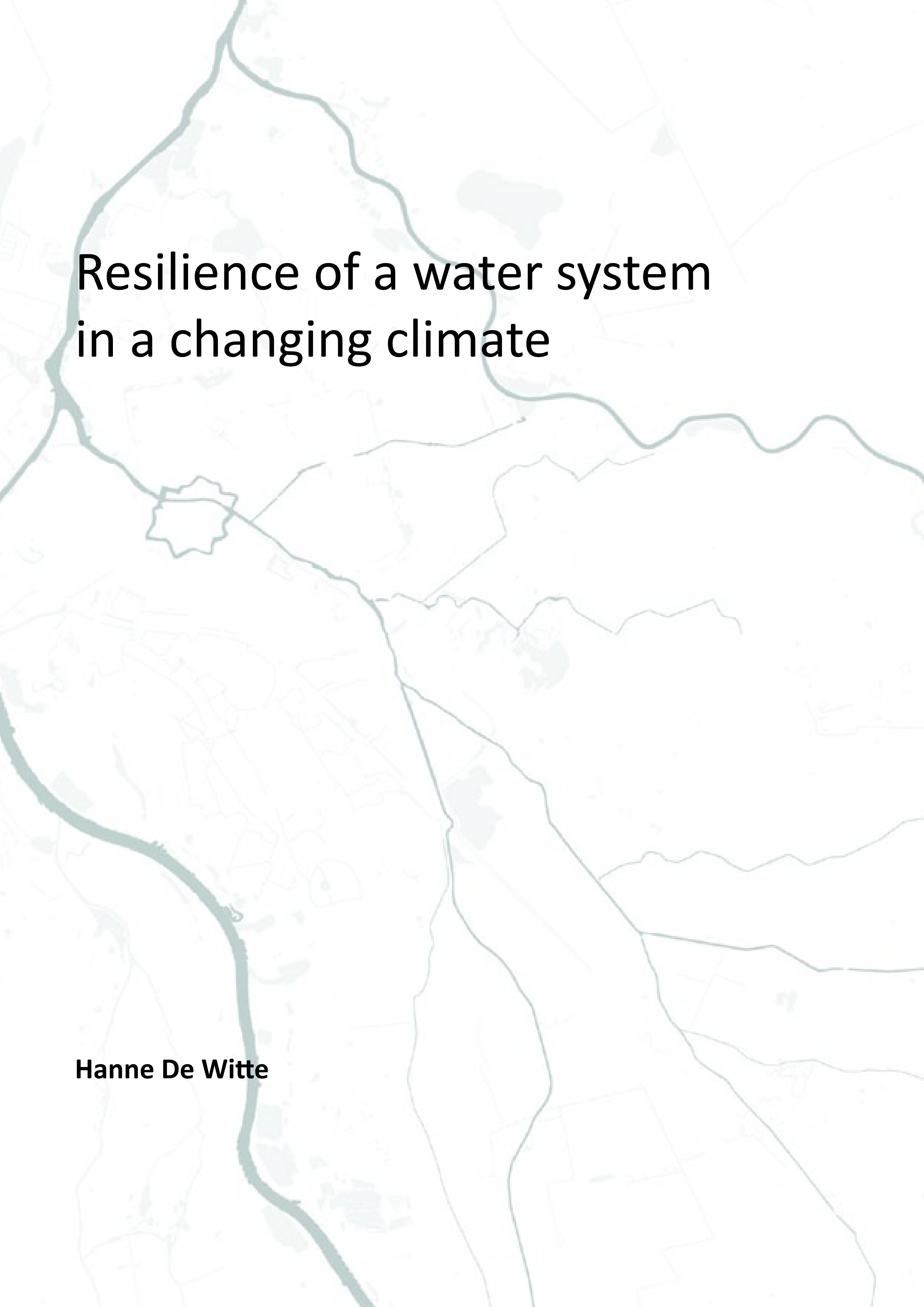

Resilience of a water system in a changing climate

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Resilience of a water system in a changing climate

An exploration of spatial adaptations in the landscape to improve the resilience of the regional water system of Zwolle

In fulfilment of the requirements for Master of science degree in Landscape Architecture at the Wageningen University, Landscape Architecture Group.

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Abstract

Climate change is an important factor of uncertainty that needs to be addressed in landscape planning and design. The impact of climate change requires future water systems to be more adaptive and resilient to extremes in the weather. This research aimed to explore the relevance of the concept of resilience in the design of climate-proof water systems. The experiences of a site-specific design formed the input for a reflection on the usefulness of the concept of resilience. A literature analysis resulted in a framework of four aspects to improve the resilience of water systems: diversity, modularity, connectivity and redundancy. This framework was applied to address the challenges of the regional water system of Zwolle. The two main challenges in this region are high water and peak discharge in the water system, and flooding risk in case of a breach. An exploration of spatial possibilities and water calculations provided input for the strategy. Based on the analysis, a compartment approach is presented as a strategy to enhance the resilience of the regional water system of Zwolle. Whereas resilience provided an important input in developing the strategy, it did not provide clear methods or guidelines to make decisions on a small scale. Therefore, this research concludes that although the concept provides less support in designing on a smaller scale, it is a relevant framework in strategic decision making as a preparation for design.

Keywords: adaptive, flooding risk, landscape design, resilience, risk approach, water system

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1. Introduction

1.1 A changing climate

Worldwide the temperature of the oceans and the atmosphere is increasing, the amount of snow and ice is decreasing, and the water level of the sea is rising (IPCC, 2013). The consequences of global warming can have a high impact in a low situated country like the Netherlands. A warmer climate is expected to lead to an increase of rainfall as well as a higher intensity and frequency of rainfall or other precipitation (IPCC, 2013). This increase in extreme weather and heavy precipitation increases the peaks of water discharges on water ways, and hereby increases the risk on flooding (IPCC, 2014). Consequently, there is the need to protect the land against water coming from the sea as well as from inland. Future water systems need to be able to deal with these extremes in the weather, in other words they have to be more adaptive and resilient.

Seeing the world as ever changing, there is the constantly need to adapt and to address uncertainties, disturbances and change (Bell, 2012). Climate change is an important factor of uncertainty that needs to be addressed in water management. A water system should be able to deal with unpredictable disturbances and change (Ahern, 2011). Improving the resilience of a system can help to make a system adaptable to unexpected changes (Ahern, 2011).

1.2 Resilience

There are numerous definitions of resilience; a well-accepted definition is *'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks'* (Walker et al., 2004). The concept of resilience can be used as a framework in developing adaptive water systems while dealing with the uncertainties of climate change (Allan and Bryant, 2011). Therefore, while searching for spatial adaptations to address the complexities of climate change, the landscape architecture discipline could benefit from the theoretical framework of resilience. Nevertheless, a lack of clarity in the use of the concept is considered problematic for landscape designers (Allan and Bryant, 2011). Furthermore, a lack of consistency in resilience enhancing principles has been identified (Biggs et al., 2012).

Research on resilience within the landscape architecture discipline recently started to explore the usefulness of the concept for design (Allan and Bryant, 2011). This study aims to add to this exploration by studying the relevance of the concept in developing climate-proof water systems.

1.3 Purpose of the study

This research explores possibilities to improve the resilience of a water system and address climate change while decreasing flood risks through spatial adaptations in the landscape. Therefore, the research starts with a theoretical exploration of the concept of resilience to develop a framework to improve the resilience of water systems.

Subsequently, this framework is applied in a real-life context to gain insight in the complex dynamics and interactions of the water system. Through landscape design, spatial possibilities are explored to address regional challenges. The study results in a landscape design to decrease the flooding risk, while enhancing the resilience of the regional water system.

The experiences of this site-specific design are input for the reflection on the usefulness of the concept of resilience for the design of climate-proof water systems, and more general, for the landscape architecture discipline.

1.4 Project area

In the Netherlands several national and regional organisations are working together on a national programme to facilitate and guide water management choices regarding the Dutch river Delta (Staf deltacommissaris, 2013). This Delta Programma wants to assure a certain degree of safety against the water, taking into account the possible consequences of climate change. Examples of measures include re-enforcing the dunes to protect against sea level rising as well as making space to collect fresh water that can be used in times of drought (Staf deltacommissaris, 2013).

To try out new ways to adapt to uncertainty and search for possibilities for improving water safety, the Delta Programma appointed seven pilot areas. One of the pilot areas is the IJssel-Vechtdelta (Figure 1.1). Challenges in this area include peak discharges from the inland, indirect influences of sea-level rise, the need for a more flexible water level, and an insufficient safety level of several dikes in the region. The region around the city of Zwolle is marked as an area with a high risk on flooding, but with restricted possibilities to do something about it (Staf deltacommissaris, 2013). The combination of these challenges emphasises the need for a more adaptive and resilient approach to develop the water system in this region. Therefore, this research focuses on the challenges in the regional water system of Zwolle.

Figure 1.1 Appointed pilot areas multi layered safety (Delta programma, 2014, p. 47)

1.5 Research and design questions

The research questions in this study are:

- Can the concept of resilience provide a framework to design spatial adaptations for a climate-proof water system?
    - What defines the concept of resilience?
    - What aspects could improve the resilience of a water system?

These research questions provide the basis for the design challenge in this research. The design questions is:

- Which spatial adaptations in the landscape could improve the resilience of the regional water system of Zwolle?

To answer the design question, the characteristics of the water system of Zwolle, and options to improve the regional water system are explored.

1.6 A view on landscape

This study is a qualitative research, with a pragmatic and emergent character by giving space to methods and questions that come up, while searching for solutions. This pragmatic view on the research means that there is an emphasis on the problem and several approaches can be used to understand the problem (Creswell, 2009). The pragmatic view on the research gives the freedom to select different approaches that come up while searching for solutions to the research problem (Creswell, 2009).

The study follows a research based design approach through an iterative process, in which designing and analysing will constantly supplement each other. It is an interaction between searching for solutions, making choices and finding new problems. Meyer and Nijhuis describe research by design as *'investigation of possible future spatial configurations' (*Meyer and Nijhuis, 2013, p. 165).

The research by design approach can also be described as 'research through designing' since designing is the process that gives form to a place or an object, while design is just the end result (Lenzholder et al., 2012). This way the design process can be seen as a research or exploration through which new knowledge is generated (Lenzholder, 2012).

Landscape architecture and design

The landscape can be seen as a complex and ever changing system, which is formed through different natural and social processes (Bell, 2012). The landscape architecture discipline takes these processes into account while designing. It considers natural processes, like water systems, geological processes and ecosystems and has a social perspective in which aspects like participation, equality, awareness and cultural influences on the landscape are addressed.

Designing landscapes starts with the selection of a subject, a location, and a question to be answered, or a problem to be solved. Subsequently, a map of the research area and tools to design with, are selected. Research is carried out by searching and trying out different possibilities or ideas. It is a combination of analysing, trying out, coming up with different possibilities or variations, making choices, and generating new information and new ideas. It is important to switch between scales constantly while designing a spatial area, to get to know the impact of choices on various scale levels. At the same time, attention is needed to address ideas, questions and problems that come up while designing.

In this way, designing helps to guide research that is site specific. It helps to find new information and develop insights. It gives answers to questions, and generates new questions. This way of exploring, supports the research by making clear what kind of information or data is still needed to solve the design assignment. Designing is about the interaction between problem solving and problem finding. It guides the practice of drawing, in which thinking and doing happen at the same time (Sennet, 2008).

The concept of landscape

There are various interpretations of the word landscape. Initially the word landscape was used to describe the natural scenery that formed the background in a painting. Flemish and Dutch painters were specialised in painting these landscapes in the 16th and 17th century (Lorzing, 2001). They also painted natural sceneries as a background for other painters. Through these paintings the word landscape was introduced and people started to observe landscape and develop ideas on what it should look like.

What do we mean when we use the word landscape and do other languages have the same meaning when using another word for landscape? Lorzing (2001) describes two different interpretations of the word landscape. There is a subjective interpretation of the word landscape. This can been identified in the French word 'paysage', which has a focus on the pictorial, poetical and emotional values of the landscape. While the German word 'landschaft' refers to a more objective and technical view on landscape in which landscape characteristics are studied (Lorzing, 2001).

This example of the various interpretations of the word landscape illustrates that landscape has a natural and social dimension. Landscape is not just matter (soil, water, trees) but also the perception and interpretation of an area by a person. It is the ever-changing surface of the earth that is under influence of natural elements and manmade interventions.

World view

The world view, or philosophy of science position, describes the approach of the researcher to the object of study. In this research the world is seen as existing, and knowledge about the world can be collected through observation and measurements. However, at the same time, our observations are influenced by our perceptions and interpretations, as illustrated by the multiple interpretations of the word landscape.

This perspective on the world fits with the relatively young philosophy of science position of critical realism, as founded by Roy Bhaskar. Critical realism combines the positivistic approach of one existing reality, with the multiple perceptions embedded in constructivism (Fraser, 2014). In this realistic view the difference between reality and the multiple layers of perception of reality is recognised (Fraser, 2014). It important to be aware that a person's background and values influence the way they see reality (Fraser, 2014). To study these different layers of perception, mixed method approaches are well accepted in this world view.

Reflecting on your assumptions and limitations as a researcher is therefore considered as important because our access to the world is always shaped by our theoretical and perceptual framework (Fleetwood, 2005).

1.7 Outline

In the next chapter the method for the thesis is introduced. Chapters 3, 4 and 5 cover the analysis of the theory, area and the assignment. An exploration of possibilities (Chapter 6), and water calculations (Chapter 7) provide input for the strategy for the design (Chapter 8). Chapter 9 presents GIS calculations that were made to test the feasibility of the strategy. The design for the area is presented in Chapter 10, followed by the discussion and conclusion in Chapter 11.

2. Method

2.1 Method of research and design

To explore how to improve the resilience of the water system, the flexible design method developed by Duarte and Beirao (2011) was adopted. This method provided structure to the research, and allowed an emergent development of the research methodology as required in an explorative study. The method exists of four parts: analysis, strategy, plan and detailed plan (Duarte and Beirao, 2011). In this study, the analysis is divided into three parts: analysis of theory, analysis of the area and an analysis of the assignment. These three aspects provide the input for the development of the strategy and plan. This flexible design approach provides a framework to design for a changing landscape and a changing society, in other words, a plan that can respond to changes. The method has been applied throughout the research systematically, as presented in Figure 2.1. In the following paragraphs the method is described in more detail.

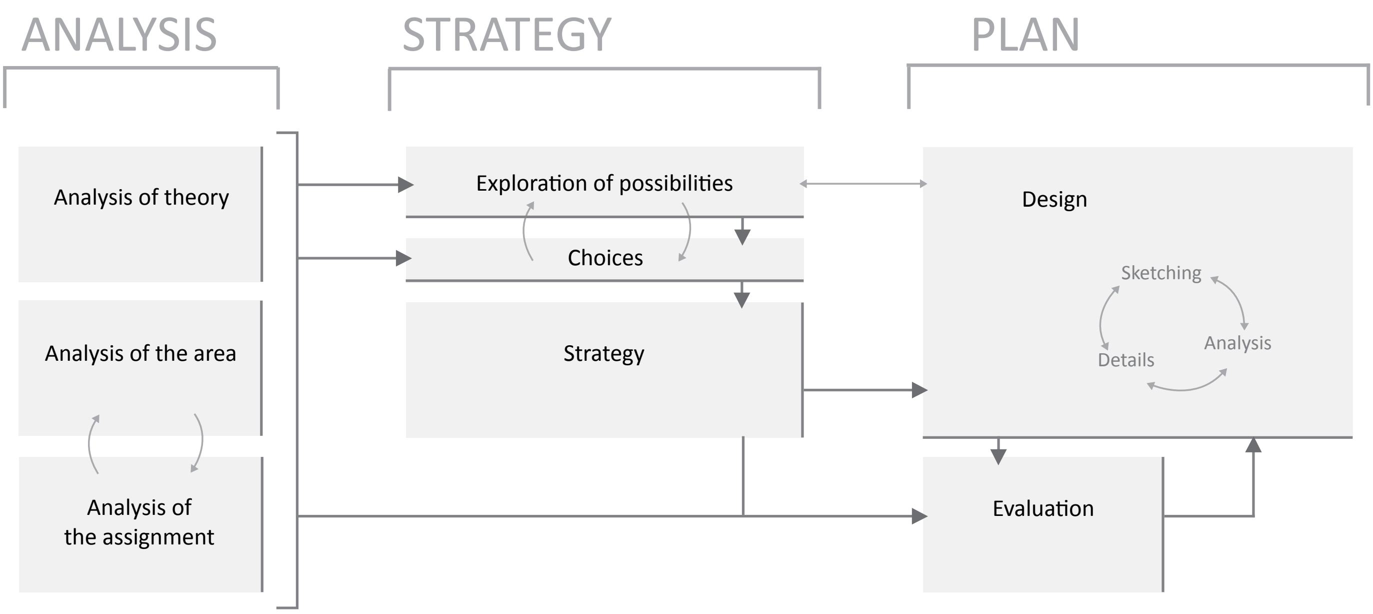


Figure 2.1 Method of research and design

2.2 Analysis

Analysis of theory

The research started with a review of literature to gain more insight in the concept of resilience and its relation to water management and landscape architecture. The results from the literature study have provided a theoretical lens and guiding perspective in the research and design process (Creswell, 2009). In the literature study the search engine Scopus was consulted, using the keywords landscape architecture, resilience and water system, to find relevant literature. Relevant literature has been selected based on a quick scan of the title and abstract. In addition, the selected papers have been scanned for relevant references using the snowballing method. Papers citing the selected papers have been included. This approach has resulted in:

- an overview of papers on resilience;
- a definition of the concept;
- a framework of aspects that enhance resilience.

Analysis of the area

An analysis of the project area was part of the predesign inventory and has provided insight in the context and the specific challenges in the area. The analysis of the area has been carried out through an analysis of maps, documentations (policy documents on national, regional and local level), interviews with eleven experts, personal observations and previous studies (Deming and Swaffield, 2011). The analysis of the area resulted in an overview of the characteristics of the water system and the surrounding landscape.

Analysis of the assignment

To define the design challenge to be addressed in this study, a study of existing documentation, policy documents and scientific literature was combined with semi-structured expert interviews.

2.3 Strategy

Analysis of possibilities

Possible solutions for the challenges in the water system were explored using the analysis of the regional water system. The solutions were tested by creating spatial models. By designing various models, possibilities to address the challenges in the region can be explored. This resulted in an overview of possibilities on how to deal with the challenges in the water system of Zwolle.

Choices

The theoretical framework of resilience was used to select a solution that can deal with the challenges in the water system, and potentially improves the resilience of the studied water system. By applying the framework of resilience, insight was obtained in the usefulness of the concept of resilience while designing water systems.

Strategy

A strategy for the design of the area was developed using the input from the previous analysis and the water analysis (in which the effects of flooding was analysed, by using flood images). The strategy gives insight in the interventions that are needed in the landscape and is presented in a description and visualisation of the strategy. The strategy was tested with the use of GIS calculations on the buffer capacity.

2.4 Plan

Design

Based on the strategy, a spatial plan for the region south of Zwolle was developed. The spatial plan addresses the design question by focussing on the spatial adaptations needed to improve the resilience of the regional water system of Zwolle. The design was developed through an iterative process of sketching, analysing and detailing on multiple scales. This design process includes decision making which was guided by the theoretical framework. The design includes maps, transects and visualisations.

Evaluation

During the design, moments of evaluation were included, in which a reflection on the analysis, theory and chosen strategy was made. These moments of reflection were needed to test if the design presents an answer to the challenges in the area and if the choices were guided by the theoretical framework on resilience.

3. Analysis of theory

3.1 Resilience

History of resilience

Resilience is a concept that was initially developed in the field of ecology as response to the equilibrium paradigm. The equilibrium paradigm considers systems as stable (Figure 3.1) whereas others consider natural and cultural systems as variable, uncertain, and subject to unexpected change (Ahern, 2011). One of the first to use the concept of resilience in this context was C.S. Holling, in 1973. While studying population models he discovered multi-stable states (Figure 3.2), instead of one stable state. As a consequence, unpredictability and uncertainty can be considered as part of ecological systems. Holling defined resilience as *'that is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'* (Holling, 1973, p. 14).

Different perspectives on resilience

At the moment various definitions of resilience can be found in literature. Some literature compares resilience with the concept of robustness, which focuses on maintaining the characteristics of a system. Others consider resilience as the capacity to absorb disturbances, also compared with buffer capacity. Another group of scholars state that resilience also covers the opportunities that are created at the renewal of a system (Folke, 2006). In that context resilience can be seen as a process of constant change, and includes adaptability and transformability (Mitchella, 2014).

Folke (2006) makes a clear division in the various perspectives on resilience. Three perspectives on resilience can be defined: engineering resilience, ecological resilience and social-ecological resilience (Folke, 2006).

- Engineering resilience relates to the time a variable requires to return to its equilibrium, also described as recovery. This perspective focuses on the conservation and maintaining function of systems, while resisting disturbance and change.

- Ecological resilience focuses on the buffer capacity and robustness of a system. It addresses the level of disturbance and change a system can absorb, while maintaining its function.

- Social-ecological resilience relates to the interaction between the disturbances and the reorganisation of a system. This is also called the adaptive capacity of a system and involves the capacity to learn, adapt and innovate as a self-organising system (Folke, 2006).

Figure 3.1 Return to equilibrium (Liao, 2012)

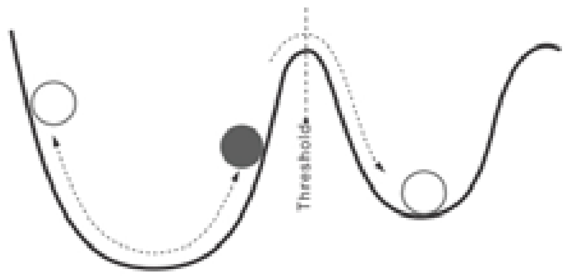


Figure 3.2 Multi-stable states (Liao, 2012)

Social-ecological resilience

The landscape is developed through natural and social processes, and requires an integrative approach. Therefore, the social-ecological perspective can provide a suitable framework to address the challenges in the landscape. Moreover, the self-organizing capacity of landscapes fit within this perspective (Walker, 2008).

As mentioned before, the generally accepted definition of resilience is the one of Walker (2004): '*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks'.*

This definition can be considered a social-ecological perspective on resilience because it focuses on the reorganisation of the system after a disturbance. Additional characteristics of social–ecological resilience have been discussed by Carpenter et al. (2001), Folke (2006), Wong, (2009), and Cumming (2011) and can be summarized in the following three characteristics:

- The capacity to absorb disturbance, while remaining within the same state
- The capability of a system of self-organization
- The capacity for learning and adaptation

Aspects to enhance resilience

To define a framework with aspects that can enhance resilience, a wide range of literature was studied. Four key publications were selected based on the following criteria:

- a focus on social-ecological resilience;
- attention for the spatial environment;
- and including resilience enhancing principles.

To structure the aspects mentioned in the four publications, a division was made following the paper of Biggs et al. (2012). Biggs et al. (2012) divides resilience enhancing aspects into two groups: aspects that improve the resilience of a system, and aspects that improve the resilience of the governance of a system. The overview of the resilience enhancing concepts mentioned in the four papers are presented in Figure 3.3.

This research will focus on the system related aspects since the aim is to research possibilities to improve the resilience of a water system. The aspects related to the governance system are considered important in the implementation phase. When focusing on the system related aspects, seven unique aspects were identified in the four papers: diversity, redundancy, modularity, feedbacks, connectivity, reserves and slow variables. Based on these seven aspects a list of four mutually exclusive and collectively exhaustive aspects were defined.

	System	Governance system
Hopkins, 2008	Diversity Modularity Tightness of feedbacks	
Biggs, 2012	Diversity and redundancy Connectivity Slow variables and feedbacks	Understanding Learning & experimentation Polycentricity Participation
Carpenter et al., 2012	Diversity Modularity Feedbacks Reserves	Openness Nestedness Monitoring Leadership Trust
Anderies, 2014	Redundancy Modularity Diversity in components or connections	

Figure 3.3 Resilience enhancing principles

3.2 Resilience framework

The following four aspects will be used as a guideline through the research to study the challenges of the area and make decisions to enhance the resilience of the water system.

Diversity

Diversity is one of the key concepts in resilience. Diversity relates to having different kinds of processes as well as different responses to disturbances (Carpenter et al., 2012). Important elements include the species and functional diversity of systems. It can be seen as a combination of variety (number of different elements), balance (number of each element), and disparity (the difference between the elements) (Biggs et al., 2012). This combination of variety and balance gives diversity to the system, through which the system will be able to react on different ways.

Modularity

Modularity is about dividing a system in several modules that can function on their own (Carpenter et al., 2012). The modules can have different functions and develop independently (Anderies, 2014).

Connectivity

Connectivity is about the interaction between the modules. These modules can be seen as nodes, such as patches, habitats or social groups (Biggs, 2012). The connections between these nodes, are the links. Connectivity is about the exchange of material and information through these links, giving space for interaction within the system (Biggs, 2012).

Redundancy

Redundancy is seen as an 'insurance' in which some system elements can compensate for others. When one subsystem fails, other elements in the system can take over, to make sure that the system still functions. This way several options are possible to respond to change and disturbance. It is about improving the response diversity of a system (Biggs, 2012).

4. Analysis of the area

In the IJssel Vecht Delta, several landscape types can be distinguished, with each their own characteristics. These landscape types can roughly be divided into the river landscape, sand landscape, moraines, peat landscape and sea clay landscape (Figure 4.1). These landscape types are shaped by natural processes, like geological and climate events, as well as humans processes, like land use and settlement. In this analysis of the area, the focus is on the influence of the rivers and water ways on the landscape in the region of Zwolle.

4.1 History river landscapes

In the Netherlands, human settlements developed on the higher grounds of riverbanks and river dunes. Zwolle developed as a settlement on a riverbank along the small river Aa. This river was situated in the IJssel valley, in between the moraines Veluwe and Sallandse Heuvelrug. The riverbanks were high enough to be safe from floods (Barends et al, 2005). Later on, to protect the small settlements against the water, levees were raised and dikes were build (Barends et al., 2005). Initially, every settlement or village was responsible for their own dikes and safety. The settlements developed as small protected islands (Pleijster and Veeken, 2014). Later on, around 1300, most dikes along the river got connected to each other (Barends et al., 2005). Also in the region of Zwolle dikes were constructed along the rivers IJssel and Vecht. These dikes form a protective ring around the city Zwolle and the region south of Zwolle (Figure 4.3).

To maintain the safety in the river landscapes, dikes had to be continuously raised and strenghtened (Pleijster and Veeken, 2014). The protection system of the dikes extended over the years and resulted in less room for the river to adapt to different water discharges. This had as a consequence that the water of the river could not reach the lower situated areas in case of high water. With the use of drainage this area became useful for agricultural purposes. Long waterways, called Weteringen, collected drained water from the lower situated agricultural land (Barends et al., 2005). Later on, this lower situated land was also used for urban development. Also the city of Zwolle expanded over time by establishing neighbourhoods on low situated areas (Figure 4.2 and 4.5). The next chapter describes the challenges related to this area.

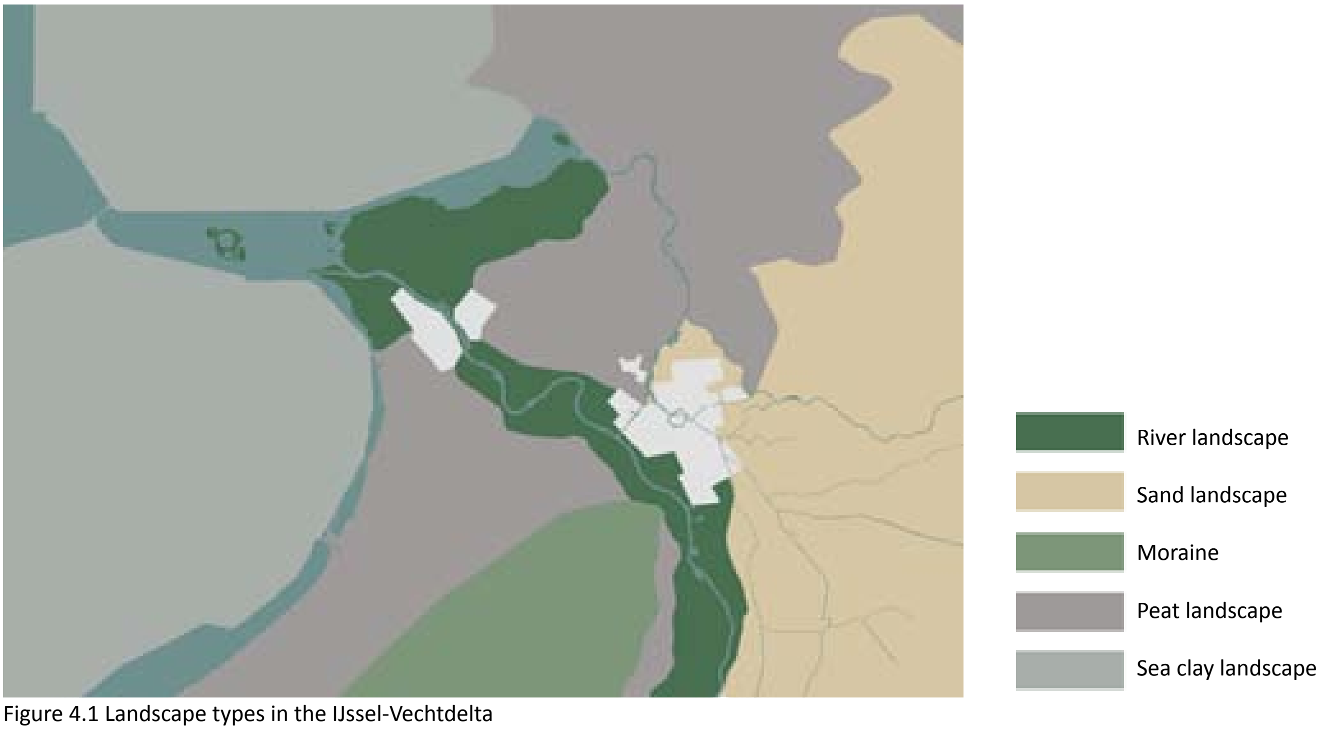


Figure 4.1 Landscape types in the IJssel-Vechtdelta

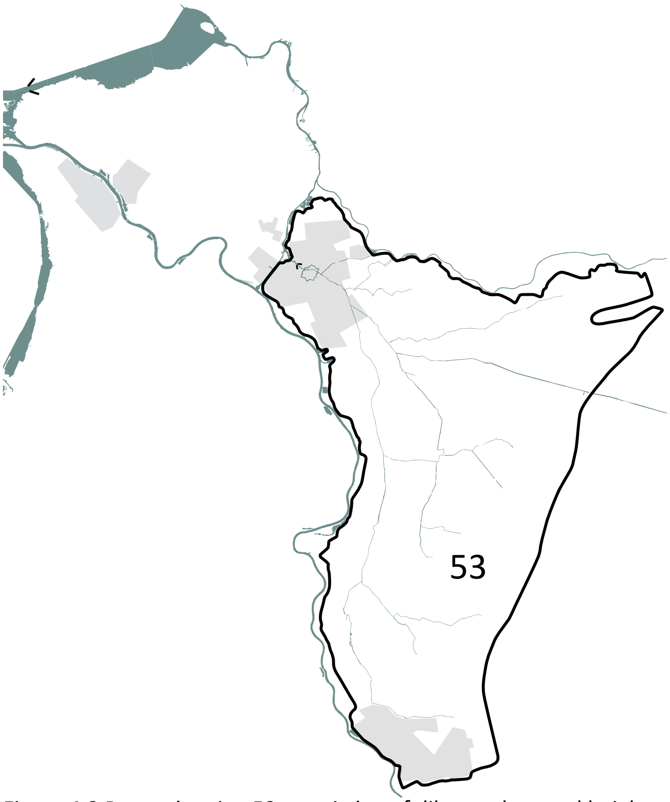


Figure 4.3 Protective ring 53, consisting of dikes and natural heights

Figure 4.4 Pictures taken in Zwolle of the Havenbrug and Wolweverstaat in Zwolle, flooded by the storm of 13 and 14 January 1916 (Municipality of Zwolle)

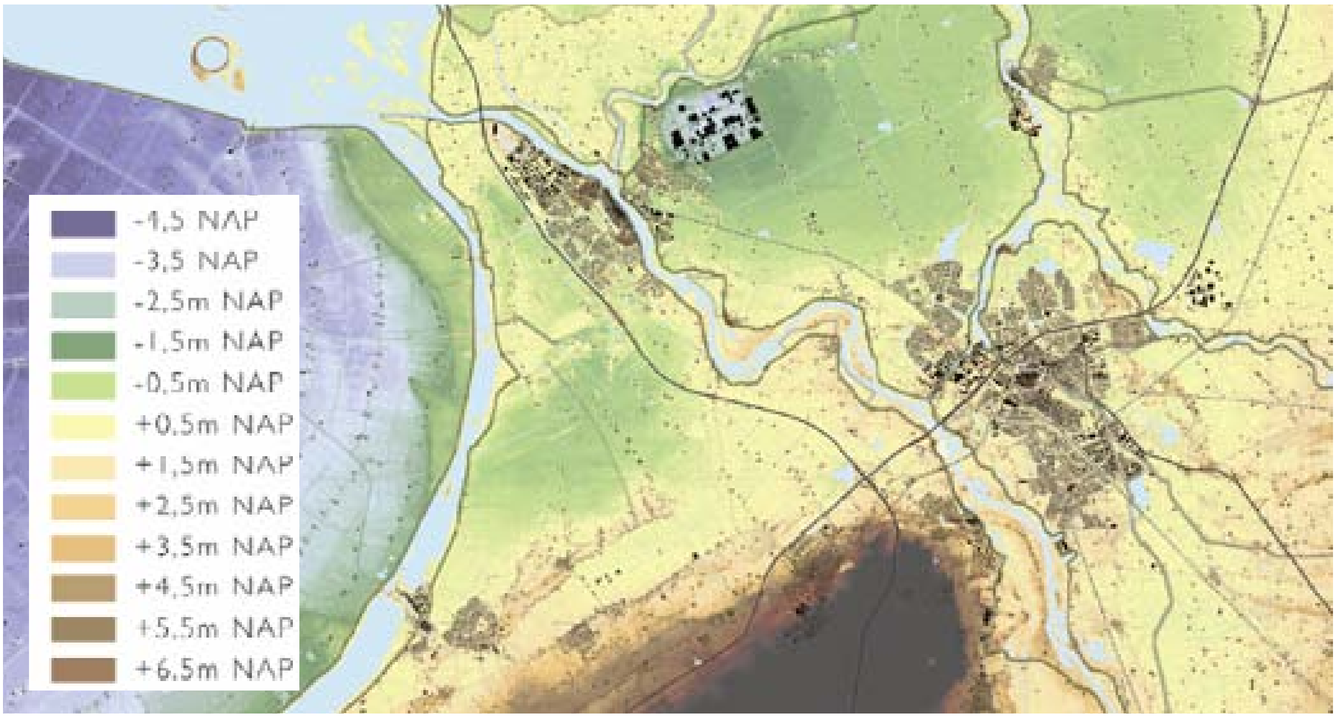


Figure 4.5 Height map of the IJssel-Vechtdelta (H+N+S, 2013, p. 42)

4.2 History water system Zwolle

In 1407, Zwolle becomes part of the Hanze, an international trading cooperation between cities by ships. To improve the water infrastructure, water from the Weteringen was guided through the city. The water of these Weteringen flows into the river Zwarte Water, and is connected to the river Vecht. The water of these two rivers flows together towards the sea. The sea, Zuiderzee, was directly connected with rivers and waterways inland. Therefore, strong storms could push the water far inland. Also in Zwolle the effects of these storms were high, as can been seen on the pictures in Figure 4.4. After the storm in 1916, the afsluitdijk was built in 1932 and transformed the Zuiderzee into a lake, the IJsselmeer (Deltawerken, 2015)

A very different defence system, the IJssellinie, was developed during the Cold War to inundate large areas and use water as a protection against a possible invasion from Russia (Pleijster and Veeken, 2014). The remains of this structure are still present in the landscape, for example in Olst.

In 1986, projects were initiated to improve the discharge and storage capacity of the rivers. In 2007, the national project 'Room for the river' was launched (in Dutch: Ruimte voor de Rivier). This project focuses on re-developing the riverbanks to lower the water level of the rivers. Measures include extending or deepening the riverbanks, removing obstacles and moving or raising dikes. These projects were often combined with recreation possibilities and nature development projects to improve the spatial quality of the landscape (Pleijster and Veeken, 2014).

Sinds a few years a new approach to water management is explored, presented in the concept of 'multi layered safety'. Which also includes decreasing the consequences of a breach. This will further be explained in paragraph 5.3.

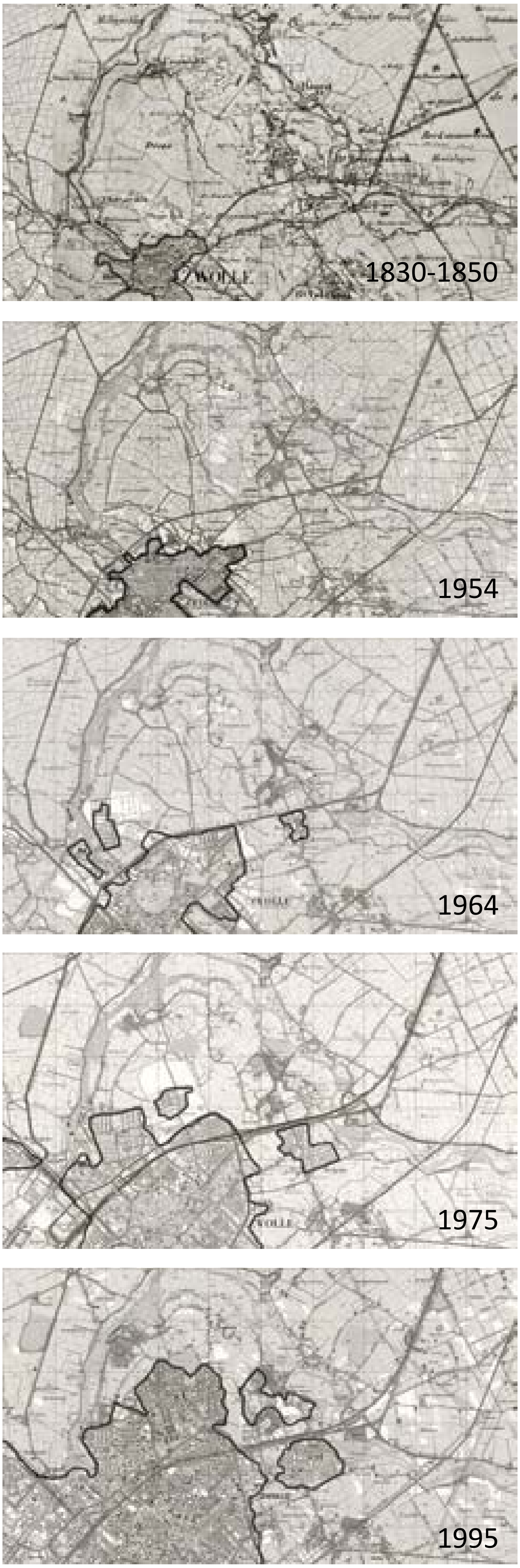


Figure 4.2 Urban expansion of Zwolle through time (adapted from watwaswaar.nl)

4.3 Impression of the water system

Figure 4.6 Sluice North of the city centre of Zwolle

Figure 4.7 Canals of the city centre of Zwolle

Figure 4.8 Balgstuw at Ramspol

Figure 4.9. Ketelmeer

Figure 4.10 Flooded area near the Vecht

Figure 4.11 Sandbags as a temporary water barrier

Figure 4.12 Sandbags

Figure 4.13 A flooded bicycle path

5. Analysis of the assignment

5.1 Components of the IJssel-Vechtdelta

This chapter describes the challenges of the project area to conclude with a specific design challenge. The following paragraphs provide background information on the various components of the IJssel-Vechtdelta water system. These components include the rivers IJssel, Vecht, and Zwarte Water, as well as the IJsselmeer and the regional water system Sallandse Weteringen (Figure 5.1). In addition, several upcoming challenges related to climate change and related water management choices, are described.

IJssel

In the south of Arnhem, the river Rhine splits into the Rhine and IJssel. The water of the IJssel runs towards the north along the cities Deventer, Zwolle and Kampen, to end up in the Ketelmeer and IJsselmeer (Figure 5.1).

Vecht

The river Overijsselse Vecht starts in Germany and ends near to the city of Zwolle where it flows into the river Zwarte Water.

Zwarte Water

The river Zwarte Water is a relatively short river that starts in Zwolle. In the Zwarte Water the water from the Sallandse Weteringen and the Overijsselse Vecht is combined and flows towards the lake Zwarte Meer, which is connected to the Ketelmeer and IJsselmeer (Rengers, 2013).

IJsselmeer

The water of the three rivers IJssel, Vecht and Zwarte Water discharges through the lake Ketelmeer into the IJsselmeer (Strootman, 2013). The IJsselmeer is a lake and is since the construction of the Afsluitdijk in 1932 no longer directly connected to the sea. The water level of the IJsselmeer is controlled by discharge through gravity (in Dutch: spuien) into the North Sea when the water level of the sea is low (H+N+S, 2013). The IJsselmeer has a regulated water system with a summer level of -0.40m NAP and a winter level of -0.30 NAP (H+N+S, 2013). Naturally, there are fluctuations in the water level through the influence of the weather.

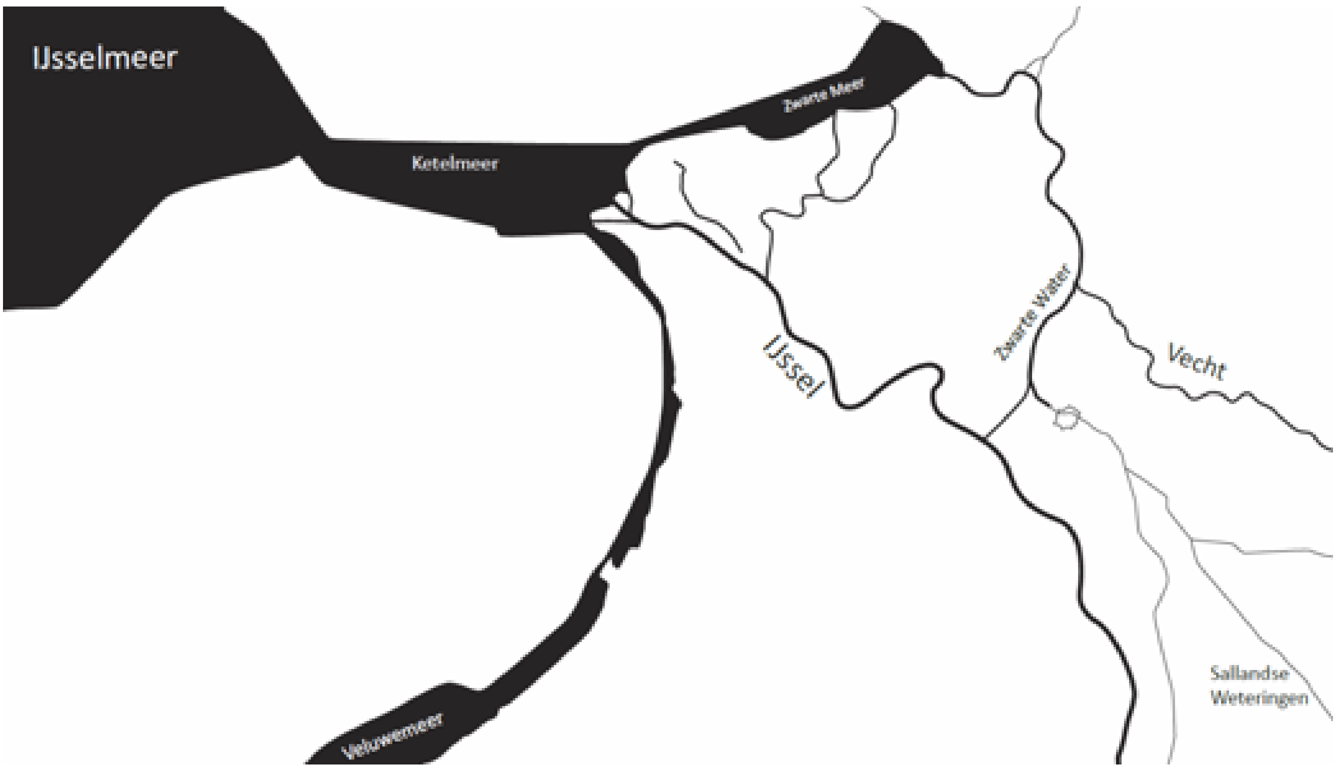


Figure 5.1 Water system of the IJssel-Vechtdelta

In case of a Northwest storm, water in the lake IJsselmeer can be pushed upwards by the wind, and thereby increase the water level in the Ketelmeer, Zwarte meer and Zwarte Water (Rengers, 2013). To protect the inland from this funnel effect, the Balgstuw, an inflatable dam, was built in Ramspol (Figure 4.8). This dam automatically inflates when two conditions are met: 1) the water level rises more than 0.50 NAP and 2) the water flows towards the east, towards the river Zwarte Water. The Balgstuw diminishes the influence of the Northwest storm. However, when the Balgstuw is inflated and in function, the river Zwarte Water can no longer discharge its water on the IJsselmeer and the water level of the river would rise (Rengers, 2013).

Zwolle

Changes in the water level of the IJsselmeer have direct consequences for the urban environment of Zwolle (Rengers, 2013). High water levels at the Zwarte Water directly influence the city because its canals are in direct contact with the Zwarte Water, and hereby also connected to the Vecht and IJsselmeer (Staf Deltacommissaris, 2013). Consequently, high water at the river Zwarte Water can result in water problems in the city centre of Zwolle (H+N+S, 2013). To protect the city against high water on the Zwarte Water, a sluice situated in the north of the old city centre, can be closed (Rengers, 2013)(Figure 4.6). However, closing this sluice could pose another threat because of water coming from inland (Sallandse Weteringen) would raise the water level in the city centre (Staf Deltacommissaris, 2013). When the water level in the city centre is higher than on the Zwarte Water, the sluice opens automatically (Rengers, 2013).

Sallandse Weteringen

The regional water system situated south of Zwolle consists of waterways, so-called Sallandse Weteringen. These waterways collect the water from catchment areas and come together at the south of Zwolle. From this point, the water flows through the city (Figure 4.7) and discharges on the Zwarte Water (Staf Deltacommissaris, 2013).

5.2 Upcoming developments

The IJssel-Vechtdelta is confronted with the challenges of climate change. To address these challenges, national and regional decision-making can have a large influence on the development of the water system.

The Royal Netherlands Meteorological Institute (KNMI) has developed four future scenarios to explore the impact of climate change. Although the future of the climate is uncertain, these climate scenarios give an indication based on observation and calculations. As described before, climate change can result in an increase of precipitation and the intensity of extreme precipitation (KNMI, 2014). This results in a higher water discharge and increases the risk on floods (KNMI, 2014). The four scenarios of the KNMI are translated into scenarios for the IJssel-Vechtdelta. In an extreme scenario for 2100, the discharge of the rivers are expected to increase by 33% (Table 1) (H+N+S, 2013).

	Normative discharge	Extreme scenario 2100
IJssel	2461 m^3/s	3260 m^3/s
Vecht	550 m^3/s	736 m^3/s
Sallandse Weteringen	75 m^3/s	100 m^3/s

Table 1. Discharges of IJssel-Vechtdelta
(adapted from H+N+S, 2013)

In conclusion, climate change is expected to increase the occurence of high water levels and peak discharge due to an increase of rainfall and extreme weather. This affects the water system in the region of Zwolle and increases the risk on flooding.

Policy

An excess of water from the rivers could be discharged in the sea via the IJsselmeer. However, due to sea level rise, the possibility to discharge this water by gravity becomes problematic (Staf Deltacommissaris, 2013). Therefore, pumps will be placed in the renewed Afsluitdijk, which is the water barrier between the sea and the IJsselmeer, to ensure the water safety of the IJsselmeer region (Staf Deltacommissaris, 2013).

Flexible water level

To enlarge the supply of fresh water, a more flexible and fluctuating water level of the IJsselmeer is desirable, as a response to climate change (Strootman, 2013). By letting the water level raise in the spring, an extra buffer of fresh water will be created that can be used by agriculture in the west of the Netherlands in case of drought in the summer period. Instead of the earlier described regulated water level a dynamic water level will be established through flexible water level management. A more flexible water level management can result in a spring water level of -0.10 NAP and a summer water level of -0.50 NAP (H+N+S, 2013). Consequently, surrounding water systems (e.g. Zwarte Water) also require a more flexible management and arrangement (Strootman, 2013). Overall, the flexible water level approach will ensure a larger supply of available fresh water and more flexibility to respond to meteorological conditions (Staf Deltacommissaris, 2013).

Dike reinforcement programme

Recent results from safety assessments indicated that a large part of the river dikes in the IJssel-Vechtdelta has an insufficient safety level (Figure 5.2). The safety of a large part of the dikes is disapproved because of problems with stability and water piping underneath the dikes (a phenomena described by van Noortwijk et al. (1999)) (H+N+S, 2013). In addition, a small part these dikes are

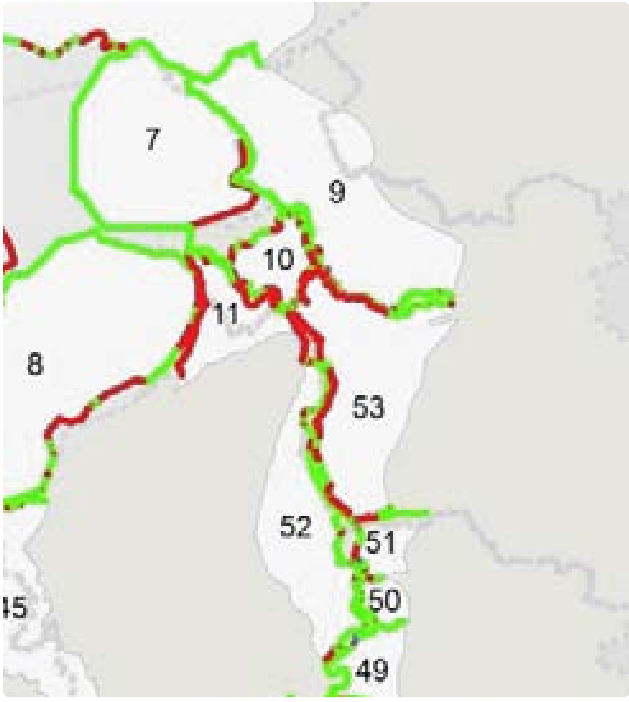


Figure 5.2 Insufficient safety level of dikes (in red) (ILT, 2013, p. 16)

considered not high enough (H+N+S, 2013). Next to the river dikes, also 50% of the regional water barriers have been found insufficient (H+N+S, 2013).

Decision making on provincial and national level

Decisions on the provincial and national level needs to be made to address the challenges of the IJssel-Vechtdelta. On the national level a decision needs to be made regarding the division of the water over the rivers Rijn, Waal and IJssel. This influences the water discharge in the IJssel-Vechtdelta. On the provincial level (Province of Overijssel), a strategy for the future development of the region has to be selected. Strategy 1 focuses on seperation of the water system of the Vecht from the IJssel and IJsselmeer. The balgstuw at Ramspol will become a fixed permanent water barrier with a pump (Figure 5.3). Along the IJssel so-called robust (reinforced) dikes (H+N+S, 2013). In strategy 2 the connection between the water system of the Vecht and the IJssel is maintained (Figure 5.4). The balgstuw will continue to function as a flexible storm barrier, and robust dikes will be constructed around the cities (H+N+S, 2013).

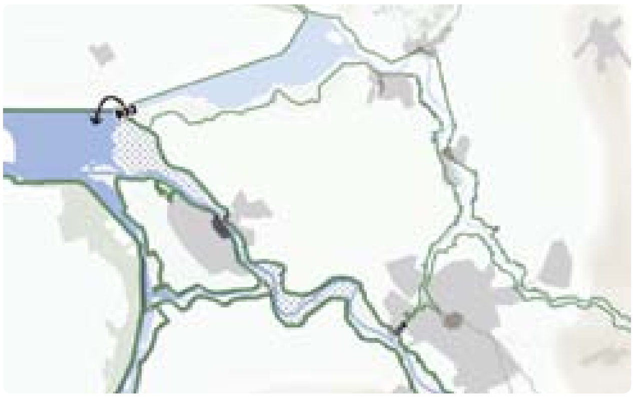


Figure 5.3 Strategy 1. Separated (H+N+S, 2013, p. 120)

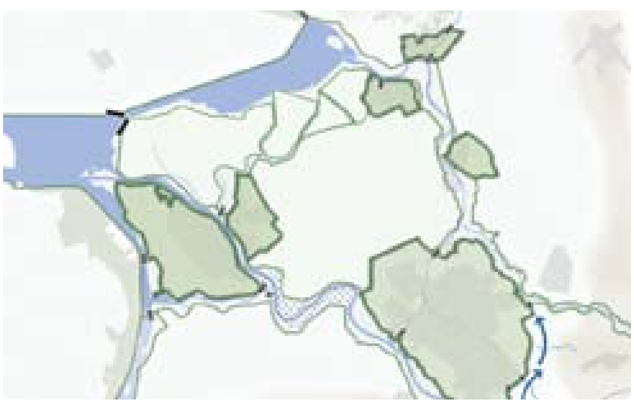


Figure 5.4 Strategy 2. Connected (H+N+S, 2013, p. 126)

5.3 Flooding risk

The upcoming developments illustrate the importance of considering flooding risk as an additional element besides resilience. Although resilience allows a water system to adapt to changes, flooding risk also stresses the importance of considering the consequences of flooding.

There are several definitions of risk, in this research risk is defined as the product of probability and consequences (Covello et al., 1981). Flooding risk is about the probability that an area gets flooded and the consequences that this flood would have. Therefore, to decrease the flooding risk in an area, you can reduce the probability or the consequences.

Risk approach in the Delta programme

The Delta programme uses a risk approach to address water safety in the Netherlands. In the delta program the probability on flooding is considered together with the possible consequences of a flood, in order to create the desired safety level (Delta programma, 2014). The Delta programme presents the concept of 'multilayered safety'. This approach is based on risk as the product of probability and consequences (Figure 5.5). This can be recognized in the three kinds of measures they have identified:

- First layer: preventing measures to minimalize the probability on floods. Reducing the probability on floods can be realized through reinforcement of the dikes or by lowering the water level (e.g. Room for the River programme).
- Second layer: spatial adaptations in the area to minimalize the consequences of a flood.
- Third layer: disaster management to minimalize the consequences of a flood. The consequences of flooding can be decreased by having an evacuation plan (Staf Delta commissaris, 2013)

Flood risk management in the Netherlands used to focus only on the first layer of safety, mainly by reinforcing dikes, also called a resistance strategy (Vis et al., 2003). This strategy resulted in high investments in low situated areas due to a false sense of safety. This increased the economic consequences of a flood as well as the flooding risk (Vis et al., 2003). More recently, a more adaptive approach, using the concept of resilience has been introduced in water management. This changes the strategy from 'fighting floods' to 'living with floods' (Vis et al., 2003). Next to the probability, also the consequences are now included in flood risk management strategies.

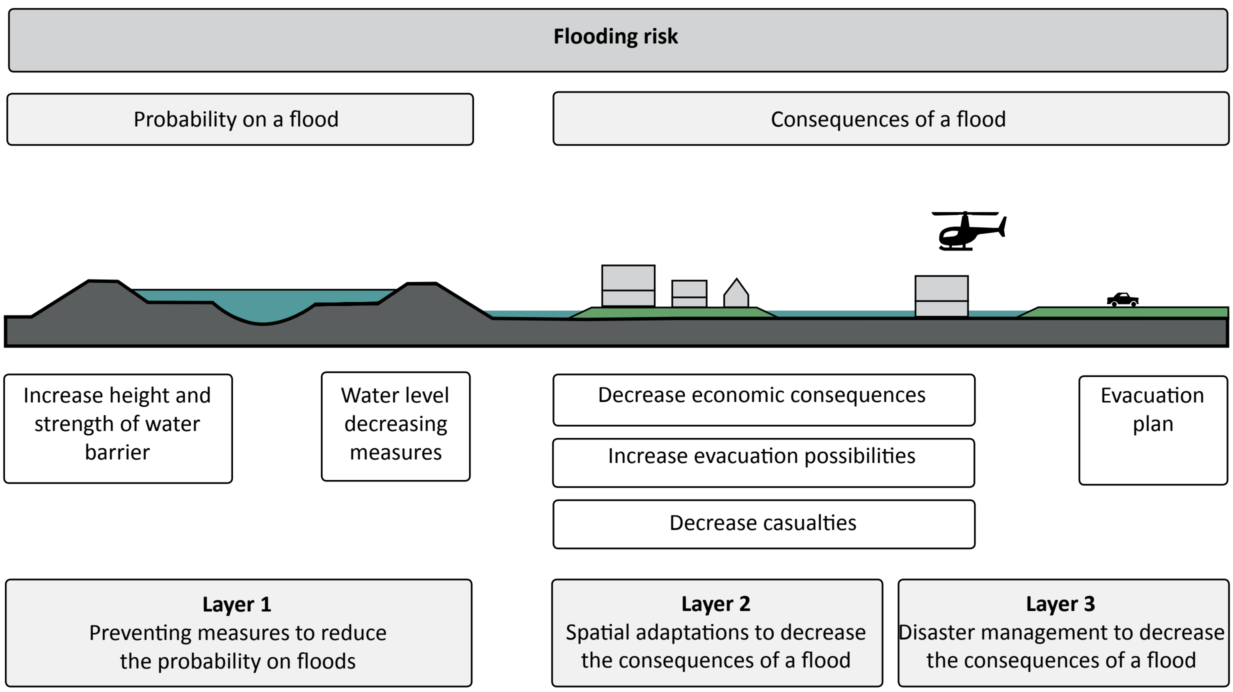


Figure 5.5 Relation between flooding risk and multi layered safety

5.4 Design challenge

The city of Zwolle is confronted with multiple challenges due to peaks in water discharge, insufficient safety levels of dikes, increase of flexibility in the water level of the IJsselmeer, and a low geographical position of the city. As a consequence, the region of Zwolle is considered as a region with a high risk on flooding (Staf Delta commissaris, 2013). The following two key challenges for the water system of Zwolle can be identified.

The first challenge relates to high water and peak discharge in the regional water system of Zwolle. As described before, protecting the city against high water coming from the Zwarte Water is possible by closing the sluice north of the city centre. However, by closing the sluice, the water level in the city would quickly increase due to water coming from the Sallandse Weteringen. This would increase the risk of flooding. Therefore, the first challenge is to find a way to deal with the water coming from the Weteringen, in case of a high water level on the Zwarte Water (Figure 5.6). This specific situation of a high water level on the Zwarte Water, is expected to occur more frequently in the future due to flexible water level of the IJsselmeer, peak discharges of the Vecht, and inflation of the Balgstuw in case of storm. In addition, the extreme scenario made for 2100 shows an increase in discharge of the Weteringen to 100 m^3/s, which is 25 m^3/s more than the city currently can handle (personal comment A. van Rooijen, 2015).

The second challenge relates to the flooding risk in Zwolle in case of a breach, along the Vecht, the IJssel, the Zwarte Water or the Weteringen. Since Zwolle is located in a geographically low area, a breach in the region in between Deventer and Zwolle would present a major problem to the city of Zwolle. Additional risks for flooding result from the rising water level, flexible water level of the IJsselmeer, and insufficient safety level of dikes in the region (Rengers & van Rooijen, 2013; ILT, 2013).

This research aims to address these challenges by focussing on the water system of the Sallandse Weteringen. The framework of resilience is used to develop and select possibilities to adapt the water system to deal with these challenges. It results in a design for a resilient regional water system of Zwolle.

Figure 5.6 Challenge 1 in the regional water system
1:300.000

6. Exploration of possibilities

6.1 Challenge 1.

The first challenge is to deal with the water from the Sallandse Weteringen, while protecting the city of Zwolle in case of a high water level at the river Zwarte Water. Different possibilities to deal with water in such a situation are explored and represented in a decision tree.

Overview of possibilities
Through literature analysis of the water challenges in the region, three main possibilities were identified to deal with the water of the Sallandse Weteringen: developing a bypass, placing pumps, or improving the buffer capacity of the water system. These possibilities can be combined, resulting in a wide range of possibilities as can be seen in the decision tree below (Figure 6.1).

Bypass
One identified possibility is to develop a bypass between the Sallandse Weteringen and the IJssel or Vecht, to guide the water of the Weteringen around the city. This study focuses on a situation with a high water level on the Zwarte Water. In this situation the water level of the Vecht and IJssel is expected to be higher than of the Sallandse Weteringen. Therefore, it is not possible to discharge the water from the Weteringen on the river without pumps or space for water storage. Pumps or water storage, or both, are needed to deal with the water coming from the Sallandse Weteringen.

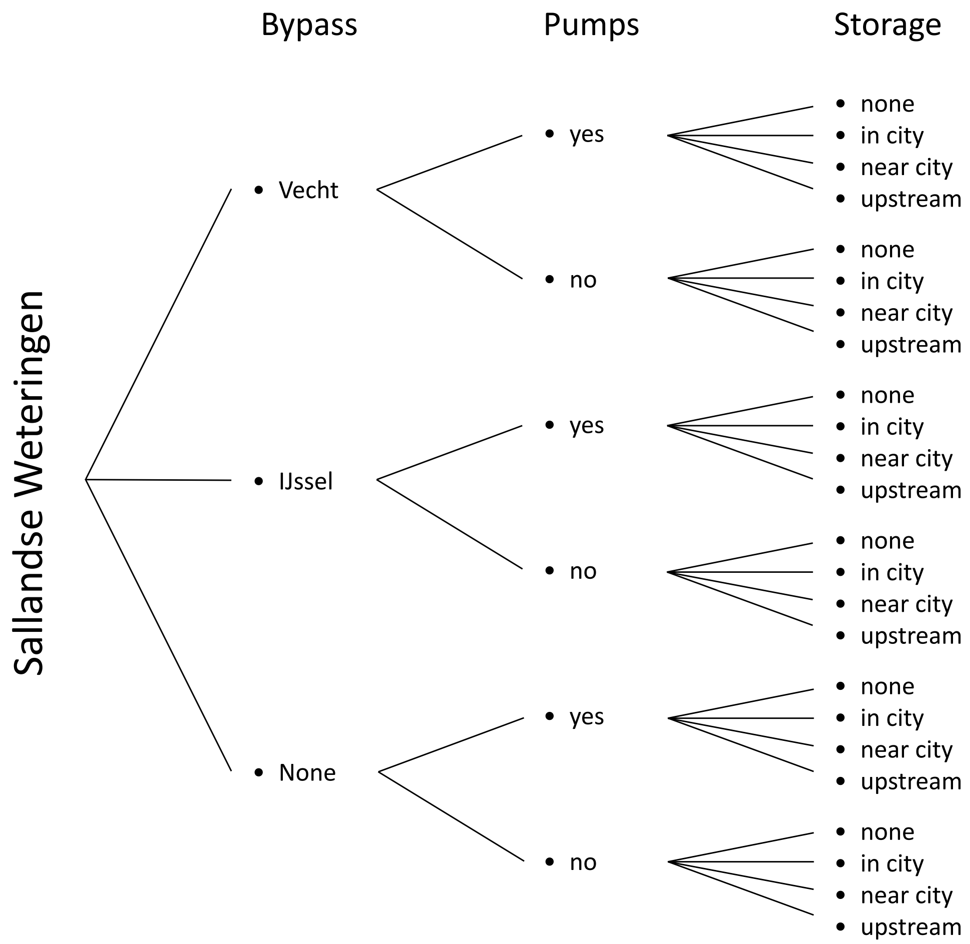


Figure 6.1 Decision tree possibilities Sallandse Weteringen

Pumps

By constructing pumps with a high enough capacity all the water of the Weteringen can be pumped towards one of the rivers, the IJssel, Vecht or Zwarte Water. If the capacity of the pumps is high enough, there is no need to store water.

Storage

The third possibility is to store water. Storing the water in an area untill the peak discharge of water has passed. This can be realized by improving the buffer capacity of the water system, for example, by creating buffer areas along the water system, or by adaptations that increase the water storage capacity within a water system. These solutions can be searched for near the city or more upstream.

Additional analysis of the possibilities

Based on the previous argumentation 6 of the 24 possibilities were rejected (Figure 6.2). Of the remaining 18 possibilities, 7 were selected for further analyse. The selection was based on having a diversity of possibilities, with limited overlap (Figure 6.2).

The possibilities were explored by sketching and placing the variations into their spatial context. When studying these possibilities more questions came up, that required additional analysis. Therefore, a more specific analysis of the heights in the area was made. In addition, a flooding analysis was carried out and provided insight in what would happen if certain areas would be flooded (Chapter 7. Water analysis).

Bypass and pumps

The first option is to place a pump along the sluice that is situated between the Zwarte Water and the canals of Zwolle (Figure 6.3). In this way the sluice prevents the water from the Zwarte Water and the Vecht to enter the city. Meanwhile the pump can make sure that the water of the Weteringen is pumped out the city, by pulling the water through the city.

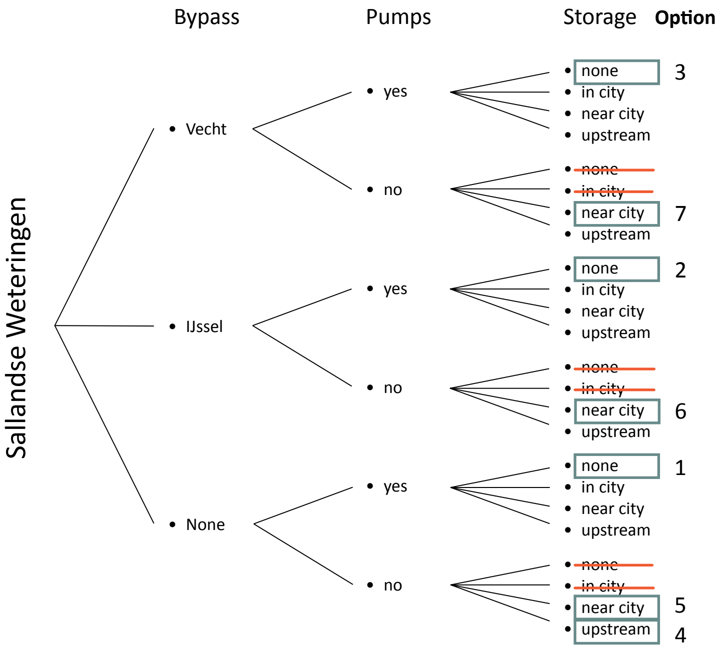


Figure 6.2 Rejected and selected possibilities

Figure 6.3 Option 1. Pump in city centre
1:300.000

Option 2 and 3 are focuses on guiding the water through a bypass towards the IJssel or the Vecht and pump the water into the river (Figure 6.4 and 6.5). Such a bypass would be around 50 meters wide (from dike top until dike top), to discharge the water from the Weteringen. This bypass would need to be constructed and deal with height differences in the landscape, like the high river banks along the IJssel and the elevation in the landscape at Herfte. Nevertheless, a pump is still required to pump the water into the river.

The three options are improving the resilience of the water system in the sense that the system can deal more easily with different peaks in the water system. However, the modularity or diversity of the water system is not increased by placing a pump. The two options with the bypass result in a small increase in connectivity between the regional water system and one of the rivers. The redundancy of the three options is low because placing a pump does not present a solution whenever something goes wrong in this water system. If one subsystem fails, the rest of the system cannot take over the failing function. Placing an emergency pump would improve the safety, when something would go wrong with the pump. Yet, it doesn't give any backup when there would be another kind of problem in the water system, like a blockage or a breach.

Figure 6.4 Option 2. Bypass to IJssel with pump
1:300.000

Figure 6.5 Option 3. Bypass to Vecht with pump
1:300.000

Increasing the water capacity upstream

By improving the storage capacity of the Weteringen and bringing back the discharge capacity of the waterways, the water capacity of the water system can be increased. The water ways could be made more shallow and narrow which would reduce the discharge capacity. Room can be made for water storage in and near the water ways. It might require additional room for water storage in every small catchment area, to allow each area to deal with its own peak of water (Figure 6.6). Consequently, peaks in discharges will be lowered in Zwolle. The peaks of water stay for a longer time period inland which enables more infiltration of water in the area.

This option could improve the resilience of the water system as it makes the water system deal with peaks already in an early stage, in the catchment areas. The option could be considered to contribute to modularity since it divides the catchment areas in different modules that could function on their own, however, there is no real interaction between these different catchment areas. The option could improve the diversity of the water system, by adding the water storage areas in each catchment area. To improve the redundancy of this option, allowing water from the Weteringen to flow into the catchment areas. This would allow the water system to deal with problems in one catchment area by redistributing the peak of water over other areas.

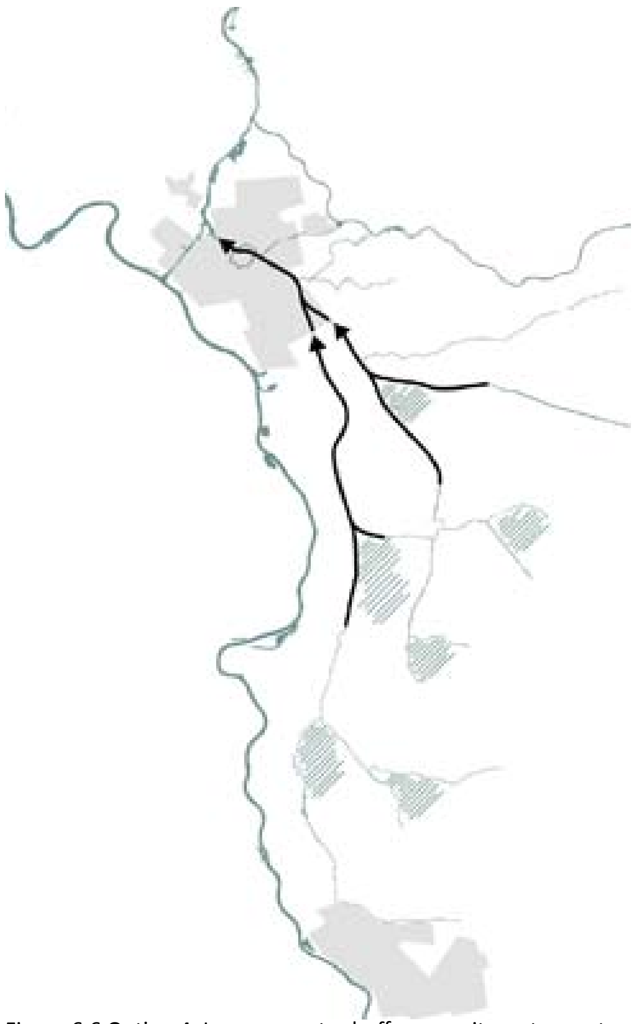


Figure 6.6 Option 4. Increase water buffer capacity water upstream 1:300.000

Storage of the water

Three options focuses on improving the storage capacity of the water system near to the city. In the fifth option, water storage south of Zwolle is developed in the low situated agricultural areas (Figure 6.7). Infrastructure and height differences in the area facilitate a division in different modules. The water is stored and when the water level on the Zwarte Water has decreased, the water could flow again through the city towards the Zwarte Water.

Option 6 combines the storage of water with a bypass towards the IJssel (Figure 6.8). Because the riverbanks are relatively high, water storage is not suitable along the IJssel. The IJssel itself is relatively high positioned in the landscape, making it hard to let water flow naturally from the Weteringen into the river.

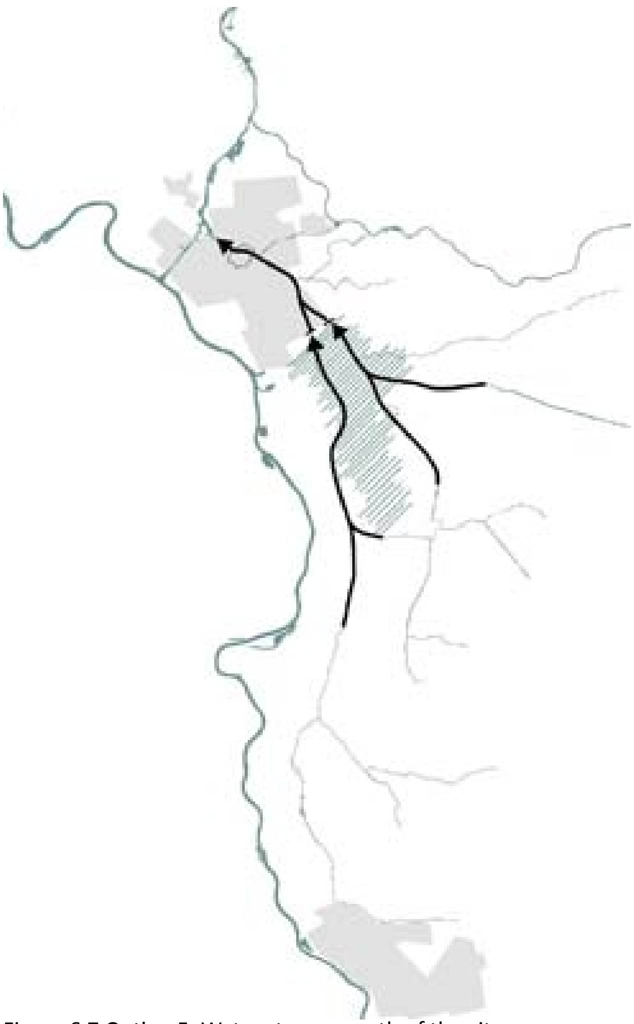


Figure 6.7 Option 5. Water storage south of the city
1:300.000

Figure 6.8 Option 6. Bypass to IJssel with water storage
1:300.000

The seventh option combines water storage with a bypass towards the Vecht, without a pump at the end (Figure 6.9). This means that water can only be discharged on the Vecht when the water level is low enough. Consequently, storage of water is needed until a peak in the water level decreases. Nevertheless, connecting the Weteringen with the Vecht can be difficult because of height differences in the landscape.

Option 5 could improve the resilience of the regional water system of Zwolle as it divides the area surrounding the Weteringen into different modules. These water buffer areas can buffer peak discharges and give flexibility to the water system. The modules can be connected to each other, and water could flow from one area to another under regulated circumstances. Hereby, the redundancy of the water system is improved because if one module wouldn't work another modules could take over.

Option 6 could improve the connectivity of the water sytem as it connects the regional water system with the IJssel. However, it does not results in additional water buffer capacity and requires substantial efforts to get the water towards the IJssel because of the high situated river and riverbanks. Overall, this option does not present additional improvements on all four aspects of reslience, compared to option 5.

The seventh option presents multiple possibilities to connect the regional water system with the Vecht. This could improve the redunancy and connectivity of the system. Similar to option 5, opportunities to buffer water and divide the area in modules, are present.

Figure 6.9 Option 7. Bypass to Vecht with water storage 1:300.000

Conclusion

Based on the exploration of the seven options, valuable insights were obtained in possible combinations and practical solutions. Key findings were:

- A bypass is only possible in combination with pumps or a water storage. The height differences in the landscapes present an obstacle for the development of a bypass.
- Placing pumps does not improve the redundancy, and hereby the resilience, of the water system.
- Storage of water upstream is a solution to decrease peak discharges of the Sallandse Weteringen. However, it is no solution in a situation of high water on the Zwarte Water, because the normal discharge would raise the water level in the city centre of Zwolle when the sluice is closed.

Consequently, option 5 in which a water buffer south of Zwolle is the best option to improve the resilience of the water system and address the challenges in the area.

6.2 Challenge 2

As stated in the design challenge, it is important for this area to address the risk of a breach along the IJssel, Vecht or one of the Sallandse Weteringen. To address the flooding risk in the area, several options can be identified. Option 0 is based on the current situation. The options 1 and 2 are based on strategy 1 and 2 developed by H+N+S (2013) for the Province of Overijssel. The third option combines the insights from challenge 1 with the background of the area.

Option 0 - current situation

In case of a breach in the region of Zwolle, water will find its way along the path of least resistance towards the lowest point in the area, in this case the city of Zwolle. This is clearly visible in height maps and flooding models (Royal Haskoning DHV, 2013; Havinga and van der Zwet, 2014).

Option 1

To reinforce the IJssel dike could prevent a breach along the IJssel. H+N+S (2013) describes the reinforcement of the IJssel dike in strategy 1. This can be done on a large scale, for example by creating a large 'climate dike' along the IJssel, to reduce the risk of a breach (Figure 6.10). It does not give a solution or protection to a breach along the Vecht of one of the Weteringen.

Box 1. Compartment dikes

The earlier described strategies that are currently discussed at the Province of Overijssel, include a strategy in which a compartment dike would be constructed south of Zwolle (H+N+S, 2013). Such a compartment dike divides an area into two compartments and prevents the water to enter the area on the other side, in case of a breach. A compartment dike would reduce the economic damage of a flood (Royal HaskoningDHV, 2013).

When developing a compartment dike, the area is divided into smaller compartments, resulting in a higher water level within the compartment in which the flood occurs. Royal HaskoningDHV (2013) developed a flood model for the area of Zwolle to determine the impact of a compartment dike south of Zwolle. If a breach would occur within the compartment in which the city is situated, the water level would rise an additional 0.25 to 0.5 meter, then without a compartment dike (Royal HaskoningDHV, 2013). The water level would in that case not rise above 2.75 meter NAP.

Figure 6.10 Option 1 - Reinforced IJssel dike
1:300.000

Option 2

Constructing a compartment dike south of Zwolle to prevent the water from entering the city, in case of a breach south of Zwolle (Figure 6.11). This option is in line with strategy 2 in which the cities would be enclosed by dikes ((H+N+S, 2013). This large scale construction would be able to buffer the impact of breaches at the IJssel, Vecht or Sallandse Weteringen. It would contribute to the modularity of the area by dividing it into two, at the same time, it could negatively affect the diversity of the landscape by creating a large scale barrier.

Option 3

Another way to deal with the risk of flooding would be to assign several compartments within the existing landscape (Figure 6.12). These compartments would buffer and delay the water, before the water would enter a next compartment area. These compartments would be able to function as single modules but are connected with each other through links, establishing a more redundant system. Hence, the modularity of the area would improve. The existing diversity of the landscape could be enhanced by this option.

Figure 6.11 Option 2 - Compartment dike
1:300.000

Figure 6.12 Option 3 - Multiple compartments
1:300.000

Conclusion
When looking at these options from a risk perspective, differences in focus can be observed. Option 0 and option 1, only focus on reducing the probability of a breach. Option 2 also reduces the consequences of a flood, as it would protect the area with the highest investments. Option 3 also reduces the consequences of a flood, by taking into account the surrounding landscapes, the function of the area and the problems in the regional water system.

When analysing the earlier described options for their contribution to resilience, the third option comes out best. By establishing multiple compartments the modularity as well as the diversity of the landscape can be enhanced. In addition, the compartments can be connected to each other to improve the redundancy of the area. Consequently, option 3 presents an opportunity to develop a flexible approach to deal with flooding and is explored further in this research.

7. Water analysis

7.1 Exploration buffer capacity

In the previous chapter the possibility to buffer the water from the Sallandse Weteringen in the area south of Zwolle, was identified. In this chapter the water storage capacity in the area south of Zwolle is evaluated to explore the water buffer capacity. For this calculation the basic volume calculation has been used: length x width x height = volume. Height maps (ahn.geodan.nl) indicate that the lowest areas (between -1 and 0.5 NAP) cover approximately 25 km^2 of the area south of Zwolle (Figure 7.1).

In the calculation a water level of 1 meter has been used. In this first exploration a rough calculation was made and did not take height differences in the area into account. This results in a buffer capacity of 25.000.000 cubic meters (25 km^2 x 1 m). A discharge of 100 m^3/s of the Sallandse Weteringen result in a maximum buffer capacity of three days.

- 100 m^3/s = 8.640.000 m^3/day
- 1 m height would give a surface of 8,6 km^2 per day
- 25/8,6 = 2,9 days

However, the 100 m^3/s is the discharge of the Weteringen in the extreme scenario for 2100 (H+N+S, 2013). Therefore, in other situations with a lower discharge of the Weteringen, water can be buffered for a longer period.

This first exploration in amounts of water and buffer capacity, confirms that increasing the buffer capacity by assigning an area as water storage area, might be a solution for improving the flexibility of the water system. It provides flexibility and time to store the water coming from the Weteringen, when the sluice would be closed. How much time such a water storage area would give depends on the discharge of the Weteringen at that moment. At the same time, the time needed to buffer the water is uncertain.

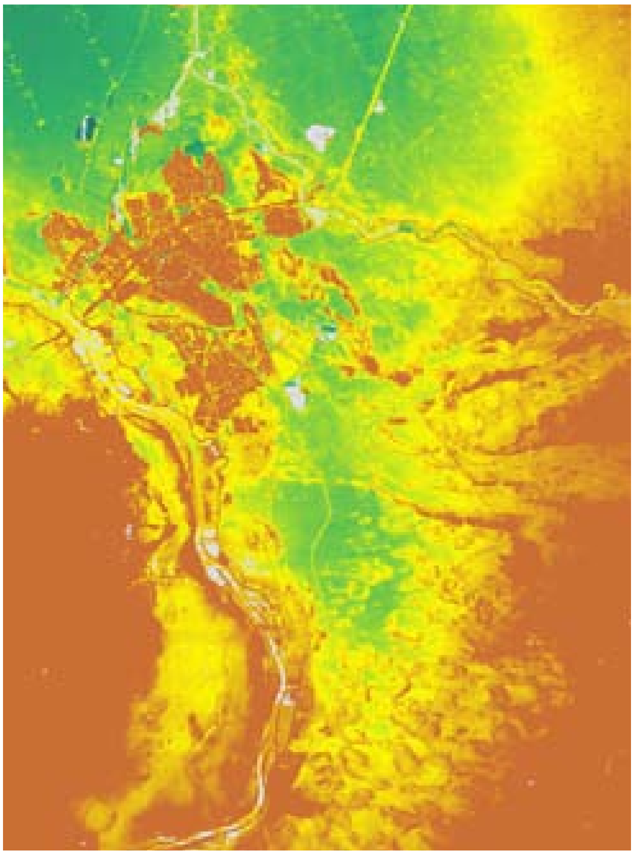


Figure 7.1 Height map - low area of 25 km^2 (ahn, 2015)

7.2 Analysis flood images

This paragraph describes the findings of an analysis of flood calculations and images provided in the Quickscan Regionale Keringen (Havinga and van der Zwet, 2014). In this document ten breach locations along the Weteringen were calculated. The images visualise which areas would be flooded in case of a breach. In addition it illustrates the height of the water and the damage of the flood.

Results

When analysing these flood images it is possible to identify landscape elements that serve as water barriers in case of a flood, e.g. railroads and natural height differences in the landscape. These elements steer the water in a certain direction, while the water flows towards the lowest areas of the region.

The images indicate that in several areas a buffer of more than 1 meter (starting point of calculation in 7.1) can be realised.

A flood in the area would result in high financial costs especially in the city of Zwolle, where large housing areas are situated in low areas, and high investments have been made in this urban area. Also the village Laag Zuthem is an area that might need extra protection against floods. The report recommends to increase the standard safety norm of a flooding in once in 200 years, to 1:1000, for the city of Zwolle. This illustrates the high impact a flood would have in this area. While in other areas a lower safety norm could be adopted.

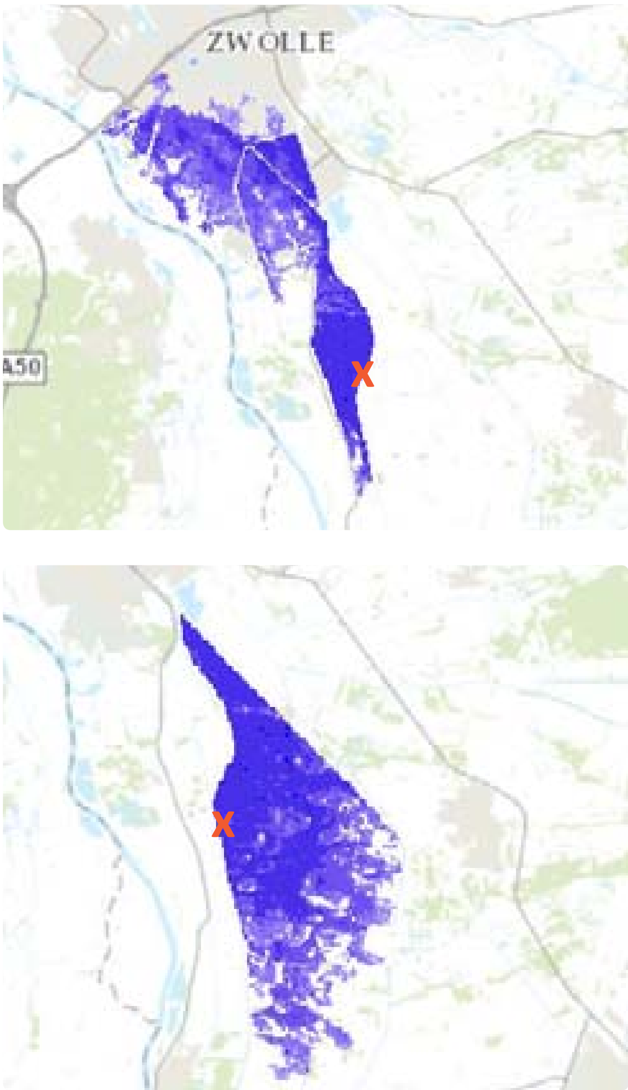


Figure 7.2 Flood images breach along the Soest Wetering (Havinga and van der Zwet, 2014, p. 9 and 10)

As we know the breach locations, (indicated with x in Figure 7.2) the flood images give also an impression on which areas would be flooded first and which would follow.

Water guiding elements and heights

The flood images formed an input to develop an overview of elements in the landscape that can guide water in case of a flood (Figure 7.4). Clearly visible are the three railroads that run straight through the landscape. Floods from the Weteringen would not give any damage to the railroads, and are therefore suitable to consider as water barrier (Royal HaskoningDHV, 2014).

The double lines in Figure 7.4 are the dikes of the Soest Wetering and the Nieuwe Wetering, which come together in the city. The dike of the river Vecht is located in the Northeast. The other two lines are the roads N35 and N337 that are situated high in the landscape. Next to these water guiding elements, natural heights in the landscape higher than 2 m. NAP are identified (grey colour).

The water guiding elements presented in Figure 7.4 have been verified by comparing them to other flood images based on flood calculations. The first verification is based on the website of HKV, that illustrates the effects of breaches along the Vecht and the IJssel (Figure 7.3). The second verification is based on a flood animation, for a breach along the IJssel river (paragraph 7.3).

Figure 7.3 Flood image of HKV website, for a breach along the Vecht (http://test.hkv.nl/mego/mego.htm)

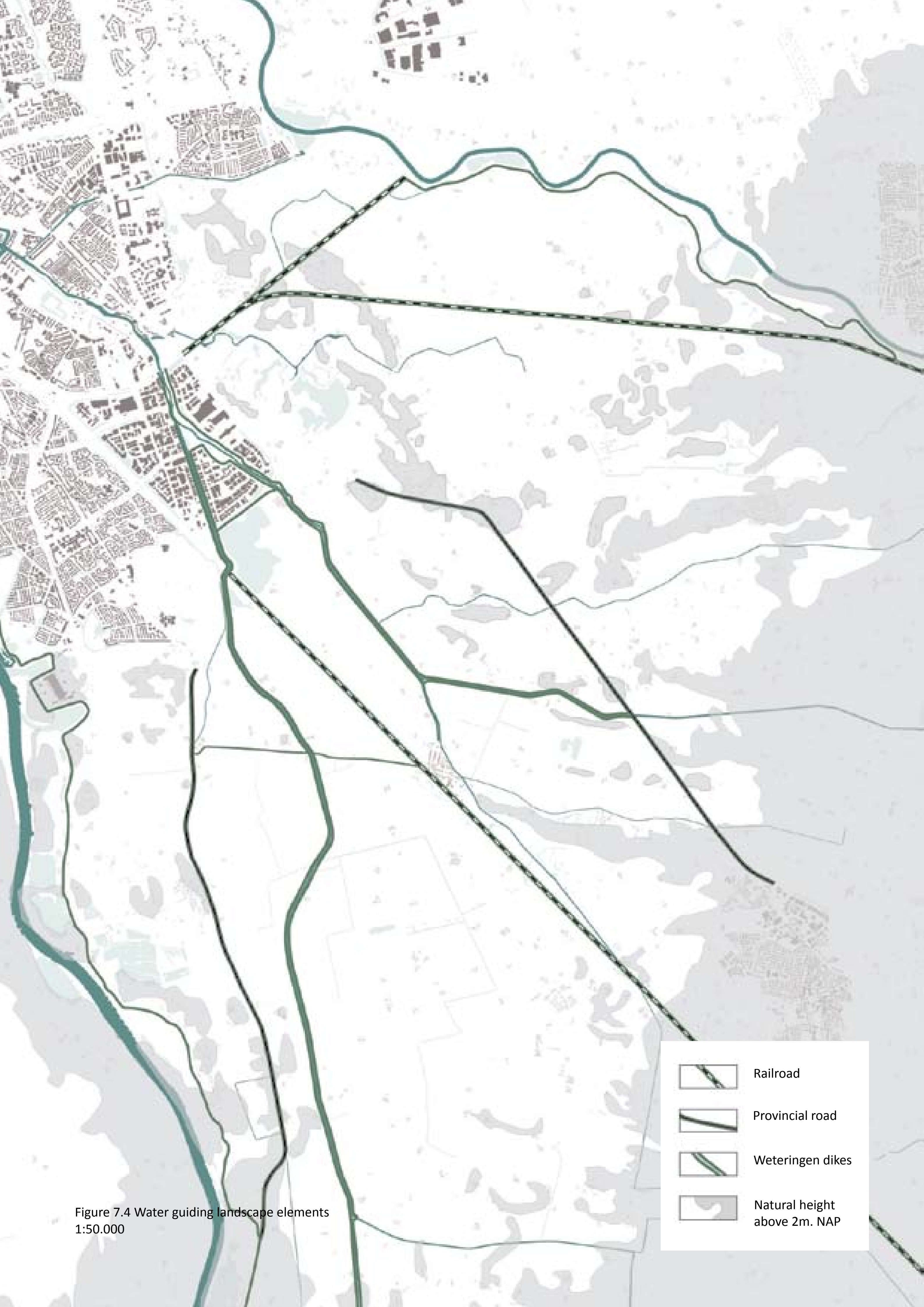


Figure 7.4 Water guiding landscape elements
1:50.000

7.3 Analysis flood animation

The second verification was based on a flood animation provided by the Municipality of Zwolle. The animation is a flood calculation, animated in time. It is a visualization of what would happen in case of a breach at the village of Olst (Presented in Figure 7.5a, b, c, d, e and f).

When analysing this movie, it is clear that the water guiding elements derived from the analyse of the flood images of the Sallandse Weteringen, are also visible in this flooding animation. The identified water guiding elements can guide the water in case of a flood.

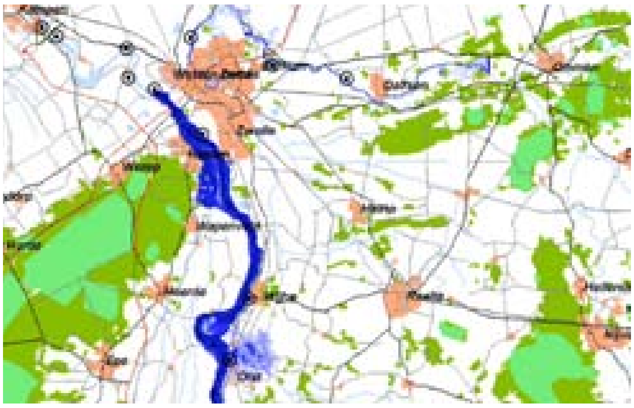


Figure 7.5a. 12 Jan 07.20 Breach along the IJssel near to Olst.

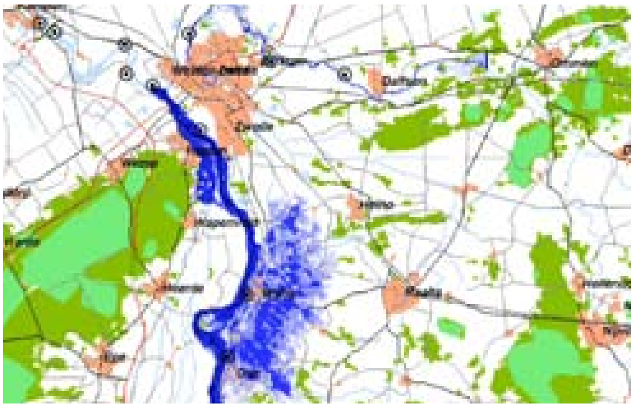


Figure 7.5b. 12 Jan 19.20 Water of the IJssel floods the lowest areas of the region. Water flows northwards towards Zwolle.

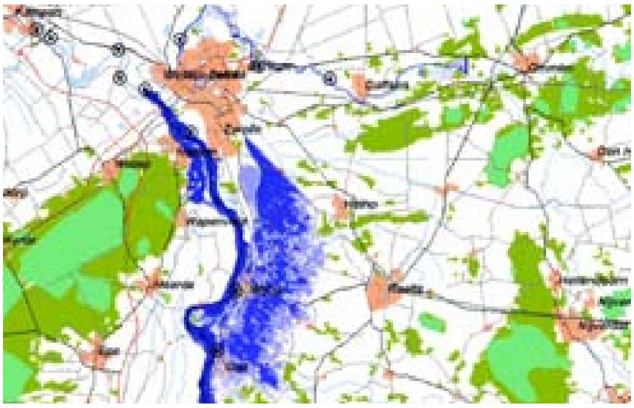


Figure 7.5c. 13 Jan 01.20 The railway and the dikes of the Soest Wetering and the N337 retain the water temporary.

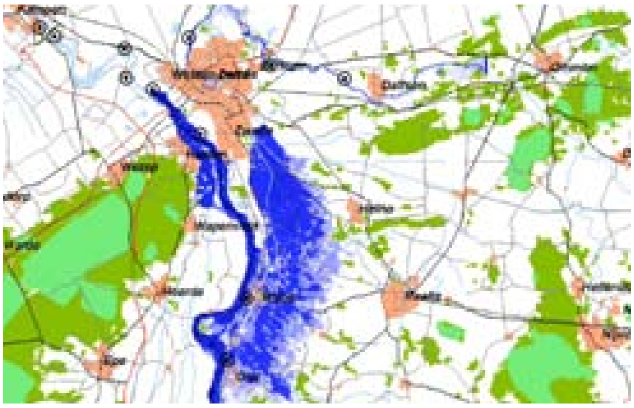


Figure 7.5d. 13 Jan 07.20 The flood reaches the city Zwolle.

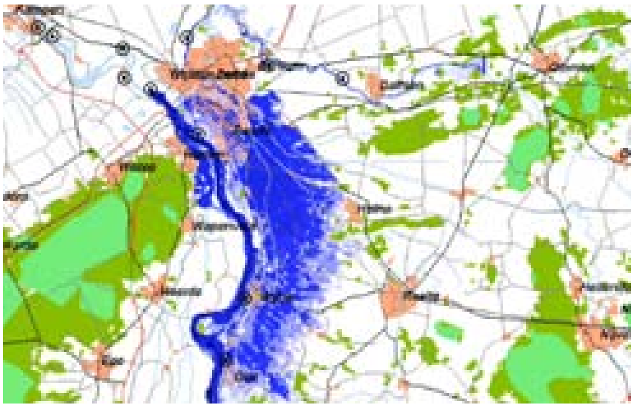


Figure 7.5e. 13 Jan 22.20 Southwest Zwolle is flooded

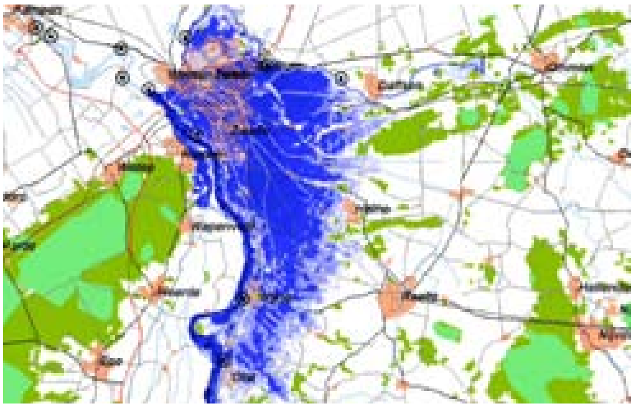


Figure 7.5f. 15 Jan 13.20 The entire city is flooded, as wel as region south of Zwolle.

8. Strategy

The strategy to deal with the challenges related to peak discharges and flooding risks is based on the concept of compartmentalisation. This strategy is selected based on the analyses described in chapter 6 and 7.

In this strategy the landscape is divided into several compartments (Figure 8.1). These compartments are built upon existing landscape elements that situated higher in the landscape, e.g. railroads, dikes, roads, and natural height differences.

The compartments have multiple functions and facilitate a more resilient water system. The compartments provide buffer capacity for water coming from the Sallandse Weteringen. Together the compartments form a water defence system suitable to address the challenges of extreme events as described in chapter 5. The following paragraphs explain more in detail how the strategy relates to the two specific challenges.

Figure 8.1 Compartment concept
1:60.000

8.1 Water buffer system

The first challenge related to protecting the city of Zwolle in case of a high water level at the river Zwarte Water, while dealing with the discharge from the Sallandse Weteringen. The analysis in Chapter 6 indicated that buffering water south of Zwolle presents a resilient solution, compared to a bypass or placing pumps.

The buffer system presents a solution for multiple situations. As described in chapter 5, the water level of the Zwarte Water can rise because of various reasons. To prevent the city from this high water, the sluice in Zwolle would close. Consequently, water discharges from the Sallandse Weteringen would enter the city and rise the water level, until the sluice is opened again. Buffering the water of the Sallandse Weteringen would be required in this situation.

Another situation is the increase of discharge from 75 m^3/s to 100 m^3/s as described by H+N+S (2013) for the extreme scenario made for 2100. This discharge is beyond the capacity of the urban water system and requires buffering (personal comment A. van Rooijen, 2015).

Compartment zones

The compartment approach allows for a gradual flooding of the area. It enables to put only those compartments into use that are in line with the needed capacity to buffer the water. It has the additional benefit of only flooding the compartments that are needed, and hereby reducing economic consequences caused by buffering water on agricultural land.

The compartments will be divided into three zones. The first zone will function most frequent as a buffer zone (Figure 8.2). These compartments are assigned to be the first to be flooded. The location of these compartments as zone 1 is based on the low ground surface, limited population density and investments, as well as the proximity to the Sallandse Weteringen and city.

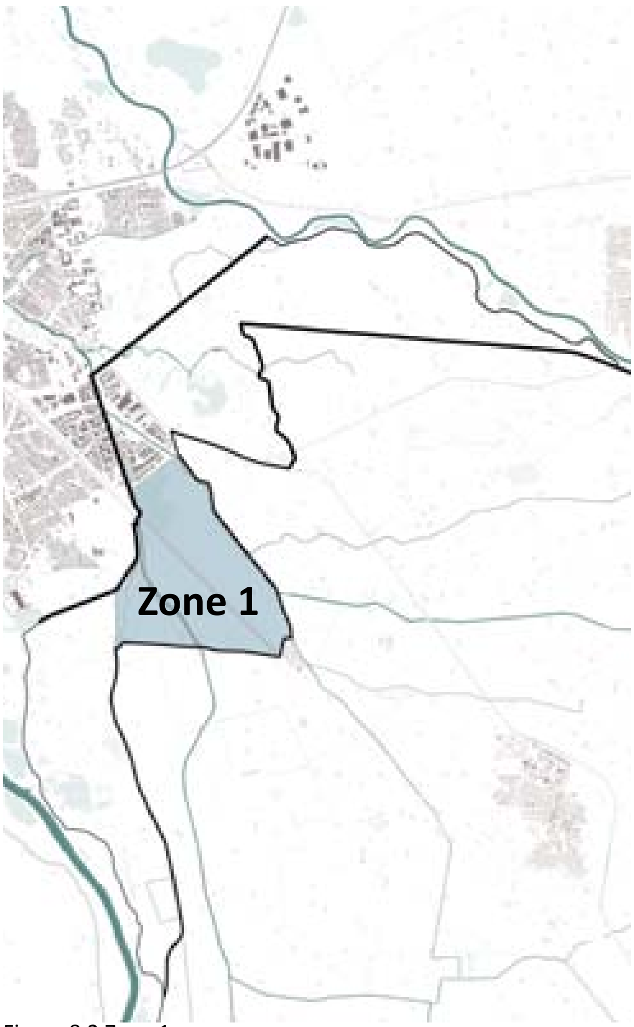


Figure 8.2 Zone 1
1:120.000

A second zone is located south of zone 1 (Figure 8.3). The compartments in this zone can be used as a buffer in case of a high discharge from the Sallandse Weteringen. How much buffer capacity is needed, depends on the discharge of the water from the Weteringen and the time that the sluice would be closed.

In extreme circumstances another zone of water buffer compartments can be used, zone 3 (Figure 8.4). These compartments are not located along the Sallandse Weteringen and would require regulated water flows from compartment to compartment.

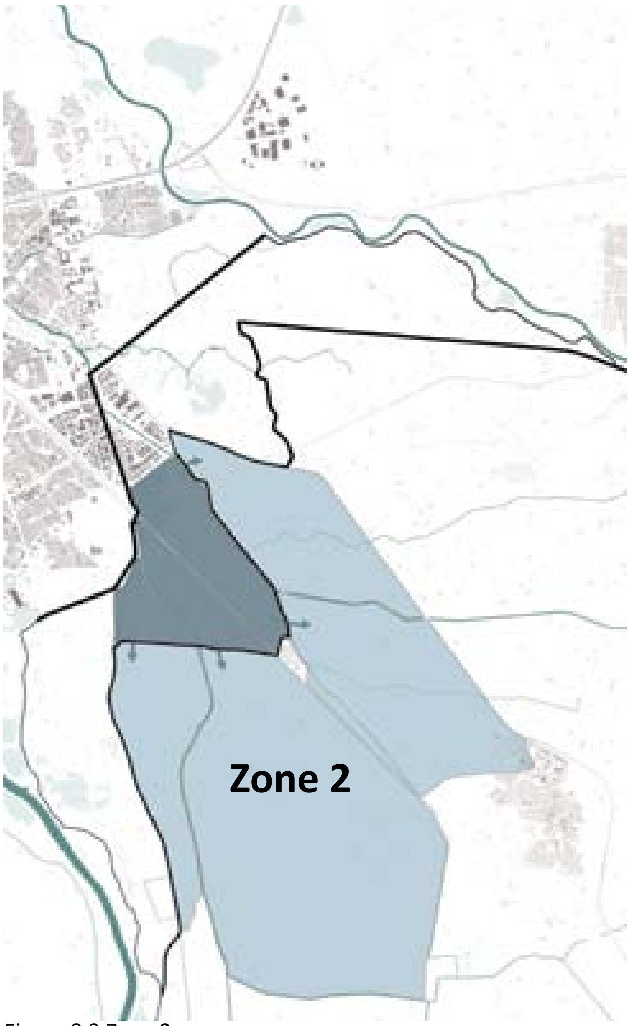


Figure 8.3 Zone 2
1:120.000

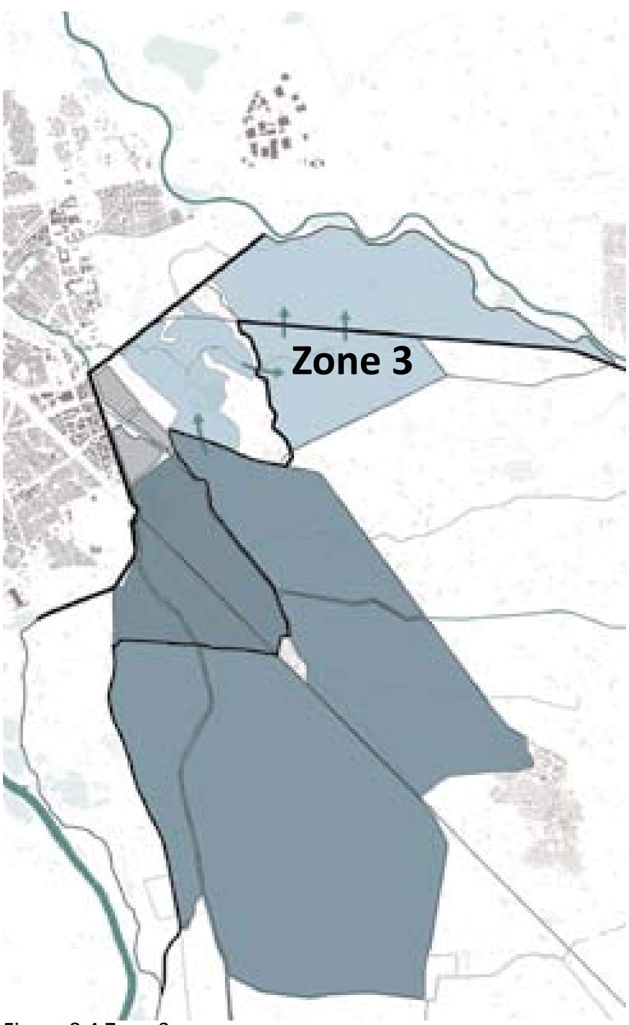


Figure 8.4 Zone 3
1:120.000

8.2 Water defence

The compartment concept also present opportunities to address challenge 2, the risk of a breach along he IJssel, Vecht or Weteringen. The compartments can buffer the water instead of letting the water flow directly into the urban environment. This way the compartments will protect the city and give time for evacuation when needed.

The compartments will prevent the water from entering the urban environment. The edges of these compartments will consist of water guiding elements existing in the landscape. These elements will be connected to each other to form a structure of line elements in the landscape with a height of at least 2 meter NAP. Near to the city the barriers will be around 3 meter NAP to prevent the water from entering the city (Figure 8.5).

Figure 8.5 Water defence structure of compartments
1:80.000

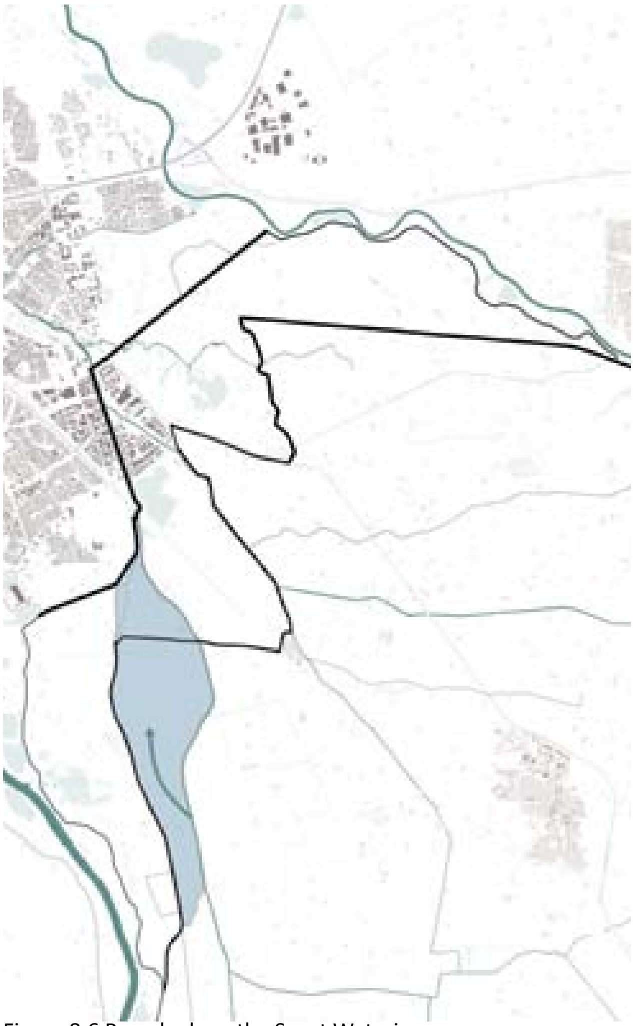


Figure 8.6 Breach along the Soest Wetering
1:120.000

Figure 8.7 Breach along the Vecht
1:120.000

Example situation 1.
In the current situation a breach along the Soest Wetering would flood the city of Zwolle, as illustrated by the flood images in the previous chapter (Figure 7.2). A structure of compartments will buffer the and decrease the consequences of the breach for the city (Figure 8.6).

Example situation 2.
Similarly, in case of a breach along the Vecht, the water will be guided from compartment to compartment, instead of entering the city (Figure 8.7). This significantly reduces the impact of the breach compared to the current situation illustrated in Figure 7.3 in chapter 7.

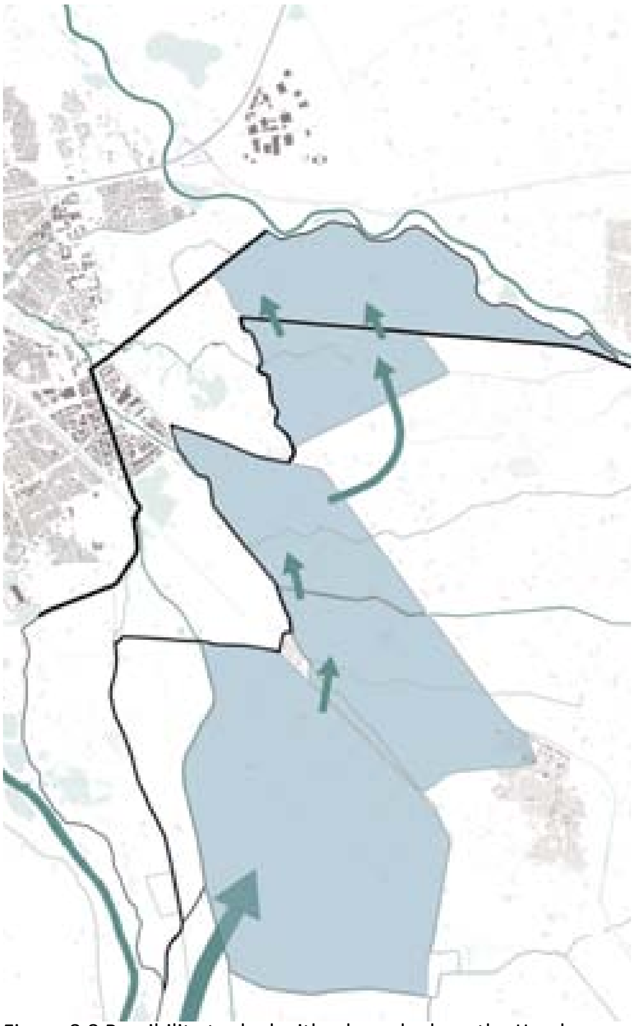


Figure 8.8 Possibility to deal with a breach along the IJssel
1:120.000

Example situation 3.

Also in case of a breach along the IJssel, water would be gathered in compartments to reduce the consequences of the breach. This can be done in different ways because of the multiple connections between compartments. In Figure 8.8 the water is guided away from the city. Meanwhile, an extra zone of compartments is kept in between the water and the city as a safety measure.

8.3 Implementation of the strategy

Several steps to implement the water strategy in the region can be identified (Figure 8.9).

Step 1. Choices
To develop a water strategy well-reasoned considerations need to be made for the water system. The analysis of the previous chapters provided arguments to chose for improving the buffer capacity of the water system near to the city.

Step 2. Selection of area
To improve the buffer capacity of the water system water buffer areas where selected based upon a few criteria:
- near to the city;
- connectivity and proximity to the Weteringen;
- low situated areas, based upon height maps;
- limited financial investments in the area.

Step 3. Making the area flood proof
The areas appointed as water buffer area need to be made flood proof. This reconsideration on the use of the area, has to be done in cooperation with all stakeholders in the area. Together with local inhabitants and users of the landscape possibilities on how to make the area flood proof need to be explored. For example, elevating houses to a safe level, and ensuring accessible roads.

Step 4. Closing the edges
The next step is to close the edges of the compartments. Existing landscape elements need to be evaluated to explore their use as compartment edges. In addition, different possibilities to close remaining edges should be considered.

Step 5. Connecting
When the entire area is flood proof and the compartments are closed, connections between the compartments and with the regional water system can be made. For every compartment the best locations should be selected for the entry and exit of water. At these places enforcement of the ground might be needed, as the force of the water can erode the ground.

Step 6. Reflection and choices
After implementing zone 1, evaluation of the process is suggested to reflect upon the need to expand the water buffer and the desired safety level in the area. In addition, input of stakeholders on the use of the landscape is needed to discuss the function of the area. If the buffer zone is frequently used, economic damage to the agricultural use should be compensated or another land use could be considered.

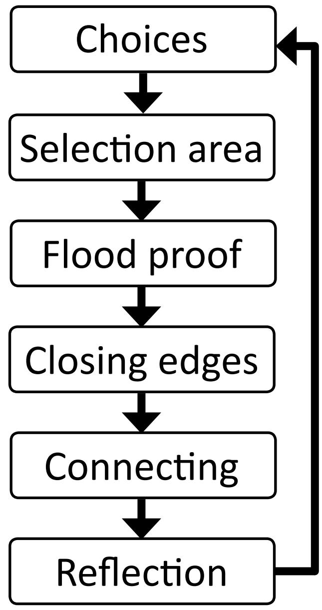


Figure 8.9 Steps in the implementation of the strategy

9. Water system calculations

9.1 Buffer capacity

The previous chapter introduced the strategy to develop a more resilient water system in the region of Zwolle. In this chapter the buffer capacity resulting from the strategy is calculated. The amount of water that can be stored in an area, the buffer capacity, depends on the surface area and the difference between the water level compared to the ground level.

Geodata is used to collect precise information regarding the surface and heights of the project area. The online catalogue of the Dutch national georegister (www.nationaalgeoregister.nl), provides access to current height data, with a grid of 5 by 5 meter. However, height maps do not visualize the landscape. Therefore, a topographical map (Top10) was used to draw the compartments based on existing water guiding elements. Based on this information, the surface of the compartments could be calculated precisely by using GIS (ArcMap 10.2.1). This resulted in the following compartment surface (Table 2).

Compartment	Hectares	Buffer capacity in m^3
1	99	1.0×10^6
2	144	2.1×10^6
3	270	3.2×10^6
4	392	5.3×10^6
5	1677	18.0×10^6
6	698	3.5×10^6
7	496	4.6×10^6
8	393	4.1×10^6
9	442	3.8×10^6
10	646	5.5×10^6

Table 2. Compartment surface and buffer capacity

To calculate the buffer capacity, a decision had to be made on the maximum height of the water level in the compartments. Based on the existing heights of the edges of the compartments, a maximum height of 2 m NAP was selected.

The next step is to calculate the amount of stored water, if the water level would be 2 meter NAP. The water depth is calculated by taking the difference between the ground level and the water level (Appendix 2. GIS calculations). This calculation using GIS is carried out for every 5 by 5 meter data point, resulting in a map that visualises the water depth for each compartment (Figure 9.2). However, the landscape also includes elements higher than 2m NAP, therefore, all data point with a landscape height above 2m NAP are excluded from the calculation.

To calculate the volume of a data point, the water depth is multiplied with the surface of the data point (5 x 5 m). To calculate the volume of a compartment, the volume of the data points within that compartment are summed up using GIS (Appendix 2. GIS calculations). This results in the buffer capacity per compartment (Table 2).

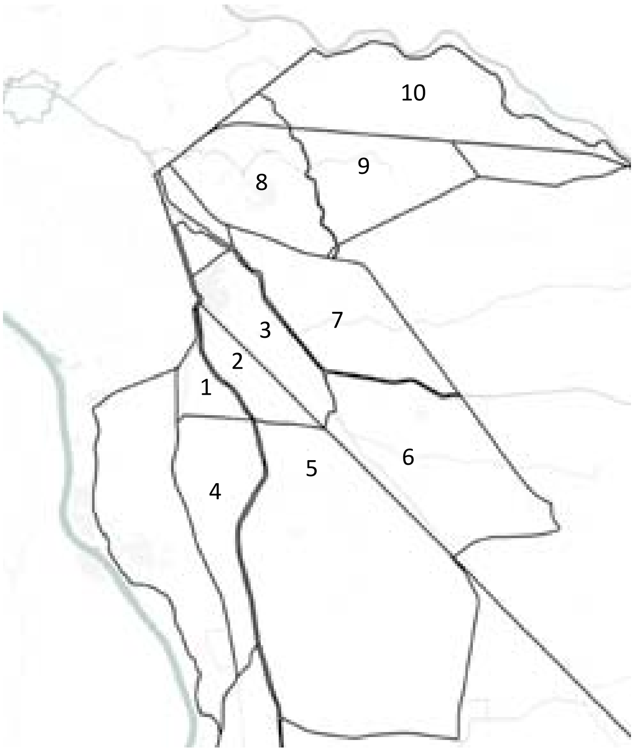


Figure 9.1 Numbered compartments

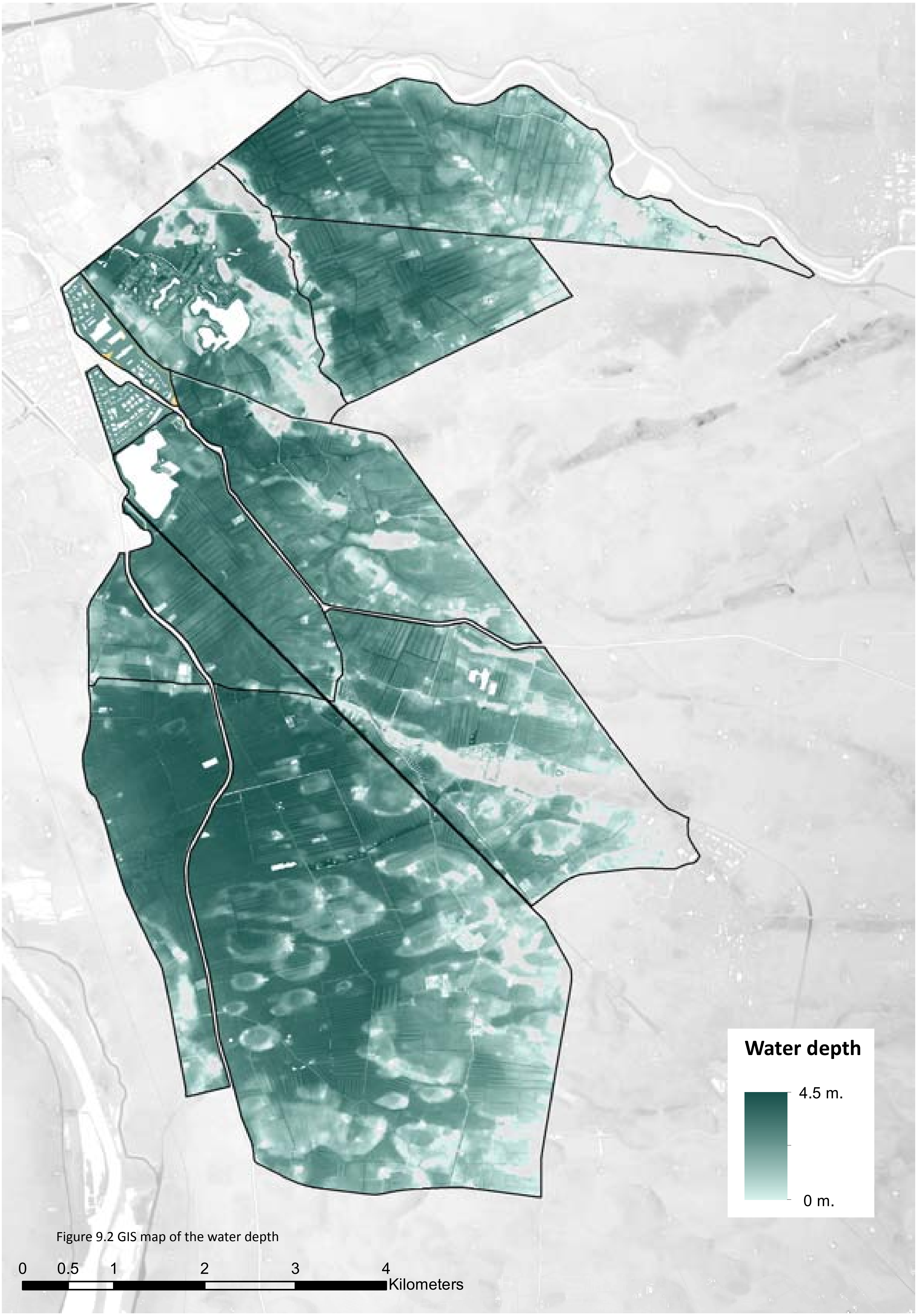


Figure 9.2 GIS map of the water depth

9.2 Discharge and time

The compartments buffer water from the Sallandse Weteringen, in case of high water on the Zwarte Water. In this paragraph, calculations of time gained by buffering in the compartments, are calculated with the water discharge from the Sallandse Weteringen, and the buffer capacity.

The discharge determines the amount of time a compartment would give. To determine the discharge, several documents were compared. The waterboard Groot Salland defined the maximum discharge of the Sallandse Weteringen as 68 m^3/s in 1998, and 75 m^3/s in 2013 (Klopstra et al., 1999; Rengers and van Rooijen, 2013). Also the recent study by H+N+S (2013) on the water strategies for the Province of Overijssel, adopted this discharge of 75 m^3/s as the maximum discharge of the Weteringen. Therefore, 75 m^3/s will be used as a starting point for the calculations in this research.

As described earlier, climate scenarios predict an increase of the water discharge between 6% and 15% by 2050. In an extreme scenario the discharge could raise with 33% by 2100 (H+N+S, 2013).

Next to the maximum discharge it is important to know the average discharge of the Weteringen. In the report of Klopstra and Vermeer (1996), an average discharge of 6 m^3/s for the Weteringen is mentioned. This average discharge could also raise by climate change with 33%, resulting in 8 m^3/s.

The discharges of the Weteringen can vary widely with averages of 6 or 8 m^3/s to extremes of 75 or 100 m^3/s. As an intermediate situation, an additional calculation was made for a discharge of 30 m^3/s. This intermediate situation was also included in calculations of Klopstra et al. (1999).

Time per buffer zone

Zone 1, consisting of three compartments, will be flooded most frequent. The buffer capacity calculated in the previous paragraph is 6.3 x 10^6 m^3. The time gain by filling a compartment, relates to the discharge of water coming from the Weteringen. Table 3 shows that in case of discharge of 6 m^3/s the three compartments of zone 1 can store water for 12 days. However, with a extreme discharge of 100 m^3/s the three compartments can only store the water for 18 hours.

This means that in a normal situation zone 1 can be considered as large enough to store water from the Weteringen until the water level of the Zwarte Water lowers. However, in case of an extreme discharge, the compartments in zone 1 would be full within 18 hours, which is assummed to be insufficient to buffer the water.

Discharge Weteringen	**Zone 1** Capacity: 6.3 x 10^6 m^3	**Zone 2** Capacity: 31.5 x 10^6 m^3	**Zone 3** Capacity: 13.4 x 10^6 m^3
Extreme climate scenario (75 m^3/s + 33% = 100 m^3/s)	18 hour	3.6 days	1.5 days
Current maximum (75 m^3/s)	24 hour	5 days	2 days
Intermediate situation (30 m^3/s)	2.4 days	12 days	5 days
Average + climate scenario (8 m^3/s + 33% = 8 m^3/s)	9 days	46 days	19 days
Current average (6 m^3/s)	12 days	61 days	26 days

Table 3. Time calculations

To buffer the water in situation of a higher discharge, more buffer capacity is needed. Therefore, additional zones are included in the strategy to function as buffer zones. Zone 2 exists of four compartments and adds at least three days extra time to store the water, in the most extreme situation (Table 3). A third zone of three compartments would add another minimum of 1.5 day storage. In the extreme situation the three zones together would give a storage time of minimum 6 days.

The calculations indicated that the compartments in zone 1 would not be suffient to deal with peak discharges from the Weteringen, and additional zones are needed. This chapter tested the compartment concept and shows the importance of having multiple zones. The compartment concept allows flexible usage and can deal with different discharges. Depending on the discharge and actual situation, different compartments can be taken into use.

10. Design

10.1 Adaptations in the landscape

The strategy to use existing landscape elements to form compartments for water buffering, requires limited adjustments in the landscape. Nevertheless, to connect existing water guiding elements, as described in chapter 7, a few crucial adaptations are needed.

Figure X, shows existing water guiding elements (in black) in the landscape, as derived from the flooding image analysis. In yellow, existing higher situated landscape elements are visualised (e.g. old dikes). The areas marked in red, are edges of the compartments that still need to be connected.

The following paragraphs will zoom into the three buffer zones to show how these adaptations could be implemented in the landscape. In the last paragraph of this chapter, the second design challenge will be addressed by presenting a water defence barrier near to the city.

Figure 10.1 Adaptations to close the edges
1:80.000

10.2 Visualising zone 1

The first adaptation is situated in zone 1. Figure 10.2 visualises the areas in need of adaptations. Adaptations include making the area flood proof (e.g. by elevating the area around existing houses and farms (Figure 10.4)), as well as connecting existing landscape elements to close the compartments (Figure 10.5). These adaptations are needed to buffer water in the area while minimizing the damage.

Making the area flood proof

The three areas in zone one are located near by the city, are low situated and near to the main waterways. The area is predominantly used as grassland due to its relatively low and wet characteristics. In this agricultural land, most of the older farms are situated already a bit higher in the landscape. To prevent flood damage to the houses in the area, their higher position can be accentuated (Figure 10.12).

Figure 10.2 Location of zone 1

Figure 10.3 Current situation zone 1

Figure 10.4 Making the area flood proof

Closing the compartments

The analysis shows two locations in zone 1 where the edges of the compartments need to be closed, to be able to use the area as water storage area (Figure 10.5). The first one is located in the Northwest of the area, along the N337. This location is crucial to prevent water from entering the city of Zwolle. Therefore, further detail of this location is presented in the next paragraph. The second location is in the southeast along the village Laag Zuthem. To close the compartment at this location, an integrated water barrier can be constructed to protect the village.

Connecting the compartments

Figure 10.6 shows where the compartments can be connected to each other. The water can go underneath the railway, through an existing tunnel and via ditches. Finally, the compartments can be connected to the water system (Figure 10.7). The figure shows multiple points along the Weteringen where the water enters the compartments. The entry points can also be used to discharge the water back to the Weteringen.

Figure 10.5 Closing the compartments

Figure 10.6 Connecting the compartments

Figure 10.7 Connecting to the water system

Visualising adaptation 1

The previous sections described the necessary adaptations in zone one. Figure 10.9 and 10.12 visualise how these adaptations in the landscape of one compartment would look like. Figure 10.9 shows the existing dikes of the Weteringen, the entry points of the water as well as elevated houses and farms in the landscape. A more recently constructed farm (on the right) is situated relatively low and will be protected by a small dike. Figure 10.12 illustrates the situation in which the area is used as water buffer.

The figures show an elevated road situated on the left, near to the forest. In the current situation this road is only partly elevated. However, to close the compartment, it should be elevated on the location shown in red in Figure 10.8. This is a crucial adaptation required to close the compartment. This elevated road is necessary to prevent the water from entering the city.

Figure 10.8. Location of adaptation 1

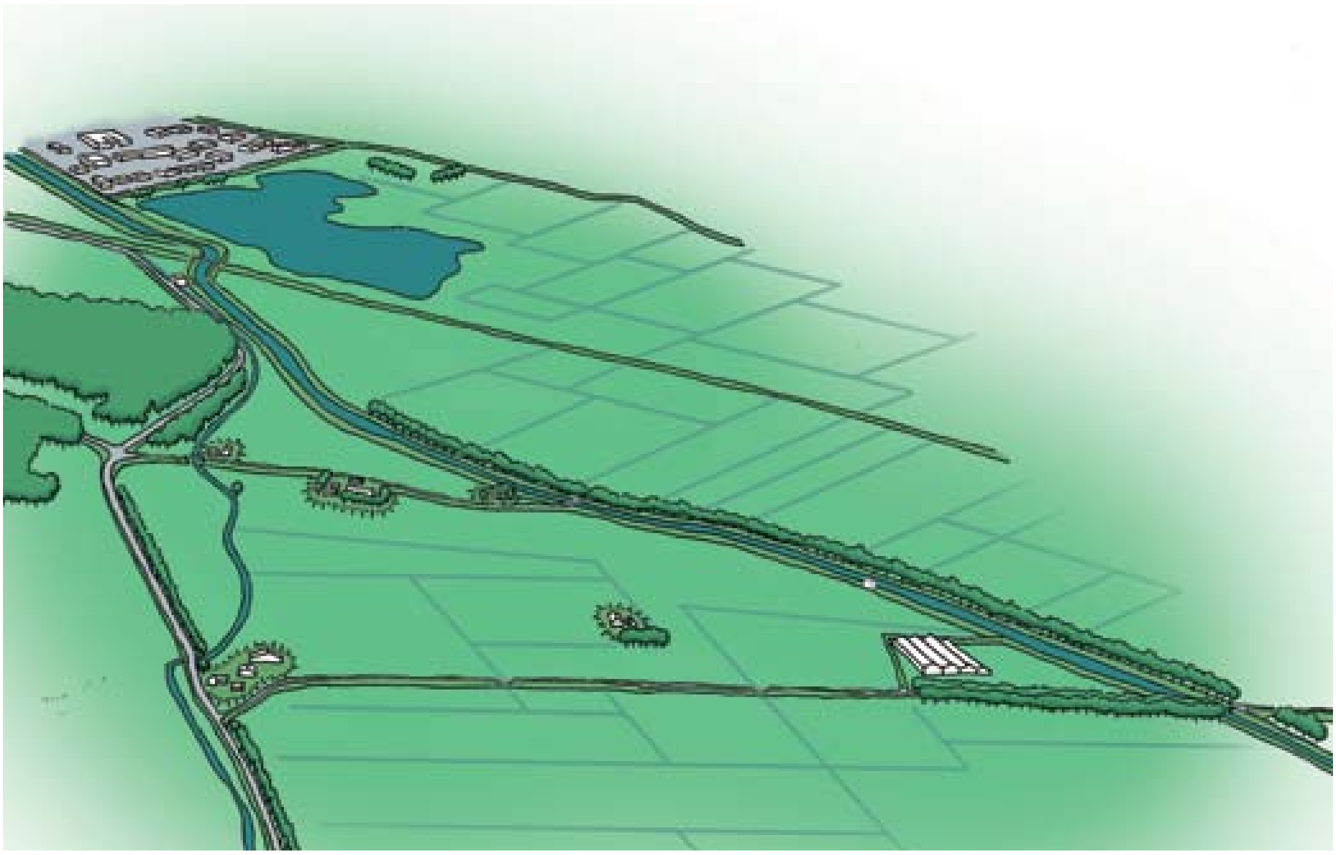


Figure 10.9 Bird's-eye view of one of the compartments in zone 1

Elevated road

In between the IJsseldijk and the crossing with the Hollewandsweg, the road (N337) is situated relatively high compared to the surrounding landscape. The height is between 2.05 and 2.35 meter above NAP, while the surrouding landscape is approximately 0 to 0.5 meter above NAP. However, after the crossing the road approaches the city and the altitude of the road lowers to ground level (Figure 10.10). This part of the road would allow the water to enter the city of Zwolle, as indicated by the flood image analysis (Chapter 7).

To protect the city against flooding and to create an compartment that is suitable as water buffer area, this part of the road needs to be elevated (Figure 10.11). This creates a connection between the high situated N337 and the dike of the Soest Wetering. By raising the road up to 3 meter above NAP, the compartment will be closed. In addition, it forms a barrier in case of a breach, and hereby protects the city. At the same time, the road can function as an evacuation road.

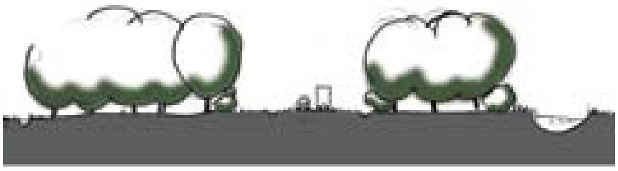


Figure 10.10. Current road
1:1000

Figure 10.11 Elevated road
1:1000

Figure 10.12. Bird's-eye view of one of the compartments in zone 1 in a flooded situation

10.3 Visualising zone 2

Similar to zone 1, zone 2 also requires adaptations in the landscape to close the compartments. The current situation, as visualised in Figure 10.13, lacks connections in the North and South of the zone (Figure 10.14).

In the North, the N35 could be elevated to close the compartment. In the South, the N337 can be connected, by making use of existing elevated landscape elements, to the dike of the Soestwetering.

Figure X shows how the four compartments in zone 2 can be connected to each other. Also the connections with zone 1 are visualised.

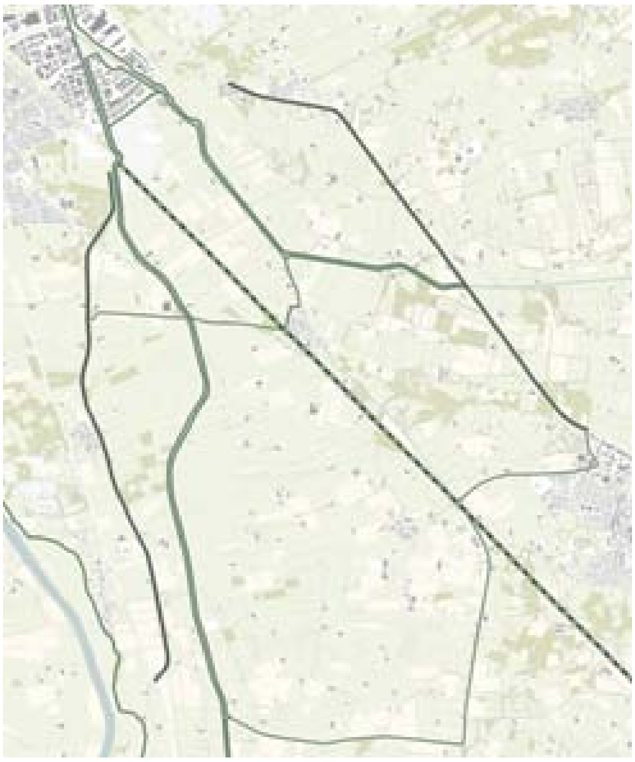


Figure 10.13 Current situation zone 2
1:100.000

Figure 10.14 Closing the edges of the compartments
1:100.000

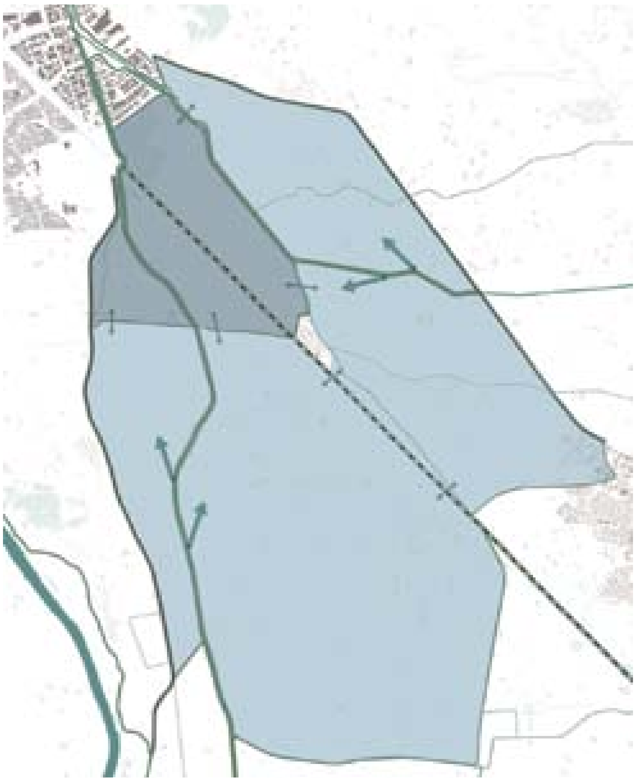


Figure 10.15 Connecting the compartments
1 1:100.000

The visualisations below illustrate the current situation, and the situation in which water would be buffered until a water level of 1 meter above NAP, or 2 meter above NAP. It shows how houses on top of old river dunes are protected from flood damage by these natural heights. These river dunes are characteristics for a specific area within zone 2.

Figure 10.16 Intersection and perspective of the current situation

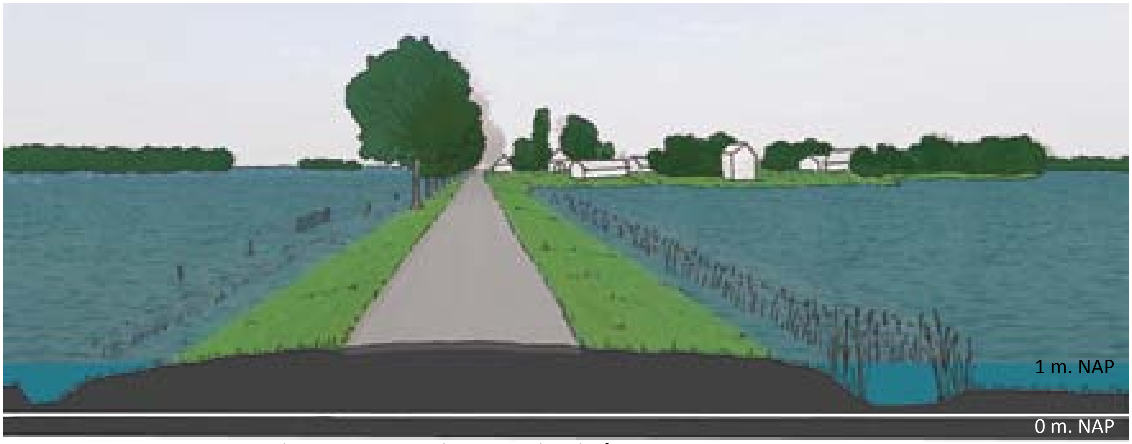


Figure 10.17 Intersection and perspective with a water level of 1 m NAP

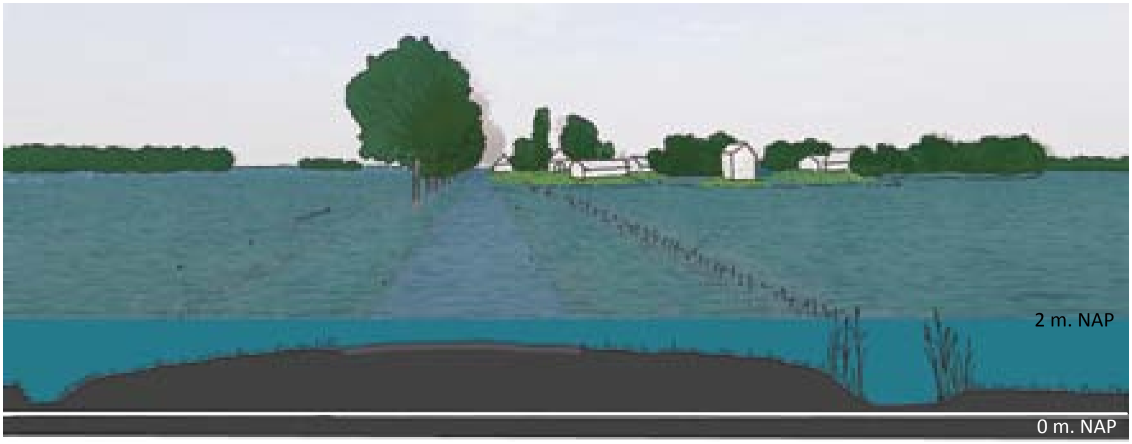


Figure 10.18 Intersection and perspective with a water level of 2 m NAP

10.4 Visualising zone 3

The current situation is given in Figure 10.19. Zone 3 requires limited adaptations to close the compartments, due to existing elevated landscape elements (Figure 10.20). Necessary adaptations include raising the entry point of a tunnel to prevent the tunnel, as well as the city, from flooding. The second adaptation is to construct a sluice underneath the railway to close the waterway.

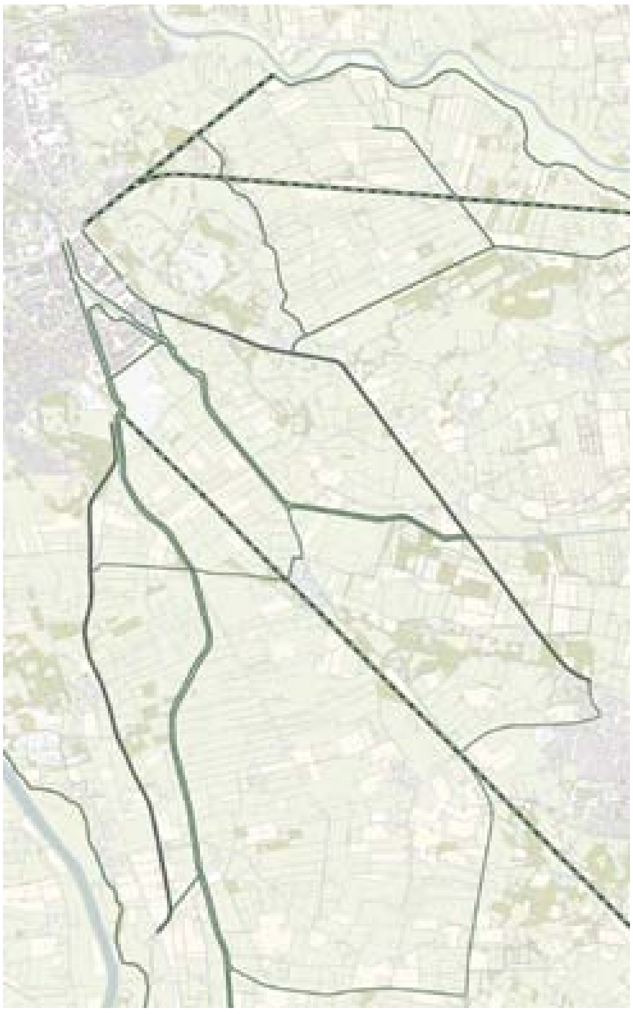


Figure 10.19 Current situation zone 3
1:100.000

Figure 10.20 Adaptations to close the compartments
1:100.000

A specific characteristic of zone 3 is that it is not connected directly to the Weteringen. Therefore, water enters via one of the compartments of zone 2 (Figure 10.21). This approach, from compartment to compartment, is limiting. To improve the redundancy of the system, another connection from zone 2 to 3 can be created by means of an emergency bypass. This bypass is not a waterway with dikes on both sides but would an area that can be flooded and hereby establish a connection between compartments (Figure 10.22).

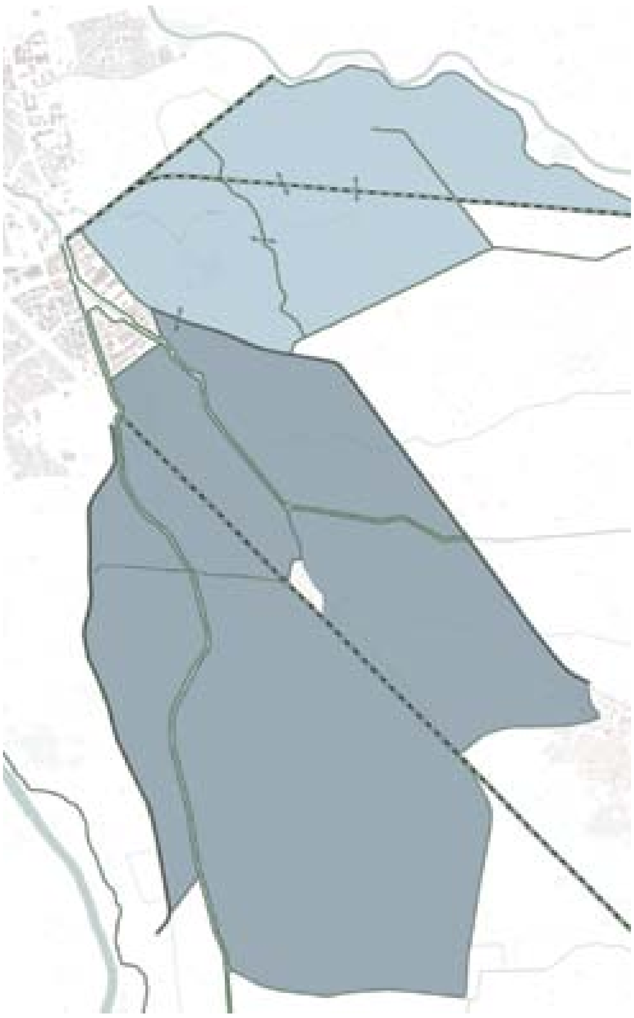


Figure 10.21 Connecting the compartments
1:100.000

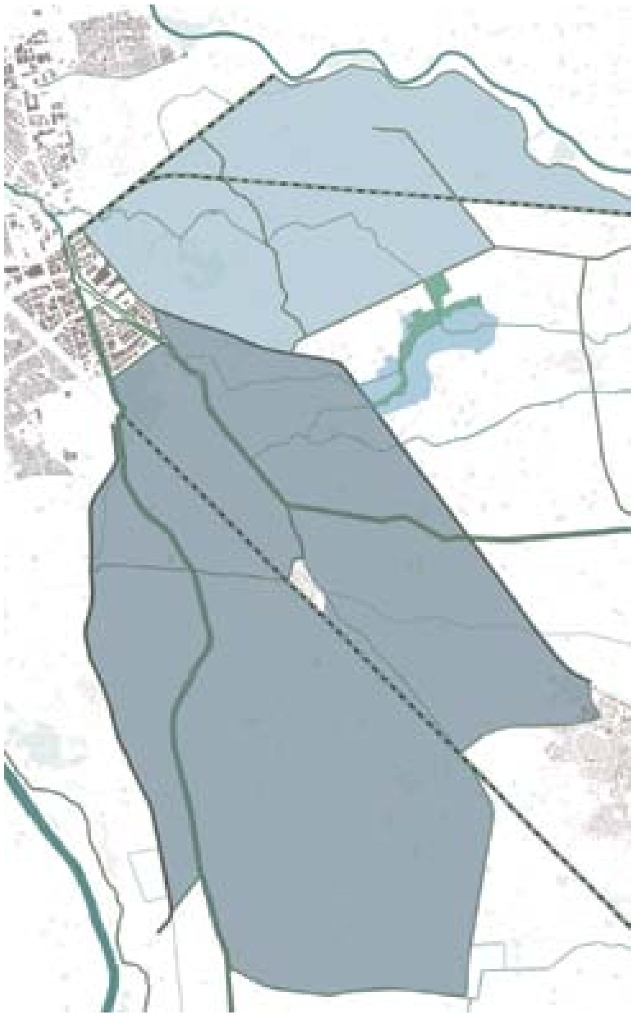


Figure 10.22 Emergency bypass to connect zone 2 with zone 3
1:100.000

Visualising emergency bypass

The emergency bypass establishes an extra connection, and improves the connectivity, redundancy and the adaptive capacity of the system (Figure 10.23). The location of this bypass is based on its relative low situation. Nevertheless, several higher areas need to be lowered to establish a connection between the compartments. This connection can form a bypass in case of the need for water buffering in zone 3 (Figure 10.31), and in case of a breach along the Vecht (Figure 10.24).

To establish a route for this emergency bypass, existing small waterways like ditches, and lowest situated areas were selected, and will be broadened (Figure 10.25a and 10.25b). A small area needs to be lowered approximately half a meter, to make ensure that the water will flow from one area to another (Figure 10.25c and 10.25d). These lowered areas will form a nature area, as visualised in Figure 27.

Figure 10.23 Emergency bypass
1:40.000

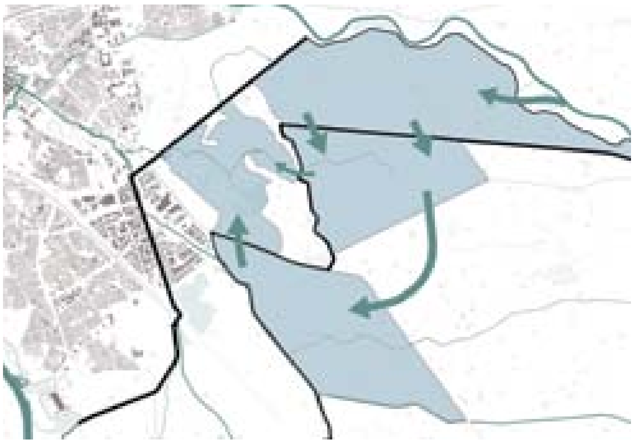


Figure 10.24 Breach along the Vecht
1:120.000

Figure 10.25a. Situation now

Figure 10.25b. Emergency bypass

Figure 10.25c. Emergency bypass flooded partly

Figure 10.25d. Emergency bypass flooded

Figure 10.26 Intersections emergency bypass
1: 5.000

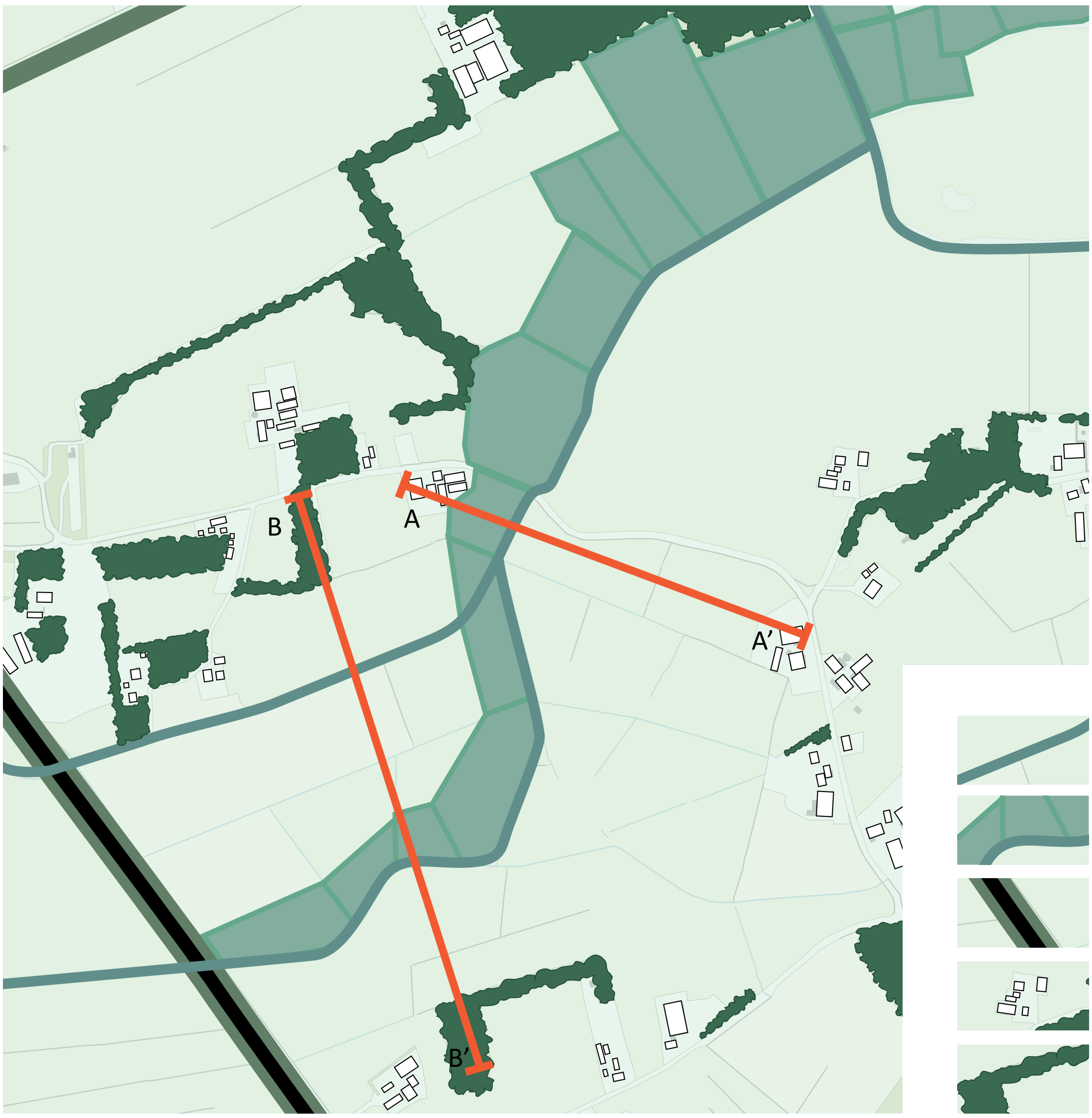


Figure 10.27 Emergency bypass
1: 10.000

Figure 10.28 Intersections emergency bypass when flooded
1: 5.000

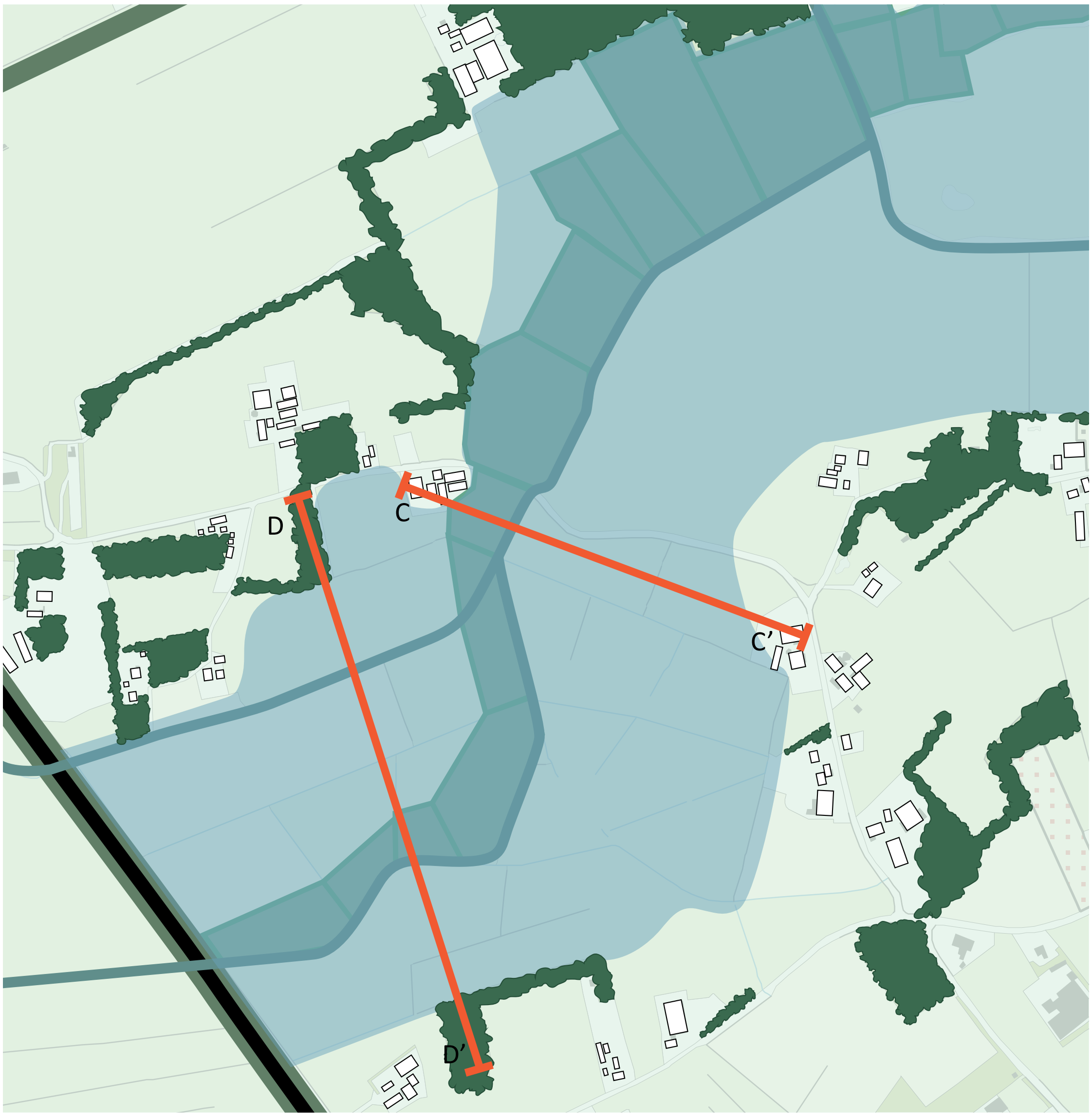


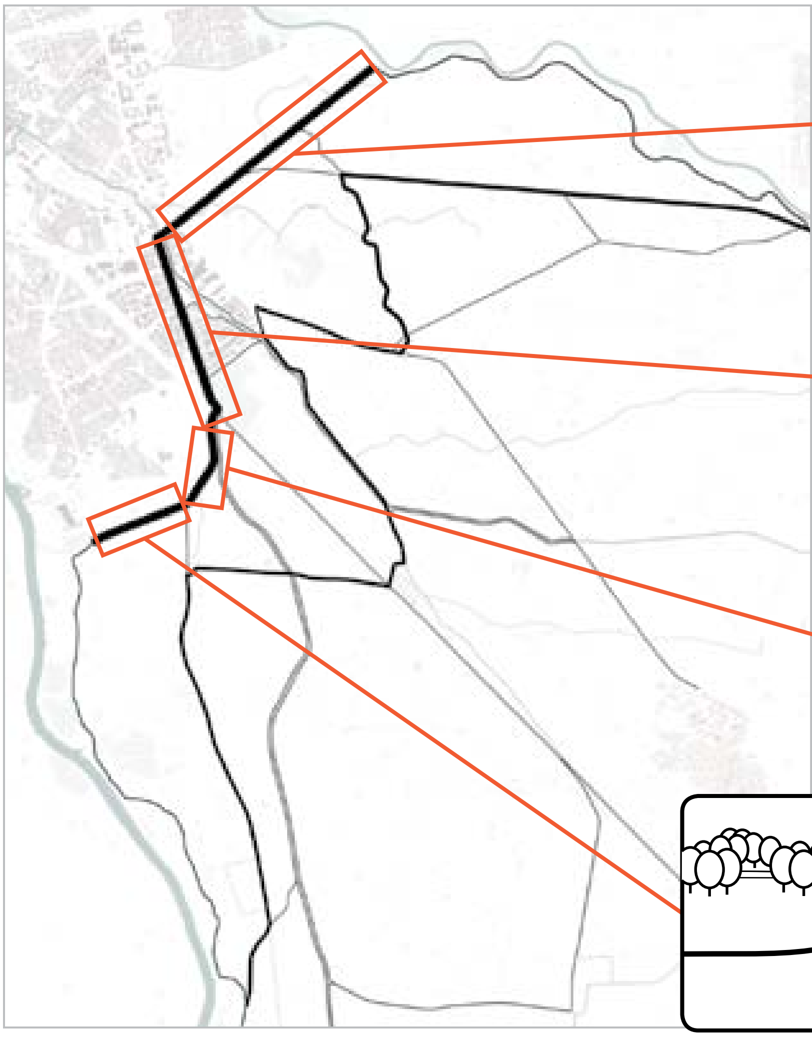
Figure 10.29 Emergency bypass when flooded
1: 10.000

Figure 10.30 Bird's-eye view of emergency bypass

Figure 10.31 Bird's-eye view of flooded emergency bypass

10.5 Water defence barrier

To address the second design challenge, related to a breach along one of the waterways, a water defence barrier is suggested. To create a closed barrier from the IJssel until the Vecht, existing landscape elements can be used. These elements include the railway from Zwolle to Meppel with a height of 3 meter NAP (Figure 10.33), and part of the Soest Wetering dike with a mean height of 2.70 NAP (Figure 10.34). Nevertheless, several adjustments are needed to create a closed barrier. This includes the earlier discussed sluice and tunnel underneath the railway. Another part of the barrier consists of the elevated road (N337) in zone 1 (Figure 10.35). The remaining connection is situated between the N337 and the IJssel dike, and is visualized in this paragraph (Figure 10.36).



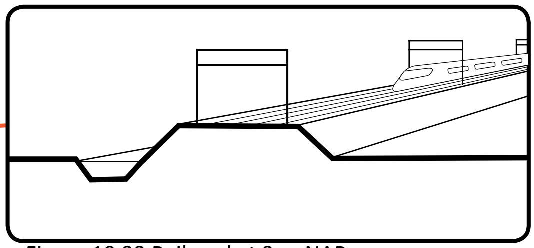


Figure 10.33 Railroad at 3m. NAP

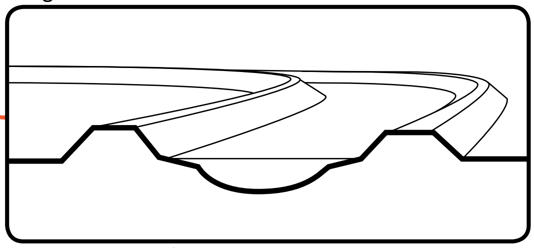


Figure 10.34 Dike Soest Wetering at 2.70 m. NAP

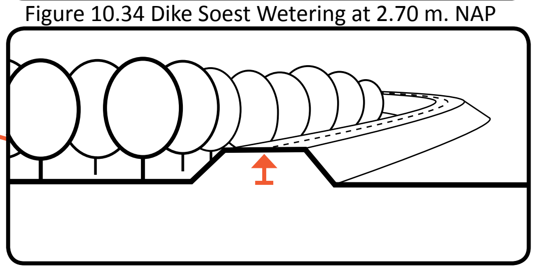


Figure 10.35 Elevated road till 3m. NAP

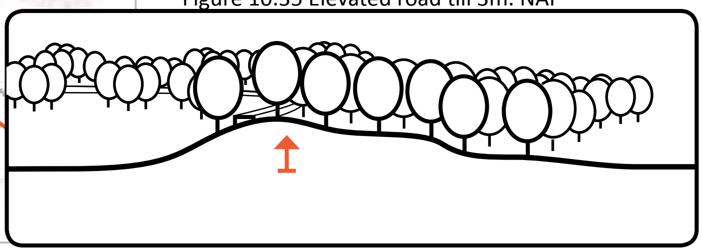


Figure 10.32 Water defence barrier and compartments

Figure 10.36 Elevated forest with a path at 3m. NAP

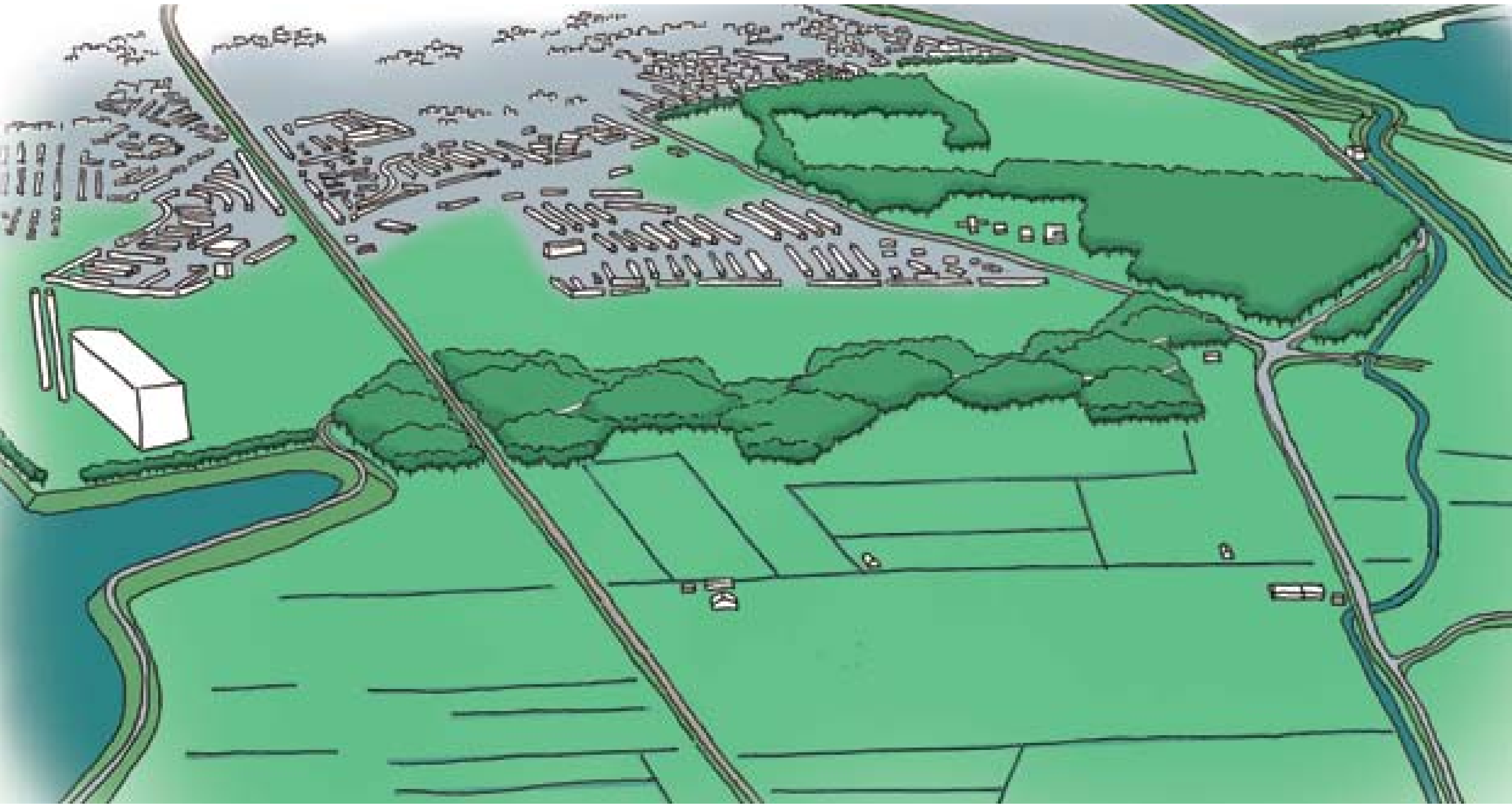


Figure 10.37 Bird's-eye view of elevated forest

Elevated path in the forest

To establish a water barrier, a connection is needed in between the N337 and the IJssel dike. This connection is constructed on agricultural land situated in a transition from a higher situation riverbank to the low situated land of the water buffer compartments. The area is located near to a neighbourhood of Zwolle, which makes it an interesting area for recreation. An existing estate is located in a nearby forest area.

Establishing a connection for the water barrier can be combined with a recreational function in the area. This can be realized by elevating the ground level into a hilly area with a height of 3 m. NAP or higher. The forest of the estate can be expanded on the elevated areas in the direction of the IJssel dike. This will result in an attractive recreational forest and a firm water defence barrier (Figure 10.37).

In the forest, the altitude of 3 meter NAP can be accentuated by creating a recreation path. This path would have a constant height level while the surrounding areas varies in height. Making visible until what height the water could come tells the story of the designed forest that protects the city against flooding (Figure 10.38).

Soil for the elevation of this area can be taken from the area in between the forest and Zwolle. This area can be lowered to function as a water retention basin to collect rain water from the city. Because of the proximity to a power plant and power lines, the area is already less suitable for various land use functions.

Figure 10.38 Visualisation of the elevated path

11. Discussion and conclusion

This research aimed to explore possibilities to improve the resilience of a water system and address climate change while decreasing flood risks through spatial adaptations in the landscape. The research aimed to answer the research question 'Can the concept of resilience provide a framework to design spatial adaptations for a climate proof water system?'

To answer this research question, a literature study provided insight in the diversity of definitions and approaches to resilience. A well accepted definition of resilience is 'the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks' (Walker, 2004). The socio-ecological perspective on resilience focuses on the integration of natural and social processes and provided a suitable perspective to address challenges in the landscape. Four key aspects to improve the resilience of a system were deducted from literature and formed a framework: diversity, modularity, connectivity and redundancy.

This framework was used to test the relevance of the concept of resilience, while designing spatial adaptations for a climate proof water system. The area of Zwolle with several water related challenges formed a suitable project area to apply the concept of resilience. Resulting in the following design question: 'Which spatial adaptations in the landscape could improve the resilience of the regional water system of Zwolle?'

To answer this design question, the characteristics and challenges of the water system in the region of Zwolle were studied. The main challenges for the water system are: to deal with peaks in the water discharge, and to decrease the flooding risk in the area. To explore which spatial adaptations could contribute to the resilience of the system, several possible solutions were compared. In the selection of possibilities the framework of resilience was used and highlighted the importance of the aspect of redundancy as a crucial aspect to address the two challenges. The redundancy is the ability of a system to maintain its function if one element of the system fails. However, the redundancy of a system can only work in coherence with the other three key aspects of resilience.

The concept of resilience provided an important input in the development of the strategy. The strategy with multiple connected compartments (connectivity and modularity) provides a flexible system that can adapt different conditions (diversity and redundancy). However, the resilience framework does not consider the consequences of a disturbance, therefore, risk as product of probability and consequences, provided an important addition to the strategy. The strategy of the compartment concept makes use of existing landscape elements to form water buffer zones to address the high peak discharge as well as the risk on breaches.

To implement the strategy in the landscape, the required spatial adaptations became apparent from the strategy, and analysis of the flood images and height map. This indicated that existing landscape elements could be used as a basis for the compartments and limited spatial adaptations were needed to compartmentalize the area. To decide upon required spatial adaptations, the compartment concept, as a strategy, provided guidance on all scale levels to make decisions for a resilient and risk reducing design.

In this study decisions on a small scale, for example how to integrate a water barrier in the landscape, were based on the strategy, knowledge of the landscape and water system, and the implications of the design. On this scale of decision-making, the resilience framework provided less guidance.

The study shows the relevance of the resilience framework in developing a strategy for a climate proof water system. The resilience approach presents opportunities to develop more adaptive and flexible water systems while embracing the diversity in land use functions (Vis et al., 2003). Whereas resilience provides an important input in developing the strategy, it does not provide clear methods or guidelines to make decision on a small scale. This is contrary to Watson & Adams (2011) who claim that resilient design principles are applicable at any scale. Resilience is an abstract term that still needs additional efforts to operationalize (Biggs et al., 2012; Anderies, 2014). Existing tools and frameworks to improve resilience lack specific design criteria, but remain rather broad design principles (Anderies, 2014). Therefore, this research concludes that resilience is especially useful in strategic planning and design on the regional level. The answer to the main research question 'Can the concept of resilience provide a framework to design spatial adaptations for a climate proof water system?' is positive. The concept of resilience can guide the design of spatial adaptations for a climate proof water system. Although the concept provides less support in designing on a smaller scale, it is a relevant framework in strategic decision making as a preparation for design.

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List of figures

Appendix 1. Consulted experts

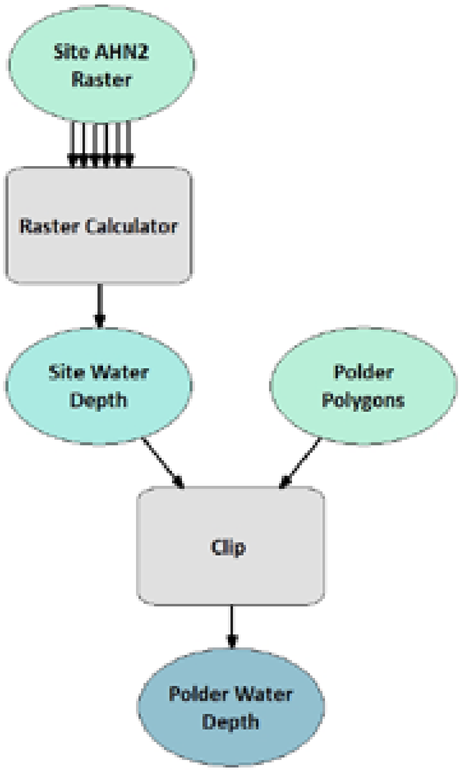
Name	Function	Organisation
Boone, P.	Head of program research by design	Alterra Wageningen UR
Heun, G.	Landscape designer	H+N+S
Luiten, E.	Government advisor on landscape and water	College van Rijksadviseurs
Raaphorst, K.	Phd researcher	Wageningen UR
Reezicht, H.	Urban designer	Bureau Maan
Searle, L. J.	Msc student GIS	Wageningen UR
Snel, H.	Urban planner	Municipality of Zwolle
van Buuren, M.	Advisor landscape architecture, research by design	Alterra Wageningen UR
van der Nat, A.	Advisor water managment and ecology	Infram
van Rooijen, A.	Advisor civil engineering	Municipality of Zwolle
van der Eijk, A.	Urban designer	Bureau Maan
Willemsen, M.	Landscape architect	Strootman landscape architects

Appendix 2. GIS calculations

Polder Water Depth Calculation

Input Datasets: AHN2 raster, Polder polygons

Output Datasets: Water Depth raster per Polder



First the water depth per pixel for the whole site is calculated using the Raster Calculator tool. This is derived from a given maximum water height of 2 metres above sea level, and using the AHN2 ground height raster at a 5 metre resolution. Next, the calculated water depth raster is separately clipped to the extent of each polder polygon using the Clip tool. The given conditions for this calculation are:

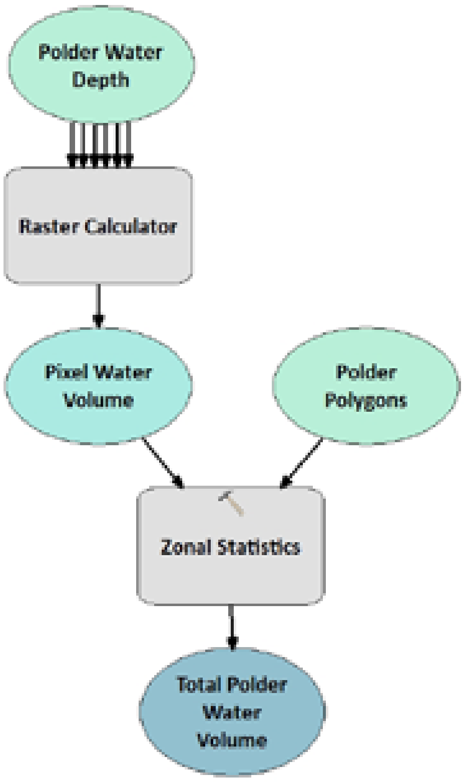
- If the ground height is greater than 2 metres, then the water depth is zero.
- If the ground height is below 2 and greater than 0 metres, then the water depth is 2 minus the ground height.
- If the ground height is below 0 metres, then the water depth is 2 plus the absolute value of the ground height.

The conditional statement for this calculation is:
Con(“%ahn2_5.%” > 2, 0, Con((“%ahn2_5.%” >= 0) & (“%ahn2_5.%” <= 2), 2 - “%ahn2_5.%”, Con(“%ahn2_5.%” < 0, 2 + Abs(“%ahn2_5.%”))))

Polder Water Volume Calculation

Input Datasets: Water Depth raster per Polder.

Output Datasets: Total Water Volume per Polder



First the water volume per pixel for each polder is calculated using the Raster Calculator tool. The water volume is derived by multiplying the pixel values in the Water Depth dataset by the 25 metre surface area of each pixel. Lastly, the total water volume for each polder is calculated using the Zonal Statistics tool. This sums the water volume pixel values within the extent of each polder, to give a final table of numerical results.