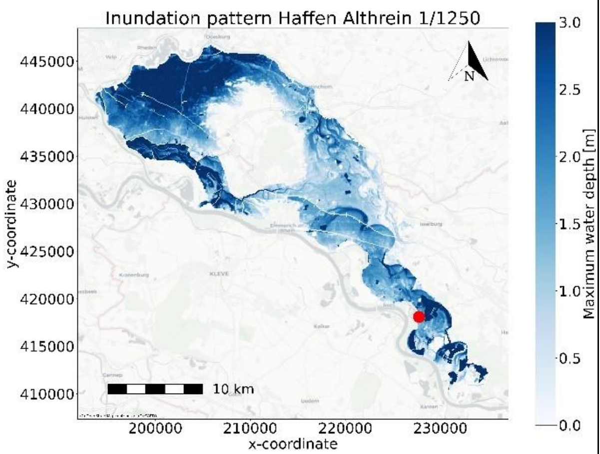
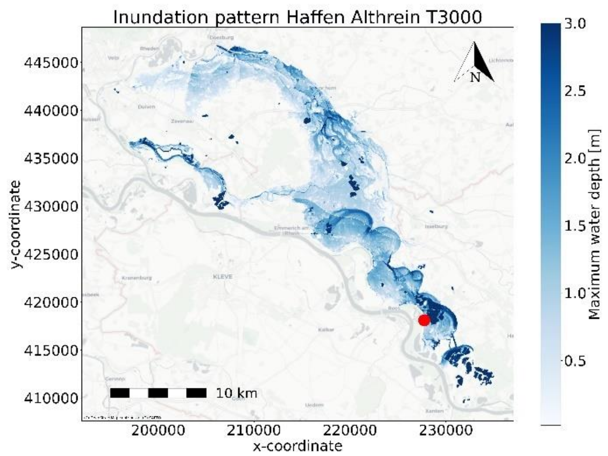
For the transition zone, where the ascent rate lies between 0.5 and 4 m/hour

$$F_D = F_{D,0} + (w - 0.5)\frac{F_{D,S} - F_{D,0}}{3.5} \quad \text{Eq. B-4}$$

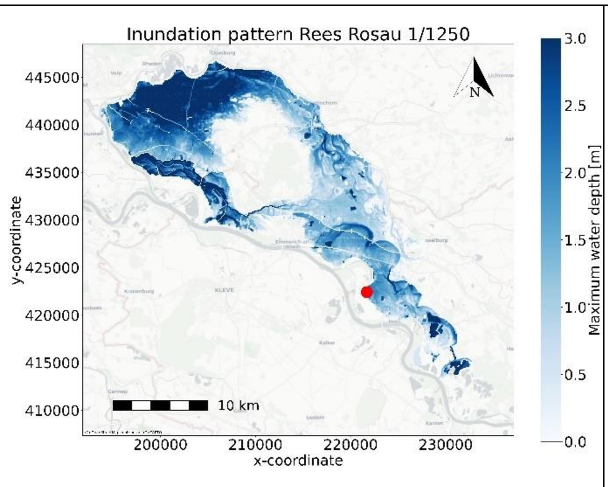
Where w represents the ascent rate [m $hour^{-1}$].

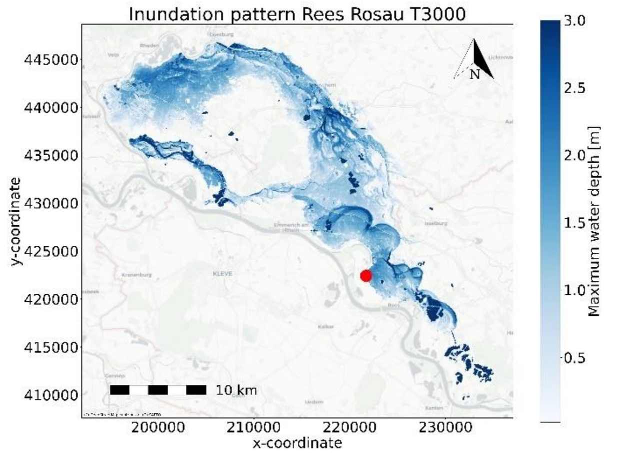
Appendix C – Water depth flood simulations reference scenario

Table C-1 - Computed maximum water depth for DelftFLS and D-Hydro for the normative scenario (breach locations are indicated with a red dot)

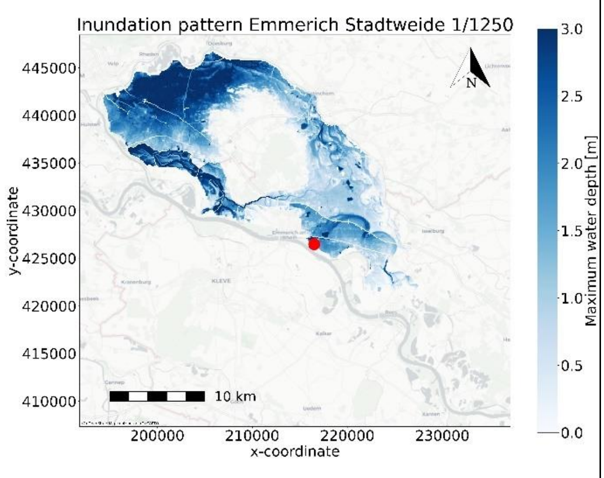
	DelftFLS	D-Hydro
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein		

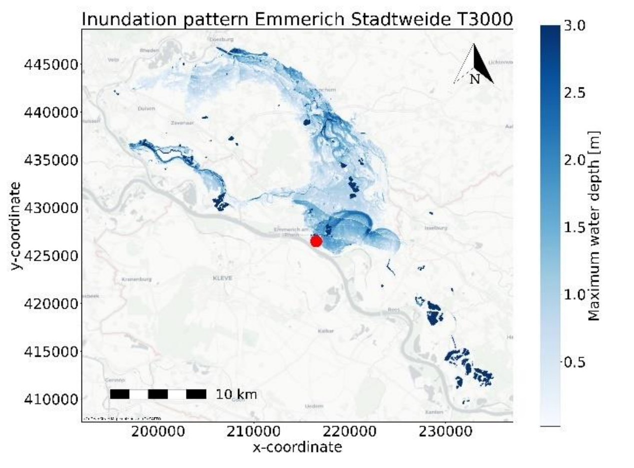
Rees Rosau





Emmerich Stadtweide





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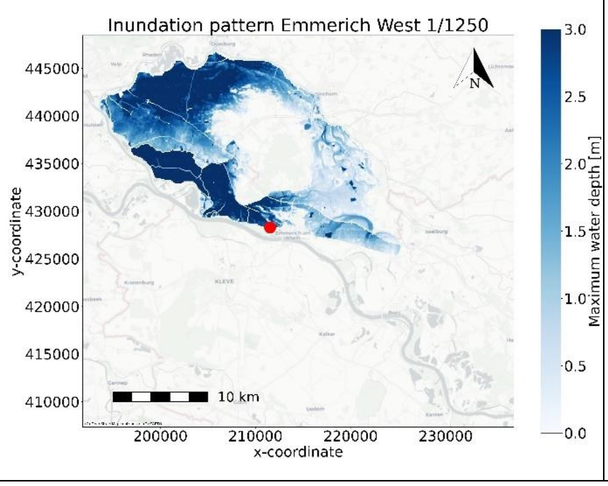

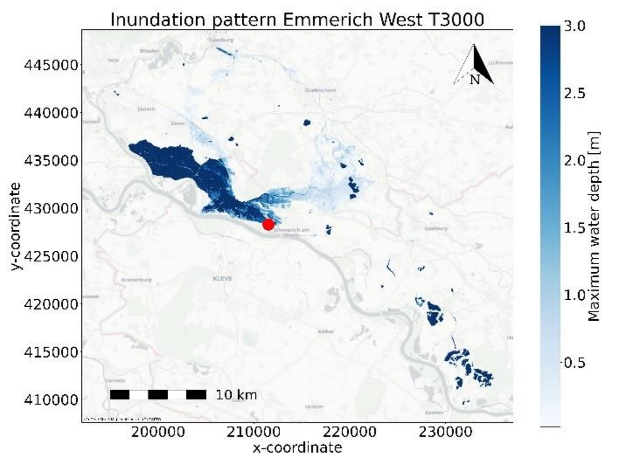

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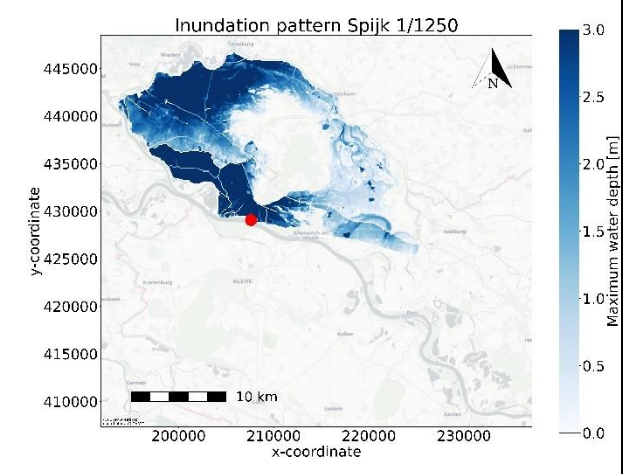

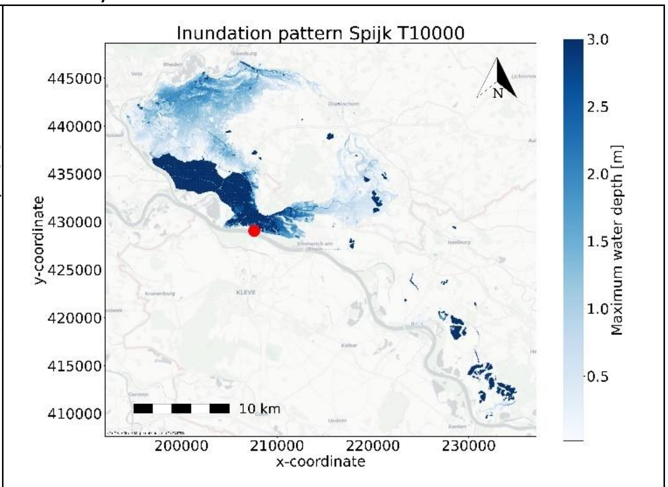

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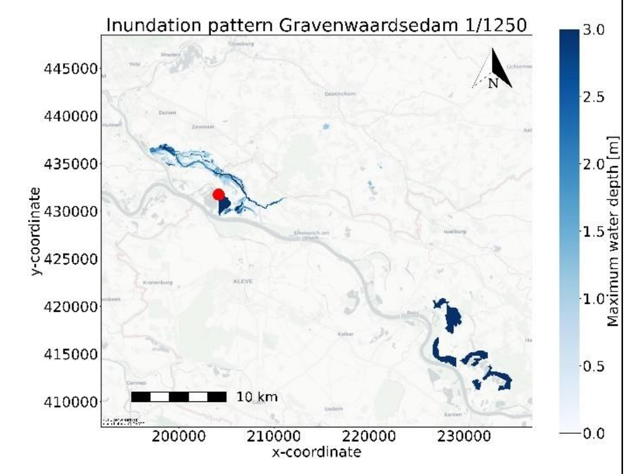

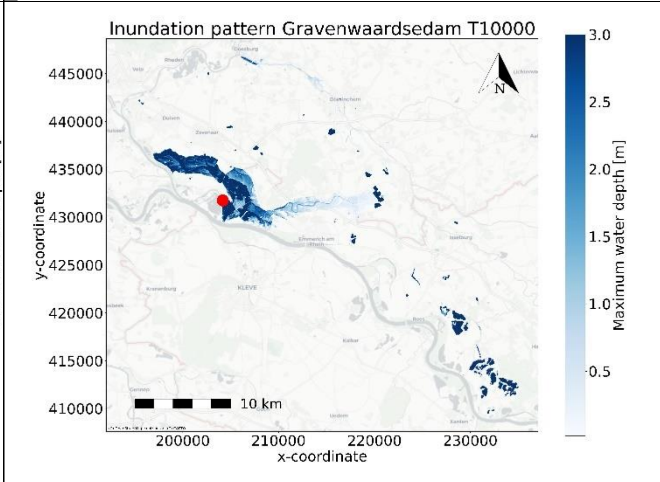

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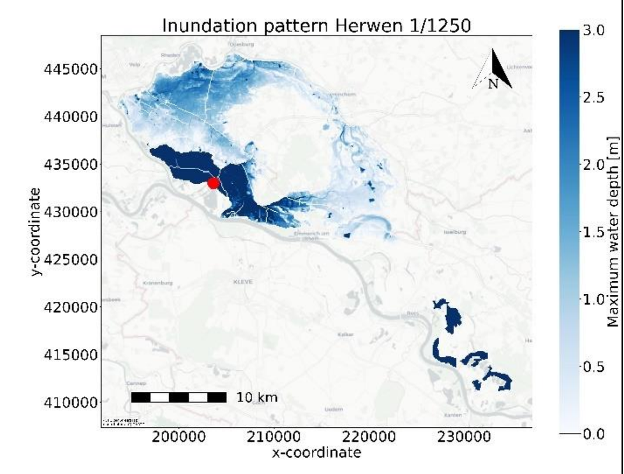
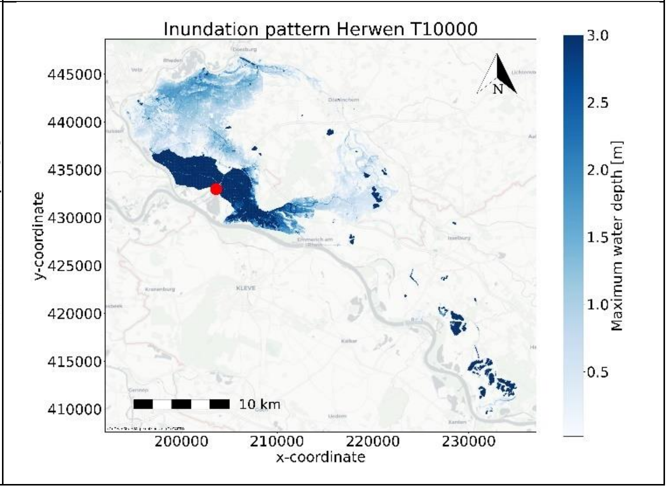
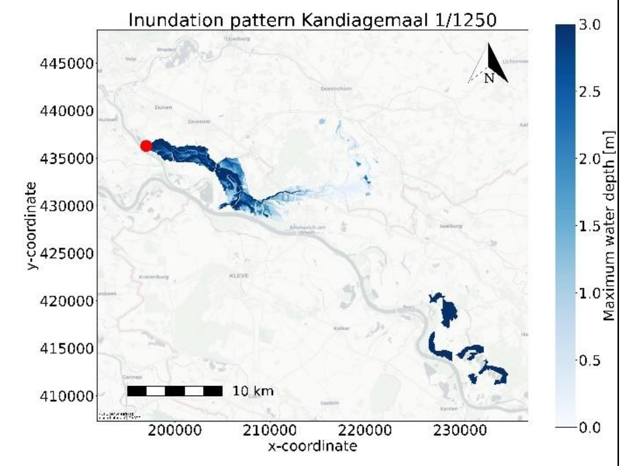
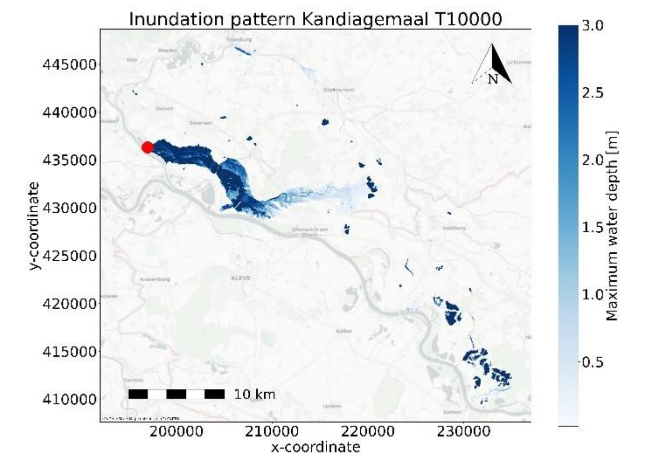
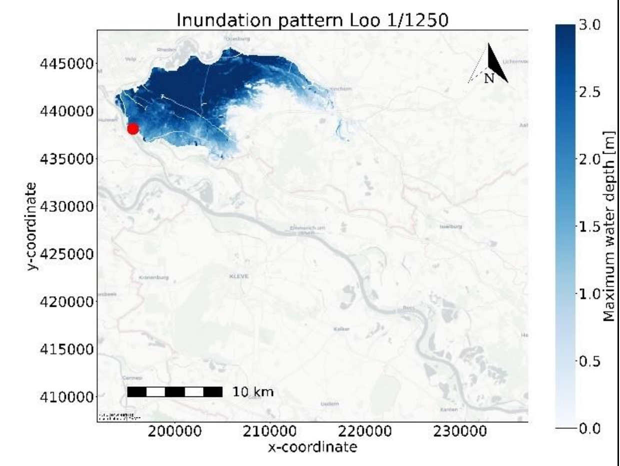
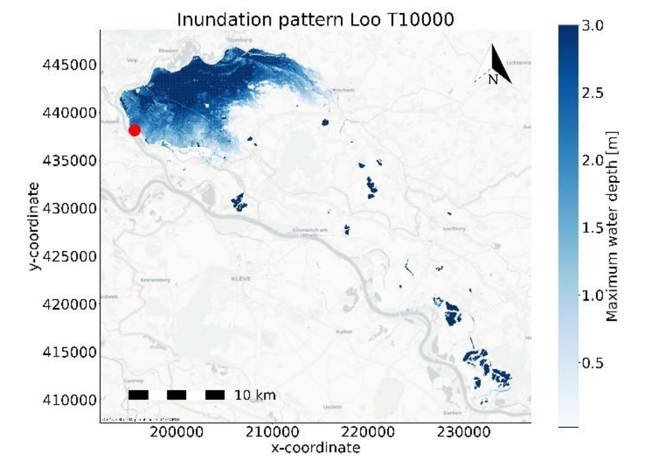
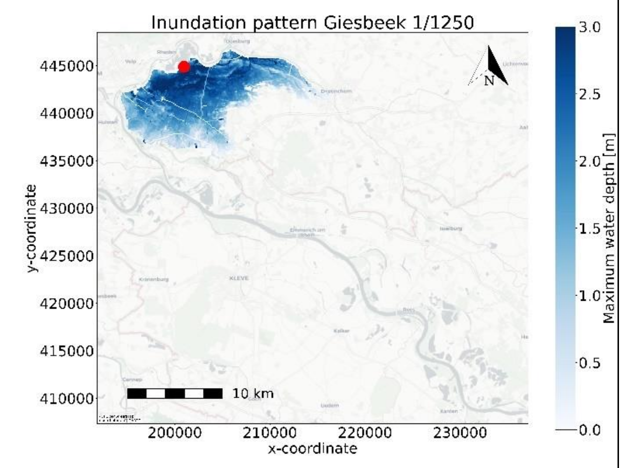
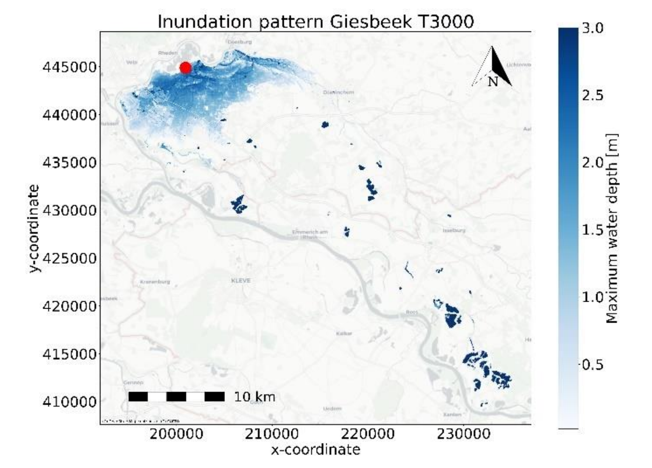




Kandiagemaal		
Loo		
Giesbeek		

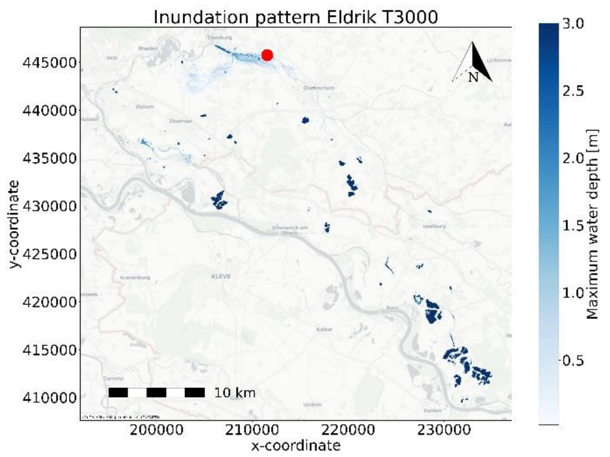
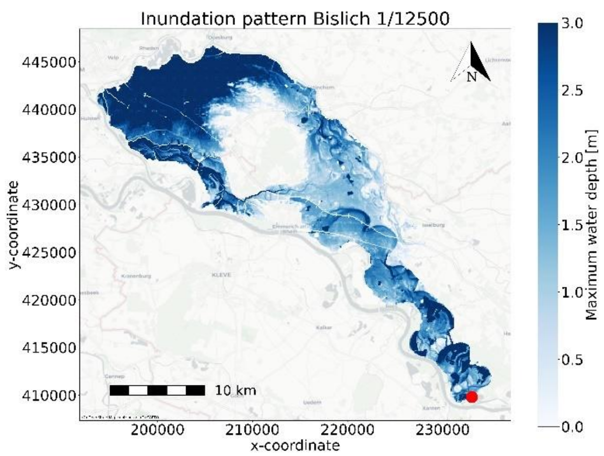
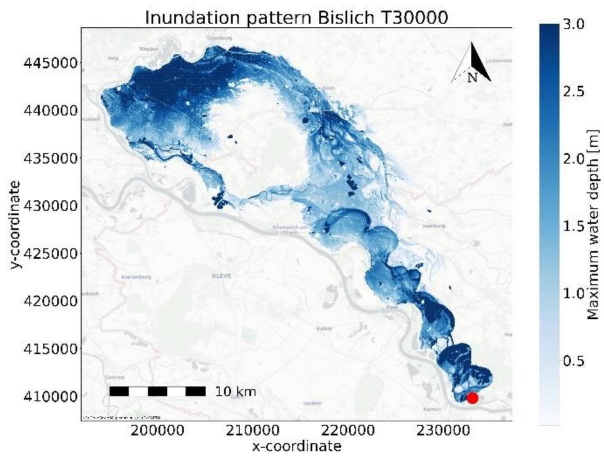
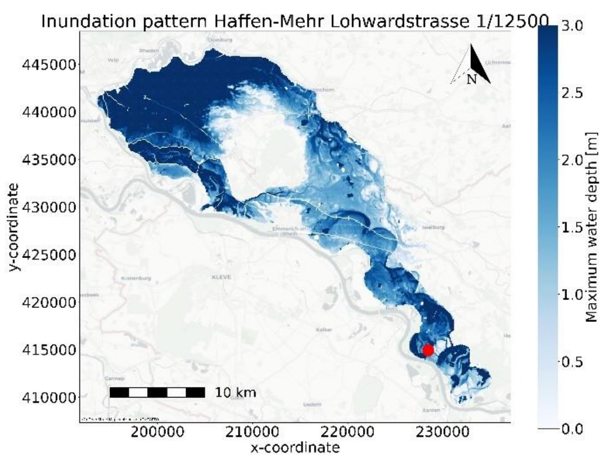
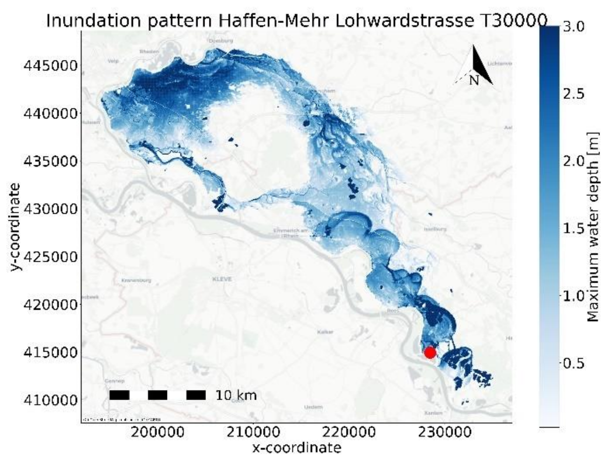
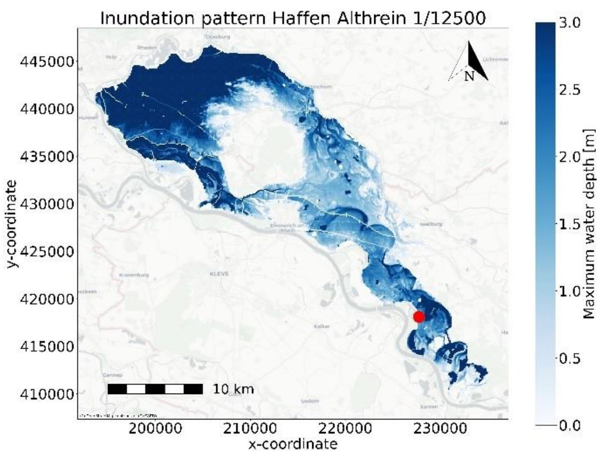
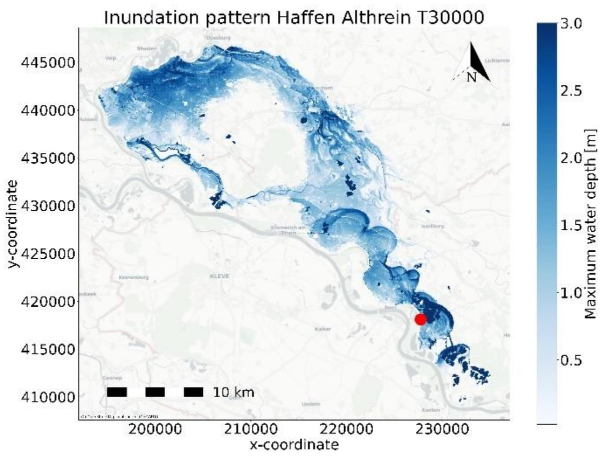
Eldrik	Not available	

Table C-2 - Computed maximum water depth for DelftFLS and D-Hydro for the above normative scenario (breach locations are indicated with a red dot)

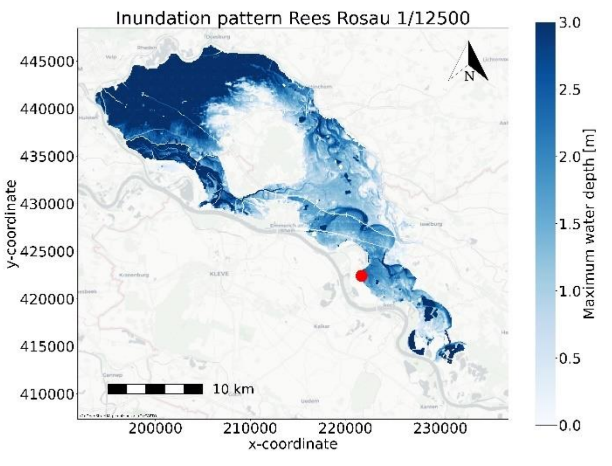
	DelftFLS	D-Hydro
Bislich		
Haffen-Mehr Lohwardstrasse		

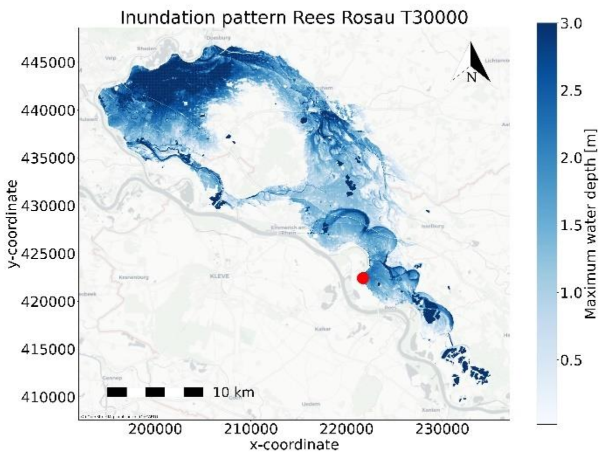
Haffen Althrein



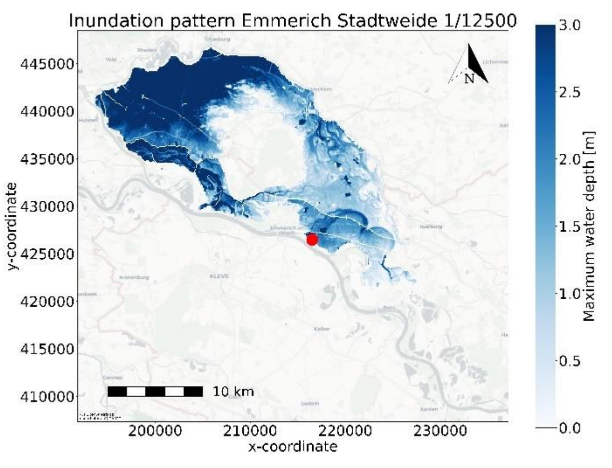


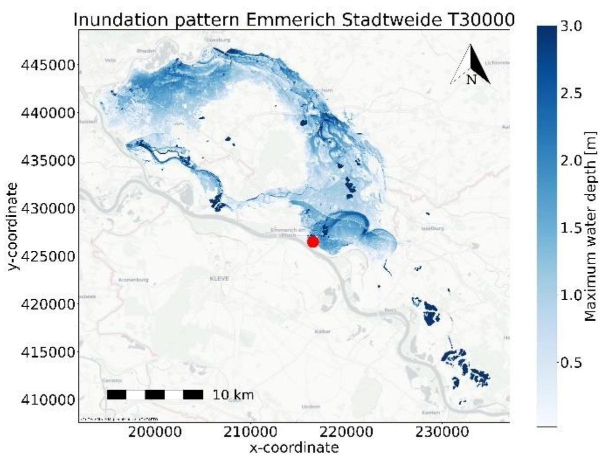
Rees Rosau

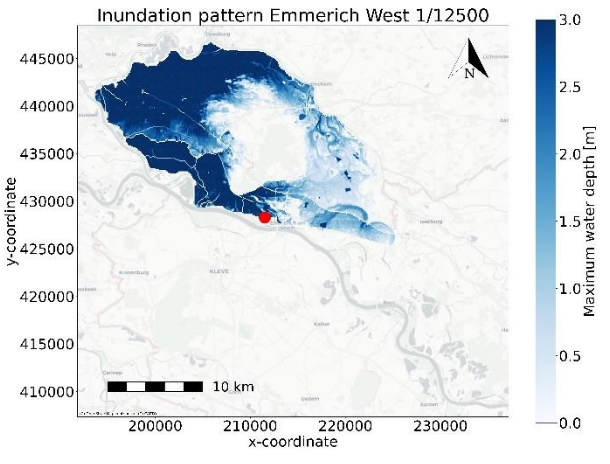
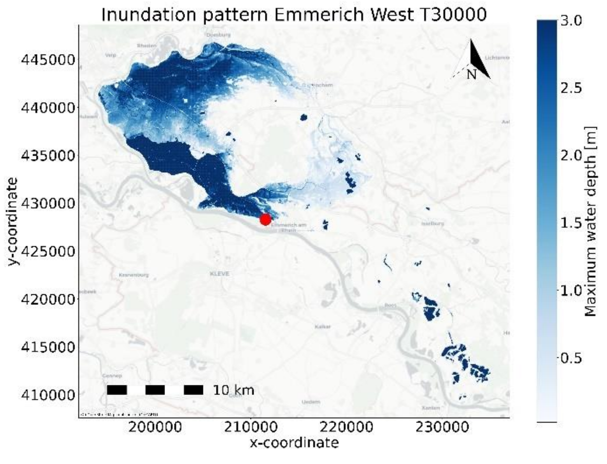
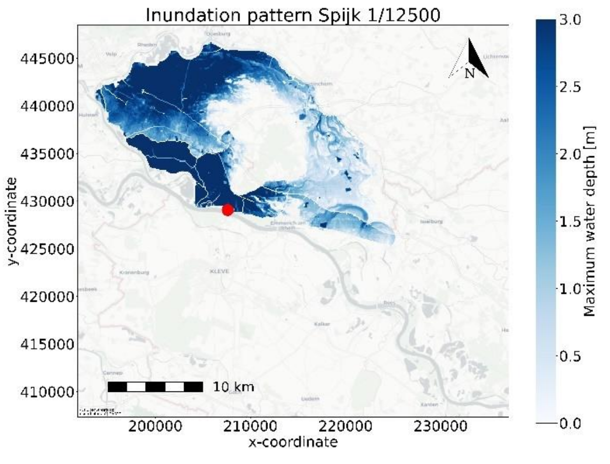
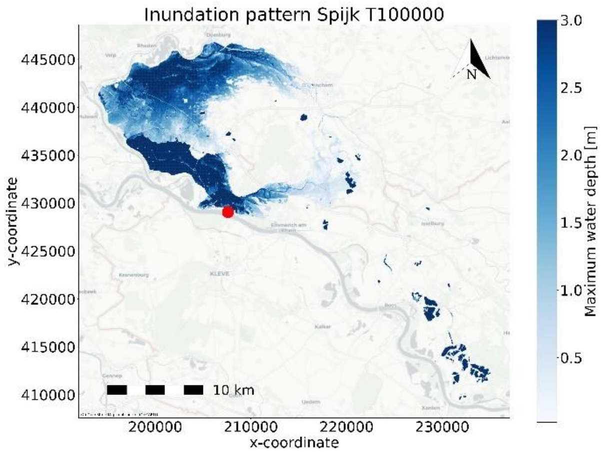
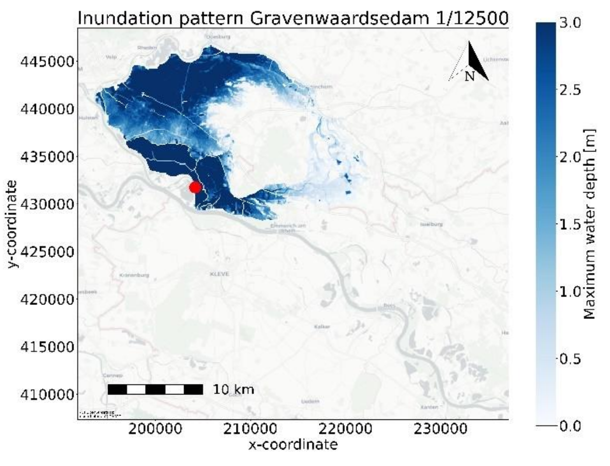
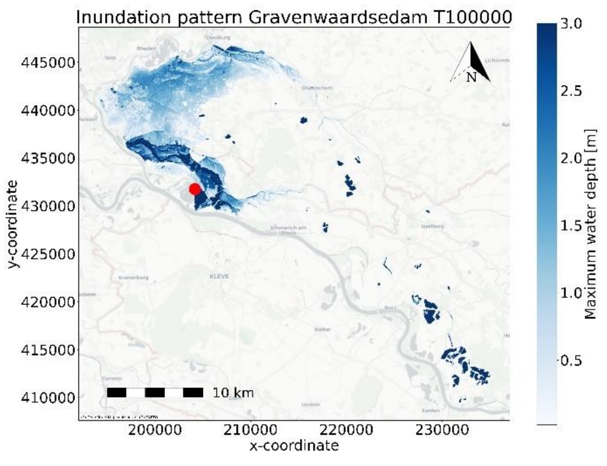


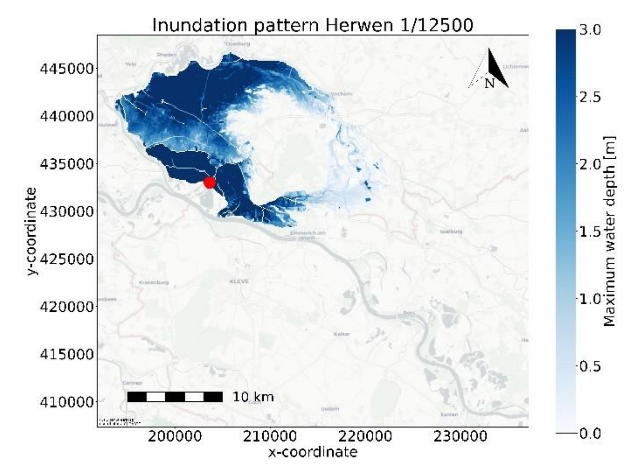
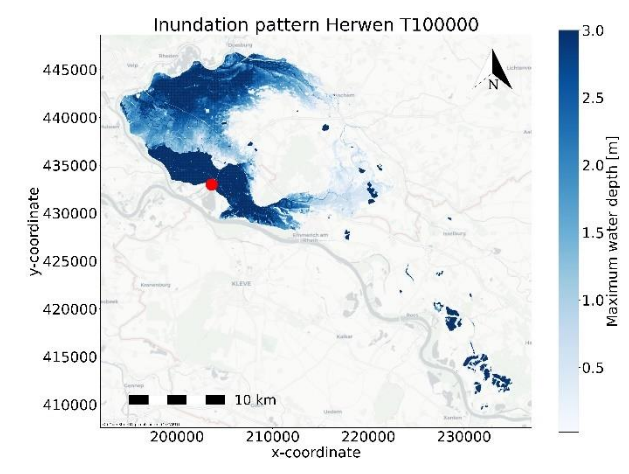
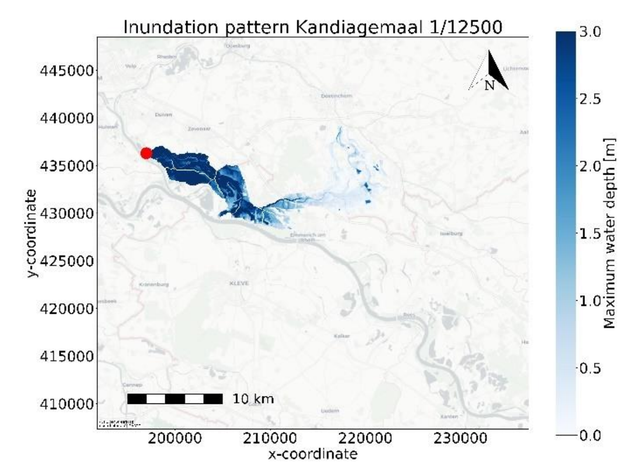
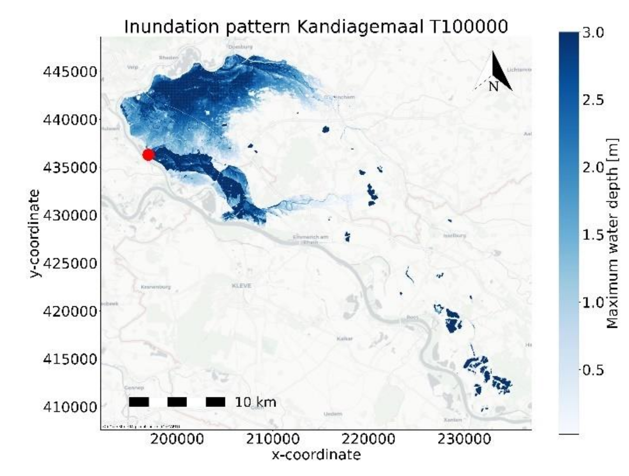
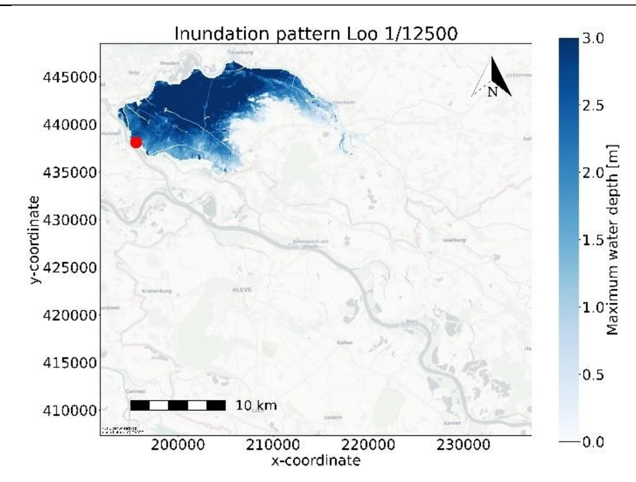
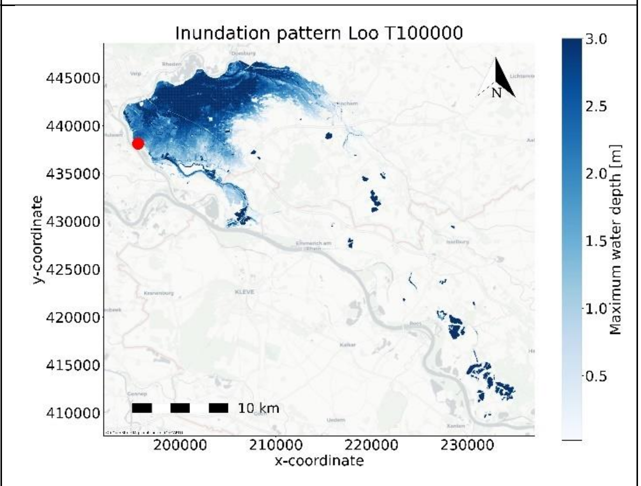


Emmerich Stadtweide





Emmerich West		
Spijk		
Gravenwaardse dam		

Herwen		
Kandiagemaal		
Loo		

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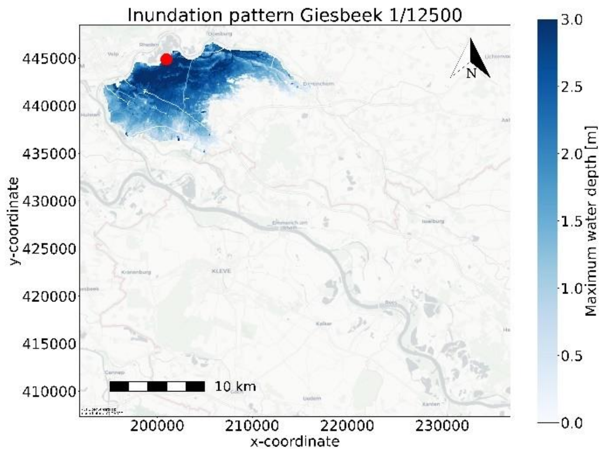

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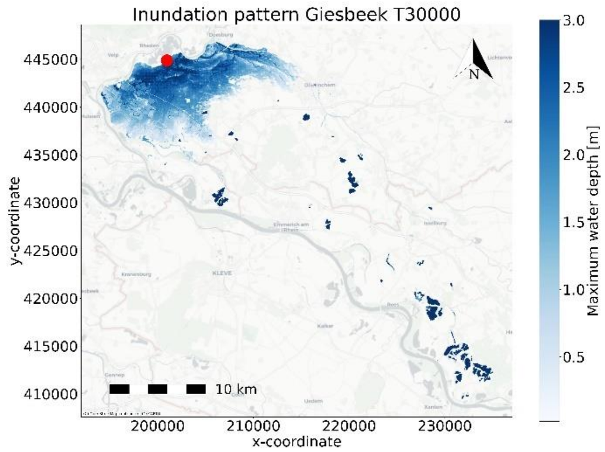

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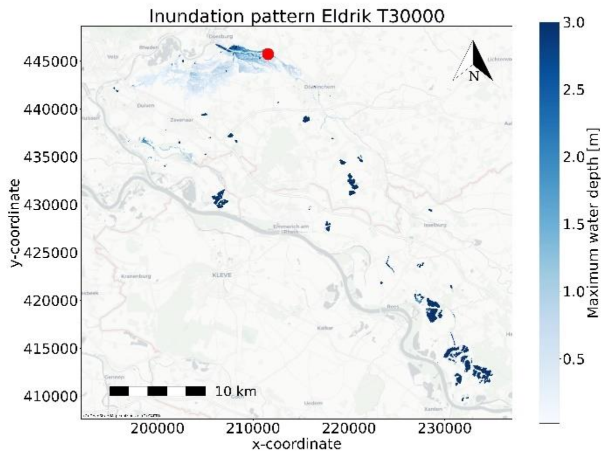

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Appendix D – Flow velocity flood simulations reference scenario

Table D-1 - Computed maximum flow velocity for DelftFLS and D-Hydro for the normative scenario (breach locations are indicated with a black dot)

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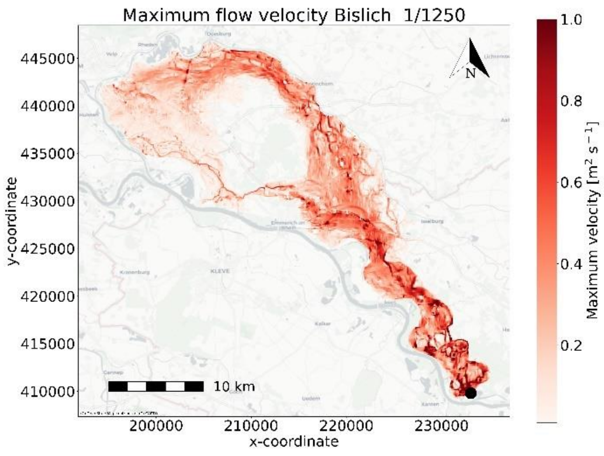
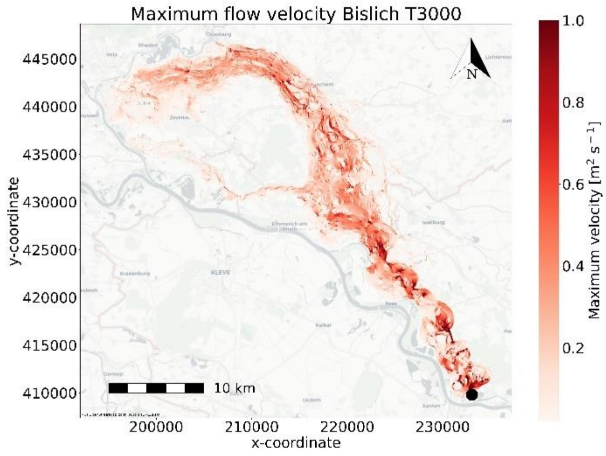
<tr><td>Bislich</td><td>
</td><td>
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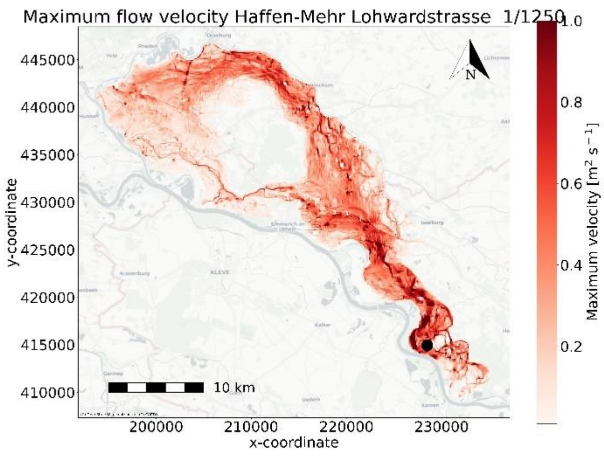
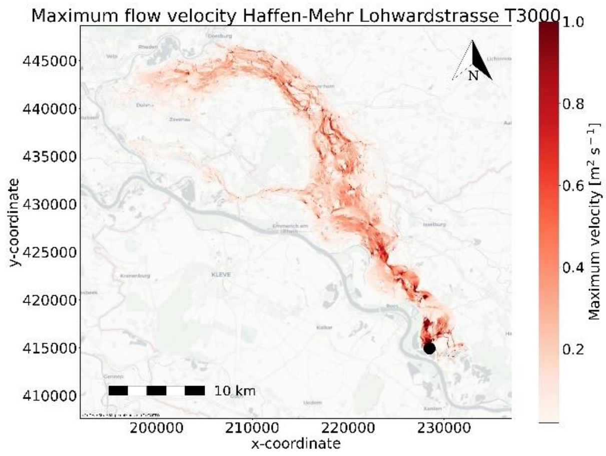
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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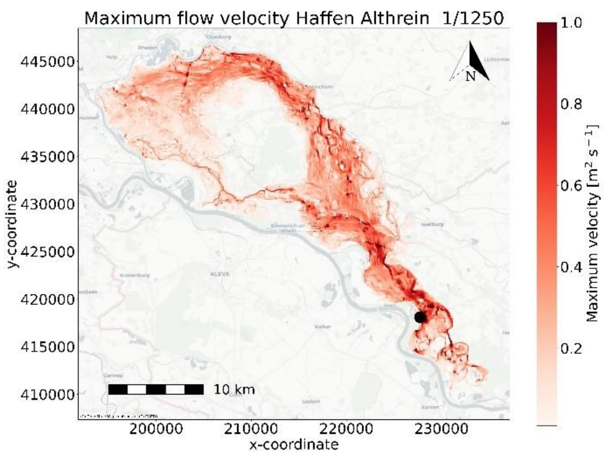
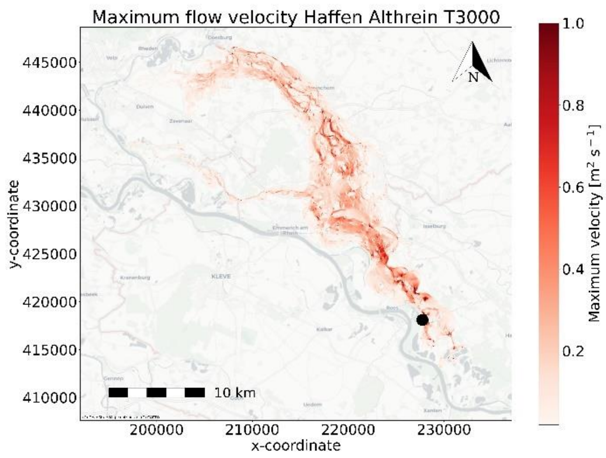
<tr><td>Haffen Althrein</td><td>
</td><td>
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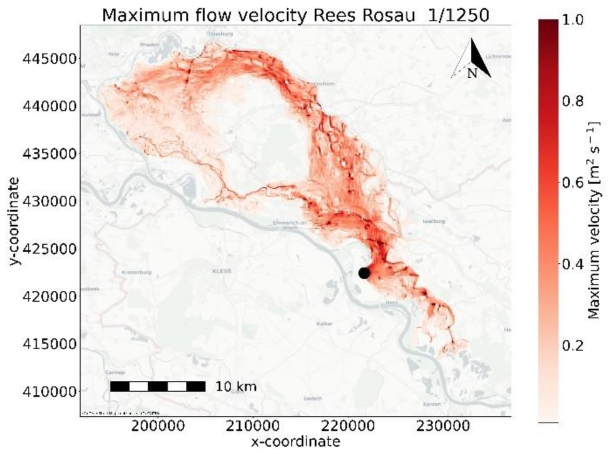
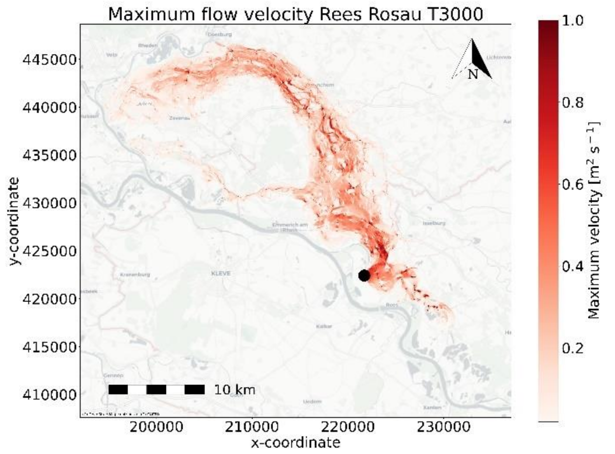
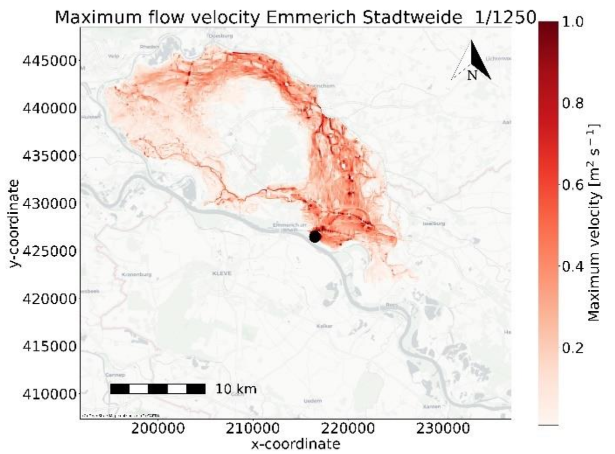
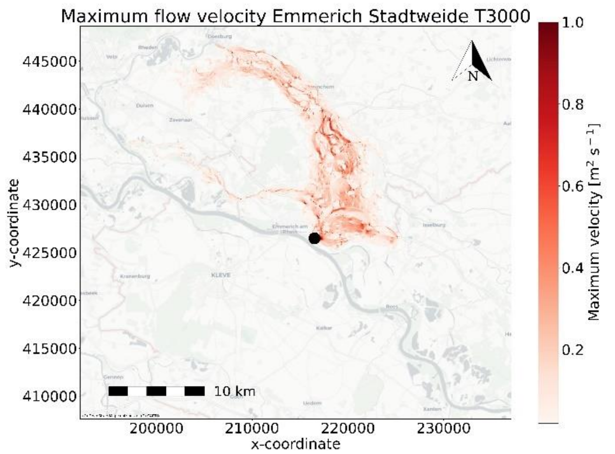
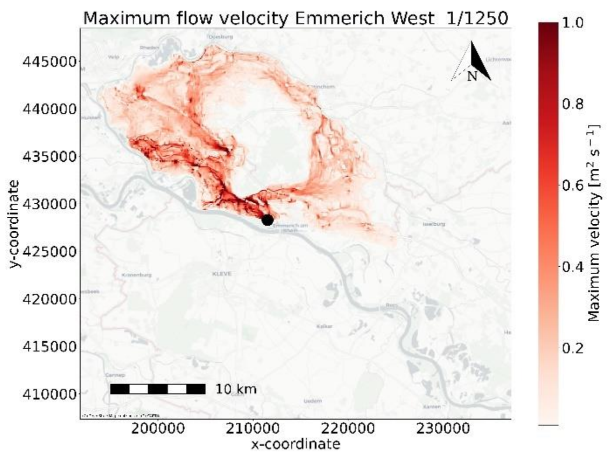
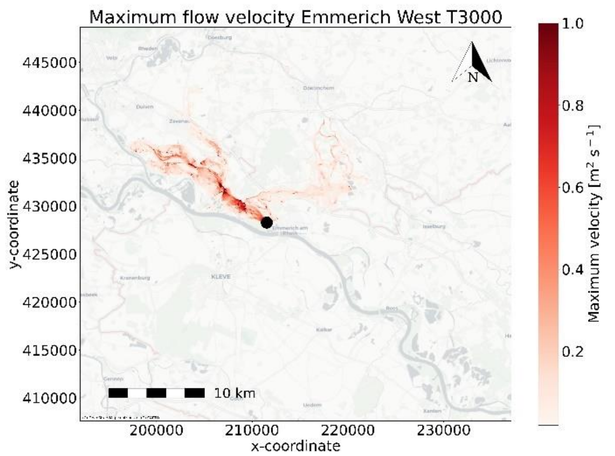
Rees Rosau		
Emmerich Stadtweide		
Emmerich West		

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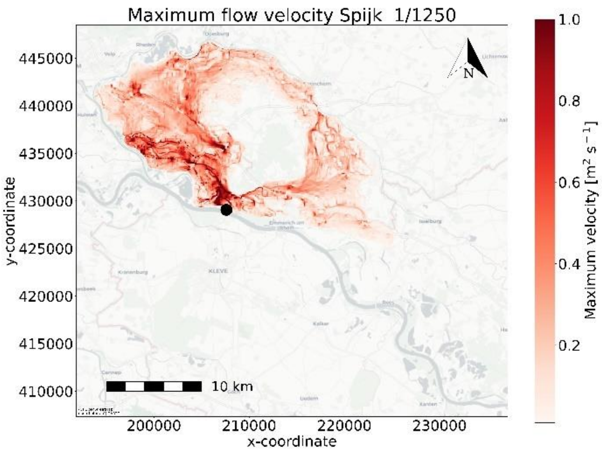

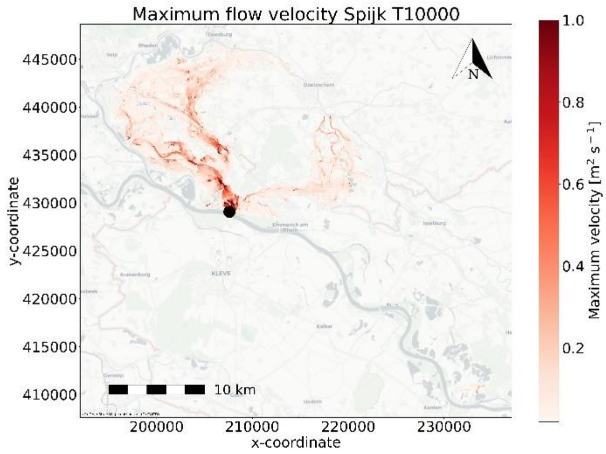

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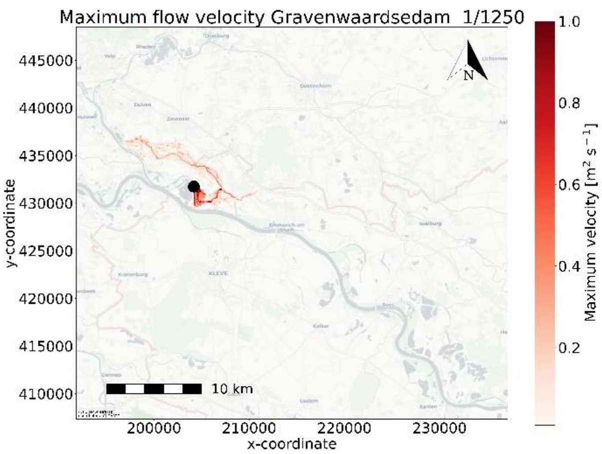

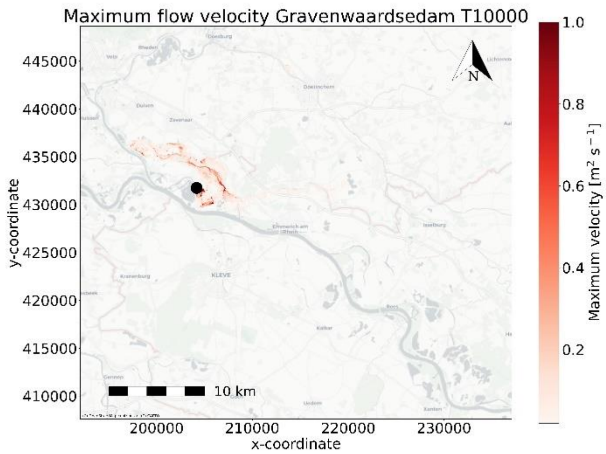

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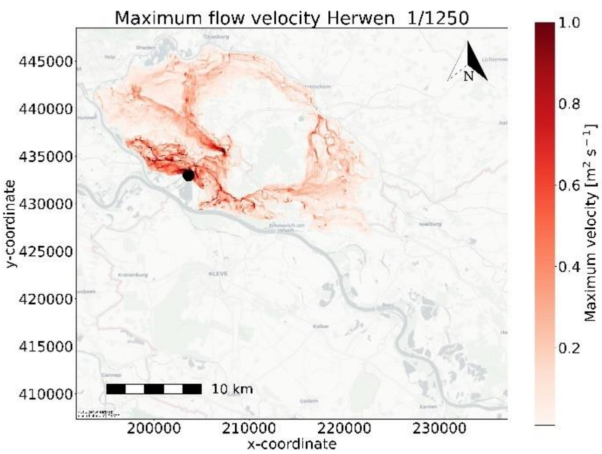
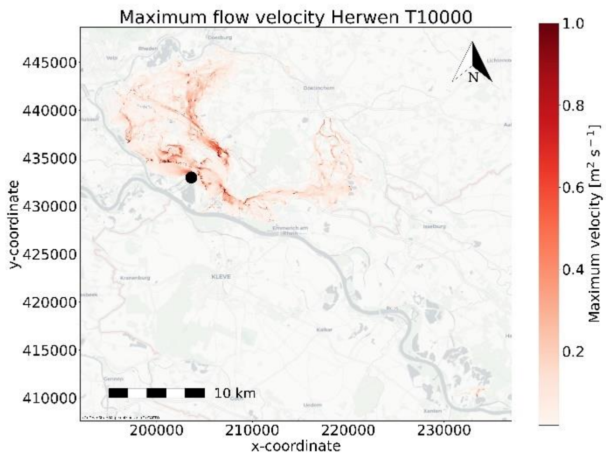
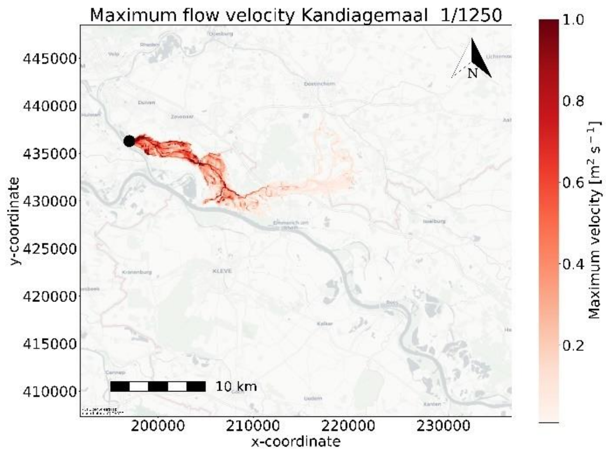
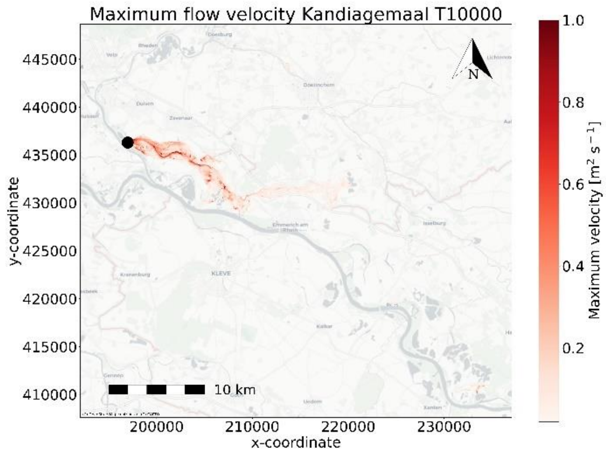
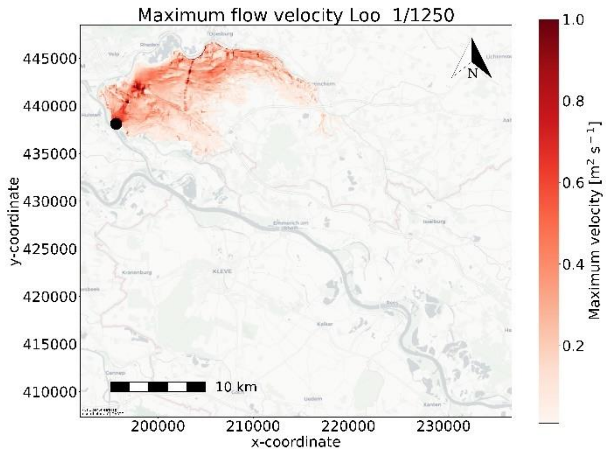
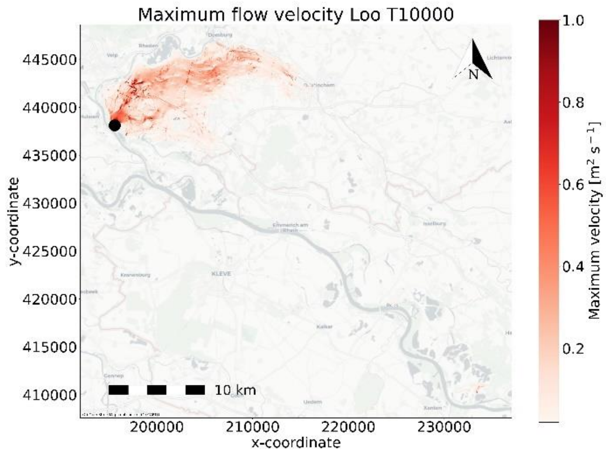
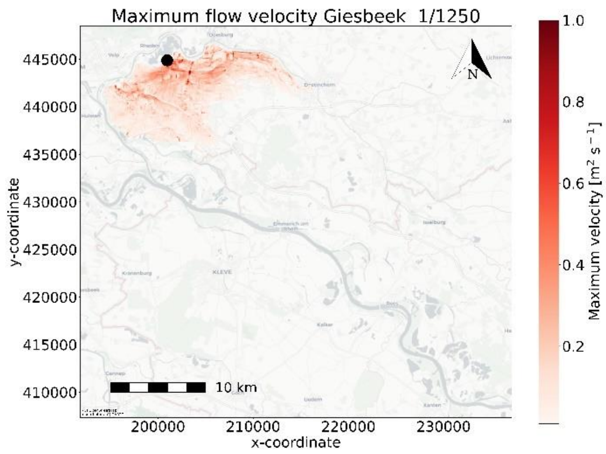
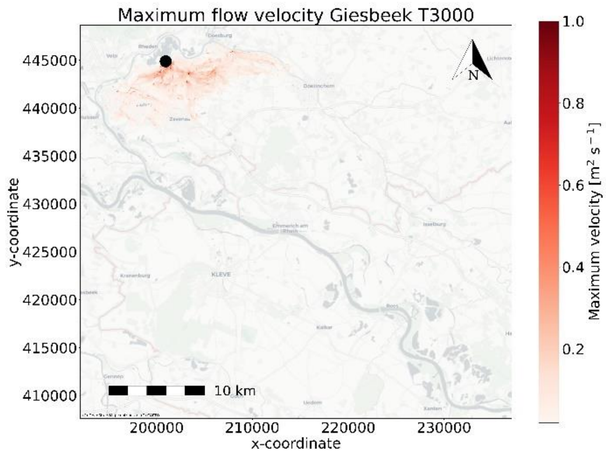




Kandiagemaal		
Loo		
Giesbeek		

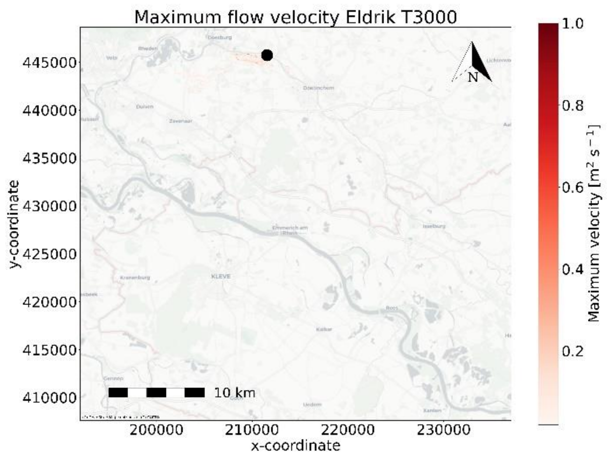
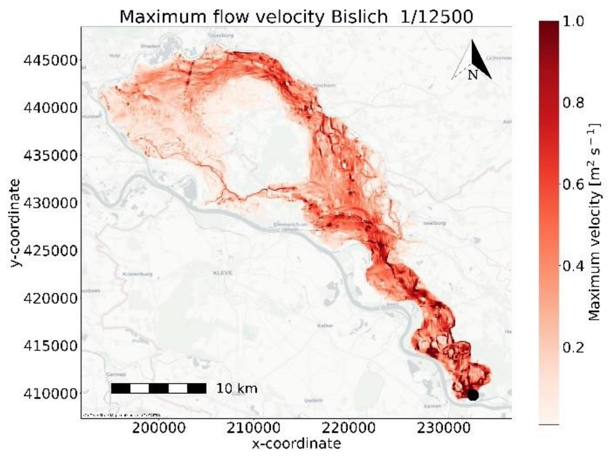
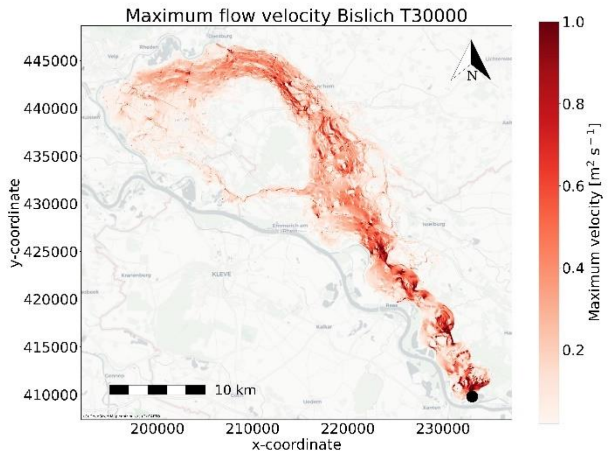
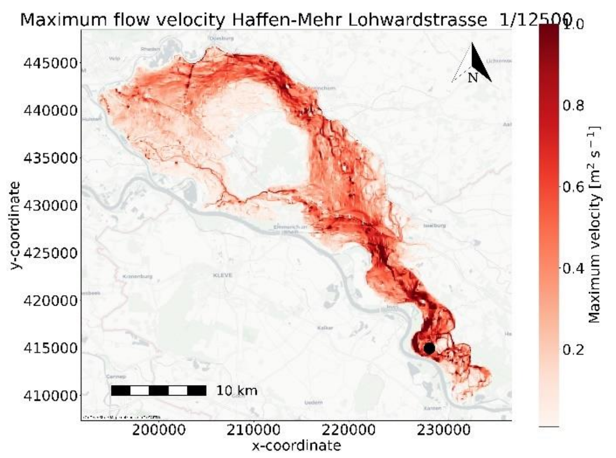
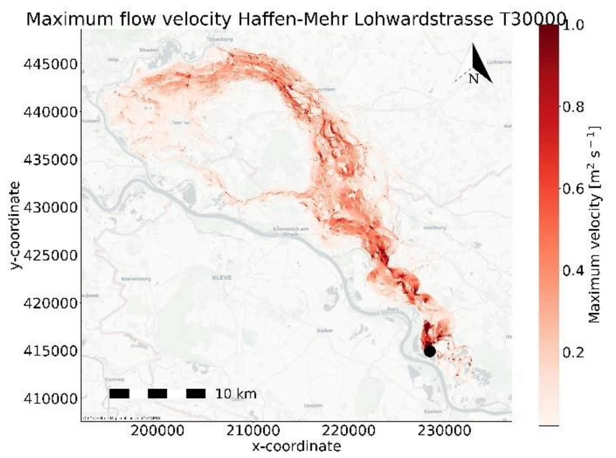
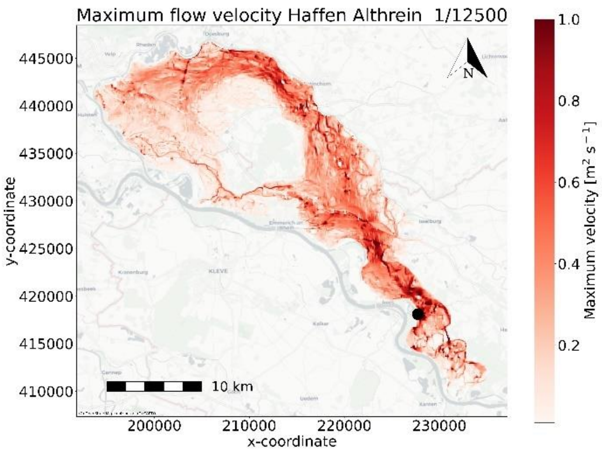
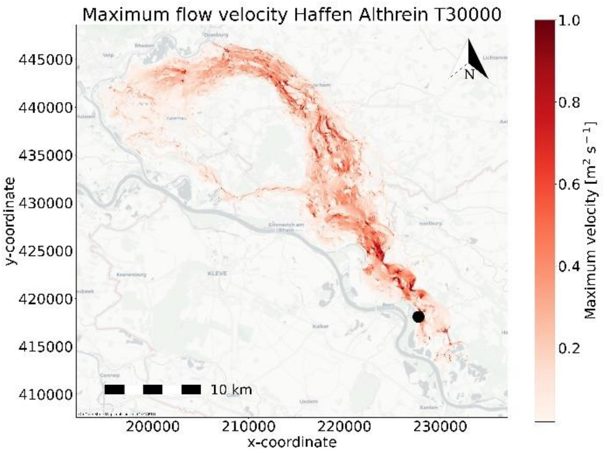
Eldrik	Not available	

Table D-2 - Computed maximum flow velocity for DelftFLS and D-Hydro for the above normative scenario (breach locations are indicated with a black dot)

	DelftFLS	D-Hydro
Bislich		
Haffen-Mehr Lohwardstrasse		

Haffen Althrein





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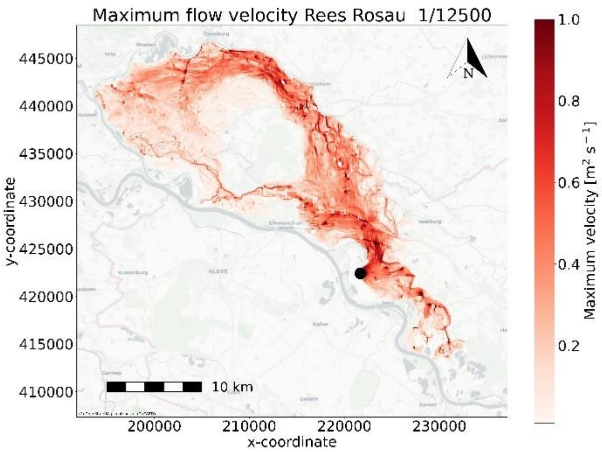

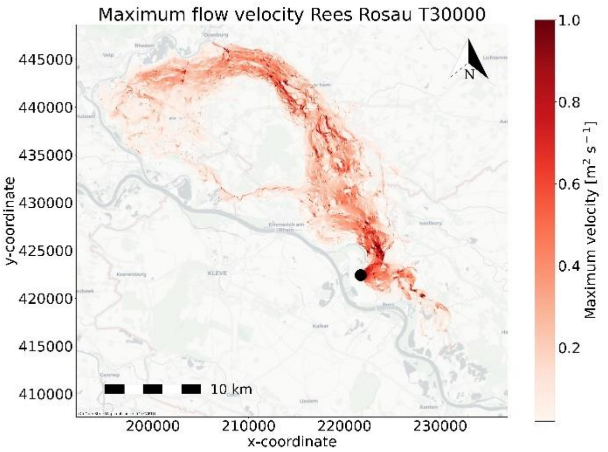

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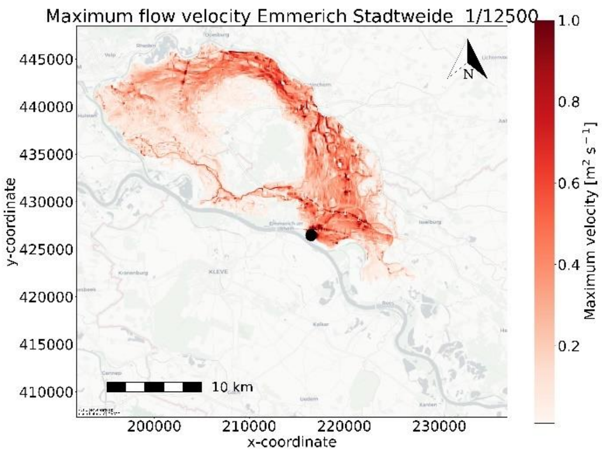
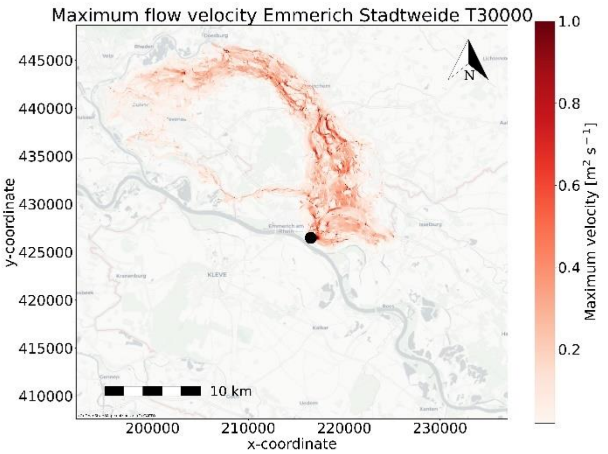
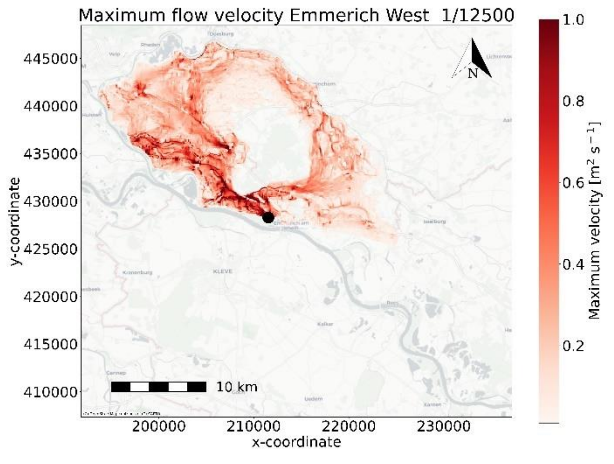
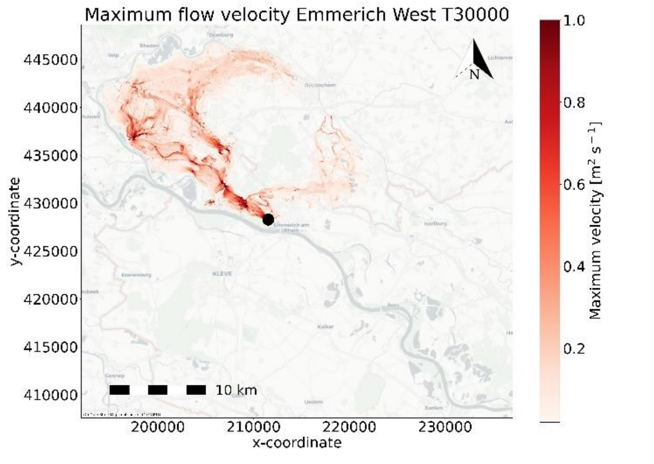




Emmerich West





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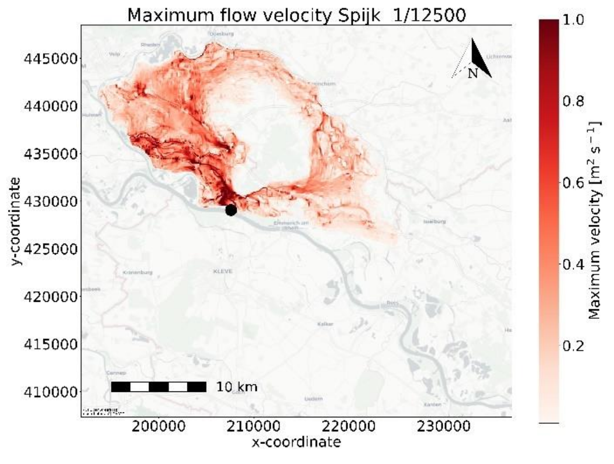
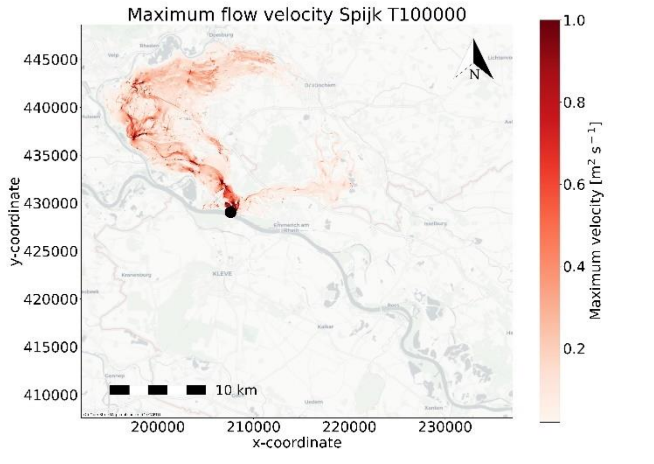
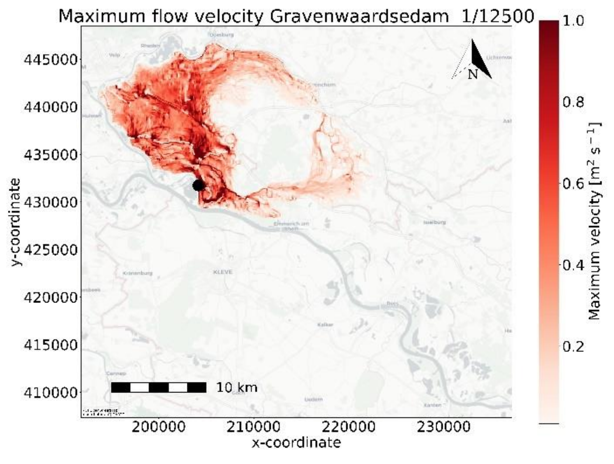
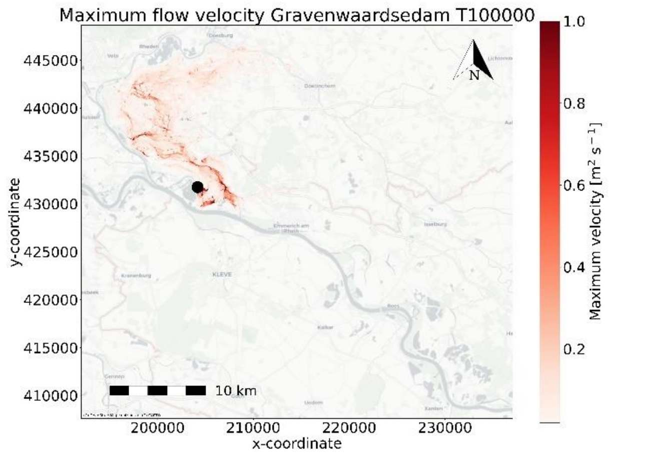




Gravenwaardse dam





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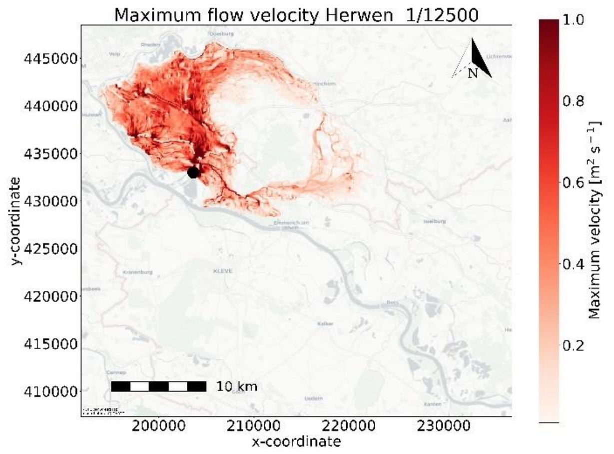
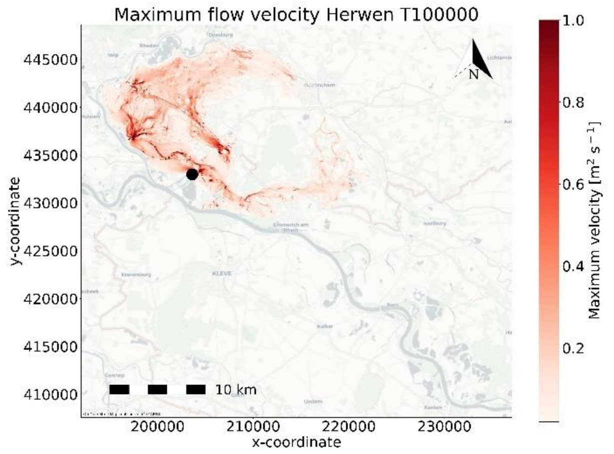
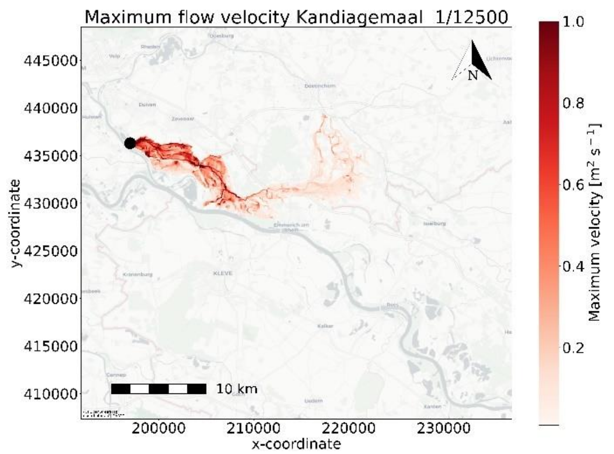
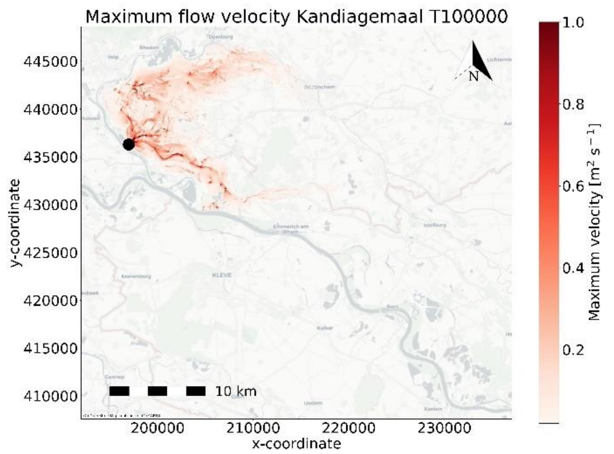


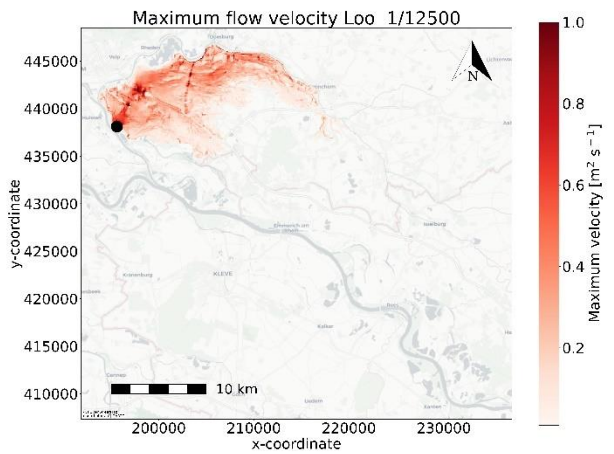


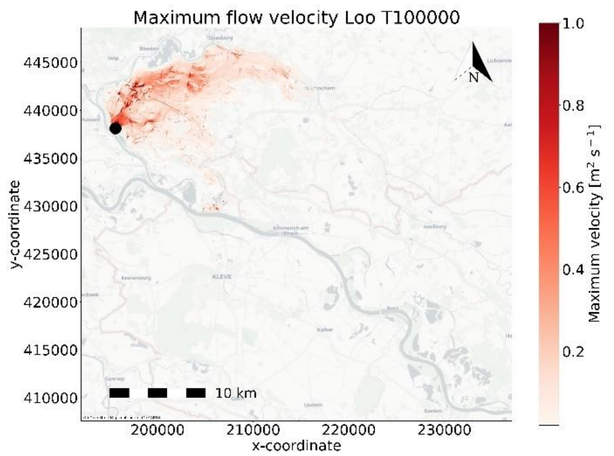
Kandiagemaal

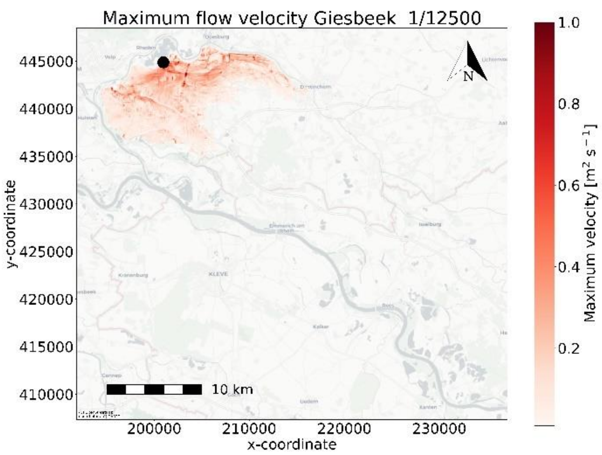
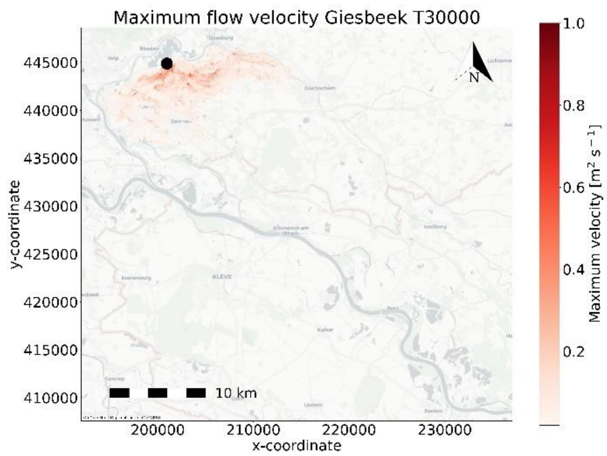
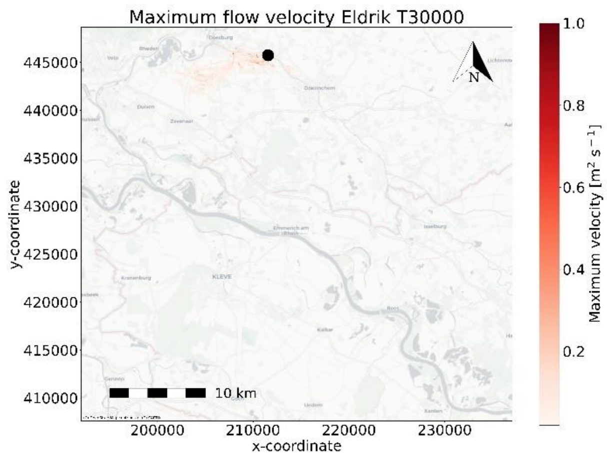




Loo

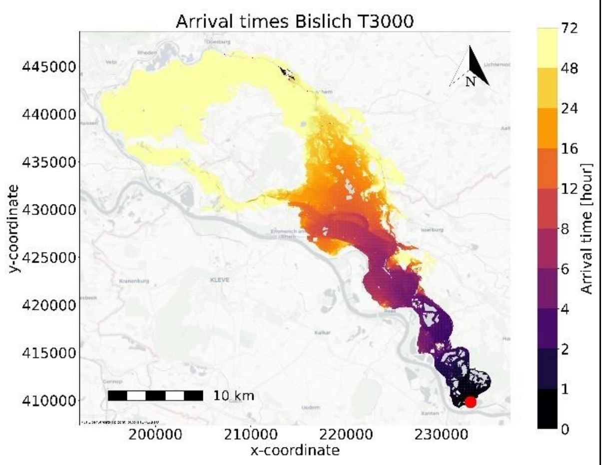
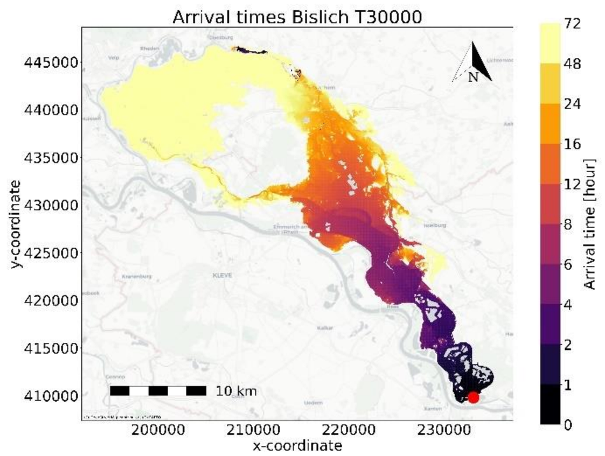
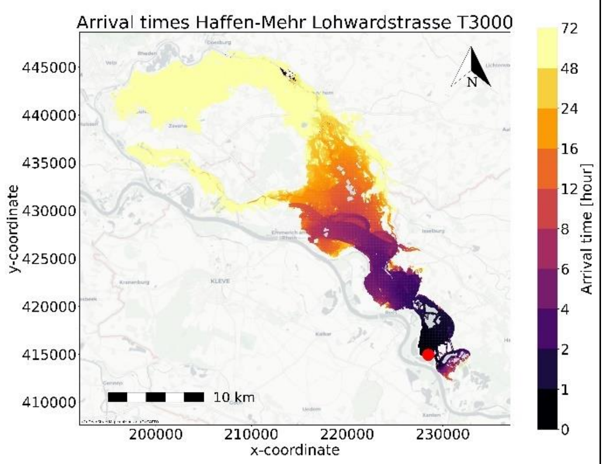
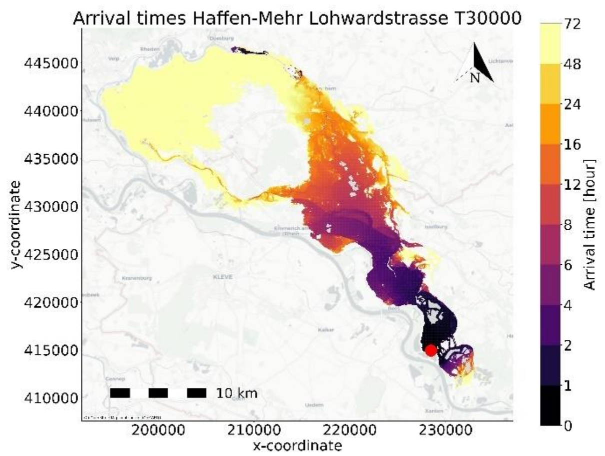
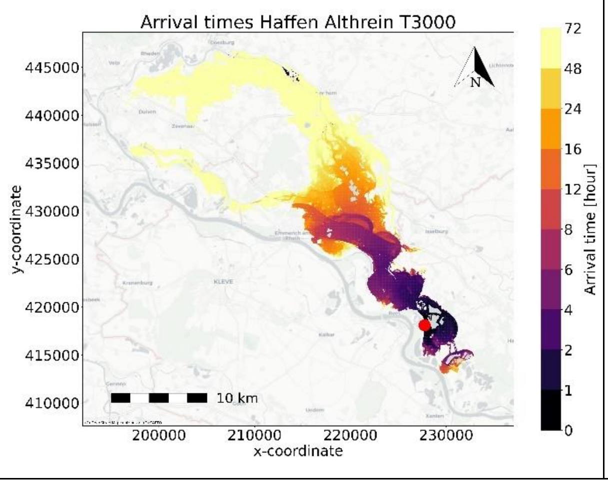
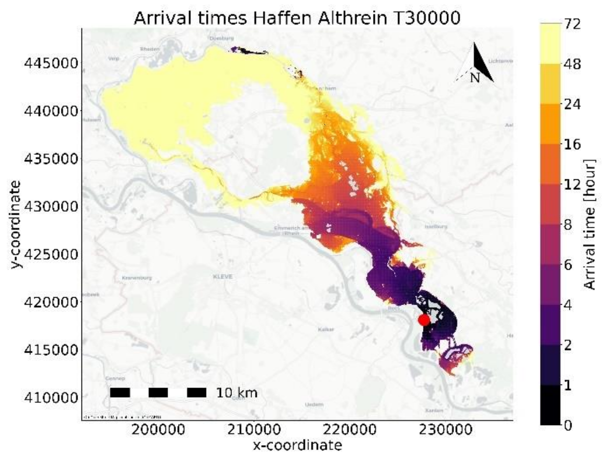




Giesbeek		
Eldrik	Not available	

Appendix E – Arrival times flood simulations reference scenario

Table E-1 - Arrival times flood simulations computed with D-HYDRO for reference scenario both for the normative discharge scenario and the above normative discharge scenario

	D-Hydro normative discharge scenario	D-Hydro above normative discharge scenario
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein		

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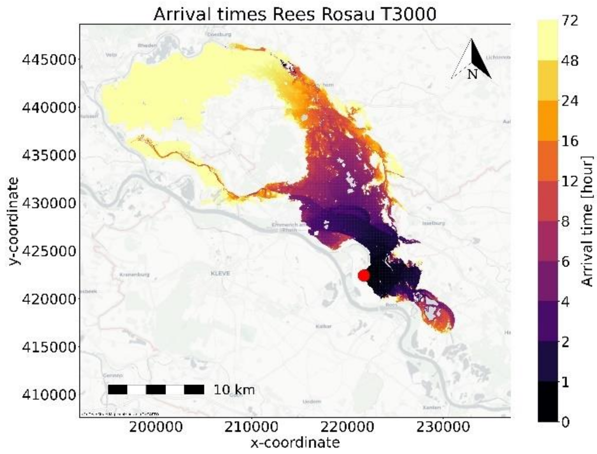
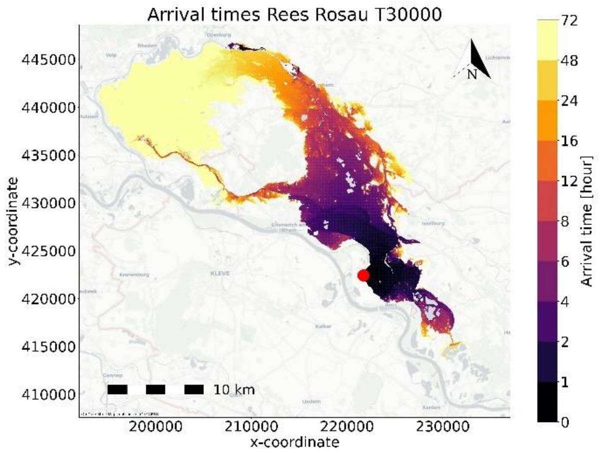
<tr><td>Rees Rosau</td><td>
</td><td>
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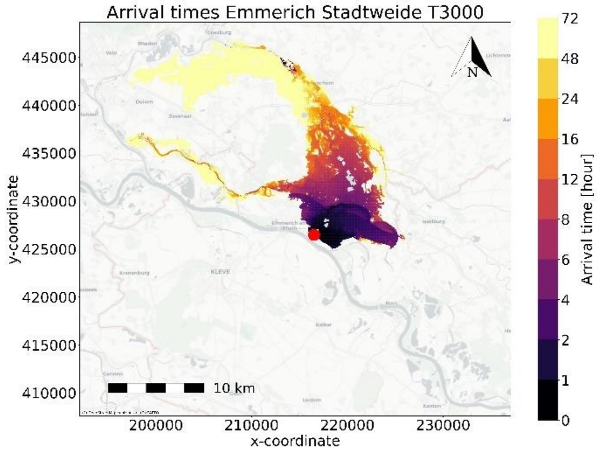
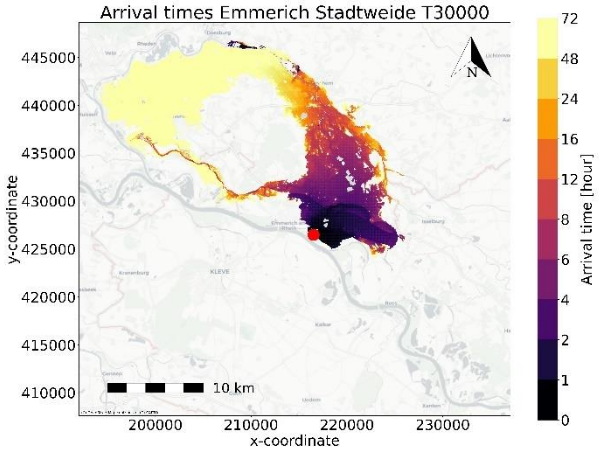
<tr><td>Emmerich Stadtweide</td><td>
</td><td>
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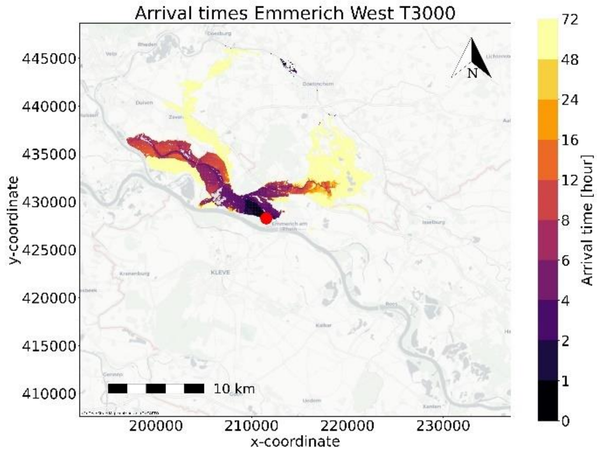
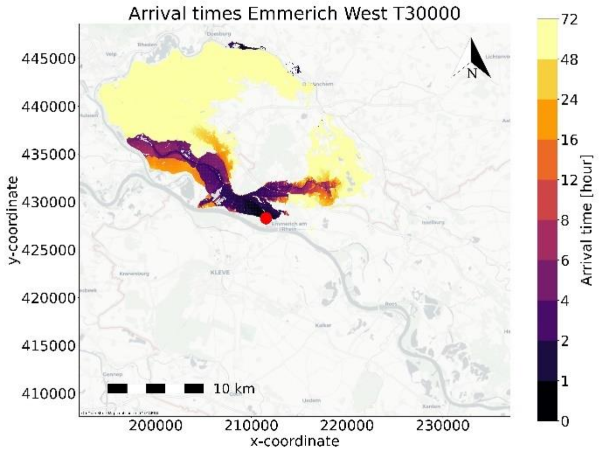
<tr><td>Emmerich West</td><td>
</td><td>
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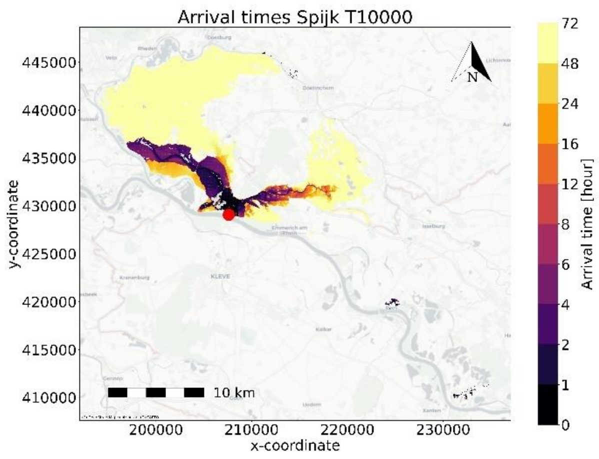
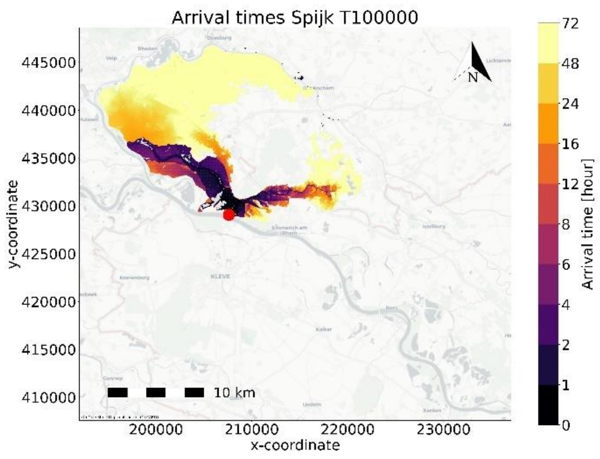
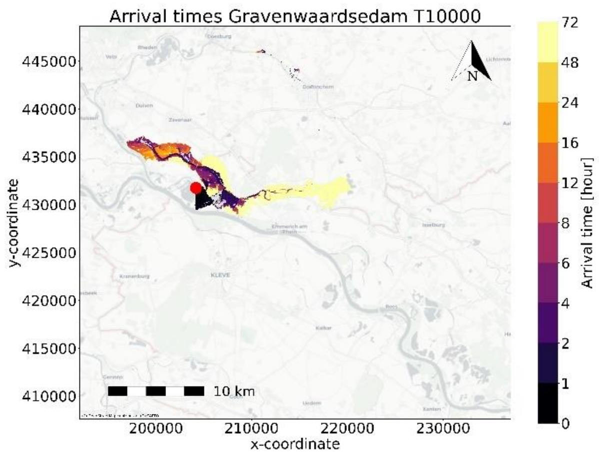
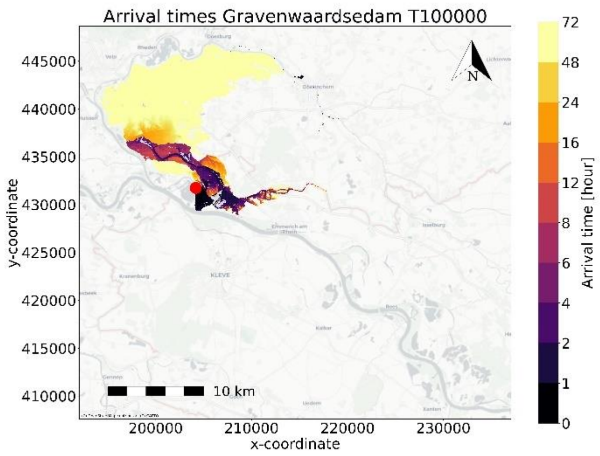
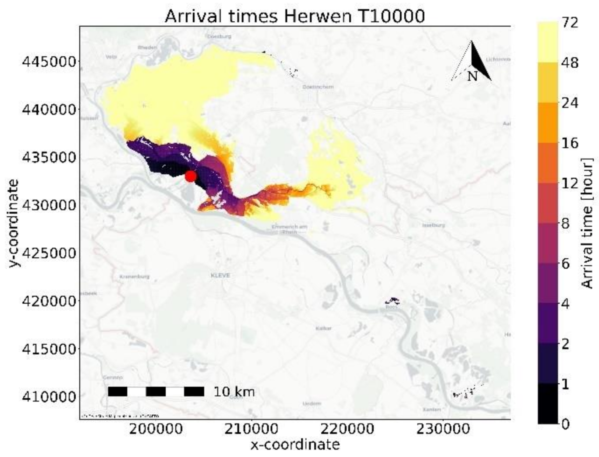
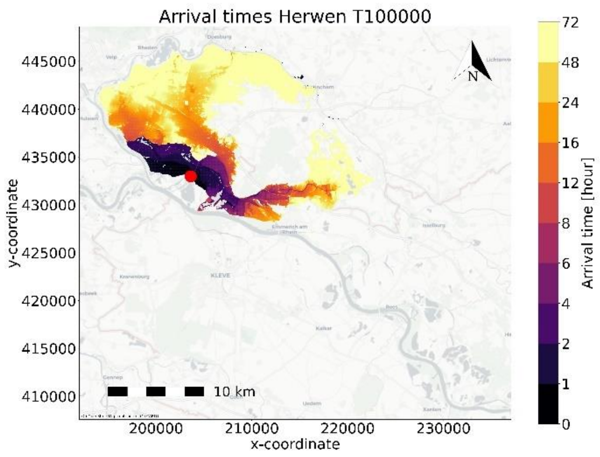
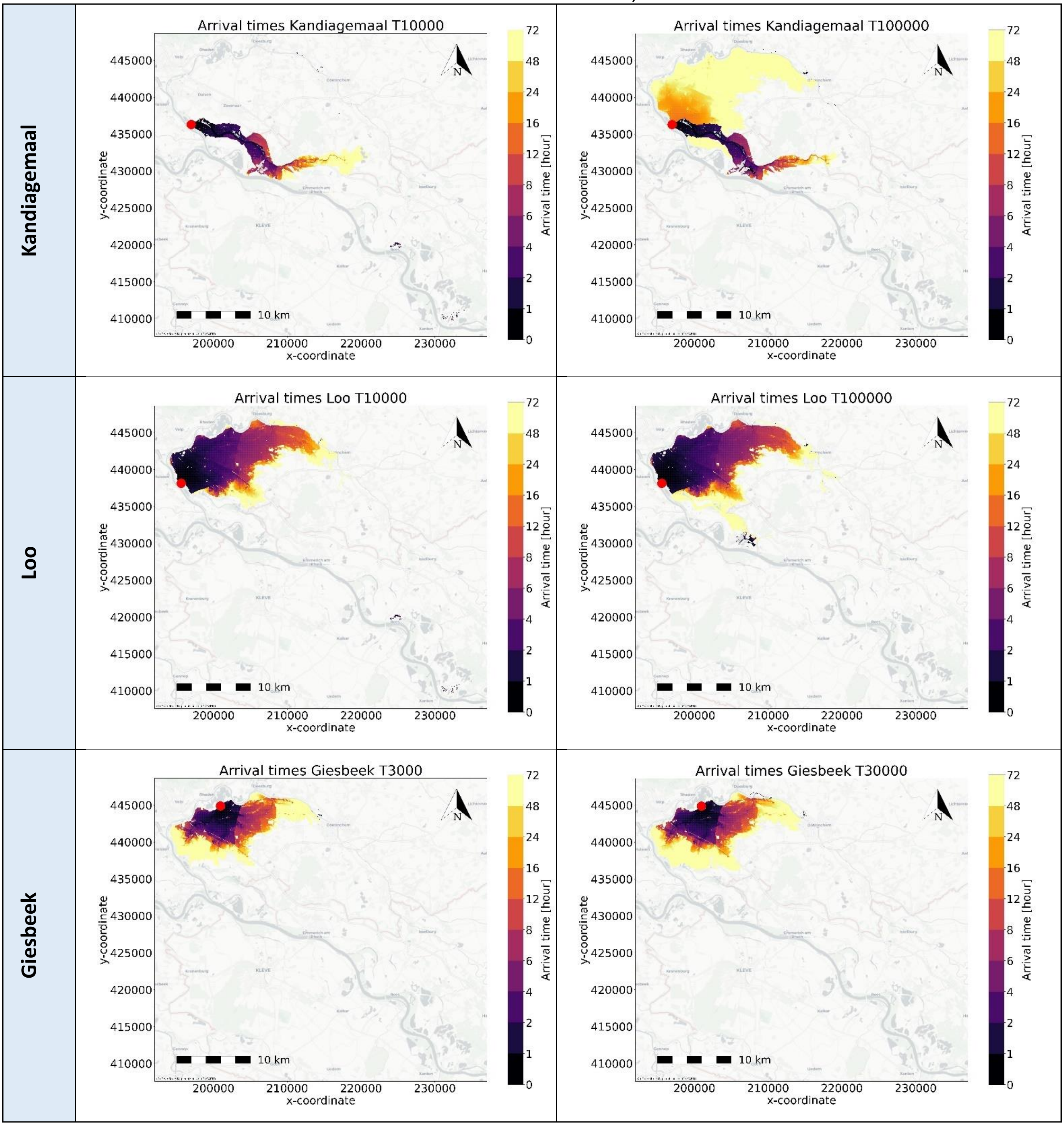
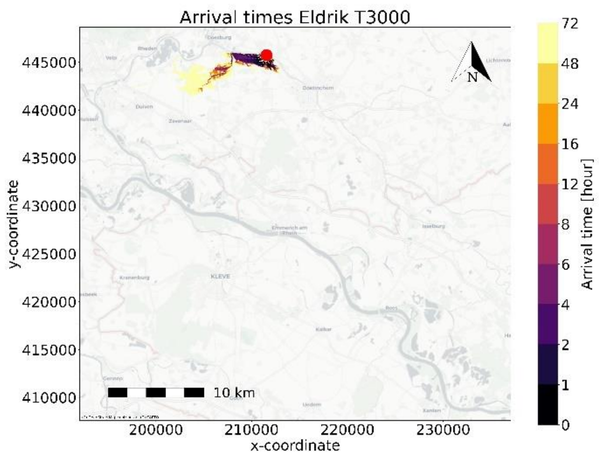
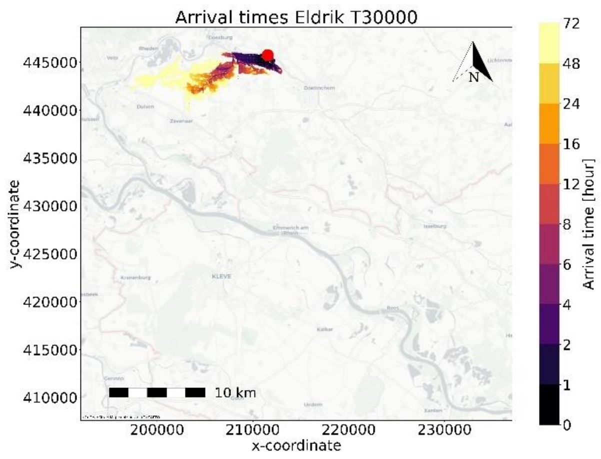
Spijk		
Gravenwaardse dam		
Herwen		


Kandiagemaal
Arrival times Kandiagemaal T10000
Arrival times Kandiagemaal T100000
Loo
Arrival times Loo T10000
Arrival times Loo T100000
Giesbeek
Arrival times Giesbeek T3000
Arrival times Giesbeek T30000
y-coordinate
x-coordinate
Arrival time [hour]
445000
440000
435000
430000
425000
420000
415000
410000
200000
210000
220000
230000
72
48
24
16
12
8
6
4
2
1
0
10 km
N

Eldrik	 Arrival times Eldrik T3000 y-coordinate x-coordinate 445000 440000 435000 430000 425000 420000 415000 410000 200000 210000 220000 230000 10 km N Arrival time [hour] 72 48 24 16 12 8 6 4 2 1 0	 Arrival times Eldrik T30000 y-coordinate x-coordinate 445000 440000 435000 430000 425000 420000 415000 410000 200000 210000 220000 230000 10 km N Arrival time [hour] 72 48 24 16 12 8 6 4 2 1 0

Appendix F – Ascent rates flood simulations reference scenario

Table F-1 - Computed maximum ascent rates for DelftFLS and D-Hydro for the normative scenario (breach locations are indicated with a red dot)

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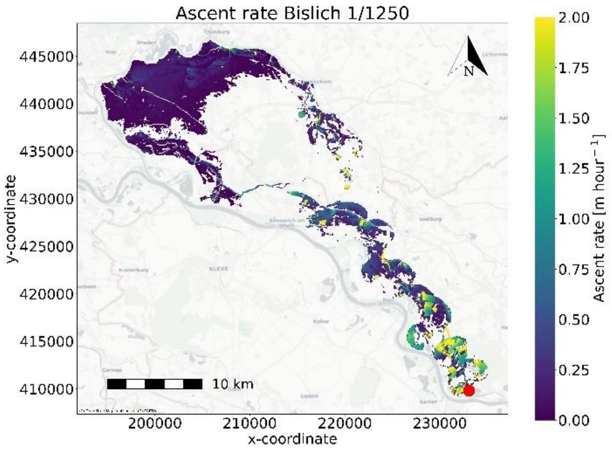
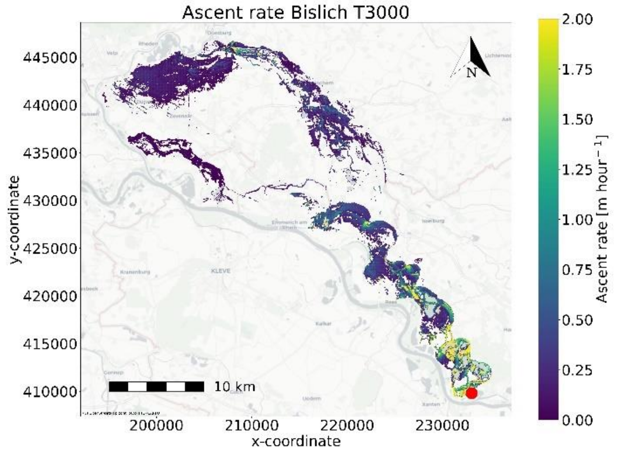
<tr><td>Bislich</td><td>
</td><td>
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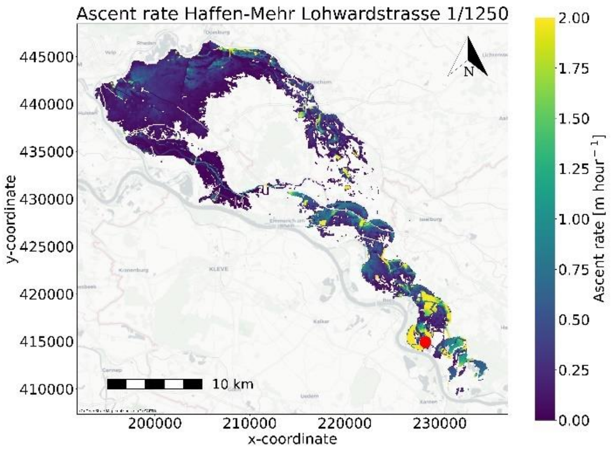
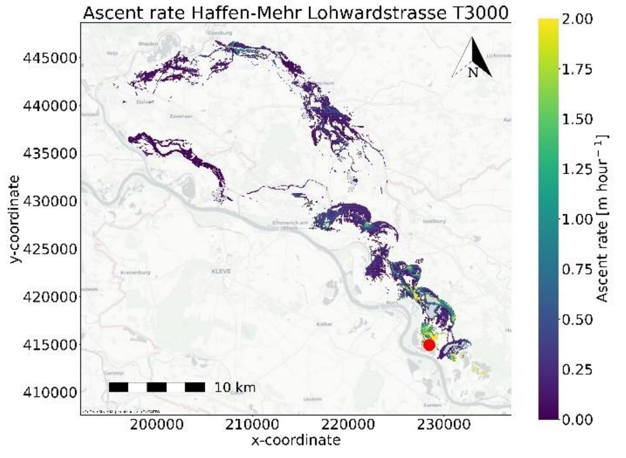
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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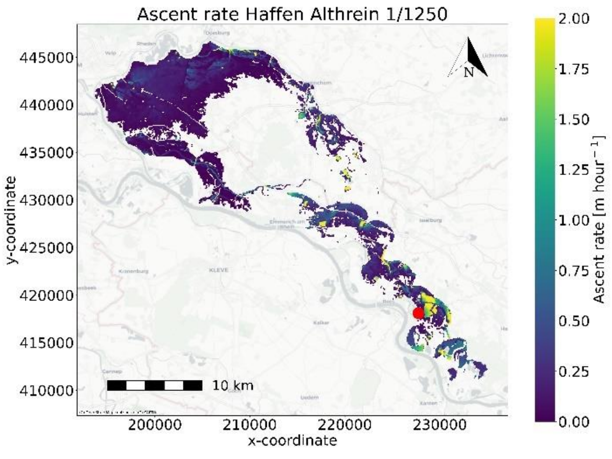
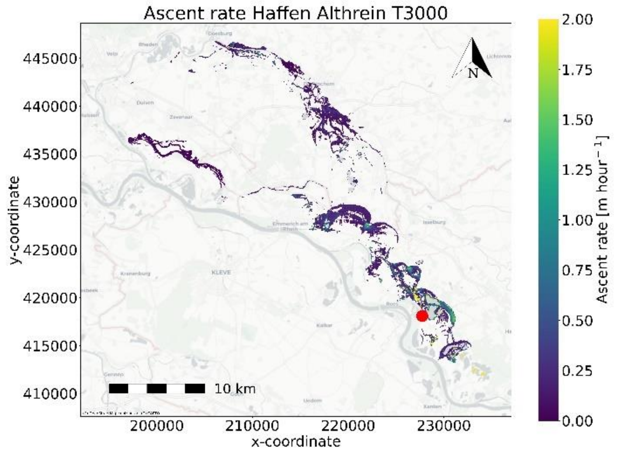
<tr><td>Haffen Althrein</td><td>
</td><td>
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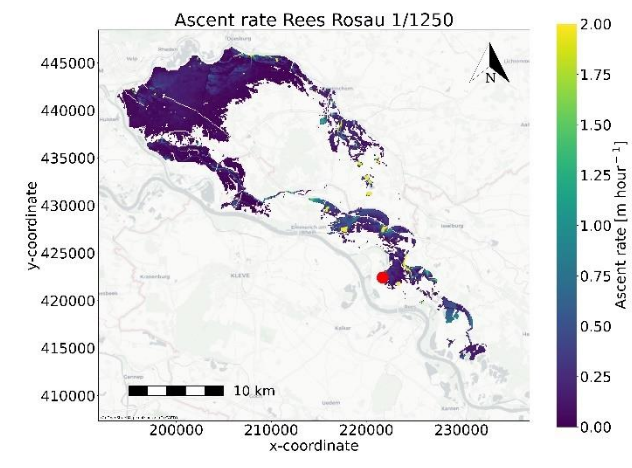
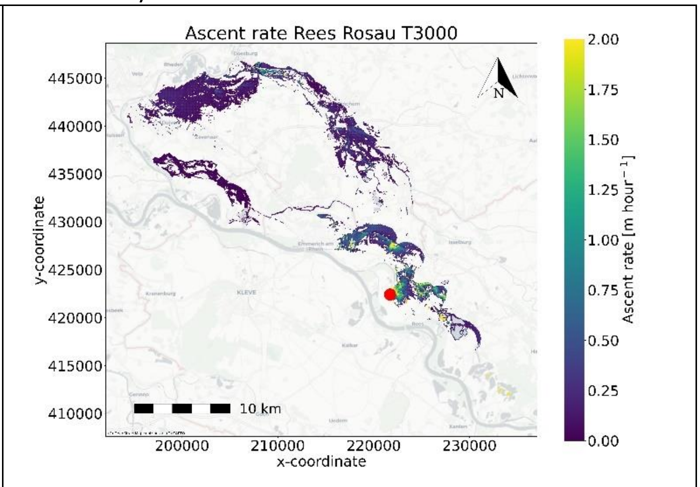
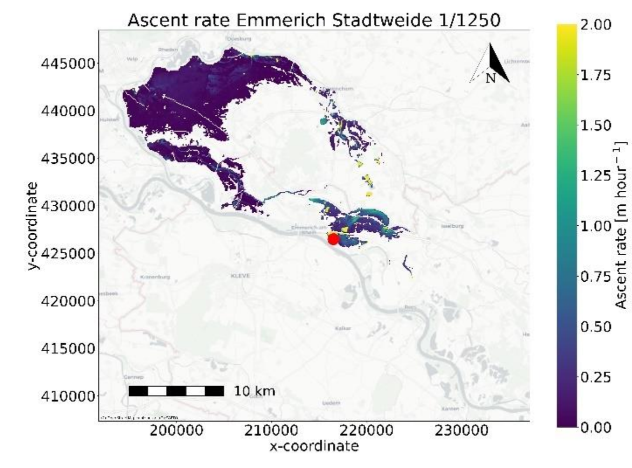
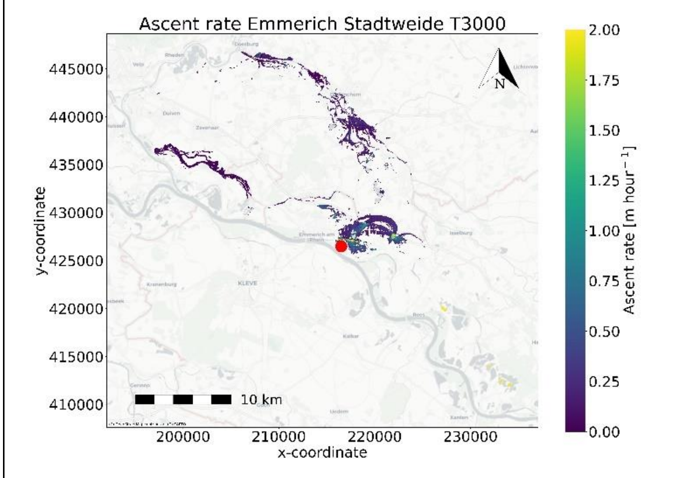
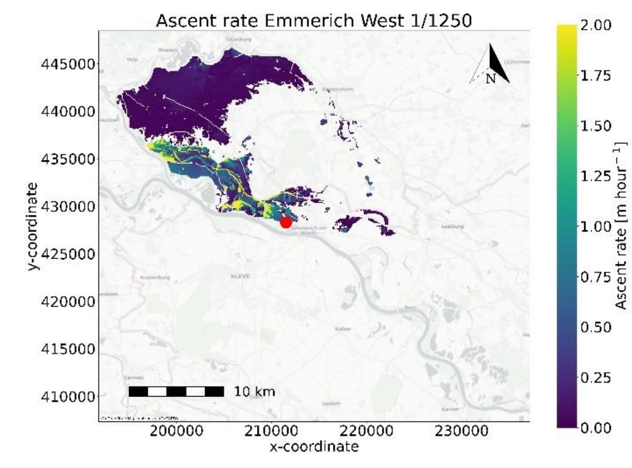
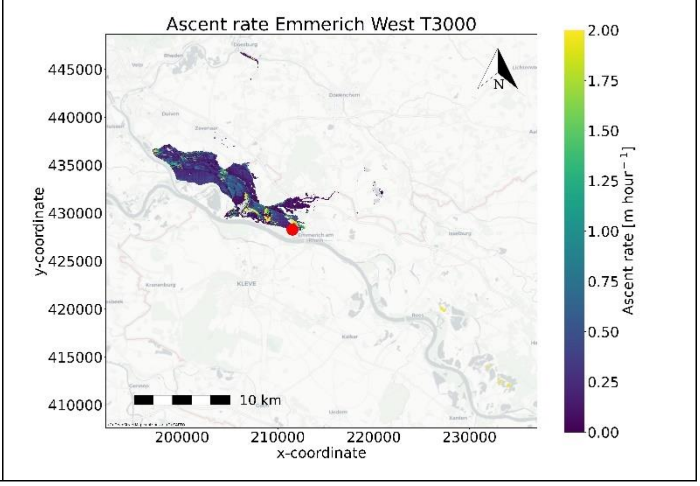
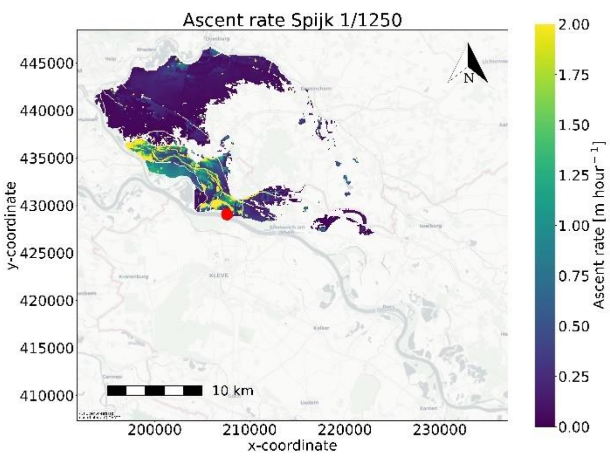
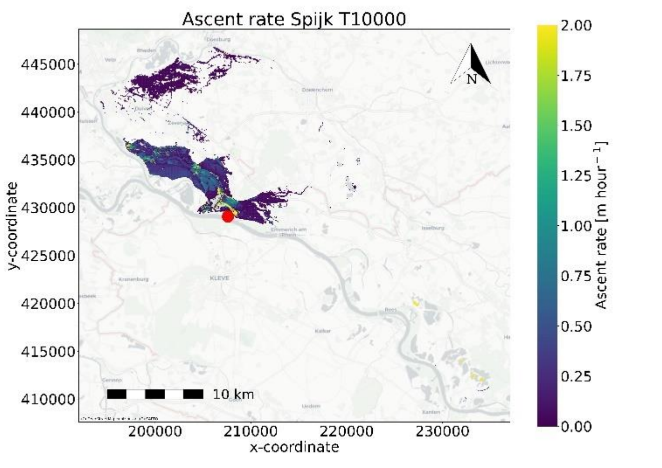
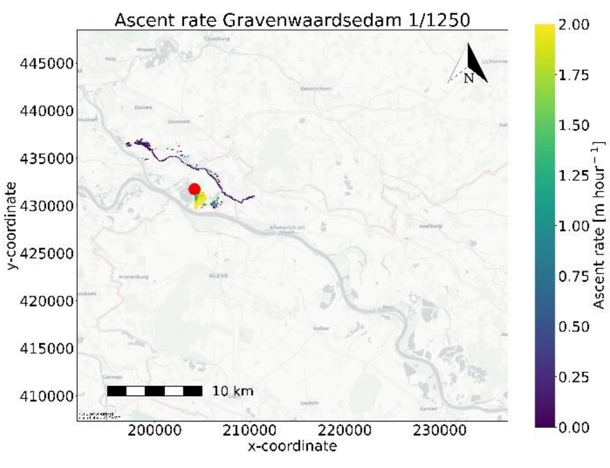
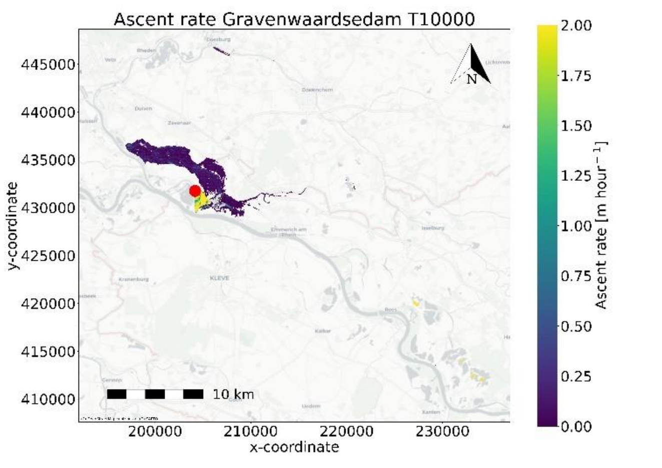
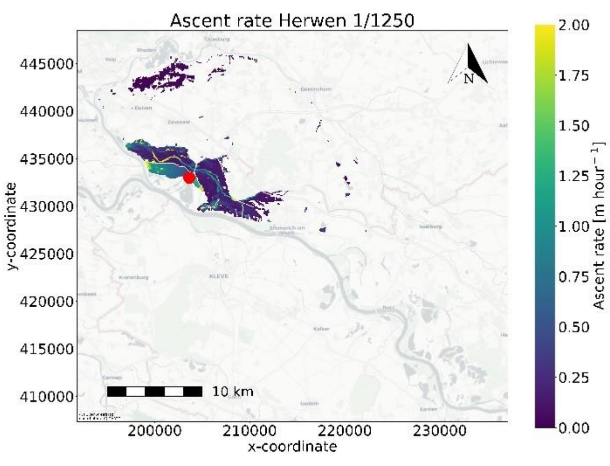
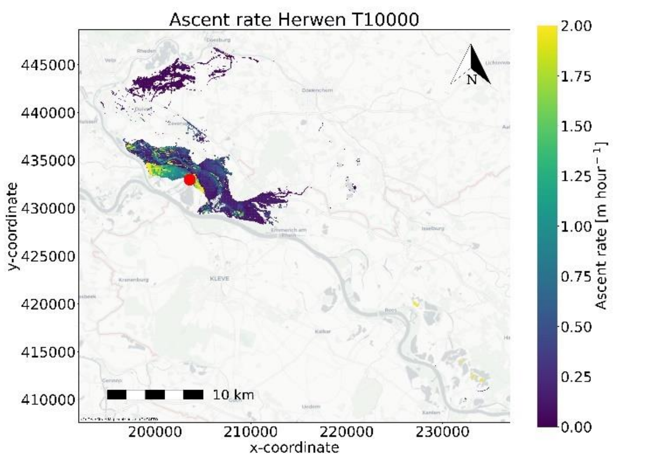
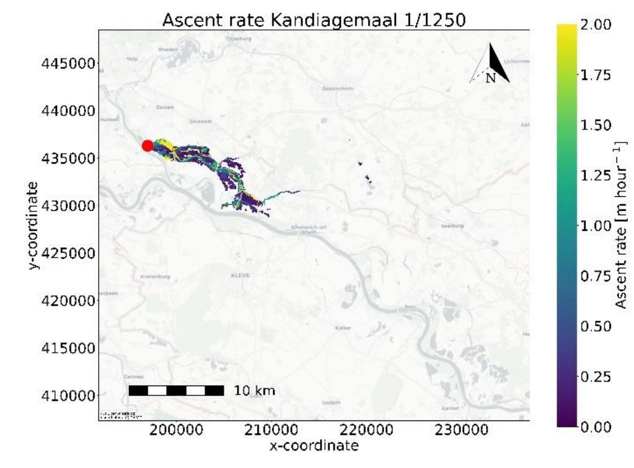
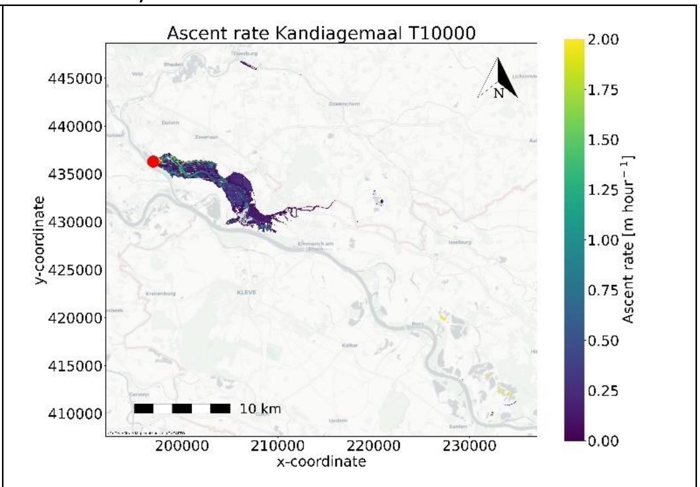
Rees Rosau		
Emmerich Stadtweide		
Emmerich West		

Spijk		
Gravenwaardse dam		
Herwen		

Kandiagemaal





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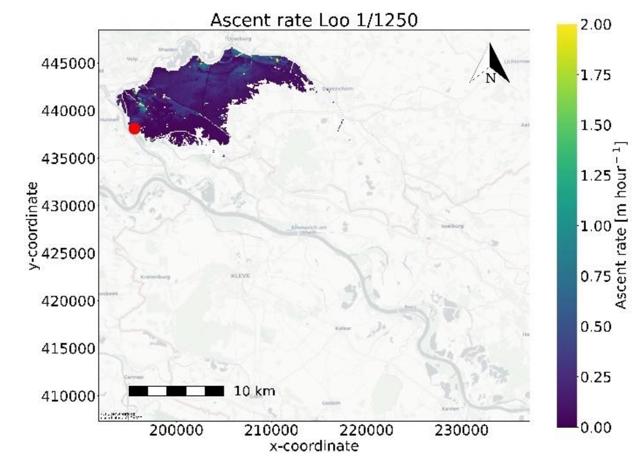
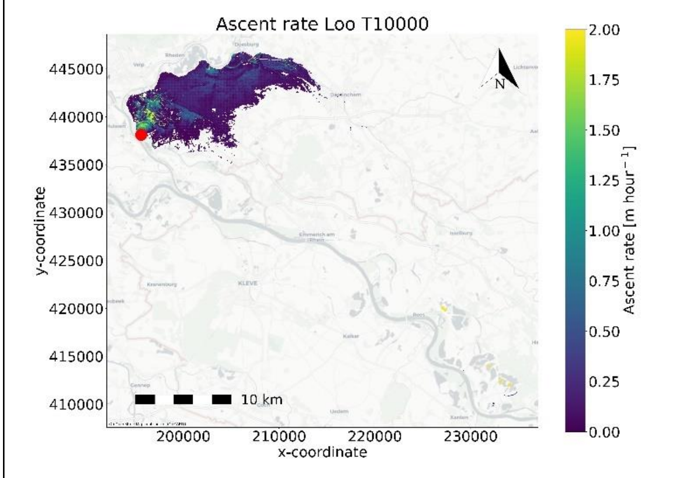
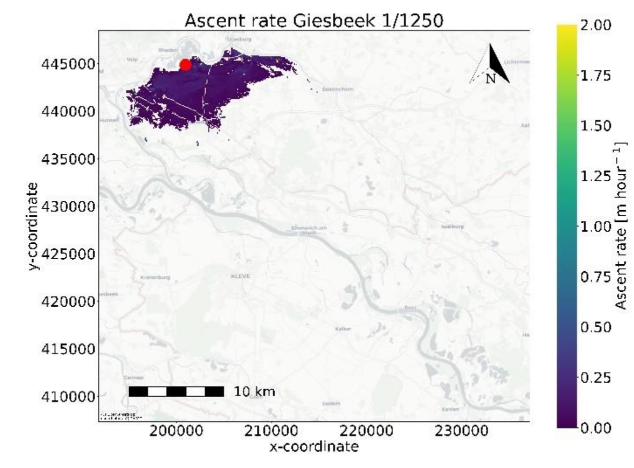
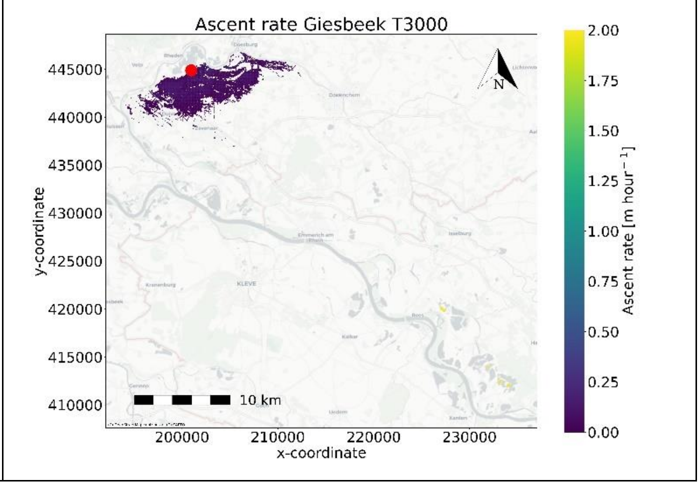




Giesbeek





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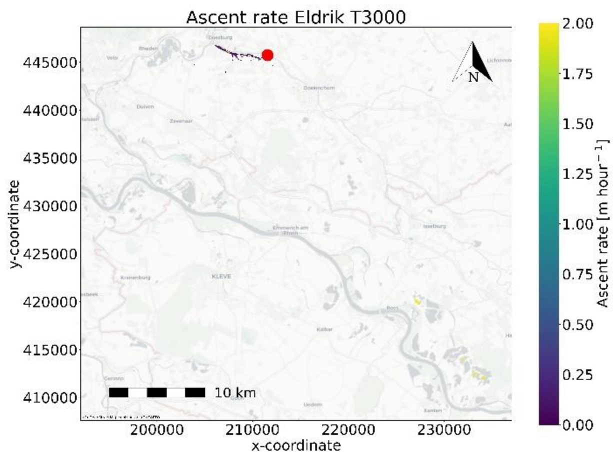
<tr><td>Eldrik</td><td>Not available</td><td>
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Table F-2 - Computed maximum flow velocity for DelftFLS and D-Hydro for the above normative scenario (breach locations are indicated with a black dot)

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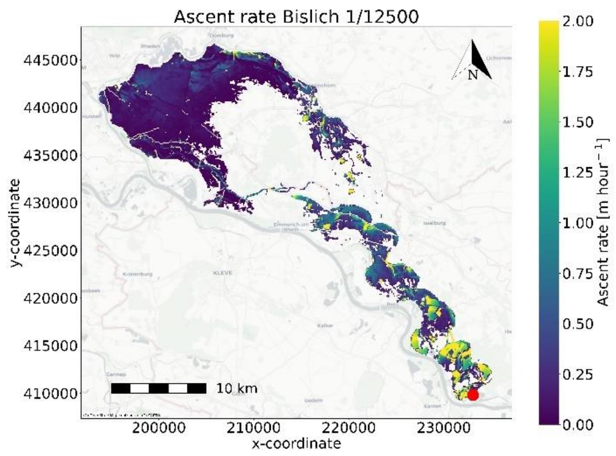
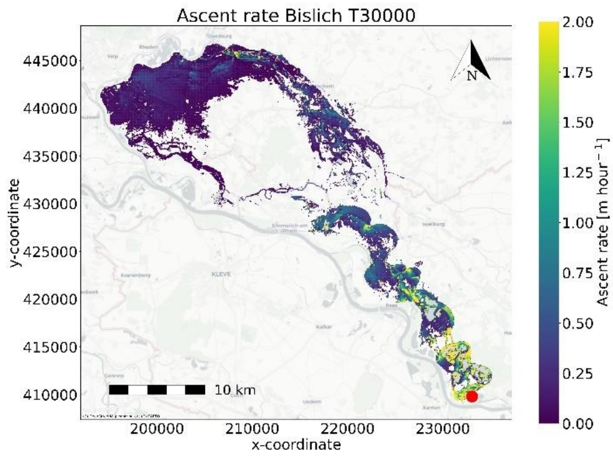
<tr><td>Bislich</td><td>
</td><td>
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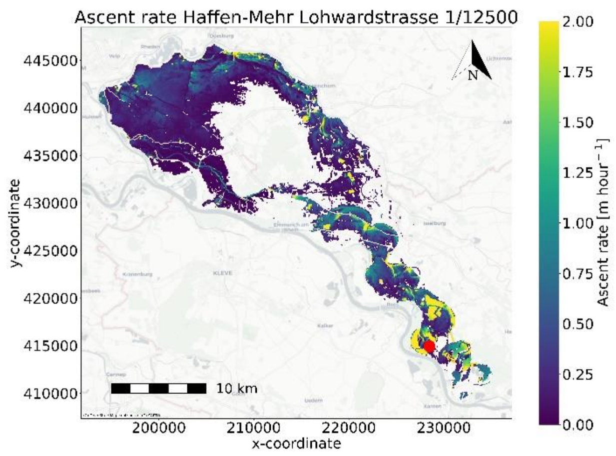
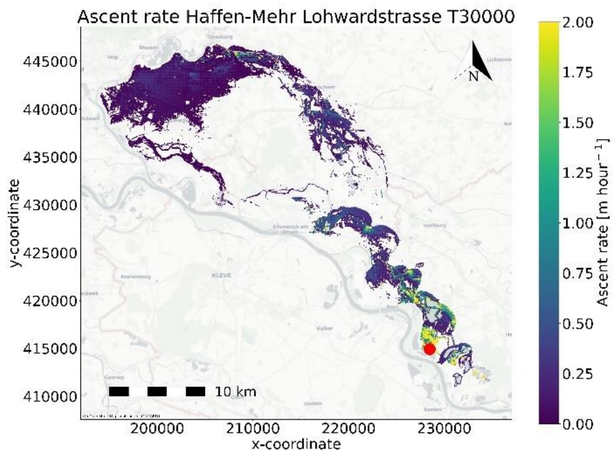
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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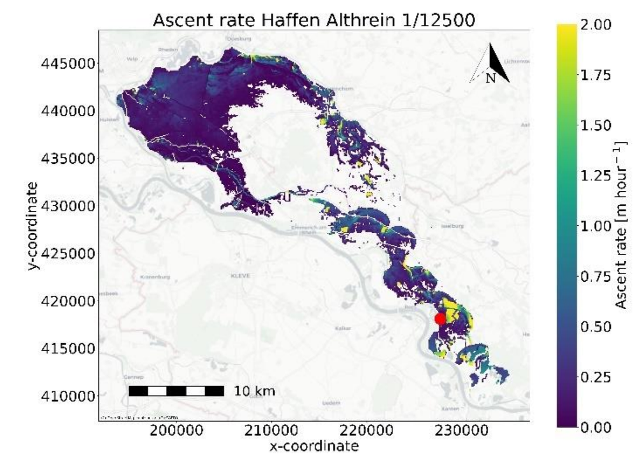
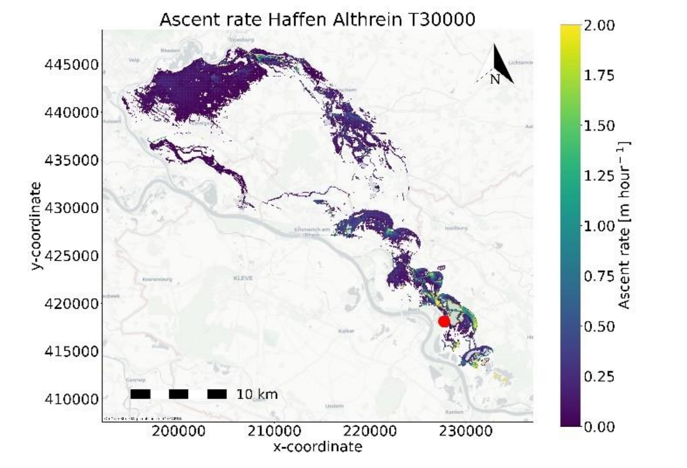
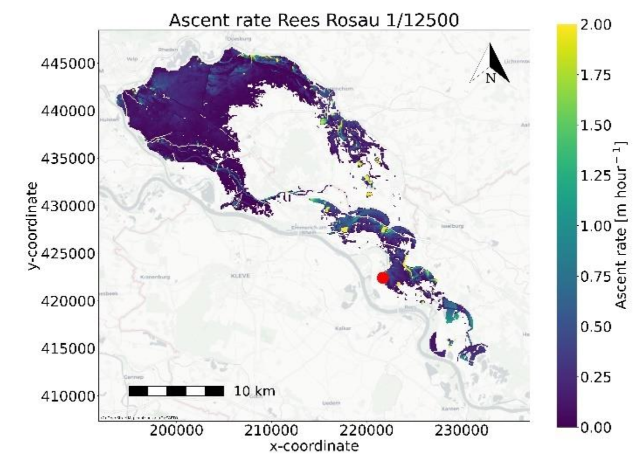
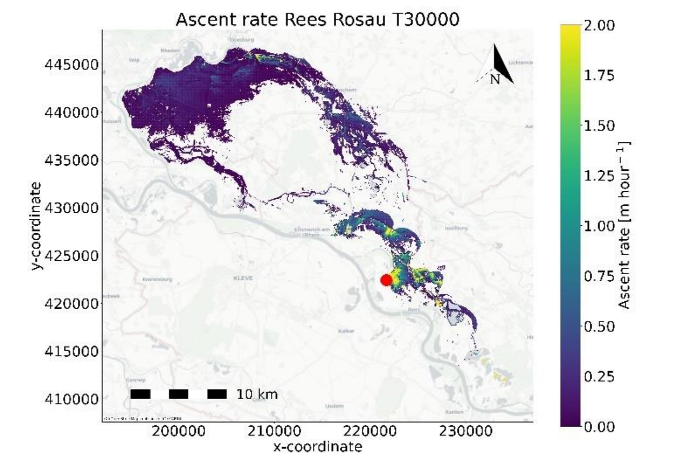
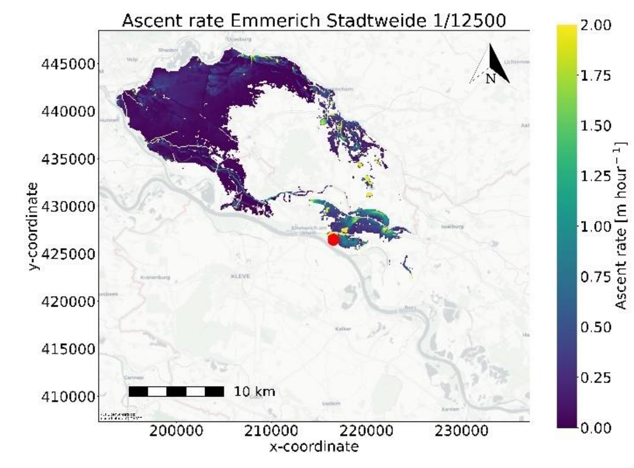
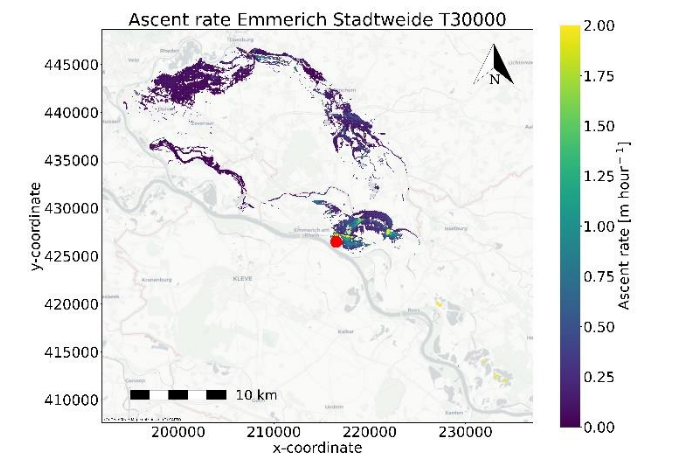
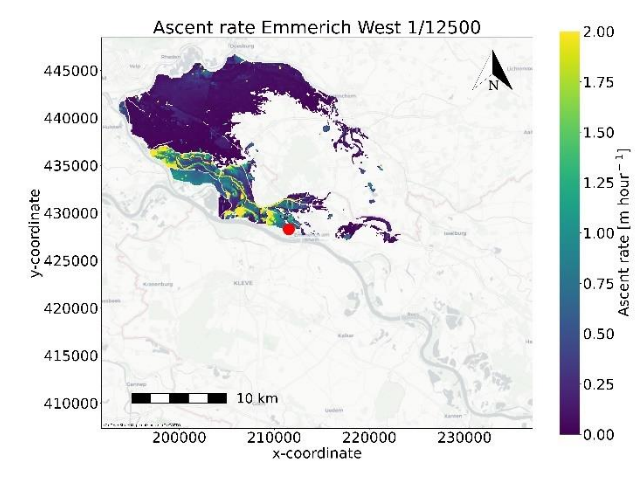
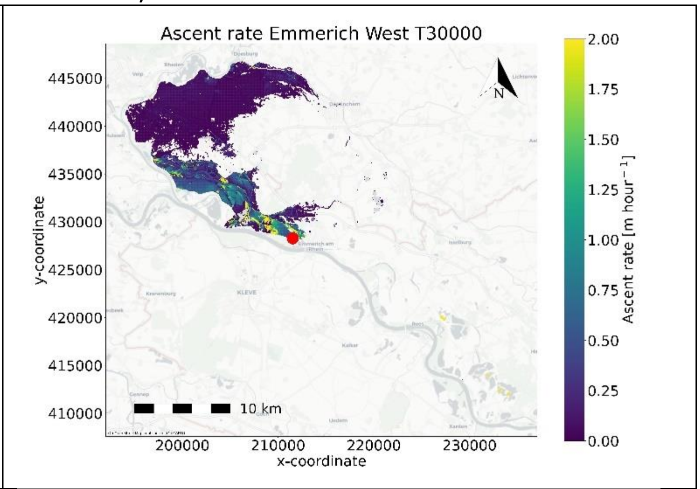
Haffen Althrein		
Rees Rosau		
Emmerich Stadtweide		

Emmerich West





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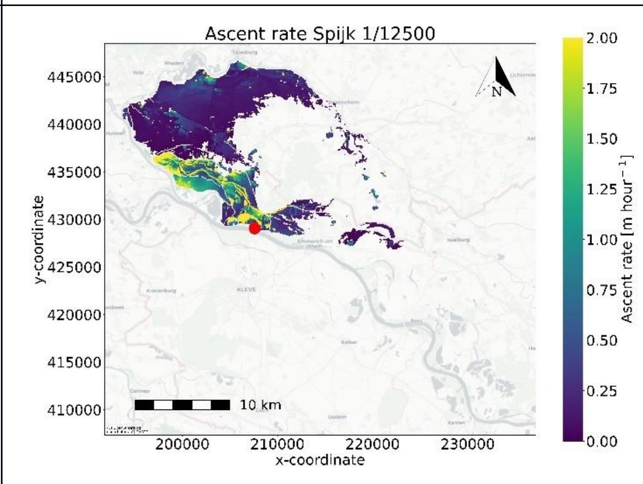
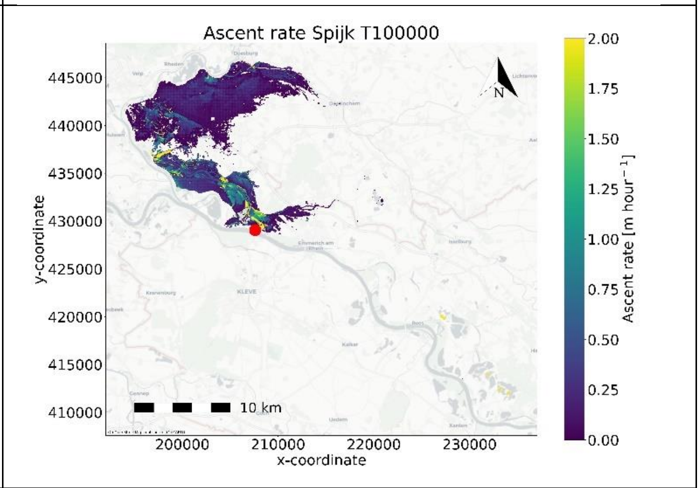
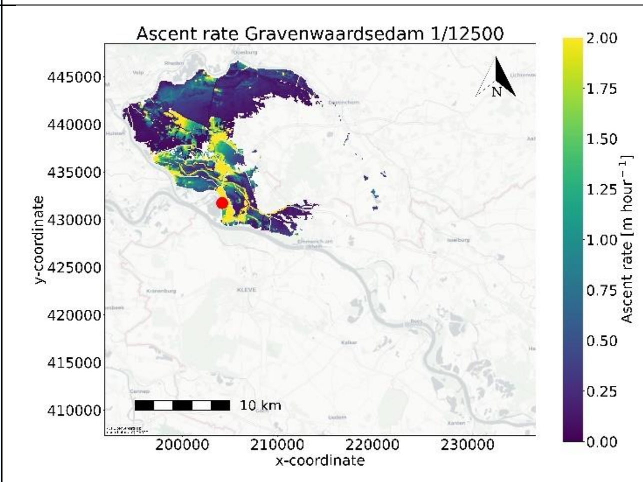
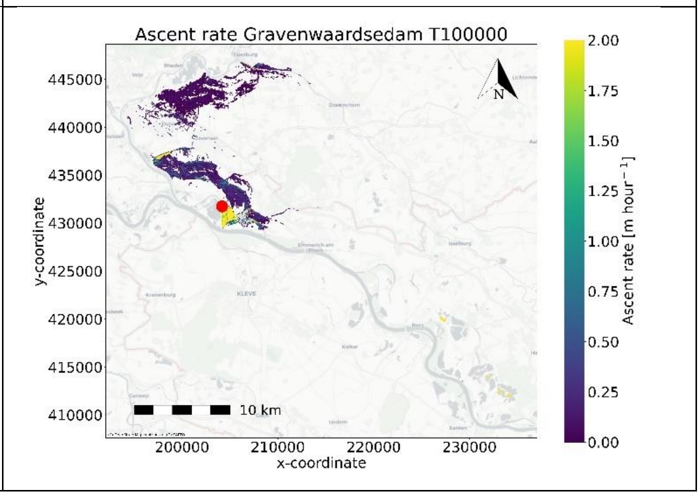
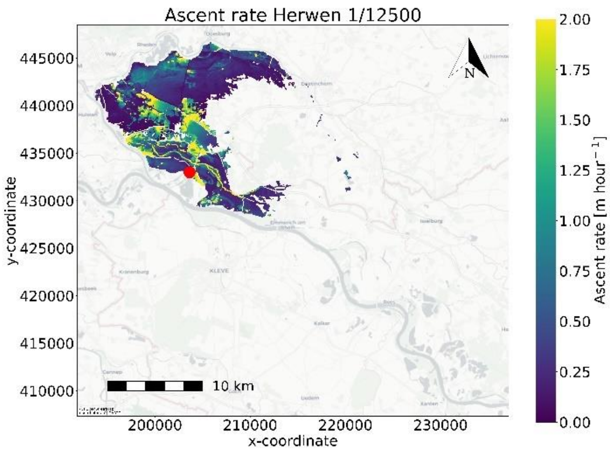
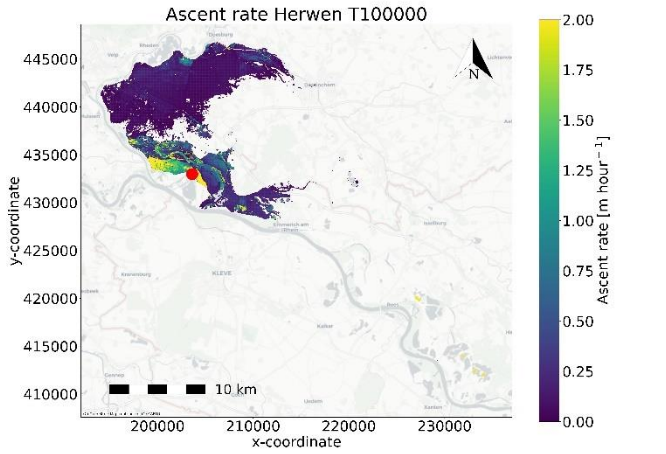
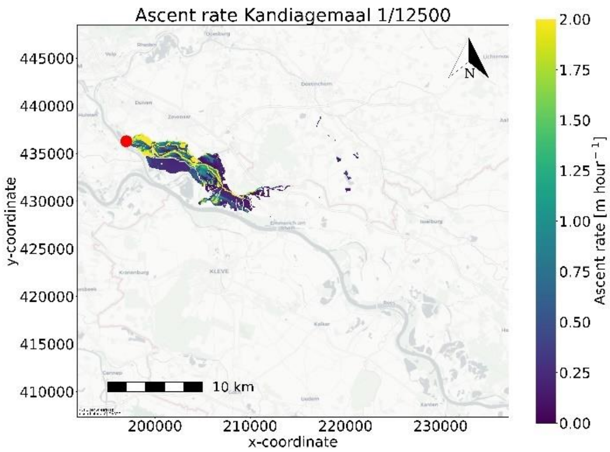
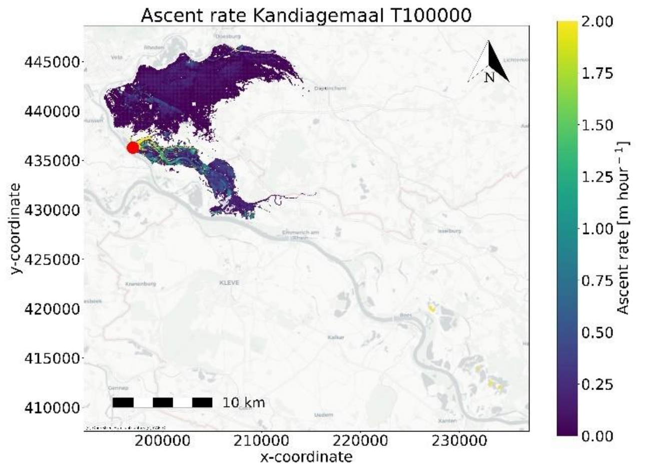
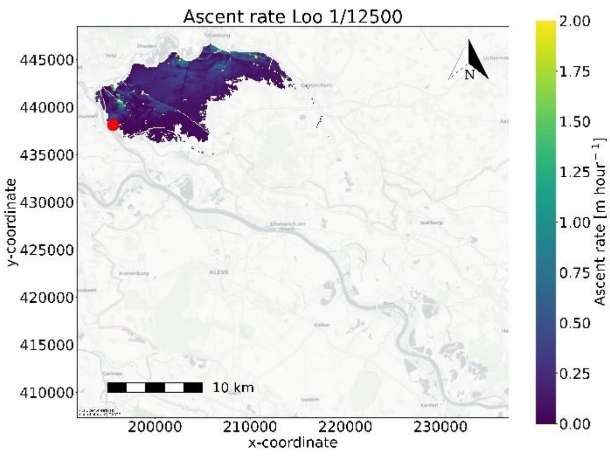
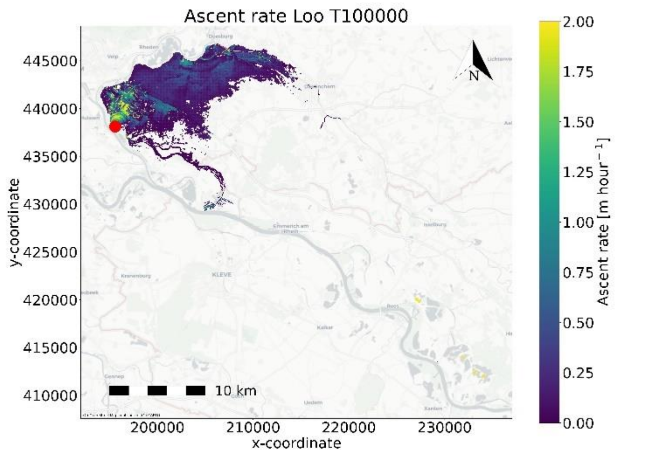


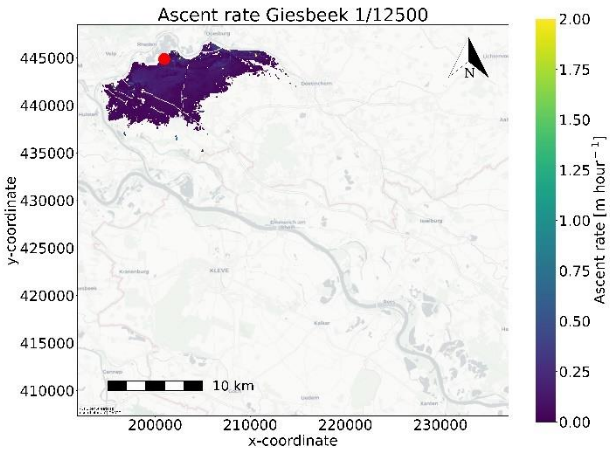
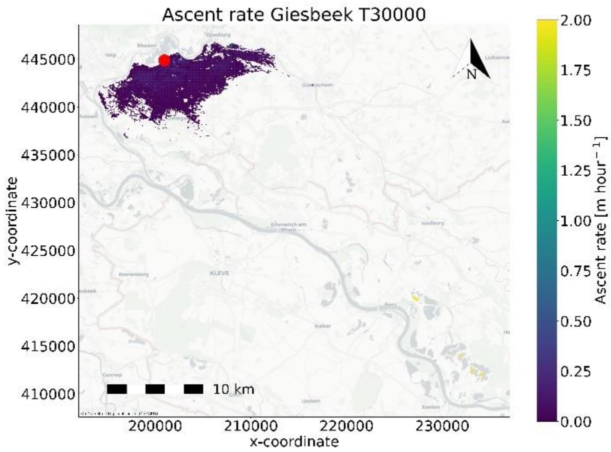
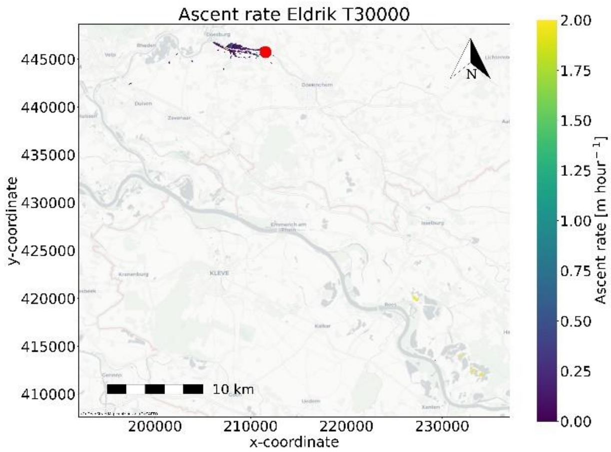


Gravenwaardse dam





Herwen		
Kandiagemaal		
Loo		

Giesbeek		
Eldrik	Not available	

Appendix G – Boundary conditions flood simulations

Table G-1 - Boundary conditions flood simulations above normative scenario

Norm segment	Breach location	Total breach volume [10^8 m^3]		Peak breach flow [m^3s^{-1}]		Maximum width breach [m]	
		DelftFLS	D-HYDRO	DelftFLS	D-Hydro	DelftFLS	D-Hydro
48-0	Bislich	9.586	9.390	3270	2287	210.00	110.14
48-0	Haffen-Mehr Lohwardstrasse	6.522	6.865	3537	1787	210.00	161.38
48-0	Haffen Althrein	4.965	5.770	2726	1418	210.00	161.71
48-0	Rees Rosau	3.803	8.852	2388	2075	210.00	144.26
48-0	Emmerich Stadtweide	1.543	4.230	1004	1084	210.00	132.12
48-0	Emmerich West	2.742	4.632	2475	1449	210.00	149.33
48-1	Spijk	No data	4.217	3285	1242	210.00	78.90
48-1	Gravenwaardse dam	1.864	1.473	2163	1090	210.00	59.34
48-1	Herwen	1.848	5.059	1998	1750	210.00	102.17
48-1	Kandiagemaal	No data	4.190	1426	920.0	210.00	131.29
48-1	Loo	9.302	9.144	1904	1655	210.00	130.72
48-2	Giesbeek	2.166	2.429	1051	561.1	210.00	106.34
48-3	Eldrik	-	0.149	-	70.99	-	31.31

Appendix H – Elaboration expert elicitation

Appendix H-1 Expert 1

Achtergrond expert

De expert is werkzaam op wateroverlast en droogte projecten, momenteel voornamelijk in het buitenland. Wat betreft wateroverlast gaat dit vooral over wateroverlast ten gevolge van (extreme) neerslag. Hij brengt met name technische kennis door middel van het opzetten van modellen en het analyseren van maatregelen (m.b.v. deze modellen). De expert geeft aan beperkte kennis te hebben van het Nederlandse normeringsproces en dijkversterkingsprojecten.

De expert heeft bijgedragen aan het opzetten van het D-Hydro model van het studiegebied dat in dit onderzoek wordt gebruikt. Daarnaast is hij ook opgegroeid in het gebied, dus kent met name het Nederlandse gedeelte van de dijkring redelijk goed.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

Het is sowieso van belang om in de strategie voor het reduceren van overstromingsrisico gevolg beperkende maatregelen te nemen, zodat effecten minder catastropisch zijn in het geval dat de kleine kans op dijkdoorbraak toch plaats vind. Maar dijken blijven we nodig hebben en deze zijn vaak ook erg kostenefficient, omdat met een meter ophoging het overstromingsrisico gelijk met een factor 10 omlaag gaat. Daarnaast vereist het implementeren van groot schalige maatregelen m.b.t. ruimtelijke inrichting vaak meer participatie van bewoners, vergeleken met dijkversterking. Wel is er in water overlast projecten steeds meer oog voor een intergrale aanpak, waarbij ook landschapsinrichting een belangrijk onderwerp is.

Geschikte locaties voor de ruimtelijke maatregelen

Tijdens het interview is er vooral samen met de expert gekeken naar of de voorafbedachte locaties geschikt zouden zijn en is er minder initatief vanuit de expert gekomen voor het zelf aanwijzen van alternatieve locaties.

Met name in het rijnstrangengebied zijn een aantal delen die tussen secundaire keringen liggen waar weinig mensen wonen en de economische waarde laag is. Deze gebieden zouden goed gebruikt kunnen worden om overtollig water te stallen. In de gebieden waar wel veel bebouwing is zou dit water juist sneller weg moeten stromen.

Daarnaast is het belangrijk dat de steden Westervoort, Duiven en Zevenaar zoveel mogelijk beschermd worden tegen economisch risico en slachtoffers. Dit zou kunnen door middel van een compartimenteringsdijk om deze steden heen te leggen, of door middel van het ophogen van de A12. Het ophogen van de A12 is met name nuttig voor doorbraak locaties in Duitsland en doorbraken op de Ijssel en de Oude Ijssel. De expert geeft aan dat er in dit alternatief aandacht behoeft aan of, afhankelijk van de doorbraak locatie, aan de andere kant van de A12 het risico niet substantieel verhoogd. De expert verwacht dat schade en slachtoffers niet veel zullen toenemen aangezien waterdieptes in eerste instantie vaak al enkele meters zijn. Een ander alternatief is het afsluiten van dit gebied bij Montfoort land door middel van een compartimenenteringsdijk. Hierbij moet er wel opgelet worden dat het water niet nog sneller naar de Oude Ijssel stroomt en daardoor schade bij Doetichem substantieel vergroot.

Verder is het beschermen van kritieke infrastructuur ook een goede manier om schade te verminderen. In het geval van kritieke infrastructuur is dit zowel voor directe schade als schade ten gevolge van bedrijfsuitval. Met name de betuwelijn is erg belangrijk, omdat het een belangrijke schakel is in het goederen vervoer van de haven van Rotterdam naar Duitsland.

De expert heeft aangegeven locaties in omstreken van Doetichem minder geschikt te vinden voor het implementeren van maatregelen, omdat aankomsstijden hier ongeveer twee dagen zijn. De expert vraagt zich daarom af of het nog daadwerkelijk toevoeging heeft dit water langer te vertragen.

Beoordeling ruimtelijke maatregelen

In tabel H-1 wordt een overzicht gegeven van de scores die de expert heeft gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-1 - Beoordeling ruimtelijke maatregelen expert 1

Ruimtelijke maatregel	Cijfer	Uitleg
Tijdelijke overstromingskeringen	5	Relatief kleine investering, daarom zou het al snel kosten efficient kunnen zijn. Belangrijk hierbij is wel dat er inderdaad geschikte locaties zijn om deze maatregel toe te passen.
Decompartimenteren	4	Decompartimenteren kan zorgen voor minder snelle opvulling van het rijnstrangen gebied. Het weghalen van een dijk is vergeleken met het toevoegen van een dijk ook eenvoudiger.
Compartimenteren	3	Uit andere studies is gebleken dat compartimenteren vaak effectief kan zijn. Zeker het verhogen van lijnelementen zou kansrijk kunnen zijn, omdat dan niet een volledig nieuwe dijk aangelegd hoeft te worden. Daarnaast zou er ook gekeken kunnen worden naar het beschermen van kritieke infrastructuur door middel van een compartimenteringsdijk.
Beïnvloeden ruwheid	3	Het aanleggen van hagen langs de watergangen zou water kunnen vertragen met een lichte kerende functie. Dit is een relatief kleine maatregel, dus zal ook snel kosten efficient zijn. Mocht een groot schaliger gebied nodig zijn om overstromingsrisico substantieel te verminderen, zoals het aanleggen van een stuk bos, dan is dat waarschijnlijk lastiger te implementeren. De expert geeft aan het lastig in te schatten te vinden op hoe grote schaal deze maatregel toegepast moet worden om invloed te hebben op het overstromingsrisico.
Preventieve dijkdoorbraak	2	Dit kan een goede maatregel zijn om piekafvoer te verlagen en zo te zorgen dat de dijk niet op een andere locatie door breekt. Het rijnstrangen gebied biedt hier ook voldoende ruimte voor, omdat er best wat lege delen zijn.
Overstromingsbestendig bouwen	2	Deze maatregel is vooral effectief in gebieden met wisselende hoogte. In dit studiegebied is het hele noordelijke gebied laag gelegen en hierom zal het waarschijnlijk niet zoveel verschil maken. Waterdieptes zijn daar vaak hoger dan 2 meter en daarom is overstromingsbestendig bouwen in dit gebied vaak niet effectief. Je zou wel kunnen nadenken over bouwen op palen en op de onderste verdieping alleen functies met lage economische waarde toestaan, zoals parkeren.
Risico zonering	1	Het gebeurt op dit moment dat er veel gebouwd wordt op plekken die kijkend naar het overstromingsrisico niet handig zijn. Deze maatregel zou vooral voor nieuwe bebouwing daarom wel kansrijk zijn. De praktische haalbaarheid van deze maatregel wordt alleen als heel laag geschat, omdat het herbestemmen van huidige bebouwing praktisch uitvoerbaar als zeer uitdagend wordt ervaren en er weinig beschikbaar

		gebied is in het Nederlandse deel van het studiegebied waar het overstromingsrisico laag is.
Drainage kanalen	0	Het bresdebiet is zo groot dat het toevoegen van drainage kanalen waarschijnlijk weinig uit zal maken. Ook retentie gebieden zouden van substantiele grootte moeten zijn om iets bij te dragen aan reductie van de water diepte. Hierom worden drainage kanalen als niet wenselijk bevonden.

Appendix H-2 Expert 2

Achtergrond expert

De expert heeft van origine een achtergrond als chemisch technoloog en heeft hierdoor veel ervaring opgedaan met risico benadering in de externe veiligheidssector. Ten tijde dat de Nederlandse normering het meest recent is aangepast was er behoefte aan kennis vanuit risico benadering, omdat er een wens was om het risico van mensen beter in de normering te verwerken. De expert is hierbij betrokken geweest en heeft daarmee de overstap naar de waterwereld gemaakt.

De expert heeft bijgedragen aan meerdere studies in dijkring 48 en geeft aan hierdoor nog veel gebiedskennis te hebben en een goed beeld van de overstromingssommen gemaakt met DelftFLS.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

Een aantal jaar geleden is het principe meerlaagse veiligheid geïntroduceerd met het idee dat maatregelen in de tweede en derde laag als vervanging voor dijkversterking kunnen gaan dienen. In werkelijkheid zal dijkversterking waarschijnlijk altijd meer kosten efficient zijn en meer draagvlak hebben bij bewoners. Hierom zullen we maatregelen in de tweede en derde laag dus meer moeten gaan zien als aanvulling op dijkversterking. Dit komt met name door de hoge normen die Nederland gesteld heeft. In het geval dat de normeringen in de orde grootte 1/10 jaar of 1/100 waren geweest, zouden meerlaagseveiligheidsmaatregelen misschien efficiënter zijn.

Geschikte locaties voor de ruimtelijke maatregelen

In veel overstromingsscenario's zijn waterdieptes in het noorden van het studiegebied van dusdanige mate dat de meeste maatregelen waarschijnlijk niet effectief zijn. Om te voorkomen dat dit gebied onder water komt te staan zou er nagedacht kunnen worden om compartimenteringsdijken zo te plaatsen dat water uit Duitsland zo erg vertraagd wordt dat hier minimale waterdieptes komen te staan. Volgens de expert kun je compartimenteren op de grens politiek gezien niet doen en mag dat vanuit de Europese richtlijnen ook niet. Het zou interessant kunnen zijn om aan de onderkant voor Montfoortland een compartimenteringsdijk te plaatsen om zo het Rijnstrangen gebied te beschermen. Daarnaast zou er gekeken kunnen worden om van de A18 een compartimenteringsdijk te maken om de meeste waardevolle delen van het gebied te beschermen. Daarnaast zouden mensen ook makkelijker uit het gebied kunnen komen omdat de A18 dan als evacuatieroute kan dienen. In het geval dat waterdieptes te overzien zijn rondom deze snelweg zou er ook nagedacht kunnen worden over noodmaatregelen, hierbij moet wel rekening gehouden worden met dat het relatief veel tijd kost om een lang stuk weg te verstevigen. De expert geeft aan dat voor overstromingsrisico's de A12 verhoogd aanleggen een hele effectieve maatregel zou kunnen zijn, maar dat dit praktisch gezien waarschijnlijk niet wenselijk is vanwege de hoge kosten en de geluidsoverlast die het zou veroorzaken. De expert geeft verder aan dat bij het verhoogd aanleggen van wegen er ook goed gekeken moet worden naar het aantal onderdoorgangen dat in een dergelijk scenario afgesloten zou moeten worden. De dijken langs de oude rijn zouden ook nog verstevigd kunnen worden, met het doel om de steden te ontlasten. Op dit moment zijn die dijken niet sterk genoeg om in alle scenario's het water tegen te houden. Als tijdelijke overstromingskeringen worden ingezet als compartimenteringsmaatregel, dan is hiervoor de meest geschikte locatie waarschijnlijk de zuidkant van Montfoortland, omdat dit het water uit Duitsland in veel gevallen tegen houd en het om maar elke honderden meters gaat. De expert geeft aan dat qua praktische implementatie de maatregel niet altijd haalbaar zal zijn in de ander genoemde locaties geschikt voor compartimenteringsmaatregelen.

Op dit moment is het grootste deel van de bebowing gepositioneerd in het laagste deel van het gebied. Omdat dit resulteert in grote waterdieptes in het geval van een overstroming zal overstromingsbestendig bouwen in deze locatie niet zinvol zijn. Wanneer je naar risicozonering kijkt zou het gunstiger zijn om te gaan wonen op Montfoortland, of meer in het oosten van het gebied omdat hier weinig tot geen overstromingsrisico is.

Een preventieve dijkdoorbraak wil je alleen doen in een gebied wat relatief leeg is en waar weinig mensen wonen. Binnen het studiegebied kan het Rijnstrangengebied zich hier goed voor lenen. Belangrijk is wel dat dan de mensen die in dit gebied wonen geheralloceert worden of eventueel geevacueerd wanneer nodig.

Beoordeling ruimtelijke maatregelen

In tabel H-2 wordt een overzicht gegeven van de scores die de expert heeft gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-2 - Beoordeling ruimtelijke maatregelen expert 2

Ruimtelijke maatregel	Cijfer	Uitleg
Tijdelijke overstromingskeringen	5	Wanneer deze maatregel geïmplementeerd wordt aan de zuid zijde van de Eltenberg is dit een hele kosten efficiente maatregel, met name omdat dit stuk niet zo breed is en er dus weinig middelen nodig zijn. Op andere locaties zou het ook heel interessant kunnen zijn als middel om het water te vertragen en zo de evacuatietijden te vergroten.
Compartimenteren	3	Deze maatregel is relatief effectief in het beïnvloeden van de overstromingspatronen en dus de impact van de overstroming. Een nadeel van deze maatregel is wel dat de kosten relatief hoog zijn. Daarnaast is het belangrijk vanuit politieke overwegingen en Europese richtlijnen om rekening te houden met in welke mate er risico wordt overgedragen van het Nederlandse deel van de dijkring naar het Duitse deel van de dijkring.
Risico zonering	3	Dit kan zeker effectief zijn, met name voor nieuwe bebouwing. Uitbreiding van de steden Westervoort, Duiven en Zevenaar zou vanuit een overstromingsperspectief bijvoorbeeld niet handig zijn. In het geval van een nieuwbouw wijk zou je deze vanuit overstromingsrisico gezien beter kunnen plaatsen in het oosten van het gebied. Landelijk wordt het begrip ‘bodem en water sturend’ steeds vaker gebruikt. Dit houd in dat in een gebiedsopgave de focus meer moet gaan liggen op het watersysteem, in plaats van alleen economische overwegingen. In lijn met dit actuele thema zou deze maatregel dus geschikt zijn.
Preventieve dijkdoorbraak	2	Een voordeel van deze maatregel is dat de druk op het watersysteem en dus het overstromingsrisico in de rest van Nederland verlaagd. Voor het gebied zelf zal het de schade waarschijnlijk niet verminderen omdat de doorbraken bovenstrooms de meeste schade opleveren.
Overstromingsbestendig bouwen	1	Deze maatregel is met name effectief voor gebieden met lage waterdieptes. In het studiegebied staat in veel overstromingsscenario’s het water in de steden enkele meters hoog en hierdoor zal deze maatregel daar weinig tot geen effect hebben. Tot een waterdiepte van 1.5 meter zou het nog kunnen keren, maar zelfs dan wordt het al erg prijzig. De maatregel zou in andere studiegebieden, zoals polders of

		andere dijkringen met lagere waterstanden wel effectief kunnen zijn.
Decompartimenteren	1	Algemeen gezien zou dit een nuttige maatregel kunnen zijn, maar het gebied leent zich niet voor deze maatregel.
Beïnvloeden ruwheid	0	De expert geeft aan dat het beïnvloeden van de ruwheid minimaal tot geen effect zal hebben op de overstromingspatronen. Vegetatie zou wel kunnen helpen in de eerste laag, door de hydraulische belasting te verlagen door het beïnvloeden van de ruwheid in de uiterwaarden.
Drainage kanalen	0	Maatregelen zoals drainage kanalen, kleine retentie gebieden en waterpleinen zijn volgens de expert vooral nuttig voor het mitigeren van overlast veroorzaakt door neerslag. Voor overstromingen zijn deze maatregelen qua bergingscapaciteit niet toereikend genoeg. Bresdebieten en waterdieptes zijn van dusmate grootte dat drainage kanalen niet gaan helpen in dit studiegebied. In polders zouden drainage kanalen mogelijk wel overstromingsrisico kunnen verkleinen. In een polder zou dit wel kansrijk kunnen zijn.
Toevoeging expert:		
Shelters	4	Het is belangrijk dat er genoeg droge plekken in het gebied zijn waar mensen heen kunnen evacueren. Het liefst is dit een droge verdieping bij mensen thuis, zodat ze niet weg hoeven. Als er in het gebied te weinig droge plekken zijn zou de meerderheid van de nieuwbouw een droge plek moeten hebben.

Appendix H-3 Expert 3 & 4

Expert 3 en expert 4 zijn samen geïntervieuwd en daarom is de uitwerking van de bevindingen van de experts samengevoegd. Beide experts hebben wel afzonderlijk een ranking gegeven van de verschillende maatregelen.

Achtergrond experts

Beide experts zijn werkzaam binnen het hoogwaterbeschermingsprogramma (HWBP), maar hebben een verschillende functie en achtergrond. Het HWBP is een uitvoeringsprogramma dat de subsidie verstrekt voor de dijkversterkingen die door de waterschappen worden voorbereid. De rol die ze hierin uitvoeren is het subsidiëren van dijkversterking, een programma maken waarin staat wanneer gesubsidieerd kan worden en het verantwoorden en faciliteren van deze projecten.

Expert 3 is innovatiecoordinator bij het hoogwaterbeschermingsprogramma en geeft aan binnen deze functie bezig te zijn met In welke mate waterschappen gevolgbeperkende maatregelen overwegen om de overstromingsrisicos voldoende klein te krijgen in Nederland. In het verleden heeft de expert ook aan overstromingsrisicobeheer en ruimte voor de rivier gewerkt. De expert geeft aan geen specifieke gebiedskennis te hebben maar is bekend met het riviersysteem van het studiegebied, vanwege betrokkenheid bij een eerdere studie naar een ruimte voor de rivier project met betrekking to de splitsingspunten van de Rijn. Verder is de expert betrokken geweest bij het deltaprogramma en de ontwikkeling van de nieuwe normering. De expert geeft aan vanuit haar beleidstijd ook in zekere mate bekend te zijn met risicobeperkende maatregelen.

Expert 4 is programmabegeleider voor waterschappen, waaronder ook waterschap Rijn & Ijssel, het waterschap wat verantwoordelijk is voor het studiegebied (dijkring 48). De expert heeft een studie civiele techniek gevolgd en hierdoor van origine een achtergrond als waterbouwer, maar heeft ook veel afiniteit en ervaring met sociale interactie tussen verschillende partijen. Verder is het binnen zijn huidige rol belangrijk om vanuit projectmanagement te kijken welke oplossingen passend zijn voor opdrachtgevers.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

Expert 3 geeft aan dat op dit moment in Nederland er voornamelijk gestuurt wordt op dijkversterking, omdat dit met een ingreep in een klein gebied (de dijk), gelijk een groot gebied beschermd wordt. Daarnaast is het gevoel van rechtvaardigheid een belangrijk aandachtspunt. Bij het vormen van de nieuwe normeringen is er wel discussie geweest of de normering weer vastgelegd moest worden op de dijk, omdat in praktijk daar de focus dan ook op blijft liggen. Echter is er wel bewust voor gekozen omdat wanneer de normering gelegd wordt op het risico in plaats van expliciet op de dijk er geen duidelijke verantwoordelijkheid ligt bij betrokken partijen, zoals gemeentes, waterschappen, provincie en particulieren, om het overstromingsrisico te waarborgen. Ook moet er bij risico beperkende maatregelen meer nagedacht worden over hoe die maatregelen in de tweede en derde laag in stand blijven. De expert geeft aan dat het daarom wenselijk is om de dijk als uitgangspunt te nemen, ook omdat dit volgens de expert vaak de meest efficiente oplossing is, maar wel die slimme combinaties mogelijk moet maken. De expert geeft aan dat gevolgenbeperking vaak wel moeilijker te implementeren is dan dijkversterking. In de toekomst zal er waarschijnlijk wel een omslagpunt komen waarin dijkversterking in sommige gevallen heel lastig wordt. De expert geeft aan dat bepaalde factoren het aantrekkelijker kunnen maken om gevolgbeperkende maatregelen toe te passen, bijvoorbeeld wanneer het overstromingsrisico ook afhankelijk is van andere factoren dan de Nederlandse normering (zoals de sterkte van de dijken en Duitsland) of als absolute gevolgen relatief klein zijn.

Expert 4 geeft aan dat het HWBP geen meerlaagseveiligheid kan financieren, ze zijn alleen bevoegd om dijkversterking te financieren. Zelfs voor alternatieve maatregelen in laag 1, zoals rivierveruimende maatregelen hebben ze niet de financieringsbevoegdheid. De financiering mag wel uit de dijkrekening (dezelfde voorziening als de financiering voor dijkversterking) worden gehaald, mits het doelmatig is, maar dit soort projecten loopt via het ministerie. De expert geeft aan dat het soms als een beperking wordt ervaren dat het HWBP alleen financiering kan verstrekken voor dijkversterking. Wanneer een meer intergrale scope van toepassing zou zijn van de financiering, dan worden gevolgbeperkende maatregelen waarschijnlijk eerder meegenomen door waterschappen als maatregel om overstromingsrisico te verminderen. De verwachting is wel dat in die alliantiebesprekeningen met het ministerie er waarschijnlijk in de toekomst vraag komt om in overleg met waterschappen al in een vroeg stadium ook gevolgbeperkende maatregelen te overwegen, omdat een aantal dijkversterkingen ook erg prijzig aan het worden zijn.

Geschikte locaties voor de ruimtelijke maatregelen

Expert 3 geeft aan dat in gebieden waar weinig mensen wonen, zoals het Rijnstrangen gebied, overstromingsbestendig bouwen kansrijk zou kunnen zijn. Voor gebieden die dichtbevolkter zijn zou het beschermen van deze kernen door middel van compartimentering kansrijk kunnen zijn. De expert geeft aan dat het gebruiken van de A12 als kerend element om de overstromingsrisico's te verminderen heel efficient zou kunnen zijn, omdat op die manier het grootste gedeelte van het risico, dat geloceert is in de plaatsen Westervoort, Duiven en Zevenaar verminderd wordt. Dit zou vooral interessant kunnen zijn voor doorbraaklocaties waar het water vanuit het noorden naar de steden stroomt. Een andere compartimenteringsmaatregel zou zijn om een dijk om deze steden te bouwen en de natuur in de rest van het gebied meer zijn gang laten gaan, door middel van een meer dynamisch systeem, waarin de steden beschermd blijven maar het meer landelijk gebied als waterbuffer kan functioneren.

Expert 4 geeft aan te beperkte specifieke gebiedskennis te hebben om gedetailleerde locaties voor de ruimtelijke maatregelen aan te wijzen. Wel geeft de expert aan dat grote delen van het studiegebied dunbevolkt zijn en deze zich goed zouden lenen voor waterbergingsmaatregelen.

Beoordeling ruimtelijke maatregelen

In tabel H-3 en tabel H-4 wordt een overzicht gegeven van de scores die de experts hebben gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-3 - Beoordeling ruimtelijke maatregelen expert 3

Ruimtelijke maatregel	Cijfer	Uitleg
Risico zonering	5	De expert ziet mogelijkheden in het meer dynamisch inrichten van het gebied. Bij de invulling hiervan wel met inachtneming van bestaande bebouwing. Huidige bebouwing zou meer beschermd kunnen worden, waardoor de rest van het gebied meer bestemd kan worden om het water meer zijn gang te laten gaan. Idealiter wordt deze maatregel dus gecombineerd met compartimenteren en overstromingsbestendig bouwen.
Compartimenteren	4	De expert ziet met name mogelijkheden in het beschermen van de kernen van de grote steden door middel van een compartimenteringsdijk om de steden heen, of door het compartimenteren van de A12. Hiermee worden de gebieden met het grootste

				slachtofferrisico en de hoogste schadefuncties beschermd. Idealiter wordt deze maatregel gecombineerd met risico zonering.
Overstromingsbestendig bouwen		4		Overstromingsbestendig bouwen is voor dunbevolkte gebieden een relatief effectieve maatregel, omdat je met relatief weinig aanpassingen gelijk een groot gebied veiliger maakt. Idealiter wordt deze maatregel gecombineerd met risico zonering.
Decompartimenteren		3		Deze maatregel kan ervoor zorgen dat mortaliteit omlaag gaat. Er moet wel gelet worden op dat risico elders in het gebied niet verhoogd wordt.
Waterberging	Retentiegebieden	4	2.5	Retentiegebieden kunnen een groot deel van het overstromingsvolume bergen en zo waterdieptes in de rest van het studiegebied verminderen. Door het tactisch bergen van water op plekken waar geen mensen wonen en economische waarde laag is, Drainage kanalen hebben als kanaal te weinig capaciteit, je moet dan echt over grotere bergingsgebieden gaan nadenken. Daarnaast zouden drainage kanalen er ook voor kunnen zorgen dat het risico alleen verplaatst wordt naar een ander gebied, in plaats van dat het risico verlaagt wordt.
	Drainage kanalen	1		
Preventieve dijkdoorbraak		1		Wanneer je een gebied moet je het zo inrichten dat het een natuurlijk(e) overloop of retentiegebied is. Op het moment dat het een politieke beslissing wordt waar en wanneer gebieden bewust onder water gezet gaan worden zal dit in de praktijk waarschijnlijk lastig gaan en discussie ontstaan over wie de verantwoordelijkheid draagt over een dergelijke beslissing.
Tijdelijke overstromingskeringen		1		De expert schat in dat de schaal waarop deze maatregel implementeerbaar en effectief is, niet groot genoeg is voor het substantieel beïnvloeden van het overstromingspatroon.
Beïnvloeden ruwheid		0		Waarschijnlijk zal deze maatregel niet veel helpen in het reduceren van het overstromingsrisico omdat de effecten te klein zijn. Daarnaast is het heel lastig te controleren en te handhaven dat deze maatregel in praktijk de gewenste risico reductie oplevert.

Table H-4 - Beoordeling ruimtelijke maatregelen expert 4

Ruimtelijke maatregel	Cijfer	Uitleg
Risico zonering	5	De expert geeft aan dat de meest aantrekkelijke maatregelen degene zijn die niet risico verhogend zijn op andere locaties. Risico zonering is zo'n maatregel, die met name op de lange termijn (langer dan twintig jaar) effectief kan zijn. Op den duur zullen we als maatschappij waarschijnlijk moeten gaan kiezen op welke plekken we accepteren dat het overstroomd en in welke gebieden we gaan bouwen. Bij nieuwbouw

		is het in ieder geval goed om altijd ook het overstromingsrisico mee te namen.
Waterberging	5	Bij een dijkdoorbraak stroomt er een bepaald volume aan water het studiegebied in, bij waterbergingsmaatregelen zorg je ervoor dat het dit volume (tijdelijk) (gedeeltelijk) opgeslagen wordt. De expert schat in dat er bij deze maatregel daarom minder risico wordt verplaatst naar elders in het gebied. De expert geeft aan dat in het studiegebied ook sprake is van water tekort in geval van droogte. Waterbergingsmaatregelen zouden daarom ook in gevallen dat er niet daadwerkelijk een overstroming plaats vind de waterbalans in het gebied verbeteren.
Compartimenteren	4	Het nemen van compartimenteringsmaatregelen kan de waterdieptes in de steden verminderen en zo het gebied met de meeste schade en slachtoffers beschermen.
Overstromingsbestendig bouwen	4	Zeker in dunbevolkte gebieden kan overstromingsbestendig bouwen uitkomsten bieden om het overstromingsrisico te verminderen. In gevallen wanneer er slechts een beperkt aantal woningen aangepast hoeft te worden kan dit in sommige gevallen kosten effectiever zijn dan het versterken van een hele dijk.
Decompartimenteren	3	Of het decompartimenteren een oplossing is, is sterk afhankelijk van het overstromingsscenario. Decompartimenteren kan meer ruimte bieden voor het water, maar dan moet de vergrootte berging wel toereikend genoeg zijn voor het bresvolume. Ook moet er nagedacht worden over de mogelijkheid dat lokaal het risico verlaagt wordt, maar elders in het gebied het risico omhoog gaat.
Tijdelijke overstromingskeringen	3	Het nemen van maatregelen heeft altijd een investeringshorizon. Deze maatregel zou op hele korte termijn al geïmplementeerd kunnen worden. Het inzetten van tijdelijke overstromingsmaatregelen zou ook gedaan kunnen worden op evacuatiewegen. Deze maatregel wordt normaliter wel vaak ingezet in smalle stroomgebieden als water snel komt opzetten. Het zou kunnen dat voor de grootte van het studiegebied de maatregel niet effectief genoeg is.
Beïnvloeden ruwheid	1	Door de ruwheid te verhogen kan de piek van de afvoergolf afgevlakt worden. Waarschijnlijk is het effect hiervan op het overstromingsrisico wel een stuk kleiner dan voor de andere maatregelen.
Preventieve dijkdoorbraak	0	De expert geeft aan dat deze maatregel maatschappelijk ongewenst is.

Appendix H-4 Expert 5

Achtergrond expert

De expert heeft een achtergrond in de civiele techniek en is gespecialiseerd op het gebied van overstromingsrisico en in het bijzonder evacuatie. De expert heeft meerdere studies gedaan naar evacuatie voor en tijdens overstromingen en de effectiviteit van maatregelen om het aantal geevacueerden te verhogen. De expert geeft ook aan bekend te zijn met het studiegebied en haar bijbehorende overstromingspatronen vanuit een eerdere studie.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

De inschatting van de expert is dat het implementeren van meerlaagseveiligheid maatregelen in de tweede en derde laag als alternatief of aanvulling op dijkversterking een gepasseerd station is. De expert is van mening dat maatregelen in de tweede laag grote inspanning kost omdat ze relatief veel geld kosten en er veel partijen bij betrokken moeten worden.

De expert is van mening dat dijkversterking relatief eenvoudig uitvoerbaar is, omdat wanneer er daar een investering in wordt gedaan, deze ervoor zorgt dat er gelijk een aantal jaar daarna geen investeringen meer gedaan hoeven worden. De expert geeft wel aan dat er nog veel winst te behalen valt op het gebied van rampenbestrijding. Niet alleen door nieuwe investeringen te doen, maar ook juist door het beter te benutten van de middelen die er al zijn. De veiligheidsregio zet op dit moment vooral in op preventieve evacuatie, maar juist ook het opzoeken van droge plekken in het gebied zou kansen kunnen bieden. Belangrijk is wel dat er vanuit waterschappen duidelijk is hoeveel tijd er beschikbaar is om te evacueren in het geval van een overstroming. De expert geeft verder aan dat deze beschikbare tijd ook vergroot kan worden door de relatieve faalkansen van de verschillende faalmechanismes aan te passen. De expert geeft aan dat nu piping en macrostabiliteit relatief veel aan mogen bijdragen aan de faalkans van de dijk en die zijn lastiger te voorspellen. Voor faalmechanismes die eenvoudiger te voorspellen zijn evacuatie tijden dus groter. De expert geeft aan dat het wel lastig is om met alleen rampenbestrijding een normklasse omlaag te gaan, omdat er een factor drie tussen de verschillende normklasses zit en de gevolgen dus drie keer zo klein moeten worden om naar een andere normklasse te gaan.

Andere belangrijke factoren zijn de governance en de tijdschaal waarop ruimtelijke maatregelen geïmplementeerd worden. De expert geeft aan dat dijkversterking als één project wordt aan gepakt inclusief het bijbehorende omgevingsmanagement. Voor de tweede laag zou dit omgevingsmanagement veel grotere uitdagen kunnen bieden omdat er op veel verschillende plekken gebouwd wordt en aanpassingen aan bebouwing continue gedaan zouden moeten worden. Daarnaast geeft de expert aan dat voor maatregelen in de tweede laag het ruimtelijke beleid constant moet worden gehouden, iets wat in Nederland niet altijd gebeurt. Daarnaast zal er vraag blijven naar nieuwe woningbouw, waarbij dan ook weer rekening gehouden moet worden met de bedachte gevolgbeperkende maatregelen.

Geschikte locaties voor de ruimtelijke maatregelen

De expert geeft aan dat het verhogen van de A12 een goede implementatie zou zijn voor een compartimenteringsmaatregel, omdat hiermee de steden worden versterkt. Het verhogen van een spoorlijn zal waarschijnlijk fysisch niet haalbaar zijn, omdat deze spoorlijnen vaak waterdoorlatend worden aangelegd omdat dit nodig is voor de stabiliteit van de trein. Wanneer een compartimenterende dijk waterdoorlatend wordt aangelegd zal het niet veel effect hebben op je overstromingsrisico.

De expert ziet wel kansen in het tijdelijk versterken van de primaire kering en/of bestaande lijnelementen (m.u.v. spoorlijnen) door het gebruik van zandzakken. Lijnelementen die hier het meest geschikt voor zouden zijn, zijn de A12 en de A8.

Het decompartimenteren van rijnstrangen gebied zou een optie kunnen om de mortaliteit in dat gebied te verminderen. De expert geeft wel aan dat schade in de steden dan misschien groter wordt in het geval dat de noordelijke regionale kering verwijderd wordt.

Beoordeling ruimtelijke maatregelen

In tabel XX wordt een overzicht gegeven van de scores die de expert heeft gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-5 - Beoordeling ruimtelijke maatregelen expert 5

Ruimtelijke maatregel	Cijfer	Uitleg
Tijdelijke overstromingskeringen	5	Volgens de expert is versterken van de primaire keringen is de meest effectieve maatregel voor het reduceren van het overstromingsrisico. Tijdelijke overstromingskeringen in de vorm van het toevoegen van zandzakken op de primaire kering zal daarom volgens de expert het meest efficient zijn.
Decompartimenteren	3	Decompartimenteren zou kunnen zorgen voor risico reductie in het rijnstrangen gebied en dus vermindering van het hoge lokaal individueel risico in dat gebied. Er moet wel rekening gehouden worden met het extra risico dat kan ontstaan in de steden.
Compartimenteren	2	De expert geeft aan dat compartimenteren niet kosten effectief is omdat je in principe een extra dijk aan moet leggen, wat duurder zal zijn dan het versterken van de primaire waterkering. Met deze maatregel bescherm je een gebied, maar aan de keerzijde wordt een ander gebied zwaarder getroffen. Daarnaast moeten ook alle tunnels en onderdoorgangen dichtgezet worden om een volledig kerende werking te bieden, wat een arbeidsintensieve en kostige opgave kan zijn. De expert geeft verder aan dat wegen op dit moment juist ook verlaagd aangelegd worden, zodat je deze niet hoort of ziet, maar wanneer deze verhoogd worden zou dit de dagelijkse overlast kunnen verhogen terwijl je er alleen in het geval van een overstroming profeit van hebt.
Risico zonering	1	De expert geeft aan dat deze maatregel niet praktisch implementeerbaar is. Op basis van overstromingsrisico's kan je verschillende zones voor landgebruik maken maar dit veranderd niet meteen iets aan het gebied. De expert geeft aan het het verstandig is om rekening houden met overstromingsrisico bij het toewijzen van landgebruik, maar dat een gebiedsopgave niet volledig geoptimaliseerd kan worden vanuit waterveiligheid. Er zullen ook altijd andere aspecten voor het ontwikkelen van woningbouw in acht genomen worden zoals nabijheid van snelwegen en waar huidige steden zich bevinden.
Preventieve dijkdoorbraak	1	De expert geeft aan dat het niet wenselijk is om een persoon verantwoordelijk te stellen om een dergelijke beslissing te maken. De expert geeft verder aan dat deze beslissing

		gemaakt moet worden op basis van voorspellingen, die van de realiteit kunnen afwijken. De timing van het doorsteken van de dijk is hierbij ook een belangrijk aspect. Het doel moet zijn om de piek van de afvoergolf afvlakken, maar wanneer de dijk te vroeg of te laat wordt doorgestoken zal dit niet altijd lukken. De expert geeft aan dat hierom preventief een gebied onderwater te zetten vaak resulteert in meer overstromingsrisico dan wanneer deze maatregel niet wordt genomen.
Overstromingsbestendig bouwen	1	Het grootste gedeelte van de schade treedt al op bij een half tot één meter water en in het LIR speelt bebouwing geen rol. Bij nieuwbouw kun je overstromingsbestendig kunnen bouwen, maar de expert geeft aan dat dit waarschijnlijk niet gaat leiden tot een andere normklasse omdat de gevolgen dan een factor drie omlaag moeten gaan. Daarnaast moet er ook goed naar de keerzijde van deze maatregel gekeken worden. Wanneer dryproofing wordt geïmplementeerd zouden de huidige huizen misschien wel in kunnen storten, omdat er dan wel water aan de buitenkant staat en niet aan de binnenkant en er dus geen tegendruk is. Bij bouwen op palen komt de keerzijde dat mensen een groter risico lopen op van de trap vallen.
Beïnvloeden ruwheid	1	De expert geeft aan dat het beïnvloeden van de stroomsnelheid waarschijnlijk geen effect heeft op de normen omdat de schade factoren niet afhankelijk zijn van stroomsnelheid en de tijd die je er mee wint niet wordt meegnomen in de evacuatiefractie omdat daarbij alleen naar preventieve evacuatie gekeken wordt. Wanneer aankomsttijden meegenomen zouden worden in het normbepalingsprocess zou het misschien een effectievere maatregel kunnen zijn.
Drainage kanalen	1	De capaciteit van drainage kanalen is te laag om effect te hebben op het overstromingsrisico. Om regenwater te bergen is dit een geschikte maatregel, maar bresdebieten zijn veel te groot om overtollig water opslaan.
Toevoeging expert:		
Shelters	3.5	Het faciliteren van shelters zou de evacuatiefractie omhoog kunnen brengen en dus het lokaal individueel risico (LIR) kunnen verbeteren. Omdat deze maatregel relatief goedkoop is, zal hij ook al snel kostenefficient zijn. Deze maatregel is met name effectief als er veel slachtoffers zijn, omdat de maatregel alleen gericht is op het reduceren van het aantal slachtoffers.

Appendix H-5 Expert 6

Achtergrond expert

De expert is beleidsadviseur waterveiligheid bij waterschap Rijn & Ijssel, het waterschap waar het studiegebied (dijkring 48) ook onder valt. Vanuit deze functie heeft de expert veel ervaring opgedaan met dijkbeheer. Daarnaast heeft de expert ook specifieke gebiedskennis, met name voor het stedelijk gebied rondom Westervoort, Duiven en Zevenaar en het Duitse deel van het studiegebied en in mindere mate het noorden van het gebied. Daarnaast heeft de expert op persoonlijk vlak ook evacuatie van de overstromingen in het rivierengebied in 1995 meegemaakt.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

De expert geeft aan dat waterschap Rijn & Ijssel in hun beleidsdocumenten het landelijke beleid meerlaagseveiligheid heeft overgenomen. Hierbij moet wel de kanttekening worden gemaakt dat de focus nog steeds op dijkversterking ligt en dat in de tweede laag het waterschap vooral adviserend is. In werkelijkheid worden deze adviesen ook niet altijd opgevolgt. Een uitdaging in het faciliteren van maatregelen in de tweede en derde laag is dan ook de kwestie wie de verantwoordelijkheid moet dragen voor deze maatregelen. De expert denkt wel dat meerlaagse veiligheid in sommige gevallen wel haalbaar kan zijn, maar dat het ook afhankelijk is van de maatregel.

Geschikte locaties voor de ruimtelijke maatregelen

Volgens de expert zou je op meerdere locaties in het gebied kunnen compartimenteren. De expert geeft wel aan dat het op dit moment lastig wordt om aan de Nederlandse normen te voldoen zonder dijken in Duitsland te versterken. Mocht het onmogelijk worden om de veiligheidsnorm in Nederland te halen omdat de sterkte van de Duitse dijken niet dezelfde standaard heeft als Nederland zou compartimentering op de grens overwogen kunnen worden. De expert geeft wel aan dat dit erg onwaarschijnlijk is dat deze maatregel op die manier ingevoerd gaat worden. Het huidige dijkversterkingsprogramma van Duitsland loopt tot 2025, waarna de dijken in Duitsland even sterk zouden moeten zijn dan de huidige dijken in Nederland. In Nederland worden de dijken alleen nog verder verstevigd tot 2050. Omdat in Duitsland een andere methode wordt gebruikt om de sterkte van de dijken te berekenen is het lastig in te schatten hoeveel verschil de stabiliteit van de dijken verschilt tussen de twee landen. Het compartimenteren van de snelwegen in het gebied, dus de A18 en de A12 zou ook interessant kunnen zijn. Eventueel door middel van tijdelijke overstromingskeringen.

Decompartimenteren door gedeeltelijk de dijken in het rijnstrangengebied weg te halen zou ervoor kunnen zorgen dat in de driedorpenpolder minder snel vol loopt, afhankelijk van de doorbraaklocatie. Voor doorbraken vanuit Duitsland zou het juist negatieve effecten kunnen hebben om deze dijk weg te halen, omdat die nu een gedeelte van het risico vanaf die kant tegen houd. Decompartimenteren zou daarom vooral nuttig kunnen zijn in combinatie met preventieve dijkdoorbraak, omdat dan de doorbraak locatie te controleren is.

De expert geeft aan dat overstromingsbestendig bouwen en risico zonering bij voorkeur gecombineerd zouden moeten worden, voornamelijk bij nieuwbouw. Bijvoorbeeld het bebouwingsvrij houden van de oude loop van de rivier goed zou werken (langs de Oude Rijn en van de Bovenrijn naar de Oude Ijssel) omdat hier veel water stroomt. Op een aantal locaties in het gebied staat een te hoge waterdiepte om ‘anders bouwen’ nuttig te maken. Op plekken waar waterdiepte minimaal is zou slim nagedacht kunnen worden over hoe dataverkeer, stroomvoorziening en infrastructuur aangelegd wordt.

Bij het gebruiken van drainage kanalen om het overstromingsrisico te verminderen zou je de capaciteit naar de Oude Ijssel kunnen verhogen, maar dit zal waarschijnlijk het risico langs de hele Ijssel in andere dijkringen verhogen. Er zijn wel nog plannen om het rijnstrangengebied weer een retentiegebied te maken, hiervoor is ook een ruimtelijke reservering opgelegd. Dit zou geimplementeerd kunnen worden door middel van een vaste of regelbare inlaat. Belangrijk hierbij is wel dat de secundarie dijken van het rijnstrangen gebied opgewaardeerd worden en dat de stadskern van Spijk wordt beschermd. Dit zorgt voor verlaging van waterstanden op het Pannerdensch Kanaal, de Waal en de Ijssel.

De expert geeft aan dat een overstrombare dijk op de primaire waterkering op normtraject 48-1 ook van waarde zou kunnen zijn om het overstromingsrisico te verminderen. Dit met het doel om de huidige afvoerverdeling van de rijntakken in stand te houden. In het geval van een overstroming zo extreem als waarop de huidige normering is vastgesteld zal de afvoerverdeling volgens de expert waarschijnlijk niet in stand blijven, hiermee zal de onvoorspelbaarheid en de impact van de overstroming waarschijnlijk toenemen. Om dit te voorkomen zou een overstrombare dijk dus uitkomst kunnen bieden.

Beoordeling ruimtelijke maatregelen

In tabel H-6 wordt een overzicht gegeven van de scores die de expert heeft gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-6 - Beoordeling ruimtelijke maatregelen expert 6

Ruimtelijke maatregel	Cijfer	Uitleg
Drainage kanalen	5	In het geval van een overstroming moet er veel water geborgen worden. In de vorm van het creeëren van een groot retentiegebied zou deze maatregel daarom erg kansrijk kunnen zijn. Het rijnstrangen gebied leent zich hier ook goed voor.
Tijdelijke overstromingskeringen	4	Dit is een relatief goedkope maatregel en het keren van water kan tactisch bepaalde gebieden beschermen. Het nadeel van tijdelijke overstromingskeringen is dat de instrumenten die je nodig hebt om tijdelijk te keren klaar moeten liggen, omdat anders de aankomstijden te kort zijn voor de voorbereiding.
Overstromingsbestendig bouwen	4	De expert schat in dat met name het verminderen van bedrijfsuitval en schade aan infrastructuur door anders te bouwen kansrijk is. Als je op een manier er voor kan zorgen dat de capitaal intensieve onderdelen van een gebouw niet onder water te komen staan scheelt dat veel schade. Daarnaast ben je dan ook weer sneller operationeel. De expert geeft aan weinig vertrouwen hebben in het integraal ophogen van gebouwen.
Compartimenteren	3	Compartimenteren met als doel het water te vertragen zou veel effect kunnen hebben. Hierdoor is er meer tijd om evacuatie op te zetten. Als je een compartimenteringsdijk alleen remmend bouwt, dus in de vorm van een overstroombare dijk dan hoeft die minder stevig te zijn dan de primaire waterkering.
Decompartimenteren	3	Door het rijnstrangen gebied te decompartimenteren zal de driedorpenpolder minder snel vollopen en dus de schade en slachtoffers in deze dorpen verlagen.

Risico zonering	3	Bij nieuwbouw is het belangrijk om goed in beeld te hebben of je in overstroombaargebied bouwt, met name voor bebouwing met kwetsbare functies. Op grote schaal zullen we dit echter waarschijnlijk niet gaan doen in Nederland.
Beïnvloeden ruwheid	1	Het beïnvloeden van de ruwheid zou het water iets kunnen vertragen maar het gaat waarschijnlijk niet hele grote verschillen opleveren. Daarnaast zou hiervoor veel landbouwgrond of bebouwd gebied opgeofferd moeten worden.
Preventieve dijkdoorbraak	1	In het geval van nood zullen hier misschien situatie afhankelijk beslissingen voor gemaakt worden. Maar de expert schat in dat er geen politiek draagvlak is om bij voorbaat al een locatie aan te wijzen waar de dijk doorgestoken gaat worden.
Toevoeging expert:		
Overstroombare dijk primaire kering	1	In praktijk zou dit een goede maatregel kunnen zijn om het overstromingsrisico te verminderen, maar het huidige normeringsconcept faciliteert de maatregel met het doel het in stand houden van de splitsingspunten niet. Omdat het geen juridische basis heeft schat de expert in dat deze maatregel niet te implementeren is, met name omdat een overstroombare dijk breed aangelegd zou moeten worden en hiervoor bestaande woningen plaats moet maken.

Appendix H-6 Expert 7

Achtergrond expert

De expert heeft een achtergrond in de landinrichting en is met name werkzaam op intergrale projecten binnen de waterveiligheid. Daarnaast heeft de expert ook kennis van de techinische details van het doorrekenen van dijken.

De expert is op dit moment een aantal jaar werkzaam bij waterschap Rijn & Ijssel en heeft vanuit deze functie specifieke gebiedskennis. De expert geeft aan ook op de hoogte te zijn van welke factoren in het gebied belangrijk zijn voor evacuatie, zoals de uitgestrekte lage woonwijken en evacuatie wegen.

Inschatting haalbaarheid ruimtelijke maatregelen als alternatief voor dijkversterking

De expert geeft aan dat in oude studies waar de expert bekend mee is maatregelen in de eerste laag vaak het meest effectief worden beschouwd. De expert geeft aan dat voor overstromingen met een lagere herhalingstijd, zoals eens in de 50 jaar, ruimtelijke maatregelen met name effectief zijn. Een kanttekening moet hierbij gemaakt worden dat in dijkring 48 het overstromingsrisico ook afhankelijk is van de sterkte van de Duitse dijken. In de toekomst zou het daarom zo kunnen zijn dat we in Nederland niet voldoen aan de normen door het risico dat vanuit Duitsland komt, zonder de implementatie van tweede en derde laags maatregelen.

Geschikte locaties voor de ruimtelijke maatregelen

De expert geeft aan dat het gebied zich lastig leent voor compartimenteringsmaatregelen vanwege de helling in het gebied. Naar zijn inschatting zal je de compartimenteringsdijken heel hoog moeten bouwen wil je zorgen dat het niet alsnog over deze dijken stroomt. Waar je wel overna zou kunnen denken is het beschermen van bestaande kernen en het ophogen van wegen zodat deze ook als evacuatie route kunnen dienen. Het beschermen van wegen en ze tijdelijk een compartimenterende werking geven zou ook gedaan kunnen worden door middel van tijdelijke overstromingskeringen in de vorm van het ophogen van de weg met zandzakken. Dit zou vooral effectief zijn op de A18, omdat dit om een kleiner stuk gaat. Voor tijdelijke overstromingskeringen moet in acht genomen worden dat deze maatregel praktisch gezien waarschijnlijk alleen ingezet kan worden op korte stukken.

De expert geeft aan geen uitkomst te zien in het volledig decompartimenteren van het Rijnstrangen gebied omdat hiermee het risico in de rest van het gebied en met name in de steden Westervoort, Duiven en Zevenaar vergroot wordt. De expert geeft aan juist als compartimenteringsmaatregel kansen te zien in het versterken van de dijken langs de Oude Rijn, om op die manier de rest van het studiegebied beter te beschermen bij doorbraken langs het rijnstrangengebied.

Bij anders bouwen is het aanpassen van huidige bebouwing waarschijnlijk niet haalbaar. Bij elke nieuwbouwwijk zou eigenlijk het overstromingsrisico wel in acht genomen moeten worden en kan er per situatie gekeken worden naar passende maatregelen. Met name aan de randen van het overstromingspatroon, waar waterdieptes beperkt zijn, zou overstromingsbestendig bouwen effectief kunnen zijn. Voor bestaande stroomstations, waterzuiveringen en infrastructuur zouden wel zo aangepast kunnen worden dat de schade daalt. De komende jaren worden er vervangingen gedaan in het stroomnet, dus het aanpassen van deze infrastructuur aan het overstromingsrisico zou hier goed mee gecombineerd kunnen worden.

Drainage kanalen zouden met name in de vorm van het maken van een retentiegebied effectief kunnen zijn. Het rijnstrangen gebied leent zich hier goed voor. In het verleden was dit gebied al aangewezen als noodoverloopgebied met een overlaat bij Spijk. Het is op die manier voor het laatst gebruikt in 1952, echter is het hele gebied er nog steeds op ingericht en bestaat er nog steeds een reservering voor. Een nadeel is wel dat je voor de gemeente een heel gebied op slot zet.

De expert geeft aan dat een preventieve dijkdoorbraak in het studiegebied waarschijnlijk geen effectieve maatregel is. Deze maatregel wordt meestal ingezet door het bovenstrooms doorsteken van de dijk om benedenstrooms de kans op dijkdoorbraak te verlagen. In het studiegebied zorgen de doorbraak locaties die het meest bovenstrooms liggen alleen voor het meeste risico. Hierom zal een dijkdoorbraak bovenstrooms de impact waarschijnlijk niet verminderen. Eventueel zou er nog wel gekeken kunnen worden naar het doorsteken van de dijk van de dijkring zuidelijk van dijkring 48 (dijkring 42), maar dan wordt het risico op een ander gebied afgeschoven, wat ook niet wenselijk is.

Beoordeling ruimtelijke maatregelen

In tabel H-7 wordt een overzicht gegeven van de scores die de expert heeft gegeven aan elke maatregel, met de bijbehorende verantwoording van deze scores.

Table H-7 - Beoordeling ruimtelijke maatregelen expert 7

Ruimtelijke maatregel	Cijfer	Uitleg
Drainage kanalen	5	Het inzetten van het Rijnstrangen gebied als retentie gebied zal waarschijnlijk zorgen voor lagere waterstanden op de rivier en in de rest van het studiegebied. Omdat dit gebied relatief leeg is zal het waarschijnlijk in dit gebied niet voor substantiele verhoging van het schade en slachtofferrisico zorgen. Daarnaast is het gebied op dit moment al aangewezen als mogelijk gebied wat gebruikt kan worden om overstromingsimpact te verkleinen. Hierom is het waarschijnlijk relatief makkelijk te implementeren. Waar wel rekening mee gehouden moet worden is of deze maatregel eventueel zorgt voor opstuwend water richting Duitsland.
Tijdelijke overstromingskeringen	3	Met tijdelijke overstromingskeringen zouden evacuatie routes langer beschikbaar kunnen worden gemaakt. De nadelen van tijdelijke overstromingskeringen zijn dat je voor het ophogen van lijnelementen met bijvoorbeeld zandzakken veel middelen nodig hebt om de maatregel daadwerkelijk te faciliteren in beperkte tijd en dat het afsluiten van coupures kan zorgen voor het afsluiten van evacuatie routes.
Compartimenteren	3	Deze maatregel zou gebruikt kunnen worden om evacuatietijd te vergroten door het water te vertragen. Het gebied is wel heel hellend dus daarom gaat het water op den duur waarschijnlijk over de compartimenteringsdijk heen.
Overstromingsbestendig bouwen	3	Met name voor nieuwe bebouwing zou dit kansrijk kunnen zijn. Aan de randen van het overstromingspatroon zijn waterdieptes minimaal dus hier zou overstromingsbestendig bouwen veel effect kunnen hebben. Ook het anders aanleggen van kritieke infrastructuur zou veel schade kunnen beperken.
Risico zonering	3	Met oog op de toekomst is het belangrijk dat gebieden zo worden in gericht dat bij een overstroming gebouwen en infrastructuur zo min mogelijk schade ondervinden. De expert verwacht dat dit met name binnen een gebied van toepassing is en niet dat de populatie van Nederland van het westen allemaal naar de minder bevolkte hoger gelegen delen van Nederland gaat verhuizen. De expert heeft het idee dat zolang we de financiële middelen hebben om Nederland te

		beschermen zullen we waarschijnlijk meegroeien met het klimaat.
Decompartimenteren	1	Het studiegebied leent zich niet voor deze maatregel.
Beïnvloeden ruwheid	1	Deze maatregel zal waarschijnlijk niet veel verschil maken. Het zou lokaal kunnen helpen maar gaat niet bepalend zijn voor het overstromingsrisico.
Preventieve dijkdoorbraak	1	Het studiegebied leent zich niet voor deze maatregel. Daarnaast geeft de expert aan dat het een lastige politieke situatie opleverd omdat iemand moet beslissen wanneer en waar je de dijk doorbreekt. Dit zou opgelost kunnen worden met een overstroombare dijk, waarbij de natuur bepaald wanneer een overstroming plaats vind op basis van de berekeningen die vooraf zijn gemaakt. Dit is alleen niet zo effectief als een regelbaar inlaatwerk omdat je afvoergolf niet altijd hetzelfde is.

Appendix I – Water depth flood simulations spatial measures

Table I-1 - Computed maximum waterdepth for D-Hydro simulations including implementation of a temporary flood defense (breach locations are indicated with a red dot)

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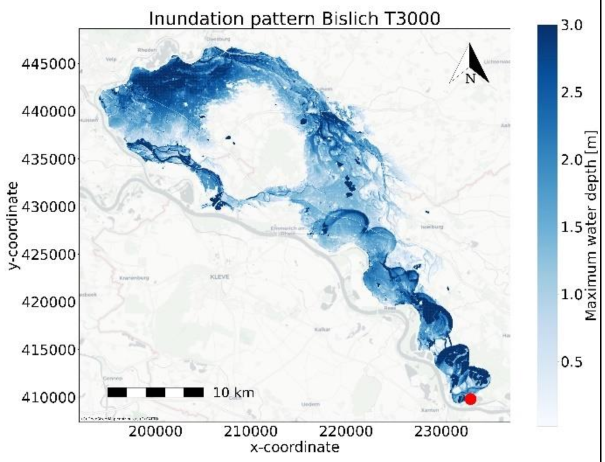
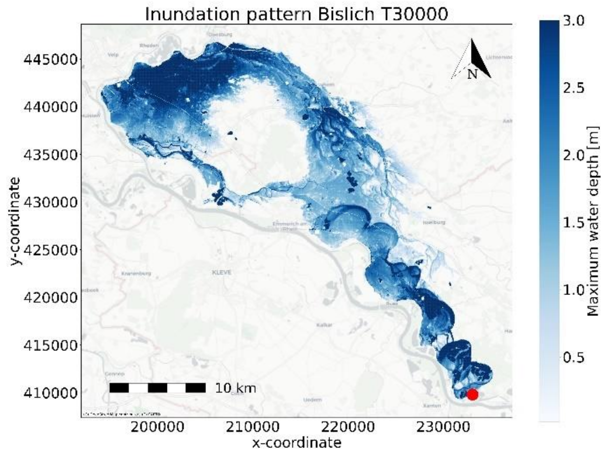
<tr><td>Bislich</td><td>
</td><td>
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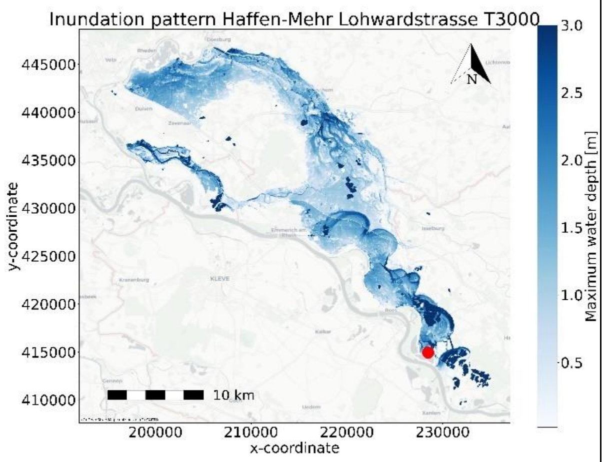
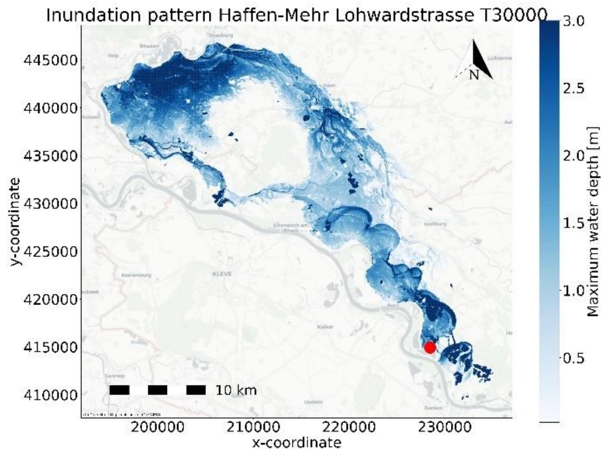
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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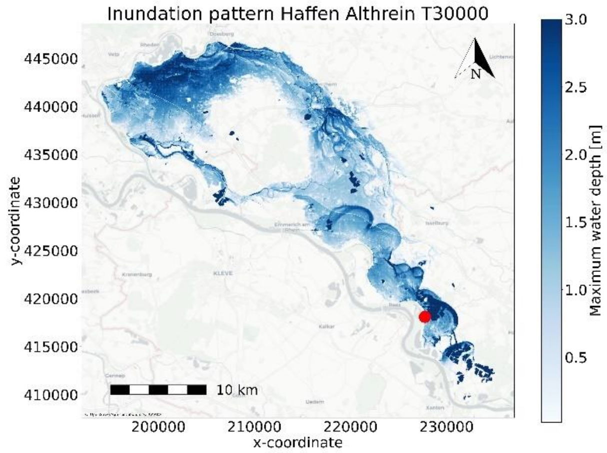
<tr><td>Haffen Althrein</td><td>Not applicable</td><td>
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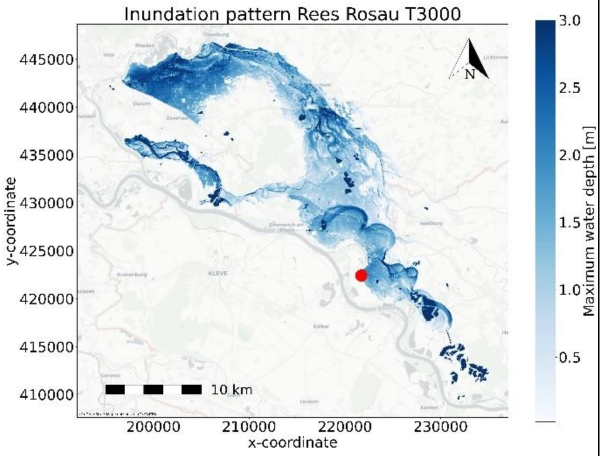
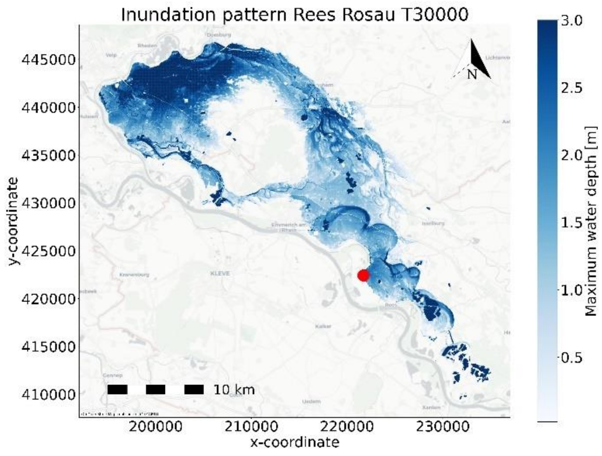
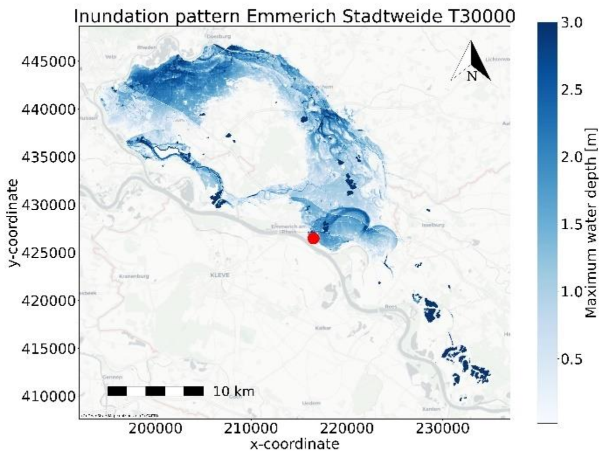
Rees Rosau





Emmerich Stadtweide

Not applicable



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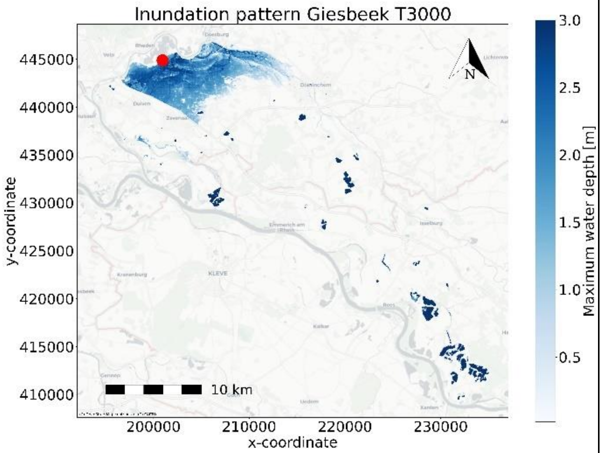


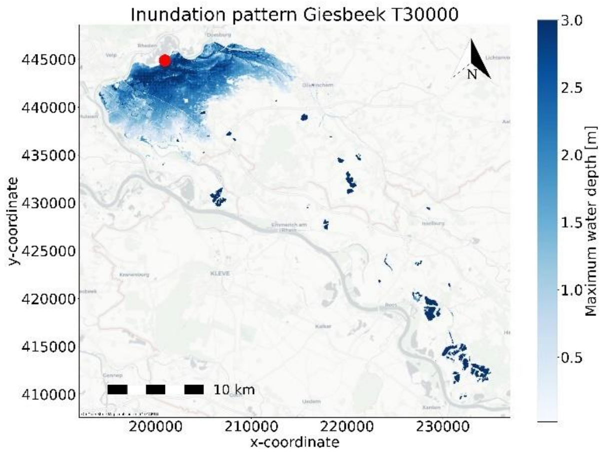
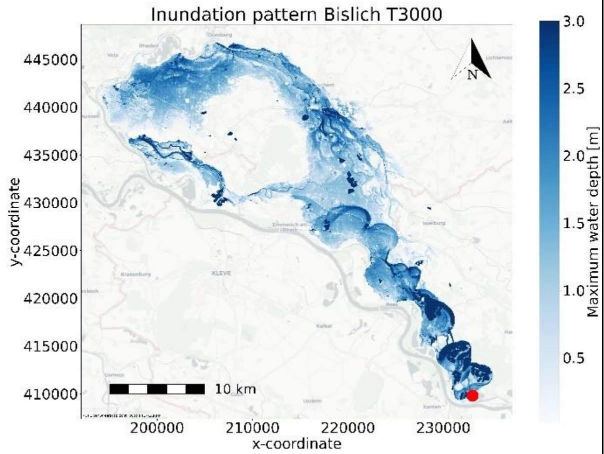
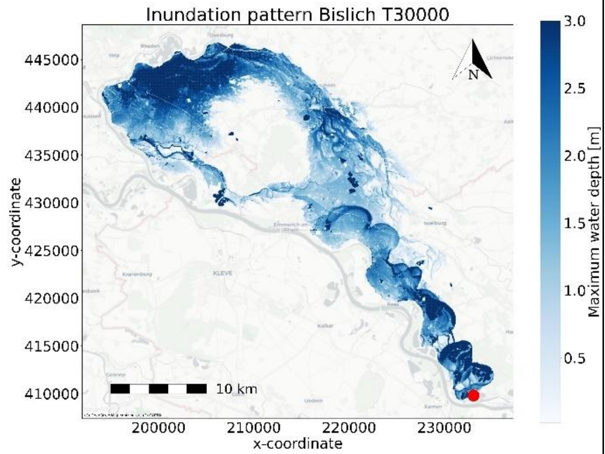
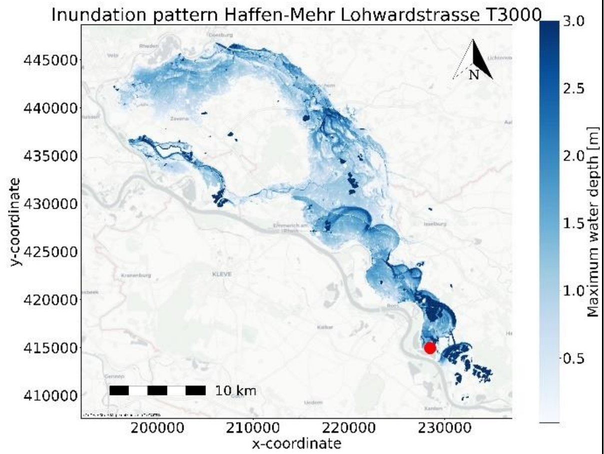
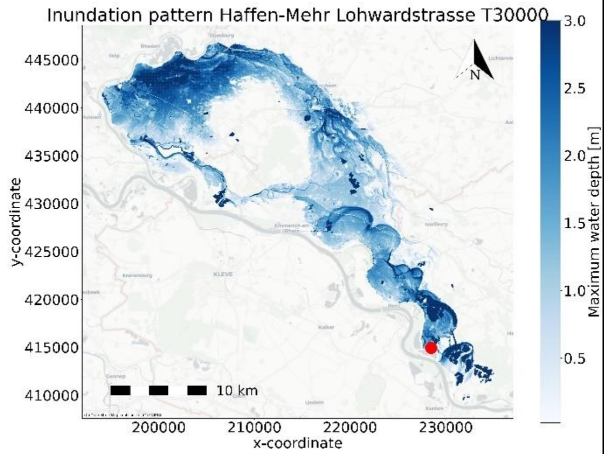
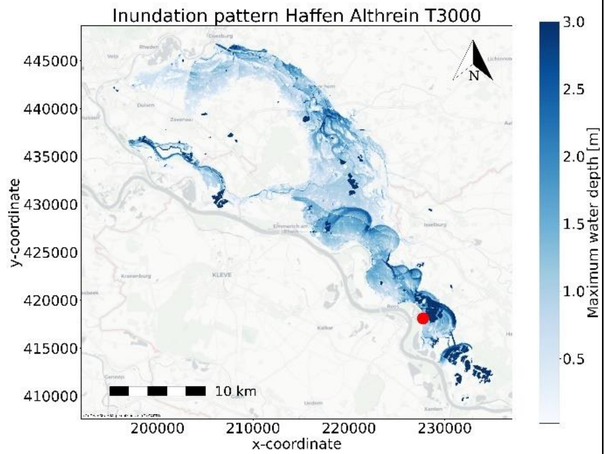
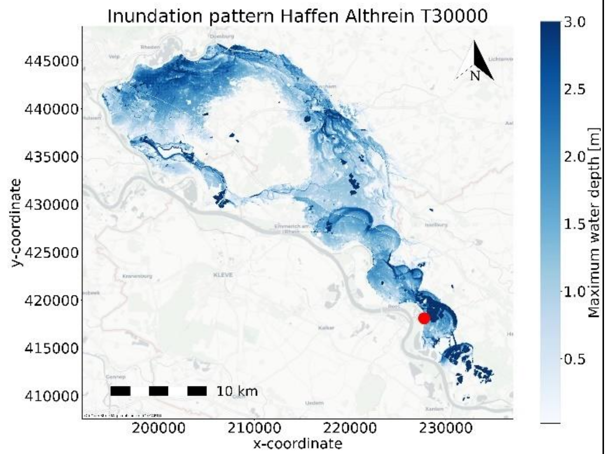
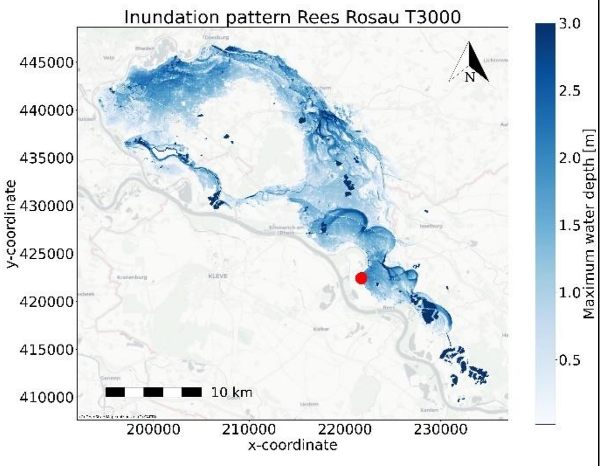
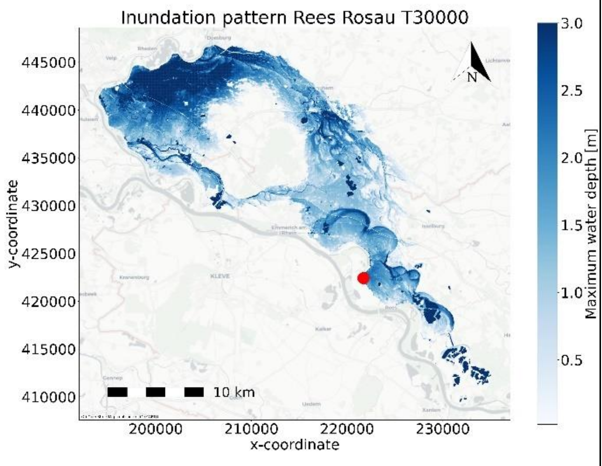
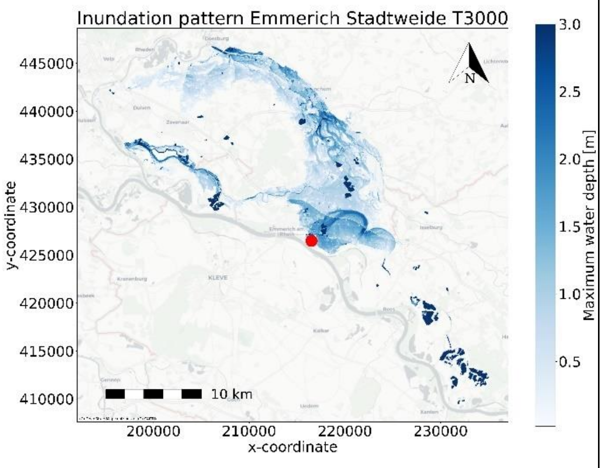
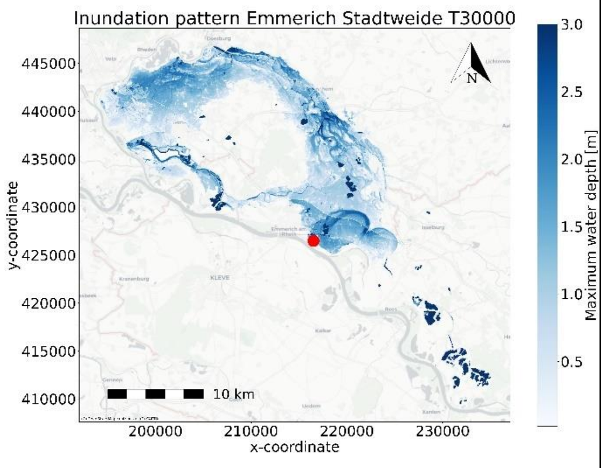
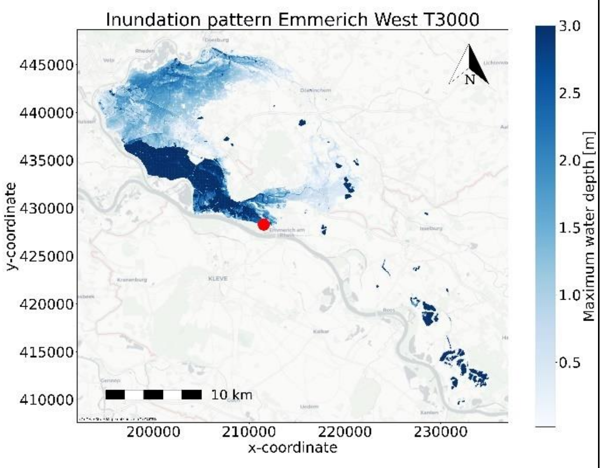
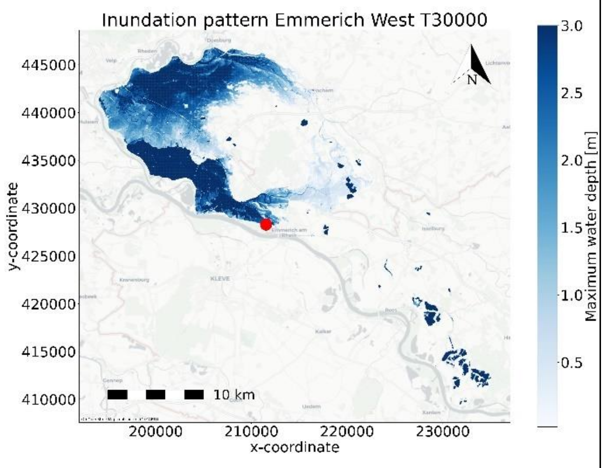
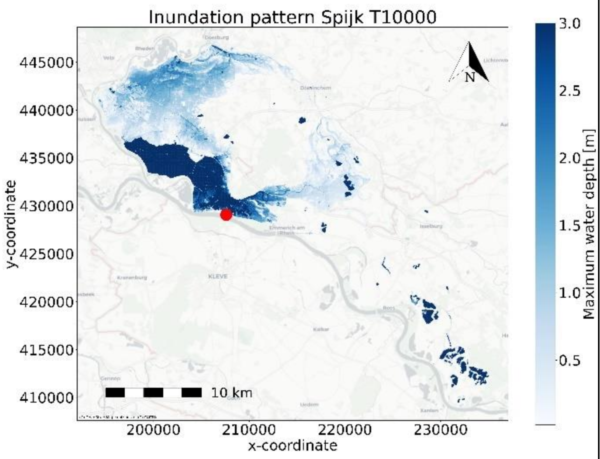


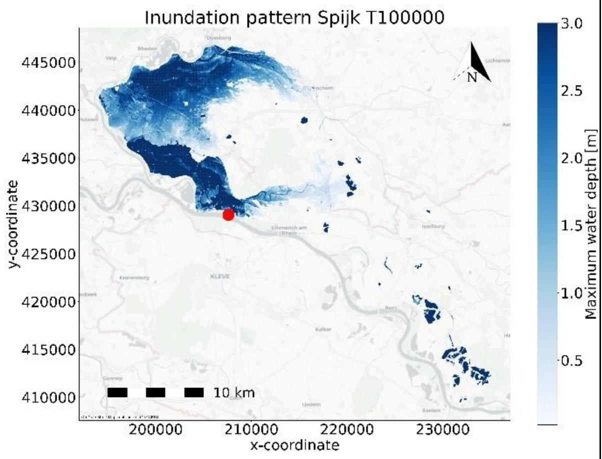
Table I-2 - Computed maximum waterdepth for D-Hydro simulations including implementation of a decompartmentation measure (breach locations are indicated with a red dot)

	Normative discharge scenario	Above normative discharge scenario
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein		

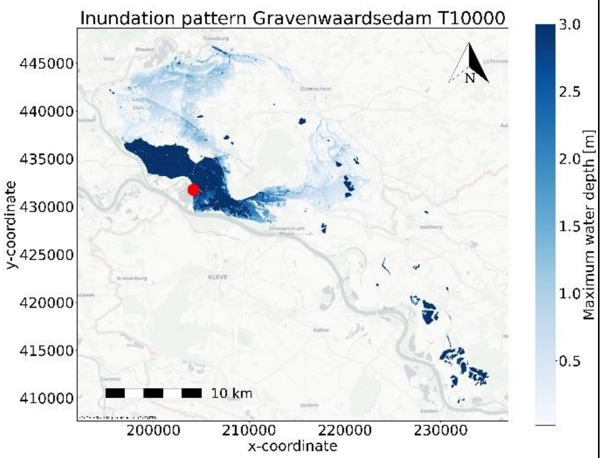
Rees Rosau		
Emmerich Stadtweide		
Emmerich West		

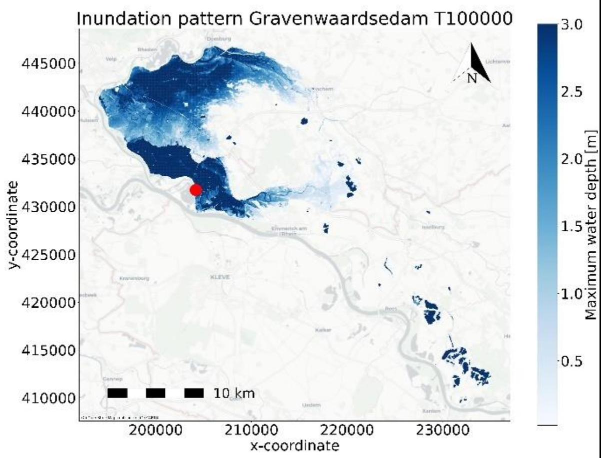
Spijk



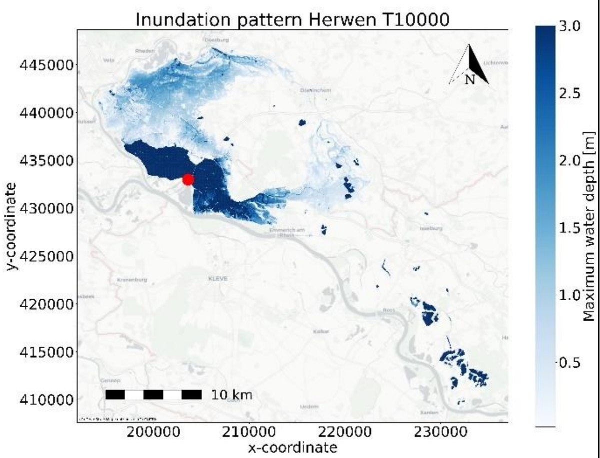


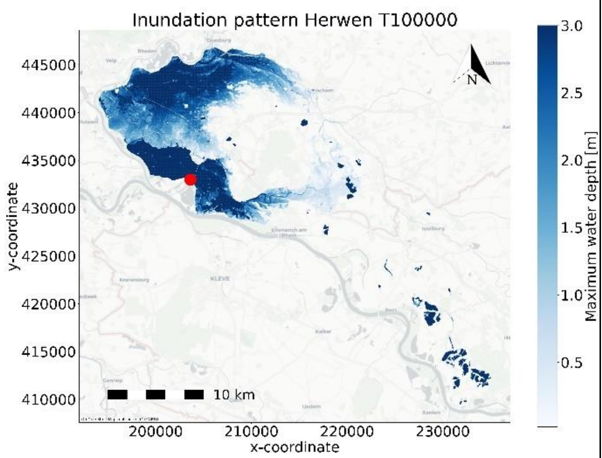
Gravenwaardsedam



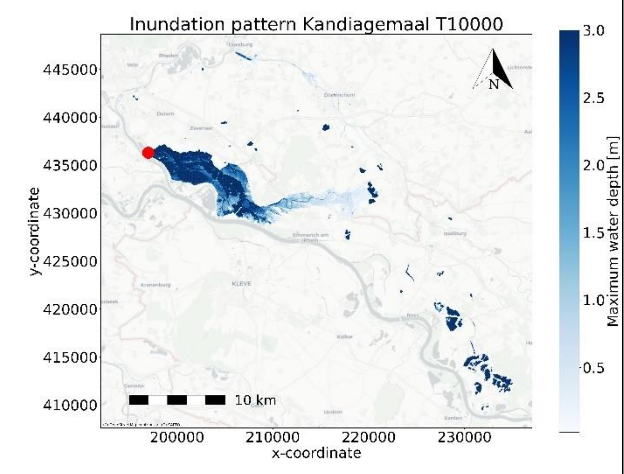


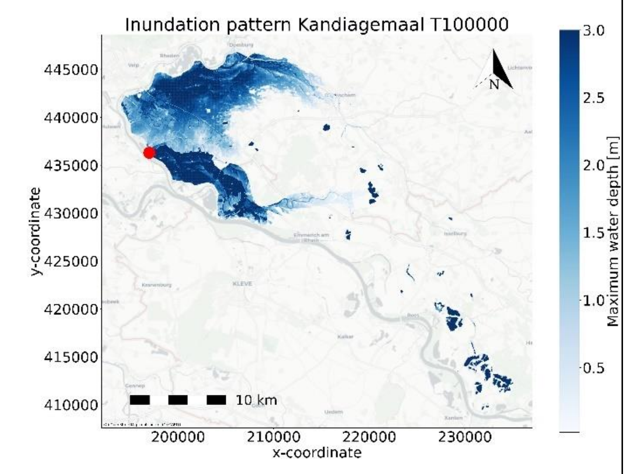
Herwen





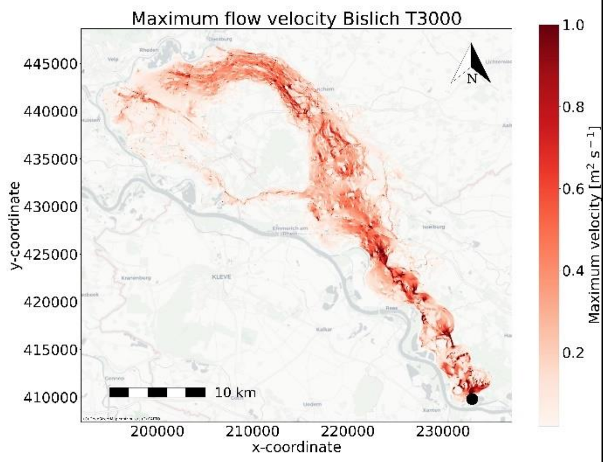
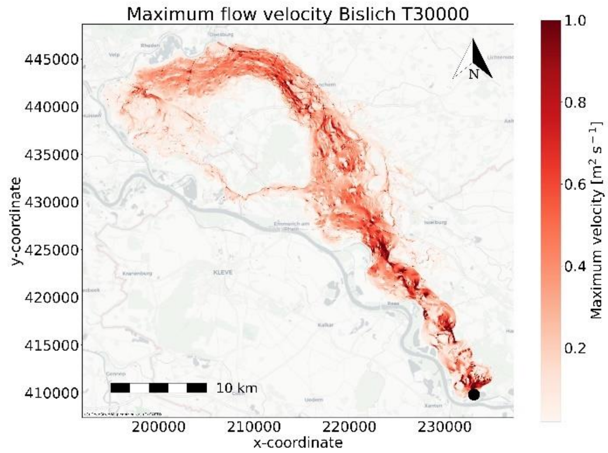
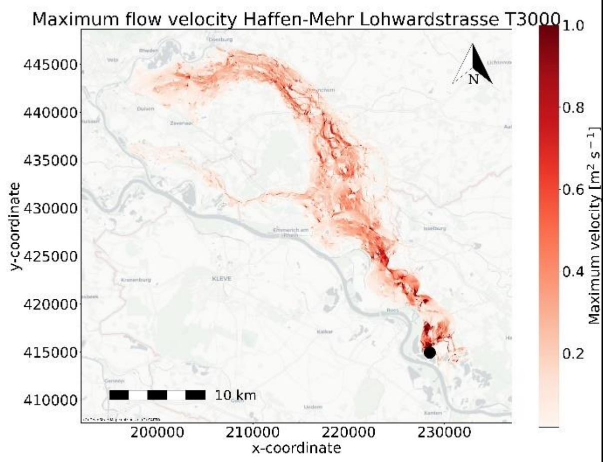
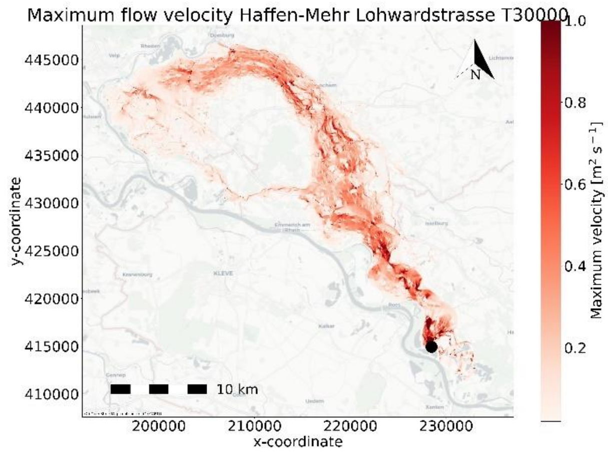
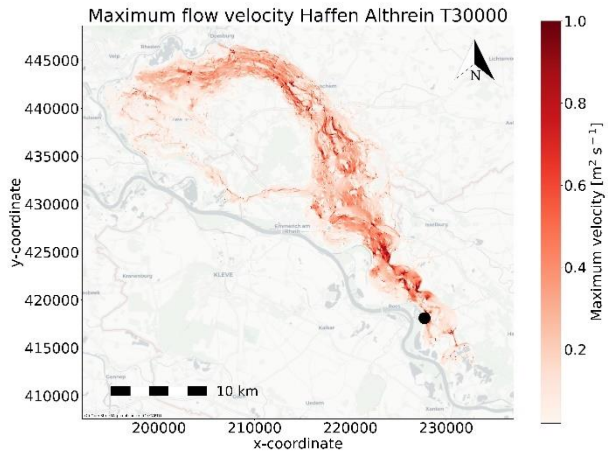
Kandiagemaal





Appendix J – Flow velocity flood simulations spatial measures

Table J-1 - Computed maximum flow velocities for D-Hydro simulations including implementation of a temporary flood defense (breach locations are indicated with a black dot)

	Normative scenario	Above normative scenario
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein	Not applicable	

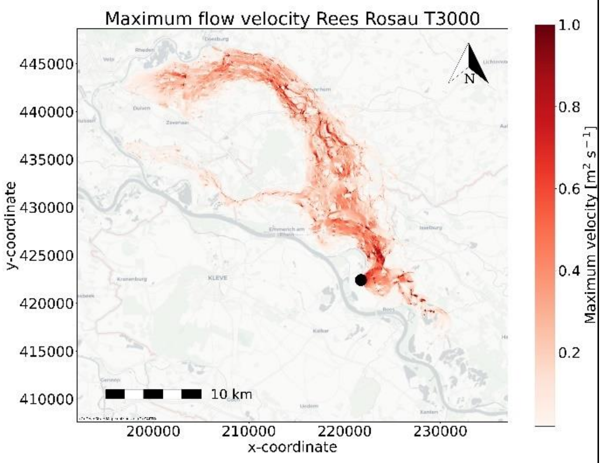
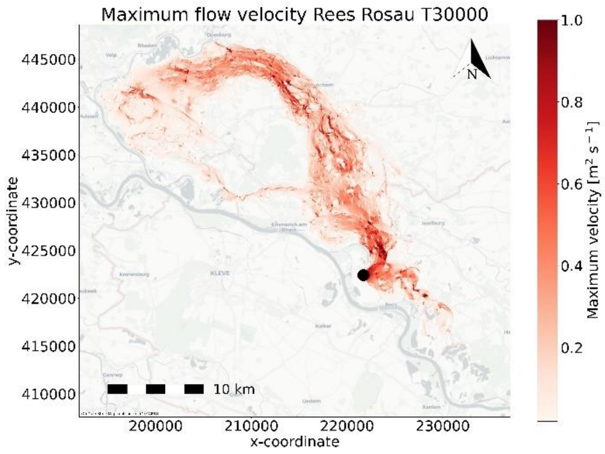
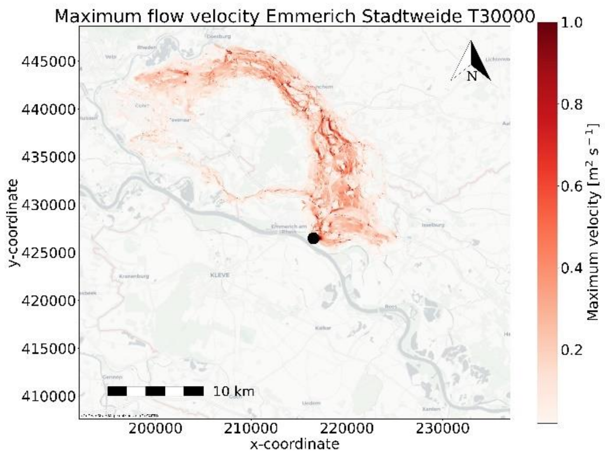
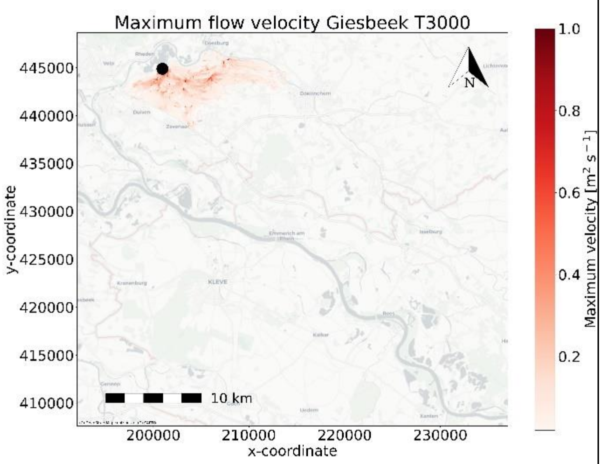
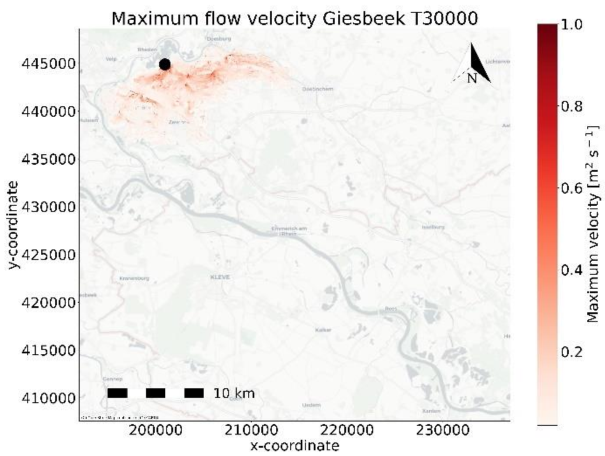
Rees Rosau		
Emmerich Stadtweide	Not applicable	
Giesbeek		

Table J-2 - Computed maximum waterdepth for D-Hydro simulations including implementation of a decompartmentation measure (breach locations are indicated with a red dot)

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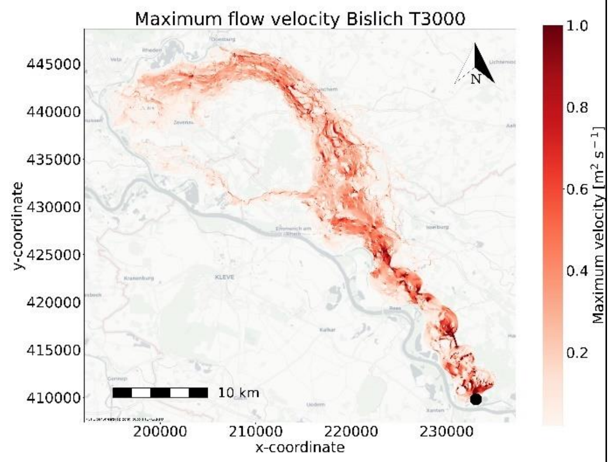
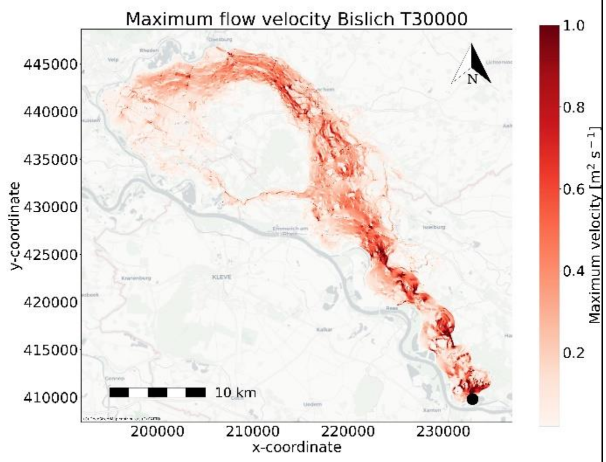
<tr><td>Bislich</td><td>
</td><td>
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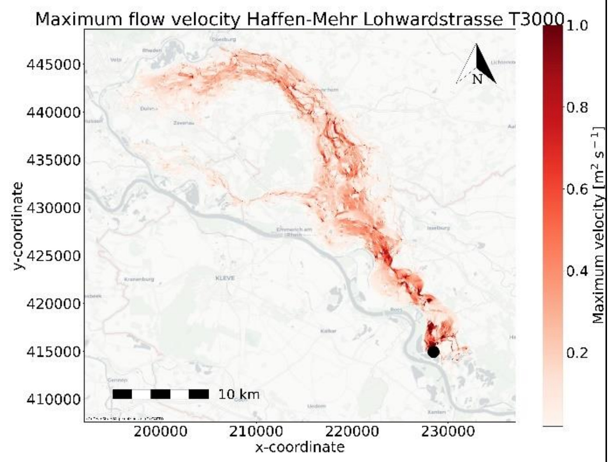
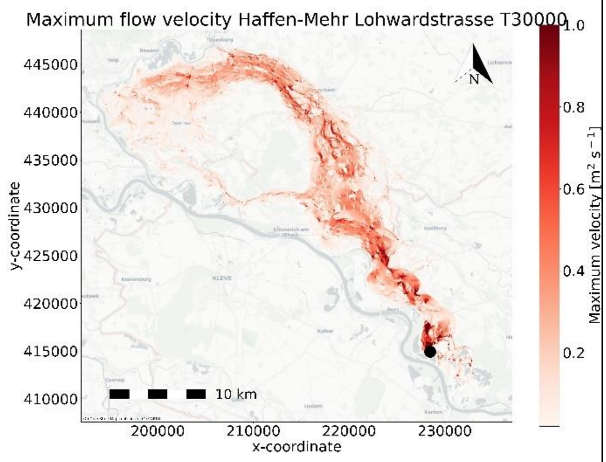
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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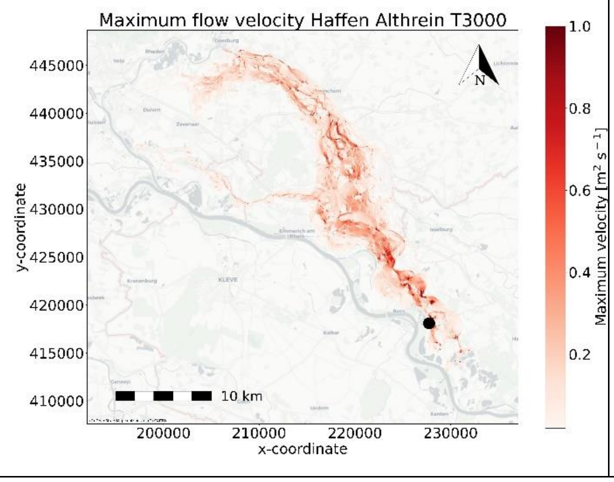
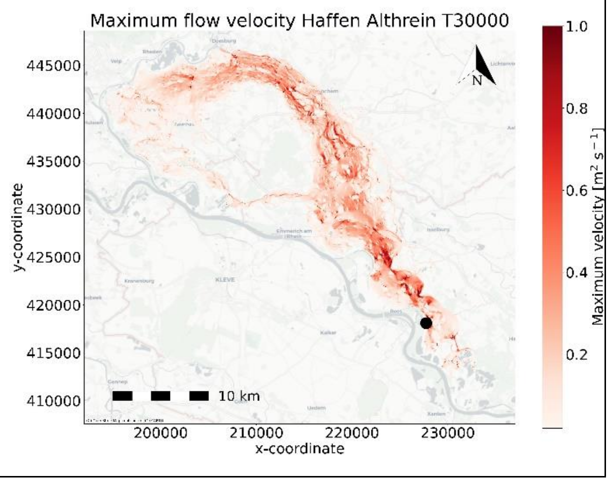
<tr><td>Haffen Althrein</td><td>
</td><td>
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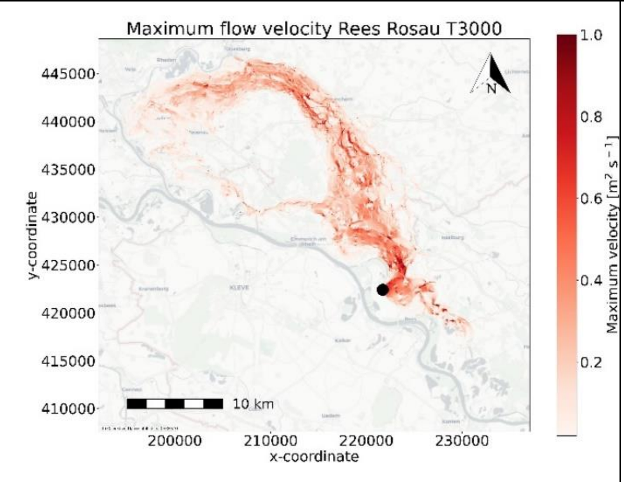

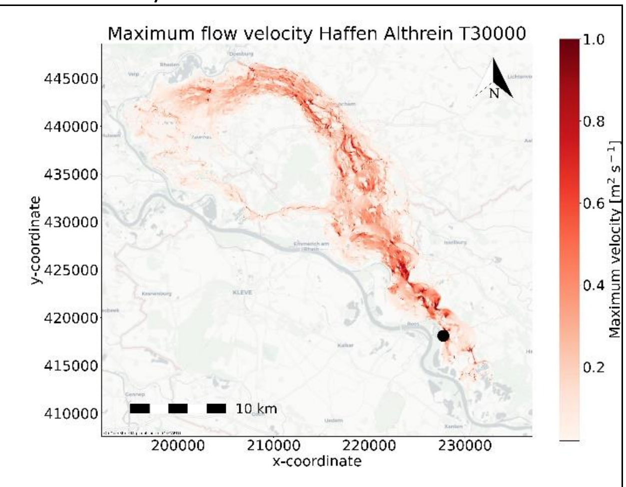

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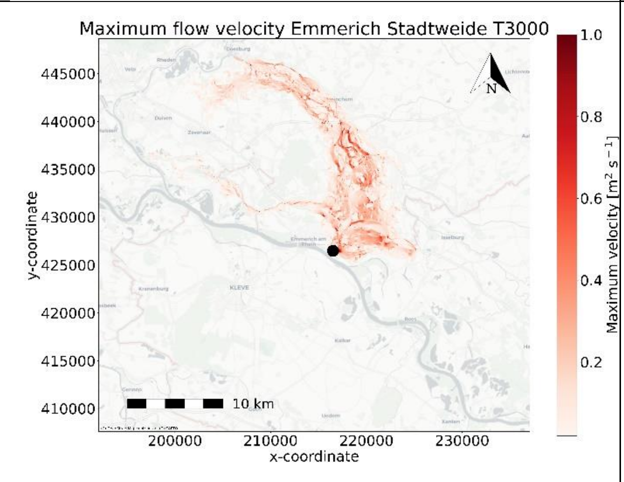
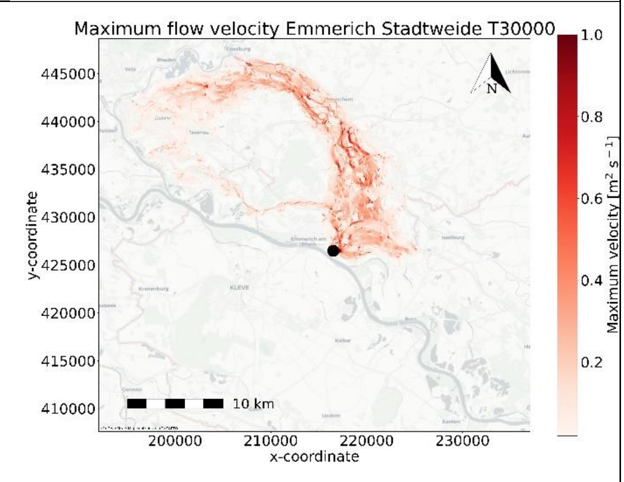
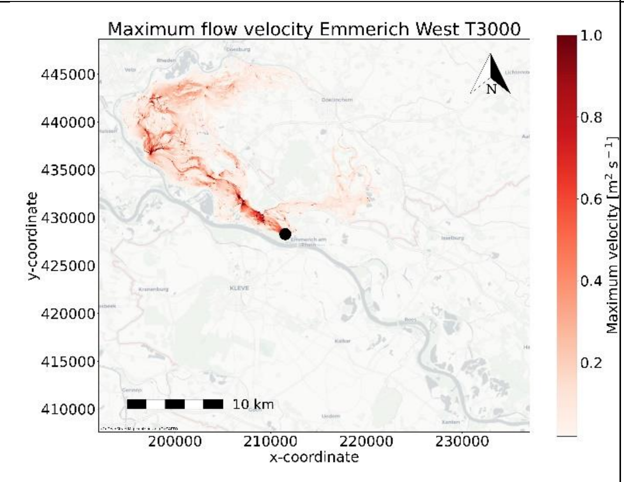
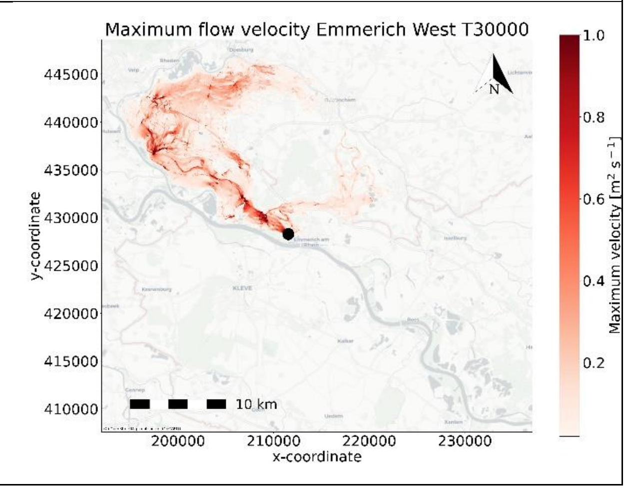


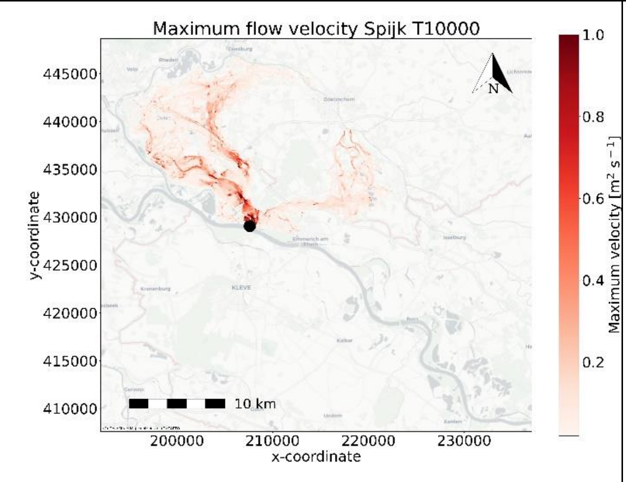


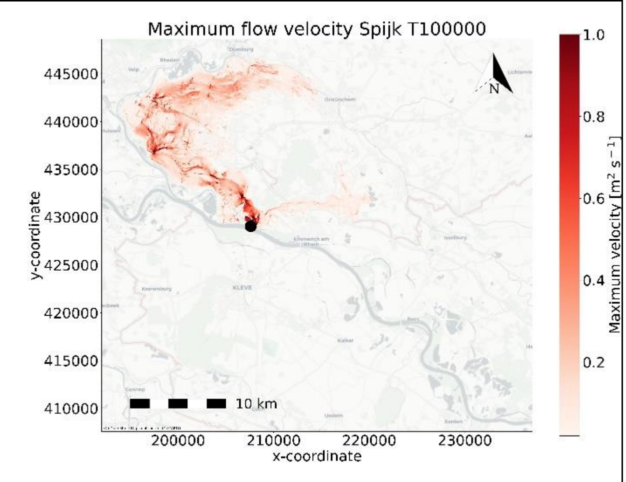
Emmerich West



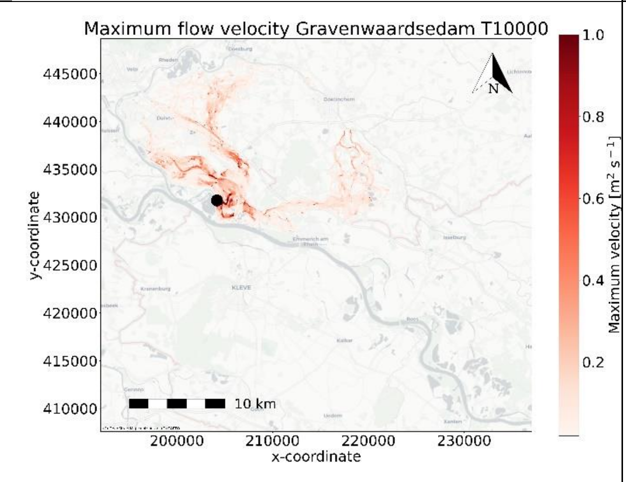


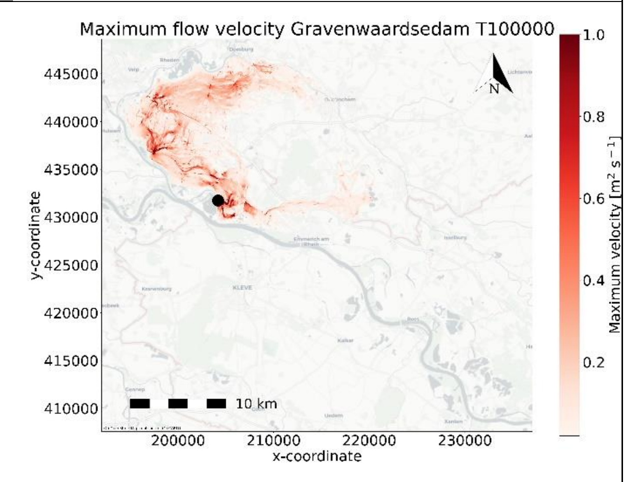
Spijk



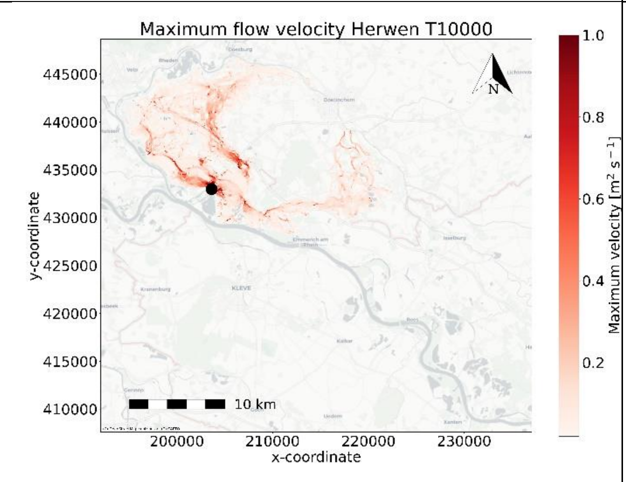


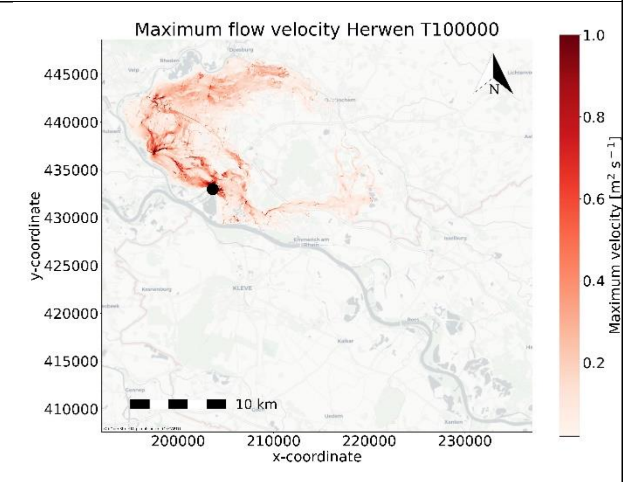
Gravenwaardsedam





Herwen





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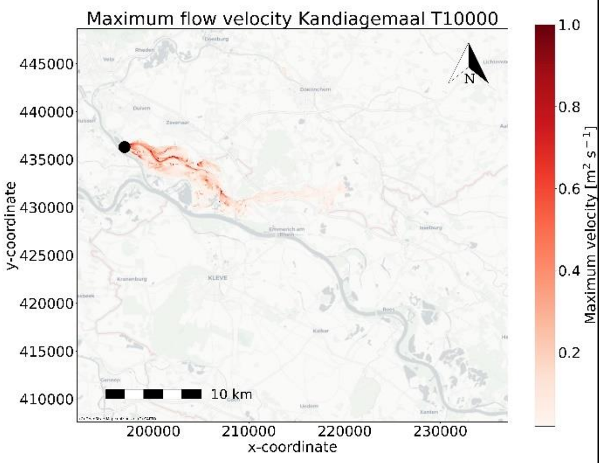
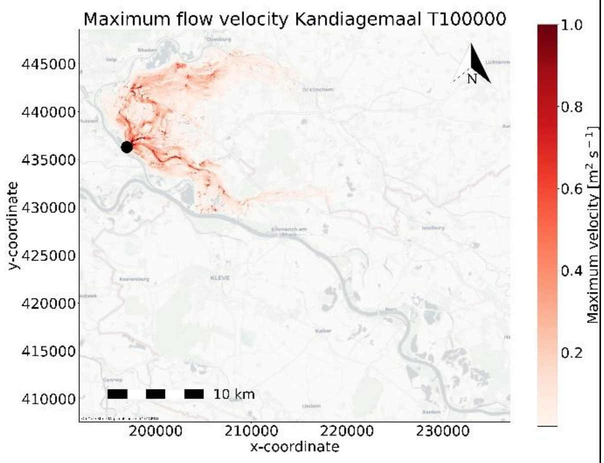
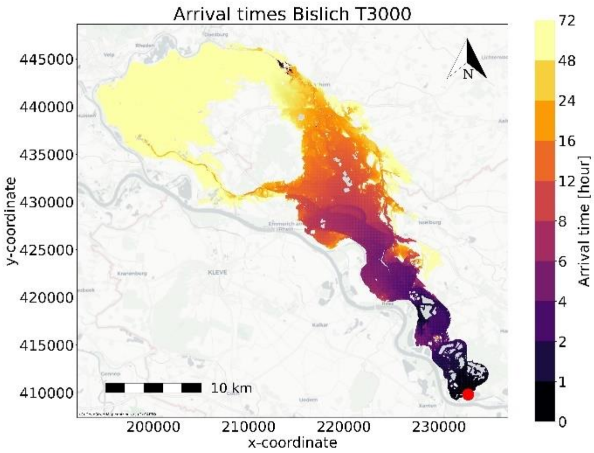
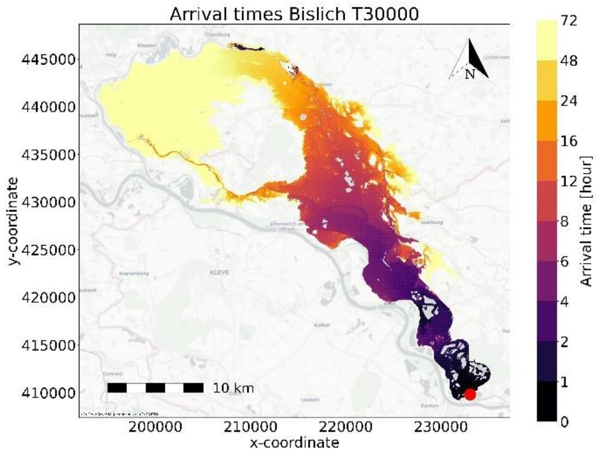
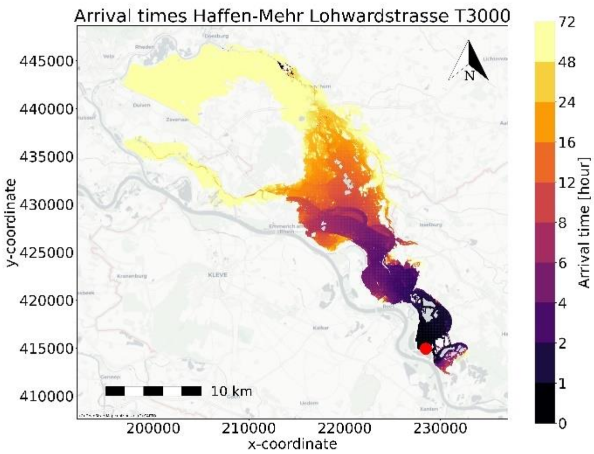
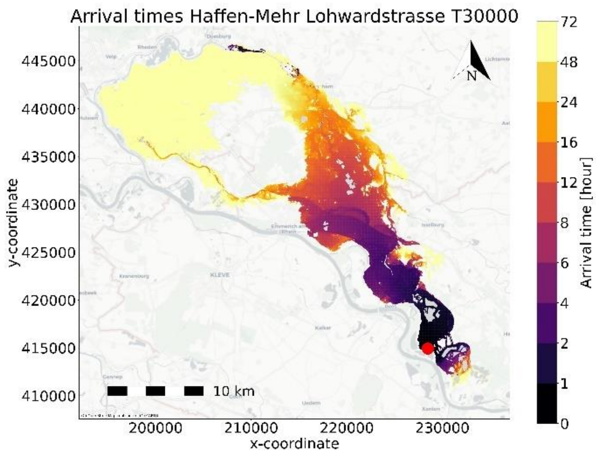
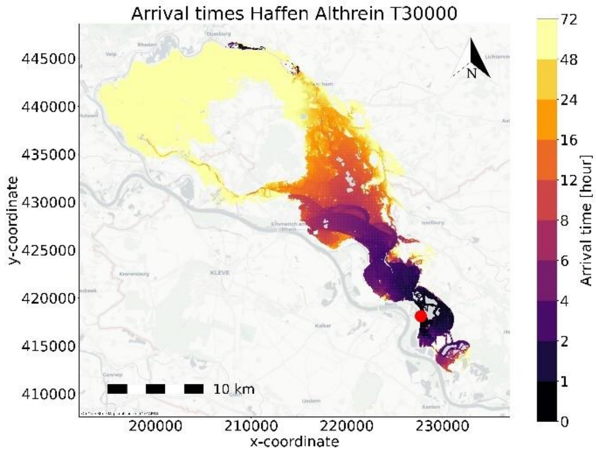




Appendix K – Arrival times flood simulations spatial measures

Table K-1 – Computed arrival times for D-Hydro simulations including implementation of a temporary flood defense (breach locations are indicated with a red dot)

	Normative scenario	Above normative scenario
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein	Not applicable	

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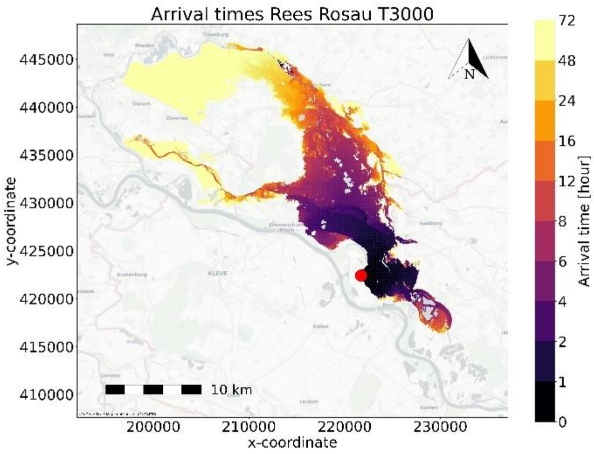
<td>
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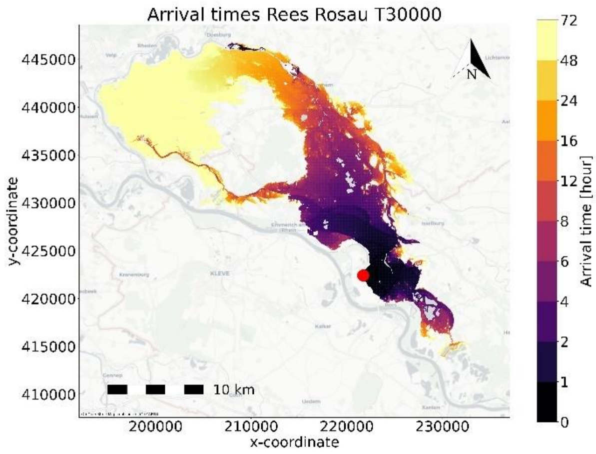
<td>
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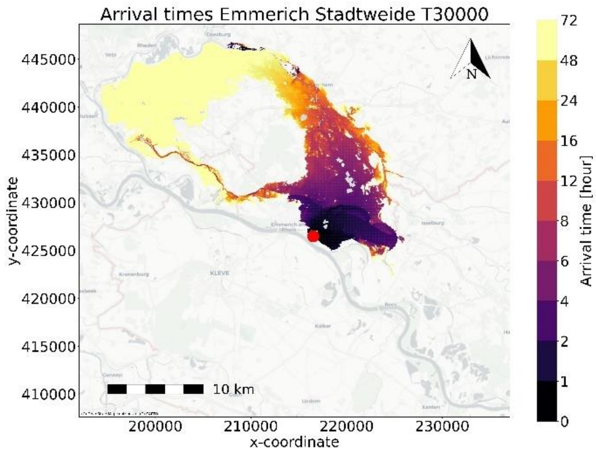
</tr>
<tr>
<td>Emmerich Stadtweide</td>
<td>Not applicable</td>
<td>
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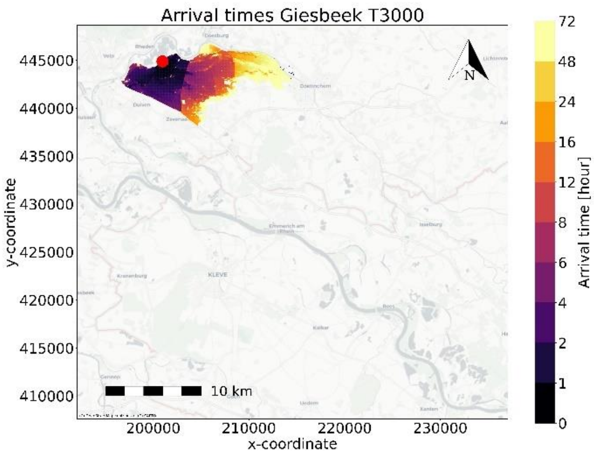
<tr>
<td>Giesbeek</td>
<td>
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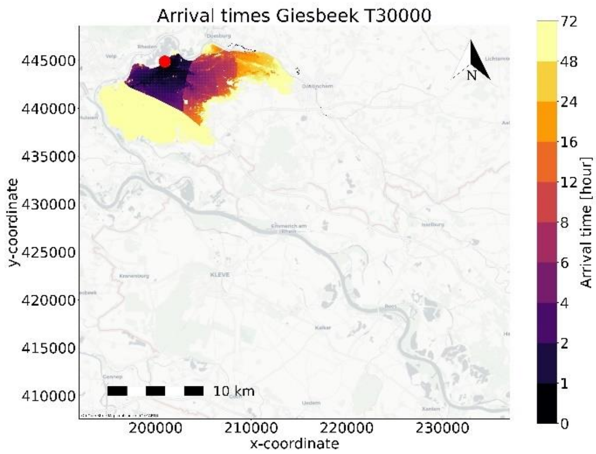
<td>
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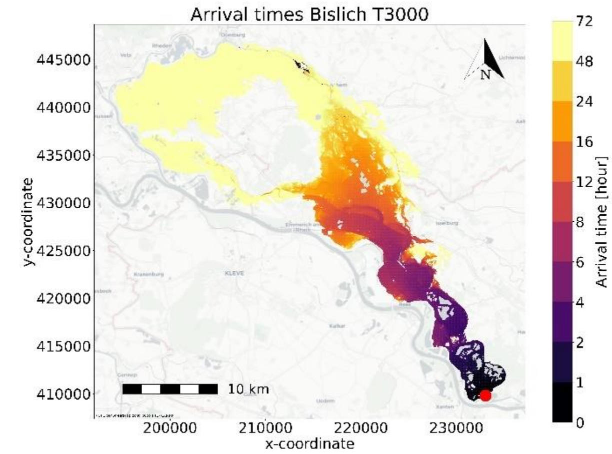
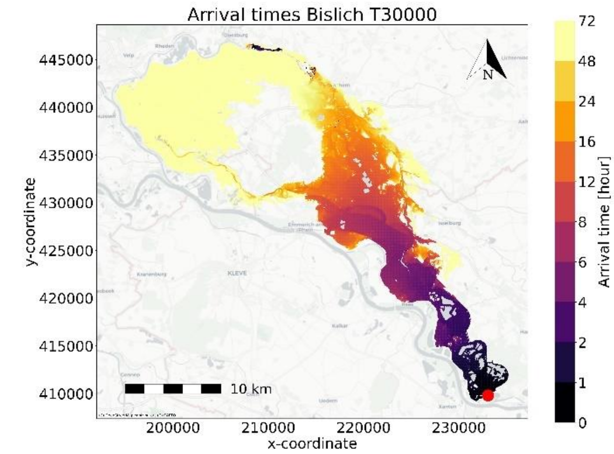
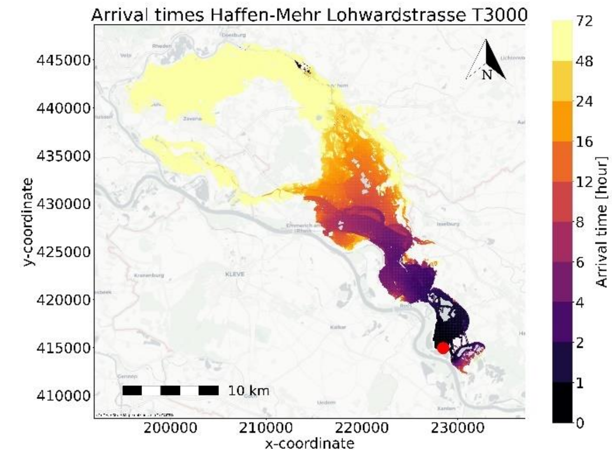
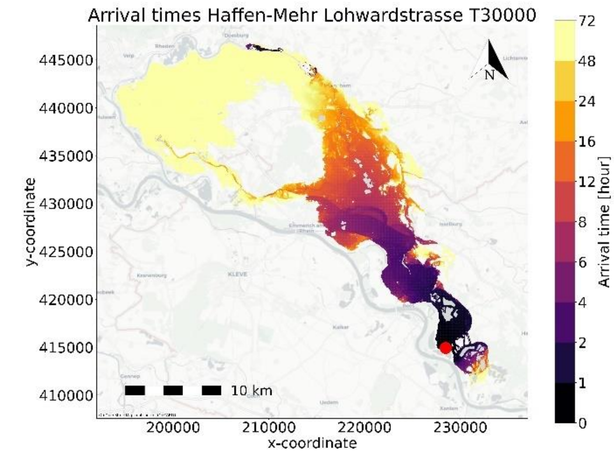
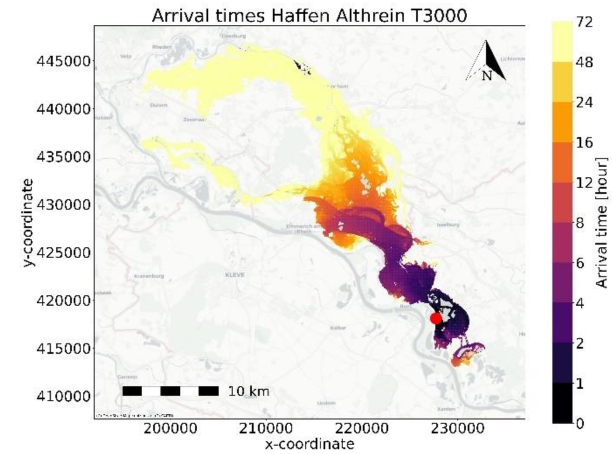
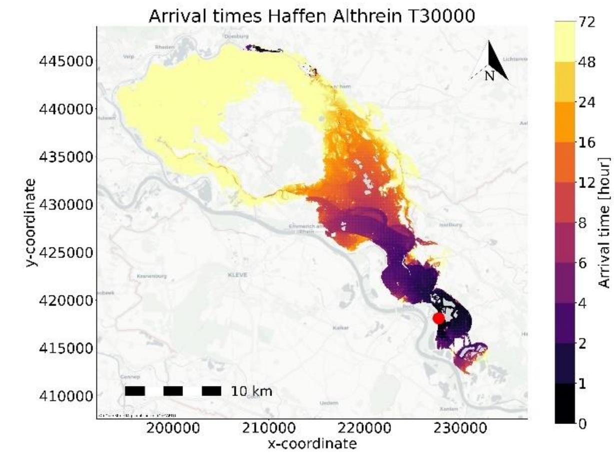
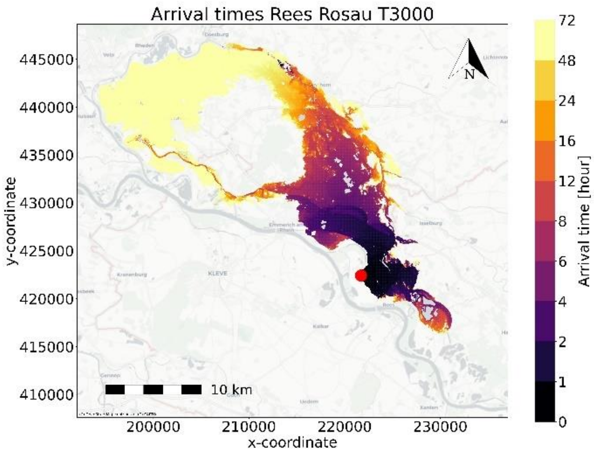
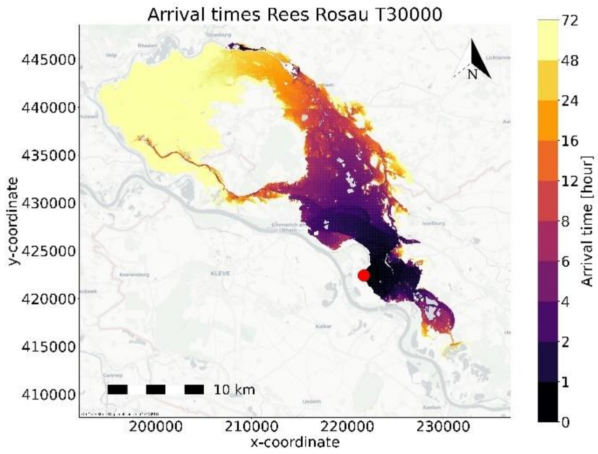
Table K-2 – Computed arrival times for D-Hydro simulations including implementation of a decompartmentation measure (breach locations are indicated with a red dot)

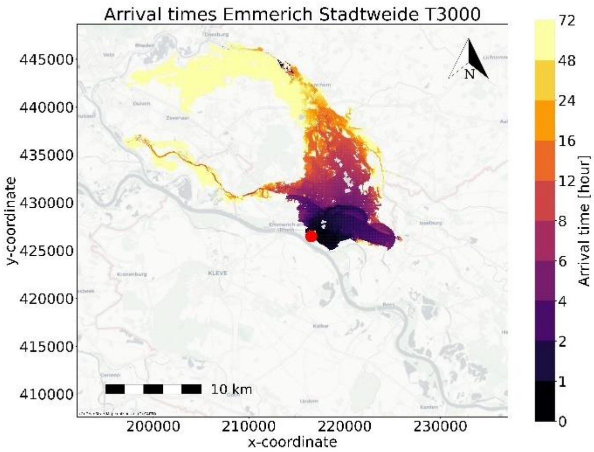
	Normative discharge scenario	Above normative discharge scenario
Bislich		
Haffen-Mehr Lohwardstrasse		
Haffen Althrein		

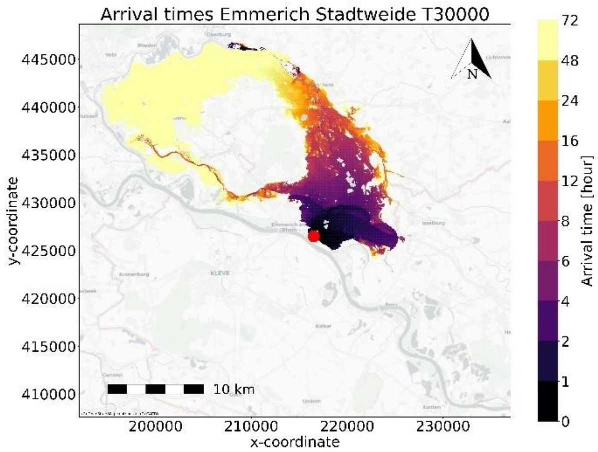
Rees Rosau



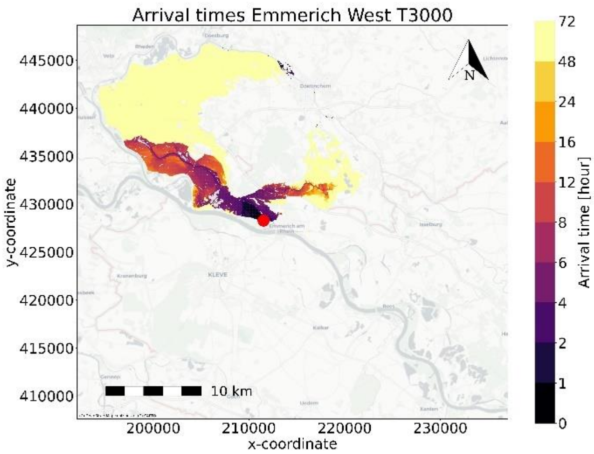


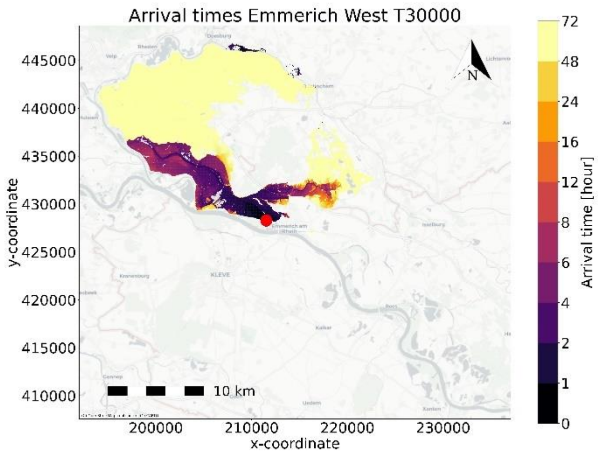
Emmerich Stadtweide

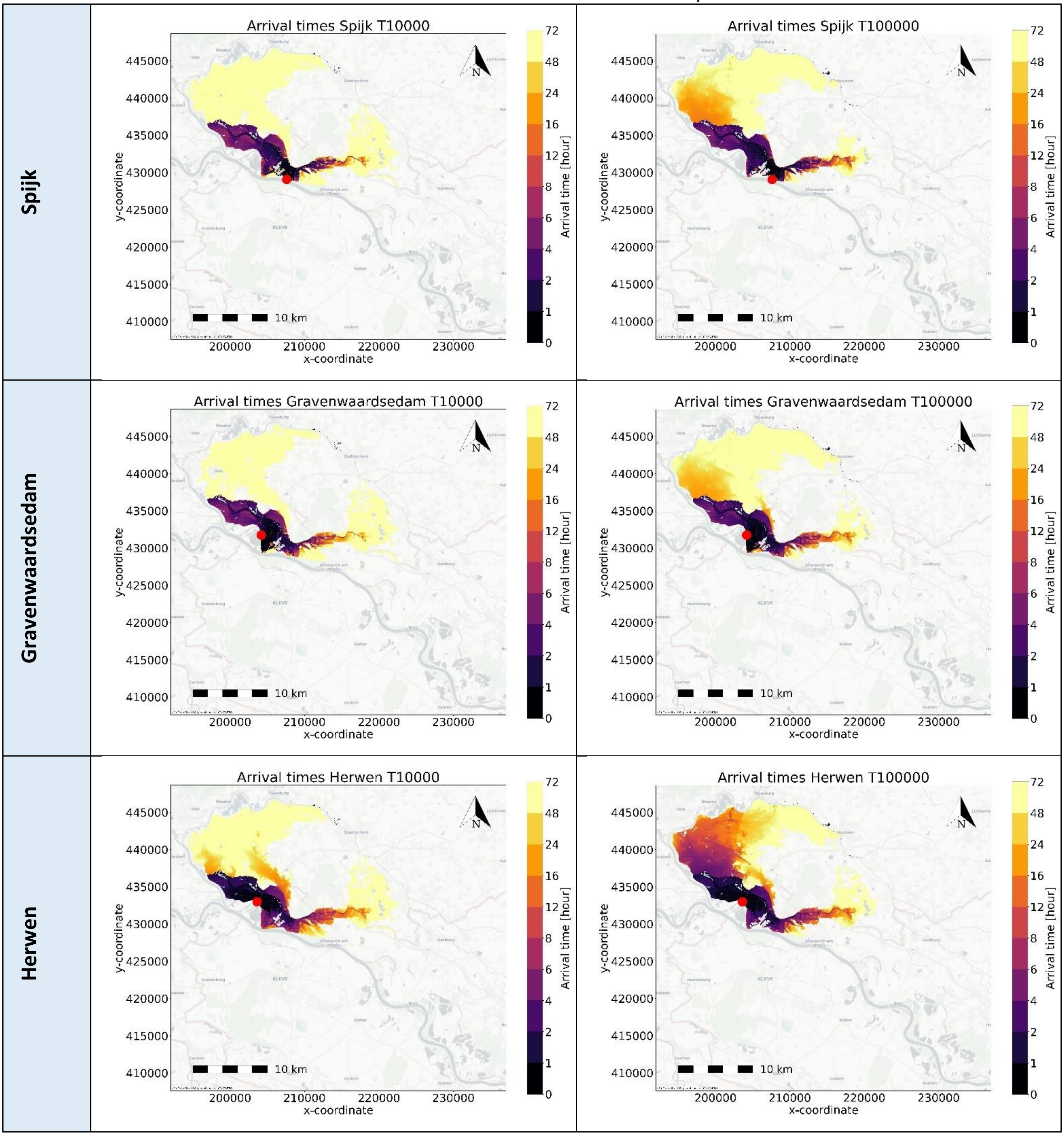


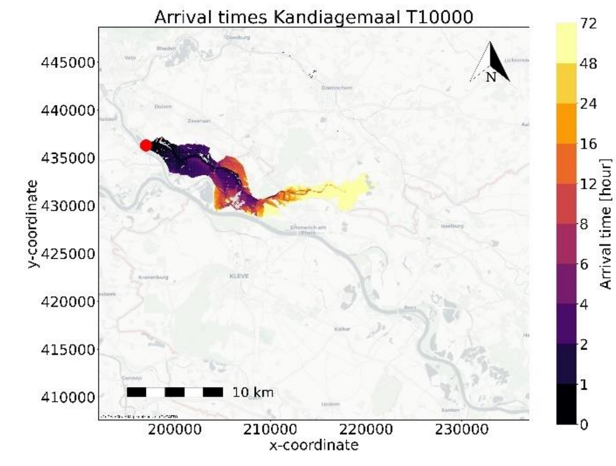
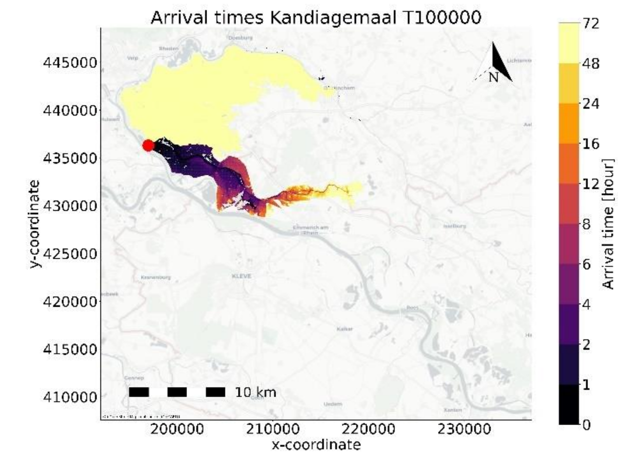


Emmerich West






Spijk
Arrival times Spijk T10000
Arrival times Spijk T100000
Gravenwaardsedam
Arrival times Gravenwaardsedam T10000
Arrival times Gravenwaardsedam T100000
Herwen
Arrival times Herwen T10000
Arrival times Herwen T100000
y-coordinate
445000
440000
435000
430000
425000
420000
415000
410000
x-coordinate
200000
210000
220000
230000
10 km
N
Arrival time [hour]
72
48
24
16
12
8
6
4
2
1
0

Kandiagemaal		

Appendix L – Ascent rates flood simulations spatial measures

Table L-1 - Computed maximum ascent rates for D-Hydro simulations including implementation of a temporary flood defense (breach locations are indicated with a red dot)

<table>
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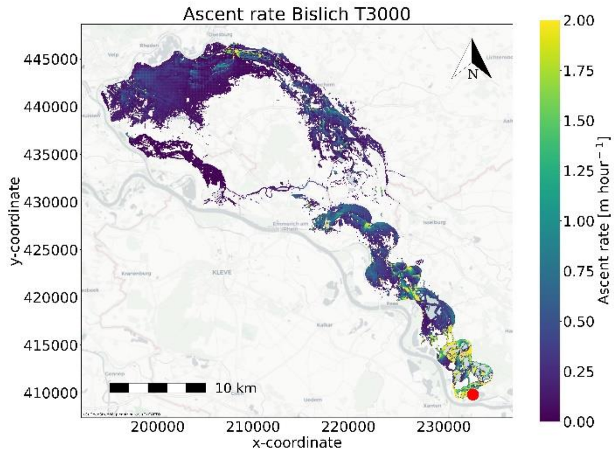

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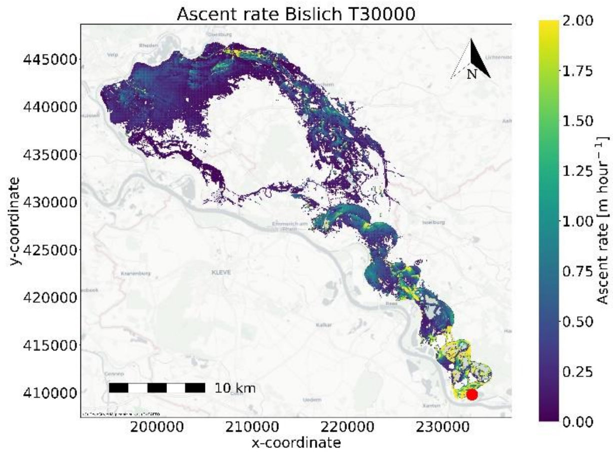

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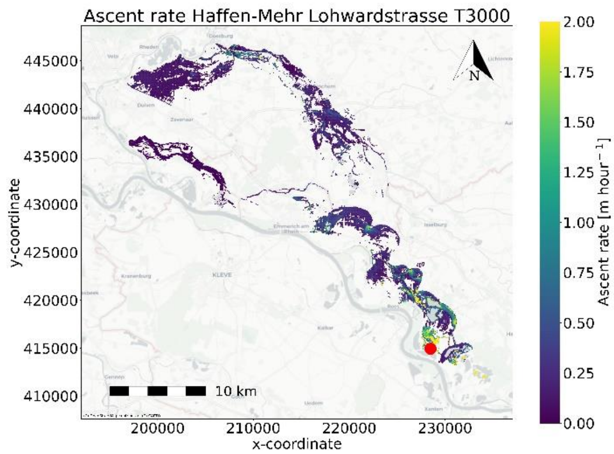

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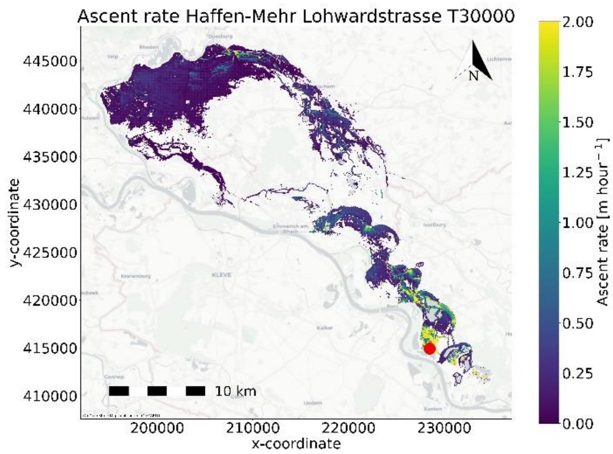
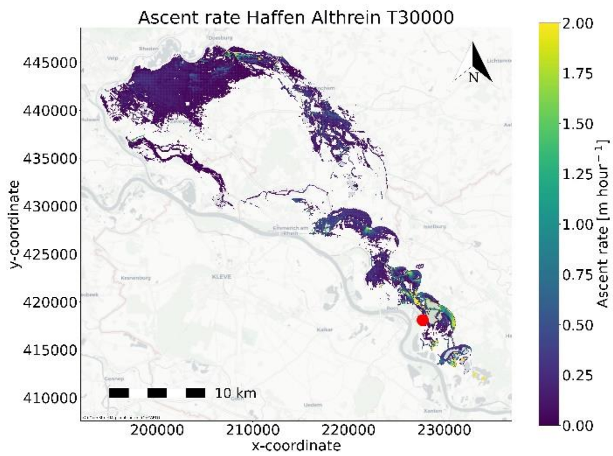


</td></tr>
<tr><td>Haffen Althrein</td><td>Not applicable</td><td>


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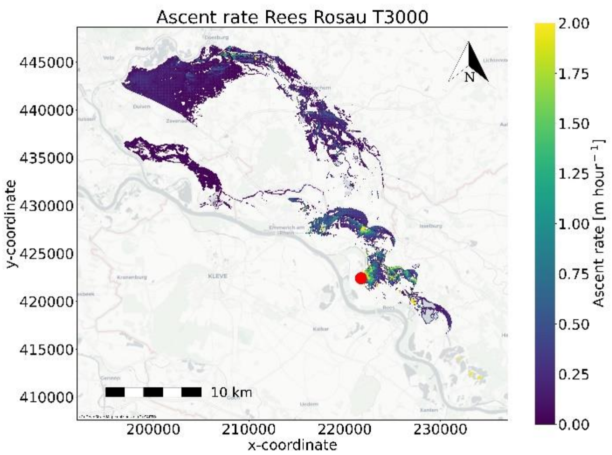
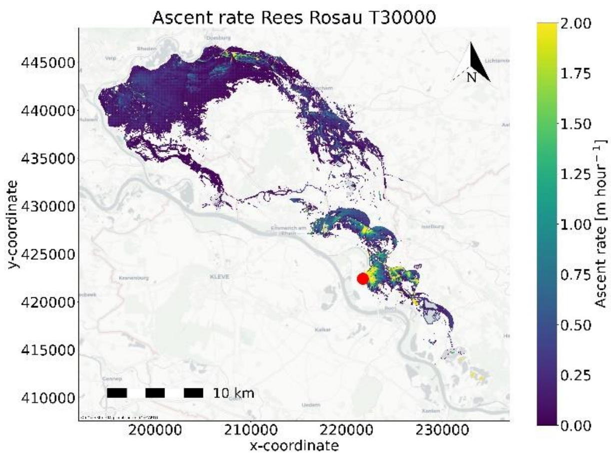
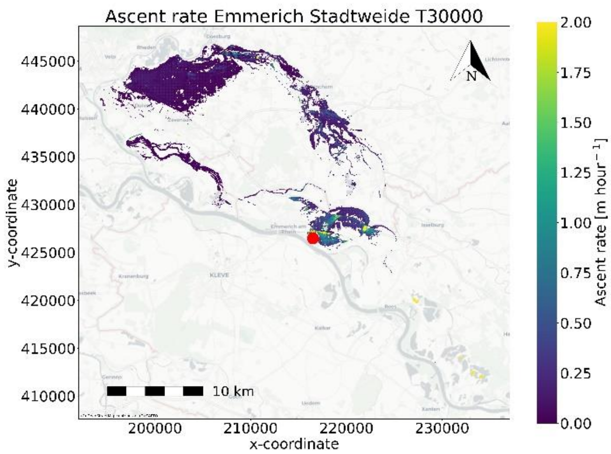
Rees Rosau



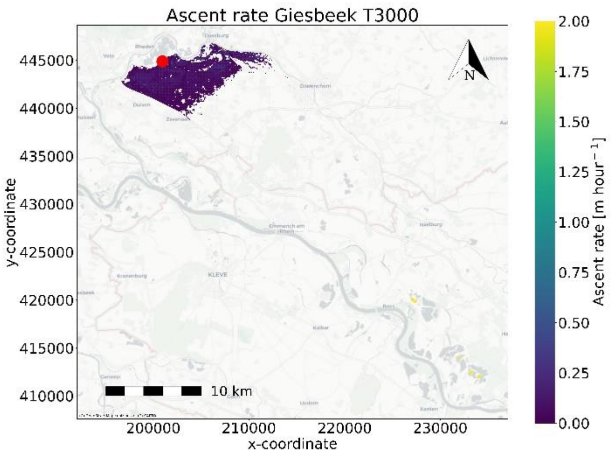


Emmerich Stadtweide

Not applicable



Giesbeek



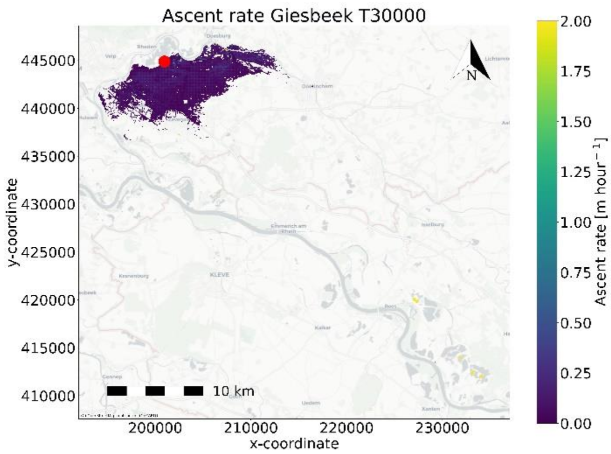


Table L-2 - Computed maximum ascent rates for D-Hydro simulations including implementation of a decompartmentation measure (breach locations are indicated with a red dot)

<table>
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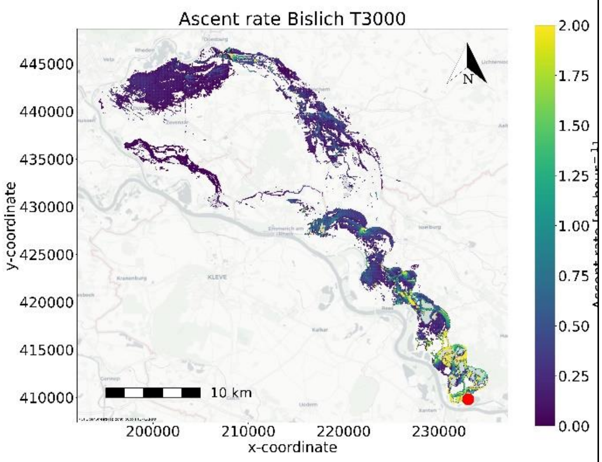
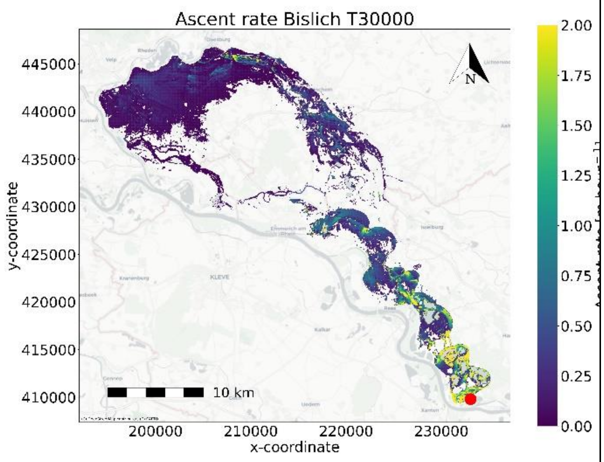
<tr><td>Bislich</td><td>
</td><td>
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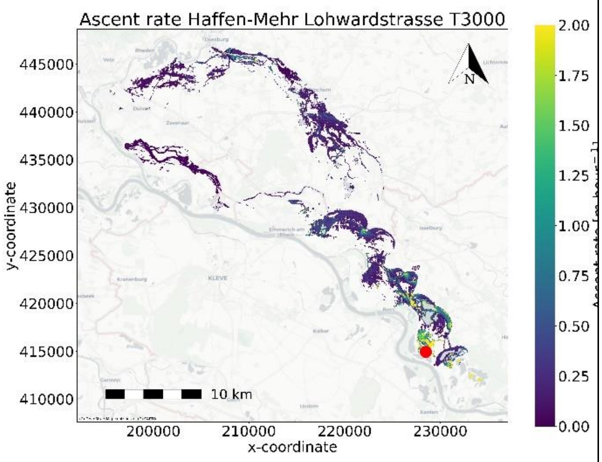
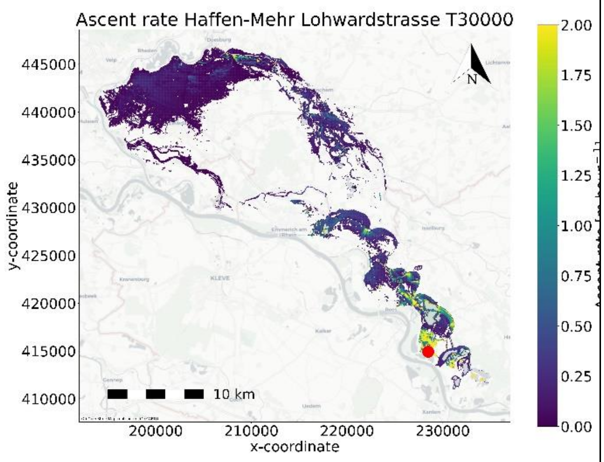
<tr><td>Haffen-Mehr Lohwardstrasse</td><td>
</td><td>
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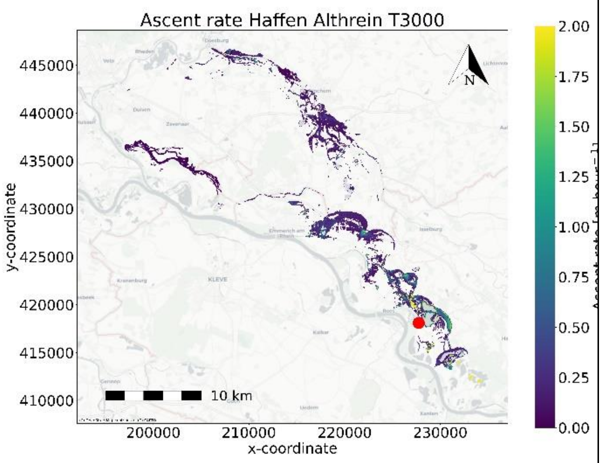
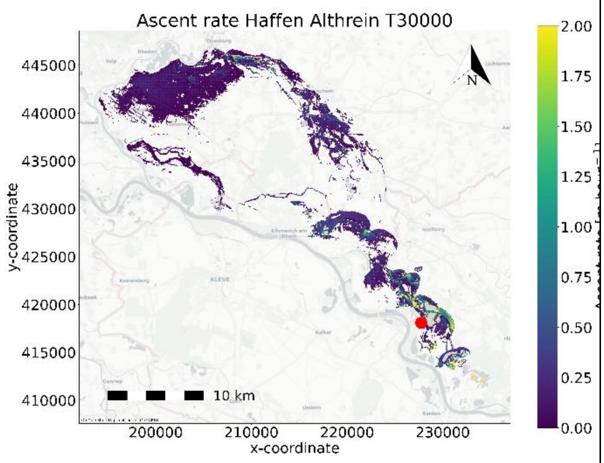
<tr><td>Haffen Althrein</td><td>
</td><td>
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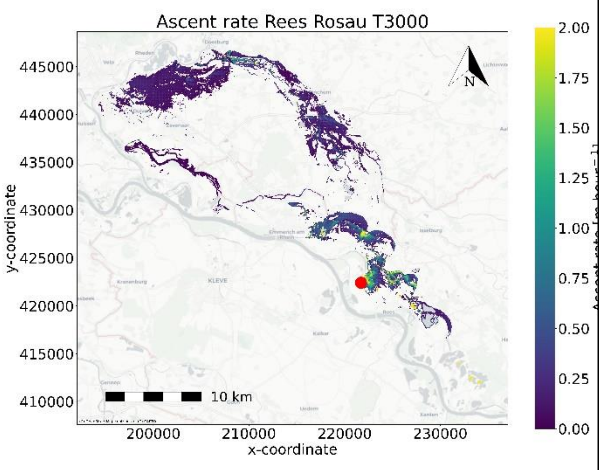

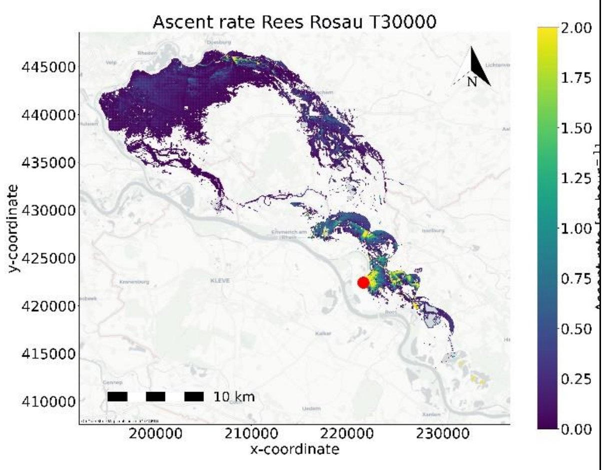

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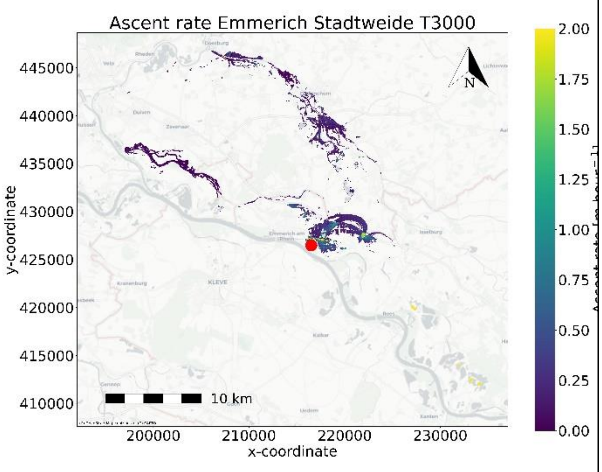

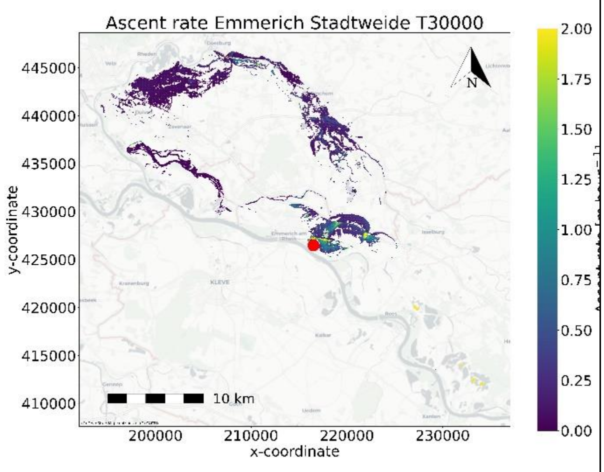

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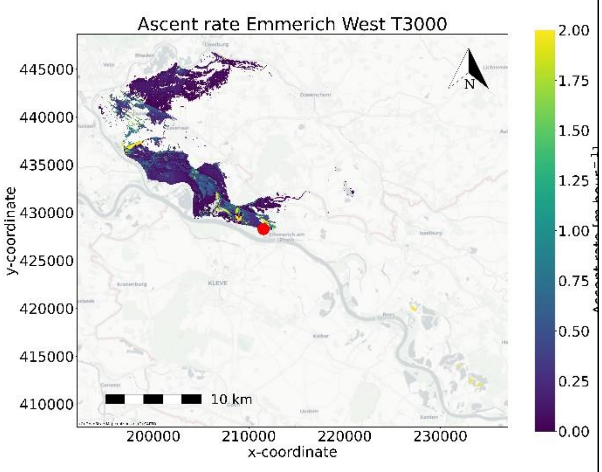

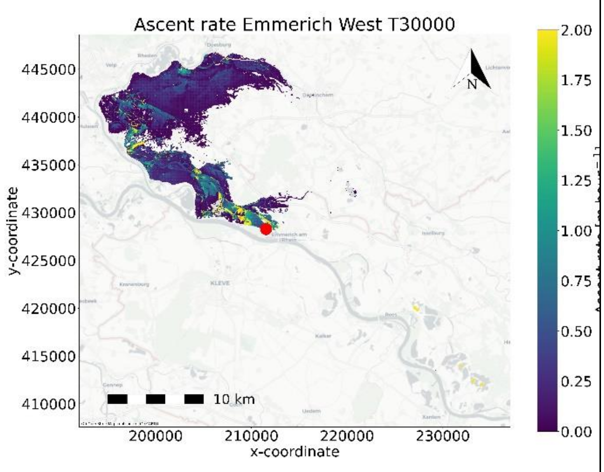

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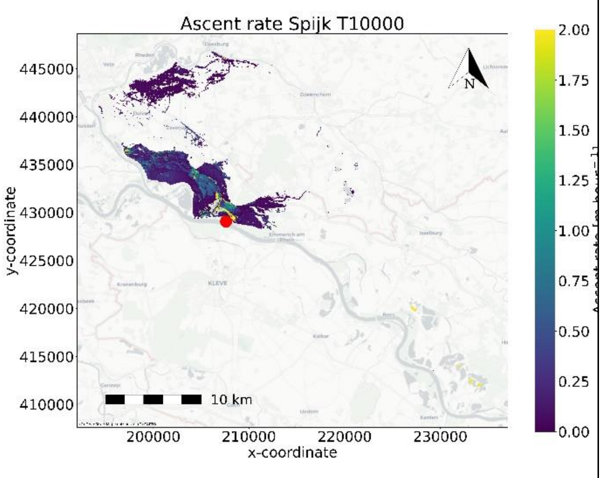

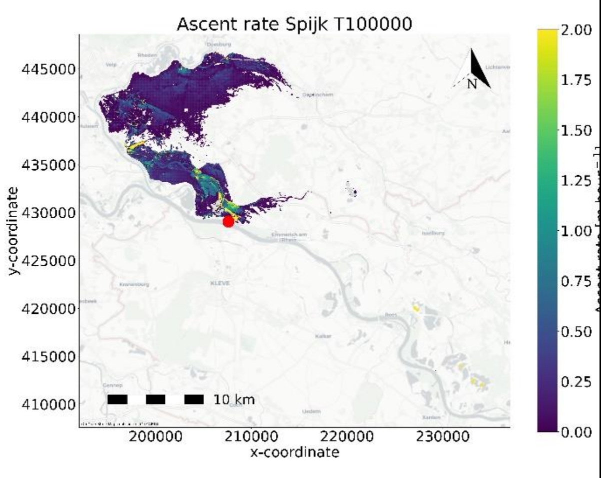

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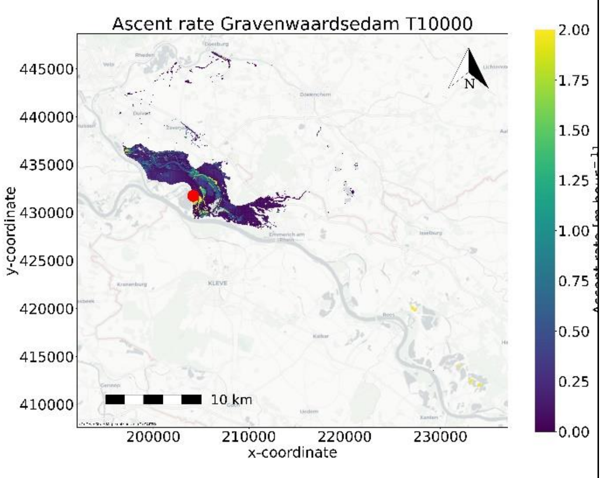

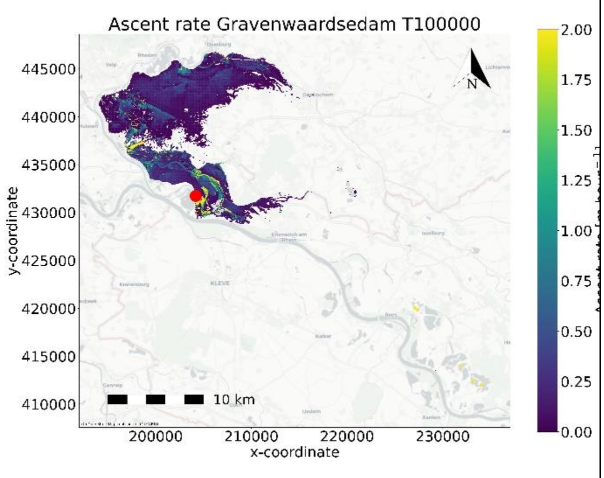

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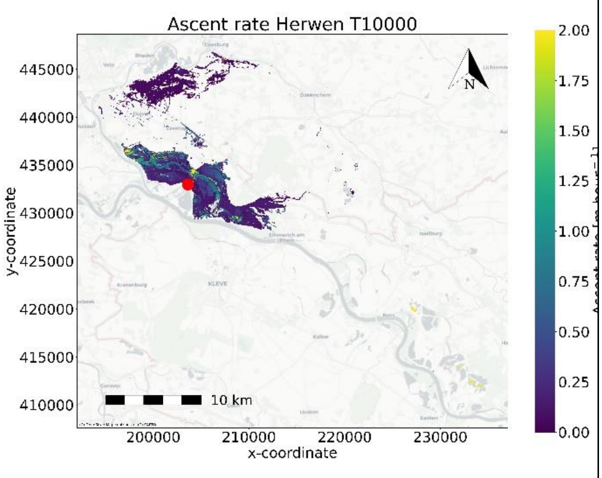

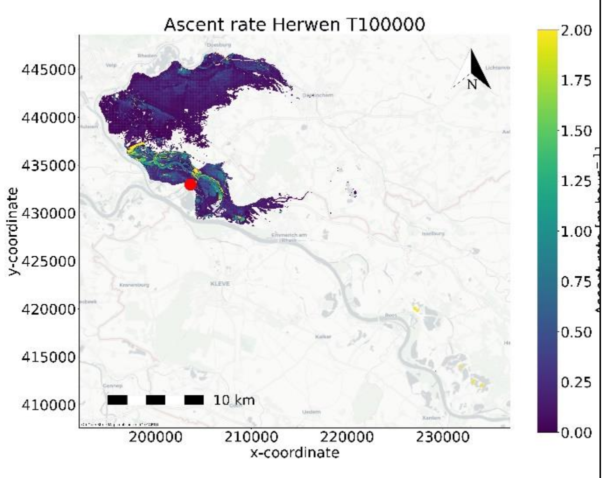

Kandiagemaal