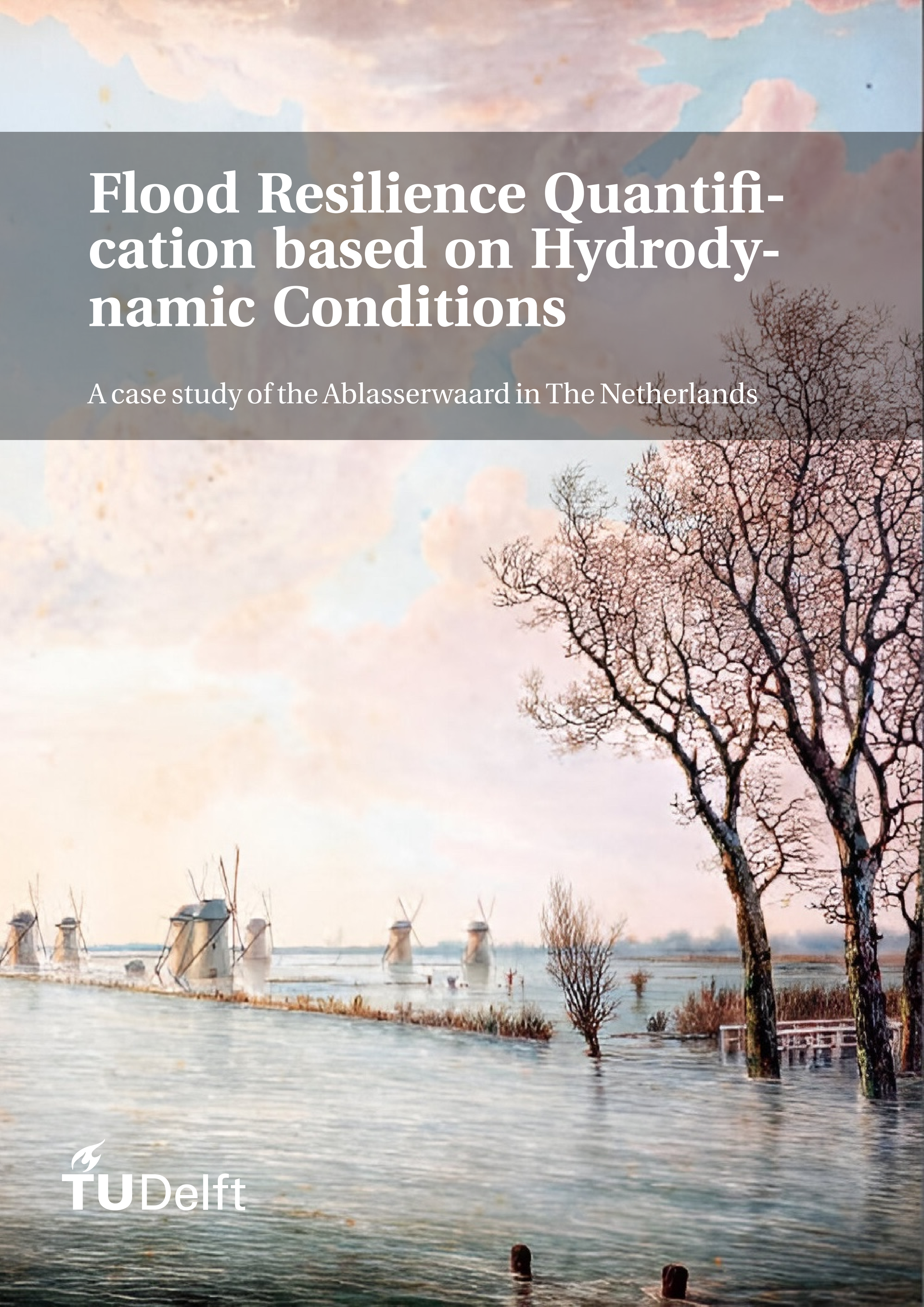
Flood Resilience Quantification based on Hydrodynamic Conditions

A case study of the Ablasserwaard in The Netherlands



TU Delft

Flood Resilience Quantification based on Hydrodynamic Conditions

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by

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Summary

Flood risk management has traditionally been centered around economic damages and casualty assessments, providing a basis for preventive measures like levees. However, with increasing climate change-induced weather extremes, a shift toward flood resilience is necessary. This shift involves accepting some level of flooding while enhancing system recovery and damage mitigation. Existing resilience frameworks offer only qualitative insights or rely on significant assumptions, limiting their applicability in objective assessments.

This research focuses on addressing the challenges of quantifying flood resilience, a concept inherently complex due to its multi-layered nature and reliance on diverse perspectives. By incorporating hydrodynamic conditions such as water depth, flow velocity, and momentum, alongside local topography and land use, this study aims to propose metrics that better capture the temporal and spatial dynamics of flood resilience. This enables objective evaluation of mitigation measures, guides resource allocation, and facilitates informed decision-making for engineers and policymakers alike. This could subsequently enhance flood risk frameworks and increase flood safety in The Netherlands.

A methodology for quantifying flood resilience through hydrodynamic modeling is presented in this study. It identifies functionality variables like temporal water depth, temporal impact, number of flooded buildings, and percentage dry area as central to assessing resilience. From these functionalities, resilience metrics are derived, like shock amplitude, arrival time, and residence time.

The methodology is tested through a case study in the Alblasserwaard. The study uses 3Di modeling software to simulate flooding scenarios and evaluate the applicability of resilience measures. This is done through model variations and interventions such as detention basins, moveable barriers, and enhanced pumping capacity. The chosen case study includes diverse land uses, enabling the assessment of resilience across residential, economic, and ecological perspectives.

The metrics of shock rate, residence time, flood arrival time, and flooded utilities provide promising insights into flood resilience. The derivative shock rate evaluates emergency response service capacity, while residence time assesses damage extent and recovery time. Adding indirect hydrodynamic conditions, like nearby flooded roads and utilities, further enhances system understanding in the provided case study. Different perspectives highlight the variability in suitable metrics as well as suitable interventions.

However, some metrics require further research or modification. The depth integrals show potential during shock and recovery, but they lose information when used as a linear metric between time and water depth. The flooded utilities metric provides valuable insights but needs expansion to accurately reflect flooding consequences. The momentum impact metrics are unsuitable for the current model due to limitations in 3Di's flow velocity calculations.

While the method proved feasible for identifying and comparing resilience in a specific system, further research is needed to address uncertainties, refine metrics for indirect effects, and test applicability beyond the presented case study. This framework represents a further development toward a comprehensive, objective approach to flood resilience, supporting effective, adaptable flood management solutions even under the continuous threat of increased climate extremes.

Acknowledgments

Before you lies my master's thesis, "Flood Resilience Quantification based on Hydrodynamic Conditions", which is the final hurdle of my time at Delft University of Technology before I get to call myself an engineer.

During my master's, I got to dip my toe in the wonderous world of hydraulic engineering, exploring a wide variety of topics in various locations, from Eastern Europe to Africa and Southeast Asia. It, therefore, seemed only fitting that I turn my focus back to The Netherlands for the final stint of my studies. I have done so by immersing myself in the complicated world of flood resilience, with conflicting views, long policy documents, and complicated metrics. However, it is also the world of more sustainable, long-term flood management, in which many strides are to be made in the coming years. I am grateful that I got to contribute to the body of research pushing flood resilience forward.

I want to thank Juan-Pablo for his never wavering enthusiasm, insights, and patience during our meetings. I have learned a lot from you, and if I'm lucky enough to supervise my own master's student soon, I'll take inspiration from your style of teaching and education. To Saul, thank you for your supervision and for helping me through the final stages of the thesis, where your positive attitude kept me going. Also, thank you, Olivier, for completing my committee and providing fresh insights, which gave new life to this project.

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I also want to thank my friends and family for their support during this time. My parents and little brother for putting up with my endless curiosity and fidgeting. I regret to inform you that this likely is not changing any time soon. To my colleagues of Fluid Mechanics that became my friends, it falls to you to keep expanding the meme wall in the office now, I'll come by to check the progress. To Patrick, Kevin, and Jan, you guys re-ignited a passion for learning that I had partially lost in my bachelor studies, for which I will be forever grateful. Patrick again, for being the person I spend the most time with in the last two years and with whom I talked for hundreds (?) of hours about the troubles in our respective study trajectories.

Lastly, to my girlfriend, for going through the whole thing with me and being there when I wasn't always the best person. Our bilateral support is what got us both through our theses, I think. Even though it is for reasons neither of us could control, I still want to say: "I did beat you in the end ;)", even if it was by only a week. Looking forward to a well-deserved holiday for the both of us.

Mats Kerver

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Introduction

For a long time safety standards for flooding have been defined by using flood risk frameworks as guidelines. Flood risk is often expressed in monetary terms or casualties, for example, annual expected damages per year in a given area (Klijn, Kreibich, De Moel, & Penning-Rowsell, 2015). With that information, it can be determined if a new resistive measure (like a levee) is an investment that is statistically and financially sound.

In The Netherlands specifically, this was initially done by defining dike rings, and subsequently assigning an allowable failure return period of, for example, once per 10.000 years. However, this method became outdated in more recent years as it can result in unnecessary high demands on levees or lower-than-expected safety standards as a result of compounding effects on these dike rings (Klijn & van der Most, 2013). To address this issue a more refined version, defining allowable failure return periods for dike sections instead of entire rings, has been in effect since January 1^{st} 2017 and is defined in the Waterwet (Rijksoverheid, n.d.). Another modification was the change from using the overtopping probability (Dutch: overschrijdingskans) to the 'flooding probability' (Dutch: overstromingskans), allowing a more refined design of individual dike sections(STOWA, 2021).

Recently, partly due to climate change, the state-of-the-art in flood safety has shifted to flood resilience. This is necessary because the changing weather patterns and increasing climate extremes make it unfeasible to completely prevent flood events. The fundamental principle of flood resilience is the acceptance of some degree of flooding and potential damage to flood-prone areas rather than attempting to completely prevent it. These areas (often referred to as systems) are designed to withstand and recover from certain limited levels of flooding. An example of this are the amphibious residences in Maasbommel, where the main structure can float in case of high water-levels (*Amfibiewoningen, Maasbommel*, n.d.). Residents in the area are then expected to cope with this limited level of flooding, becoming more experienced in mitigating its consequences. This approach is advantageous because flood resilience frameworks employ a more comprehensive approach to designing a system with flood safety in mind. This results in a more accurate representation of system response behavior.

To that end, in The Netherlands, the concept of Meerlaagsveiligheid (multi-layered flood safety) was introduced in the 'Nationaal Waterplan 2009-2015' (Rijksoverheid, 2009). The idea of this plan was to not simply prevent floods, but also learn how to mitigate the consequences and streamline rescue and evacuation procedures. In practice, these layers were described by (STOWA, 2015):

1. *Flood prevention:* Increase the size of levees and dams, reduce hydraulic load, and building-with-nature solutions.
2. *Flood mitigation:* In case a flooding event occurs, reduce the consequences of this event. This can be done by compartmentalizing areas, protecting critical infrastructure, adaptive building (on piles), and preventing building in risky locations.
3. *Emergency response:* Improve the protocols and infrastructure for emergency services or evacuation,

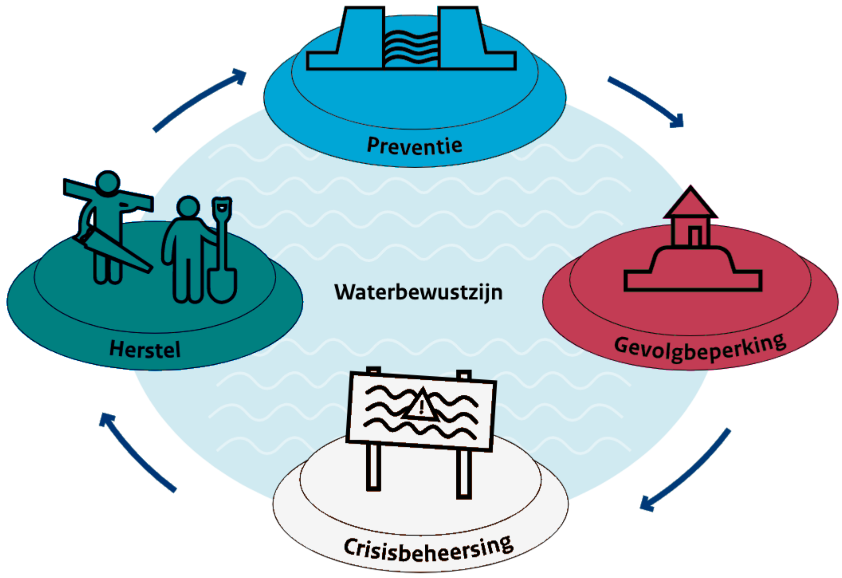


Figure 1.1: The concept of Multi-layered flood safety in The Netherlands, modified from (Eindadvies Beleidstafel wateroverlast en hoogwater, 2024)

improve information distribution to stakeholders, etc.

After the 2021 Limburg floods, the multi-layered flood safety approach was extended further. It received two extra layers (Eindadvies Beleidstafel wateroverlast en hoogwater, 2024) that can also be seen in Figure 1.1:

0. *Water awareness:* Inform residents that they reside in flood-prone areas, and make sure they are prepared and informed before floods occur. When floods occur the expectation is that residents can stay self-sufficient for a while and know what actions to undertake.

4. *Recovery:* After a flood event, the area should be repaired and recovered in such a way that a similar flood event will lead to less severe consequences on the system functionality (Disse, Johnson, Leandro, & Hartmann, 2020).

In this multi-layered flood safety approach, the older flood risk strategy primarily focuses on prevention. All other layers are interconnected with flood resilience in some manner, demonstrating a more comprehensive approach to flood management. When implemented effectively, this holistic approach could establish a new benchmark in flood management in years to come.

1.1. Problem Description

When designing an area for flood resilience, one of the largest problems is determining the definition of resilience and how to quantify it. The multi-layered approach, present in the definition of (flood) resilience, makes this quantification problematic. Furthermore, the definition of resilience as '*the measure of a system to absorb shocks and still persist*' (Holling, 1973) can be interpreted in many different ways, which makes quantification difficult.

Hosseini, Barker, and Ramirez-Marquez (2016) provides an extensive overview of the different frameworks and methods that can be used to quantify resilience. However, most of these metrics use either qualitative methods (Kahan, Allen, & George, 2009; Vugrin, Warren, & Ehlen, 2011) or quantitive methods, usually based on cost-benefit analysis, that require significant simplifications or assumptions (Ayyub, 2014; Baroud, Barker, Ramirez-Marquez, & Rocco S., 2014).

These assumptions render the quantification of flood resilience challenging. For example, Wever (2022) noted that damage from floods is often significantly over- or underestimated (between -36% and +62% in the paper study case of Beira). This stems from the inherent complexity of determining monetary damage based on strictly maximum water depth, which is often used. Two methods frequently used in The Netherlands to determine the estimated damage of flooding are the Waterschadeschatter (WSS) (STOWA, n.d.) and the Schade-en Slachtoffer Module (SSM) (Rijkswaterstaat, 2024). In a study, the authors found that in 42 out of 96 scenarios (43.75%), the difference between both models was more than 100% (Hoff & Lieshout van, 2023). It should be noted that these models have different intended uses, with the SSM trying to accurately capture damage due to large-scale flooding and the WSS attempting to calculate small-scale flooding. Especially damage due to regional flooding is therefore hard to properly calculate, as it falls outside of the targeted flooding occurrence for both methods. This makes it difficult to asses and compare flood-prone areas on the regional scales, something this research attempts to contribute to.

Resilience (quantification) is also highly dependent on the perspective from which it is evaluated. A system may exhibit resilience from an economic standpoint, allowing companies to continue operating within the region. Conversely, it may completely collapse when viewed from an ecological perspective, as the ecosystem in the area does not recover. Without distinguishing between these divergent interests, a quantification of resilience will remain at a superficial level.

Furthermore, in some areas, flooding damage occurs instantly upon inundation, independent of water depth, whereas in other areas the damage only occurs after a certain time, water depth, or flow velocity (Choi, Lee, Chung-Seong, Shim, & Kim, 2006; Kreibich et al., 2009). This temporal aspect of flooding also affects the recovery of an area of interest, which is an important part of the flood resilience frameworks. Current frameworks for flood risk and resilience mostly don't take this temporal evolution into account.

In conclusion, while many frameworks exist attempting to quantify the flood resilience of a system, the current assumptions and applications make it difficult to compare these different systems and solutions. As a result, the application of flood-resilient strategies has remained problematic in the (re)design of flood-prone areas.

1.2. Objective

The objective of this thesis is to develop a methodology that is capable of quantifying flood resilience based on hydrodynamic variables and their post-processing. This is attempted by proposing and testing different metrics that include the variables time, depth, velocity, and momentum along with local topographic and land-use conditions. By doing this, the evaluation of different mitigation measures can be done more objectively, clarifying information for engineers and policymakers alike. This approach enables the allocation of resources to areas where the positive impact on the system is most significant.

This research aims to achieve this quantification of flood resilience by utilizing hydrodynamic conditions, incorporating the factors shock, impact, recovery, and mitigation while enabling the comparison of different perspectives and interests within a specific study area.

1.3. Research Questions

This thesis attempts to answer the following question in its research, with the subquestions needed to answer the main research question. Each of the questions is elaborated upon with a short hypotheses. The main research question of this thesis is:

Can the flood resilience of a system be meaningfully quantified using only a combination of hydrodynamic conditions and different perspectives?

While the exact hydrodynamic characteristics for damage to properties vary based on what is being damaged, in general, it should be possible to quantify this based on water depth, flow velocities, flood arrival times, and inundation time. These functionalities may not lead to a measure of resilience directly but can be translated into resilience metrics that quantify the flood resilience of a certain area. Subsequently combining these metrics with differing perspectives indicating interest in ecology/housing/economics should give meaningful, objective information to design a flood-prone area for flood resilience. Meaningful in this context means that information should be able to enhance or support flood management practices.

Subquestions
Before the research question is answered, three subquestions are posed. These are mostly answered through literature research and inform modeling and quantification metric decisions.

1. *What system definition, boundaries, and initial conditions need to be chosen to accurately model the flooding scenarios needed to quantify resilience?*

The system should be defined in such a way that a variety of land uses is present in the area and a sufficient amount of water should be able to enter the study area. Besides this, the system needs to be large enough that the water is not able to propagate to the end of the domain. This can also be achieved by using existing dikes as boundaries, as they are unlikely to be overtopped in the model simulations.

Depending on the characteristics of the flooding, differing conditions should be used. For example, when dealing with a large waterbody, a constant level can be assumed. However, for smaller channels, it depends on the internal friction of the surrounding waterways. Besides this, the response of local (water) Authorities is important for the progression of a flooding event, so this should also be taken into account. Other important properties include dike breach development, breach location, evacuation procedures, flood arrival times, maximum water depth, flow velocities, and more.

2. *What are the current challenges in quantifying the shock, impact, and recovery in flood resilience?*

Current challenges in quantification include the fact that while flood risk is easily quantified in monetary value, casualties, or GDP, resilience cannot be defined in such a straightforward way. This is because accepting some level of damage/inconvenience is inherent in the definition of flood resilience. Furthermore, the different perspectives on resilience and priorities in what to protect lead to different outcomes based on these perspectives.

3. *What functionality units and resilience metrics are most suitable for quantification of flood resilience?*

Functionality units like the water depth, percentage dry area and residence time can potentially be used and combined with mathematical operations such as derivatives and integrals to obtain informative resilience metrics.

1.4. Scope

This research limits itself to the hydrodynamic conditions in the study area to quantify flood resilience. Multiple hydrodynamic conditions are used like water depth, flooded area, and flow velocities. These resulting hydrodynamic variables are used to attempt to quantify flood resilience from different perspectives. An emphasis is placed on the temporal evolution of these hydrodynamic conditions in the study area.

In this study, resilience is defined as: The ability of the system to cope with the effects of fluvial flooding initiated by a dike breach in a polder in The Netherlands. The primary focus of this research is to quantify flood resilience using a model of a dike breach in a polder that belongs to the Alblasserwaard region in The Netherlands. Multiple different breach locations are tested to understand system dynamics from a resilience point of view. Multiple interventions are also tested to compare the response based on the chosen interventions.

The evaluation is also discussed with the new layers of the multi-layered flood safety in mind (Eindadvies Beleidstafel wateroverlast en hoogwater, 2024). The main focus is placed on the quantification of the consequence mitigation and emergency response layers, as they can best be linked to hydrodynamic conditions. The effects of subsidence are not considered in this study but can be added in a later stage.

1.5. Outline

This thesis explores flood resilience quantification based on hydrodynamic conditions. Chapter 2 reviews relevant literature on flood risk and resilience, highlighting existing frameworks and key hydrodynamic variables. Chapter 3 outlines the research methodology, detailing the hydrodynamic modeling approach, resilience metrics, and the case study setup. Chapter 4 presents the results of the flood resilience analysis, evaluating metrics such as flood arrival times, residence times, and recovery rate. Chapter 5 discusses the findings, their implications, and the strengths and limitations of the approach. Finally, Chapter 6 draws the research conclusions and Chapter 7 outlines recommendations for future research and practical applications in flood management.

2

Literature Review

In this chapter, the current state and descriptions of both flood risk and resilience are briefly discussed. This is done by initially describing the theoretical ideas behind these approaches, before discussing the application of these principles currently in The Netherlands. The differences between flood risk and flood resilience are described, followed by the identification of interesting hydrodynamic variables for this research. Lastly, these hydrodynamics are linked to practical consequences before concluding this chapter with a summary.

2.1. System Response

In resilience, the first step is defining a system and its boundaries. The system is the area of interest that can be changed and responds to certain events affecting it. These events are often referred to as disturbances. When looking at the response of a system to a certain disturbance (i.e. a flood event), two different regimes can be distinguished (K. De Bruijn, 2004):

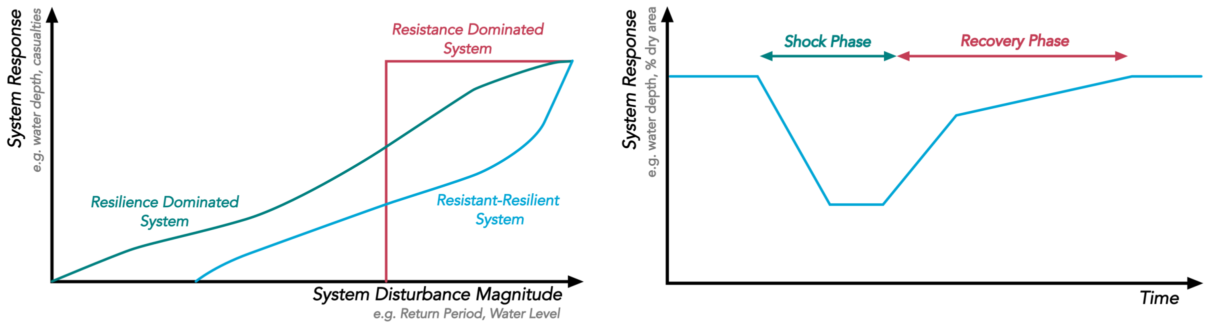
1. The system does not respond at all to the disturbance, or the system does not recover. In this case, we talk about resistance. Resistance determines which disturbances the system withstands without reacting.
2. The system responds in some way to the disturbance. In this case, we talk about resilience. This response can take a variety of different forms, which is discussed in Section 2.3.1

These responses and a combination of both response types are given in Figure 2.1a. Two types of curves are most common when considering system response curves. The first is the system response as a function of disturbance magnitude (for example different return periods) indicating how the response changes for stronger disturbances. The second is a temporal response curve to a certain disturbance. In essence, each point on the line in 2.1a represents a temporal curve like 2.1b in its third dimension. In a way, these curves can be combined to create a system response landscape, but this is not often seen in literature.

2.2. Flood Risk

While this research focuses on flood resilience, The Netherlands has had a strong focus on flood risk in the past. Therefore, it is important to consider changes to flood risk policy as well as flood resilience when trying to attempt this research. This section starts by outlining the fundamentals of flood risk, subsequently explaining how this has been outlined in The Netherlands in the past.

Flood risk in its most basic form is given by multiplying the probability of a flooding event with the expected damage (e.g. casualties, money, etc.) as a result of such a flooding event (Klijn et al., 2015). Phrased more comprehensively, it is the expected annual damage as a result of flooding in a given timeframe. Damages then refer to both monetary and non-monetary consequences of flooding. By subsequently comparing this to the expected cost of for example a dike reinforcement, a judgment can be made about the economic efficiency of the proposal.



(a) Response curves as a function of disturbance magnitude. Image adapted from Juan Aguilar-Lopez.

(b) Temporal response curves with different phases, adapted from (Hosseini et al., 2016)

Figure 2.1: Most common types of system response curves present in Resilience literature.

2.2.1. Frameworks Flood Risk

Recently, more comprehensive frameworks for flood risk assessment have been developed. While numerous frameworks have been proposed over the years, the most significant one was developed by the United Nations. The United Nations defines exposure, hazard, and vulnerability as the guiding principles, and these have been defined as follows: (UN, 2016) (UN, 2016):

- *Exposure:* 'The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.'
- *Hazard:* 'A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.'
- *Vulnerability:* 'The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.'

This framework has been used to guide flood risk principles in The Netherlands and other countries alike.

2.2.2. Flood risk in The Netherlands

Flood risk in The Netherlands was initially done by defining dike rings, and subsequently assigning an allowable failure return period of, for example, once per 10.000 years. However, this method started to become outdated in more recent years as it can result in unnecessary high demands on dikes or lower-than-expected safety standards (Klijn & van der Most, 2013). Between 2009 and 2015 modernisation of the current regulations took place in the so-called 'Deltaprogramma'. In this program, two main starting points were defined in the determination of the water safety policy (Slootjes & Most van der, 2024).

1. Each person behind a dike or a dune has a chance of perishing due to a flooding event of at most 1/100.000 years.
2. If large groups of casualties, large economic damage, or vital infrastructure destruction can occur the safety standard may be enhanced.

These principles were incorporated into the Waterwet (Rijksoverheid, n.d.) and have been in effect since 01-01-2017. As a result, large dike-strengthening projects have been carried out over the last few years on the primary flood defenses, and many more are still scheduled to occur. This is done under the banner of Hoogwaterbeschermingsprogramma (Rijkswaterstaat, 2020) and it is scheduled to be completed by 2050.

Another change in this Waterwet was the change from overtopping probability Dutch: overschrijdingskans) to flooding probability (Dutch: overstromingskans) (STOWA, 2021). The overtopping probability is the probability that a certain waterlevel, that needs to be withstood by the dike, occurs. The flooding probability describes the probability of flooding in the area that the dike needs to protect. The main difference is the failure of the dike. In overtopping probability damage is expected to the dike, not leading to failure. In flooding probability, the assumption is that the dike fails(STOWA, 2021). The main advantage of using the flooding probability is that it makes it easier to effectively reach a certain protection level. This is achieved through reconsiderations surrounding the length effects and failure probability distribution.

Flood risk policies have proven highly effective in quantifying risk, damage, and casualty estimation. However, their narrow focus on impact makes it unfeasible as a comprehensive long-term principle for all areas of interest. Before comparing flood risk frameworks to resilience, highlighting some advantages and disadvantages between the two, some frameworks for resilience in The Netherlands are discussed.

2.3. Resilience

Holling introduced one of the first broadly accepted definitions of resilience, stating that "Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. In this definition resilience is the property of the system and persistence or probability of extinction is the result" - (Holling, 1973). Since this paper was published, three main types of resilience have emerged. They are Engineering resilience, Ecological resilience, and socio-ecological resilience (also known as evolutionary resilience).

1. In engineering resilience, the focus is on disturbances or shocks to the system that threaten the functional stability of the system. It encompasses both resistance and recovery but has a narrow focus on returning to its original state. A different, adapted state is not desirable from an engineering resilience point of view (Liao, 2012).

2. In ecological resilience, similarly to engineering resilience, a system's response to shocks and stresses is described. The most important distinction is that the system can also reach a new equilibrium(Disse et al., 2020). For small shocks, both perspectives may yield the same results, but when looking at large disturbances differences emerge. A system may have 'collapsed' from the engineering perspective as the equilibrium is not restored but still be functional from the ecological perspective as it has maintained its function, albeit in an altered form. Importantly in this framework is to note that the system itself cannot change, only new equilibriums can be reached.

3. In social-ecological, also known as evolutionary resilience, there are some further extensions on the idea of ecological resilience (Disse et al., 2020). The main difference between the two perspectives is that in social-ecological resistance, the system itself can also change. This means a wider range of resilient solutions can exist as the system itself adapts to disturbances.

2.3.1. System Response Types

If a system responds to a disturbance, this response can take one of the following different response types (K. De Bruijn, 2004):

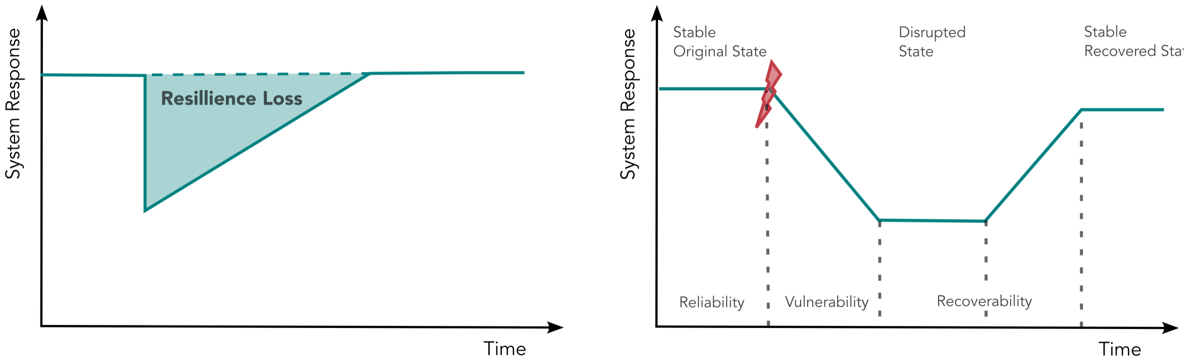
1. The system reacts, but it will come back to the original equilibrium. This response aligns with the engineering resilience perspective.

2. The system reacts and reaches a new equilibrium. This idea aligns more with the ideas for Ecological and socio-ecological resilience.

3. The system becomes unstable or collapses. In this case, it is no longer resilient as the system has completely failed.

In this research the engineering resilience perspective is used, as this perspective is the most straightforward to objectively measure. If systems can reach a new equilibrium, it is more difficult to asses the desirability of this outcome.

If a system does respond, an impact or system functionality curve is the most frequently used way to show the system's response to the disruption over time. This curve can take many different forms, showing the different phases of the system response. Some examples of these response curves can be seen in Figure 2.2 (Bruneau et al., 2003; Henry & Emmanuel Ramirez-Marquez, 2012)



(a) Adapted from Kahan et al. (2009)

(b) Adapted from Henry and Emmanuel Ramirez-Marquez (2012)

Figure 2.2: Examples of system response curves from existing literature.

Both the response curves in Figure 2.2 show the response of a system due to a certain disruptive load. If this load is smaller than the resistive capacity of the system, it is in the resistive regime. If disruption occurs, the resilience of the system matters. This response is dependent on different indicators of the response, namely (K. M. De Bruijn, 2004):

1. *Amplitude shock*

Amplitude shock is the decrease in system functionality as a result of a shock applied to the system. The larger this value, the less resilient a system is generally found to be.

2. *Graduality of the response*

Graduality of response is a measure of how quickly the system response increases for amplification of the shock or stress. A graph plotting the graduality of response usually shows discontinuities, which are the result of for example a dike overtopping in which case the impact suddenly moves to this new flooded state.

3. *Recovery*

A measure of how quickly a system can bounce back to its previous functionality or, in the case of socio-ecological resilience, bounce forward to a new and improved stable state. The measure of recovery can be seen from multiple perspectives, from physical factors (when is the land dry) to social factors (are people prepared, economically stable, and more).

It should also be noted that ’recovery’ is not a single metric that applies to all in an affected community. A community as a whole might be recovered or even improved but this does not mean that the individuals are all back to their starting point. In fact, some individuals may never recover (K. M. De Bruijn, 2004).

Recovery is not really measurable, at least not directly as it is part of a complex pattern with other processes. Instead, one can use some characteristics of society, which can give us an idea of the vulnerability of the community. Vulnerability is a combination of susceptibility and recovery capacity. Some potential frameworks have been developed to help with the quantification of the recovery process (Anderson & Woodrow, 1998; Cannon, Twigg, & Rowell, 2001), but in general it remains system-specific and highly dependent on the initial conditions.

One of the difficulties in combining these three aspects of resilience is the fact that they tend to have different units or measures. Recovery, for example, is often measured in time to full system service, while amplitude shock is more often measured in monetary damage. Therefore these measurements need to be made dimensionless, or different metrics need to be developed for all three before designing a system for resilience.

2.3.2. Resilience Measures

Resilience measures can fall into two main categories: Structural measures and emergency measures. Looking at the principles of multi-layered-flood safety Section 2.3.3 in The Netherlands, it can be concluded that emergency response is mainly located in layer 3(emergency response control) and structural measures mainly in layer 2 (recovery and consequence mitigation).

Structural Measures
A variety of different structural measures can be implemented to improve the passive flood resilience of a flood-prone area. Some of these measures are briefly discussed:

- *Detention basins:* Detention basins can serve as a location to temporarily store the excess water. By letting water flow into these basins, the pressure on the system as a whole is alleviated. An added benefit of allowing water to flow into a designated area during a flood is that the use of emergency pumps becomes more efficient, as these pumps work best during high water levels.
- *Elevating vital assets:* Critical infrastructure or emergency response service buildings can be raised off the ground by a certain amount. That way, upon flooding access to these services can be maintained. This can also be an iterative process, where something that gets damaged in a flood event is raised in the rebuilding process, incorporating the idea of enhanced recovery. De Moel, Van Vliet, and Aerts (2013) showed that elevating buildings by 50 – 200cm can reduce the damage to property by 50 – 74 percent respectively, making it potentially an interesting mitigation strategy, provided the costs are sufficiently low.
- *Dryproofing and wetproofing of buildings:* In the report written by Eindadvies Beleidstafel wateroverlast en hoogwater (2024) one of the new pillars of flood resilience is the recovery process, specifically rebuilding in a more resilient way after a flood. One of the ways to achieve this is by wetproofing or dryproofing buildings. It was found that this way of making a building more resilient, while expensive (Linham & Nicholls, 2016) can reduce damage upon flooding significantly (Schinke et al., 2016).
- *Resilient Pumps & Sewers:* During large-scale flooding, the sewer system and pumps often experience malfunctions. To mitigate this, some pilots are now attempting to enable the pumps and other electronic components to continue functioning during a flooding event(*Waterschap Amstel, Gooi en Vecht*, n.d.). This approach facilitates the earlier pumping of water, contributing to resilience.
- *Moveable barriers:* In locations where large-scale resistive infrastructure measures are impractical due to economic, practical, or aesthetic considerations, moveable or flexible barriers can be implemented(White, Connelly, Garvin, Lawson, & O'Hare, 2018). These barriers serve as resistive measures for the protected assets, yet they are still considered resilience measures for the area as a whole.
- *Other measures*: These include changing the location of critical infrastructure to less flood-prone areas. Moving these assets is often not practical, but locations for new development can be designed with these principles in mind.

Emergency Response
The second set of measures are the emergency response measures, that can be taken in response to a flood occurring. These measures can be considered active flood resilience, as they require a response by inhabitants and authorities to be effective.

- *Artificial breaches:* If a dike breach becomes inevitable due to high water levels or instabilities, it can be an idea to breach the dike in a controlled location, for example near a basin or in a sparsely inhabited area. This can be done both as a structural measure (deliberately creating a weak spot) or as an emergency response, though it is then difficult to control the breach. This can reduce the magnitude of the system response curve at its maximum deflection, increasing resilience.
- *Crash stop:* The idea of the crash stop is to place a large vessel into a breached dike location to stabilize the breach. It can then be filled with sandbags to make it watertight (Janssen, 2024). Some examples of this succeeding are available, for example, the ship Twee Gebroeders in The Netherlands during the 1953 floods, but it is difficult to consistently succeed using this method. Janssen (2024) attempted to design a purpose-built vessel adapted from a military pontoon to improve the effectiveness of this solution, which could be used in times of flooding. This can also reduce the magnitude of the response curve, by

reducing the discharged volume of water.

- *Emergency pumps:* Pumps can be placed in locations that are prone to flooding to pump out excess water from an area. These pumps tend to work best when the water level is higher, as pumps usually shut off when the water level falls below a certain threshold. This intervention affects the recovery phase of the system response curve, by draining the area faster.

2.3.3. Resilience in The Netherlands

The principles outlining the strategy of resilience in The Netherlands were already discussed in the introduction and can be found in Chapter 1. Some additional challenges for implementing flood resilience frameworks are discussed here.

While there is in principle a strong consensus that flood resilience practices enhances flood-safety in The Netherlands in the long term, there is still resistance to the practicalities of implementing these principles. Policymakers, when confronted with the reality of increasing the probability flooding, still tend to revert to the classic resistive approach with dikes and dams (Molenveld & Van Buuren, 2019). While not part of this study, this tendency should be taken into account when designing flood-resilient areas in The Netherlands.

A potential other challenge was also pointed out by an expert at Nelen & Schuurmans, saying that resilience might be more difficult to achieve in a polder, especially one under subsidence, as the water level is often multiple meters higher than the ground level. This means that any flooding, especially if originating from a primary waterway, can lead to high inundation levels, making it difficult to implement resilience measures like dry proofing, wet proofing, or elevated construction, see also Section 2.3.2.

2.4. Differences Resilience and Flood Risk

The main difference between flood risk and flood resilience is that flood risk focuses on the likelihood and potential impact of flooding, while flood resilience focuses on the ability to cope with and recover from flooding. This gives both their applications, advantages and disadvantages, though there is also some overlap in their definitions.

Disse et al. (2020) conclude that "Flood risk and flood resilience both have much to offer in the management of floods .... Resilience, for example, offers a more integrated approach to the problem of managing floods by measuring and strengthening the less tangible aspects of the community. This, however, comes at the expense of sometimes complicated metrics plagued by individualized approaches and a general lack of comparability across regions." By comparison, flood risk usually offers up clearly comparable numbers by which a design can be judged. This does however come at the expense of only taking in the immediate impacts of a flood event and not taking into account long-term consequences or recovery efforts (Disse et al., 2020). This is not an issue by itself, but flood resilience frameworks have much value to add, by incorporating resistance as but a part of a greater flood mitigation strategy.

Furthermore Disse et al. (2020) also note that "the current strategies attempting to bridge risk and resilience are lacking. They are often little more than a peripheral application of flood resilience while focusing primarily on flood risk management. This falls well short of reaching the potential benefits of a truly combined approach".

In The Netherlands, the theoretical framework of Multi-layered flood safety has the potential of being such an approach, combining resistive measures (layer 1) with resilient measures (layers 0,2,3,4). However, it is needed to build on the resistive culture that is currently present in The Netherlands to attain the potential benefits of this multi-layered approach.

This research helps to contribute to this combined approach by trying to use measurable, objective quantities like water depth and flow velocities to compare resilience measures to each other. System response curves can be used to determine the response to different shocks and stresses, making it possible to design these systems objectively from not just a flood risk perspective, but a resilient perspective as well.

2.5. Quantification of Resilience

Due to the interconnected and varying nature of resilience, it is complicated to assign values and units to resilience measures. In this section, some options for quantification are explored.

Before discussing the metrics, the focus of this research should be further defined, as the metrics for resilience are functionally endless. This research focusses on deterministic quantification, as the methodology is deemed most important, rather than adding extra complexity using probabilistic methods. These can, of course, be added in later work. Furthermore, as outlined in the introduction, temporal evolution is one of the challenges in quantifying flood resilience, so this is considered.

Furthermore, some other areas of interest remain when reviewing the existing literature (Hosseini et al., 2016). One of these areas is the interdependencies and interconnectedness of infrastructure networks. While some research investigating these dependencies does exist (Ouyang, Hong, Mao, Yu, & Qi, 2009), this can be linked to the system functionality based on hydrodynamics in this research. Besides interdependencies in infrastructure networks, similar dependencies exist in different facets of society, whether they are economic, educational, or residential. Some research into this area has been conducted (Pant, Barker, & Zobel, 2014) but this can be adapted to this research as well.

2.5.1. Hydrodynamic Functionality

Hydrodynamic models usually provide at least two variables: the water depth and flow velocity. From these variables, functionality curves, like the ones shown in Figure 2.2 can be composed based on different units. Based on the available literature, the following metrics have been determined to be important in the quantification of flood resilience in an area.

1. *Temporal Water depth:* Models that include water depth to determine damage to an area tend to only use the maximum water depth (STOWA, n.d.), while a temporal evolution of the water depth could be more informative. This is because for recovery and coping with floods, key aspects of resilience, it matters not only what the maximum depth of the water was, but also how long this maximum depth was present. Other important factors in considering the temporal water depth include FLood Arrival Time (K. M. De Bruijn, Klijn, Van De Pas, & Slager, 2015) and residence time (Choi et al., 2006).

2. *Temporal Flow velocities:* Small flow velocities lead to fewer casualties and easier emergency response, as evacuation becomes largely impossible with high flow velocities. Furthermore, flow velocities also have a large impact on (specifically) damage to infrastructure (Kreibich et al., 2009), which has a large effect on the recovery time of a system.

These variables can be turned into functionality curves by, for example, counting the number of buildings that experience flooding at any given time. When this is done, functionality curves are created, from which resilience metrics are subsequently derived.

2.5.2. Resilience Metrics

The functionality curves can be used to derive metrics for resilience quantification. These metrics then indicate the system's resilience for the different phases of the system response curve.

Ways to objectively quantify flood resilience have been extensively researched and summarized (Hosseini et al., 2016). One of the ways to derive these metrics is to look at the maximum shock of a functionality curve or the maximum disruption occurring in a flood-prone area. This can for example be quantified by the total area percentage that is flooded or the fraction of buildings that is affected. While this is close to existing flood risk frameworks, it can still inform resilience metrics, provided it is not the dominant deciding factor in determining resilience.

This research also focuses on temporal aspects of resilience. One of the ways to asses total temporal system impact is by summing the impact of all timesteps, effectively creating an impact integral of the system (Bruneau et al., 2003; Kahan et al., 2009). This can also be seen in Figure 2.2a, where the total surface under the impact is defined as the resilience loss. This metric can be defined for the system as a whole, but also be split up into individual entities.

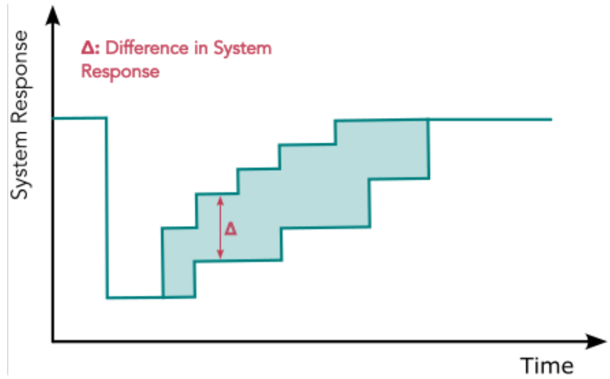


Figure 2.3: The concept of Dynamic Resilience, adapted from (Rose, 2007). The indicated Δ is the difference between normal recovery conditions and hastened recovery efforts, for example when using emergency pumps.

Besides the integral, resilience metrics can also move in the opposite direction using derivatives. Using Figure 2.2b it can be seen that the derivatives of both the shock and recovery phases are indications of resilience. A system that recovers more rapidly to its original (or even an enhanced state) is deemed more resilient. These derivatives are disguised in the integral measure but are deemed important in the quantification of resilience.

Another important concept for quantification is dynamic resilience (Rose, 2007). The concept of dynamic resilience is used to define multiple paths to recovery, one where the regular system is left unmodified to recover on its own and one where extra effort is put into the recovery process. In the context of flood resilience, this means for example the difference in recovery times when extra emergency pumps are placed in a study area. Conceptually, the system response curve for dynamic resilience can be seen in Figure 2.3. Dynamic resilience can be quantified by measuring the difference between recovery times in the cases with and without emergency pumps. Another way this can be determined is by comparing the derivative of the slope of the impact curve, which could change for both types of recovery.

2.6. Consequences of Hydrodynamics

While hydrodynamics are interesting in determining system response, they need to be linked to things that these hydrodynamics can affect. For the methodology of the research, it is not necessary to comprehensively describe all assets in the study area, but some thresholds for flooding should be determined for the most frequent assets like buildings and roads. These assets are discussed in this section.

2.6.1. Buildings

For the flooding of houses, inundation depth is the most important factor when considering the impact on the system (Kreibich et al., 2009). Flow velocity does matter, but only above about $1.5ms^{-1}$ (Kelman & Spence, 2004) which is not expected to occur frequently in the current study area. Should higher velocities occur in the study area, flow velocity should be taken into account. For example, flow velocities of 3.0ms^{-1} can lead to a damage increase of 18% compared to the hydrostatic case as found in a casestudy by Nadal, Zapata, Pagán, López, and Agudelo (2010). When considering a flood risk perspective, damage as a function of maximum water depth is the most important factor (Wever, 2022). However, from a flood resilience perspective, it is more important to consider the time a building is non-functional due to flooding.

Instead of flow velocity, momentum can potentially be used to determine times of the largest impact. This can be interesting because momentum takes into account both water depth and flow velocity in its formulation, making it an interesting data point when considering hydrodynamics in a certain area.

2.6.2. Critical Infrastructure

Critical infrastructure does not only concern roads used for evacuation, but also sewer systems, electricity (sub)stations, pumping stations, hospitals, and more. These utilities are not only critical in the impact phase of a flooding event but also in the recovery phase. If critical infrastructure is still operational, residents can be evacuated, injured people can be cured and pumping stations can immediately start pumping the water out of the area.

Initially, critical infrastructure is divided into two categories:

1. Roadways. Evacuation can still take place if there is some water on the road itself. Evacuation times tend to start increasing at around 0.05m of water depth, increasing with depth until about 0.3m(Suwanno et al., 2023). At this depth, evacuation is no longer possible with regular vehicles due to stability and motor-related issues (Kramer, Terheiden, & Wieprecht, 2016). Concerning damage to roadways, flood velocity is usually said to be the most important parameter(Kreibich et al., 2009).

2. For critical infrastructure like hospitals, pumps, and (sub)stations, damage is directly related to the water level. Above certain heights, there are shortcircuits and many components need to be replaced. The exact levels of damage to these structures are variable and are dependent on the exact design of the structure. This is therefore important to consider when choosing the flooding thresholds for the study area.

2.6.3. Ecology

Ecological areas come in many varieties, but areas that are particularly vulnerable to (increased) flooding are wetlands (Cai, Huang, Tan, & Chen, 2011). These wetlands are also present in the study area for this research. Under the influence of human interventions, these areas usually experience increased flooding frequency and severity, as well as lowered groundwater tables (Detenbeck, Galatowitsch, Atkinson, & Ball, 1999; Rai, 2008). If floods occur more frequently, this can lead to an increase in invasive species, as well as loss of biodiversity in the original population (Brinson & Malvárez, 2002). As the study only looks at a single event, it is difficult to quantify the long-term effects on the system. However, present species of high ecological value are expected to be affected by flooding of the study area (*Donkse Laagten | Natura 2000*, n.d.).

2.7. Conclusion

Based on the literature review, it can be concluded that while theoretical frameworks exist to quantify resilience, their practical application for system design is limited, and objective design remains challenging. The Dutch framework of Multi-layered flood safety holds promise as a comprehensive approach that integrates flood risk and flood resilience. This entails utilizing quantifiable and measurable metrics employed in flood risk assessment and translating them into metrics specifically designed for assessing flood resilience within a particular system.

3

Research Method

This chapter presents the methodology for the hydrodynamic quantification of flood resilience, combining theoretical frameworks with a practical case study. The chapter begins by introducing key hydrodynamic variables and their applicability. The methodology integrates these variables with different perspectives—residential, ecological, and economic—to assess both direct and indirect flood impacts on flood-prone areas.

The latter part of the chapter applies this methodology to a case study in the Alblasserwaard polder, demonstrating its applicability for quantifying flood resilience using hydrodynamic modeling. The case study serves to illustrate how this approach can be used to enhance flood resilience assessments and inform flood risk management strategies

3.1. Model Method

The main focus of this research is the hydrodynamic quantification of resilience. The hydrodynamics variables of interest have been discussed in Section 3.1.2. In this section, the possibilities for these variables are discussed when looking at flood resilience. This is done with the layers of the multi-layered flood safety in mind as a framework for resilience in The Netherlands (Eindadvies Beleidstafel wateroverlast en hoogwater, 2024). Based on the literature, this research uses a depth threshold for flooding of 0.05 meters, unless otherwise indicated.

The methodology of the research can be seen in Figure 3.1. Each subsection explains part of this methodology, which is subsequently implemented in the case study.

3.1.1. Hydrodynamic Quantification

A hydrodynamic model usually gives two main variables for a given timestep and location: The water depth and flow velocity vector. In the proposed method the flow velocity vector is transformed into temporal momentum impact rather than strictly velocity. This is because velocity by itself is not necessarily damaging to structures or dangerous for vehicles or people, but only when combined with sufficient depth (Cox, Shand, & Blacka, 2010). The product of the water depth and flow velocity is then considered as momentum impact, despite it not strictly carrying the unit for momentum flux.

The calculations of these water depths and momentum impacts are computationally expensive, taking a few hours for a 10 day simulation. As such, these are both intermittently saved for later reference. The resulting files can then be used to calculate the hydrodynamic functionality curves. Before these are set up, the Regions of Interest (ROI) need to be discussed.

3.1.2. Regions of Interest

When considering the hydrodynamics and the effect on flood resilience importance needs to be given to certain locations. This is because it rather matters what is protected from flooding during a certain event to give

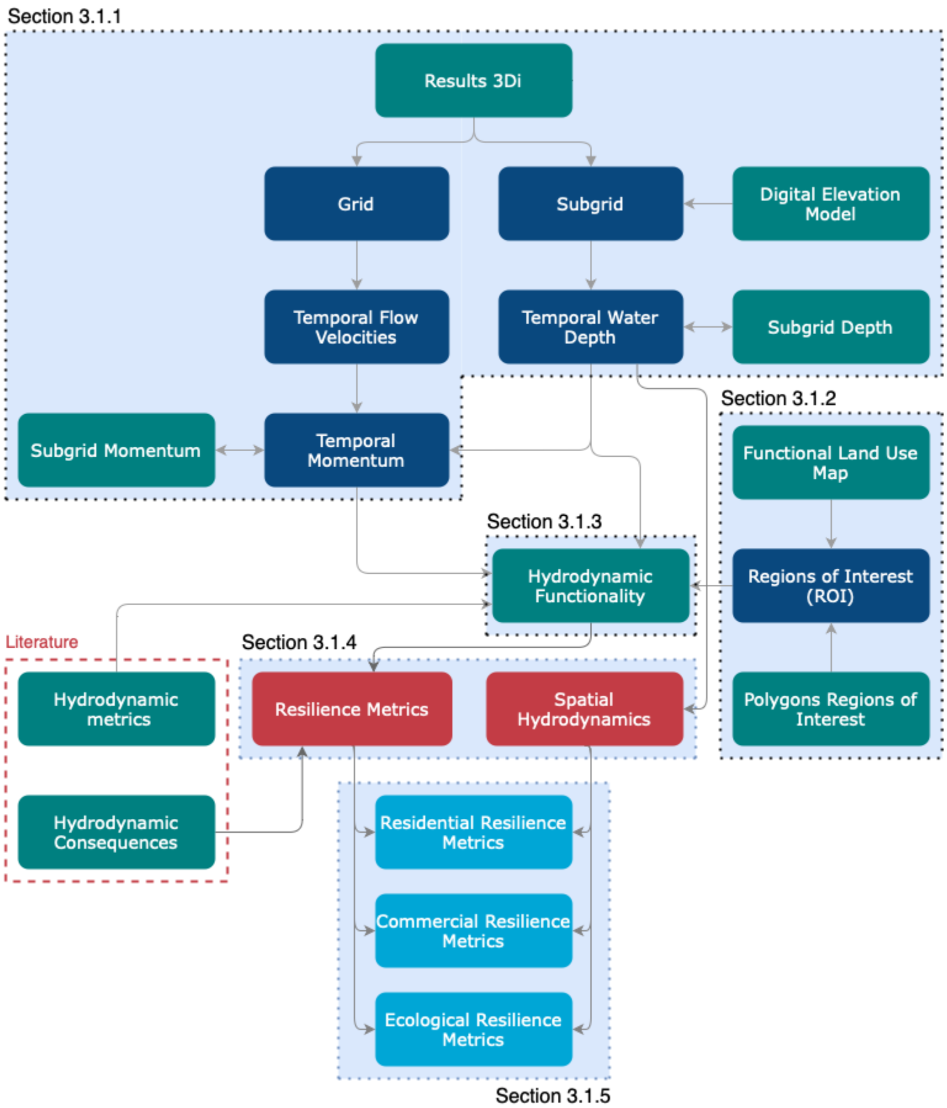


Figure 3.1: The Method used for this research. Dark blue boxes indicated intermediate calculations done in Python. Green boxes include data sources. If arrows go both ways the layer is saved during the processing to speed up iterations. Red boxes include results used for the quantification of resilience in blue.

a meaningful reflection on the resilience of that area. So for example, increasing the flood arrival time near a village should give a better resulting resilience increase compared to increasing the flood arrival time in an empty field. To address this issue, the method centers itself around buildings and other areas of interest. In this thesis, these are referred to as buildings as this is more instinctively understood, but in principle, any area can be designated as one or more regions of Interest. This approach yields the following benefits.

1. Higher valued areas with more buildings are automatically more predictive of the system response compared to areas with fewer buildings, representing the effect on the area more accurately.
2. This centering on buildings allows us to not only look at the complete system response of all buildings but also evaluate the performance of higher valued assets, like hospitals or emergency evacuation locations.
3. Assets can more explicitly be linked to a certain perspective, allowing the evaluation of the system from different perspectives as introduced in Chapter 1. This is done by combining the buildings with a functional land use map, that assigns the building the most frequently occurring land use in that area, like residential or commercial. Section 3.1.5 elaborates on this further.

Hydrodynamic functionality curves can then also be based on, for example, the number of flooded buildings, as discussed in . Before this is done, this thesis makes a distinction between two types of flooding affecting a building in the considered area: Direct flooding and indirect flooding.

Direct Hydrodynamics
Direct hydrodynamics is simply the flooding conditions around the building. It is a powerful way of considering the effects on buildings in a flood-prone area that has been used extensively in hydrodynamic modeling.

Indirect Hydrodynamics
The challenge with only considering the hydrodynamics of flooded buildings is that it is not only closely related to the existing flood risk analogy, but it also does not take into account the effects of flooding in the broader vicinity of a considered asset. For example, while the house in Figure 3.2a is technically not flooded due to the moveable barrier protecting it, this house is still experiencing the consequences of flooding such as the sewer system around the house likely being non-functional. In Figure 3.2b, the highway A79 in Limburg is flooded during the 2021 floods. The closure of this road affected residences and industries in the wide surroundings, even including the border regions of Germany and Belgium. Furthermore, recovering activities cannot commence if the infrastructure and utilities are still affected by flooding and it is still unsafe for inhabitants to return to their homes.

(a) Flooded surroundings of a residential asset in Limburg. Picture by the municipality of Voerendaal

(b) Flooded Highway A79 during the 2021 Limburg floods. Picture by ANP.

Figure 3.2: Illustration of indirect consequences of flooding

Instead, it is tracked if a building suffered only indirect, or also direct damage. Direct damage in this case would be the building encountering direct hydrodynamics, like a house flooding. Indirect damage by comparison considers for example the roads surrounding a house flooding, but the house itself remaining dry for the duration of the flooding event. The important factors for indirect damage are dependent on the assets and perspectives considered. This is discussed in more detail in Section 3.1.5. More comprehensive research in this area remains necessary, but this method still gives some indication of the type of flooding that occurs, and how this can inform resilience metrics in the future.

3.1.3. Hydrodynamic Functionality

With the considered regions defined and the distinction between direct and indirect flooding explained, the method focuses on the hydrodynamic functionality variables as discussed in Chapter 2. Based on the previous section, the amount of flooded buildings is added. This is a summation of the temporal water depth of each building, but can still be considered a functionality curve with a different unit on the y-axis. They are the following variables, with the brackets indicating the variable on the y-axis of the impact curve.

1. Temporal water depth [m]
2. Number of flooded buildings [# of buildings]
3. Temporal momentum impact [$kgm^{-1}s{-}1$]
4. Percentage Dry Area [%]

Temporal water depth
The temporal water depth is determined by determining the maximum water depth in a buffer 0.5m around the building. This is done for each timestep, obtaining a temporal water depth curve for each building.

Number of flooded buildings
This metric is a derivation of the temporal water depth, considering all buildings in the study area. For each timestep it is determined if each of the buildings is (directly) flooded. This is then summed on the y-axis for each timestep, showing the evolution of total number of flooded buildings over time.

Temporal Momentum Impact
The momentum impact is determined in a similar way to the depth. The product of the velocity and water depth is multiplied by the density of the fluid, which is of course water. The maximum momentum impact is then taken for each timestep in the same 0.5m buffer used for the water depth.

Percentage Dry Area
The percentage dry area is determined by counting the number of pixels (based on the resolution of the Digital Elevation Model) with a water depth of more than 0.05m. Any pixel that meets this criteria is classified as flooded. The percentage dry area is then obtained by dividing the amount of dry pixels by the total amount of pixels.

3.1.4. Resilience Metrics

From the functionality curves, the resilience metrics can be determined. For each of the identified hydrodynamic functionalities in the previous section it is described what resilience metrics can be derived from this functionality curve.

Temporal water depth Temporal water depth can be presented in a large number of different ways, which is why it is often used in existing hydrodynamic modelling. This research uses the following metrics in an attempt to quantify flood resilience. The metrics are shown in Figure 3.3

- *Depth-Integrals.* Temporal evolution is important in flood resilience, but it can be complex to analyze the resulting temporal graphs for a complete system. Instead, this metric attempts to reduce the complexity of flooding depth to a single value. This value is determined by integrating the water depth curve for a building over the entire flooding duration. This is similar to the Resilience loss in Chapter 2, but with the important distinction that it is determined for each building in the model run. By then aggregating and binning the results for all buildings the total system behavior can be plotted for interventions and variations. Lower results tend to indicate less total temporal impact on the system, meaning more of the system functions during the flood or the total duration of impact is lower.
  One of the problems with this approach is that the projected unit (meters · hours) is not intuitive. Instead, the depth integral can be compared to multiple possible interventions and/or variations. If the

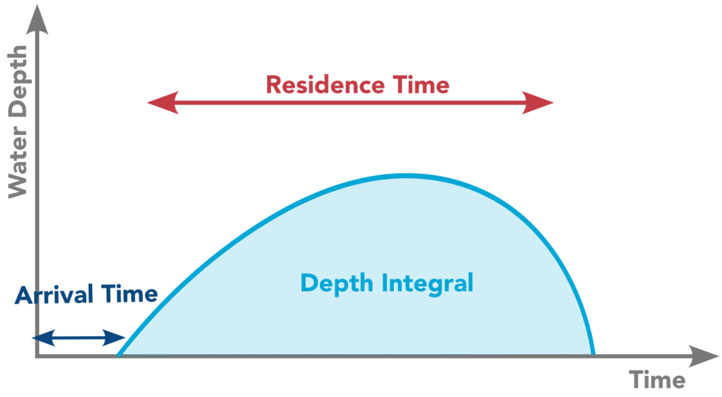


Figure 3.3: Resilience metrics based on the temporal water depth of buildings in the study area.

bars move towards the left (towards zero), this means that the buildings experienced less temporal flooding, indicating less impact, and therefore better resilience of the area. Some properties of this aggregate can be evaluated to quantify what is seen in the graph, as this might still not be intuitive. Properties that are interesting to evaluate include the average, median, and spread of buildings in the simulation run. *Residence time:* It matters how long water is present in a certain area, especially when looking at ecology or agriculture in an area. Damage increases over time and this is also dependent on the asset affected by the flooding event . Besides damage increases, which is closely related to flood risk frameworks, longer residence times also affect the time residents are displaced and affected. If residents can return to their homes earlier, they can start to resume their normal activities, indicating recovery (Choi et al., 2006).

- *Food Arrival Time*. Flood Arrival Time determines how long residents have to act once a breach occurs. Acting can be divided in either preparing assets for an upcoming flood event, or evacuating to prevent injury and death (K. M. De Bruijn et al., 2015). For both of these responses, longer lead times likely lead to fewer adverse consequences.

Number of flooded buildings
Some interesting metrics have been determined for quantifying resilience based on the number of flooded buildings. An illustration of these metrics is given in Figure 3.4

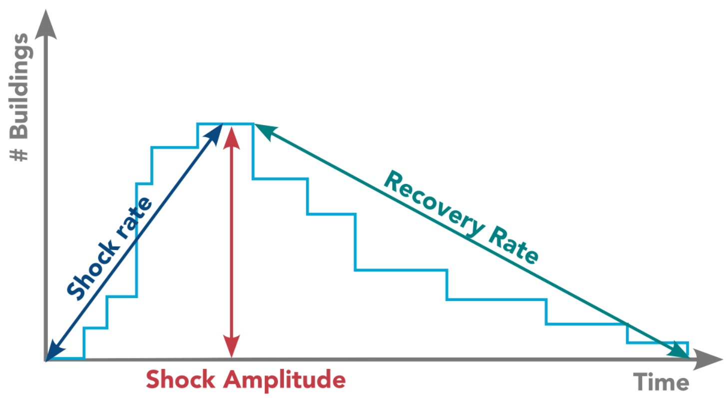


Figure 3.4: Conceptual curve of affected buildings over time with the derived resilience metrics.

- *Maximum Amplitude Shock*: The maximum amount of flooded buildings gives an indication for the total impact on a system, which is a vital part for resilience. This metric is used both for direct flooding of the buildings, but can also be used to determine indirect flooding impacts.
- *Amplitude shock rate*: Another interesting aspect of the impact curves for flooded buildings is the deriva-

tive of the shock. In this research, this derivative is quantified a the rate of change from the onset of the flood event until the maximum amplitude shock is reached. With a higher shock derivative, more buildings are flooding per unit time, and this has an effect on how well an area can cope with a flooding event. For example, emergency services may be overwhelmed if to many buildings start flooding at once.

- *Recovery Rate*: In a similar way to the amplitude shock derivative, this metric potentially indicates better recovery of a system, which is a vital part of resilience. It is defined by taking the average rate of change between the start of the recovery phase (i.e. the draining of the area has commenced) until the system is recovered, or is no longer recovering further because it reached a new equilibrium.

The proposed metric of flooded buildings has a challenge that needs to be addressed, as it could be argued that its absolute values are of limited use. For example, when the maximum amplitude shock of a certain system is 50 flooded buildings, the total number of buildings in the area matters a lot. Relative metrics are important to give meaningful insights into the system's behavior. Two main solution strategies can be attempted to address this challenge.

1. Multiple different runs of the same system are conducted. These runs encompass both variations in breach location and attempted interventions as described in Section 2.3.2. The percentual change in the metrics outlined above indicates the change in resilience.
2. If a measure of resilience in the abstract needs to be determined (meaning we don't want to compare with other runs), a better approach could be normalizing the metrics to the whole study area. By doing this, instead of a number of buildings, a percentage of buildings is found, which is likely more intuitive.

Temporal momentum impact
The temporal momentum curves are quantified in a similar manner to the water depth metrics. However, due to the momentum being dependent on both the velocity and water depth, the obtained temporal and integral values span a large order of magnitudes. To address this challenge, the resilience metrics for this functionality are all plotted on a logarithmic scale. The integral metric from the water depth is used.

Temporal momentum can also be plotted for individual buildings. When this is done, usually multiple peaks in momentum impact can be identified as the floodwave passes. The magnitude of this flood wave can be interesting as a metric for resilience as it affects the damage done to the building.

Percentage Dry Area:
The percentage dry area is also used to derive a resilience metric. Each building has an indirect radius around it, in which the percentage dry area is calculated for each time step. The radius is different for different types of buildings, which is elaborated upon in the next section. This is done for all buildings in the area, returning an average value for all buildings. For quantification of resilience using this metric, it was determined that the maximum flooded area (i.e. the smallest percentage dry area during a model run) and the total recovery (i.e. the percentage dry area at the end of a run) are the most important for quantification of flood resilience.

3.1.5. Perspective Resilience Metrics

Within a system, multiple functions can be identified. While many possible perspectives can be applied to the hydrodynamic quantification method, this research focuses on three in particular: Residential, Ecology, and Economic Activity (or commercial). This section outlines the considerations for each perspective and how hydrodynamics are linked to certain aspects of these perspectives.

A perspective in this research is seen as related to land-use, but with a more broad interpretation. When considering commercial activities, not only the shop is considered, but also the surrounding activities affecting it. This is why the term perspective is used instead of simply land use. Each perspective that is selected for this thesis is described in more detail below.

Residential
Primary function: Conducting residential activities (sleeping, eating, relaxing, etc.)

When considering residential areas, multiple factors determine the functionality of the perspective. When looking at a residential area, this research considers the following factors, combining them with hydrodynamic

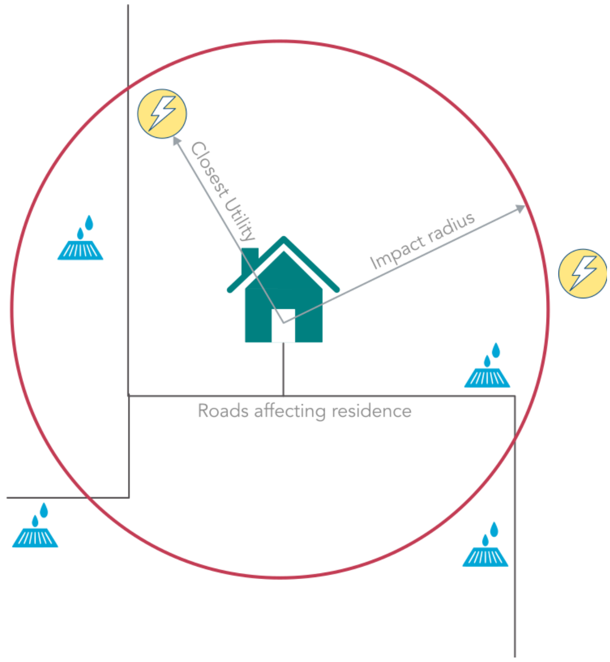


Figure 3.5: Illustration of multiple factors affecting the residential building.

conditions:

1. The house itself. A house that is flooded cannot satisfy the demands of the residents to conduct normal residential activities there. The degree to which the house is affected is mainly dependent on the water depth.

2. Infrastructure around the house. If all roads leading to a house are impacted, it could be argued that it is not functional, as it cannot partake in economic or societal activities. To determine which roads are affected a circle with a fixed radius can be drawn. Any impacted road in this radius also impacts the house itself. Alternatively, escape routes out of the affected area can be used to see if it is impacted. This would increase the accuracy of the method, as in real life residents look for alternative roads in case of a road closure. However, for presenting the methodology it is not deemed critical, so this research works with a binary presence of water in a circle with a fixed radius. This is illustrated in Figure 3.5.

3. Sewer system and electricity. Without utilities, a house is not completely functional. To determine if hydrodynamics in the surrounding area affect the utilities two methods can be used. As the sewer system is not modeled in the presented case study in Section 3.2, this research only considers electrical substations in the vicinity of the flooded residential building. If multiple substations are present, the research considers the closest substation to the building and use hydrodynamics in that station to determine the functionality of the building. Once again, accuracy could be improved by modeling the electrical configuration, but this is not deemed critical for demonstrating the applicability of the proposed method.

The illustration with these multiple factors impacting a building is given in Figure 3.5. By taking the broader context around a certain perspective and not just looking at maximum water depth or arrival times at the building, insight is gained into the resilience of the system, and meaningful conclusions can be drawn as to when residents can start moving back to their homes, and start the rebuilding process.

Economic Activity
Primary function: Generating economic value

In a similar way to the residential perspective, not only the hydrodynamic conditions in/near a commercial activity govern the functioning of that commercial activity. When goods can't be shipped, nearby land can't be worked or no electricity is available the function of the commercial activity is impaired. The impacted radius of an economic activity is considered to be larger than the radius for a residential building.

While most criteria are the same for residential and commercial activities, the acces nearby land is more important for commercial activities. If each house in the village is flooded, but for some reason, not the roads leading to the houses, a baker still will not be functional, as it is lacking customers. A farm is not be able to generate value if the surrounding land is flooded. This perspective therefore also takes into account the hydrodynamic conditions in the surrounding areas, regardless of what is flooded. To determine whether the surrounding area of a building is flooded the percentage of dry area is used. From this percentage, it is determined if a commercial asset can fulfill its economic function. What percentage is needed is dependent on the type of economic activity, but for the methodology in this research, a threshold of 95% is used for a functional activity. This threshold is based on the NBW norms for pluvial flooding (Dekker, Hamel van, Kolen, & Honingh, 2021), but this is deemed applicable for fluvial flooding as well since the effect on system functionality is similar and resilience is looking at acceptable levels of affected functionality. Besides this, it should be noted that in reality, this function is not binary, but the functionality increases with an increase in dry percentage. However, this exact relationship is not determined in this research and serves as one of the potential improvements in future research.

Ecology
Primary function: Maintaining the ecosystem present in the area

The ecology perspective is complicated to implement, as it cannot simply be said that inundation is problematic. Wetlands and floodplains benefit from periodic flooding for example, but this is only true up to a point, as discussed in Section 2.6. In general, two main hydrodynamic quantities are expected to affect the functionality of ecological areas.

- Percentage of dry area. For an ecological area, inundation is not necessarily an issue, provided species are spread out through the area, or have the opportunity to evacuate. This possibility is impaired if a large fraction of the habitat is flooded, meaning the percentage of dry area is a suitable metric.
- Inundation duration. Short periods of flooding can be beneficial to ecological areas, as flooding events tend to bring nutrients to the area. Longer inundation can affect species in the area, so it should be used as a metric for resilience in this research.

This makes the translation from hydrodynamics to functionality more straightforward. By considering inundation time and percentage dry area as metrics for quantification of resilience from the ecological perspective, the resilience of this area can be compared between flooding events and interventions.

3.1.6. Summary

All considered resilience metrics are given in Table 3.1. For each resilience metric it is indicated which hydrodynamic variable from the hydrodynamic model is needed. Furthermore, it indicates for which perspective the resilience metric can be used.

To test if this proposed relationship between resilience and resilience metrics indeed exists, this thesis uses a case study done in the Alblasserwaard. This case study is described before presenting the results in the next chapter.

3.2. Case Study Alblasserwaard

The applicability of the proposed method is tested in a case study. This case study takes place in the Alblasserwaard Polder in The Netherlands and can be seen in Figure 3.6.

3.2.1. System Definition

Hydrodynamic quantification of flood resilience requires a consistent and bounded definition of the system, which is discussed in this section. The area itself is a subsection of the Nederwaard polder, under the governance of the water authority of Rivierenland. The system can be seen in Figure 3.6. The choice for this system

Table 3.1: Resilience metrics that are evaluated in this thesis.

Direct	Hydrodynamic Condition		Perspective		
	Water Depth	Momentum Impact	Residential	Commercial	Ecology
Depth Integral	x		x	x	x
Momentum Integral		x	x	x	x
Amplitude Shock Rate	x		x	x	
Arrival Time	x		x	x	
Amplitude Shock	x	x	x	x	x
Residence Time	x		x	x	x
Recovery Rate	x		x	x	
Indirect					
Percentage Dry Area	x			x	x
<5% Flooded Buildings	x			x	
Flooded Utilities	x		x		

is based on the following considerations.

1. One of the research goals is to determine the resilience of a system for multiple perspectives. To enable the comparison of these perspectives it is required that the system contains at least some built-up area, some critical infrastructure for evacuation, and an area of ecological importance.

2. The area needs to be bounded in such a way that water is not able to flow out of the model domain. If that occurs the results cannot be considered reliable as hydrodynamics outside the system are not properly captured.

3. The chosen system contains four smaller polders with some division between- and within them. This allows for the comparison of the different subsystems as well as the system as a whole.

4. Recently the water board of Rivierenland has published large-scale plans for the renovation of the water system of the Alblasserwaard and the municipality of Vijfherenlanden (Rivierenland, 2019). Any interesting results from this research can therefore be taken into account for the renovation of the area.

The resulting system can be seen in Figure 3.6. The system consists of four polders in the area of the Alblasserwaard, under the water authority of Rivierenland: Laag Blokland (NDW001), Gijbeland (NDW002), Brandwijk (NDW010), and Bleskensgraaf Noordzijde (NDW015). These polders can be identified in Figure 3.7. Each of the polders could also be considered as a subsystem of the larger Alblasserwaard polder considered in this study. The subdivision with its different codes is given in Figure 3.7 The polders are separated by small levees, usually with a road on top. These different polders are incorporated into the model, as it enables studying the interaction between these smaller subsystems within the larger system.

Two main canals border the area. The northern canal is used for dewatering of the Overwaard and is called the Achterwaterschap. The southern canal is used for dewatering of the Nederwaard and is called the Graafstroom.

The dewatering of the study area is done through the pumping stations near the Graafstroom marked in Figure 3.7. The capacity for these pumping stations is given in Table 3.2 and was provided by the Water Authority of Rivierenland. The provided capacity is the expected pumping capacity for the year 2026. It is assumed that no water is pumped into the canals by the other pumping stations in a flooding scenario. Also, no water is being pumped out of the canals into the Lek during a flooding event. This is because low water levels in the canals are undesirable due to soil instability for buildings on the dikes of these waterways. This was pointed out by Marien Boers and a summary of the meetings can be found in Appendix B. The pumps used in the model initially remove water from the model, instead of pumping it back into the canals. This is needed as the breach is not closed, meaning water would circulate back into the model, preventing the system from recovering.

In this study, water enters the polder through a dike breach in selected locations along the canals. The model

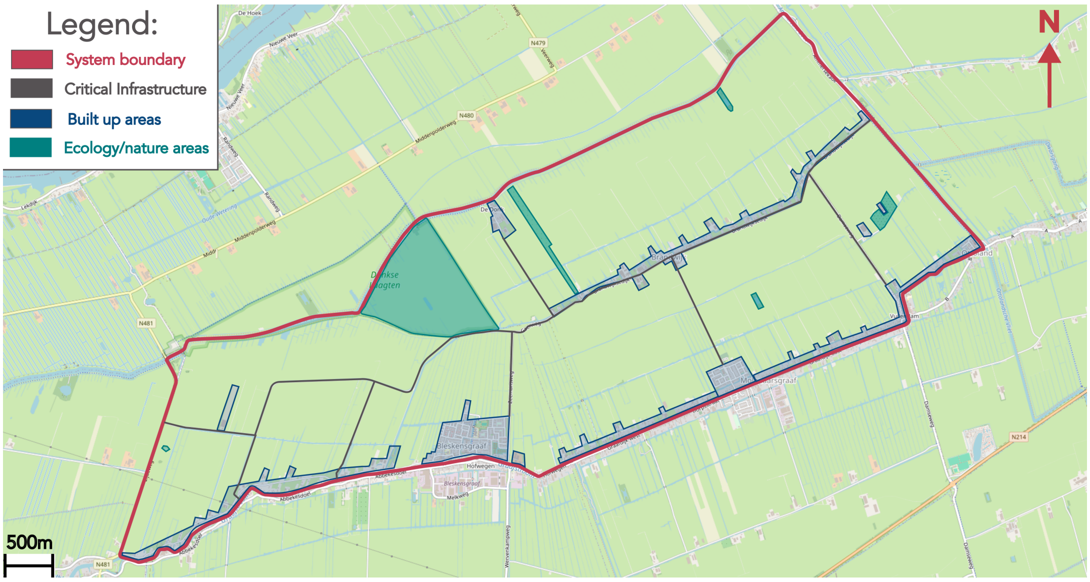


Figure 3.6: The chosen system in the Alblasserwaard with the different distinguished areas.

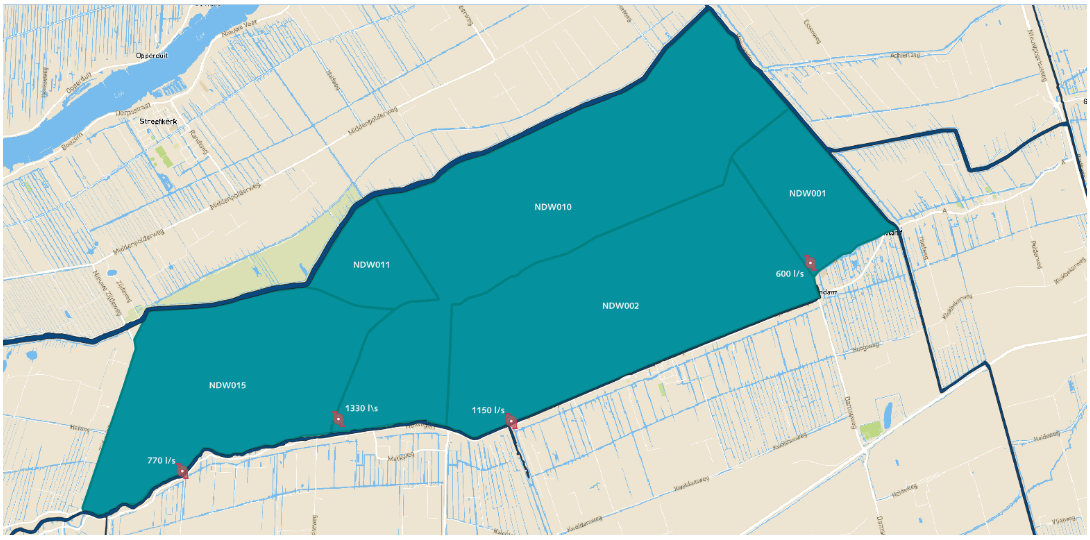


Figure 3.7: System with subdivisions and available pumping capacity.

Table 3.2: Available pumping capacity. The polder Laag Blokland (NDW001) crosses the border of the study area. While it is located at a slightly higher average elevation (AHN, 2019) it could still flood in certain scenarios, meaning a pumping capacity is needed to drain water from this area. An estimate of $0.6m^3/s$ was chosen based on the area of the polder and the drainage capacity of nearby stations.

Polder Name	Pumping Capacity [m^3/s]
Bleskensgraaf Noordzijde	0.77
Brandwijk	1.33
Gijbeland	1.15
Laag Blokland	0.6

boundaries are chosen in such a way that water cannot flow out of the model. This is done to ensure that the different attempted model runs don't perform better because more or less water flows out of the model, which would unfairly improve the resilience of these runs. The Northern, Eastern, and Southern boundaries are given by the canal berms of the same height. This means that a flood into the polder cannot leave the system as the canal berms are higher than the maximum flood level in the polder. The Western border does not contain a canal berm, but it consists of a road that is about 0.5m above the mean polder level (AHN, 2019). While this could lead to leakage out of the model, the breaches are set to not occur within 3 kilometers of this boundary, mitigating this possibility.

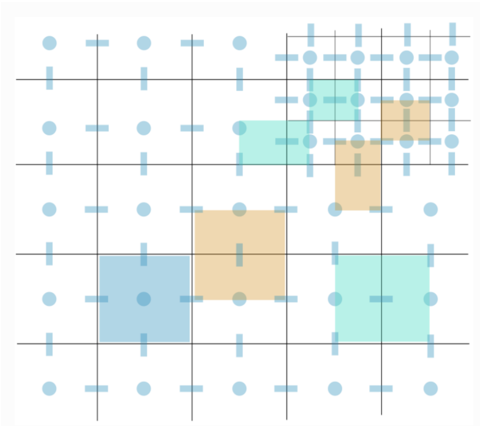
The flooding scenario depicted in the model can be accurately characterized as fluvial flooding, characterized by the discharge of a substantial volume of water into the study area. During such flood events, infiltration becomes a relatively minor factor compared to pluvial events. Consequently, the sewer system is anticipated to be overwhelmed, rendering it inoperable. Therefore, the sewer system is not modeled in this casestudy.

Boundary & Initial Conditions
To accurately model the flooding in the study area, it is crucial to know the volume of water in the surrounding canal. To achieve this, the canals in the study area are fully modeled as a set of 1D channels. The width of the channel was based on the centerline of the channel and the water edges from the Basisregistratie Grootschalige Topografie (BGT) (*Basisregistratie Grootschalige Topografie (BGT)*, 2018). The total 1D set contains 2600 cross-sections in the channel, one for each of the available centerline segments, between which linear interpolation takes place. The complete profile of these canals is determined by some provided cross-sections, which are used to approximate the full channel. The details of this modeling are described in Appendix A.

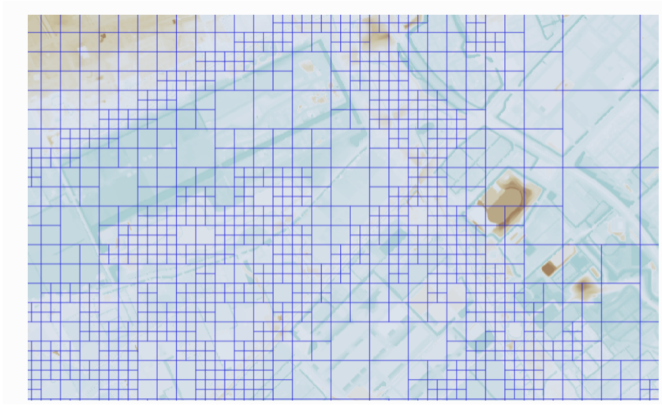
The water level in the polders varies between the different polders and is assumed to be within the range specified by the Peilbesluit Alblasserwaard (Rivierenland, 2024). The water levels in the canals are also assumed to be at normal levels. These levels are −0.75m and −0.9m with respect to NAP for the Achterwaterschap and Graafstroom respectively (Rivierenland, 2024). Different return periods or water levels are not tested as the water level is not expected to fluctuate much in practice. This is because pumping stops are imposed for the polders if the water level threatens to exceed safe levels.

3.2.2. Model
The 3Di modeling software by Nelen & Schuurmans is used for this (3DI, 2024). 3Di is a hydrodynamic simulation software that can be used to model pluvial, fluvial, and coastal floods. Besides this it is possible to make hydraulic designs of open channel and sewer networks, enabling climate impact studies. All 3Di models are simulated on computational offsite clusters, enabling fast computations of large study areas as well as quick 'prototyping' of different models (3DI, 2024). The user interface for 3Di is based on QGIS (QGIS, n.d.), as the interface presents itself as a plugin for QGIS through which the simulations can be controlled.

3Di uses a structured, staggered (2D, 1D) grid with quad-tree refinement (2D). Here, water levels and volumes are defined at cell centers, and velocities/discharges are defined at the cell edges. This works the same for the vertical coupling between different layers. To speed up the calculation process, quadtree refinement is used. Based on the flow conditions and intererest in a particular area the grid becomes more or less defined as can be seen in Figure 3.8. This is usually done in built-up areas or near waterways, where flow patterns are more complex and the interest in accurate models is usually higher.



(a) Staggered grid as implemented in 3Di



(b) Quadtree refinement as implemented in 3Di

Figure 3.8: Illustration of the working principles of Staggered grid and quadtree refinement around waterways from the official 3Di documentation. (3DI, 2024)

Another important feature of 3Di is the use of the subgrid method. In the subgrid method, the flow is computed on a coarser grid than the bathymetry, allowing for faster computations while still capturing the effect of bathymetry on a high resolution. It also means that a cell can be wet, dry, or partly wet, making it suitable for small water depths as well as periodic flooding of areas like tidal flats.

Before a simulation, the relationships between the water level and a set of other parameters (volumes, cross-sectional area, friction parameters, etc.) are calculated and compressed in tables, allowing easy access during the simulation.

In this research, two main types of flow are used: 2D surface flow (in the flooding polder) and 1D flow (in the channels). Both these types of flow are calculated using the depth-averaged shallow water equations.

Model Settings
This research mainly focuses on the methodology behind the quantification of flood resilience. As such, the accuracy of the model is not critical, but it should capture the most important flow patterns to verify the methodology against. As such, this section describes the resolution and model layers used for this research.

The computational grid size was determined by a combination of expert consultation and some trials. Based on this, it was decided to make a distinction between open areas, (larger) waterways/nature reserves, and built-up areas. The principle of this approach can also be seen in Figure 3.8b. The final resolution is 80 meters for open fields, 20 meters for ecological areas/canals, and 5 meters for built-up areas. The base timestep is 10 seconds, but as the 3Di models use time stretching and compression the actual timestep varies throughout the model. The output timestep has to be specified by the user and cannot be dynamically chosen. This research uses an output timestep of one hour, which is a tradeoff between computational speed and accuracy.

Required model layers
To accurately model the flooding of the study area, certain datasets are required. In this section, the used datasets and assumptions are discussed.

Digital Elevation Map (DEM): To accurately model a flooding scenario the height map of the terrain being flooded is crucial. In The Netherlands, these measurements are stored in the Algemeen Hoogtebestand Nederland (AHN, 2019) and the layers are also stored in the data warehouse Lizard (Lizard, 2024). The spatial resolution of AHN4 0.5x0.5 meters, with an accuracy in height of 0.05 meters(AHN, 2019).

Friction Map: The spatial friction map is needed to accurately model the flood wave propagating through the model, as it has a strong effect on the flood arrival time. While it is possible to model the whole area with a

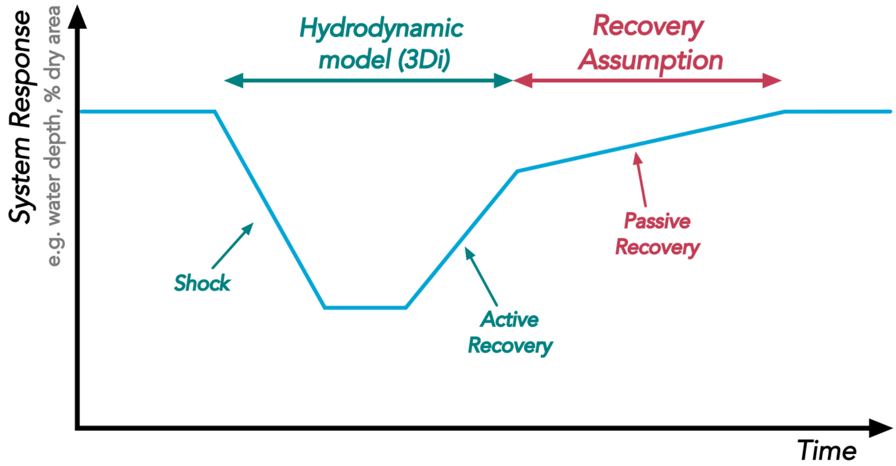


Figure 3.9: Phases of the system response curve in this research

constant Manning or Chezy bed friction coefficient, a more accurate metric is to use land use as an indication of the friction at that location. These files are also stored in Lizard and are therefore imported directly.

1D channel layer: The canals of both the Ablasserwaard and Nederwaard are modelled as a 1D system of channels based on their centerlines and BGT watervlakken (*Basisregistratie Grootschalige Topografie (BGT)*, 2018). This gives an approximation of the amount of water available to flood the study area.

Model Phases

The simulation is split into three different parts. The first phase is the shock, in which the flooding occurs in the polder. In the second phase, named active recovery, the (emergency) pumps kick in, the breach is closed and the water is pumped out of the polder. At some point, the model will not be able to properly capture the pumping behavior, so an assumption needs to be made about the recovery. This phase is called passive recovery. Each phase is elaborated upon in the next section. An illustration of the different phases is given in Figure 3.9.

Shock

When a breach occurs in the model, the canals start emptying into the polder itself. These channels are finite in volume, as discussed in Section 3.2.1, meaning the flow through the breach stops after a few days. It is assumed that the pumps can start pumping water out of the area about a day later, based on consultation of experts from Delft University of Technology. After 2 days the flow through the breach is limited, meaning the recovery phase can begin after 3 days.

Active Recovery

After 72 hours, the pumping stations are assumed to be repaired and water is slowly evacuated from the polder. The pumping capacity is provided by the water authority of Rivierenland and given in Table 3.2. Runs with and without emergency pumps are attempted. The capacity of the emergency pumps was set to be equal to the already present pumping capacity, effectively doubling the pumping capacity. The choice for this doubling was made based on expert consultation from Delft University of Technology.

Passive Recovery

Because the model does not include the smaller canals and sewer system, at some point the water is not reaching the pumping stations anymore, which would be the case in the actual scenario. This time is dependent on the scenario that is being tested but usually ranges from 3-8 days.

An assumption can be made about the decrease in water level by considering the pumping stations that are present in the respective polders. If the pumping capacity and surface area of a given polder are known, an estimate for the water level difference per day can be calculated. If this is used in the model, it is a decent assumption for the recovery of the polder. By using this assumption, locations that remain inundated due to the absence of a sewer system still have a mechanism for recovery.

Breach Behaviour
The exact temporal evolution of a dike breach is a highly complex process, which is not fully understood, and often empirical models are used (Danka & Zhang, 2015; Verheij & Van der Knaap, 2002). Often, the internal resistance of the channel becomes the dominant factor for determining the discharge through a breach. To verify if this is also the case for this model, a sensitivity analysis was conducted. This analysis can be found in Appendix A.3. While there is a small difference in total discharged volume for different breach behavior assumptions, this difference is reduced to less than 2.38% after 12 hours and only becomes smaller from that point on. As a result, the default breach behavior of the 3Di modeling software is used.

Model Runs
To validate the proposed methodology, it is needed to conduct tests involving various breach locations and implement some interventions. The variation in breach locations is primarily intended to enhance our understanding of the system's response, which is influenced by the presence of smaller subsystems. The interventions are executed to assess the feasibility of the hydrodynamic quantification methodology.

Table 3.3: Model runs attempted in the study

Model	Type	Intervention	Remarks
1	Base	Default breach locations	-
2	Scenario	Nature conserve breach	Donkse laagten (Natura2000)
3	Scenario	Breach village	Bleskensgraaf
4	Scenario	Breach subsystem NDW010 east	Near Ottoland
5	Intervention	Detention Basin	Modified DEM
6	Intervention	Moveable barriers	0.2 meters
7	Intervention	Moveable barriers	0.4 meters
8	Intervention	Double pump capacity	-
9	Intervention	Resilient pumps	Pumps remain on for all timesteps

The location variations have been selected to expose distinct subsystems of the model, thereby facilitating the comprehension of its behavior as previously discussed. Consequently, the model does not accurately represent reality, where weak points in dikes are the most probable initiation points for breaches. This is not crucial for testing the proposed methodology, it should be taken into account when conducting further research.

The detention basin is partially located in each of the subsystems in which the breaches occur, NDW002 and NDW010. It has a surface area of 0.9m^2 and was achieved by lowering the DEM to 2.15 meters below NAP. The moveable barriers were created by increasing the height of the dikes by 0.2 and 0.4 meters for the two different runs. By increasing the height of these dikes the flooding will likely lessen in adjacent areas, but may increase in the initially flooded area as the water cannot diffuse to other locations. Two interventions with pumps were also tested. In the first, the capacity of the pumps was doubled. This could either be because the capacity is structurally increased or because emergency pumps would be put in place. In the second intervention, the pumps were not shut off in the initial flooding stage, meaning the draining of the polder could commence immediately. This idea of building a resilient pumping station has been implemented in some locations already, for example in the wastewater treatment plant near Weesp (*Waterschap Amstel, Gooi en Vecht*, n.d.)

3.3. Summary

This chapter introduces a methodology for the hydrodynamic quantification of flood resilience, focusing on a multi-layered flood safety framework as applied in The Netherlands. By utilizing hydrodynamic models, key variables such as flood arrival time, residence time, temporal water depth, and temporal impact are derived to assess flood resilience. The methodology emphasizes the need to consider not only direct impacts on specific

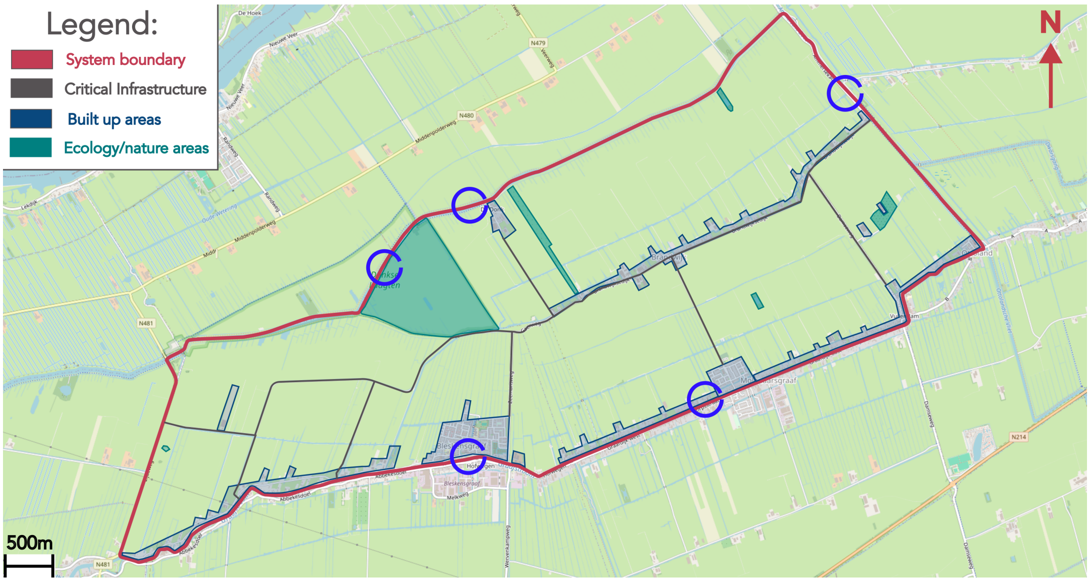


Figure 3.10: The considered systems with distinct breach locations for the model runs.

assets like buildings but also indirect impacts, such as flooded infrastructure and utility networks, to provide a comprehensive understanding of flood resilience.

The proposed approach integrates hydrodynamic results with various functional perspectives, namely residential, ecological, and economic. For residential areas, factors such as house inundation, affected infrastructure, and utility functionality are evaluated. Similarly, for economic activities, the analysis extends to surrounding land use and the percentage of dry area, recognizing the broader implications of flooding on economic recovery. Various metrics, such as percentage dry area, derivatives of change in flooded buildings, and depth integrals, are proposed to evaluate resilience across different perspectives.

The methodology is applied to a case study in the Alblasserwaard polder, encompassing four subsystems under the governance of the Rivierenland water authority. Using the 3Di hydrodynamic modeling software, the study simulates flooding scenarios and evaluates the impact of various interventions, such as detention basins, moveable barriers, and enhanced pumping capacity. By integrating hydrodynamic modeling with perspective-based analysis, this method aims to improve flood resilience quantification, offering insights that can inform flood management strategies and future research.

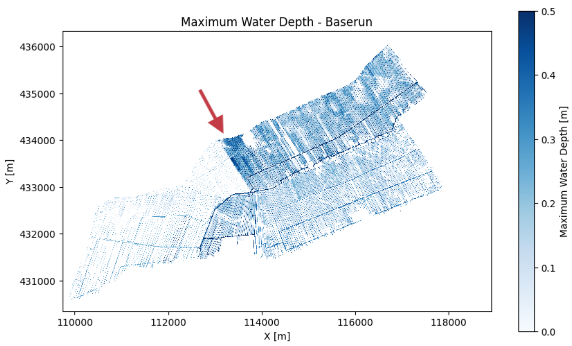
4

Results

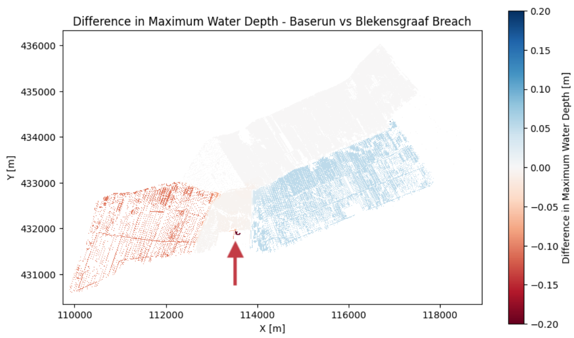
This chapter describes the research results. Each functionality curve is presented in a different section, with the resilience metrics originating from that curve also shown.

4.1. Temporal Water Depth

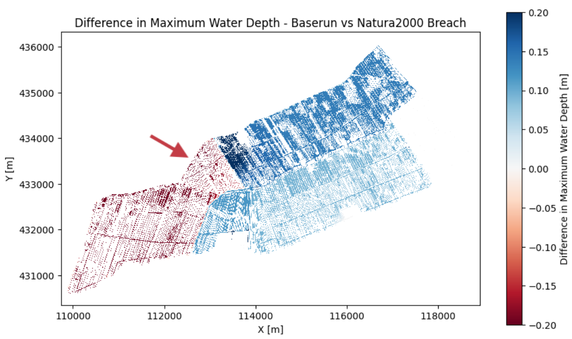
This section presents the resilience metrics that are derived from the temporal water depth. The four different location variations all exhibit different flood characteristics. One way this can easily be shown is by plotting the spatial maximum water depth for each location, as seen in Figure 4.1.



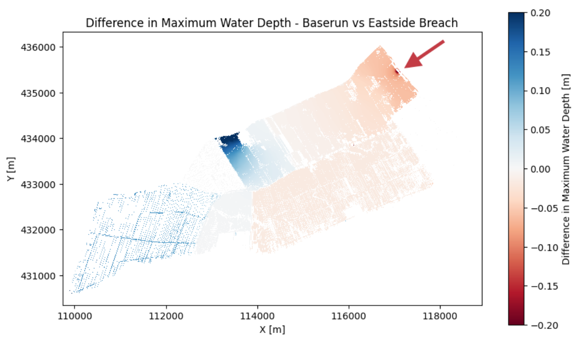
(a) Maximum water depth baserun



(b) Comparison baserun and Bleskensgraaf breach



(c) Comparison between baserun and nature reserve



(d) Comparison baserun and eastside breach

Figure 4.1: The maximum water depth of the base run and the comparison of the maximum water depth of all the variations with the baserun. The arrow shows the breach location. Red indicates a larger maximum inundation compared to the baserun, blue indicates a smaller maximum inundation.

The separation between different subsystems can be clearly seen in the different variations, with the subsystem containing the breach experiencing the largest water depth. The differences in Flood Arrival Time are even more dependent on the initial breach location. As such, this section on water depth focuses mainly on the differences between resilience interventions and whether the metrics indeed show improving flood resilience. For some of the individual buildings, the functionality curves are shown in Figure 4.2.

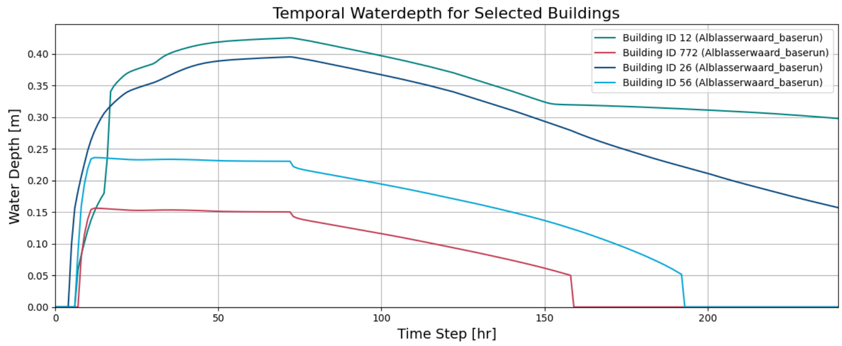


Figure 4.2: Water depth functionality curve for some buildings. The water depth resilience metrics are derived from the curves of all individual buildings.

4.1.1. Flood Arrival Time

For the baserun, Flood Arrival Times are given in Figure 4.3a. For most areas, the FAT is between 0 and 20 hours, though values as high as 70 hours are present, which is the last timestep before the pumps are engaged. For other runs, the difference in FAT is presented. These differences are plotted in Figure 4.3b, Figure 4.3c, and Figure 4.3d.

A clear duality can be seen in the run with the detention basin in Figure 4.3b. The overview of the different subsystems is shown in Figure 3.7. With the breach occurring from the north, as seen in Figure 3.10, the subsystem NDW010 closest to the breach experiences little difference in flood arrival times, as this area is inundated before the detention basin is reached. For all subsystems where the detention basin is either present (NDW002) or the flood passes by the detention basin before reaching it (NDW015), the arrival times are multiple hours later.

The moveable barrier paints a more complex picture, with roughly three distinguishable responses in the model. As the water needs to be higher before it can overflow into a different subsystem, the southern NDW002 polder experiences an increase in FAT. By contrast, the NDW010 polder where the breach occurs experiences a decrease in FAT, indicating this subsystem has lower resilience after introducing the barriers. The Western NDW015 polder no longer experiences any flooding in this scenario, meaning the moveable barriers could be considered a resistive measure for this system. The differences for the constant pump are small.

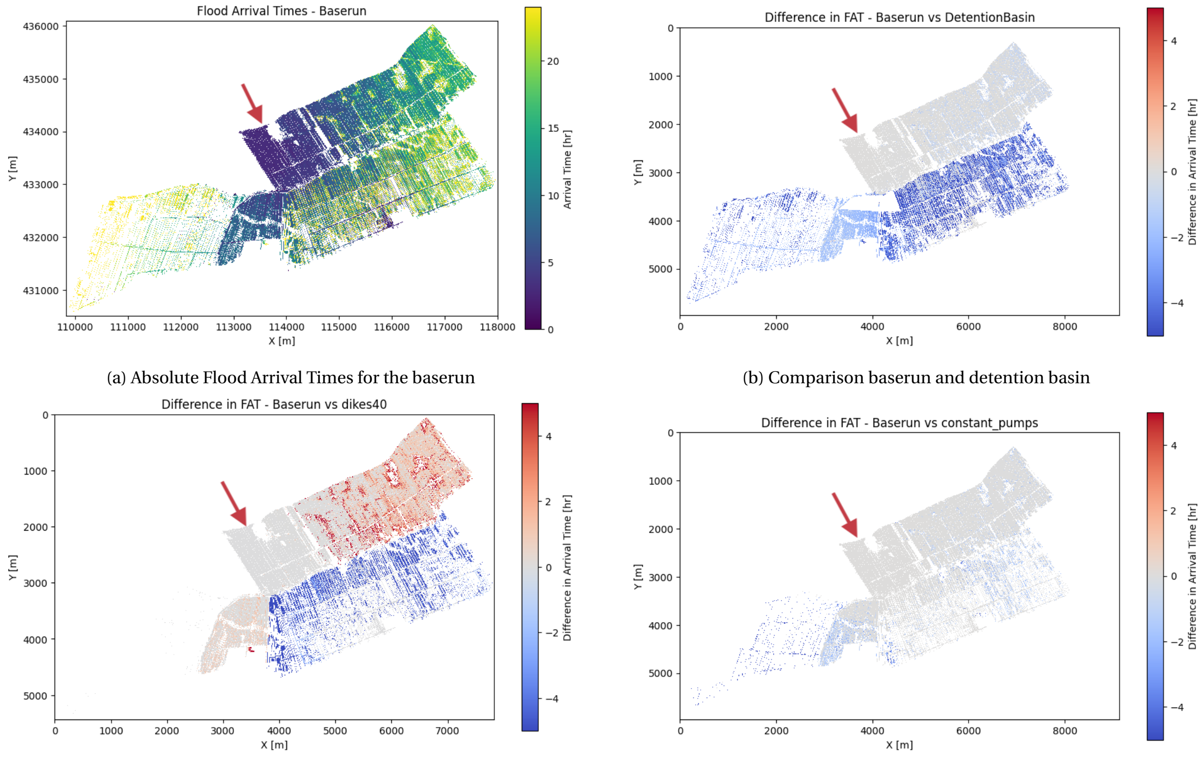
4.1.2. Residence Times

For residence time, the distinction between direct and indirect hydrodynamics is presented. It can be seen in Figure 4.4 that this distinction does show large differences, with larger sections of the study area being affected by the flooding. Large clumps of similar colors can be seen in Figure 4.4b, due to flooded utilities and roads affecting large sections of the villages in the study area.

Differences in residence times can be seen when implementing the resilience measures in the intervention runs, showing the potential applicability of using this metric for the quantification of flood resilience. The exact differences are shown in Appendix C.2

4.1.3. Water Depth Integral

The water depth integral shows that the water depth for the flooded buildings spans multiple orders of magnitude and is generally below 100mhr. Some outliers are present, but the amount is small (four buildings).



(a) Absolute Flood Arrival Times for the baserun

(b) Comparison baserun and detention basin

(c) Comparison between baserun and moveable barriers

(d) Comparison baserun and constant pumps

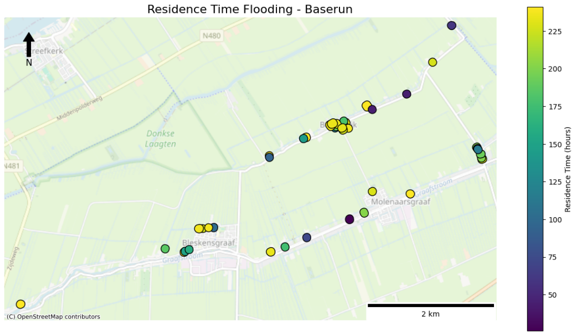
Figure 4.3: FAT of the base runs and comparative runs for multiple interventions, with the red arrow indicating the breach location. The values in Figure 4.3a are hours passed since the breach commenced. In the other plots, red colors indicate faster flooding (lower FAT) compared to the baserun, and blue colors indicate slower flooding.

The comparisons between the baserun and two interventions, the detention basin, and moveable barriers, can be seen in Figure 4.6. The interventions appear to affect the integral, but the amount is difficult to quantify using just these integrals. A more insightful answer is obtained by taking the median and average values for the depth integrals.

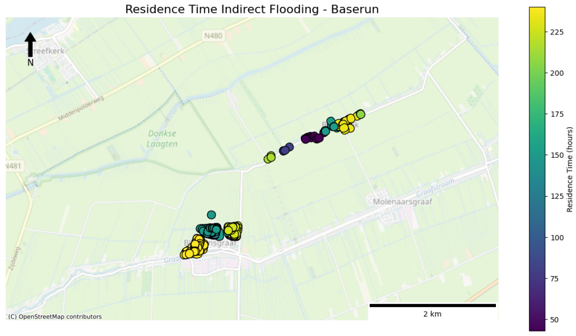
The moveable barrier performs worse compared to the detention basin, performing approximately equal to the baserun in these metrics. The detention basin shows a small difference of less than 2% for the average integral, but the median amount is nearly 10% lower than the baserun. The constant pumps outperform this further, improving both the median and average integrals by 12.5% and 14%, respectively. This indicates the relevance of this metric in the shock phase, as the constant pumps mainly affect this part of the model run. The emergency pumps improve on this further, indicating this metric's relevance in the recovery phase.

Table 4.1: Intervention Comparison: Integrals and Percentual Changes

Intervention	Average Integral [m·hr]	Change [%]	Median Integral [m·hr]	Change [%]
Baserun	50.10	-	33.45	-
Detention Basin	49.30	-1.60%	30.14	-9.88%
Moveable Barriers	50.83	+1.46%	32.26	-3.55%
Constant Pumps	43.15	-13.85%	29.29	-12.46%
Emergency Pumps	40.86	-18.45%	24.10	-27.96%



(a) Absolute residence times baserun



(b) Absolute indirect residence times

Figure 4.4: Total residence time of all affected buildings in the study area. The left pane is the direct residence time of flooded buildings in the area. The right pane shows the residence time of flooded utilities around the building.

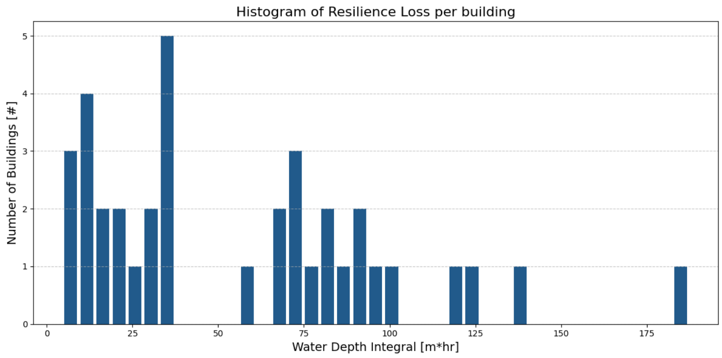


Figure 4.5: The absolute integral values of temporal water depth for the baserun. The vertical axis shows the number of buildings in each bin, and the horizontal axis shows the value of that bin.

4.2. Number of Flooded Buildings

When looking at the number of flooded buildings over time, the residential perspective is taken. The maximum amount of flooded buildings from the commercial perspective, usually around five, was determined to be too few for accurate results. The results for the commercial perspective are shown in Appendix C.1. In Figure 4.7a, the number of flooded buildings over time is shown for the different breach variations. The derivative of that value, or the rate of change in flooding buildings over the last five hours, is shown in Figure 4.7b. This derivative is only shown for the shock phase of the model, up until timestep 72.

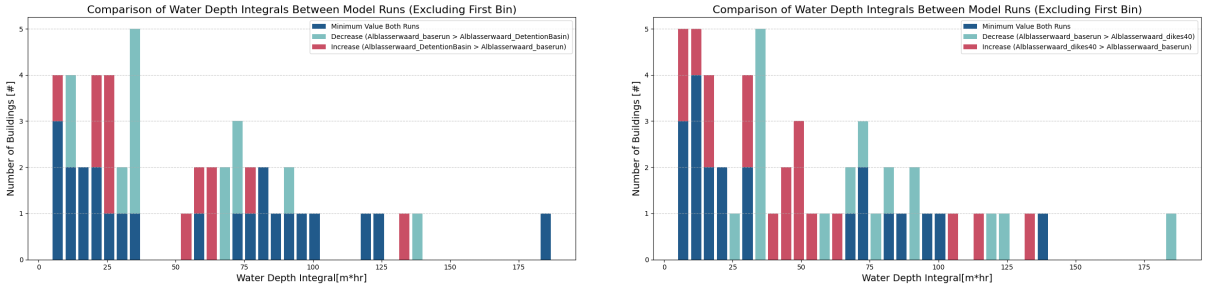
Besides the location variation, the different resilience measures can also be shown in a similar way. The result for direct flooding can be seen in Figure 4.8.

Lastly, the number of affected buildings over time can also be plotted using indirect hydrodynamics. In the case of Figure 4.9, the number of buildings with affected utilities or roads is plotted over time. The three resilience metrics are discussed using the presented graphs. An overview of the different metrics for the interventions is given in Table 4.2.

4.2.1. Maximum Amplitude Shock

First, it should be noted that only a small percentage of the total buildings get flooded in all the attempted scenarios. In the baserun, 37 buildings were flooded, which is 2.58% of the 1428 buildings present in the study area. For all scenarios, the percentage of flooded buildings is between 1.68% and 7.91%, which indicates an already high resilience of the system against this type of flooding.

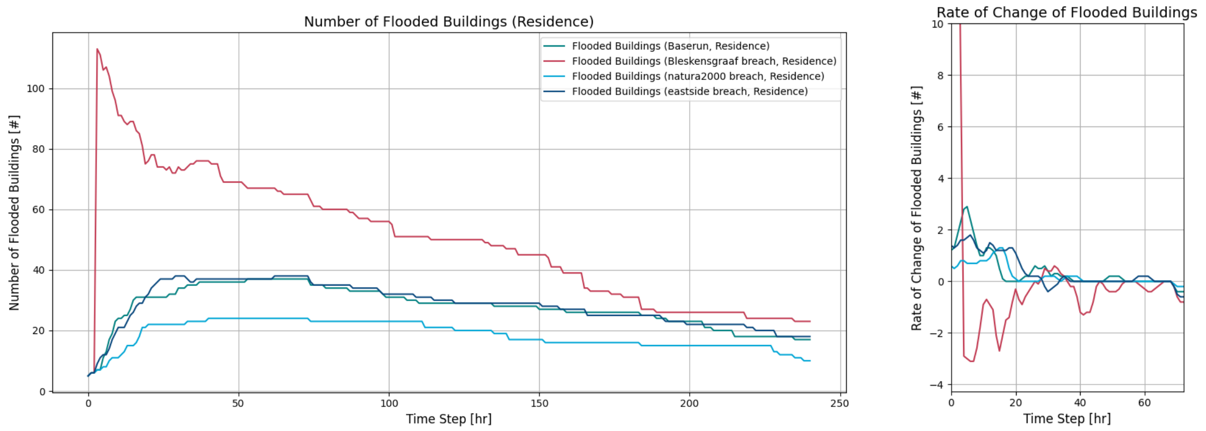
Unsurprisingly, the breach occurring in the village led to the largest number of flooded residences. After a sharp rise just after the breach, the number of flooded residences does go down sharply, as can be seen in



(a) Comparison baserun and detention basin

(b) Comparison between baserun and moveable barriers

Figure 4.6: Comparison of the depth integrals between the baserun and an intervention. The blue part indicates the minimum of both runs. If more buildings are present in a certain bucket, this is indicated with red. If there are fewer buildings, this is indicated in green.



(a) Flooded residential buildings in the four different model variation runs.

(b) Rate of change of flooded buildings

Figure 4.7: Comparison of flooded assets and their average rate of change taking into account the past 5 timesteps.

Figure 4.7b. The baserun and eastside breach runs perform similarly, as both breaches occur in the same subsystem NDW010. The largest differences between these model runs are directly near the breach location, as the flood wave propagating through the domain has the largest amplitude in this area. The difference in the number of flooded buildings between runs suggests that it could be an interesting metric for the quantification of flood resilience.

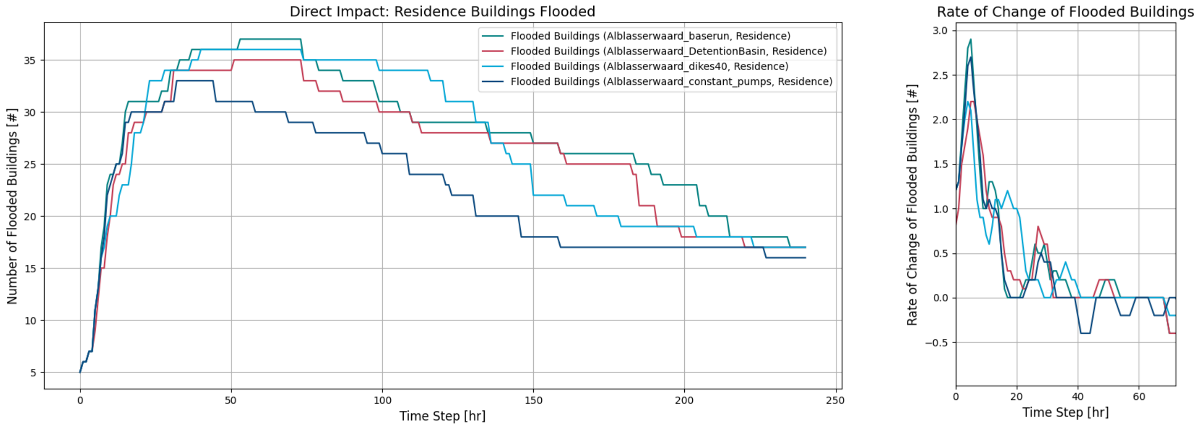
When considering the different intervention runs in Figure 4.8, the maximum amplitude shock only varies a little between different runs. The difference in time to maximum amplitude shock does vary significantly, as much as 55 hours. The baserun does show the largest shock amplitude of all runs, indicating that this metric does improve under flood resilience measures, meaning it is potentially correlated with the resilience of the system.

The strongest differences for the intervention runs are present in the indirect flooding metrics. The moveable barrier intervention performed much worse, even compared to the baserun, due to more roads flooding in the considered system. This indicates that the indirect flooding metrics can provide additional insights into the complex system response during a flood event.

4.2.2. Amplitude Shock Rate

The amplitude shock rate varies strongly between the model variations, which is expected due to the large difference in amplitude shock, affecting the derivative as well. For this metric, then, the focus is placed on the different interventions and if the shock rate is affected by these.

Simply averaging the amplitude shock rate shows shock rates between 0.66 for the baserun and 0.55 for the



(a) Flooded residential buildings due to direct flooding

(b) Rate of change in flooded buildings

Figure 4.8: Comparison of flooded assets and their temporal rate of change over the past 5 timesteps

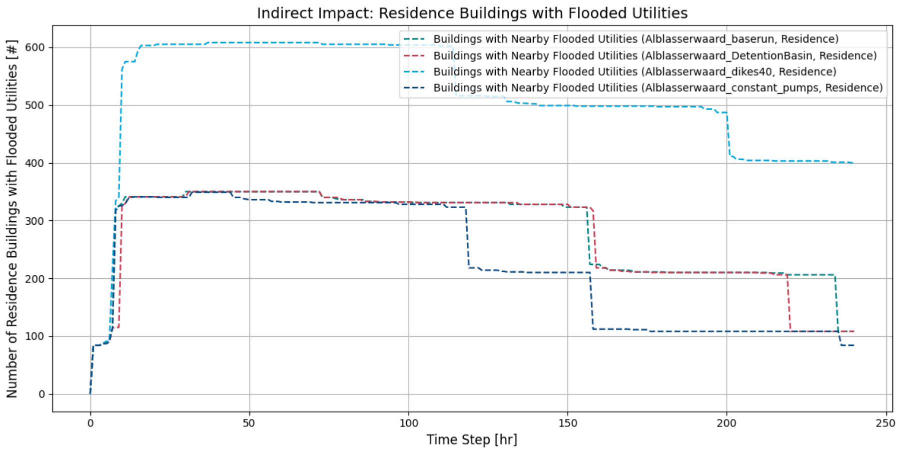


Figure 4.9: Residential buildings with flooded roads or transformer stations in the determined radius.

constant pumps, as seen in Table 4.2. However, when looking at the absolute value of flooded residential buildings over time, a more nuanced picture emerges. For the first 20 hours, the difference is negligible, after which the moveable barriers start performing the best. The total amplitude shock rate is the lowest for the constant pumps because these also have the lowest shock amplitude.

4.2.3. Recovery Rate

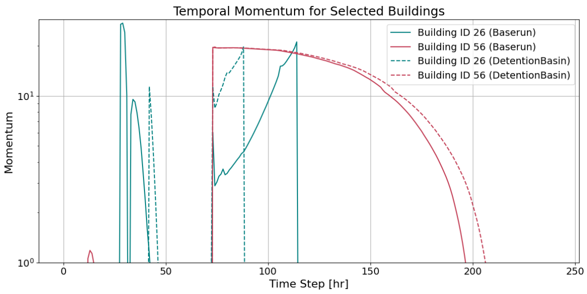
In a similar manner to the amplitude shock rate, the recovery rate is also strongly dependent on the shock amplitude. Differences can once again be seen in Table 4.2, but due to each model run ending with 16 or 17 buildings flooded, the total recovery rate is similar between runs.

4.3. Temporal Momentum Impact

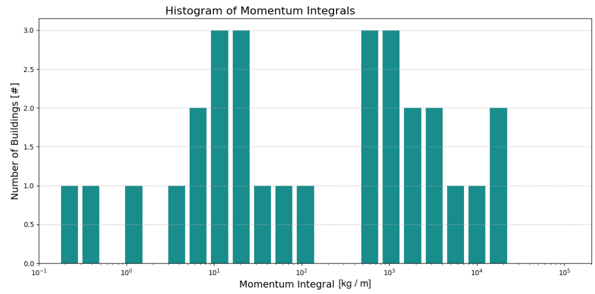
In a similar manner to what is done in Figure 4.2, the temporal momentum can be plotted for individual buildings. However, as can be seen in Figure 4.10, the curves originating from the individual buildings are erratic, changing significantly between model runs. The total momentum integrals span over six orders of magnitude as a result of this behavior, making comparison difficult. This is likely because of fundamental principles of 3Di like the subgrid, which is discussed in more detail in Chapter 5. Due to the limited applicability of this result, these metrics are not split out further into the separate perspectives.

Table 4.2: Intervention Comparison: Shock, Recovery, and Indirect Effects. Shock Rate (0-48 hours), Shock and Recovery Rate (48-240 hours) are all defined as the number of affected buildings.

Intervention	Shock Rate	Shock	Recovery Rate	Indirect Shock	Indirect Recovery Rate
Base	0.66	37	-0.12	350	-1.44
Detention Basin	0.61	35	-0.13	350	-1.44
Moveable Barriers	0.66	36	-0.12	606	-1.64
Constant Pumps	0.55	33	-0.11	350	-1.41



(a) Momentum impact for two buildings in the baserun and detention basin.

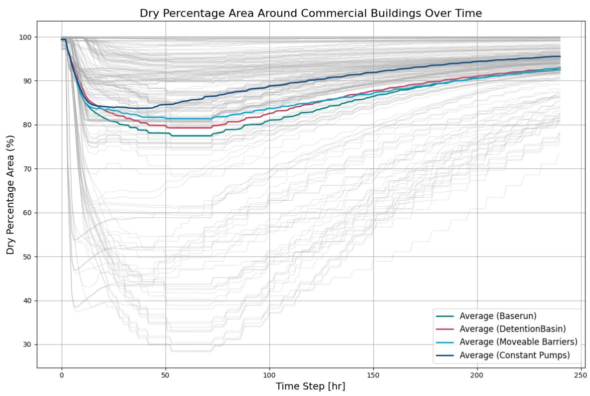


(b) Momentum impact integral for each building in the baserun.

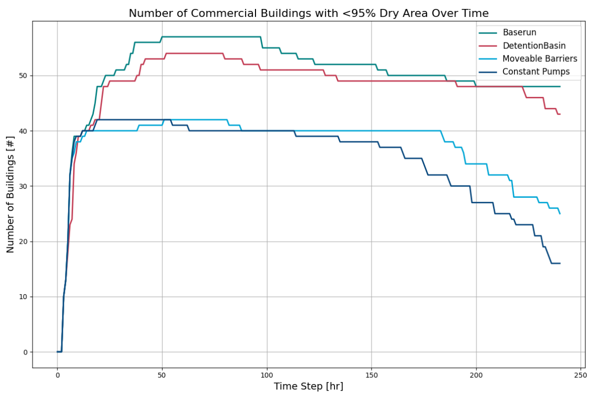
Figure 4.10: Functionality curve and resilience metric attempted for the momentum impact.

4.4. Percentage Dry Area

Lastly, the percentage dry area is also considered. The percentage dry area is only considered for the commercial perspective, as it was deemed important only for that perspective in Chapter 3. The two considered resilience metrics are based on the functionality curves in Figure 4.11.



(a) Average percentage dry area around commercial assets. The grey lines are individual assets, the colored line shows the average for a given intervention.



(b) Amount of commercial buildings over time with more than 5% of the surrounding land flooded for multiple tested interventions.

Figure 4.11: Two representations of indirect hydrodynamics on Commercial buildings in the study area

4.4.1. Percentage dry area in buffer

The percentage dry area in the buffers of commercial buildings broadly follows the distribution seen in the number of flooded residential buildings and temporal water depth curves. However, some differences can also be seen, with floodwaves passing through the commercial buildings' buffer. This can be seen as a rapid drop in percentage dry area, followed by a sharp rise to an earlier level, before the pumps are turned on at timestep 72. The resilience measures affect the average percentage dry area curve, indicating that it could be used for the quantification of flood resilience.

4.4.2. <5% Flooded Buildings

By adding a threshold to the percentage dry area and subsequently counting the number of buildings that meet this criteria, a more actionable insight is obtained for the percentage dry area. If we consider any building that meets the criteria affected by the flooding, once again, a metric for affected commercial buildings is obtained.

This metric paints a different picture from earlier metrics, where the constant pump and moveable barrier intervention perform better compared to the detention basin and baserun, especially in the recovering phase of the model. As such, this metric can potentially add an extra layer of information in the quantification of flood resilience.

5 Discussion

This chapter examines the findings of this thesis, with a focus on quantifying flood resilience through hydrodynamic modeling in the Alblasserwaard polder. It begins by evaluating the performance of the hydrodynamic model, assessing its strengths and limitations in representing flood dynamics. The discussion then shifts to the applicability and constraints of the proposed resilience metrics, analyzing their effectiveness in capturing key aspects of flood resilience. Furthermore, the resilience of the system is explored from residential, commercial, and ecological perspectives, highlighting the trade-offs associated with different intervention strategies. Finally, the chapter summarizes the findings of this thesis in a single qualitative table.

5.1. Hydrodynamic Model Performance

Before discussing the quantification of flood resilience in the case study, some reflections on the model performance are done. As described in Section 3.2, the accuracy of the model is not the primary focus of the research. Nevertheless, the model needs to somewhat accurately predict the hydrodynamics present in the system. This was mainly ensured by using expert consultation from the company Nelen & Schuurmans, but some points specific to this study remain.

The biggest deficiency in model performance regarding the research method is in the use of a subgrid for the determination of momentum. For both velocity and water level, the model uses a coarser computational grid than the bathymetry grid, as discussed in Section 3.2.2. The water depth is then calculated using the coarse water level grid and the more detailed bathymetry grid. This works well for water depth, but for momentum, this likely leads to inaccurate results. This is because the velocity vector obtained is the average for the computational cell, as illustrated in Figure 5.1. Depending on the bathymetry in the cell, the real-world flow velocity could be much higher, as the flow can be constricted by the bathymetry. The problem is exacerbated by the fact that the grid size is non-uniform throughout the model. For larger grid sizes, the average flow velocity is likely lower, meaning buildings near grid refinement experience larger momentum compared to buildings in the open field, even though this is not true in practice. To solve this issue, the computational grid should be modified in two ways.

1. The grid needs to be made uniform in size.
2. The resolution of the grid needs to be much finer, preferably equal to the resolution of the bathymetry. This can be done, but this loses the advantages in computational speed of using the subgrid method.

By doing this, however, much of the computational efficiency of 3Di is given up, and it is unclear whether the momentum would be more informative compared to using the existing water depth metrics and its derivatives. The computational time with the current spatiotemporal settings is about 1.5 hours, and this would increase to over two days when increasing the computational resolution.

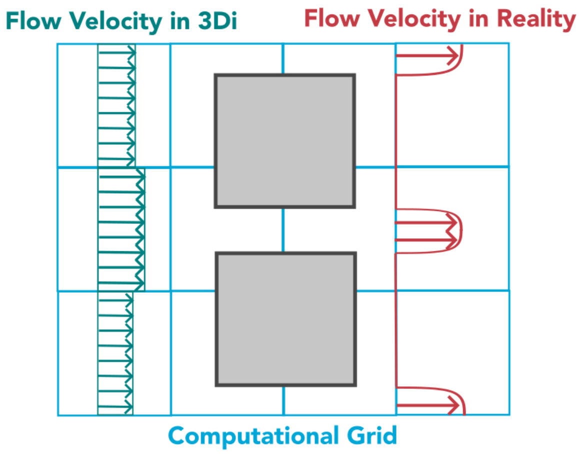


Figure 5.1: Difference in flow velocity between the computational grid and reality, complicating quantifying momentum impact.

5.2. Temporal Water Depth

The temporal water depth functionality curve has been split up into three different resilience metrics. These metrics are individually discussed in this section.

5.2.1. Flood Arrival Time

Flood arrival time is an important metric in both flood risk and flood resilience. It shows the time inhabitants have to evacuate themselves and their properties or the time available to prepare for the flood event. This metric is best presented in a spatial context, as shown in Figure 4.3, as it allows the flood dynamics to be presented in an informative way. Implementing the resilience measures can be seen to improve the flood arrival time (i.e. make them longer), further indicating that this measure can be used for the quantification of flood resilience.

5.2.2. Residence Time

The metric of residence time has two primary applications. First, it serves as an indicator of the areas of interest that are affected. Clusters that emerge in the study area are evident in **??**. These clusters are crucial points of consideration for resilience metrics. Although the clusters themselves may not directly provide information about the resilience of the system, they do suggest where priority should be allocated.

Besides this, the residence times of buildings serve as a good indicator of the total impact time on buildings. The total impact time on buildings offers a distinct advantage in quantifying system resilience. Residence time provides a clear indication of the total duration of impact on a building. The average or median of residence times may be the most suitable quantification method for measuring the total duration of impact.

5.2.3. Water Depth Integral

In its current form, the depth integral seems unsuitable for the quantification of flood resilience. This is because, by combining the variables of water depth and time into a single dimension, important information is lost. As mentioned before, the proposed metric makes no distinction between one meter of water for ten hours or ten meters of water for an hour, which matters a lot in determining the consequences. One of the solutions could be to make the integral non-linear. For example, we could take the integral of the water depth squared. By doing this, higher water depths are additionally weighed as being detrimental to flood resilience. While this means that information is still lost, this metric could start to introduce the idea that low water depths are acceptable to a degree while strongly advocating against large water depths.

Another issue in using the metric for quantification of flood resilience is that it is not intuitive. Policy-makers or system designers might have problems interpreting the results of these depth integral metrics. However, taking the median and averages of these depth integrals did show that for different interventions, the median and average values went down. This was the case both for interventions designed to mitigate the consequences (like the moveable barrier) and for interventions designed to speed up recovery (like the emergency pumps). The depth integral was able to capture both these interventions in a single metric, showing there is potential in using it for resilience quantification.

5.3. Number of flooded buildings

With all the attempted model runs, the number of flooded assets was low. With over 1400 buildings present in the study area, only 2.58% of the buildings flooded in the baserun. The main reason for this is the elevation of assets in the study area. This elevation of assets is not necessarily by design but rather due to the subsidence of the surrounding land. The Alblasserwaard is an area of The Netherlands experiencing heavy subsidence, mainly due to dewatering for agricultural practices (*Soil Subsidence Prediction Maps*, 2021). This means that the buildings, which are often constructed on piles, are elevated above the surrounding area. Roads are often located on elevated separation dikes as well, keeping them dry from most flooding events. This effect is expected to grow stronger in the years to come, with nearly the whole study area experiencing more than 0.6m of subsidence by the year 2100 (*Soil Subsidence Prediction Maps*, 2021). In essence, this subsidence causes the relative elevation of assets discussed in Section 2.3.2.

This paints a different picture of resilience compared to the work by Raychel Baynick in this same area. In her work, the shock amplitude of the system increased when model runs under subsidence were done. While it needs to be verified by implementing these subsidence projections, it shows a potential advantage of using the buildings of interest as the governing metric for the system response, compared to the hydrodynamics of the whole system. This also shows a first metric through which resilience can meaningfully be quantified using the hydrodynamics centered around buildings. When looking at flood risk, the maximum water depth in the area might be relatively large, but it is not affecting the system as the areas critical for system functionality are still unaffected. The maximum percentage of flooded buildings, or perhaps the temporal percentage of flooded buildings, therefore, indicates the overall resilience of the area.

The difference between direct and indirect hydrodynamics is large in the functionality of flooded buildings. For example, for the shock amplitude, the direct and indirect metrics are nearly a factor of two apart. The fact that many more roads are flooding in certain model runs is an important factor when looking at resilience, but this is not captured by simply using direct hydrodynamics. The indirect hydrodynamics need much more refinement, but the principle value that they can add is demonstrated in the functionality curves of flooded buildings.

5.3.1. Shock Amplitude

Shock amplitude is likely the best single metric for estimating the total impact of a certain flooding event. If the number of residential buildings, commercial activities, and ecological areas affected is known, a first estimation of the impact can be done. Like the temporal water depth, it is also the metric that is closest to existing flood risk measures, as it only takes the maximum value of the impact, losing the temporal component important for resilience in the process.

The current metric, which only counts the absolute number of affected buildings, makes it difficult to compare the metric between different flood-prone areas. If 200 buildings are present in an area, of which 40 flood, that is a significant portion. By contrast, if there are 5000 buildings, 40 flooded buildings might not be a big issue. Normalizing the metric to the percentage of flooded buildings could provide more actionable insights when comparing different flood-prone areas.

5.3.2. Shock Amplitude Rate

The shock amplitude rate is potentially the most important metric when considering the emergency response layer of the multi-layered flood safety framework. This is because the number of buildings flooding over time gives a strong indication of the required capacity for evacuation and the need for emergency services. It could even be argued that emergency services and roads have a certain capacity to absorb the adverse effects of flooding events. If this capacity is exceeded, the full service can no longer be provided. The shock amplitude rate has the potential to be linked to this capacity, in which case it could prove to be useful in the quantification of flood resilience, but more research is needed to make this link more explicit.

5.3.3. Recovery Rate

The recovery rate, as currently proposed, is strongly dependent on the shock amplitude of the flood event. This means that a flood event with limited flooding buildings will perform poorly on this metric, despite the consequences being small. The idea of the metric is that increased recovery rates would mean that residents can return to their homes and shops earlier, making sure the system functionality can be restored sooner. The problem of the metric being dependent on the shock amplitude could potentially be solved by dividing the total area under the functionality curve by this rate. In this way, the results are normalized to the total 'size' of the flood event.

However, it is potentially more straightforward to take the residence time instead of the recovery rate as a measure of the time residents can return to the area. A shorter residence time is a good measure for the total time a building is affected and is also easy to plot spatially, as seen in **??**.

5.4. Temporal Momentum Impact

As mentioned, the momentum impact metric is limited by the use of the subgrid method, which is a fundamental part of the 3Di modeling software used in this thesis. The resolution can be increased in such a way that the computational grid and bathymetry grid are identical, but by doing this, the computational time is increased substantially.

The other challenge with this metric is that it is not only dependent on the water flowing by/through the buildings but also on the geometry of the building itself. A building with a more streamlined or open shape is affected less by a certain momentum impact in its vicinity. To solve this, surrogate modeling for these buildings could perhaps be used, but this is beyond the scope of this research. Even if this method proves successful, the computational costs are still high, as the postprocessing of the datasets to include momentum impact takes significant computational time as well. More research remains necessary to determine if including momentum impact is useful when quantifying flood resilience.

5.5. Percentage Dry Area

The percentage dry area is mainly useful for quantifying the performance of commercial buildings. When considering farms, for example, the percentage dry area surrounding a farmhouse or barn is indicative of the state of the land, which is especially crucial for crop performance. Two different metrics were considered for this functionality curve, each with its applicability.

5.5.1. Percentage Dry Area in buffer

The percentage dry area in the buffer can be used to obtain a general temporal response of the system to the flood event occurring. By plotting both the individual buildings and aggregated behavior, the flood wave can also be seen to be passing through the area, which can perhaps be used as a proxy for the impact on these areas.

The challenge with this metric is that for other commercial activities than farming, the metric of percentage dry area is not the most indicative of performance. Instead, for small shops like supermarkets, the percentage of flooded buildings nearby could be more indicative of the state of the customer base. For commercial activities, having customers is critical, so this metric might indicate the performance of commercial activities in a better way.

Just using the percentage dry area in a circle around a commercial activity is not sufficient for determining the state of that commercial activity. As such, this metric in its current state is not useful for quantifying flood resilience.

5.5.2. Number of buildings <5% flooded

By assigning a threshold to an affected state, a potentially more useful metric appears. Counting the number of commercial buildings with <95% of their surrounding area (as determined by the same buffer as the previous metric) over time is closely related to the number of flooded buildings, with the added information that it is informative regarding the state of the land. Even if the commercial activity itself is not flooded, having large flooded areas around it can impact the performance of that activity. As a result, this metric may provide additional insights when quantifying flood resilience.

The challenge with this metric is the fact that the threshold is currently chosen based on a pluvial norm when the considered flood-prone area is experiencing fluvial flooding. Furthermore, this threshold is once again based on agricultural land, so it may have limited indicative value when considering other types of commercial activities. A variety of thresholds may need to be established before this metric becomes effective in determining resilience.

5.6. Summary

When considering the metrics presented in Chapter 3, the same table can be presented, but with the applicability of each attempted metric presented and whether it is suitable for one or more perspectives. The results are shown in Table 5.1. The results for the ecology are left blank, as no significant flooding occurred in the ecological areas, making it impossible to draw conclusions on these metrics.

Table 5.1: The evaluated metrics for resilience and their qualitative applicability for quantifying flood resilience.

Direct	**Hydrodynamic Condition**		**Perspective**		
	Water Depth	Mom. Impact	Residential	Commercial	Ecology
Depth Integral	x		-	-	?
Momentum Integral		x	–	–	?
Derivative Shock Rate Buildings	x		++	++	
Arrival Time	x		++	++	
Amplitude Shock	x	x	+ ∣ −	+ ∣ −	?
Residence Time	x		++	++	?
Recovery Rate	x		-	-	
Indirect					
Percentage Dry Area	x			-	?
<5% Flooded Buildings	x			+	
Flooded Utilities	x		+		

6 Conclusion

This thesis explored the quantification of flood resilience using hydrodynamic conditions, focusing on the Alblasserwaard polder in the Netherlands. Through hydrodynamic modeling and the integration of diverse perspectives, the study aimed to establish a framework for assessing resilience across residential, ecological, and commercial domains. This quantification was done with the Multi-layered flood safety resilience policies of The Netherlands in mind. It specifically considered the consequence mitigation and emergency response layers of this framework, as they are deemed most suitable for hydrodynamic quantification of resilience. The research posed the following questions in the introduction.

1. *What system definition, boundaries, and initial conditions need to be chosen to accurately model the flooding scenarios needed to quantify resilience?*

To accurately quantify metrics and measures, it's crucial to ensure that no water escapes the system, as this can lead to distorted results. Additionally, low-lying polders with a primary waterway breaching are less suitable for resilience quantification due to the significant height difference between the water and the dry land, as well as the substantial volume of water.

2. *What are the current challenges in quantifying the shock, impact, and recovery in flood resilience?*

Quantifying shock, impact, and recovery in flood resilience presents several challenges due to the complexity and interconnectedness of resilience metrics. One of the primary difficulties is defining a standardized and universally applicable approach to measuring resilience, as different frameworks offer varying ideas on how systems respond to disturbances. While flood risk frameworks rely on clear and comparable numerical assessments, resilience is more dynamic and often involves hard-to-measure variables. The shock phase is difficult to quantify, as the magnitude of impact depends on a range of hydrodynamic factors, including water depth, flow velocity, and flood arrival time. Additionally, different assets and communities experience shock differently, making it challenging to establish a single metric that captures the full extent of the disruption.

Measuring recovery introduces further complexities, as it requires assessing not just the physical drainage of floodwaters but also the restoration of functionality in critical infrastructure, ecological systems, and social structures. The temporal aspect of resilience is challenging to capture, as the speed of recovery is influenced by a multitude of factors, such as economic capacity, governance efficiency, and community preparedness. Additionally, existing models struggle to integrate the cascading effects of floods on interdependent systems, such as transportation networks and energy infrastructure. Addressing these challenges requires further refinement of hydrodynamic indicators, improved integration of resilience measures into existing flood risk models, and continued exploration of standardized methodologies for resilience quantification.

3. *What functionality units and resilience metrics are most suitable for quantification of flood resilience?*

The metrics of Derivative Shock Rate Buildings and residence time performed best and could be used to quantify flood resilience, enhancing the flood risk frameworks currently in place in the Netherlands. The metric of Flood Arrival Time also looks promising, although it is already being utilized in current flood management practices. The Derivative shock rate can be employed to evaluate the capacity of current emergency response services. Additionally, it can quantify the extent to which a flood-prone area is affected, thereby informing the demand for evacuation. The metric of residence time appears most suitable for assessing the degree of damage inflicted on a flood-prone area, as well as determining when an area can begin to regain its full functionality. This temporal component is very important in quantifying flood resilience.

Other metrics show promise in quantifying flood resilience, but more research is required and/or the metric needs to be modified. For instance, the depth integrals demonstrated potential in showing both improvements during the shock and recovery phases of a flood event. However, some information is lost when using a linear metric between time and water depth, compressing it into a single value for each building. Similarly, the flooded utilities metric for buildings provided insights into flood dynamics that were not evident from solely examining flooded buildings. Nevertheless, the metric needs to be expanded to accurately reflect the actual consequences of these flooding utilities. The percentage dry area metric showed promise, but the current method fails to capture the complexity of flooding nearby land to a building.

Lastly, some metrics were not suitable for quantification in the current model. These metrics included the metrics using momentum impact, as the modeling software 3Di is not capable of capturing these fine details in flow velocity. Furthermore, buildings would need to be modeled in much more detail to assess accurately the impact on them. Besides the momentum metrics, the recovery rate proposed is also not considered suitable for quantifying flood resilience. Even with modifications, it is unlikely to provide additional information beyond what some of the other metrics, such as the residence time, already offer.

With the subquestions answered, the main question of the thesis can now also be answered.

Can the flood resilience of a system be meaningfully quantified using a combination of hydrodynamic conditions and different perspectives?

Yes, flood resilience can be meaningfully quantified with some of the attempted metrics. While the hydrodynamics, perspectives, and resilience metrics all need to be adapted and expanded, a more complex and nuanced understanding of the flood characteristics is starting to emerge using this method. This understanding can complement existing flood risk frameworks in certain locations, with limited extra modeling required. The integration and comparison of diverse perspectives offered a nuanced understanding of how flooding affects different stakeholders and systems. Metrics like amplitude shock showed significant differences for various perspectives, highlighting the information that these different viewpoints can provide.

This research also highlights key areas for improvement. For instance, while the current framework effectively incorporates hydrodynamic variables, a more precise implementation is required for indirect effects on buildings within the study area. Furthermore, the methodology has only been tested on a specific flood-prone area, a polder in The Netherlands. Consequently, the applicability of the method outside this case study remains uncertain and should be investigated further.

The proposed framework advances the field of flood resilience by offering some objective, actionable insights and a replicable methodology for hydrodynamic quantification. Other metrics have shown promise, but need to be expanded before they can be applied in the field of flood resilience. By incorporating diverse perspectives, this framework provides a more comprehensive understanding of flood management. While further research is necessary to expand the method's applicability before practical implementation, this research demonstrates the feasibility of objective quantification of flood resilience, paving the way for a novel approach to flood management in the years to come.

7 Recommendations

This chapter states recommendations for future research and applicability in other case studies. Each recommendation briefly summarizes the problems raised in the results and discussion before describing the recommended way to improve on these issues.

Choose a system that is less flood-resilient
The considered case study of the polder in the Alblasserwaard in The Netherlands was already fairly resilient against the flooding of the smaller dewatering channels. While this is an interesting conclusion for the case study, for the proposed methodology, more flooding in the base model would demonstrate more quantification methods for resilience. Some of the attempted metrics, like several flooded commercial buildings, could not be meaningfully quantified in this system. Similarly, the resilience metrics from the ecology perspective could not be quantified due to the lack of flooding in these areas. While no flooding is still an indication of resilience, differences in this metric for different scenarios would help determine the meaning of these metrics.

For future research, an area that is flooded more gradually could be interesting, for example, a village located near a river. This would allow a more gradual system response curve, testing for different river water levels and flow conditions.

Adapt the Depth Integral measures
Currently, the depth integral seems unsuitable for the quantification of flood resilience. This is because in combining the variables of water depth and time into a single dimension, important information is lost. As mentioned before, the proposed metric makes no distinction between one meter of water for ten hours or ten meters of water for an hour, which matters a lot in determining the consequences. One of the solutions could be to make the integral non-linear. For example, we could take the integral of the water depth squared. By doing this, higher water depths are additionally weighed as being detrimental to flood resilience. While this means that information is still lost, this metric could start to introduce the idea that low water depths are acceptable to a degree while strongly advocating against large water depths.

Normalize resilience metrics for comparison between flood-prone areas
Currently, the number of affected buildings is difficult to compare, as the total number of buildings in an area is not taken into account. This can be changed by normalizing the metrics that are dependent on this number, for example, by dividing by the total number of buildings in a flood-prone area.

In this way, comparable fractions are obtained for the shock amplitude, amplitude shock rate, and recovery rate alike. If these metrics are comparable between areas, absolute metrics can also start to be established, informing norms for flood resilience in the future. For example, anything under 10% flooded could be deemed acceptable, provided the shock rate is also under 0.15% per hour. Assessing the thresholds for these metrics between systems would require a large variety of case studies comparing different types of flood-prone areas to determine these flood resilience norms.

Improve the metrics for indirect resilience
This research showed that taking indirect consequences of flooding, like the flooding of nearby roads, gives a different result compared to just looking at the direct flooding of buildings. However, the current assessed metrics are crude, simply drawing a circle around buildings and applying a filter on the flooding of interesting land uses. Instead, this approach can be extended by implementing the network structures of affecting networks. For example, instead of looking at the binary property 'are there flooded roads nearby', a metric taking pathfinding into account would be much more representative. The question for the roads then becomes: is there an escape route possible? Similar structures can be implemented for sewer systems and electrical networks. This would give impact curves closer to the real-world response to the tested flood events.

Do a small-scale study to test momentum metrics for resilience
The 3Di model with a large discrepancy between the computational grid and bathymetry will not give accurate results for impact or momentum on the buildings in a study area. Furthermore, even setting these grids to the same resolution of $0.5x0.5$m would still miss the small-scale patterns in the flow velocity, especially around buildings.

A small-scale test could be conducted to see what resolution is required to achieve sufficient detail in the flow velocity modeling. When this small-scale test shows promise, surrogate modeling could be used to implement this small-scale test in larger case studies.

Explore the applicability of the method in raising awareness
Besides the applicability in preparing and assessing flood-prone areas for flood resilience, the metrics could also help to raise awareness among residents, especially when looking at the indirect hydrodynamic consequences. Showing residents that even though their houses may not flood, they could still be cut off from electricity and evacuation for multiple days. This, in turn, could move more residents to make sure they have supplies in their homes to make it through these days.

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A

Model considerations

This Appendix explains the (model) choices made for the case study.

A.1. Creation of the canal system

While the water levels were provided by the water authority of Rivierenland, limited information was available to calculate the volume of water present in the canal system around the system. To approximate this, a variety of data sources was combined. First, the centerlines and surface area polygons were available from the BGT (*Basisregistratie Grootschalige Topografie (BGT)*, 2018). However, a few problems existed in using this data source directly. First, the relative distance of water to the breach location needed to be considered, as this has a strong influence on the discharge into the polder system. Secondly, limited information was available for the cross-section profiles of the canals.

To solve this, the centerline was exploded into more than 2600 individual segments. Next, a perpendicular line was drawn on each segment. This segment intersected the edges of the water surface polygon and was cut off at that location. By calculating the length of that line segment, the width of the channel at that location was determined. From visual observation, it could be verified that the method seemed to work in all locations besides the intersections of centerlines. Near these intersections, perpendicular lines would not intersect with a polygon edge, giving large channel widths in these areas. To exclude these larger widths, the intersection points between centerlines are searched, and a circle with a fixed radius is drawn. From the intersection point, 36 segments were drawn radially out up to the intersection with the aforementioned circle or the water surface polygons. By then taking the average of these segments, an approximation for the width at the intersection could be found. Any centerline segment within the circle area was then assigned a width of this average value.

Multiplying the length by the width of each segment provided the surface area of the approximation, which was less than 1.5% compared to the provided water surface polygon. The full canal system and approximation near intersections used can be seen in Figure A.1.

Only a few cross-sections of the canal system of the Alblasserwaard were provided for the research. As a result, some assumptions have been made regarding the depth. The average ratio between the top width and bottom width was calculated for the eight available cross-sections and determined to be 1.64. From there, the channel was modeled as having a trapezium shape with a bed level of -3m with respect to NAP based on the same cross-sections. The water levels in the canals are -0.75m and -0.9m with respect to NAP for the Achterwaterschap and Graafstroom, respectively (Rivierenland, 2024). The global Manning coefficient was deemed to be 0.05 based on the channels having small meanders and vegetation along the channel edges (Arcement & Schneider, 1989).

A.2. Model Settings

For the model, the spatial resolution and timestep are determined based on a combination of expert consultation and a sensitivity study. The initial guess for spatial resolution was 160m for the open field and then going down to 40m and 10m, respectively. To test if this is indeed accurate while being fast enough to iterate on, the models outlined in Table A.1 will be used. A computational time of about 2 hours was deemed acceptable for the model. As this was still achieved for the model run with a spatial resolution of 80-20-5 meters, this resolution was used in the final model.

Model	Open area [m]	Waterway [m]	Build-up area [m]	Timestep [s]
1	320	80	20	40
2	240	60	15	30
3	160	40	10	20
4	80	20	5	10
5	40	10	2.5	5

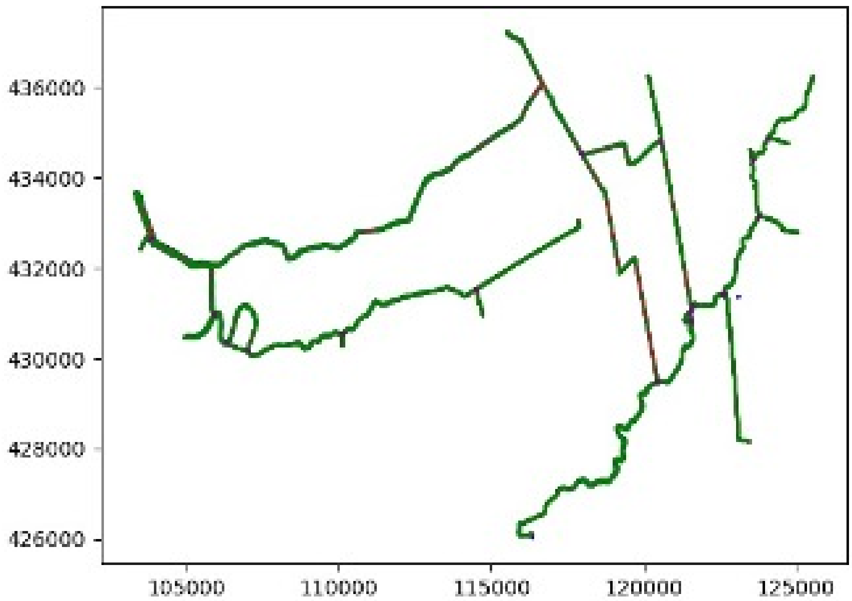
Table A.1: Different attempted model resolutions

The timestep is then loosely based on the CFL condition and a combination of the maximum expected flow velocity of about $2ms^{-1}$ and the grid size near the waterway, where the highest velocity is expected to occur. This leads to the values given in Table A.1. It should be noted that 3Di uses time stretching and compression, so larger and smaller time steps can be dynamically chosen if flow velocities allow for this to happen.

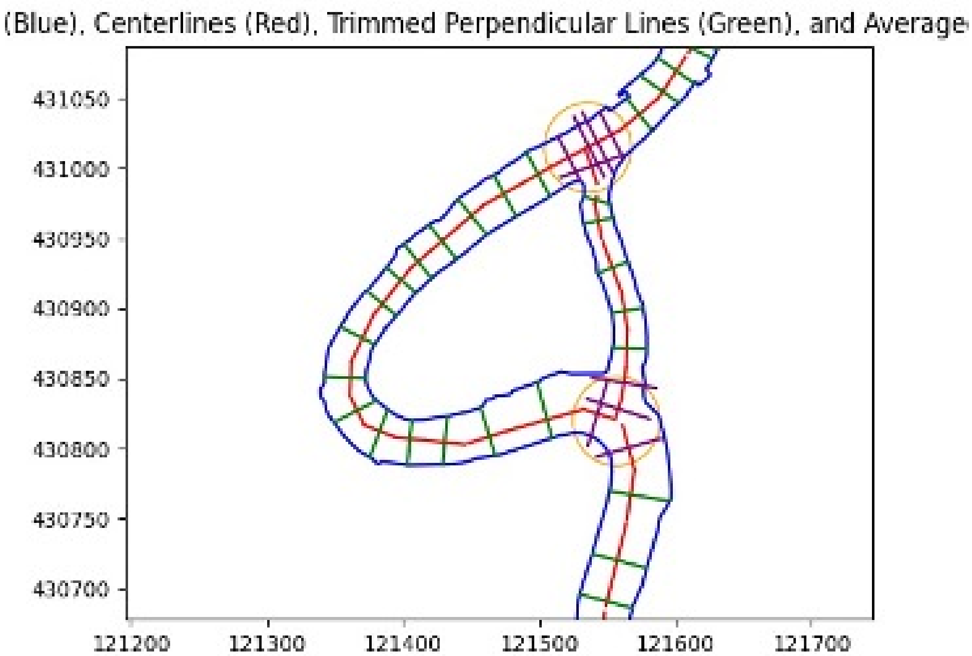
A.3. Breach behavior

The exact temporal evolution of a dike breach is a highly complex process that is not fully understood, and often, empirical models are used (Danka & Zhang, 2015; Verheij & Van der Knaap, 2002). In the current model, however, it was assessed that for the breach behavior in the 3Di model, which uses the Verheij en van der Knaap method (Verheij & Van der Knaap, 2002), the flow through the breach was more determined by the channel friction than the breach development. In the model, the breach first deepens, subsequently widening when the maximum depth has been reached. This parameter is user-controlled, and experimentation shows that after this user-defined period ends, the breach behaves in a similar way determined by flow velocities and water levels. Two models were run, with a breach deepening period of 4 hours for the slow breach and 10 minutes for the fast breach. The slow breaches were then shifted 3.87 hours in time to ensure the breach-widening phase (determined by flow velocities and water levels) started at the same point in the graph. 12 hours after the breach, the difference between discharge and total cumulative discharge is less than 2.38% for the Graafstroom breach and less than 1.56% for the Achterwaterschap breach. After 24 hours, the difference has reached close to zero (less than $3500m^3$) for a total discharged volume of $5.5 \cdot 10^5$ and $3.5 \cdot 10^5$ cubic meters for the Achterwaterschap and Graafstroom, respectively. The resulting hydrographs can be seen in Figure A.2.

The peak outflow for the fast breaches is slightly higher compared to the slow breaches. This is expected as some water has already flowed out of the model when the breach starts widening, leading to lower peak velocities. These peak discharges also reach the same level after about 30 hours, showing the internal resistance of the channel becoming the dominant mechanism in governing the outflow.

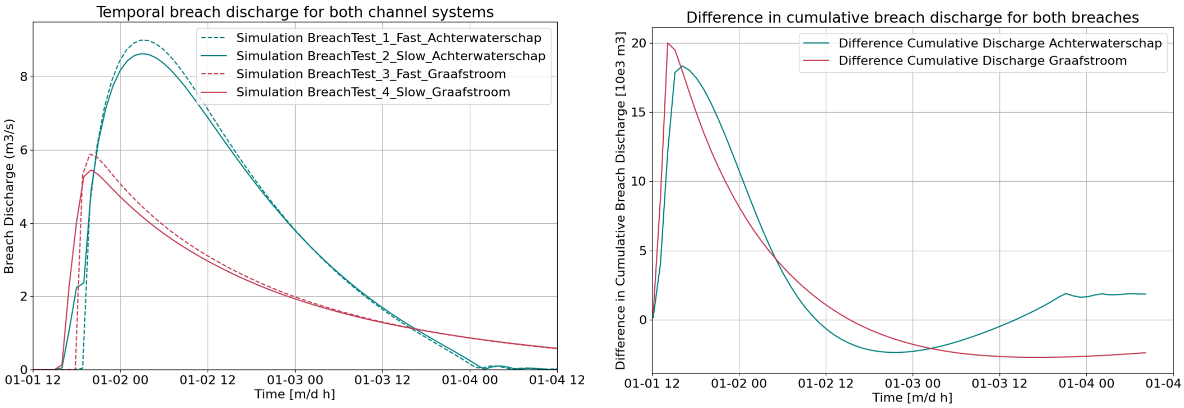


(a) The full system of channels as modelled in this study



(b) The approximation of the channel width near junctions of channels

Figure A.1: The representation of the channel system in python. This representation was subsequently imported back into the hydrodynamic model.



(a) Temporal breach discharge in the model.

(b) Difference in cumulative discharge between the fast and slow breaches.

Figure A.2: Resulting hydrographs for the different breach behavior parameters.

B

Interviews

B.1. Marien Boers

During a case day outlining the reorganized dewatering system of the Alblasserwaard Polder (Rivierenland, 2019) and in a later meeting, Marien Boers provided the author with interesting information regarding the mechanics of flooding, dimensions of canals and other considerations.

A point of attention regarding the location of buildings in the study area was raised. Namely, the buildings in the study area are often located on the dikes of the main canals surrounding the considered system. When the water level in the canals decreases, the stability of the houses on the dikes becomes a problem, leading to potentially substantial damages. As such, trying to maintain the water levels in these channels might be more important than protecting the flooding hinterland in the study area, as this is largely agricultural.

Another point raised was that the exact characteristics of the dike breach might not be the dominant factor in determining discharge. Instead, the internal resistance of the channels might become more important. This was subsequently confirmed in the model study by sensitivity analysis outlined in Appendix A.3.

Lastly, the fact that pumping stops are imposed whenever the water level in the channel system becomes to high means that there is little variation in the water level for different return periods. Wind set-up can cause variation in the water levels, but this was mainly a problem for the eastern parts of the dewatering systems, far away from the pumps at Kinderdijk. The considered study area is roughly in the middle of the larger Overwaard and Nederwaard area, making this set-up less important.

C
Results

C.1. Fooded commercial buildings

The direct number of flooded commercial buildings over time can be seen in Figure C.1. Due to the low number of total buildings, the derivative is not shown in this Figure.

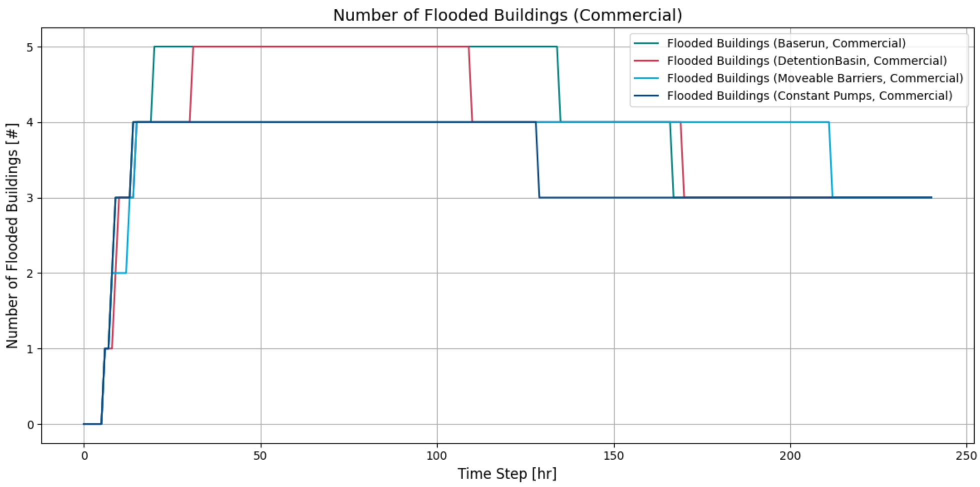
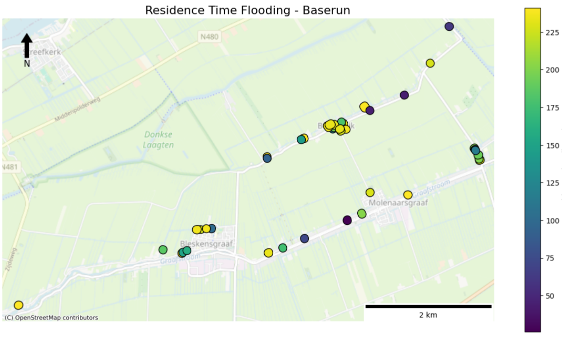


Figure C.1: Amount of flooded commercial building in the study area.

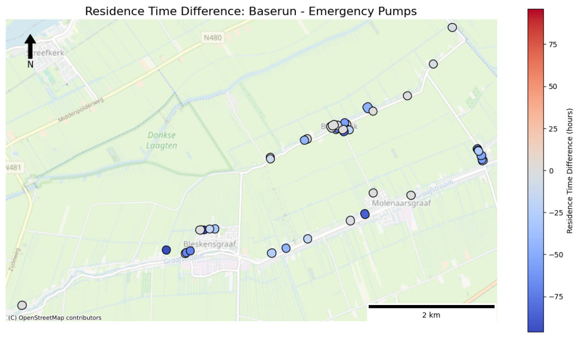
The total amount of flooded commercial buildings is low in all attempted runs, including the baserun. The difference in amplitude shock is no more than a single building, with the constant pumps and moveable barrier interventions performing slightly better, though this is not conclusive based on the small number of flooding buildings.

C.2. Residence Times

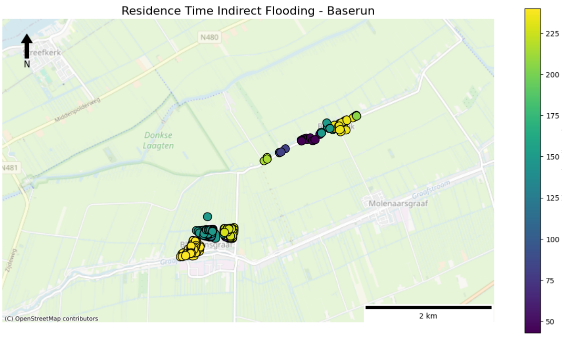
The residence times between interventions were also compared. The intervention with the best reduction in total residence time compared to the baserun, the emergency pumps, is presented in Figure C.2. It can be seen that the placement of emergency pumps causes some properties to be drained more than 3 days earlier. The resulting average and median values can be seen in Table C.1.



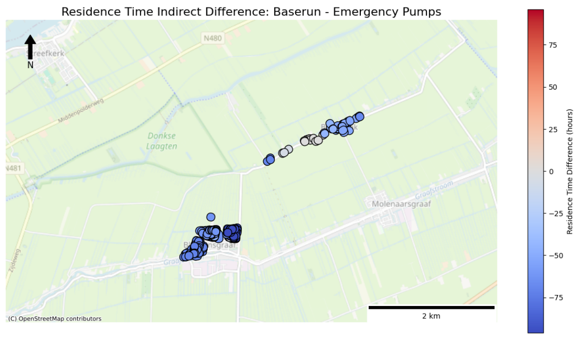
(a) Absolute residence times baserun



(b) Comparison residence times baserun and emergency pumps



(c) Absolute indirect residence times



(d) Comparison indirect residence times baserun and emergency pumps

Figure C.2: Total residence time of all affected buildings in the study area. The left panes give the absolute residence times for the baserun for direct flooding and indirect impact, respectively. The right panes give the temporal difference between the baserun and the emergency pumps intervention for both cases.

Table C.1: Intervention Comparison: Residence Times (RT) in buildings

Intervention	Average RT [hr]	Change [%]	Median RT [hr]	Change [%]
Baserun	182.1	0.00%	214	0.00%
Detention Basin	181	-0.60%	214	0.00%
Moveable Barriers	183.7	+0.88%	214	0.00%
Constant Pumps	169	-7.19%	227	+6.07%
Emergency Pumps	153.7	-15.60%	143	-33.18%