Spatial planning & Flood risk

Development of a spatial planning framework for the mitigation of flood risks

O.S. Bakker (S1935291)
Supervisors:
Dr. Ir. M.J. Booij (University of Twente)
Dr. Ir. A. Bomers (University of Twente)
Ir. R.J.M. Huting (Royal HaskoningDHV)
Ir. S.G. Westerhof (Royal HaskoningDHV)
Ir. M.C.J. Van den Berg (Royal HaskoningDHV)

Date: 9-8-2022

Royal HaskoningDHV
Enhancing Society Together

Preface

This thesis marks the end of my master Civil Engineering and Management at the University of Twente. I would like to thank my friends and family for the wonderful time here in Twente and for all their support and distraction during the study, which really made a difference. I really did enjoy my study and my time here in Twente to the fullest. Furthermore, I would also like to extend my gratitude to all my supervisors.

First, I would like to thank my daily supervisors at Royal HaskoningDHV for their guidance and support during the thesis. The feedback, enthusiasm and knowledge of Marcel, Sam and Ric helped me tremendously during the thesis and was an important source of inspiration for this study. Also, I'm very grateful for the opportunity they provided me to do this study in the first place. I would also like to thank all my colleagues at Royal HaskoningDHV, who were always willing to help me out, and who provided a welcoming working environment. A special mention should be made of my Royal HaskoningDHV colleague and fellow student Niek, who made the long train journeys to Amersfoort much more entertaining.

Furthermore, I would like to thank UT supervisors Martijn and Anouk. Over the course of the master thesis, they helped me hugely by keeping me focused with their sharp-cut feedback, assisted me with academic writing and providing valuable ideas.

I hope that you will enjoy reading this thesis report and acquire new knowledge and insights.

Hengelo, July 2022

Summary

Due to large housing shortages in the Netherlands, large scale housing projects are planned across the country, with plans to build up to 1 million new houses till 2030. Most of those new houses are planned in areas that are at risk of flooding, which has several negative consequences. The arrival of new inhabitants and new spatial structures increases the severity of flood events, leading to extra flood risk. The last effect is directly related to the introduction of the new Dutch flood safety system for primary flood defences in 2017. This system is based on the computation of the most stringent flood safety standard from three flood risk criteria: the social cost benefit analysis (SCBA), the local individual risk (LIR) and the group risk (GR). The SCBA flood safety standard is based on an economic optimum between expected flood damage and the expected costs to improve flood defences. Thus, the construction of new spatial structures behind the dikes is of direct influence on the strictness of flood safety standards and the total flood risk. Therefore, this study aims to research whether it is possible to develop and test an effective spatial planning framework. The aim of this spatial planning framework is to consider flood risk in a certain area and adjust the current spatial planning, to minimize increases in flood risk associated with new spatial developments.

The study used three dike ring areas as case studies. First, the impact of current spatial planning on the flood risk and financial flood damage for case study 1 was quantified. This was done using the SSM2017 (*damage and casualty module*) model for the computation of financial flood damage and (fatal) flood casualties. All new residences and industrial objects planned in the period 2021-2030 were implemented in the damage model. The results showed that following the official spatial planning for the next decade leads to a significant increase in flood risk for case study 1. Similarly, large increases in financial flood damage were computed in case study 1. Next was the development of the spatial planning framework. The spatial planning framework considers four damage categories: family homes, apartments, industrial objects, and casualties. Two versions of the spatial planning framework were made: a basic and an extended version, where the latter version also included flood probability. Both framework versions were applied to case study 1. The results of the framework application showed that both versions of the framework were very effective in the reduction of financial flood damage related to new spatial developments compared to the financial flood damage and flood risk computed based on the official spatial planning.

The third and final step was to apply the extended framework to case studies 2 and 3. The choice for the extended spatial framework was made because the validation results showed that the extended framework has the same financial flood damage reduction capability as the basic framework, while including the element of flood probability, which is relevant for the computation of flood risk. Application of the framework led to significant decreases in financial flood damage for both case studies, although on a different scale. The main conclusion of the study is that it is possible to develop in a well-structured manner an effective spatial planning framework that can decrease flood risk for different types of spatial objects in different dike ring areas. The effectivity of the spatial planning framework highly depends on the spatial scale at which the framework is used: increasing the area within which spatial structures can be relocated leads to larger reductions in flood risk and damage compared to use of the framework within smaller areas. Furthermore, the dominant flood type is also important: the framework leads to higher flood risk reductions in dike ring areas which have a more varied flood type compared to dike ring areas that have a uniform flood type pattern. It is recommended to integrate a cost-benefit component into the framework, with which it can be determined whether the reduction in flood risk is worth the extra costs in utilities and infrastructure for housing relocated further away from existing population centres.

Glossary of terms

Term	Definition
Dike ring area	An area protected by dikes, dunes and hydraulic structures from the threat of water, which often surround the complete dike ring area
Dike ring section/Section	A certain part of a dike ring area for which the origin of flood hazards and the flood consequences are roughly similar, and for which a single flood safety standard is determined (Kok et al., 2017)
Breach location	Location of dike breach
Dike ring segment	Segment of a dike ring area for which the flood consequences (damage and casualties) are similar regardless of the specific location of dike breach within that dike ring segment (Projectbureau VNK2, 2011)
Flood safety standard	Legal requirement for the level of flood safety that should be provided by all the flood defenses belonging to a certain dike ring section
Alert standard	The flood safety standard that accounts for the gradual loss in strength of flood defenses over time. Exceedance (which is allowed) of the alert standard signal to authorities that preparations for dike reinforcement should be undertaken. Two times more stringent than the lower limit standard (Slootjes & Van der Most, 2016a)
Lower limit standard	The flood safety standard that legally cannot be exceeded in any case, providing the minimum level of flood safety for Dutch citizens (Slootjes & Van der Most, 2016a)
Flood scenario	A flood scenario describes how a flood event takes places defined by flood characteristics as breach location, water rise rate and maximum inundation depth (Projectbureau VNK2, 2011)
Fatalities	Individuals who die because of a flood event
Affected persons	Individuals affected by a flood event
Test level (TL)	Water level used for the assessment of flood defenses
Test level + 1 decimal height (TL + 1D)	Water level return period with a return period that is a factor of 10 higher than the test level (TL)
Decimal height (flood defense crest level)	The decimal height is the increase in dike crest level for which the annual flood probability decreases tenfold (Slootjes & Van der Most, 2016a). Raising a flood defense that has an annual flood probability 1/1000 with one decimal height reduces the flood probability to 1/10,000.

Brownfield projects	Locations for new spatial development within existing built environment
Greenfield projects	Locations for new spatial developments outside the existing built environment

Table of contents

Table of figures

Table of tables

1. Introduction

1.1. Background

The Netherlands has been at the forefront in the struggle against water for centuries. Ever since the first arrival of humans in what later became the Netherlands people had to deal with frequent floods, which was aptly described by the Roman writer Pliny in the 1st century: "*More people have died here in the struggle against water than in the struggle against men*" (Lendering, 2020). The vulnerability of the Netherlands to flooding is related to its geographical location as a low-lying delta at the confluence of several major river systems. Over the centuries, an effective system of flood defenses has been developed. This flood defense system defends the Netherlands from the threat it faces from the North Sea and the main rivers. The flood defense system consists of an elaborate network of dikes, dunes, and hydraulic structures. The current system for flood safety has its origin in the dramatic flood event of 1953, which caused large numbers of casualties and enormous material losses. As a reaction, a nationwide system of flood safety standards was set up in the 1960's (Kabat et al., 2009). This system of flood safety standards was based on the exceedance probability of design peak water levels that a certain flood defense system must be able to withstand (Figure 1a). Each dike ring area had one uniform flood safety standard, defined by this exceedance probability. This system was replaced by a new, legally binding risk-based approach to flood safety in 2017.

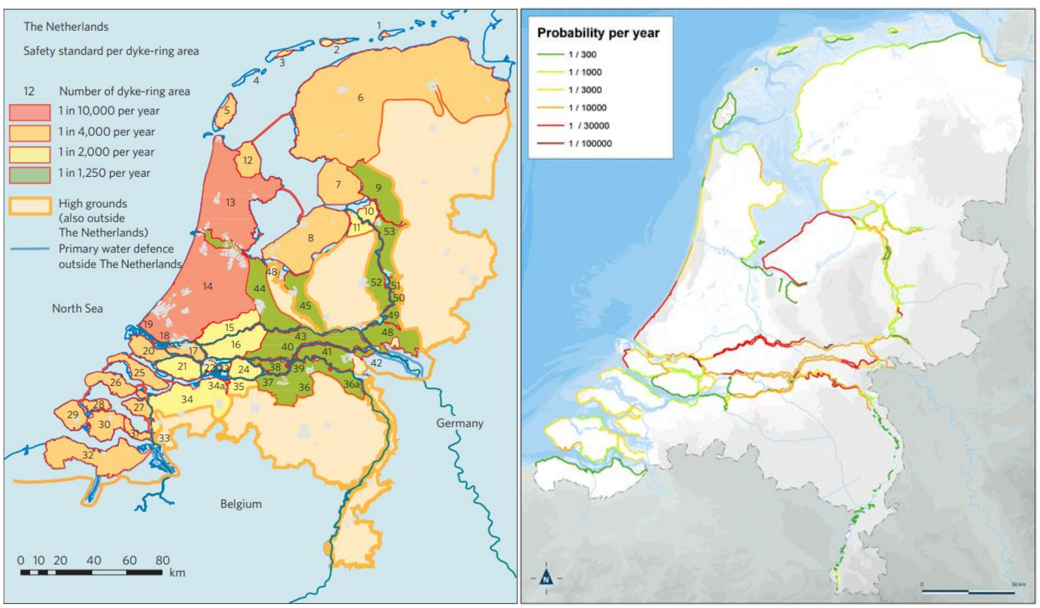

Figure 1: A) System of flood safety standards before 2017 (Hillen et al., 2010) B) Risk-based flood safety standards after 2017 (Kabat et al., 2009)

The current risk-based approach to flood safety defines the flood safety standards using the flood probability of flood defenses, as opposed to the use of the exceedance probability (Van der Most & Nijenhuis, 2019). The exceedance probability is the probability that the burden on a flood defense structure exerted by water exceeds the strength of the flood defense. However, computation of the flood probability is only a part of the flood safety standard determination process, which relies on the concept of flood risk. The concept of flood risk is an important element in the current flood protection system with regards to the computation and determination of flood safety standards for the Dutch flood defenses (Van der Most & Nijenhuis, 2019). Flood risk is defined as probability times consequence.

The flood probability is defined as the probability of occurrence of a certain flood scenario, considering the probability of occurrence of all dike failure mechanisms for a certain section of flood defenses (Projectbureau VNK2, 2011). The flood consequences are integrated into the Dutch system of flood safety by means of flood risk criteria (Van der Most & Nijenhuis, 2019). The flood risk criteria are legally binding requirements for flood safety. There are three flood risk criteria: the local individual risk (LIR), the group risk (GR) and the social cost benefit analysis (SCBA).

The LIR flood risk criterion describes a requirement for the maximum allowable level of flood risk to be faced by each Dutch citizen living behind flood defenses. The LIR criterion obliges that the maximum flood risk faced by any individual cannot exceed the probability of 1/100,000 per year (Slootjes & Van der Most, 2016a). The SCBA flood risk criterion is the requirement for economic efficiency in flood safety management. Practically, it means that the SCBA determines an economic cost-benefit optimum between the expected financial flood damage and the expected required costs of dike reinforcement (Van der Most & Nijenhuis, 2019). The expected financial flood damage costs depend on the number of people and the number and worth of economic assets in the inundated area (Kind et al., 2011). Flood casualties, both flood fatalities and flood victims are monetized as part of the SCBA. Damage to economic assets consists of both material damage and indirect damage, for example due to the interruption of commercial activities and infrastructure (Kind et al., 2011).

The flood safety standards are computed for both the SCBA and LIR, for one dike ring section. Each dike ring area has been divided into one or more dike ring sections, in which the flood hazards (most likely dike failure mechanism) and the flood consequences are similar (Kok et al., 2017) (Figure 1b). The most stringent flood safety standard as computed from those two flood risk criteria is the normative flood safety standard for that dike ring section. The computed flood safety standard is aggregated into one of the six flood safety standard classes, that range from 1/300 to 1/100,000 year (Slootjes & Van der Most, 2016a). No flood safety standard is computed for the group risk criterion. The group risk criterion considers the probability of flood events with large numbers of casualties. The group risk criterion serves as an aggravating factor: if expert judgement deems the group risk to be considerably large compared to the LIR/SCBA derived flood safety standards, the minister for infrastructure and water management can decide to set the LIR/SCBA flood safety standard one safety class higher (Slootjes & Van der Most, 2016a). Two different types of flood safety classes are in use: the alert standard and the lower limit standard (Slootjes & Van der Most, 2016a). The alert standard is used to consider the gradual loss in flood defense strength over time. Exceedance of the alert standard signals the authorities that preparations must be made for dike reinforcement soon. Its exceedance is not a problem per se, as it was considered that there is a long(er) period between exceedance of the alert standard and the commencement of dike reinforcement. The lower limit standard is two times more stringent than the alert standard.

New (spatial) developments in the number and value of economic assets in a dike ring area are of direct influence on the SCBA criterion, especially with regards to housing. Housing has not been mentioned without reason, as one of the most pressing issues of the last years in the Netherlands is the severe shortage of available and affordable housing. As of 2022, there is an estimated housing shortage of more than 279,000 houses according to a study by Groenemeijer et al. (2021). This housing shortage is expected to increase in the coming years, with a projected shortage of up to 420,000 houses in 2025. Because the population is projected to increase in the next decade towards 18 million and the size of the average household decreases, the need for housing will only increase in the coming decade (Groenemeijer et al., 2021). To counter these housing shortages, plans have been drawn up for the largescale construction of new houses. The Dutch Ministry of the Interior announced in a letter to the Delta commissioner that about 1 million new houses must be build towards 2030 to accommodate the demand for housing and tackle the existing housing shortages (van Kempen & Slootmaker, 2021).

1.2. Problem context

An important challenge in the realization of 1 million new houses is where to build these new houses and other forms of spatial structures and objects associated with them. The enormous demand for new housing is not the only issue in the Dutch spatial planning agenda, leading to competing interests. The Dutch spatial planning strategy with respect to new spatial development has to consider different, competing interests: affordable housing, flood protection, agriculture, climate adaptation, commercial and industrial activities, nature, and recreation (Rijksoverheid, 2022). One interest that is generally not considered during spatial planning is flood risk: according to Glas (2021), an estimated 820.000 of 1 million planned houses are planned in flood-prone areas. A telling example of this are current plans for 8000 new houses in the Zuidplaspolder, the lowest polder of the Netherlands at -6.74 m + NAP (Schoorel, 2021). Planning new spatial developments in flood-prone areas leads to several problems: new spatial development increases the number of inhabitants and raises the economic value of an area. This increases the consequences of a potential flood event and might affect the SCBA flood safety standards, leading to more stringent standards. The current choices for spatial development in one area could lead to higher flood risks and higher investments in flood protection and climate adaptation measures in the long-term.

This disregard of flood risk in the spatial planning process can be attributed to the lack of integration between flood safety management and Dutch spatial planning (Van Kempen & Slootmaker, 2021). The Dutch governmental bodies that are responsible for spatial planning have no integrated strategy for the inclusion of flood risk as a criterion for the choice of locations for new spatial developments (Neuvel & Van den Brink, 2009). The need for new housing tends to overrule all other spatial interests. Neuvel & Van den Brink (2009) state that there are examples of Dutch spatial planning authorities including flood risk as a factor for spatial planning, but these are on an incidental basis. As a result, many spatial developments will be planned in areas where the flood risk is high, and the potential consequences of a flood event are large.

Thus, the main problem is that currently, there exists no instrument or study that effectively considers and quantifies the effects of choosing certain locations for new spatial developments on flood risks and at the same time offers alternative locations that would lead to a reduction in additional flood risks.

1.3. Current knowledge and research gap

The current knowledge base on the connection between new spatial developments, spatial planning and (future) flood risks is rather limited. A few studies have investigated the effects of new spatial developments on flood risk. One of these studies is by de Bruijn et al. (2019). De Bruijn et al. (2019) did research on the influence of new spatial developments on the strictness of SCBA flood safety standards. They stated that the impact of new spatial developments on the strictness of safety standards varies considerably per dike ring section, depending on the scale of the value of economic assets currently present. De Bruijn et al. (2019) concluded that for some dike ring sections with a normative LIR flood safety standard, even an increase of 300% in the number of houses would not lead to a change in flood safety standard class. De Bruijn et al. (2019) explicitly states that although the flood safety standards are relatively robust, new spatial developments do significantly increase the flood risks in an area. This conclusion is supported by Klijn et al. (2015), who state that based on a number of performed flooding simulations for representative polder areas, economic flood risk for the Netherlands could increase by a factor 1.7 in 2050 with respect to 2008 due to increased inundation depth and flood extent alone.

More detailed are the studies by Bouwer et al. (2010) and Mustafa et al. (2018). Mustafa et al. (2018) assessed the effects of spatial planning on future flood risks. For that purpose, 24 different urbanization scenarios were formulated. The scenarios were divided in 2 categories: densification (i.e. increasing concentration of spatial developments) and expansion (i.e. the expansion of urbanization into rural areas). The scenarios further specified the urbanization rate for each of the categories: high, medium, or low. These urbanization scenarios were implemented in damage models for the computation of the financial flood damages. Bouwer et al. (2010) evaluated future flood risks in a similar way, by means of devising four scenarios for different levels of socio-economic and physical development for dike ring area 35. The four scenarios were defined based on different assumptions for population and economic growth. A model was used to create land-use maps based on these scenarios, which were consequently used to assess financial flood damage for a limited selection of flood scenarios.

Only one paper discussed and developed a framework for flood risks and spatial planning: Pieterse et al. (2009). Pieterse et al. (2009) developed a conceptual flood risk framework, for which they introduced the concept of flood risk zoning. According to Pieterse et al. (2009), flood risk zoning is a method to differentiate areas based on flood risk and classify them into different flood risk zones. Flood risk zones are defined as areas where the level and nature of flood risk is roughly similar. The flood risk zones were classified based on the flood characteristics inundation depth and flood arrival. The inundation depths were divided in three classes: low (<0.5 m), medium (0.5 – 2 m) and deep (>2 m). The flood arrival time was either slow (>9 hours) or fast (< 9 hours). The expected damage for each flood risk zone was defined by casualty and flood damage risk, defined as either small, moderate, or large. For each flood risk zone, a set of spatial measures was worked out, with the aim to reduce the flood risks for both the planned and existing built environment. The spatial measures are not specified in the framework. Instead, Pieterse et al. (2009) only indicated the extent of the spatial measures: national, regional, or local.

Thus, it can be concluded that no study has yet attempted to reduce flood risk for planned spatial developments through the assessment of current flood risks and allocation of alternative locations. The flood risk framework by Pieterse et al. (2009) for example did not try to quantify the flood risk reduction effectiveness of the framework for new spatial structures. Furthermore, the framework did not include the rise rate of water, which is acknowledged by Slager & Wagenaar (2017) as one of the most important factors influencing mortality rates during flooding. For its expectations about the level of material flood damage that could occur at a given inundation depth, it relied on a rather coarse assessment of a 'number' of damage functions from the old SSM2005 (Dutch abbreviation for *damage- and casualty module*) model. Pieterse et al. (2009) considered two types of material damage: damage to vital and non-vital objects. Damage to non-vital objects such as housing and industry are not separately classified, even though Pieterse et al. (2009) themselves acknowledged that the vulnerability of different types of objects can vary considerably. Although both Mustafa et al. (2018) and Bouwer et al. (2010) quantified future flood risks, they did only so based on artificial spatial development scenarios rather than official spatial planning. As was the case for Pieterse et al. (2009), both studies did not attempt to assess their respective study areas for more suitable spatial development locations in relation to flood risks.

1.4. Research goal & questions

The main research aim is formulated as follows:

"*The aim is twofold: (1) to develop a spatial planning framework for the mitigation of flood risks associated with new spatial developments, and (2) to test whether this framework can also be used for flood risk mitigation in dike ring areas with different flood types and surface areas*"

The main research aim is supported by three research questions. These three research questions are connected to three main steps. The first part of the thesis consists of implementing an existing plan for new spatial developments in a damage and casualty model for case study 1. This is followed by a damage and casualty analysis of the casualty and damage model results. The following first research question belongs to this step:

1. What is the impact of the current plans for new spatial developments on flood risks?

The second part of the thesis is to develop the spatial planning framework and validate it with the first case study. The results from the first research question are used to analyse the effectiveness of the spatial planning framework in mitigating flood risks for the first case study:

2. According to what specifications can a spatial planning framework be developed?

The final part of the thesis deals with the question whether the developed spatial planning framework can be applied to other case studies for the mitigation of flood risks. The objective of this research question is to analyse whether a spatial planning framework that is developed and validated for one case study can be applied effectively for other case studies as well:

3. What is the impact of the spatial planning framework on flood risks associated with new spatial developments for different case studies?

1.5. Research scope

The research scope defines the boundaries of the thesis research. Part of the thesis is to compute the flood safety standards after the implementation of new spatial developments. However only the SCBA alert flood safety standards will be considered, since the LIR derived flood safety standards appear to be barely affected by the arrival of new spatial developments (de Bruijn et al., 2019). The LIR criterion is computed by the evacuation fraction and mortality functions. De Bruijn et al. (2019) states that neither of these two factors are likely to change significantly as a result of new spatial developments: the mortality functions are fixed, and the evacuation fraction does only slightly decrease for population increases. Therefore, the LIR flood safety standards are not included in this study. Because the group risk criterion is also computed using the mortality functions and evacuation fraction, it will likewise be excluded from the scope.

The scope of this thesis is confined to spatial developments in the form of residences and industrial objects. Furthermore, the impact of choosing new locations for new spatial developments needs to be considered as well. The main aim of this thesis is the development of a spatial planning framework for the mitigation of flood risk. The practical goal of this framework is to develop a strategy for selecting the locations of new spatial developments based on flood risks. In practice however, the choice for new spatial development locations involves a multitude of criteria, such as proximity to other urban areas and services. The research scope for the spatial planning framework is limited to basing the choice for new locations on flood risk only, with two exceptions. The first exception is that areas designated as nature reserves (Natura2000 areas) will be considered as off-limit for new spatial developments. The same holds for urban areas, with the exception of brownfield projects for new residences that are mentioned in official spatial planning documents. Brownfield projects are housing projects planned within existing urban areas.

Another important aspect to consider is whether the construction of new spatial developments significantly alters the flood pattern of a flood scenario. If so, the flood characteristics for a flood scenario have to be computed and cannot be assumed from established flood scenarios. Van der Most & Klijn (2013) do not consider housing to be an important factor. However, de Bruijn et al. (2018) state that flood scenarios should be reconsidered in case of 'large scale' new spatial developments and changes in the geography, such as the heightening of certain areas. Unfortunately, de Bruijn et al. (2018) do not quantify the number of new spatial developments. Therefore, the decision is made to exclude the computation of new flood scenarios.

1.6. Report structure

The report starts with a chapter 2 about the materials used for this study. Chapter 3 provides a description of the case study selection process and the selected case studies. Chapter 4 elaborates on the methodology used for each research question, and chapter 5 describes the results of the research question. In chapter 6, the results, and the study itself are subjected to a discussion, which is followed by the conclusion in chapter 7. The last and final chapter 8 consists of a set of recommendations, both for further research and general recommendations relevant for the general topic of this thesis.

2. Materials

The chapter materials describes the main model and input data used in this study. First, a detailed description of the flood and casualty is provided, which includes elaborations on the model input and output data. The second part of this chapter provides more general background information about flood scenarios.

2.1. Flood damage model

The flood risk assessment is carried out based on the flood damage and flood casualties as computed by the SSM2017 flood impact model. The SSM2017 V3.4 model has been developed by Deltares and is used by Rijkswaterstaat and regional water authorities. SSM2017 computes the total amount of financial damage and casualties based on the flood characteristics of a flood scenario. Other input consists of data about the type and number of spatial objects, population, and land-use as present in a certain area (Heymen, 2020). Input in the form of four flood characteristics is required: inundation depth, rise rate of water, flow velocity and flood arrival times. The required data for each flood scenario was retrieved from LIWO. LIWO, short for the National information system for Water and Floods, is a Rijkswaterstaat database that contains all Dutch flood scenarios.

SSM2017 divides flood damage into material and immaterial flood damage (Slager & Wagenaar, 2017). Material flood damage is divided into direct and indirect material flood damage. Direct material flood damage includes damage to objects such as housing and infrastructure, but also to livestock and crops. Indirect material flood damage concerns the disruption of (business) activities and supplies as a result of flooding, which also extends to suppliers and companies not present in the flooded area. Direct material flood damage and some forms of indirect material flood damage are divided into 5 'damage categories':

- Companies
- Residences
- Infrastructure
- Miscellaneous
- Vulnerable objects

Each damage category is divided into different damage sources (Slager & Wagenaar, 2017). Damage sources specify the nature of damage (structural, indirect) and the type of object which incurs the damage. Examples of damage sources for the damage category companies are 'offices', 'shops', 'industries' and 'education' (Table B1). The material damage for each damage source is determined using damage functions, describing the damage as a function of the inundation depth, with the damage as a percentage of the total asset value. An example of the general infrastructure damage function is shown in Figure 2. According to de Bruijn et al. (2015), the damage functions were derived based on data from historical Dutch flood events (1945 and 1953) and expert input. Thirteen damage function are used by SSM2017, in which different damage sources often have the same damage function. The average total value of spatial objects, including damages incurred due to disruption of business is derived from the CBS statistics agency (Slager & Wagenaar, 2017).

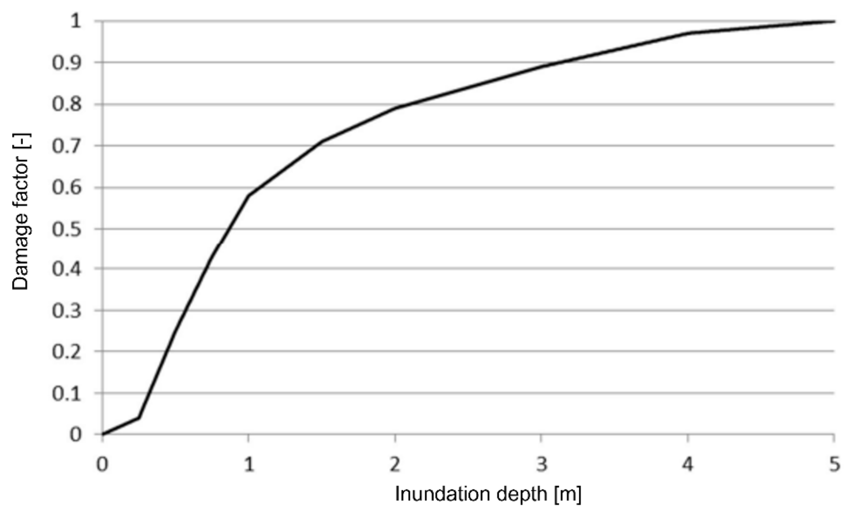

Figure 2: Damage function for infrastructure (Slager & Wagenaar, 2017)

Immaterial flood damage is expressed in the monetary value of flood casualties. The flood casualties are split into flood casualties (fatal) and flood affected individuals. The number of flood casualties and flood affected individuals are computed by SSM2017 based on mortality functions using data about the inundation depth, flow velocity and rise rate. Four different mortality functions are used for the computation of flood casualties. Depending on the rise rate and flow velocity (only near the breach location), one mortality function is selected by the model to express the mortality rate per grid cell as a function of the inundation depth. The total number of flood casualties are computed without evacuation. SSM2017 simulates the flood consequences using a grid of 100 by 100 m. Not all immaterial and indirect material flood damage sources are quantified by the model. Financial losses due to the wider disruption of infrastructure, the long-term impact on the investment climate, damage to vulnerable objects, the post-flood clean up and evacuation costs are not covered or monetarized by the model itself. To account for these indirect damage sources, an additional factor of 1.42 to the total material damage as computed by SSM2017 has been proposed by Slager & Wagenaar (2017). Slager & Wagenaar (2017) report the contribution of each indirect damage source to this additional factor, but do not go into detail about how these contributions were derived.

The flood damage incurred by spatial assets requires information about the number and location of these assets in SSM2017. SSM2017 contains maps for each damage source, quantifying for each grid cell either the number of objects or the surface area occupied by the specific damage source. The SSM2017 model package includes basic land-use maps, whose data is retrieved from a set of different sources according to the SSM2017 manual (Slager & Wagenaar, 2017). Data about spatial objects is derived from the BAG register (Basis administration of Addresses and Buildings). The reference date for this data is July 2014 (Slager & Wagenaar, 2017). BAG provides information about the xy-coordinates of spatial objects, the purpose of use of objects and surface area of objects. Data for all roads was derived from the *National datafile road networks*, reference date January 2015 and from *Basis administration topography (BRT)* for all railroads. The population density per grid cell was derived from the CBS, based on average household size per neighborhood as registered in 2013. The land-use classifications are also from the CBS.

2.2. Flood scenario data

The flood scenarios are the main input for SSM2017. A flood scenario describes how a flood takes place, defined by flood characteristics such as the breach location, water rise rate, flood arrival time, flow velocity and maximum inundation depth (Projectbureau VNK2, 2011). Each dike ring segment is characterized by one flood scenario. Flood scenarios are determined by performing flood computations in hydraulic models. The LIWO website by Rijkswaterstaat contains all Dutch flood scenarios. According to LIWO (2020), the data for all these flood scenarios have been provided for by regional water authorities, Rijkswaterstaat, the Dutch provinces and from individual projects such as the VNK flood risk project. Because the data was generated by different organizations, not all flood scenarios contain data for all flood characteristics. For example: the flood scenario in dike ring segment 7 for dike ring section 45-3 only contained data about the inundation depth. LIWO (2020) mentions that some flood scenarios are updated from time to time, depending on the attentiveness of the relevant authorities and the use of these flood scenarios in recent projects. Therefore, it can be the case that the flood scenarios retrieved from LIWO are not the exact same flood scenarios that were used to compute financial flood damage and casualties with for the derivation of flood safety standards.

3. Case studies

Three dike ring area were selected to serve as three case studies. These dike ring areas needed to have completely different spatial and flood characteristics, so that the spatial planning framework could be properly tested and analyzed. This chapter consists of two parts: a description of the case study selection process and a description of the three case studies.

3.1.1. Case study selection process

The aim of the selection process was to select for case study 1 a large dike ring area with an inclined plane flood type, for case study 2 a smaller dike ring area with an inclined plane flood type and for case study 3 a large dike ring area with a flat polder flood type. The flood types are explained in the description of the fourth selection criterion. The selection of three dike ring areas required the formulation of six selection criteria, whose purpose and interpretation will be explained in this section (Figure 3).

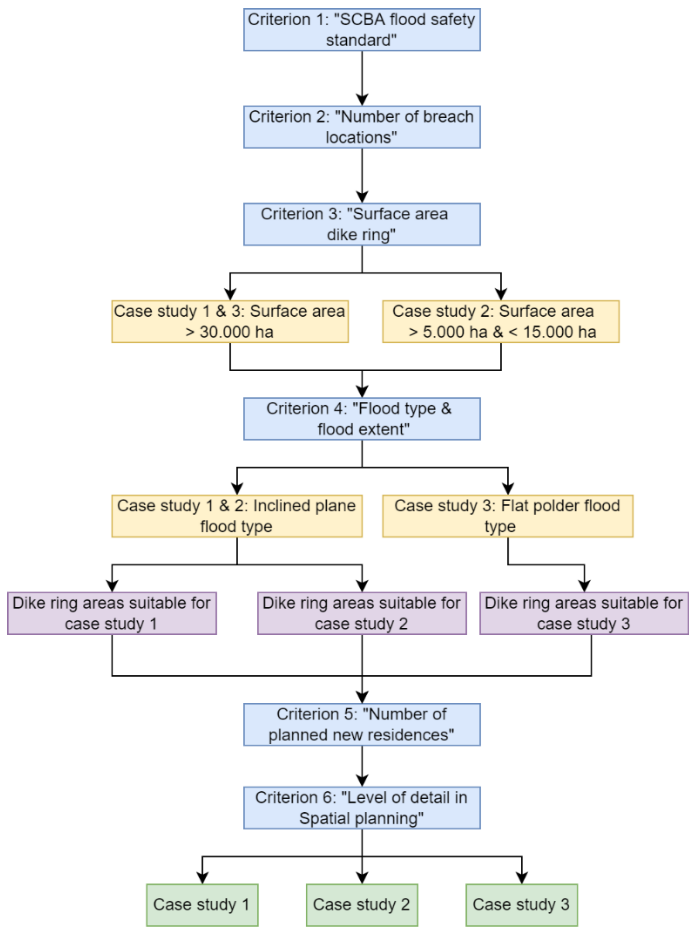

Figure 3: Methodology case study selection

Selection criterion 1 "SCBA flood safety standard"

The first selection criterion was that only dike ring areas with normative flood safety standards are derived from the SCBA criterion are selected, since these dike ring areas directly depend on the value of economic assets present in the area. Flood safety standards derived from the LIR and GR flood risk criteria are at most only marginally affected by new spatial developments. The selection criterion was applied by selection of dike ring areas of which more than 50% of the corresponding dike ring sections have flood safety standards derived from the SCBA criterion. This 50% limit was determined arbitrarily. A certain number of dike ring areas that fell within these limits were excluded based on the presence of dike ring sections whose flood safety standard are determined on 'additional grounds'. Since these additional grounds are not specified in the literature, it would be difficult to derive accurate alert standards for these dike ring sections.

Selection criterion 2 "Breach locations"

According to Projectbureau VNK2 (2011), the number of breach locations can be equated to the number of single-breach flood scenarios. It is important to ensure that there is a minimum number of flood scenarios to work with during the framework development phase, for which case study 1 is used: flood scenarios contain information about the flood characteristics, and that information is important for the implementation of the second research question. For case studies 1 and 3, dike ring areas with a minimum of 5 and a maximum of 12 (arbitrarily chosen) breach locations were selected. Although case study 3 does not necessarily require the same limitations in terms of breach locations as case study 1, the distinction between case studies 1 and 3 is made in a later stage of the selection process. There was no need to impose the same limitations for case study 2 as for case studies 1 and 3, because the aim for case study 2 was to select a smaller dike ring area compared to the other two case studies. A higher lower boundary would needlessly exclude smaller dike ring areas. Therefore, the second criterion for this case study has been applied by selection of dike ring areas with 2 to 12 breach locations. The use of this lower limit removes from consideration very small dike ring areas that could not be excluded through application of selection criterion 3 "surface area" due to a lack of available data.

Selection criterion 3 "Surface area"

For case study 1 it is important that a larger sized dike ring area is selected, because there must be enough space in the dike ring to come up with an effective spatial development framework and validation process in research question 2. Thus, for case studies 1 and 3 only dike ring areas with a surface area larger than 30,000 ha (arbitrarily chosen value) were selected. For case study 2 it was necessary to select a dike ring which is considerably smaller compared to the other case studies, because case study 2 is used in the fourth research question to validate and analyze the applicability of the spatial planning framework to smaller dike ring areas. Therefore, dike ring areas larger than 5,000 ha and smaller than 15,000 ha were selected for case study 2.

Selection criteria 4 "Flood type and flood extent"

Vergouwe (2014) states that there are three different types of floods: 'flat polder', 'inclined plane' and 'variable' floods. The variable flood type displays a flood pattern where only part of the dike ring area is inundated, due to the presence of regional flood defenses and line objects (Figure 4A). The variable flood type is undesirable for any of the case studies, as the flood extent is rather limited. A limited flood extent makes it more challenging to test the effectiveness of a spatial planning framework, because it makes it 'too easy' to place new spatial development in non-floodable areas, which is an impediment to testing the framework for different flood characteristics.

The flood type 'inclined plane' (Figure 4B) is found in dike rings with a height gradient. This flood type displays geographical differences in the flood characteristics, with smaller and larger inundation levels. The geographical differences in flood characteristics make this flood type is particularly useful for the identification of different flood risk zones, which is necessary for the spatial planning framework development.

The flood type 'flat polder' (Figure 4C) leads to dike ring areas which are either completely or almost completely inundated, coupled with a relatively uniform inundation depth. This flood type can be found in lower elevated polders. The group of dike ring areas suitable for case studies 1 and 3 has been split by application of this fourth selection criterion: for case studies 1 and 2, dike ring areas with flood type 'inclined plane' have been selected. For case study 3, dike ring areas with flood type flat polder have been selected. Dike ring areas with a limited flooding extent are excluded for all three case studies. The orange circles in Figure 4 show the breach location. Selection was done by visual analysis of the maximum inundation flood scenarios for each dike ring section as presented in the report of Slootjes & Wagenaar (2016).

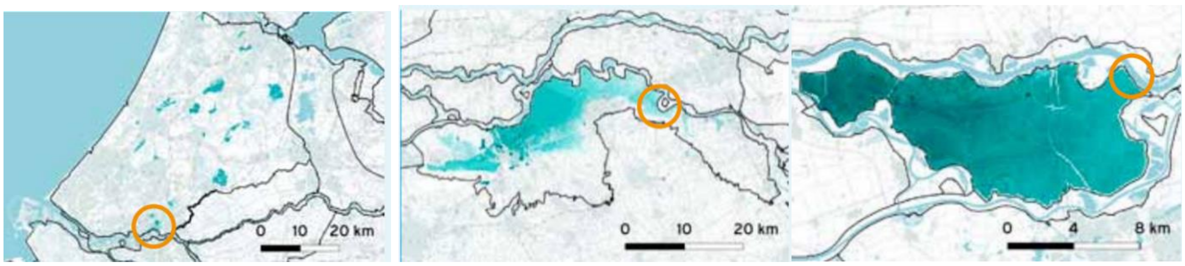

Figure 4: Flood types qhA) "Variable" B) "Inclined plane" C) "Flat polder" (Vergouwe, 2014)

Selection criterion 5 "Number of new residences"

The validation of the spatial planning framework in research questions 2 and 3 requires the presence of planned spatial developments. If there is a sizeable number of new spatial developments in a dike ring area, it can be determined with more clarity whether the spatial planning framework is effective in reducing flood risks and flood consequences compared to a dike ring area with limited plans for new spatial developments. The number of planned spatial developments has been indicated by the number of planned new residences, because spatial plans for new residences are published by all municipalities. This made it a transparent indicator for this criterion.

A targeted search for information about the number of planned residences for the period 2021-2030 was conducted by means of investigating municipal structure visions, spatial development plans and housing program reports. The target period of 2021-2030 was chosen as most municipalities published their spatial development plans for this specific period. In case that municipalities reported their spatial development plans for a different period, the reported numbers of planned new residences were adjusted to the 2021-2030 period. For each case study, the two dike ring areas with the largest number of planned residences were selected.

Selection criterion 6: "Detailed spatial planning"

The final and sixth selection criterion was concerned with the level of detail in the spatial plans. The level of detail is expressed in information about the number of new residences, the availability of information about the locations where new residences will be built and the availability of information about the type of residences (apartments, single family homes, et cetera) that are planned. For each case study, the dike ring area with the most detailed amount of information on the three aspects (number, location, type) of spatial plans was selected to serve as case study. The data and results for each selection criterion can be found in the tables in appendix A.

3.2. Description case studies

Case study 1: Dike ring area 45

Dike ring area 45 is a large dike ring area of 35,100 ha located in a valley between the higher grounds of the Veluwe forest in the east and the Utrechtse Heuvelrug in the west, which is roughly in the centre of the Netherlands (Figure A1). Figure 5A shows that there is an elevation gradient from the south-east to the north, with an overall height difference of around 12 meters. The dike ring area is bordered by two large water bodies: in the north it faces the Randmeren, connected to the larger IJssel and Marker lakes. The threat it faces from the lakes in the north is limited, due to the higher elevation in southern direction. Two of the three dike ring sections (45-2 and 45-3) are in the north (Figure 5A). The biggest threat comes from the Nederrijn in the south, in dike ring section 45-1 west of Wageningen. As shown by the maximum inundation flood scenario (Figure 5B), a large part of the dike ring area floods in case a dike breach occurs in 45-1 due to the height gradient (Van der Scheer & Huting, 2012). An alert standard of 1/100,000 per year was determined for this dike ring section (consisting of dike ring segment 1 alone). The other two dike ring sections have alert standards of 1/300 per year. The dike ring area has about 262,300 inhabitants, who are concentrated in the western part of the dike ring area (Vergouwe, 2014). Most new housing is concentrated near Amersfoort, where roughly 9,000 of the 22,000 new residences are planned (Figure 5C). A further 6,000 new residences are planned in Nijkerk and Veenendaal. Agricultural activities dominate the spaces between the urban centers. The dike ring area includes part of the Veluwe and the Utrechtse Heuvelrug nature areas. Slootjes & Wagenaar (2016) report that the potential damage per flood event is considerable in case of a dike breach in dike ring section 45-1, with an expected 2050 flood damage of €56 billion and around 231,000 individuals affected by flooding without considering evacuation measures.

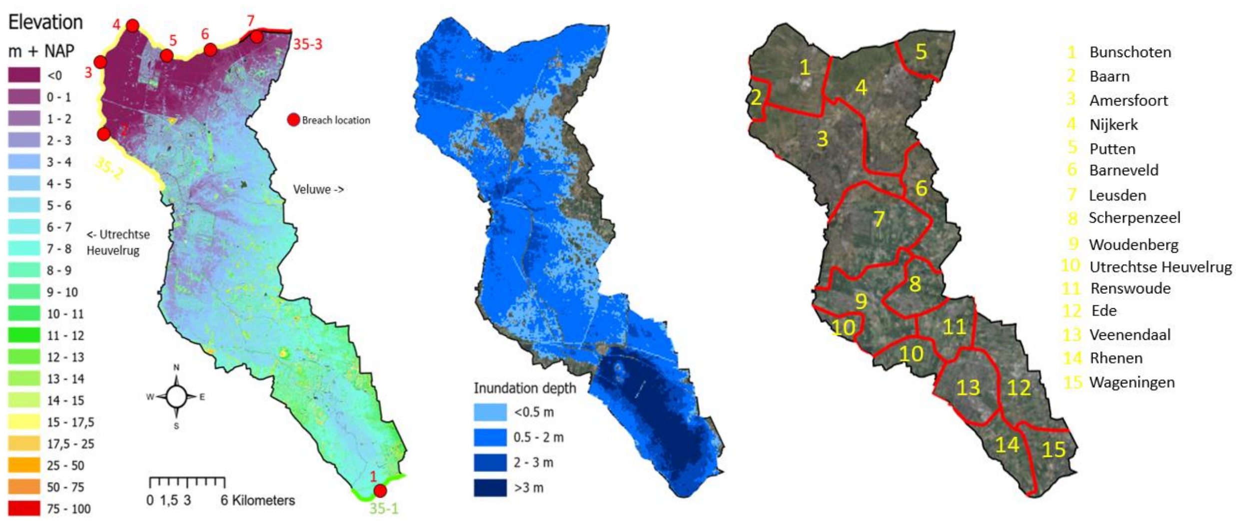

Figure 5A) Map dike ring area 45 B) Flood scenario 45-1 C) Municipalities

Case study 2: Dike ring area 35

Dike ring area 35 is a relatively small dike ring area of 12,500 ha located in the western part of Noord-Brabant (Figure A1). The dike ring area is home to 97,600 inhabitants (Vergouwe, 2014). Like dike ring area 45, there is a height gradient from the north to the south, with a total height difference of around 8 meters (Figure 6A). The dike ring area only borders one water system: the Bergsche Maas in the north. The dike ring area consists of dike ring sections 35-1 and 35-2, with alert standard values of respectively 1/10,000 and 1/3,000 per year (Slootjes & Wagenaar, 2016). In case of flooding, an inclined plane flood type develops with large inundation depths in the north and dry zones in the south (Figure 6B). The dike ring area contains five municipalities, the largest of which are Waalwijk in the north-east and Dongen in the south-west. The dike ring area is dominated by agricultural activities, with the main urban centers positioned along the dike ring area boundaries. Most new residences of the 4,439 new residences in total are planned in Oosterhout (1,015) and Waalwijk (2,526). Slootjes & Wagenaar (2016) estimated that the potential 2050 flood damage is €5.4 billion, including 40,000 individuals affected by flooding without evacuation measures. Thus, even a flood event in a relatively small dike ring area can have far reaching consequences.

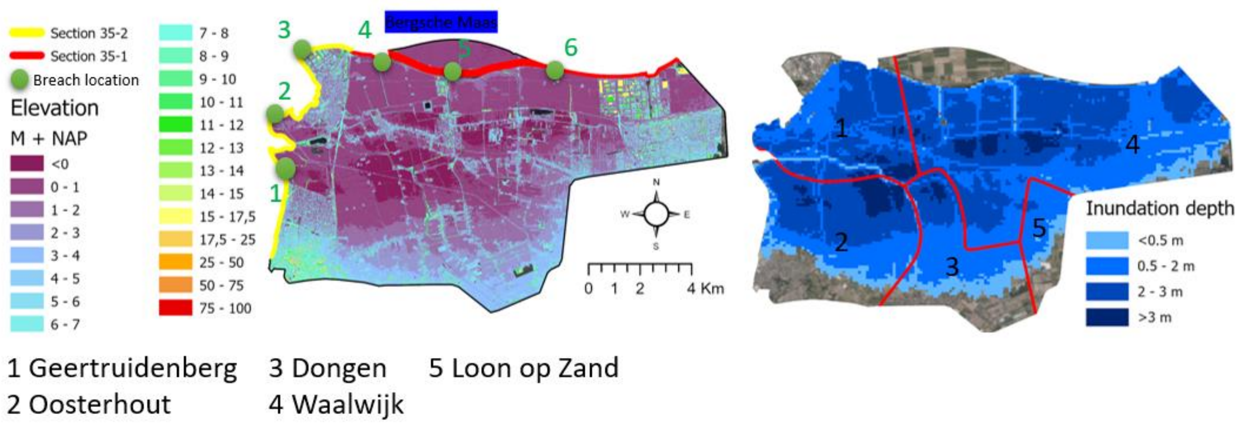

Figure 6A) Dike ring area 35 elevation map B) Worst case flood scenario 35-1

Case study 3: Dike ring area 15

Dike ring area 15 is a large dike ring area of 31,400 ha, located in the southern parts of the Zuid-Holland and Utrecht provinces (Figure A1). The dike ring area consists of a selection of polders and contains the Krimpenerwaard and Lopikerwaard regions. Dike ring area 15 is bordered by several rivers: in the south it faces the river Lek and, in the north, the Hollandse IJssel. At the confluence of these two rivers lies the Nieuwe Maas, next to the city of Krimpen aan den IJssel (Figure 7A). The dike ring area consists of three dike ring sections: 15-1, 15-2 and 15-3 (Figure 7). According to Slootjes & Wagenaar (2016) these dike ring sections have alert standards of respectively 1/30,000, 1/10,000 and 1/10,000 per year, which are relatively strict. Although there is a considerable height gradient from west to east, the dominant flood type as determined during the selection process is the flat polder flood type (Figure 7B). The dike ring area contains 13 municipalities in total, but some municipalities such as Gouda only have a few hectares within the dike ring area. The largest population centers are Nieuwegein, Krimpen aan den IJssel and IJsselstein, home to the majority of the 201,500 inhabitants of the dike ring area (Vergouwe, 2014). Most of the 11,000 new residences are planned in IJsselstein (2,685) and Nieuwegein (5,146). The dike ring area can be classified as rural, as most of the land is used for agricultural purposes (Boon, 2011). Slootjes & Wagenaar

(2016) report that the potential flood consequences for 2050 are estimated at more than €11 billion, with 80,000 affected persons.

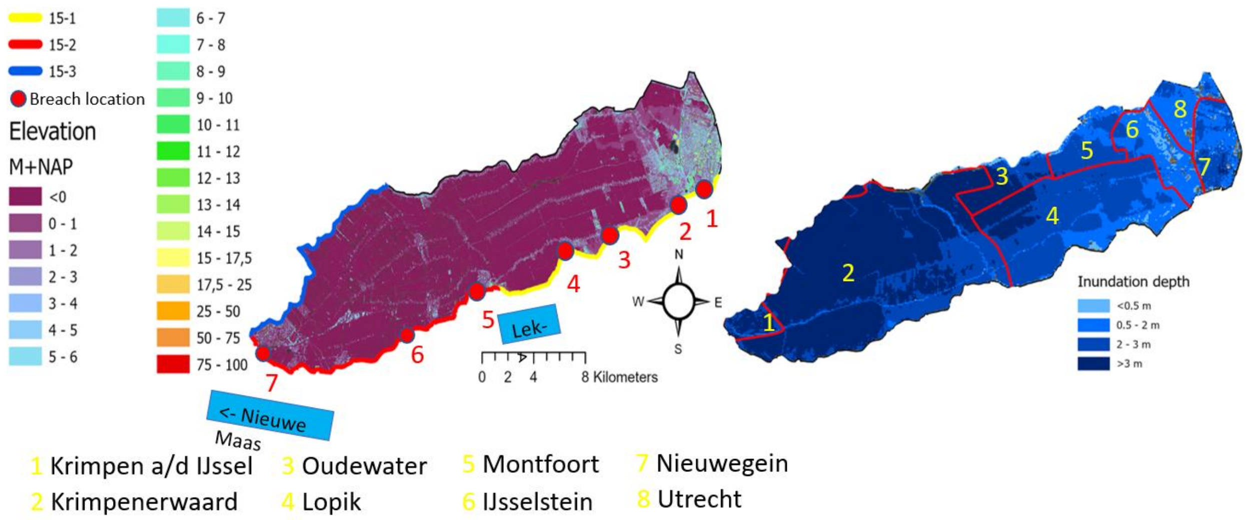

Figure 7A) Dike ring area 15 elevation map B) Worst case flood scenario 15-1

4. Methodology

This chapter describes the methodology for the three research questions. The general methodology, including the most important steps for each research question is shown in Figure 8. Each of the grey boxes in Figure 8 corresponds to a research question.

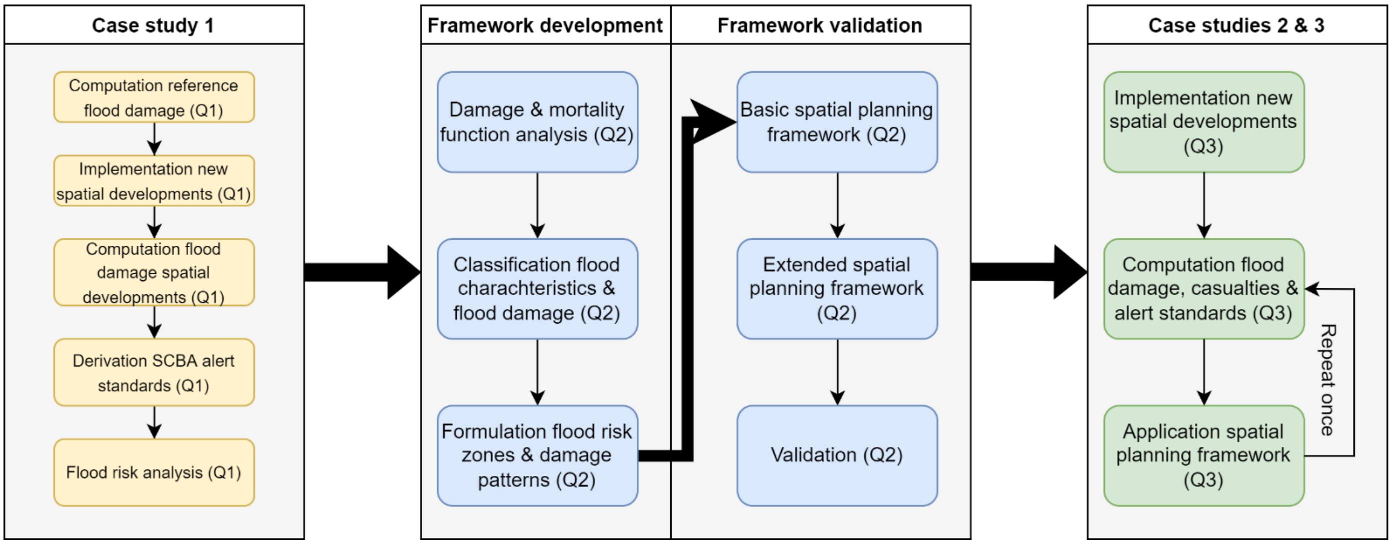

Figure 8: General methodology

4.1. Flood risk assessment case study 1

The methodology for the first research question consists of five steps (Figure 8). First, the flood damage and casualties for the case study 1 reference scenario without new spatial developments are computed with SSM2017. Then, the new spatial developments retrieved from official spatial planning sources are implemented in the SSM2017 land-use maps. With data from the SSM2017 computations, the reference and new SCBA alert standards were computed, which were used in the flood risk analysis of case study 1.

4.1.1. Implementation spatial developments

The new spatial developments for case study 1 were implemented in the SSM2017 land-use maps using GIS. The number, type and location of these new spatial structures were derived from the sources retrieved as part of the analysis of future spatial planning in research question 1 (Table A6 and Table A9). The general approach for the implementation of new spatial developments was to follow the official spatial plans as close as possible. Three types of spatial structures were implemented in GIS: family homes, apartments, and industrial structures.

Four types of residences are used in SSM2017: family homes, ground floor apartments, first floor apartments and apartments on the remaining higher floors. For each type, the number of new objects, the number of new inhabitants and added surface area needed to be determined for each grid cell. The average surface area per apartment in dike ring area 45 was computed to be 80 m^2 based on the total amount of flooded apartment surface area and the number of flooded apartments as reported by the SSM2017 model results for dike ring area 45. The same method was used to determine the average surface area for family homes: 130 m^2 per object. The average household size as derived from CBS (2021) is 2.1 persons in 2021. No distinction is made in the household size between apartments and family homes, as no additional information is available. Furthermore, the distribution of apartments over the different floors (ground-, first- and higher floors) was derived by computing the existing distribution of apartments over these floors based on the entire number of apartments present in the Netherlands. The analysis showed that the apartments are distributed equally over the three mentioned floors. This distribution was therefore also used for the implementation of new apartments.

The ‘construction’ of new residences also meant that new roads would have to be constructed. It was assumed that no changes are made to the road grids at those locations. For expansion location outside the urban centers, additional roads are added to the land-use maps. From a random neighborhood in Amersfoort (Figure B1), the average length of road per residence has been measured in GIS. That resulted in 13 meter of new road per ground-based residence. This is a rather general value, as some new neighborhoods will be set up more spacious and some less. Nevertheless, this value was assumed for all new greenfield locations (spatial developments in non-urban areas). New residences are also related to the damage source ‘urban area’. This damage source expresses how much space within a grid cell is occupied by urban area. New spatial developments within cities were assumed to be ‘fully urbanized’, meaning that of each 1 ha grid cell, 1 ha of space is occupied by urban area. Expansion areas at the outskirts of settlements were assigned urbanization rates of 0,5 ha per grid cell, based on the average urbanization rate of similar areas as computed from the existing SSM2017 input. At locations previously having no residences, where new residences with a surface area less than 2500 m^2 were implemented, the value for the damage source urbanization is equal to the surface area of new residences.

Besides new residences, also new industrial sites were implemented based on information found in Zandbelt et al. (2021). The length of the new road network required for these sites was estimated in a similar way as the length of the new road network for new residences: this resulted in a value of 1 meter of new road for each 58 m^2 of new industrial land-use. The implementation of new objects leads to decreases in other forms of land-use. It is assumed that implementation of new spatial developments will take place in areas previously designated for recreational or agricultural purposes. Therefore, implementation of new spatial developments in one grid cell leads to the disappearance of objects belonging to the following damage sources:

- Extensive recreation
- Intensive recreation
- Agriculture
- Horticulture

These specific damage sources were assumed to be the objects most likely to be replaced by new residences and industries. The grid cell values for all damage sources belonging to all other damage sources were kept unchanged. For the computation of financial flood damage, it is assumed that all new residences and industries are not built flood proof. In total, 21,672 new residences were implemented in GIS, of which 10,542 single family homes, 11,130 apartments and 55.16 ha of industry (Figure 9). Figure B2 and Figure B3 show the locations of new spatial developments in a higher resolution.

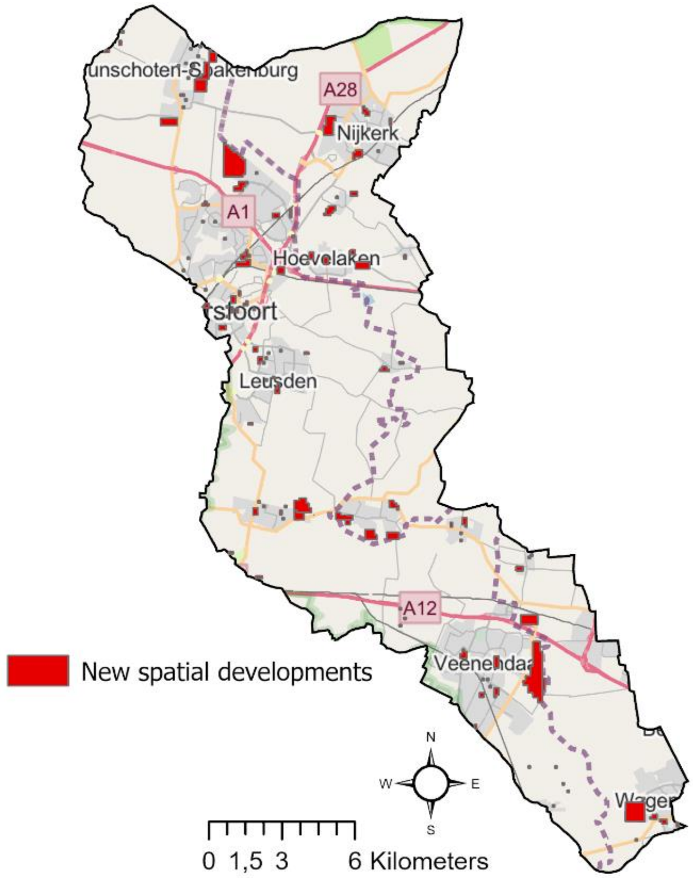

Figure 9: New spatial developments as implemented in GIS for dike ring area 45

4.1.2. Derivation of new SCBA flood safety standards

The results of the SSM2017 computations for each flood scenario were used to compute the SCBA derived alert value of the flood safety standard for each dike ring section. The first step in the derivation of the alert flood safety standard was to compute the weighted total damage for reference year 2050 ($D_{w,2050}$) with equation 1 (Slootjes & Van der Most, 2016b):

$$D_{w,2050} = F_{TL} * \left(\sum_{i=1}^{n} D_{i,TL,2050} * \frac{L_i}{L_{section}} \right) + F_{wc} * D_{worstcase} \qquad Eq. 1$$

<u>Where:</u>

- $D_{i,TL,2050}$= *Total damage in 2050 for a single TL (test level) flood scenario at breach location i [€]*
- L_i = *Length of dikes in dike ring segment for which the dike breach location in flood scenario i is representative [m]*
- $L_{section}$ = *Total length of dikes in a certain dike ring section*
- n = *Number of dike ring segments part of a certain dike ring section*
- $D_{worstcase}$= *Total damage in 2050 for the worst-case flood scenario [€]*
- F_{TL} = *Weighing factor TL flood scenarios [-]*
- F_{wc}= *Weighing factor worst case flood scenario [-]*

The TL (test level) flood scenario is the flood scenario with the water level return period associated to the normative pre-2017 flood safety standards. Because the water level return period for dike ring area 45 was 1/1,250 per year, the TL flood scenarios were retrieved for this return period (Slootjes & Van der Most, 2016a). The TL+1D flood scenarios have a water level return period that is a factor 10 higher than the TL flood scenario: 1/12,500 per year. Because only flood scenarios for a 1/10,000 return period were available, these were used. Two dike ring segments in dike ring section 45-2 lacked TL+1D flood scenarios. As a result, these dike ring segments were ignored for the determination of the worst case flood scenario. Values for L_i and $L_{section}$ were retrieved from Slootjes & Wagenaar (2016). The worst-case flood scenario is the flood scenario in which dike breaches occur simultaneously in each dike ring segment belonging to a dike ring section, coupled with the individual TL+1D flood scenarios of each breach location if available. The factors F_{TL} and F_{WC} reflect whether the threat of flooding is fluvial or marine in nature. The threat of flooding for dike ring area 45 is fluvial (Van der Scheer & Huting, 2012).

The values for $D_{i,TL,2050}$ and $D_{TL+1D,worstcase}$ were computed with equation 2:

$$D_{i,TL,2050} = D_{2011} * F_{ssm} * G^{39} + F(1-E) * 6{,}700{,}000 + A * 12{,}500 \qquad Eq.2$$

<u>Where:</u>

- *D_{2011} = Flood damage in reference year 2011 [€]*
- *G = Factor for economic growth*
- *F = Number of flood casualties*
- *A = Number of affected individuals*
- *E = Evacuation fraction*
- *F_{ssm} = SSM2017 factor*

The yearly growth rate *G* to the power of 39 accounts for the 39 years between SSM2017 price reference year 2011 and 2050 (Kind et al., 2011). The number of flood fatalities and flood victims were computed by SSM2017, but not monetized: the €6.7 million and €12,500 reflect the value of casualties and affected individuals, respectively (Kind et al., 2011). The evacuation fraction is the percentage of individuals who managed to leave the flooded area successfully before or after flooding (Maaskant et al., 2009). The last step was to compute the alert flood safety standard $p_{2050}^{alert\ standard}$ with equation 3:

$$p_{2050}^{alert\ standard} = \frac{1}{38}\left(\frac{I(h_{10})}{D_{w,2050}}\right) \qquad Eq.3$$

<u>Where:</u>

- $p_{2050}^{alert\ standard}$ *= alert flood safety standard [1/year]*
- *1/38 = Factor to account for discount rate of 5,5%*
- *$I(h_{10})$ = Investment costs for a dike reinforcement with one decimal height [€]*
- *$D_{w,2050}$ = Total weighted damage in 2050 [€]*

One decimal height is the increase in dike crest level required to reduce the annual flood probability of a flood defense with a factor 10 (see glossary of terms). Input data for the calculations can be found in Table B2. First, the new flood safety standards were derived for the base line situation without new spatial development for comparison with the flood safety standards mentioned in Slootjes & Wagenaar (2016), followed by the computation of the alert standards after implementation of new spatial developments.

The number of normative casualties as used for the flood risk analysis was computed by using equation 1 and replacing the values for the total damage per flood scenario with the number of casualties per flood scenario. The normative flood damage for industry, apartments and family homes in each section was computed with this method as well.

4.2. Spatial planning framework development and validation

The flood damage and flood casualties predominantly depend on two flood characteristics: the rise rate of water and the inundation depth (Slager & Wagenaar, 2017). Flow velocity matters only directly at the breach location with respect to mortality rates. Different combinations of inundation depths and rise rates lead to different values of financial flood damage and number of flood casualties. It is the aim of the spatial planning framework to aggregate these combinations into 'flood risk zones'. Flood risk zones are defined as zones in a dike ring area for which the damage profile is equal for a certain combination of inundation depths and rise rates. The damage profile shows for each relevant object what degree of damage occurs. The damage profile was defined in this study for four damage groups: family homes, apartments, industrial objects, and casualties. The first step in the framework development was to conduct an analysis of the SSM2017 damage and mortality functions (section 4.2.1). The aim of this analysis was to reveal for which values of the inundation depth and rise rate, what level of damage could be expected for each of the four damage groups. This information was used as input for the classification of damage and flood characteristics (section 4.2.2). The third step was to formulate a basic spatial planning framework and an extended spatial planning framework that included the aspect of flood probability (section 4.2.3). Both versions of the framework were then applied in different variants to the spatial developments of case study 1 as part of the framework validation (section 4.2.4).

4.2.1. Analysis damage & mortality functions

The first step in the formulation of flood risk zone was to classify the values for the two flood characteristics into different classes. The same had to be done for financial flood damage. An example might be required to clarify the concept of flood risk zones: "*in flood risk zone A, the inundation depths are considered to be small and the rise rates to be large. It is expected that there is a low risk at damage to housing, but a large risk at casualties*". To enable the classification of damage and flood characteristics by means of labels ("*small*" and "*large*"), an analysis of the SSM2017 damage and mortality functions was conducted.

Three types of spatial objects were considered with respect to material flood damage: family homes, apartments, and industry (section 1.5). In SSM2017, different damage sources exist for each damage category that quantify the maximum amount of damage (see section 2.1). Table 1 shows the maximum asset value per unit for each damage source for each relevant spatial object. The first step in the development of the spatial planning framework was to determine the total asset value for family homes, apartments, and industrial objects by combining the maximum asset value of each relevant damage source for these objects. For family homes and apartments, the total asset value was determined using the average surface area of family homes (130 m^2) and apartments (80 m^2) as assumed in section 4.1.1. For industrial objects, the total asset value is expressed in €/m^2, as it is the unit of both damage sources. The total asset values for family homes, apartments and industrial objects are shown in Table 1 as well.

Table 1: Damage values per damage source for each object type

Object type	Damage source	Maximum asset value per unit	Value per object [€]
Family home	Direct damage	1,000 [€/m^2]	130,000
	Furniture	70,000 [€/object]	70,000
	Outage of services	10,665 [€/object]	10,665
	Total asset value	-	*210,665*
Apartments (all floors)	Direct damage	1,000 [€/m2]	80,000
	Furniture	70,000 [€/object]	70,000
	Outage of services	10,665 [€/object]	10,665
	Total asset value	-	*160,665*
Industry	Direct damage	1,497 [€/m^2]	-
	Outage of services	700 [€/m^2]	-
	Total asset value	*2,197* [€/m^2]	-

As described in section 2.1., for each damage source is a damage function. Damage functions display damage as a function of the inundation depth, where the damage is represented as a percentage of the maximum asset value (Slager & Wagenaar, 2017). By computing the cumulative damage of the damage sources at each inundation depth, it was possible to determine for each inundation depth the percentage of incurred damage with respect to the total asset value (Table 1). The computation of the total financial flood damage for family homes is shown in Figure 10. Figure C1 and Figure C2 show the total financial flood damage for apartments and industry. The computation of the total financial flood damage for apartments was more complicated, as there are three types of apartments (ground-, first- and higher floors) coupled with the same damage function for outage of services. The total financial flood damage to apartments was computed with equation 4:

$$D_{apart} = \frac{D_{ground}}{3} + \frac{D_{first}}{3} + \frac{D_{higher}}{3} + D_{outage} \ [€] \qquad Eq. 4$$

The rationale behind equation 4 is that in this way, the total financial flood damage reflects the distribution of apartments of the three different floors as determined from the SSM2017 land-use maps (section 4.1.1) The direct damage function for the higher floor apartments reaches 100% asset damage only at an inundation depth of 15 m. As this inundation depth is unlikely to ever be reached in the Netherlands, it was decided to cut off the damage function at an inundation depth of 8 m and regard the damage incurred at this level as the maximum asset value for higher floor apartments.

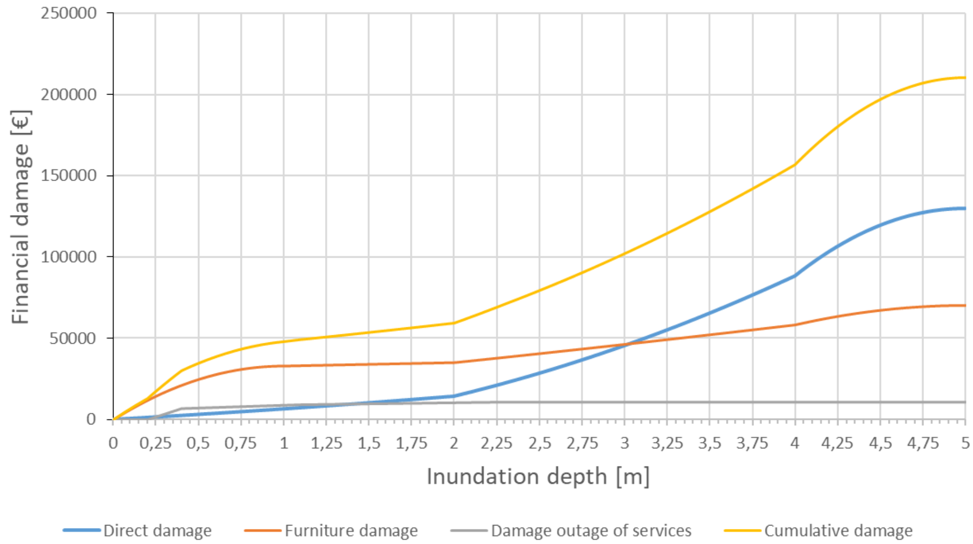

Figure 10: Total financial flood damage to family homes based on SSM2017 damage functions

Casualties and the monetarization of casualties contribute considerably to the total financial flood damage (Kind et al., 2011). In SSM2017, casualties depend on the inundation depth and the rise rate of water. By plotting these mortality functions, it was possible to determine at which combinations of rise rate and inundation depth certain mortality rates occurred (Figure 11). Although high flow velocities do influence the mortality at the breach location, they were not considered because higher mortality rates are already considered to be sufficiently covered by the > 4 m/hour rise rate function.

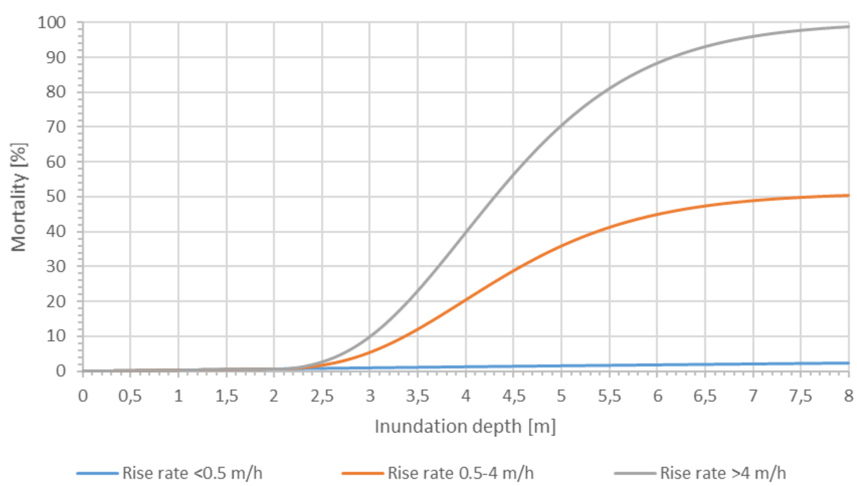

Figure 11: Mortality functions SSM2017

4.2.2. Classification of flood damage & flood characteristics

The analysis of the damage and mortality functions enabled the classification of flood damage and flood characteristics into classes. The inundation depths were classified into five classes: not floodable, small, medium, large and extreme inundation depths. The classification of inundation depths was supported by Pieterse et al. (2009). One extra inundation depth class was added in comparison to Pieterse et al. (2009), in order to obtain a higher level of detail.

The classification process for casualties was supported by a statistical analysis of the mortality rates generated by the Grebbedijk TL+1D flood scenario of case study 1. The rise rates were classified into three classes: low, medium, and high casualty rates, equal to the mortality function classification in SSM2017 (Figure 11). Flood damage was classified into five classes: zero, low, medium, high, and catastrophic damage. Except for the not floodable class, all classes captured an equal share of the flood damage. The damage classes express damage as the percentage of total financial flood damage that could be incurred by each of the four damage groups.

4.2.3. Formulation spatial planning framework

The first step in the formulation of the basic spatial planning framework was to define all possible flood pattern combinations using the flood characteristic classifications. This led to for example combinations as ‘small’ inundation depths and ‘medium’ rise rates, or ‘large inundation depths’ and ‘small’ rise rates. For each of the flood patterns, a damage profile was established. The damage profile connects the flood pattern with the damage classification. By comparison of the flood characteristic values of a certain flood pattern with the results of the damage and mortality function analysis (Figure 10, Figure 11, Figure C1 and Figure C2), it could be determined what percentage of flood damage is incurred by each damage group. Then, this damage percentage was compared to the damage classification, after which a flood class was selected that represented the level of flood damage. The damage profile with damage classification for each damage group together with the flood pattern forms a flood risk zone. To prevent duplicate flood risk zones, flood risk zones with the same damage profiles were combined into one flood risk zone, which then covered a larger range of inundation depths and rise rates.

Two versions of the spatial planning framework were made: a basic framework including inundation depth, rise rate, flood damage and mortality and an extended framework that included the element of flood probability as well. For case study 1, the flood probability per dike ring section was expressed with the official lower limit flood safety standard derived from Slootjes & Wagenaar (2016). In GIS, for every grid cell the sum of the flood probabilities was computed based on the flood extent for the worst-case flood scenario of each dike ring section. Using the resulting flood probability map, the flood probability values were split in two different classes (low and high), as there were two different flood probability values present in the flood probability map. The flood probability was incorporated into the basic spatial planning framework by making two versions of each flood risk zone with the exception of the flood risk zone for dry conditions: one version with a smaller flood probability, and one version with a larger flood probability.

4.2.4. Validation spatial planning framework

Validation of the spatial planning framework was carried out by application of the two framework versions to case study 1 using three different variants. The first variant (“Full dike ring area”) was to allow for the relocation of new spatial developments outside the municipalities they were originally planned in. The second variant (“Municipality”) was to allow relocation of spatial developments only within the municipality itself. The third variant (“City outskirts”) was to only allow the implementation of new spatial developments directly at the boundaries of the urban centers within the municipalities. The implementation of new spatial developments was done by first implementing the most vulnerable new spatial developments into the safest flood risk zones. If there was no place left in that flood risk zone, the remaining spatial developments were placed into the second safest flood risk zone and so on. For the third variant “city outskirts”, preference in construction was assigned to apartments and family homes instead of industry, because those objects are the most probable form of urban expansion at the boundaries of urban centers. Furthermore, no brown field projects were allowed for the city outskirts method. For the implementation of new spatial developments, an average residence density of 35 residences per ha was assumed, which was mentioned by Ellis (2004) as the global average number of residences in urban areas.

The yearly economic flood risk is the yearly expectancy value for financial flood damage (Vergouwe, 2014). To compute the yearly economic flood risk, the weighted flood damage for reference year 2050 ($D_{w,2050}$) is multiplied with the lower limit flood safety standard of each dike ring section. The lower limit flood safety standards reflect the realistic flood probability of each dike ring section. The economic flood risk for the entire dike ring area is computed by summing up the economic flood risk values of each dike ring section.

4.3. Applicability spatial planning framework

The objective of this research question was to apply one of the spatial planning frameworks developed and validated in research question 2 in two other case studies and test the effectiveness of this spatial planning framework in dike ring areas with different spatial and flood characteristics. The first step was to implement for both case study 2 (dike ring area 35) and case study 3 (dike ring area 15) the new spatial developments as stated in official government plans in the land-use maps (Table 2). The official planning locations of the new spatial developments for case studies 2 and 3 are shown in Figure 12 and Figure 13, respectively. For the implementation of new spatial developments, the same assumptions about household size (2.1 persons), surface area of family homes (130 m^2) and apartments (80 m^2), as well as meter road per residence and industrial object were used as discussed in section 4.1.1.

Table 2: Implemented new spatial developments case studies 2 and 3

Types of spatial objects	Case study 2	Case study 3
Family homes	2,302	5,461
Apartments	2,137	5,526
Total number of residences	4,439	10,987
Industry [ha]	77	11.5

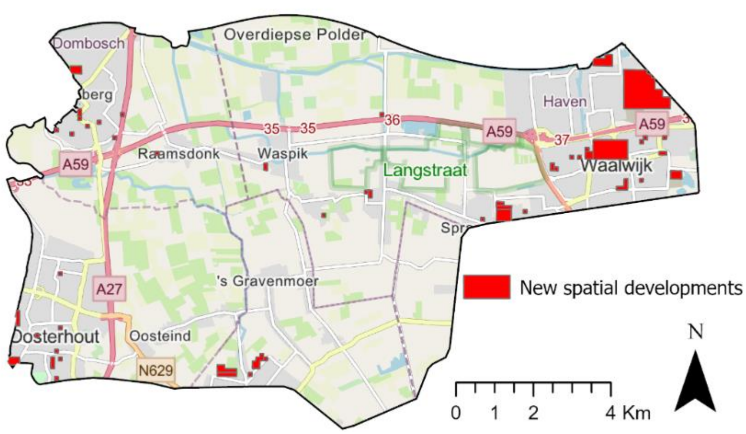

Figure 12: Official planning locations spatial developments case study 2

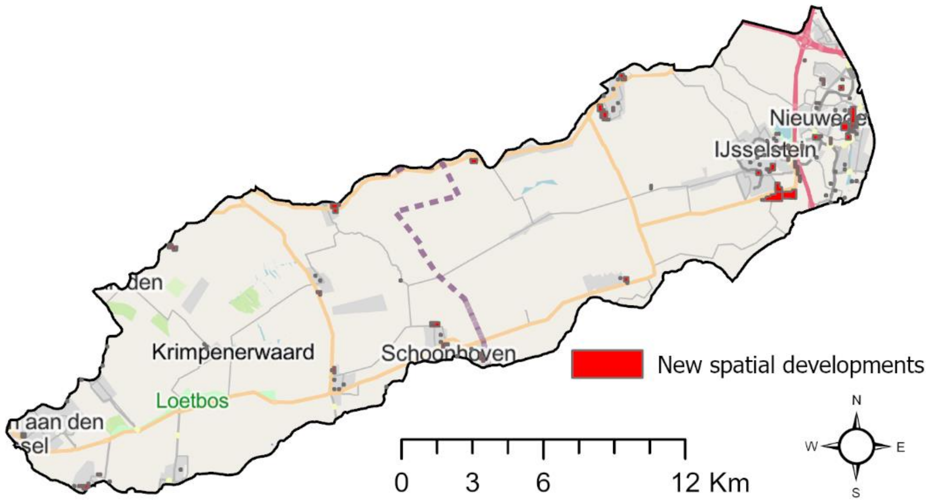

Figure 13: Official spatial planning case study 3

After the implementation of new spatial developments in both case studies, the spatial planning framework was applied. The SSM2017 model was used to compute the financial flood damage for the reference case without added new spatial developments, the 'official planning' case with added spatial developments and the 'framework' case after application of the extended spatial planning framework. The financial flood damage and casualty results per flood scenario were used as input for the SCBA alert standard derivation. The SCBA alert standard derivation process was similar to the process described in section 4.1.2., except for changes in the evacuation fractions and weighing factors. Because both case study 2 (De Groot, 2014) and case study 3 (Boon, 2011) are facing threats from the sea instead of the rivers, a different set of weighing factors was used in equation 1 for the test level (TL) and worst-case flood scenario damage (Slootjes & Van der Most, 2016a). Furthermore, different evacuation fractions were used as well. It should be mentioned that in case study 2, the flood scenario from LIWO only contained data about the inundation depths. SSM2017 is capable of computing flood damage with the inundation depth alone, but for creating the flood risk zoning maps it was assumed that in all inundated grid cells the rise rate belonged to the lowest rise rate class. The input data for case studies 2 and 3 is shown in Table D1 and Table D2, respectively. The derivation of the alert standards was followed by a flood damage and casualty analysis.

5. Results

5.1. Flood risk assessment case study 1 (Q1)

The implementation of new spatial developments according to the official spatial planning locations resulted in a significant increase in financial flood damage compared to the references scenario without spatial developments (Table 3). The difference between the reference and official spatial planning financial flood damage is referred to as the additional flood damage in this section. The impact of new spatial development on the amount of financial flood damage differs per dike ring section. For dike ring section 45-1, the flood extent covers almost the entire dike ring area (Figure B4a). As a result, most planned spatial developments in case study 1 will be impacted, which resulted in a large financial flood damage increase of €6,631 million (Table 3), or +11.6%. The largest relative increase in financial flood damage (expressed in the weighted 2050 flood damage $D_{w,2050}$) is observed for dike ring section 45-2 (Figure 5A), where the financial flood damage increases with 145.3%. This can be attributed to the relative high number of new spatial developments (2,340 new residences) planned in Bunschoten, which is the only city significantly impacted by flood scenarios in section 45-2 (Figure B4b). For section 45-3, no increases were computed, because no new spatial developments were planned in its very limited inundation zone (Figure B4c).

The increase in financial flood damage also impacts the strictness of the SCBA alert standard. For dike ring section 45-1, these new spatial developments led to a significant increase in the strictness of the alert standard: from 1/155,718 to 1/173,716 per year (Table 3). Although this does not result in a more stringent flood safety standard class as per Slootjes & Van der Most (2016a), it still means that there is a considerable increase in flood risk that can directly be attributed to the current spatial planning in the case study 1 area. As for section 45-1, a strong increase in the strictness of the alert standard is observed in dike ring section 45-2, where the 'official planning' alert standard is more than two times as strict as the reference alert standard: 1/488 versus 1/199 per year (Table 3). However, the sharp increase in the section 45-2 SCBA alert standard strictness does not lead to a more stringent flood safety standard class. No changes were computed for dike ring section 45-3, as no new spatial developments were planned in that area. The economic flood risk for the entire dike ring 45 area almost doubles, with an increase of 97%: new spatial developments add €5.5 million extra economic flood risk to the reference value of €5.7 million.

Table 3: Weighted 2050 flood damage ($D_{w,2050}$), economic flood risk and SCBA alert standards case study 1 (Q1)

Dike ring section ->	**45-1**	**45-2**	**45-3**
Reference $D_{w,2050}$ [million €]	57,370	366	14
Official planning $D_{w,2050}$ [million €]	64,001	899	14
Additional flood damage [million €]	+6,631 (11.6%)	+533 (145.3%)	-
Reference economic flood risk [million €/year]	5.7		
Official planning economic flood risk [million €/year]	11.3 (+5.5 / 97 %)		
Reference alert standard [yr^{-1}]	1/155,718	1/199	1/177
Official planning alert standard [yr^{-1}]	1/173,716	1/488	1/177

Both the reference and official planning scenarios show that the financial flood damage is naturally concentrated in the major population centers of the dike ring area (Figure 14). It can be observed that near the north-eastern and south-western boundaries of the dike ring area, there are areas that are not inundated, even during the Grebbedijk TL+1D flood scenario that is shown here, which is the flood scenario with the largest flood extent. Furthermore, the amount of additional flood damage for all spatial development projects can be described as large even for relatively smaller housing projects, as many projects have financial flood damages of at least €100,000 per ha (Figure 14). Two new industrial projects even have financial flood damages upwards to +€5 million per ha, marked with green and yellow. Highlighted in green is a planned new industrial site of 14 ha near the city of Bunschoten. An even larger industrial site of 22.86 ha is planned near Veenendaal, marked in yellow. Large housing projects are also recognizable in Figure 14: marked in blue is the Vathorst Bovendruist housing project in the Amersfoort municipality, the largest project in the entire dike ring area with 2,500 new residences planned. This project leads to an additional flood damage of €1.7 million per ha.

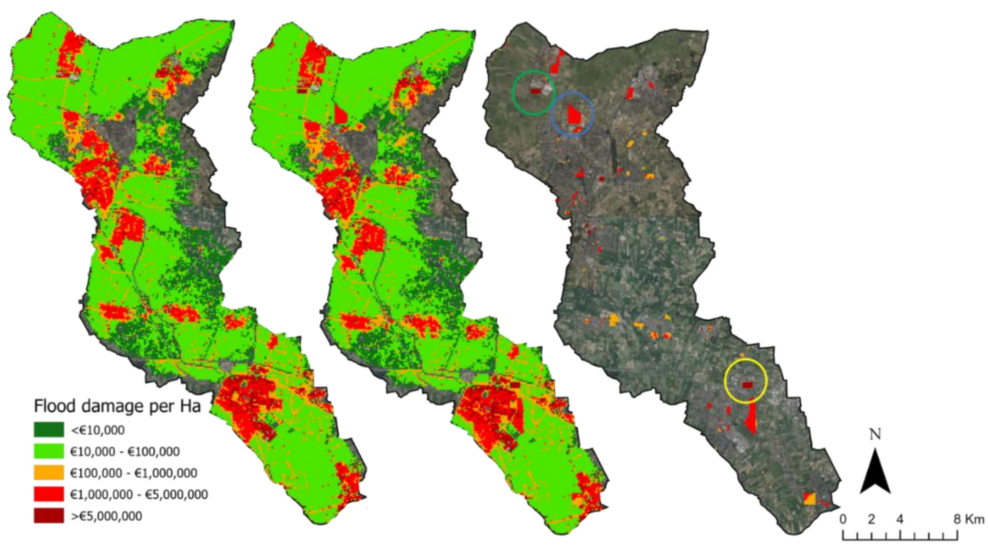

Figure 14: Total financial flood damage (price level 2011) Grebbedijk TL+1D scenario (Q2): from left to right the SSM reference scenario, the official planning scenario, and the difference

An important contribution to the total financial flood damage is formed by monetarized casualties. Most casualties will fall in section 45-1 (Table 4): 1,257 flood casualties in the reference case. This number rises with 182 additional casualties to 1,439 because of the new spatial developments. The limited extent of 45-2 and 45-3 are reflected in the low number of casualties. Both sections 45-2 and 45-3 cover predominantly rural areas, with large Natura2000 reserves in section 45-3. Because flood events in section 45-3 cover mostly Natura2000 nature reserve areas, no casualties were computed.

Table 4: Casualties per flood scenario case study 1 (Q2)

Dike ring section	Flood casualties reference scenario	Flood casualties official planning scenario	Difference
45-1	1,257	1,439	+182
45-2	2	9	+7
45-3	0	0	0

5.2. Development & validation spatial planning framework (Q2)

5.2.1. Development spatial planning framework

The classification of flood characteristics and flood damage was an important step in the development of the spatial planning framework. The classification of the inundation depth (Table 5) was derived partially from Pieterse et al. (2009). Pieterse et al. (2009) describe their own concept of flood risk zoning, which also relies on the formulation of certain classes for variables like the inundation depth. Pieterse et al. (2009) consider inundation depths of <0.5 m as 'shallow', 0.5 – 2 m as 'medium deep' and > 2 m as 'deep'. This system of inundation depth classification was used and expanded upon by adding the extra class 'extreme' that captures all inundation depths larger than 3 m, allowing for a more detailed classification of inundation depths. The classification of the different rise rates was kept in accordance with the SSM2017 classification for different rise rates (Table 5). Five damage classes were formulated, each of which (except for the *Zero* class) captured an equal part of the potential flood damage relative to the total asset value as derived from the damage function analysis (Table 6). The inundation depths in Table 6 show for which inundation depths a spatial object incurs damage that falls within that particular damage class. A similar classification system was developed for the different mortality classes (Table C1). A statistical analysis showed that for the Grebbedijk TL+1D flood scenario, the mean mortality per grid cell was 0.5%, with a standard deviation of 0.7%. Because of the large standard deviation, it was decided to define all mortality rates between 0 and 0.5% as low, between 0.5 and 1.2% as medium and all mortality rates higher than 1.2% as high.

Table 5: Flood characteristics classification

Classes	Inundation depth [m]	Rise rate [m/hour]	Flood class	Flood probability [year^{-1}]
Not floodable	0	0	**Small**	0.000333
Small	0 – 0.5	0 – 0.5	**Large**	>0.00033
Medium	0.5 – 2	0.5 - 4	-	-
Large	2 - 3	>4	-	-
Extreme	>3	-	-	-

Table 6: Damage classification

Classes	Damage to total asset value	Inundation depth family homes [m]	Inundation depth apartments [m]	Inundation depth industry [m]
Zero	0%	0	0	0
Small	0-25%	0 -1.4	0 - 1.03	0 - 0.35
Medium	25-50%	1.4 - 3.06	1.03 - 2.94	0.35 - 0.94
Large	50-75%	3.06 - 4	2.94 - 5.02	0.94 - 2.45
Catastrophic	> 75%	> 4	> 5.02	> 2.45

After the classification of damage and flood characteristics, the initial set of flood risk zones was formulated, which consisted of all possible flood pattern combinations, including the damage profile for each flood pattern (Table C2). The next step was to remove all flood risk zones with similar damage profiles from this initial set of flood risk zones. This resulted in the basic spatial planning framework (Table C3), which consists of six flood risk zones. From each flood risk zone in the basic spatial planning framework (except for flood risk zone 1), two new versions were made: one version with a small flood probability and one with a large flood probability. This resulted in the creation of the extended spatial planning framework, with 11 flood risk zones (Table 7). Both the basic and extended spatial planning frameworks show that industrial objects are the most vulnerable of all spatial structures considered, followed by apartments. Family homes are less prone to flood damage for higher inundation depths. The result that apartments have a higher flood vulnerability than family homes is a direct consequence of how SSM2017 estimates flood damage for apartments: the damage functions for direct damage to ground- and first floor apartments show that these objects experience more damage at lower inundation depths than family homes (Heymen, 2020). Higher floor apartments on the other hand are less vulnerable to flooding. Furthermore, the evaluation of apartment flood damage in section 4.2.1. largely depends on the ground- and first floor apartment damage functions by using the 1/3rd distribution of apartments (also see section 4.1.1.). The prioritization from most (industry) to least (family homes) vulnerable spatial objects was used in the implementation of new spatial structures as part of the application of both the basic and extended spatial planning framework.

Table 7: Spatial planning framework

Flood risk zone	Inundation depth	Rise rate	Damage to family homes	Damage to apartments	Casualty rates	Damage to industry	Flood probability
1	Not floodable	Not floodable	Zero	Zero	Zero	Zero	Zero
2	Small	All	Low	Low	Low	Medium	Small
3	Small	All	Low	Low	Low	Medium	Large
4	Medium	All	Medium	Medium	Medium	High	Small
5	Medium	All	Medium	Medium	Medium	High	Large
6	Large	Low	Medium	High	Medium	Catastrophic	Small
7	Large	Low	Medium	High	Medium	Catastrophic	Large
8	High	Medium, high	Medium	High	High	Catastrophic	Small
9	High	Medium, high	Medium	High	High	Catastrophic	Large
10	Extreme	All	Catastrophic	Catastrophic	High	Catastrophic	Small
11	Extreme	All	Catastrophic	Catastrophic	High	Catastrophic	Large

5.2.2. Validation spatial planning framework

The validation of the extended version of the spatial planning framework was done with three variants (section 4.2.4.). The application of the spatial planning framework in the full dike ring area variant did completely eliminate all additional flood damages (Table 8) for sections 45-1 and 45-2. Additional flood damage is defined as the difference in financial flood damage between the reference scenario and any other variant (official planning, full dike ring area, municipality, and city outskirts). The total reduction of additional flood damage the full dike ring area variant means that €6,631 million in additional flood damage could be prevented for section 45-1 by relocating the new spatial developments to flood risk zone 1. For section 45-2, it meant that the additional flood damage was reduced with €523 million to zero as well. The application of the extended framework in the municipality variant (relocation of spatial developments within the municipalities) did not lead to the total elimination of total financial flood damage as it was the case for in the full dike ring area variant, but a significant reduction in additional flood damage was obtained nonetheless (Table 8). Use of the framework in the municipality variant led to €1,936 million additional flood damage in section 45-1. This means that the additional flood damage as a result of the official spatial planning was reduced by 70.3% (Table C4). Although the relative reduction in additional flood damage is not as large as in section 45-1, the additional flood damage in section 45-2 was considerably reduced by more than a half: -54.7%. The variant city outskirts (relocation of spatial developments only to the outskirts of urban centers) leads to more additional flood damage compared to the other two variants: €2,906 million for section 45-1 and €395 million for section 45-2. Nevertheless, this means that the additional flood damage was more than halved in section 45-1 (-56.2%) and reduced by 24.5% in section 45-2. The results show that more flexibility in the relocation of new spatial developments leads to progressively less additional flood damage, as can be observed from the differences in computed financial flood damages between the full dike ring area and city outskirts variants. As no spatial structures were planned in section 45-3, no changes in financial flood damage were computed.

Table 8: Weighted 2050 flood damage ($D_{w,2050}$) with application of the extended framework for the case study 1 validation (Q2)

Variant	$D_{w,2050}$ 45-1 [million €] *(additional damage)*	Reduction additional flood damage 45-1	$D_{w,2050}$ 45-2 [million €] *(additional damage)*	Reduction in additional flood damage 45-2	$D_{w,2050}$ 45-3 [million €]
Reference	57,370	-	366	-	14
Official planning	64,001 (+6,631/ 11.6%)	-	899 (+523/ 145.3%)	-	14
Full dike ring area	57,370	100%	366	100%	14
Municipality	59,306 (+1,936 /3.4%)	70.8%	603 (+237/ 64.7%)	54.7%	14
City outskirts	60,276 (+2,906 /5.1%)	56.2%	762 (+395/ 107.9%)	24.5%	14

Reductions in additional flood damage naturally led to smaller increases in the strictness of the SCBA alert standards. Whereas the official spatial planning led to new SCBA alert standards of 1/73,716 and 1/488 per year for sections 45-1 and 45-2 respectively (Table 9), application of the framework for the full dike ring area variant managed to retain the alert standards at reference level. Application of the framework with the municipality variant resulted in somewhat stricter alert standards that are still roughly comparable to the reference alert standards. The same holds true for the city outskirts variant, for which the section 45-1 and 45-2 alert standards are closer in strictness to the reference alert standards than to the official planning alert standards. Another indication of the effectiveness of the framework application is the reduction in additional economic flood risk in dike ring area 45: in the municipality variant, use of the framework reduced additional economic flood risk with 27.6% compared to the official planning. In the city outskirts variant, additional economic flood risk was reduced by 13.3%.

The application of the framework also yielded a reduction of the number of additional casualties compared to the reference scenario: whereas the official planning led to 181 additional casualties in section 45-1, the spatial planning framework could reduce this number to around 40 to 60 additional casualties depending on the variant used (Table C6). Large reductions in financial flood damage were also achieved for all object types, especially for apartments and family homes despite the prioritization of industry (Table C7 till Table C9).

Table 9: SCBA alert standards and economic flood risk extended framework case study 1 (Q2), with the reduction in additional economic flood risk marked in green

Variant ->	Reference	Official planning	Full dike ring area	Municipality	City outskirts
Alert standard 45-1 [yr^{1}]	1/155,718	1/173,716	1/155,718	1/160,972	1/163,606
Alert standard 45-2 [yr^{1}]	1/199	1/488	1/199	1/327	1/413
Alert standard 45-3 [yr^{1}]	1/177	1/177	1/177	1/177	1/177
Economic flood risk dike ring area 45 [million €/yr]	5.7	11.3	5.7 (-5.5/ 100%)	8.1 (-3.1 / 27.6%)	9.8 (-1.5 / 13.3%)

The effectiveness of both spatial planning frameworks in the full dike ring area variant is the result of being able to relocate all new spatial developments to areas belonging to the non-floodable flood risk zone 1 (Figure 15A). As the case study area is located in a valley, large zones of land at the north-eastern and south-western boundaries of the case study area remain dry even during the most extreme flood events. Therefore, most of the new spatial developments were located to these locations, highlighted in orange and yellow (Figure 15B). Part of the old locations could be retained, as they also fell into flood risk zone 1. A good example of this is Amersfoort, where parts of the city center and the rural areas west and east of the city remain dry (marked red).

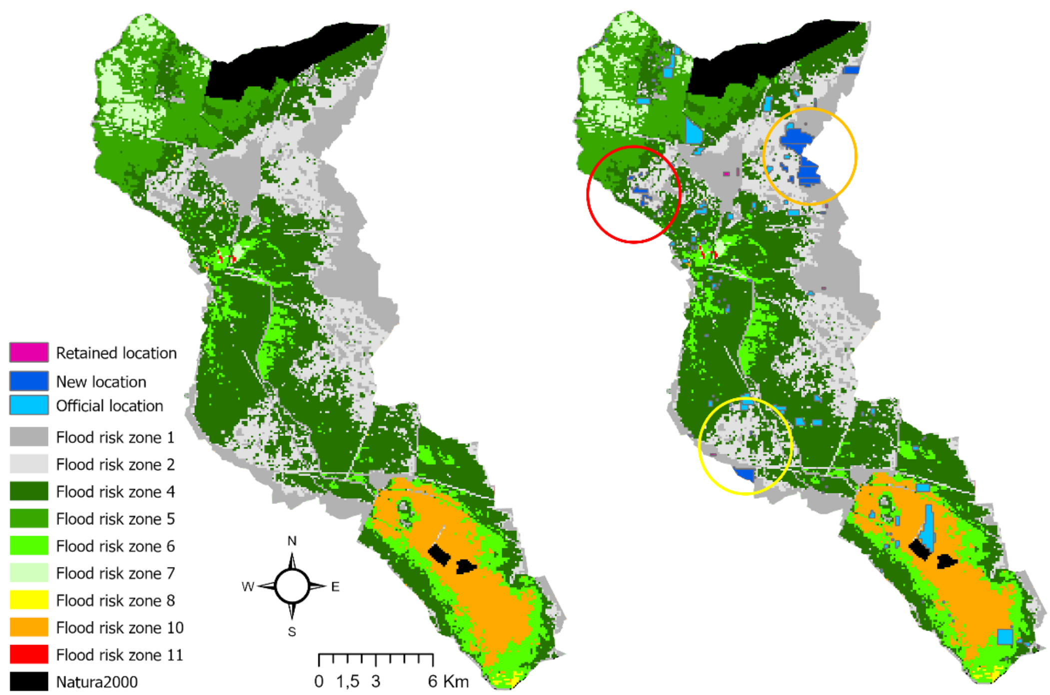

Figure 15A) Flood risk zoning extended framework B) Full dike ring area spatial planning

The spatial planning after application of the extended framework differs clearly from the official spatial planning (Figure 16A): only for some spatial development projects, the original location could be retained based on the spatial planning framework. in nearly every municipality, the most favorable locations were found at the municipal boundaries. An example of this is Nijkerk (highlighted in yellow), where it was easy to relocate all spatial developments to the east. For municipalities as Bunschoten (red), the most favorable flood risk zones were already occupied by the existing built environment. Therefore, part of the official locations could be retained, especially the brownfield projects. An interesting municipality to highlight is Amersfoort (Figure 16B): in the east of the city, a handful of small spatial development projects could be retained. The large housing project Vathorst Buivendruist (marked orange) was located in a rather unfavorable area. Under the new spatial planning, new spatial developments were concentrated in the west of the city, as the areas with flood risk zone 1 in the east were already occupied by the built environment.

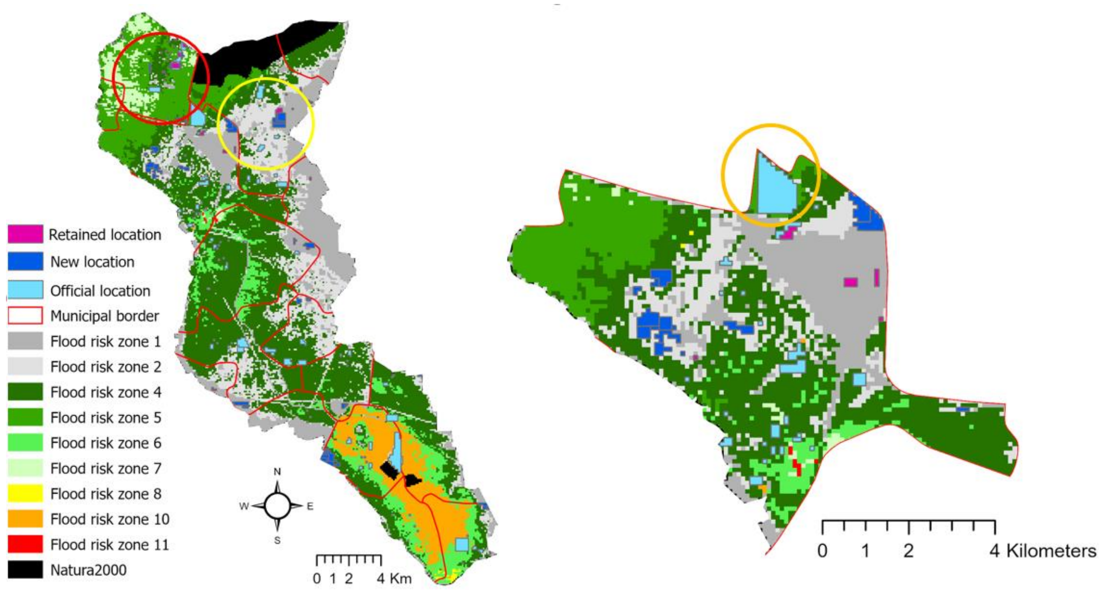

Figure 16A) Municipality spatial planning B) Amersfoort spatial planning

The relocation of new spatial developments to the boundaries of existing urban areas leads to interesting results (Figure 17A). For municipalities like Bunschoten (marked yellow), it meant that all spatial developments were shifted to the west, as there was more room there to implement all new spatial objects in the same (favorable) flood risk zone. In Wageningen (marked red), the new residences were shifted towards the north of the city, similar to the relocation based on the municipality variant (Figure 16). In some municipalities such as Woudenberg, the framework showed that the most favorable locations at the city outskirts could be found at the exact opposite site of where urban expansion was actually planned (Figure 17B).

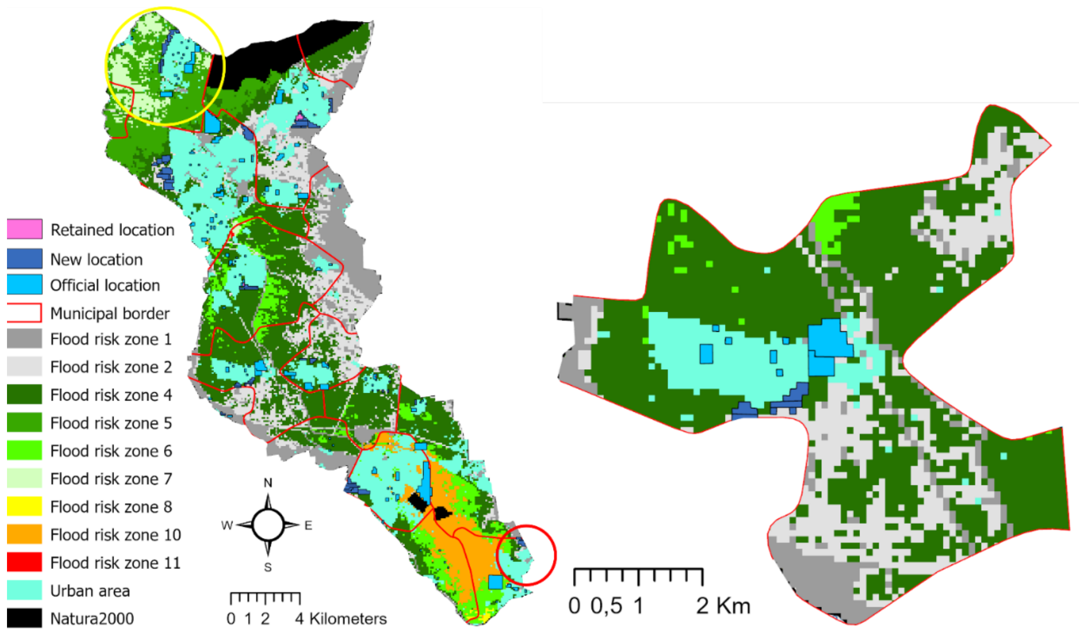

Figure 17A) City outskirts – Extended spatial planning framework B) Woudenberg new spatial planning

The values for the municipal median flood risk zone numbers (Table 10) show that for most municipalities, the median flood risk zone is quite low. This is the case for the municipalities of Nijkerk, Barneveld, Utrechtse Heuvelrug and to a lesser extent Amersfoort, Ede and Leusden. Municipalities as Veenendaal, Rhenen and Wageningen on the other hand have a rather high median flood risk zone. The median flood risk zone for new spatial developments according to the official planning does not deviate significantly from the municipal flood risk zone (Table 10). Only in Woudenberg and the Utrechtse Heuvelrug can small differences between the official planning and municipal median flood risk zone be observed. The large similarity between the municipal median food risk zones shows that municipalities do not seem to consider flood risks when considering locations for new spatial developments, as previously stated in section 1.2. Application of the extended framework in the municipality variant lead to positive changes in the median flood risk zone for new spatial developments: for 12 of the 13 municipalities, new spatial developments were relocated to flood risk zones with considerably lower flood risk compared to the official planning or did not need to be relocated. For most municipalities, all new spatial developments could be relocated to flood risk zone 1. Only for Bunschoten no meaningful improvements in flood risk zone could be achieved, because new spatial projects were already planned in the most favorable locations.

Table 10: Median flood risk zone for case study 1 (Q2)

Median Flood risk zone / Municipality	Municipal flood risk zone	Official planning	Full dike ring area variant	Municipality variant (difference to official planning)	City outskirts variant (difference to official planning)
Rhenen	6	6	1	2 (-4)	2 (-4)
Veenendaal	10	10	1	4 (-6)	4 (-6)
Wageningen	6	6	1	1 (-5)	1 (-5)
Ede	4	4	1	1 (-3)	4
Leusden	4	4	1	1 (-3)	4

Utrechtse Heuvelrug	2	1	1	1	1
Renswoude	4	4	1	1 (-3)	2 (-2)
Scherpenzeel	4	4	1	1 (-3)	2 (-2)
Woudenberg	4	2	1	1 (-1)	2
Amersfoort	4	4	1	1 (-3)	1 (-3)
Barneveld	1	1	1	1	1
Nijkerk	2	2	1	1 (-1)	1 (-1)
Bunschoten	5	5	1	5	5

The level of flood risk reduction obtained through use of the extended spatial planning framework is quite similar to the level of flood risk reduction obtained by the basic version of the framework. The reduction in additional flood damage and flood risk for the basic framework for the full dike ring area and city outskirts variants (Table C4 and Table C5) is exactly the same as for the extended version. Only for the municipality variant, small changes in the level the flood risk reduction between both framework versions were computed. Because the inundation depths are aggregated into classes that have a relatively large range it could have been possible that due to the inclusion of flood probability, an area was selected that falls within the same inundation depth class as another area but has a slightly larger inundation depth that leads to more financial flood damage. Because financial flood damage for a certain spatial object in two flood risk zones with the same damage pattern but different flood probability will always fall within certain boundaries, this result could be expected to some degree. The same holds for flood risk reduction results of the different variants, as more flexibility in the relocation of spatial objects leads to more flood risk reduction. Therefore, in the remainder of this study the municipality variant was used because it represents a trade-off between flexibility and realism, as most spatial developments are planned on a municipal basis. Because the extended framework includes more flood characteristics for roughly the same results as the basic framework, the extended framework is selected as the main spatial planning framework in this study. The benefit of including flood probability is that the extended framework covers both components (probability and consequences) of flood risk.

5.3. Results application framework case studies 2 & 3 (Q3)

For case study 2 (dike ring area 35), the construction of new spatial developments according to the official spatial planning leads to a large increase of 21.6 % (+€2,401 million) in financial flood damage for section 35-1 (Table 11). The amount of additional flood damage in section 35-2 can be considered as minor. The large increase in section 35-1 can be attributed to the larger concentration of new spatial development in this part of the dike ring area, especially in Waalwijk. However, this additional flood damage can be reduced effectively through use of the extended spatial planning framework: the additional flood damage for section 35-1 can be reduced with 48.6% (-€1,167 million). A small reduction in additional damage of €17 million could be achieved for section 35-2, which is still a significant reduction of 27.9% (Table 11). For case study 3 (dike ring area 15), the current spatial planning had a relatively small effect on the financial flood damage, with an increase in flood damage of 3.1% for section 15-1 and 2.7% for section 15-2. This is due to the fact that the flood extent of most flood scenarios is such that also large parts of dike ring area 14 in the north are affected (Figure D1). Because dike ring area 14 contains many spatial structures with a large combined economic value, the impact of new spatial developments in dike ring area 15 is relatively small. Still, the financial flood damage increases with large amounts, with +€2,401 million for section 15-1 alone. Application of the framework is successful in reducing the amount of additional flood damage relative to the official planning scenario: for section 15-1, a reduction of 33% could be achieved and 26.9% for section 15-2. For dike ring section 35, a larger reduction in additional flood damage than for dike ring section 15 could be achieved by application of the framework.

Table 11: Weighted flood damage $D_{w,2050}$ (Q3)

Dike ring section	$D_{w,2050}$ "SSM reference" [million €]	$D_{w,2050}$ "Official planning" [million €]	Difference reference vs. official planning [million €]	$D_{w,2050}$ "Framework" [million €]	Difference reference - framework [million €]	Reduction in additional flood damage by framework
35-1	11,115	13,516	+2,401 (21.6%)	12,348	+1,234 (9.1%)	-1,167 (48.6%)
35-2	3,406	3,466	+61 (1.8%)	3,449	+44 (1,3%)	-17 (27.9%)
15-1	84,854	87,499	+2,645 (3.1%)	86,618	+1,763 (2.1%)	-882 (33%)
15-2	53,359	54,782	+1,423 (2.7%)	54,408	+1,049 (2.0%)	-383 (26.9%)

The impact of the increased financial flood damage in section 35-1 is quite significant, leading to a change in alert standard from 1/12,481 to 1/15,564 yr^{-1} (Table 12). For section 35-2, there were no meaningful changes in the alert standard for the spatial planning according to either the official planning or the framework due to only a small increase in financial flood damage. For dike ring area 15, the increases in financial flood damage were large, but the impact was small as the total value of spatial assets in the impacted area is significant. This is reflected in the official planning and framework alert standards for section 15-1 and 15-2, which do not significantly differ from the reference alert standard. For all dike ring sections in case studies 2 and 3, it holds that the newly computed alert standards do not lead to the adaptation of a more stringent flood safety standard class (Slootjes & Van der Most, 2016a). In terms economic flood risk, there are significant differences (Table 12) between the reference scenario and after the implementation of new spatial developments: in dike ring areas 35 and 15, the economic flood risk increases with 12.1% and 2.8% respectively. Application of the framework does lead to a relatively large reduction in additional economic flood risk of 5.1% for dike ring area 35. For dike ring area 15, application of the framework results in a small economic flood risk reduction of 0.8% compared to the official planning situation.

Table 12: SCBA alert standards and economic flood risk case studies 2 and 3 (Q3)

Variants ->	SSM reference	Official planning	Framework	Reduction additional economic flood risk
35-1 alert standard [yr^{-1}]	1/12,481	1/15,564	1/13,866	/
35-2 alert standard [yr^{-1}]	1/1,488	1/1,514	1/1,507	/
15-1 alert standard [yr^{-1}]	1/18,447	1/19,022	1/18,830	/
15-2 alert standard [yr^{-1}]	1/11,265	1/11,565	1/11,486	/
Dike ring area 35 economic flood risk [million €/yr^{-1}]	7.1	8.0 (+12.1%)	7.6 (+6.4%)	-0.4 (5.1%)
Dike ring area 15 economic flood risk [million €/yr^{-1}]	26.3	27.0 (+2.8%)	26.8 (+2.0%)	-0.2 (0.8%)

Application of the framework did not yield a reduction in the number of flood casualties for case study 2 (Table D3): the number of casualties for sections 35-1 and 35-2 do not change after relocation of new spatial developments to safer areas. There could be several reasons for this result, the first being that the new spatial developments in the municipalities of Dongen and Oosterhout were already planned in areas with an median flood risk zone of 1, which means that the potential for flood risk and casualty reduction is small to none in the first place (Table 13). The second reason is that for Waalwijk, the municipality with the majority of new spatial developments, there were no changes in the median flood risk zone for spatial developments after application of the framework (Table 13). The statistical analysis of flood risk zones and spatial developments does show that the mean flood risk zone decreases due to the framework, but not with a large margin. These reasons could explain the lack in flood casualty reduction. In general, the median flood risk zones (Table 13) for case study 2 show that application of the framework does not lead to a large shift towards lower, more favourable flood risk zones, because either the official planning already planned new spatial project in favourable flood risk zones (Dongen and Oosterhout) or there were not many favourable areas available for construction (Waalwijk and Geertruidenberg).

For case study 3, application of the framework did lead to a shift towards more favourable flood risk zones in comparison to case study 2. The high median flood risk zone present in each municipality reflects the flat polder flood type in dike ring area 15 (Table 13), which is especially visible in the Krimpenerwaard and Krimpen a/d IJssel municipalities. The differences between median municipal flood risk zones and the median flood risk zones for spatial projects according to the official planning show that municipalities planned new spatial developments in areas with less flood risk compared to the municipial median. This might be caused by the fact that most urban centers are located at the boundary of the dike ring area, where on average more favourable flood risk zones can be found (Figure 19). Despite high levels of flood risk, it was possible to singificantly reduce flood risk in most municipalities, especially for IJsselstein and Lopik. In case study 3, application of the framework did lead to a reduction in the number of additional flood casualties compared to the references scenario (Table D3): from +83 to +54 casualties for section 15-1, and from +34 to +22 for section 15-2. The larger effectiveness in reducing casualties for case study 3 compared to case study 2 could be caused by the fact that in case study 3, spatial developments were relocated to new flood risk zones that on average differed more from the official planning flood risk zones than in case study 2 (Table 13). Despite that in case study 3, there is a larger shift towards more favorable flood risk zones than in case study 2, the financial flood damage computations show that the framework leads to the largest additional flood damage reduction in case study 2 (Table 12). Because the framework median flood risk zones in case study 2 are lower than in case study 3, this difference in additional flood damage reduction could be caused by the non-linearity in the level of flood risk captured by each consecutive flood risk zone. Because SSM2017 damage functions are non-linear, the change in the level of flood risk between for example flood risk zones 2 and 3 can be different than between flood risk zones 5 and 6. For both case studies 2 and 3 it holds that overall, the spatial planning framework is effective in reducing additional flood risks but not as successful as in case study 1 with the municipality variant.

Table 13: Median flood risk zone case studies 2 and 3 (Q3)

Median flood risk zone / Case study	Municipality	Municipal flood risk zone	Official planning	Framework
2	Dongen	4	1	1
	Oosterhout	5	1	1
	Geertruidenberg	6	5	4 (-1)
	Waalwijk	5	4	4
3	Krimpen a/d IJssel	11	7	5 (-2)
	Krimpenerwaard	11	7	5 (-2)
	Lopik	7	5	1 (-4)
	Nieuwegein	4	4	4
	IJsselstein	5	5	2 (-3)
	Montfoort	7	5	5
	Oudewater	11	7	5 (-2)

In case study 2, the modified spatial planning shows that new spatial developments were relocated to the boundaries of the dike ring area where possible, especially towards the southern dike ring area border (Figure 18). There were some specific areas of interest: marked in yellow is the Overdiepsche Polder. Although the polder has been classified into flood risk zone 1 based on the official LIWO flood maps, Waterschap Brabantse Delta (2015) mentioned that it is used as a water retention basin. Therefore, it was excluded as possible area for the relocation of spatial developments. Marked in blue is a large industrial area planned in the Waalwijk municipality. This industrial area has partially been relocated to the south-eastern part of the municipality (marked red). Most brownfield projects in Waalwijk could be retained. The same holds true for almost all housing projects in Dongen (marked white) and neighbouring Oosterhout, the municipality west of Dongen.

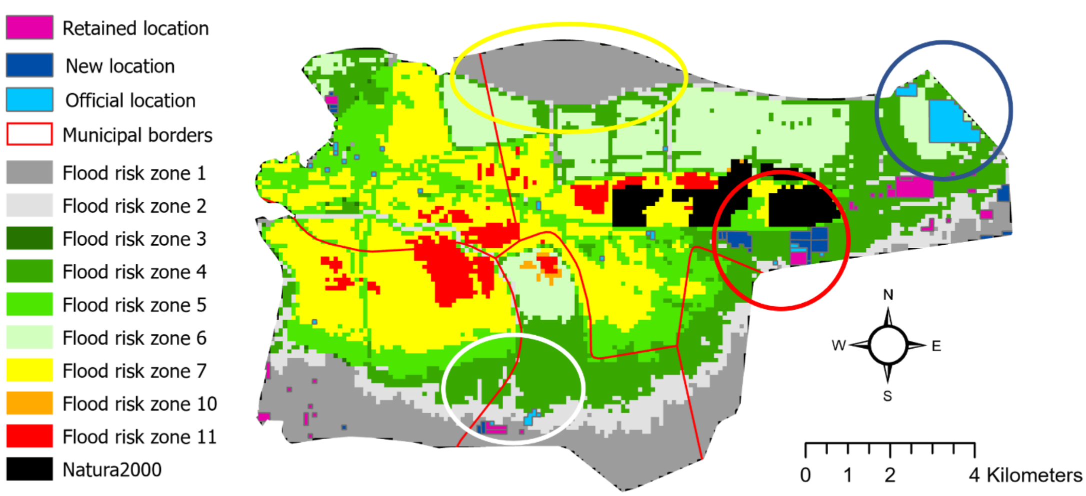

Figure 18: Case study 2 modified spatial planning

Figure 19 shows the modified spatial planning for case study 3. The most favorable flood risk zones are located in the east to north-east of the dike ring area, which made it difficult to find better locations for municipalities as Krimpen a/d IJssel (marked yellow), where the spatial developments were relocated from flood risk zone 11 to a location with flood risk zone 7, behind a road. An example of a municipality where most locations could be retained are the Montfoort (marked blue) and Nieuwegein municipalities. The majority of new spatial developments were planned in the east (Nieuwegein and IJsselstein) of the dike ring area, where flood risk was lower than in the west.

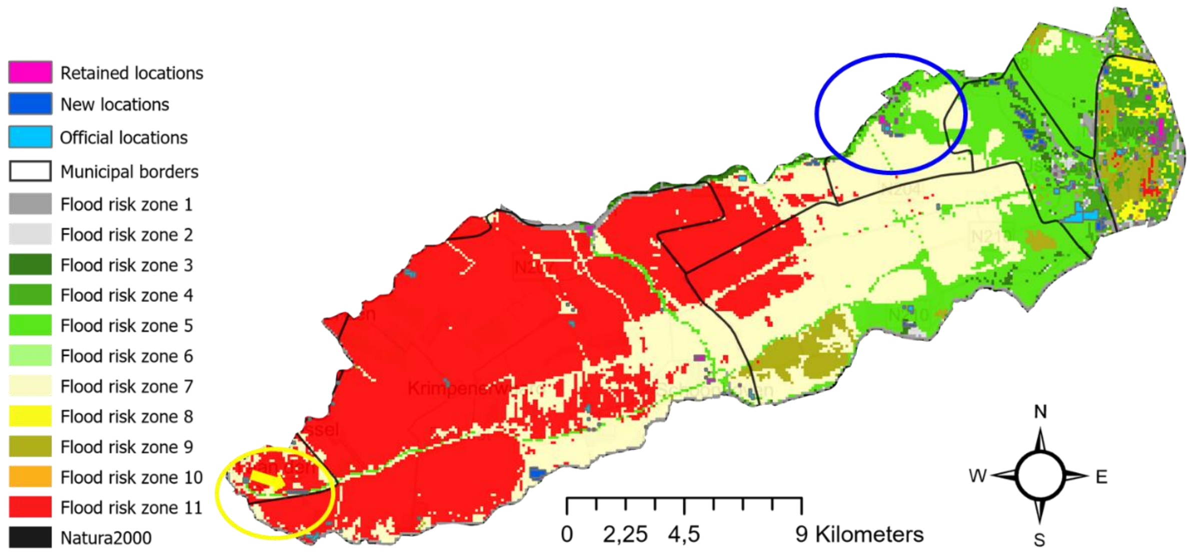

Figure 19: Case study 3 modified spatial planning

6. Discussion

In this section, the results, limitations, and potential of this study are discussed. Section 6.1 consists of a critical assessment of the methods and assumptions used in this study and their impact on the results. Section 6.2. describes the potential of this study.

6.1. Methods and results

6.1.1. Assumptions and limitations study

A potential issue with the methodology for the classification of flood characteristics and damage is that the classification is based partially or fully on arbitrarily selected threshold values. Part of the inundation depth classification was based on the classification by Pieterse et al. (2009), which in itself was admitted by the authors as being based on 'rough assumptions'. The classification of financial flood damage was entirely based on the authors' own interpretation of the impact of certain percentages of financial flood damage. The same issue of arbitrariness could also be raised for the classification of low and high flood probabilities for each case study. The classification of flood probability was guided by the necessity to limit the number of flood risk zones. Ideally, more sources or input from expert would have been available to guide the classification process. The classification of flood damage and characteristics had a large impact on the results, because it formed the basis under the spatial planning framework and the flood risk zone mapping of the case studies.

Furthermore, it should be considered whether the framework could have included more aspects relevant for the determination of flood risk. Flood characteristics such as the flood arrival time were not included in the framework. The Pieterse et al. (2009) framework uses flood arrival time instead of the rise rate. A case could be made for the inclusion of flood arrival time: according to Pieterse et al. (2009), the arrival time is an important indicator for the survival chances (evacuation fraction) in the first days of flooding, especially combined with the rise rate. Thus, ideally the flood arrival time would have been included into the framework as an extra indicator for casualty risk. This could have improved the framework but was not done so. The reason for this is that the framework is based on SSM2017, which only uses the rise rate and inundation depth to compute casualties with. Therefore, exclusion of the flood arrival time did not impact the results but use of the framework in the context of different damage and casualty models could lead to a requirement to include the flood arrival time or other flood characteristics.

The discussion about the inclusion or exclusion of certain flood characteristics has a direct link to the flood risk criteria. The framework that was developed in this study focusses exclusively on financial flood damage related to the SCBA flood risk criterion and ignores aspects important to LIR criterion, such as the evacuation fraction (flood arrival time) and the flood characteristics of a flood scenario (Slootjes & Van der Most, 2016a). According to de Bruijn et al. (2018), large scale spatial developments do influence flood patterns, which in turn leads to different outcomes in the computation of casualties and damage. However, flood risk and flood related processes are not the only threat to new spatial developments: processes like soil subsidence also play a role in the suitability of certain areas for new spatial developments. Therefore, the framework does not consider all factors that contribute to flood risk and the suitability of different areas for new spatial developments. A similar issue concerns the spatial measures used in this study. The framework only used relocation as a spatial planning measure, but there are different spatial planning measures that could have been used, such as using denser housing concentrations. Building in denser concentrations could have led to larger reductions in flood risk, as more spatial structures would have fitted into favorable flood risk zones.

The choice between the basic version of the spatial planning framework without flood probability and the extend version could not be made based on the results generated by this study alone, due to the high similarity in the results of these two versions. The choice for the extended framework was made based on the main argument that the extended framework leads to similar reductions in flood risk in comparison to the basic framework, while including more flood characteristics (flood probability). The opposite argument is that the basic framework offers the same effectiveness as the extended framework as the extended framework for a more limited set of flood risk zones. The basic framework might leave more space for the addition of flood characteristics other than the flood probability, as expanding on the set of 11 flood risk zones from the extended framework could lead to an unworkable amount of flood risk zones. This is relevant for the attractiveness of the framework to spatial planning and flood safety institutions. Related to this topic is that this study did not consider whether spatial planning institutions would be interested in the concept of spatial planning frameworks in relation to flood risk, and what their requirements are for a spatial planning framework or similar instruments.

Another comment is that during the study, areas belonging to dike ring area municipalities that were not inside the dike ring area itself were not considered for the relocation of new spatial developments as part of the application of the framework. This could have had a large positive impact on the reduction of flood risk in some instances: for case study 1 it could have made a difference, as many municipalities had large areas outside the dike ring area in the higher elevated areas of the Veluwe and the Utrechtse Heuvelrug. This is the case for Amersfoort, Bunschoten and Scherpenzeel, where not all spatial structures could be relocated to dry zones but which at the same time had dry areas outside of the dike ring area. For case study 2 it would have mattered as well, because the Waalwijk municipality, which had more than 50% of all new spatial developments in the case study, could have relocated more housing and industry to flood risk zone 1 in the south. For case study 3 it would not have mattered, as all the areas surrounding it are at risk of flooding as well. In general, the scale at which relocations were allowed did have a large impact on the results. Using the spatial scale of a dike ring area for the relocation of new spatial developments is not likely for spatial planning authorities, who might have more interest in a municipal, provincial, or even national approach to spatial planning.

The final issue concerns the construction of new residences between 2014 and 2021. In SSM2017, the reference date for all spatial structures considered in the land use maps is July 2014, meaning that structures built between 2014 and 2021 were not considered during computation of flood risk and flood damages. For a small selection of municipalities from case study 1, the changes in housing stock between 2014 and 2021 were compared to the number of new residences implemented in this study (Table E1). This comparison shows that for the selected municipalities, the 2014-2021 changes in housing stock are comparable in magnitude to the number of new residences planned in the period 2021-2030, meaning that ignoring housing construction between 2014 and 2021 could have had a large impact on the results. For the conclusion, the omission of the 2014-2021 spatial developments matters less, because the added value of the 2021-2030 spatial developments remains unchanged.

6.1.2. Data and model limitations

All data for the different flood scenarios used in this study were derived from LIWO, the database by Rijkswaterstaat. However, in some instances data about certain flood scenarios or flood characteristics was not available. For case study 1, TL+1D flood scenarios were missing for 2 out of 5 breach locations in section 45-2, and for section 45-3 in its entirety. Furthermore, the TL flood scenario in section 45-3 provided by LIWO only contained data about the inundation depth. Similarly, all flood scenarios in dike ring area 35 lacked data about the rise rate. For breach locations without TL+1D scenarios, their TL scenarios were used in the construction of worst-case flood scenarios for each dike ring section. The impact of missing data on the results was negligible, as either SSM2017 could go without certain data or solid assumptions could be made. However, for future use of the framework in either the Netherlands or abroad, a lack of flood data could be a serious limitation.

The choice for the use of SSM2017 in this study was made as it was the most modern model available which included all required damage functions. Therefore, the framework is fully designed for SSM2017 and its damage and mortality functions. The drawback to using SSM2017 is that its damage and mortality functions cannot be modified, and modifications to its land-use maps can only be made if the model is run outside the user interface. Therefore, other damage and casualty models might offer more freedom in the computation of financial flood damages, especially for areas where data might be lacking or only input data for different flood characteristics than used in this study is available.

The lack of access to flood scenarios used in the past by Rijkswaterstaat also impaired the accurate computation of reference SCBA alert standards. The derivation of the SCBA alert safety standards for each dike ring section in this study did not always lead to alert standards that were comparable to the official SCBA alert standards as computed by Rijkswaterstaat. For case study 1, the computed SCBA alert standards based on SSM2017 model results without new spatial development showed that the basic alert standard derivation process as used in this study were correct, albeit based on slightly different financial flood damage values (Table 14).

Table 14: Comparison data case study 1

Dike ring section	Official alert standard [yr^{-1}]	SSM Reference alert standard [yr^{-1}]	Official $D_{w,2050}$ [million €]	SSM reference $D_{w,2050}$ [million €]
45-1	1/152,400	1/155,718	56,000	57,370
45-2	1/200	1/199	410	366
45-3	1/200	1/177	20	14

For case studies 2 and 3, the computed alert standards in this study were not always comparable to the official alert standards. For sections 35-1 and 35-2 in case study, the derivation of the alert standard did not yield satisfactory results (Table 15). In case study 3, the computed financial flood damages and alert standards for section 15-1 and 15-2 were roughly comparable to the official values. The differences between the official SCBA alert standards, the SSM derived reference SCBA alert standards and computed financial flood damages could stem from different causes: Slager & Wagenaar (2017) state that the SSM2017 model has slightly modified damage functions compared to older SSM type models. Westerhof (2019) also mentions that there is a certain degree of uncertainty involved with the official Dutch flood safety standard process, especially regarding the documentation of the official calculation process. Because Rijkswaterstaat did not share the exact derivation process for each individual dike ring section, it was not possible to determine the exact cause of the deviations. A possibility might be that the flooding maps have been updated, therefore leading to different outcomes. Section 15-3 was not considered in this study, because the financial flood damages and alert standard did not at all resemble the official values.

Table 15: Comparison data case studies 2 and 3

Dike ring sections	Official SCBA alert standard [yr^{-1}]	SSM Reference alert standard [yr^{-1}]	Official $D_{w,2050}$ [million €]	SSM reference $D_{w,2050}$ [million €]
35-1	1/8,400	1/12,481	7,300	11,115
35-2	1/1,800	1/1,488	4,000	3,406
15-1	1/19,100	1/18,447	90,000	84,854
15-2	1/12,600	1/11,265	60,000	53,359
15-3	1/7,500	1/1,907	17,000	4,267

6.2. Potential and strengths of this study

This study delivers a meaningful contribution to the topic of future flood risk by its accurate quantification of the effects of the effects of the current spatial planning policies on flood damage and flood risk through use of the official Dutch method for the quantification of financial flood damage and flood risk. A feature of past studies on the quantification of future flood risks is that they did not consider the exact official spatial planning or specific known spatial planning projects on a municipal or even neighborhood scale as in this study, but instead used a range of different economic development scenarios to determine the general changes in housing stock on a regional basis. Examples are studies by Mustafa et al. (2018) and Bouwer et al. (2010) (section 1.3). The accurate computation of future flood risk in this study can also be attributed to the use of SSM2017 instead of the more simplified damage models used in other studies. Use of the official Dutch method offered a structured way of processing the SSM2017 results. It also allowed the evaluation of flood risk instead of financial flood damage alone, by computation of the official SCBA alert standards and using the derivation method to compute economic flood risk. Another strength of using the official Dutch method is that the economic impact of spatial planning decisions is quantified in the same way as was done for the derivation of Dutch flood safety standards. The study shows that the costs of a 'bad' spatial planning decision can be measured and expressed in both added flood risk and added financial flood damage. The added flood risk and financial flood damage can be used as a starting point for the potential budget for flood risk mitigating measures.

The framework developed in this study differentiates itself from the only other spatial planning framework by Pieterse et al. (2009) by using more detailed classifications of the flood characteristics and damage, and by actually defining the damage classification on multiple types of spatial objects (family homes, apartments, industrial objects) rather than by broad categories such as 'vital and non-vital' objects. Further improvements compared to the Pieterse et al. (2009) spatial planning framework are the inclusion of rise rate for the classification and quantification of casualties, as well the quantification of the effects of the framework on the reduction of flood risks associated with spatial developments.

Because the methodology for the development of a spatial planning framework is quite general, it is possible to use this methodology for modifications of further improvements to the framework proposed in this study, depending on the needs of its future uses. It is therefore possible to use even more detailed classifications or add other flood characteristics and spatial objects. Flood characteristics such as the flood arrival time or flow velocity could be added to the existing framework, using either the basic or extended framework version as basis. Similarly, the framework can be adjusted for different flood damage and casualty models, or in situations where there is either a lack of data or different data compared to this study.

7. Conclusion

The aim of this chapter is to provide answers to the three research questions posed at the start of this study and to conclude whether the research aim has been fulfilled or not.

1. *What is the impact of the current plans for new spatial developments on flood risks?*

The computation of the yearly economic flood risk of each case study shows that the current spatial planning leads to a significant increase in flood risk for case study 1. Considering the two other case studies, it can be concluded that for both case studies the impact of the current spatial plans on future flood risk is significant, but not as significant as for case study 1. The impact of current spatial planning on future financial flood damage is also substantial. For case study 3, the impact of the current spatial plans is comparatively less than in the other case studies, because the scale of new spatial developments is relatively small compared to the value of the current spatial assets in the dike ring area. New spatial developments in all case studies do not lead to the adaptation of stricter flood safety standards, despite all dike ring sections considered in this study having a SCBA normative flood safety standard. Thus, the current plans for new spatial developments have a large impact on the flood risk in dike ring areas, but in some case studies more so than for others depending on the value of spatial assets already present in the dike ring area relative to the number of new spatial structures, and whether new spatial developments are planned in areas with favorable or unfavorable flood characteristics.

2. *According to what specifications can a spatial planning framework be developed?*

Two flood characteristics matter most: the inundation depth for flood damage and the inundation depth coupled with the rise rate of water for flood casualties. The development process was successful in defining unique damage profiles for each flood risk zone, despite using four damage categories. Furthermore, the inclusion of casualties as an indicator of financial flood damage was a valuable addition to the aggregation of flood risk. Because the monetary value of casualties forms a significant contribution to financial flood damage, it is vital for it to be included in any spatial planning framework that aims to reduce financial flood damage. The further expansion of the basic framework into the extended spatial planning framework could be achieved fairly easy. Although the number of flood risk zones used by the basic framework nearly doubled for the extended framework, it can be concluded that even using a spatial planning framework that consists of 11 flood risk zones still yields clear flood risk zoning maps. Thus, the spatial planning framework development process offers a novel and structured way of analyzing, classifying, and presenting flood risk, while at the same time leaving the door open for new additions and improvements.

This study has shown that both the basic and extended versions of the spatial planning framework are highly effective in reducing flood risk for different types of spatial objects and casualties, using a simple method for the relocation and prioritization of vulnerable spatial developments towards more favorable locations. The results of applying both framework versions to the new spatial developments in case study 1 prove that additional flood damage associated with these spatial developments can be eliminated completely, depending on the application scale of the spatial planning framework. The largest reductions in flood risk can be achieved when spatial developments are allowed to be relocated throughout the entire dike ring area. Less freedom in the relocation of spatial developments lead to smaller reductions in financial flood damage, but even then, additional flood risk can be reduced by more than 50%. Therefore, it is worthwhile for spatial planning authorities to consider flood risk as a factor in spatial planning, and for flood safety authorities to consider spatial planning as a useful flood risk mitigation instrument. Because the results did not show significant differences between the basic and extended frameworks and the latter integrates all components of flood risk (probability and consequences), it was decided to select the extended spatial framework as the main spatial planning framework.

3. *What is the impact of the spatial planning framework on flood risks associated with new spatial developments for different case studies?*

The study results show that significant reductions in financial flood damage for case studies 2 and 3 can be achieved by using the extended spatial planning framework in the municipality variant. The effectiveness of the extended spatial planning framework does change for different flood types: the results point out that the potential for flood damage reduction through use of the framework seems to be higher for dike ring areas with an inclined plane flood type (case studies 1 and 2) than for dike ring areas with the flood type flat polder, such as case study 3. This is because dike ring areas with the inclined plane flood type contain more areas with a lower flood risk zone and thus more potential for flood risk reduction. Still, this does not mean that the framework cannot be used effectively for different flood types: even for the flat polder flood type, reductions in financial flood damage from 26.9% to 33% can be achieved, as proven by case study 3. Use of the framework might not always be effective. In some cases, there is less potential for use of the framework in the ‘municipality’ variant, such as for municipalities where flood risk is already minimal and for municipalities with small housing projects. In such cases, it is necessary to research whether the reduction in flood risks outweigh costs made in other areas. Thus, it can be concluded that the study proved that this spatial planning framework is able to mitigate additional flood risks for multiple different dike ring areas with different spatial and flood characteristics.

8. Recommendations

8.1. Recommendations for further research

The results of this study prove that in many cases, proper spatial planning can aid flood safety authorities in the reduction of flood risks. the first recommendation is to look into how this spatial planning framework and the use of it can be improved. There are several ways to improve the spatial planning framework. The first is to include more flood characteristics, such as the flood arrival time and flow velocity. Especially inclusion of the flood arrival time can be helpful in identifying areas with a high risk at casualties. Furthermore, potential room for improvement can be found in the addition of different spatial planning measures. In this study spatial planning measures were defined quite narrowly: only relocation was considered. However, spatial planning measures are much broader than just relocation: densification of housing projects, partial restrictions on spatial developments, the construction of higher apartment buildings or building waterproof are all spatial planning measures with flood risk reducing potential. Lastly, the classification system that forms the basis of the current framework could be modified, creating more detailed classes for flood damage and the flood characteristics. improvement of the spatial planning framework developed in this study is done best in collaboration with institutions that have a potential interest in using spatial planning frameworks. Examples of potentially interested institutions are the spatial planning departments of municipalities and provinces, and flood safety institutions such as the HWBP (*Flood protection program*), formed by Rijkswaterstaat and multiple regional water authorities.

The second recommendation is to extend the spatial planning framework beyond flood risk alone and include other factors that also affect the resilience and safety of housing. A recent report by Sweco commissioned by the Dutch Delta committee offers a starting point for this recommendation (Booister et al., 2021). Booister et al. (2021) state that climate change will negatively affect the Dutch housing program in different ways. The framework already considers up to a certain degree the increasing probability of flooding as a result of climate change by considering worst case flood scenarios. However, it does not consider aspects such as soil subsidence, the carrying capacity of soils, wet soils *(*areas with high groundwater levels, low retention capacity and low infiltration velocity*)*, soils that are at risk of droughts and saline soils (Booister et al., 2021). Booister et al. (2021) state that alle these soil conditions play a part in whether a location is suitable for new spatial developments or not. Because most of these conditions can be linked to climate change and water management, Booister et al. (2021) provide an interesting starting point for the expansion of the current spatial planning framework.

A final recommendation for further study is to compute the effect of large concentrations of new spatial developments on the flood pattern of flood scenarios. Although sources like Van der Most & Klijn (2013) did not consider housing to be a significant factor that influences flood pattern, De Bruijn et al. (2018) state explicitly that flood scenarios should be reconsidered in case of large scale new spatial developments. Large housing projects like Amersfoort Bovendruist in case study 1 with its 2,500 new residences can be considered large scale, so this recommendation has also a direct relevance for this study.

8.2. Recommendations for policy

A recommendation in the field of spatial planning policy is to include a cost-benefit analysis in the framework. Other interests in the planning of new housing projects, such as the proximity to existing population centers, existing infrastructure and other services has been purposefully left out of the research scope. However, in practice these are important interests that in current spatial planning carry much more weight than flood risks. Therefore, they cannot be ignored. The relocation of new spatial developments under application of the spatial planning framework led to instances where new spatial developments were either located far away from the population centers, spread out in small pockets or both. If new housing would be constructed like this in the real world, it would lead to significant extra costs in the construction of new infrastructure and utilities, notwithstanding the extra costs in both time and finances of buying out or expropriating landowners of those plots and making the area ready for construction. It is therefore relevant to compare the benefits of reducing flood risks versus the costs of building in locations further away from existing cities.

A second recommendation for policy makers is to use the framework to prioritize areas that are currently being considered for new spatial developments based on flood risk. In this way, the spatial planning framework can be applied without disregarding other interests important for the choice of new development locations. The final recommendation is to apply the framework (or similar tools) on a larger scale than just per municipality or dike ring area. This could include application of the framework on a provincial or even national scale. As this study showed that increasing the spatial scale at which relocations are considered improves the flood risk reduction effectiveness of the framework, it is useful to deal with the issue of spatial planning and flood risk at a larger scale.

References

Atrivé. (2018). Regionale woningmarktstrategie van het Land van Cuijk 2018. *In de kern wil iedereen wonen*. Kopgroup Wonen het Land van Cuijk. Retrieved from https://www.atrive.nl/static/default/files/Atriv%C3%A9/downloads%20Atriv%C3%A9/Regionale%20woningmarktstrategie%20van%20het%20Land%20van%20Cuijk%202018.pdf

Berg, A. (2022, May 7). *Stedelijkheid (van een gebied)*. Opgehaald van www.cbs.nl: https://www.cbs.nl/nl-nl/onze-diensten/methoden/begrippen/stedelijkheid--van-een-gebied--

Blaauw, E. (2022, February 1). Voorstel college van burgemeesters en wethouders. Gemeente Bronckhorst.

Booister, N., Hekman, A., Swinkels, R., Wienhoven, M., Hek, M., Nillessen, A., . . . Van Alphen, J. (2021). *Het effect van de klimaatverandering op de woningbouwopgave.* Sweco.

Boon, M. (2011). *Overstromingsrisico dijkring 15: Lopiker- en Krimpenerwaard.* Rijkswaterstaat. Opgehaald van https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/publicaties/dijkringrapporten/overzichtspagina/dijkringrapporten-in/

Bouma, A., & Lentferink, L. (2021). Woonvisie 2021-2030. Stec Group.

Bouwer, L., Bubeck, P., & Aerts, J. (2010). *Changes in future flood risk due to climate and development in a Dutch polder area.* Amsterdam: Global Environmental Change. doi:10.1016/j.gloenvcha.2010.04.002

Braggerman, K., & Bayer, M. (2022, February 27). *Kamer dwing utrecht to woningbouw in Rijnenburg*. Opgehaald van stadszaken.nl: https://stadszaken.nl/artikel/3213/kamer-dwingt-utrecht-tot-woningbouw-in-rijnenburg

Buck consultants international. (2019, November 15). Onderbouwing uitbreidingen Oudewater buiten de rode contour. Den Haag. Opgehaald van https://www.planviewer.nl/imro/files/NL.IMRO.0589.BPTH3-ON01/b_NL.IMRO.0589.BPTH3-ON01_tb1.pdf

CBS. (2021). *Huishoudens nu.* Den Haag: CBS. Opgeroepen op April 4, 2022, van https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/woonsituatie/huishoudens-nu

De Bruijn, K., Cappendijk, P., Van Buren, R., & Hendriks, A. (2011). *Analyse van slachtofferrisico's waterveiligheid 21e eeuw.* Delft: Deltares. Opgehaald van https://repository.tudelft.nl/islandora/object/uuid%3A863a2ba5-296b-499e-9650-77c459403a04

De Bruijn, K., Kind, J., & De Grave, P. (2019). *Waterveiligheidsnormen: achterliggende factoren en relatie met nieuwbouw en vitale infrastructuur.* Delft: Deltares.

De Bruijn, K., Kind, J., & De Grave, P. (2019). *Waterveiligheidsnormen: achterliggende factoren en relatie met nieuwbouw en vitale infrastructuur.* Delft: Deltares.

De Bruijn, K., Slager, K., Piek, R., Riedstra, D., & Slomp, R. (2018). *Leidraad voor het maken van overstromingssimulaties.* Deltares. Opgehaald van https://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/europese-richtlijn-overstromingsrisico/overstromingsgevaar-overstromingsrisicokaarten/leidraad/

De Bruijn, K., Wagenaar, D., Slager, K., De Bel, M., & Burzel, A. (2015). *Updated and improved method for flood damage assessment: SSM2015.* Deltares. Opgehaald van https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/aanleg-onderhoud/aanleg-onderhoud/schade-slachtoffer/

De Groot, B. (2014). *Overstromingsrisico dijkringgebied 35, Donge.* Rijkswaterstaat WVL. Retrieved from https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/publicaties/dijkringrapporten/overzichtspagina/dijkringrapporten-in/

De Jong, F., & Hin, M. (2019). *Wonen in krachtige kernen.* Gemeente Landerd . Atrivé . Opgehaald van https://www.atrive.nl/actueel/projecten/woonvisie-landerd.html

De Vree, J. (2022). *Bebouwingsdichtheid*. Opgeroepen op May 7, 2022, van https://www.joostdevree.nl/shtmls/bebouwingsdichtheid.shtml

Dijksterhuis, H., Toonen, P., Van der Burgt, J., Weil, R., & Van Dasler, W. (2021). *Woningbouwmonitor gemeente Nijkerk.* Nijkerk. Retrieved from https://nijkerk.bestuurlijkeinformatie.nl/Reports/Item/1db0d17b-5741-44e6-92fe-3a5d416ca1b9

Ellis, J. (2004). *Explaining Residential Density.* Places. Opgehaald van https://escholarship.org/content/qt2np5t9ct/qt2np5t9ct_noSplash_218d42b13dacd75d9d0a60b4c635dcf7.pdf

Gemeente Apeldoorn. (2018). Afwegingskader woningbouw 2018 t/m 2027. *'De juiste woonkwaliteit voor Apeldoorn'*. Opgehaald van https://www.apeldoorn.nl/ter/fl-afwegingskader-2019

Gemeente Bronckhorst. (2022). Uitwerking uitbreidingslocaties woningbouw en werkwijze. Opgehaald van https://www.bronckhorst.nl/home/uitbreidingslocaties_47130/

Gemeente Brummen. (2018). Woonagenda 2019-2023. Retrieved from https://www.brummen.nl/fileadmin/brummen/Documenten/Inwoners/Bouwen_en_wonen/Woonagenda_2019_-_2023_definitief.pdf

Gemeente Den Bosch. (2014). *Ruimtelijke structuurvisie.* Opgehaald van https://www.s-hertogenbosch.nl/ruimtelijkeplannen/vastgestelde-structuur-en-gebiedsvisies/

Gemeente Deventer. (2004). Structuurplan Deventer 2025. *Synergie van Stad en Land*. Opgehaald van https://www.deventer.nl/ruimtelijke-plannen/structuurvisies/structuurplan-deventer-2025

Gemeente Dongen. (2022, January). Overzicht woningbouwcapaciteiten per gemeente. Dongen: Municipality Dongen.

Gemeente Dronten. (2009). Structuurvisie Dronten 2030. Opgeroepen op February 27, 2022, van https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.0303.SVDronten2030-VA01/d_NL.IMRO.0303.SVDronten2030-VA01.html

Gemeente Duiven. (2018). *Woningbouwprogramma Gemeente Duiven 2018-2027.* Duiven.

Gemeente Epe. (2019). Woonagenda gemeente Epe 2019-2023. *Mijn Thuis*. Opgehaald van https://www.epe.nl/document.php?m=10&fileid=58174&f=a49b862c566326717ef59fd31abe9fa5&attachment=0&c=29260

Gemeente Geertruidenberg. (2021, June 3). *Omgevingsvisie Geertruidenberg*. Retrieved February 28, 2022, from www.omgevingsvisie.geertruidenberg.nl: https://omgevingsvisie.geertruidenberg.nl/

Gemeente Heusden. (2019). Welstandsnota Heusden 2019. Opgeroepen op February 25, 2022, van https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.0797.Welstandsnota2019-0001/d_NL.IMRO.0797.Welstandsnota2019-0001.html

Gemeente Loon op Zand. (2018). Structuurvisiekaart 2030. Opgehaald van https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.0809.StructuurvisieWijz-VG01/b_NL.IMRO.0809.StructuurvisieWijz-VG01_bd.html

Gemeente Nieuwegein. (2017, July 18). Woningbouwprogramma 2030 gemeente Nieuwegein. Opgehaald van https://www.nieuwegein.nl/fileadmin/bestanden/Inwoner/Wonen_in_Nieuwegein/Woningbouwprogramma_2030_definitief.pdf

Gemeente Nijkerk. (2011). *Structuurvisie Nijkerk/Hoevelaken 2030.* Opgehaald van https://www.bing.com/search?q=structuurvisie+nijkerk&cvid=490c1a262014462b8083047a7dc61b3c&aqs=edge.0.0l3j69i60.5396j0j1&pglt=2083&FORM=ANNTA1&PC=U531

Gemeente Noord-Beveland. (2020). 2020. *Woningmarktafspraken De Bevelanden 2020-2030*. Retrieved from https://www.reimerswaal.nl/sites/reimerswaal/files/2021-06/Woningmarktafspraken%20de%20Bevelanden.pdf

Gemeente Olst-Wijhe. (2017). Structuurvisie Olst-Wijhe. *Ruimte voor initiatief en innovatie*. Opgehaald van https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.1773.SV2017012003-0301/d_NL.IMRO.1773.SV2017012003-0301.pdf

Gemeente Oosterhout. (2021, November 23). *De goede woning op de goede plek*. Retrieved February 27, 2022, from www.omgevingsvisieoosterhout.nl: https://www.omgevingsvisieoosterhout.nl/aantrekkelijk-wonen-in-een-aantrekkelijke-omgeving

Gemeente Oosterhout. (2022). *Projecten en woningbouwplannen*. Opgeroepen op February 25, 2022, van www.oosterhout.nl: https://www.oosterhout.nl/inwoners/ruimtelijke-ontwikkeling/projecten-en-woningbouwprojecten

Gemeente Putten. (2019). *Structuurvisie Putten 2030.* Opgehaald van https://www.putten.nl/Inwoners/Bouwen_Verbouwen/Bestemmingsplannen/Ruimtelijke_visies/Structuurvisie_Putten_2030_vastgesteld/Kaart_structuurvisie_Putten_2030_PDF_2_44MB

Gemeente Rheden. (2014). Structuurvisie Rheden. *Dorp van morgen*. Opgehaald van https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.0275.SVRHEDEN-VA01/d_NL.IMRO.0275.SVRHEDEN-VA01.pdf

Gemeente Scherpenzeel. (2013). *Structuurvisie Scherpenzeel.* Croonen Adviseurs. Opgehaald van https://www.scherpenzeel.nl/_flysystem/media/03a-structuurvisie.pdf-deel-1.pdf

Gemeente Voorst. (2021, October 26). *Woningbouw in kleine en grote dorpskernen stap dichterbij*. Retrieved February 23, 2022, from www.voorst.nl: https://www.voorst.nl/nieuws/artikel/woningbouw-in-kleine-en-middelgrote-dorpskernen-stap-dichterbij

Gemeente Vught. (2019). *Woningbouwprogramma Vught 2019-2028.*

Gemeente Waalwijk. (2020). *Uitvoeringsprogramma Waalwijk.* Opgehaald van https://www.waalwijk.nl/document.php?m=23&fileid=24798&f=c23d95beccc1ed4d9d56152a456c04bc&attachment=0

Gemeente Westervoort. (2021). *Woonvisie Westervoort 2021-2030.* Westervoort. Opgehaald van https://ris2.ibabs.eu/Agenda/Details/Westervoort/db0754e1-6d3c-4625-aed8-510fff385000

Gemeente Woudenberg. (2018). *Goed wonen = Samen doen.* Retrieved from https://www.regiofoodvalley.nl/projecten/woonagenda-20

Gemeente Zeewolde. (2012). Structuurvisie 2022. Retrieved from https://www.leefbaarzeewolde.nl/wp-content/uploads/2020/05/d_NL.IMRO_.0050.SVStructvisie2022-VA01.pdf

Gemeente Zutphen. (2018). Structuurvisie Noordrand de Hoven. Zutphen. Opgehaald van https://raad.zutphen.nl/data/raadsstuk-raad/vaststelling-structuurvisie-noordrand-de-hoven/1.%20Ontwerp-structuurvisie,%20zoals%20deze%20ter%20inzage%20gelegen%20heeft.pdf

Geuting, E., & Schouten, J. (2020, October 21). Woonvisie 2020-2025 Gemeente Bunschoten. *Bijzonder wonen in bedrijvig Bunschoten*. Bunschoten: Stec Group. Retrieved from https://storage.googleapis.com/caramel-binder-207612.appspot.com/uploaded/bunschoten.vvd.nl/files/5fc12c61d9d29/rv-1156651-bijlage-woonvisie-bunschoten-2020-2025.pdf

Glas, P. (2021). *Spoor 2 briefadvies woningbouw en klimaatadaptatie.* Deltaprogramma. Opgeroepen op June 13, 2022, van https://www.deltaprogramma.nl/documenten/publicaties/2021/12/06/briefadvies-deltacommissaris-woningbouw-en-klimaatadaptatie-spoor-2

Groenemeijer, L., Gopal, K., Stuart-Fox, M., Van Leeuwen, G., & Omtzigt, D. (2021). *Vooruitzichten bevolking, huishoudens en woningmarkt.* Delft: ABF Research.

Heymen, R. (2020). *Gebruikershandleiding Schade Slachtoffer Module (SSM).* Rijkswaterstaat WVL.

Hillen, M., Jonkman, S., Kanning, W., Kok, M., Geldenhuys, M., & Stive, M. (2010). *Coastal defence costs estimates.* Delft: TU Delft. Opgehaald van https://www.researchgate.net/publication/283986030_Coastal_defence_cost_estimates_a_case_study_of_the_Netherlands_Vietnam_and_New_Orleans

Kabat, P., Fresco, L., Stive, M., Veerman, C., Van Alphen, J., Parmet, B., . . . Katsman, C. (2009). *Dutch coasts in transition.* University of Amsterdam. Nature Geoscience. Retrieved from https://www.researchgate.net/figure/Flood-safety-standards-of-dykes-in-The-NetherlandsThe-current-level-of-protection-ranges_fig2_46383972

Kind, J., Bak, C., De Bruijn, K., & Van der Doef, M. (2011). *Maatschappelijke kosten-batenanalyse.* Delft: Deltares. Opgehaald van https://puc.overheid.nl/rijkswaterstaat/doc/PUC_139011_31/

Klijn, F., Baan, P., De Bruijn, K., & Kwadijk, J. (2007). *Overstromingsrisico's in Nederland in een verandered klimaat.* Delft: Delft hydraulics. Opgehaald van https://repository.tudelft.nl/islandora/object/uuid%3A015c62a1-558d-422c-8706-efc0e4db2fc3

Klijn, F., Kreibich, H., De Moel, H., & Penning-Roswell, E. (Adaptive flood risk management planning based on a comprehensive flood risk conceptualisation). *2015.* Delft: Springer. doi:doi:10.1007/s11027-015-9638-z

Klouwen, B., & Klouwen, K. (2021). *Woonvisie 2021-2025.*

Klouwen, B., & Tiekstra, C. (2019a, July 8). Woonvisie gemeente Montfoort 2019-2030. Companen. Retrieved from https://www.montfoort.nl/mozard/document/docnr/1942337/Woonvisie%202019-2030

Klouwen, B., & Tiekstra, C. (2019b, July 4). Woonvisie gemeente IJsselstein 2019-2030. Opgehaald van https://lokaleregelgeving.overheid.nl/CVDR626553?&show-wti=true

Klouwen, B., & Westgeest, J. (2017, December 1). Woonvisie Lopik 2018-2022. *Ruimte met kwaliteit*. Companen. Opgehaald van https://www.lopik.nl/_flysystem/media/woonvisie-lopik-2018-2022-ruimte-met-kwaliteit-vastgesteld-in-de-raad-van-6-februari-2018-2.pdf

Kok, M., Nieuwjaar, R., & Tánczos, I. (2017). *Grondslagen voor hoogwaterbescherming.* Delft: ENW. Opgehaald van https://puc.overheid.nl/rijkswaterstaat/doc/PUC_151040_31/1/

Lambregts, I., Langeveld, F., & Telder, K. (2016). Concept lokale woonagenda gemeente Doetinchem 2016-2025. Retrieved from https://besluitvorming.doetinchem.nl/Vergaderingen/beeldvormende-raad/2016/08-september/19:30/Lokale-woonagenda/Concept-lokale-woonagenda-gemeente-Doetinchem-2016-2025.pdf

Lendering, J. (2020, April 23). *The Edges of the Earth*. Opgeroepen op March 18, 2022, van Livius.org: https://www.livius.org/articles/concept/the-edges-of-the-earth-1/the-edges-of-the-earth-3/

LIWO. (2020). *Vragen en antwoorden LIWO webinar.* Rijkswaterstaat. Opgehaald van https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/watermanagement/watermanagement/liwo/@242496/beantwoording-vragen-liwo-webinar/

Maaskant, B., Jonkman, S., & Kok, M. (2009). *Evacuatieschattingen Nederland.* HKV lijn in water.

Mulder-Metselaar, E. (2017). Woonvisie 2017-2022 gemeente Doesburg.

Mustafa, A., Bruwier, M., Archambeau, P., Erpicum, S., Pirotton, M., Dewals, B., & Teller, J. (2018). *Effects of spatial planning on future flood in urban environments.* Luik: Journal of Environmental management. doi:10.1016/j.jenvman.2018.07.090

Neuvel, J., & Van den Brink, A. (2009). *Flood risk management in Dutch local spatial planning practices.* Wageningen: Journal of Environmental Planning and Management. Opgehaald van doi:10.1080/09640560903180909

Omroep Flevoland. (2021, December 2021). *Flevoland wil van 170.000 naar 300.000 woingen*. Opgeroepen op February 22, 2022, van www.omroepflevoland.nl: https://www.omroepflevoland.nl/nieuws/264749/flevoland-wil-van-170-000-naar-300-000-woningen

Pieterse, N., Knoop, J., Nabielek, L., Pols, K., & Tennekes, J. (2009). *Overstromingsrisicozonering in Nederland.* Den Haag/Bilthoven: Planbureau voor de leefomgeving (PBL). Opgehaald van https://www.pbl.nl/publicaties/overstromingsrisicozonering-in-nederland

Project team omgevingsvisie gemeente Gouda. (2022, February 26). Opgehaald van Ontwerp omgevingsvisie Gouda: https://omgevingsvisie.gouda.nl/

Projectbureau VNK2. (2011). *De methode van VNK2 nader verklaard.* Den Haag. Retrieved from https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/publicaties/

Provincie Noord-Brabant. (2021a). *Ontwikkeling van de Brabantse woningvoorraad.* Retrieved February 28, 2022, from Bevolkingsprognose.brabant.nl: https://bevolkingsprognose.brabant.nl/hoofdstuk/ontwikkeling-van-de-brabantse-woningvoorraad.html

Provincie Noord-Brabant. (2021b). Omgevingsverordening Brabant. *(Interim version)*. Noord-Brabant. Retrieved from https://www.ruimtelijkeplannen.nl/web-roo/transform/NL.IMRO.9930.InterimOvrgc-1121/pt_NL.IMRO.9930.InterimOvrgc-1121.xml#NL.IMRO.PT.s06d2d8f7-510e-4627-8457-d467e7808ce2

Provincie Noord-Holland, & Metropoolregio Amsterdam. (2022, February 18). Opgehaald van Monitor plancapaciteit: https://plancapaciteit.nl/

Provincie Overijssel. (2021). *Woonagenda West-Overijssel.* Opgehaald van https://d3v5xt11159cxv.cloudfront.net/PDF-bestanden/Regionale-Woonagenda-West-definitief-concept-feb-2021.pdf?mtime=20210211154817&focal=none

Reith, A. (2020). *Woonvisie gemeente Zeewolde.* Zeewolde. Retrieved from https://zeewolde.bestuurlijkeinformatie.nl/Agenda/Document/0d7fd34d-6b13-45d5-99ee-92278ed42838?documentId=e090e8ee-b576-46b9-b9a7-25f9737d4e9c

Rijksoverheid. (2022). *Doelen ruimtelijk beleid*. Opgeroepen op June 13, 2022`, van www.rijksoverheid.nl: https://www.rijksoverheid.nl/onderwerpen/ruimtelijke-ordening-en-gebiedsontwikkeling/doelen-ruimtelijk-beleid

Schoorel, E. (2021, May 19). *Woningbouw lage polders gaat door, maar is ook omstreden*. Opgeroepen op June 13, 2022, van https://vastgoedactueel.nl/woningbouw-lage-polders-gaat-door-maar-is-ook-omstreden/#:~:text=Woningbouw%20lage%20polders%20gaat%20door%2C%20maar%20is%20ook,wonen%20in%20overstromingsgebieden%20te%20veel%20op%20achtergrond%20raken.

Slager, K., & Wagenaar, D. (2017). *Standaardmethode 2017.* Rijkswaterstaat.

Slootjes, N., & Van der Most, H. (2016a). *Achtergronden bij de normering van primaire waterkeringen in Nederland.* Ministerie van Infrastructuur en Milieu. Retrieved from https://docplayer.nl/31939562-Achtergronden-bij-de-normering-van-de-primaire-waterkeringen-in-nederland-hoofdrapport.html

Slootjes, N., & Van der Most, H. (2016b). *Technische-inhoudelijke uitwerking van eisen aan primaire keringen.* Delft: Deltaprogramma. Opgehaald van https://docplayer.nl/68886965-Synthesedocument-veiligheid.html

Slootjes, N., & Wagenaar, D. (2016). Factsheets normering primaire waterkeringen. Deltares. Retrieved from https://iplo.nl/thema/water/waterveiligheid/primaire-waterkeringen/normen-voor-primaire-waterkeringen-oud/

Spronk, J., Voorburg, A., Van Loon, H., & Dresmé-Spiegelenberg, E. (2012). Structuurvisie gemeente Heerder 2025. Arcadis . Opgehaald van https://www.heerde.nl/Bestuur_en_organisatie/Beleid_en_regelgeving/Beleidsbibliotheek/Wonen_en_leefomgeving/Structuurvisie_Heerde_2025

Ten Cate, C. (2017). *De Liemers mag 2800 huizen in 10 jaar tijd bouwen*. Opgeroepen op February 22, 2022, van Ad.nl: https://www.gelderlander.nl/liemers/de-liemers-mag-2-800-huizen-in-tien-jaar-bouwen~aa189224d/?referrer=https%3A%2F%2Fwww.bing.com%2F

Tiggeloven, P., & Van Dongen, L. (2021, March 21). Woonvisie 2021-2025. Leusden: Companen. Opgehaald van https://gemeentebestuur.leusden.nl/Vergaderingen/Raadsvergadering/2021/03-juni/20:00/Bijlage-1-Woonvisie-Leusden-2021-2025.pdf

Van den Berg, M., Hepp, M., Hoitink, G., Murre, C., Van Oostveen, M., Van der Thiel, C., & Timmerman, J. (2013). Toekomstvisie en Structuurvisie "Baarn in 2030". Baarn. Opgehaald van http://bestemmingsplannen.baarn.nl/BB56457D-BE04-4FC7-AEE3-E07478C15FA6/t_NL.IMRO.0308.SV0042-VA01.pdf

Van der Laan, L., Navis, G., Westerhof, L., & Van Beek, W. (2021). Prestatieafspraken wonen Montferland 2022-2025. Opgehaald van https://www.montferland.info/sites/default/files/2021-12/Prestatieafspraken%20wonen%202022%20versie%207%20december.pdf

Van der Most, H., & Klijn, F. (2013). *De werking van het waterkeringssysteem: de dijkring voorbij.* Delft: Deltares.

Van der Most, H., & Nijenhuis, A. (2019). *Nieuwe normering van waterveiligheid.* Delft: Deltares. Opgehaald van https://www.stowa.nl/sites/default/files/assets/DELTAFACTS/Deltafacts%20NL%20PDF%20nieu w%20format/Nieuwe%20normering%20van%20waterveiligheid%20deltafact%20def%2C%20juni%202019.pdf

Van der Most, H., Bouwer, L., Asselman, N., Hoogendoorn, R., Ellen, G., Schasfoort, F., & Wagenaar, D. (2017). *Meerlaagsveiligheid in de praktijk.* Delft: Deltares. Opgehaald van https://www.stowa.nl/deltafacts/waterveiligheid/innovatieve-dijkconcepten/meerlaagsveiligheid-de-praktijk

Van der Scheer, P., & Huting, R. (2012). *Overstromingsrisico dijkringgebied 45, Gelderse Vallei.* DHV-Oranjewoud-Tauw. Rijkswaterstaat Waterdienst. Opgehaald van https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/publicaties/dijkringrapporten/overzichtspagina/dijkringrapporten-in/

Van der Vecht, B. (2014). *Woonvisie Heusden 2014-2024.* Gemeente Heusden. Rigo Research en Advies.

Van der Wal, H. (2020). Woonvisie 2020-2030. Krimpen aan den IJssel. Retrieved from krimpenaandenijssel

Van Dijk, H. (2020). *Onder de pannen.* Gemeente Scherpenzeel.

Van Hees, W. (2020, September 22). *tHuis in Heusden*. Retrieved February 25, 2022, from Overheid.nl: https://lokaleregelgeving.overheid.nl/CVDR644711/1

Van Kempen, E., & Slootmaker, J. (2021, July 13). Adviesaanvraag woningbouw en klimaatadaptatie. Den Haag. Retrieved from https://www.deltaprogramma.nl/documenten/publicaties/2021/07/13/adviesbrief-woningbouw-en-klimaatadaptatie

Van Kempen, E., & Slootmaker, J. (2021). *Adviesaanvraag woningbouw en klimaatadaptatie.* Den Haag: Deltaprogramma. Opgehaald van https://www.deltaprogramma.nl/documenten/publicaties/2021/07/13/adviesbrief-woningbouw-en-klimaatadaptatie

Van Orsouw, J. (2020). *Structuurvisie Oss-West.* Antea Group, Oss. Retrieved from https://www.oss.nl/Tonen-op-pagina-standaard/-VOORNEMEN-VOORBEREIDING-STRUCTUURVISIE-OSS-WEST-.htm#:~:text=De%20structuurvisie%20Oss-West%20gaat%20over%20het%20nieuwe%20gebied,en%20%E2%80%98s-Hertogenbosch%20en%20de%20aanliggende%20bebouwing%20en%20functi

Van Orsouw, J., & Van der Schoot, J. (2019). *Woonvisie Oss 2020.*

Van Roosmalen, H. (2011). *Structuurvisie "Sint-Michielsgestel 2025".* Retrieved from http://vind.sint-michielsgestel.nl/Durp_SintMichielsgestel/plans_SintMichielsgestel/NL.IMRO.0845.SV2011SMG2025-/NL.IMRO.0845.SV2011SMG2025-OH01/b_NL.IMRO.0845.SV2011SMG2025-OH01.pdf#:~:text=De%20structuurvisie%20maakt%20het%20mogelijk%20om%20lopende%20en,

Van Tienen, Y., Drenth, P., Van Waart, N., & Teunissen-Ordelman, K. (2013, September). Structuurvisie Doetinchem 2035. Gemeente Doetinchem. Retrieved from https://www.ruimtelijkeplannen.nl/documents/NL.IMRO.0222.R60S003A-0001/t_NL.IMRO.0222.R60S003A-0001.html

Vergouwe, R. (2014). De veiligheid van Nederland in kaart. *HB 2540621*. Rijkwaterstaat projectbureau VNK. Retrieved from https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/

Vos, W. (2019, March 29). Notitie Uitwerking woonvisie naar kernen.

Wagteveld, T. (2018). Uitvoeringsplan voor de regionale woonagenda 2.0. Gelderland. Opgehaald van https://www.regiofoodvalley.nl/projecten/woonagenda-20

Waterschap Brabantse Delta. (2015). *Overdiepsche Polder.* Opgeroepen op May 4, 2022, van https://www.brabantsedelta.nl/overdiepse-polder

Westerhof, S. (2019). *Uncertainties in the derivation of Dutch flood safety standards.* Enschede: University of Twente. Opgehaald van https://essay.utwente.nl/view/programme/60026.html

Zandbelt, D., Ram, M., Van der Reijden, H., & Van Loon, J. (2021). *Nieuwekaartnl.nl*. Opgehaald van De Nieuwe Kaart van Nederland: https://nieuwekaartnl.nl/

Appendices

Appendix A: Case study selection

Appendix A1: Selection criterion 1 ‘SCBA’

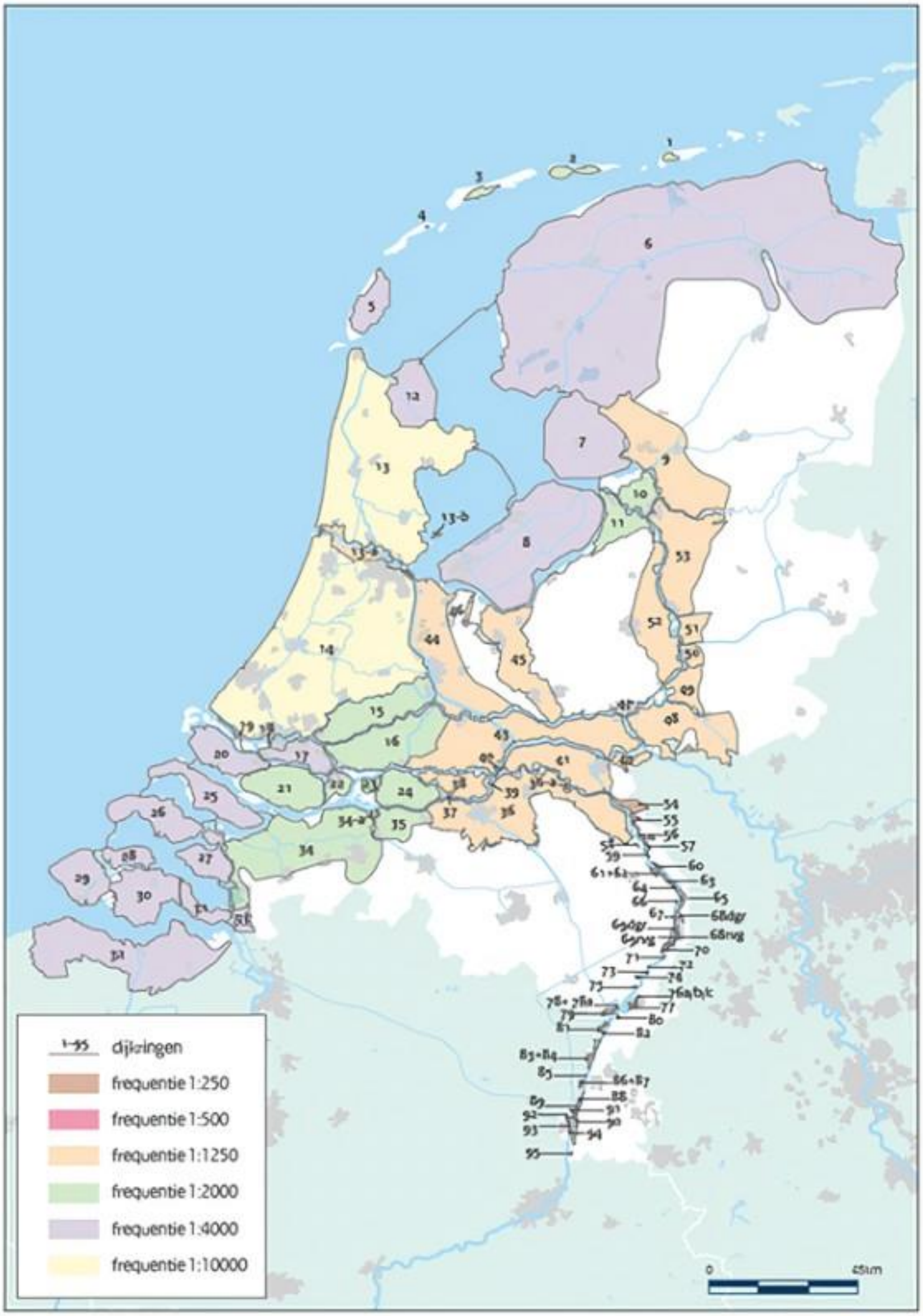

Figure A1: Dike ring areas in the Netherlands

Table A1: Data and results selection criterion 1 "SCBA'

Dike ring area	Dike ring section	Normative flood risk criterion dike ring section (Slootjes & Wagenaar, 2016)	Dike ring area	Dike ring section	Normative flood risk criterion dike ring section (Slootjes & Wagenaar, 2016)
1	1	LIR	32	1	LIR
	2	LIR		2	LIR
2	1	LIR		3	SCBA & LIR
	2	LIR		4	LIR
3	1	LIR	33	1	SCBA & LIR
	2	LIR	34	1	LIR
4	1	LIR		2	LIR
	2	SCBA		3	SCBA
5	1	LIR		4	SCBA
	2	LIR		5	SCBA & LIR
6	1	SCBA	35	1	SCBA
	2	Additional grounds		2	SCBA
	3	LIR & SCBA	36	1	SCBA
	4	Additional grounds		2	SCBA
	5	LIR		3	SCBA
	6	LIR		4	SCBA
	7	SCBA		5	SCBA
7	1	SCBA	37	1	SCBA
	2	LIR & SCBA	38	1	SCBA & LIR
8	1	SCBA		2	SCBA
	2	SCBA	39	1	LIR
	3	SCBA	40	1	LIR
	4	SCBA		2	LIR
	5	SCBA	41	1	SCBA
	6	SCBA		2	SCBA & LIR
	7	SCBA		3	LIR
9	1	LIR & SCBA		4	SCBA & LIR
	2	SCBA	42	1	LIR
10	1	LIR & SCBA	43	1	SCBA
	2	LIR		2	SCBA & LIR
	3	LIR & SCBA		3	SCBA
11	1	LIR & SCBA		4	SCBA & LIR
	2	Additional grounds		5	LIR
	3	LIR & SCBA		6	LIR
12	1	LIR	44	1	SCBA
	2	Additional grounds		2	SCBA & LIR
13	1	LIR & SCBA	45	1	SCBA

	2	LIR		2	SCBA & LIR
	3	LIR & SCBA		3	SCBA & LIR
	4	LIR & SCBA	46	1	SCBA & LIR
	5	SCBA	47	1	SCBA & LIR
	6	SCBA	48	1	LIR
	7	LIR & SCBA		2	SCBA
	8	LIR & SCBA		3	SCBA
	9	Additional grounds	49	1	SCBA & LIR
14	1	SCBA		2	SCBA
	2	GR	50	1	SCBA
	3	LIR		2	SCBA
	4	Additional grounds	51	1	SCBA & LIR
	5	SCBA	52	1	SCBA & LIR
	6	SCBA		2	LIR
	7	LIR & SCBA		3	SCBA & LIR
	8	LIR & SCBA		4	SCBA
	9	LIR & SCBA	53	1	SCBA
	10	LIR		2	SCBA & LIR
15	1	SCBA		3	SCBA
	2	LIR & SCBA	54	1	SCBA
	3	LIR & SCBA	55	1	SCBA
16	1	GR & LIR	56	1	SCBA & LIR
	2	GR & LIR	57	1	SCBA & LIR
	3	LIR & SCBA	58	1	SCBA & LIR
	4	LIR & SCBA	59	1	SCBA & LIR
17	1	LIR	60	1	SCBA & LIR
	2	SCBA	61	1	SCBA & LIR
	3	SCBA	62	1	SCBA & LIR
18	1	LIR & SCBA	63	1	SCBA & LIR
19	1	GR	64	1	SCBA & LIR
20	1	SCBA	65	1	SCBA & LIR
	2	LIR	66	1	SCBA & LIR
	3	GR & LIR	67	1	SCBA & LIR
	4	SCBA & LIR	68	1	Additional grounds
21	1	LIR		2	SCBA & LIR
	2	SCBA & LIR	69	1	Additional grounds
22	1	SCBA & LIR	70	1	SCBA & LIR
	2	GR & LIR	71	1	SCBA & LIR
23	1	LIR	72	1	SCBA & LIR
24	1	SCBA	73	1	SCBA & LIR
	2	SCBA & LIR	74	1	SCBA & LIR
	3	LIR	75	1	Additional grounds
25	1	SCBA & LIR	76	1	SCBA & LIR

	2	SCBA & LIR		2	SCBA & LIR
	3	SCBA & LIR	77	1	SCBA & LIR
	4	LIR	78	1	SCBA & LIR
26	1	SCBA & LIR	79	1	SCBA & LIR
	2	SCBA & LIR	80	1	SCBA & LIR
	3	LIR	81	1	SCBA & LIR
	4	LIR	82	1	SCBA & LIR
27	1	LIR	83	1	SCBA & LIR
	2	LIR	84	1	SCBA & LIR
	3	SCBA	85	1	SCBA & LIR
	4	LIR	86	1	SCBA & LIR
28	1	SCBA & LIR	87	1	SCBA
29	1	LIR	88	1	SCBA & LIR
	2	LIR	89	1	SCBA & LIR
	3	LIR	90	1	SCBA
	4	LIR	91	1	SCBA & LIR
30	1	SCBA & LIR	92	1	SCBA & LIR
	2	LIR	93	1	SCBA
	3	LIR	94	1	SCBA & LIR
	4	-	95	1	SCBA
31	1	LIR			
	2	LIR			
	3	SCBA & LIR			

Appendix A2: Selection criterion 2 'Breach locations'

Table A2: Results selection criterion 2 "Breach locations"

Dike ring area	Number of breach locations (Slootjes & Wagenaar, 2016)	Selected for case studies 1 and 3?	Selected for case study 2?
7	2	No	Yes
8	8	Yes	Yes
9	9	Yes	Yes
10	15	No	No
15	8	Yes	Yes
17	16	No	No
18	1	No	No
24	6	Yes	Yes
25	13	No	No
28	12	Yes	Yes
33	1	No	No
34	18	No	No
35	5	Yes	Yes
36	12	Yes	Yes
38	3	No	Yes
37	1	No	No

41	9	Yes	Yes
43	15	No	No
44	9	Yes	Yes
45	7	Yes	Yes
46	1	No	No
47	4	No	Yes
48	7	Yes	Yes
49	2	No	Yes
50	3	No	Yes
51	2	No	Yes
52	7	Yes	Yes
53	13	No	No
54	Overflow	No	No
55	Overflow	No	No
56	Overflow	No	No
57	Overflow	No	No
58	Overflow	No	No
59	Overflow	No	No
60	Overflow	No	No
61	Overflow	No	No
62	Overflow	No	No
63	Overflow	No	No
64	Overflow	No	No
65	Overflow	No	No
66	Overflow	No	No
67	Overflow	No	No
70	Overflow	No	No
71	Overflow	No	No
72	Overflow	No	No
73	Overflow	No	No
74	Overflow	No	No
76	Overflow	No	No
77	Overflow	No	No
78	Overflow	No	No
79	Overflow	No	No
80	Overflow	No	No
81	Overflow	No	No
82	Overflow	No	No
83	Overflow	No	No
84	Overflow	No	No
85	Overflow	No	No
86	Overflow	No	No
87	Overflow	No	No
88	Overflow	No	No
89	Overflow	No	No
90	Overflow	No	No

91	Overflow	No	No
92	Overflow	No	No
93	Overflow	No	No
94	Overflow	No	No
95	Overflow	No	No

Appendix A3: selection criterion 3 'Surface area'

Table A3: Results selection criterion 3 for case studies 1 and 3

Dike ring area	Surface area [ha] (Vergouwe, 2014)	Selected for case studies 1 and 3?
8	97400	Yes
9	58200	Yes
15	31400	Yes
24	16300	No
28	7750	No
35	12500	No
36	66600	Yes
41	27900	No
44	63800	Yes
45	37300	Yes
48	36300	Yes
52	31000	Yes

Table A4: Results selection criterion 3 for case study 2

Dike ring area	Surface area [ha]	Selected for case study 2?
7	50.100	No
8	97400	No
9	58200	No
15	31400	No
24	16300	No
28	7750	Yes
35	12500	Yes
36	66600	No
38	10900	Yes
41	27900	No
44	63800	No
45	37300	No
47	2020	No
48	36300	No
49	8700	Yes
50	4060	No
51	6470	Yes
52	31000	No

Appendix A4: Selection criterion 4

Table A5: Results selection criterion 4 "Flood type"

Considered case study	Dike ring area	Assessment flood type (Slootjes & Wagenaar, 2016)	Selected?
1 & 3	8	Flat polder type	For case study 3
	9	Flat polder type, albeit rather shallow flooding	For case study 3
	15	Flat polder type, with deep inundations	For case study 3
	36	Inclined plane flood type, with a large east-west inundation depth gradient	For case study 1
	44	Disjoint dike ring area, with both the flat polder and inclined plane flood types	No
	45	Inclined plane flood type	For case study 1
	48	Inclined plane flood type	For case study 1
	52	Inclined plane flood type	For case study 1
2	28	Incline plane flood type	For case study 2
	35	Incline plane flood type	For case study 2
	38	Flat polder flood type	No
	49	Inclined plane flood type, flood extent limited but acceptable	For case study 2
	51	Inclined plane, very limited flood extent	No

Appendix A5: Results selection criterion 5 "Number of residences"

Table A6: Results selection criterion 5 case study 1

Dike ring	Municipality	Number of planned residences 2021-2030	Source(s)	Comments
36	Land van Cuijk	3,180	(Provincie Noord-Brabant, 2021a)	-
	Heusden	2,155	(Provincie Noord-Brabant, 2021a)	-
	Maashorst (Landerd)	555	(Provincie Noord-Brabant, 2021a)	-
	Oss	5,785	(Provincie Noord-Brabant, 2021a)	-
	Den Bosch	11,530	(Provincie Noord-Brabant, 2021a)	-
	St. Michielsgestel	1,080	(Provincie Noord-Brabant, 2021a)	Partially outside dike ring area
	Vught	1,435	(Provincie Noord-Brabant, 2021a)	Partially outside dike ring area
	Total:	**25,720**	**-**	**-**
45	Barneveld	48	(Zandbelt et al., 2021)	Small part of municipality within dike ring area
	Ede	86	(Zandbelt et al., 2021)	Small part of municipality within dike ring area
	Nijkerk	3,545	(Zandbelt et al., 2021)	-
	Putten	0	(Gemeente Putten, 2019), (Zandbelt et al, 2021)	No planned spatial developments within dike ring area
	Wageningen	888	(Zandbelt et al., 2021)	-

	Amersfoort	9,160	(Zandbelt et al., 2021)	-
	Baarn	0	(Van den Berg et al., 2013)	No planned spatial developments within dike ring area
	Bunschoten	2,340	(Geuting & Schouten, 2020)	-
	Leusden	825	(Tiggeloven & Van Dongen, 2021)	-
	Rhenen	7	(Zandbelt et al., 2021)	Rural part of municipality inside dike ring area
	Veenendaal	2,740	(Wagteveld, 2018)	Based on the housing program for the period 2017-2027
	Woudenberg	1,167	(Zandbelt et al., 2021)	-
	Utrechtse heuvelrug	91	(Zandbelt et al., 2021)	-
	Renswoude	217	(Wagteveld, 2018)	Based on the housing program for the period 2017-2027
	Scherpenzeel	560	(Van Dijk, 2020)	-
	Total:	**21,674**	**-**	-
48	Duiven	245	(Gemeente Duiven, 2018)	Based on the housing program for period 2018-2027
	Westervoort	715	(Gemeente Westervoort, 2021)	-
	Zevenaar	521	(Ten Cate, 2017)	Based on the housing program for period 2017-2027
	Montferland	1,250	(Van der Laan et al, 2021)	-
	Doetinchem	46	(Lambregts et al, 2016)	Most residences in this housing program have already been realized as of 2021.
	Total:	**2,777**	**-**	-
52	Apeldoorn	1,008	(Gemeente Apeldoorn, 2018)	Based on the housing program for 2018-2027
	Deventer (De Worp)	0	(Gemeente Deventer, 2004)	No spatial developments planned for De Worp, only part of the municipality within the dike ring area
	Zutphen (Hoven)	50	(Gemeente Zutphen, 2018)	Limited spatial development in one urban center falling within the dike ring area
	Rheden (Spankeren)	0	(Gemeente Rheden, 2014)	No spatial developments mentioned for Spankeren village within dike ring area
	Epe	415	(Gemeente Epe, 2019)	-
	Voorst	30	(Gemeente Voorst, 2021)	-

	Brummen	494	(Gemeente Brummen, 2018)	Spatial agenda for period 2018-2027
	Heerde	0	(Spronk et al, 2012)	Municipality leaves it to the free market
	Olst-Wijhe	0	(Gemeente Olst-Wijhe, 2017)	No spatial developments planned in dike ring area
	Total:	**1,997**	**-**	-

Table A7: Results selection criterion 5 case study 2

Dike ring	Municipality	Number of planned residences 2021-2030	Source(s)	Comments
28	Noord-Beveland	493	(Gemeente Noord-Beveland, 2020)	-
35	Oosterhout	1,015	(Gemeente Oosterhout, 2021) & (Gemeente Oosterhout, 2022)	Oosterhout is located partially outside of the dike ring area, but from the total number of residences (2800) as stated by Gemeente Oosterhout (2021), the number of new residences in the dike ring area could be determined with information from Gemeente Oosterhout (2022)
	Geertruidenberg	447	(Gemeente Geertruidenberg, 2021)	New spatial developments for the villages Raamsdonkerveer and Raamsdonk that lie within the dike ring area
	Waalwijk	2,526	(Gemeente Waalwijk, 2020)	-
	Loop op Zand	0	(Gemeente Loon op Zand, 2018)	Only a small part of the village of Kaatsheuvel is located within the dike ring area, and no spatial developments will take place there
	Dongen	451	(Gemeente Dongen, 2022)	Dongen is located partially outside of the dike ring area
	Total:	**4,439**	**-**	**-**
49	Doetinchem	0	(van Tienten et al., 2013)	No spatial developments in the small zone that is part of the dike ring area
	Doesburg	169	(Mulder-Metselaar, 2017)	-
	Bronckhorst	1,950	(Blaauw, 2022)	The municipality stated that between 1700 and 2200 residences will be built, so

				the mean value of this range is used
	Total:	**2,119**	**-**	**-**

Table A8: Results selection criterion 5 case study 3

Dike ring	Municipality	Number of planned residences 2021-2030	Source(s)	Comments
8	Lelystad	9,910	(Provincie Noord-Holland & Metropoolregio Amsterdam, 2022)	-
	Dronten	2,500	(Omroep Flevoland, 2021)	-
	Almere	26.342	(Provincie Noord-Holland & Metropoolregio Amsterdam, 2022)	-
	Zeewolde	1322	(Reith, 2020)	-
	Total:	**40,074**	**-**	**-**
9	Steenwijkerland	871	(Provincie Overijssel, 2021)	-
	Staphorst	465	(Provincie Overijssel, 2021)	-
	Zwartewaterland	759	(Provincie Overijssel, 2021)	-
	Dalfsen	662	(Provincie Overijssel, 2021)	-
	Total:	**2,757**	**-**	**-**
15	Krimpenerwaard	1,560	(Vos, 2019)	-
	Krimpen aan den Ijssel	454	(Van der Wal, 2020)	-
	Oudewater	150	(Buck consultants international, 2019)	Only small part of the municipality falls within the dike ring area
	Lopik	201	(Klouwen & Westgeest, 2017)	-
	Montfoort	791	(Tiekstra & Klouwen, 2019a)	Municipality partially outside dike ring area
	IJsselstein	2,685	(Tiekstra & Klouwen, 2019b)	-
	Nieuwegein	5,146	(Gemeente Nieuwegein, 2017)	-
	Gouda	0	(Project team omgevingsvisie gemeente Gouda, 2022)	No spatial developments planned in the dike ring area
	Utrecht	0	(Braggerman & Bayer, 2022)	No new spatial developments planned outside one large project that has not been confirmed yet
	Total:	**10,987**	**-**	**-**

Appendix A6: Final selection case studies

Table A9: Results selection criterion 6 case study 1

Dike ring	Municipality	Information about number of planned residences	Information about the location	Information about the type of housing
36	Land van Cuijk	Provincie Noord-Brabant (2021a) provides clear information	Atrivé (2018) states that spatial developments will 'predominantly' take place within urban centers. General indications for locations for possible spatial development outside villages given by Provincie Noord-Brabant (2021b)	Atrivé (2018) provides general indications for the desired type of housing for each village within the municipality
	Heusden	Provincie Noord-Brabant (2021a) provides clear information	Gemeente Heusden (2019) indicates areas designated for spatial development. No information over the number of residences planned in each area. Van der Vecht (2014) provides number of houses per street as planned till 2024	Van Hees (2020) indicates that 18% of total housing will be apartments, the rest as single-family residences
	Maashorst (Landerd)	Provincie Noord- Brabant (2021a) provides clear information	De Jong & Hin (2019) provide for each village the number of residences. No information about locations within urban centers. Rough locations outside urban centers given by Provincie Noord-Brabant (2021b)	De Jong & Hin (2019) only mention that 'there will be few apartments'
	Oss	Provincie Noord- Brabant (2021a) provides clear information. Different number mentioned by Van Orsouw & Van der Schoot (2019) by large margin	Van Orsouw (2020) gives a clear expansion location for Oss-West. No indications for locations within Oss are given	Van Orsouw & Van der Schoot (2019) state that 40% of the new residences will be in the form of apartments.
	Den Bosch	Provincie Noord- Brabant (2021a) provides clear information	Gemeente Den Bosch (2014) states that as of now, there are too few locations for the planned number of new residences, and new locations have to be found. Locations outside city given by Provincie Noord-Brabant (2021b)	No information available
	St. Michielsgestel	Provincie Noord- Brabant (2021a) provides clear information	Van Roosmalen (2011) provides detailed information about the locations and number of new residences per location	Van Roosmalen (2011) provides clear information about the type of residence for each location
	Vught	Provincie Noord- Brabant (2021a) provides clear information	Gemeente Vught (2019) provides the exact locations for new spatial developments on street level,	Klouwen & Klouwen (2021) provide detailed information about the type of residences to be build

			including number of new residences per location	
45	Barneveld	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Ede	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Nijkerk	Zandbelt et al. (2021) provides a smaller number of residences compared to Dijksterhuis et al (2021)	The combination of information from Zandbelt et al. (2021) and Gemeente Nijkerk (2011) yields a clear overview of the locations	Less detailed information available. Zandbelt et al. (2021) only cover part of the planned new residences, but its information could be used as an indication for the remaining residences
	Wageningen	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Amersfoort	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Bunschoten	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Geuting & Schouten (2020) state that the municipality plans a 50/50 distribution between apartments and ground-based residences
	Leusden	Tiggeloven & Van Dongen (2021) provide clear information	Zandbelt et al. (2021) provides the location of about 75% of the planned new residences.	Tiggeloven & Van Dongen (2021) state that new residences 'should fit into the neighborhood they are placed in'. Zandbelt et al. (2021) provide for 1/3 of the houses an indication
	Rhenen	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Veenendaal	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location

	Woudenberg	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide only for a minority of the residences the type
	Utrechtse heuvelrug	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Renswoude	Zandbelt et al. (2021) provide clear information	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Scherpenzeel	Van Dijk (2020) provides clear information	Van Dijk (2020) provides clear locations for the planned spatial developments for the Scherpenzeel-Zuid locations. Rest of the locations are indicated clearly by Gemeente Scherpenzeel (2013)	Van Dijk (2020) provides the exact numbers of apartments and other types of residences.

Table A10: Results selection criterion 6 case study 2

Dike ring	Municipality	Information about number of planned residences	Information about the location	Information about the type of housing
35	Oosterhout	Gemeente Oosterhout (2021) is quite clear in its plans about the number of new residences, corroborated by Gemeente Oosterhout (2022)	Gemeente Oosterhout (2021) provides information about the general location of construction sites throughout the municipality, but without the number of new residences per site. Gemeente Oosterhout (2022) provides for all the internal urban locations the number and type of residences. For expansion locations in the rural area, general indications of the construction sites is given by Provincie Noord-Brabant (2021b)	Gemeente Oosterhout (2021) states that 65% of all new residences are apartments in apartment complexes, and the remaining 35% will be ground based single-family homes.
	Geertruidenberg	Gemeente Geertruidenberg (2021) provides clear information	Gemeente Geertruidenberg (2021) provides the location of all new residences	Gemeente Geertruidenberg (2021) states that with few exceptions, all new residences are ground based single-family homes. Because Gemeente Geertruidenberg (2021) mentions the exact streets where new residences will

				be built, it could be determined from the available space whether apartments or other residences are to be built
	Waalwijk	Gemeente Waalwijk (2020) provides a clear number of new residences	The municipality provided an excel sheet with the number of planned residences per project, including the exact location	Gemeente Waalwijk (2020) indicated that new residences 'should fit' into the neighborhood.
	Dongen	Gemeente Dongen (2022) is clear on the number of residences	Gemeente Dongen (2022) provides the location for all the new residences, by providing the location on a street level	Gemeente Dongen (2022) provides for all new residences the type of housing
49	Doesburg	Clear information by Mulder-Metselaar (2017)	The location of the planned spatial developments is provided by Mulder-Metselaar (2017) on street level scale	For all new residences the housing type has been described by Mulder-Metselaar (2017)
	Bronckhorst	Clear information by Blaauw (2022)	Gemeente Bronckhorst (2022) provides a map with a wide array of locations. For about half of these locations, the number of planned residences is mentioned	According to Gemeente Bronckhorst (2022), all these residences are ground-based single-family homes

Table A11: Results selection criterion 6 case study 3

Dike ring	Municipality	Information about number of planned residences	Information about the location	Information about the type of housing
8	Lelystad	Provincie Noord-Holland & Metropoolregio Amsterdam (2022) provide clear information	Zandbelt et al. (2021) accounts for all planned residences	Bouma & Lentferink (2021) provide detailed information per location the type of new housing
	Dronten	Omroep Flevoland (2021) gives a clear number of residences. Official municipial reports do not give numbers	Gemeente Dronten (2009) provides maps with the spatial development location for all villages, but do not indicate the number of new residences per location. A further issue is the lack of recent information, as the structure vision is from 2009	Gemeente Dronten (2009) gives only indication for housing projects that have already been realized as of 2022
	Almere	Provincie Noord-Holland & Metropoolregio Amsterdam (2022) provide clear information	Zandbelt et al. (2021) accounts for all planned residences. Other reports do not provide information regarding this topic	Zandbelt et al. (2021) provides the housing type for only a quarter of all planned residences
	Zeewolde	Reith (2020) provides clear information	Gemeente Zeewolde (2012) provides detailed information about the locations for new spatial developments. Because	No information on the type of housing. Could be partially derived from the Zeewoldenieuwbouw.nl

			the structure vision is older, large parts of these locations have already been developed. Newer structure vision to be released in 2023	website, that publishes new spatial development projects.
15	Krimpenerwaard	Vos (2019) provides clear information about the number of new residences	Vos (2019) provides the number of residences per village, on street scale	Vos (2019) provides information about the type of housing for each village in detail.
	Krimpen aan den IJssel	Van der Wal (2020) provides clear information regarding the number of new residences, in agreement with Zandbelt et al. (2021)	Zandbelt et al. (2021) provide all exact locations	Zandbelt et al. (2021) provide all information regarding the type of residence, for each location
	Oudewater	Buck consultants international (2019) provide clear information	Location is clear, as it is the last stretch of 'free' land available in the dike ring area	Two-thirds of all new residences are apartments (Buck consultants international, 2019)
	Lopik	Klouwen & Westgeest (2017) provide clear information, in agreement with Zandbelt et al. (2021)	Zandbelt et al. (2021) provide all exact locations	Clear information provided by Klouwen & Westgeest (2017)
	Montfoort	Clear information provided by Klouwen & Tiekstra (2019a), supported by Zandbelt et al. (2021)	Zandbelt et al. (2021) provide all exact locations	All required information provided by Klouwen & Tiekstra (2019a)
	IJsselstein	Clear information provided by Klouwen & Tiekstra (2019b)	Documents about the housing program provided by the municipality provide information for all locations on street level. Large development location provided by Klouwen & Tiekstra (2019b)	Klouwen & Tiekstra (2019b) state that the housing program contains a maximum of 1000 apartments
	Nieuwegein	Clear information by Gemeente Nieuwegein (2017)	Gemeente Nieuwegein (2017) provides a detailed map with specific locations and the number of new residences per location. Supported by Zandbelt et al (2021)	Zandbelt et al. (2021) provide for all new residences information for the housing types

Appendix B: Flood damage assessment case study 1

Appendix B1: Damage categories and damage sources

Table B1: SSM2017 damage categories and damage sources

Damage categories	Damage sources	Damage function
Companies	Meeting objects	Shop damage function
	Shops	
	Sport	Industrial damage function
	Industry	
	Office	Office damage function
	Education	
	Healthcare objects	
	Outage of services (all companies)	Outage damage function
Residences	Family homes- direct damage	Family home direct damage function
	Family homes- furniture	
	Ground floor apartments- direct damage	Ground floor direct damage function
	Ground floor apartments- furniture	
	First floor apartments- direct damage	First floor direct damage function
	First floor apartments- furniture	
	Higher floor apartments- direct damage	Higher floor direct damage function
	Higher floor apartments- furniture	
	Outage of services	Outage damage function
Infrastructure	National roads	Infrastructural damage function
	Car roads	
	Miscellaneous roads	
	Railroads- electrified	
	Railroads- not electrified	
Miscellaneous	Agriculture	Agricultural damage function
	Horticulture	
	Airports	
	Extensive recreation	
	Intensive recreation	
	Urbanization rate	Infrastructural damage function
	Means of transportation	Means of transportation damage function
	Pumping station	Pumping station damage function
	Purification installations	Purification damage function
Vulnerable objects	Drinkwater locations	No damage function

	IPPC companies	
	Vulnerable ‘other’ objects	
	Vulnerable hotel/pension	
	Vulnerable office/company	
	Vulnerable public building	
	Vulnerable residences	
	Vulnerable hospital/care home	
	Vulnerable education location	
	Natura2000 areas	
	Monuments	
	Swimwater locations	

Appendix B2: New spatial developments

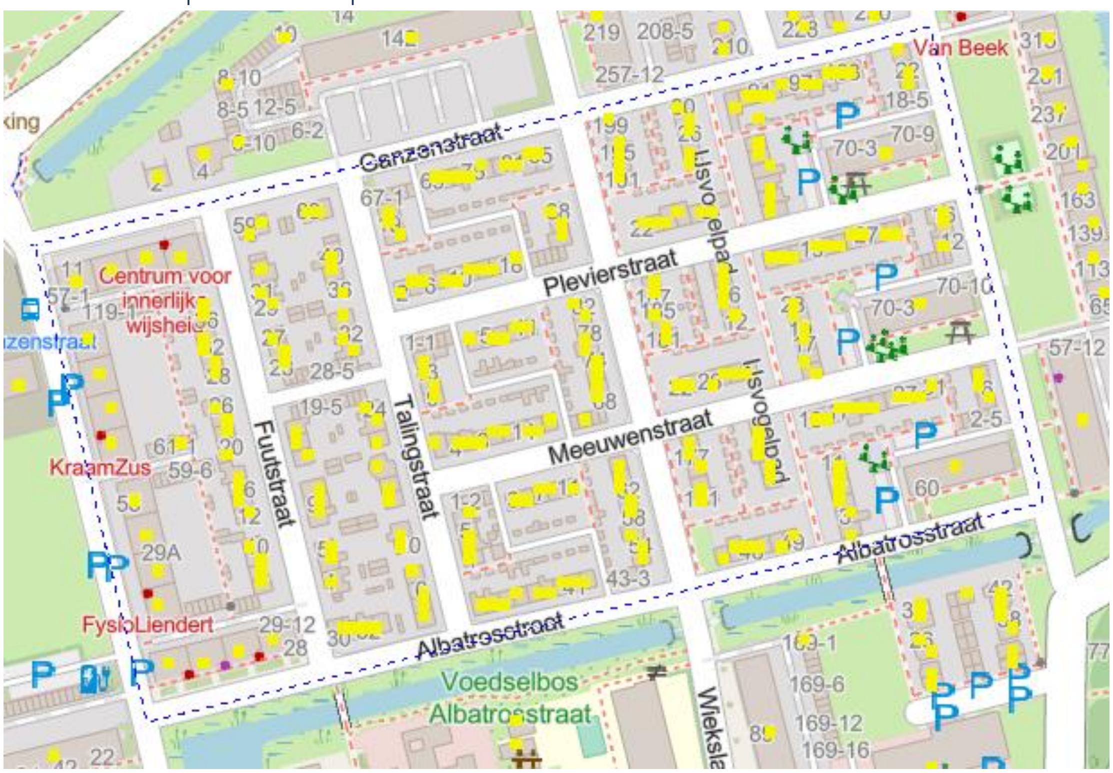

Figure B1: Neighborhood for road network assumption

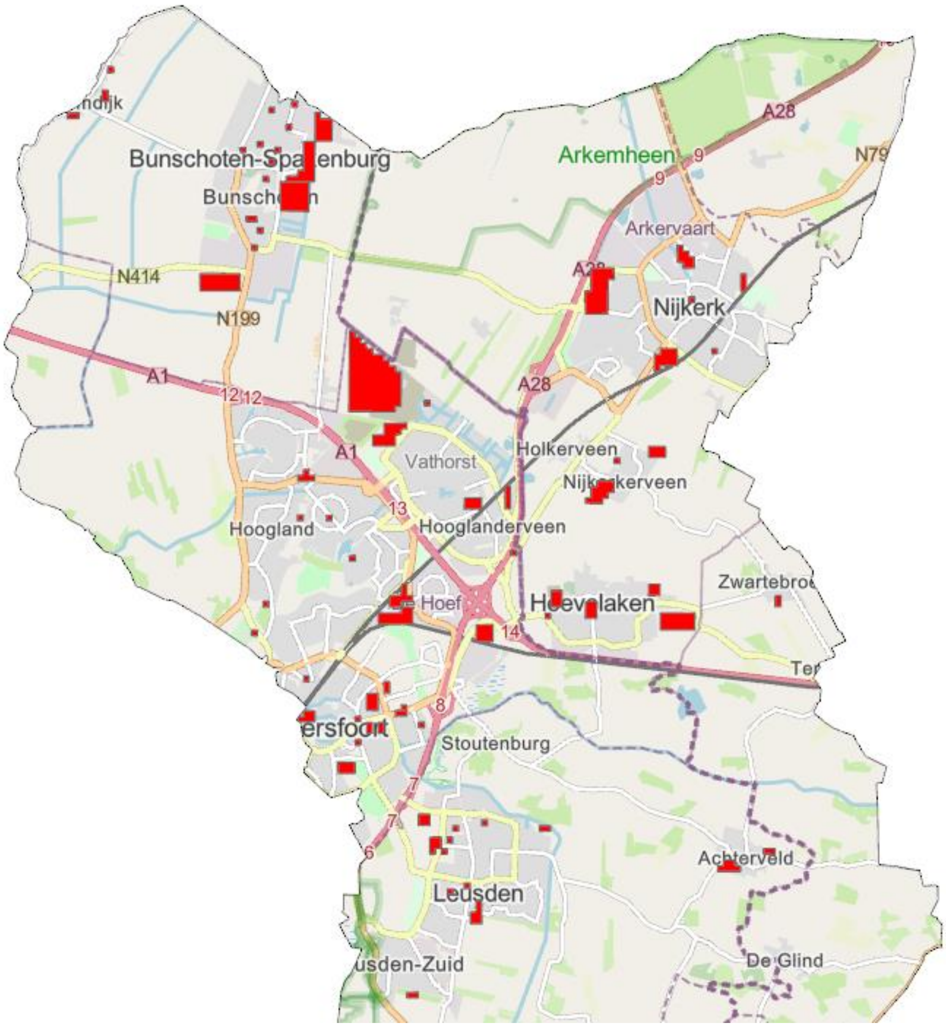

Figure B2: New spatial developments in northern part case study 1 (Q1)

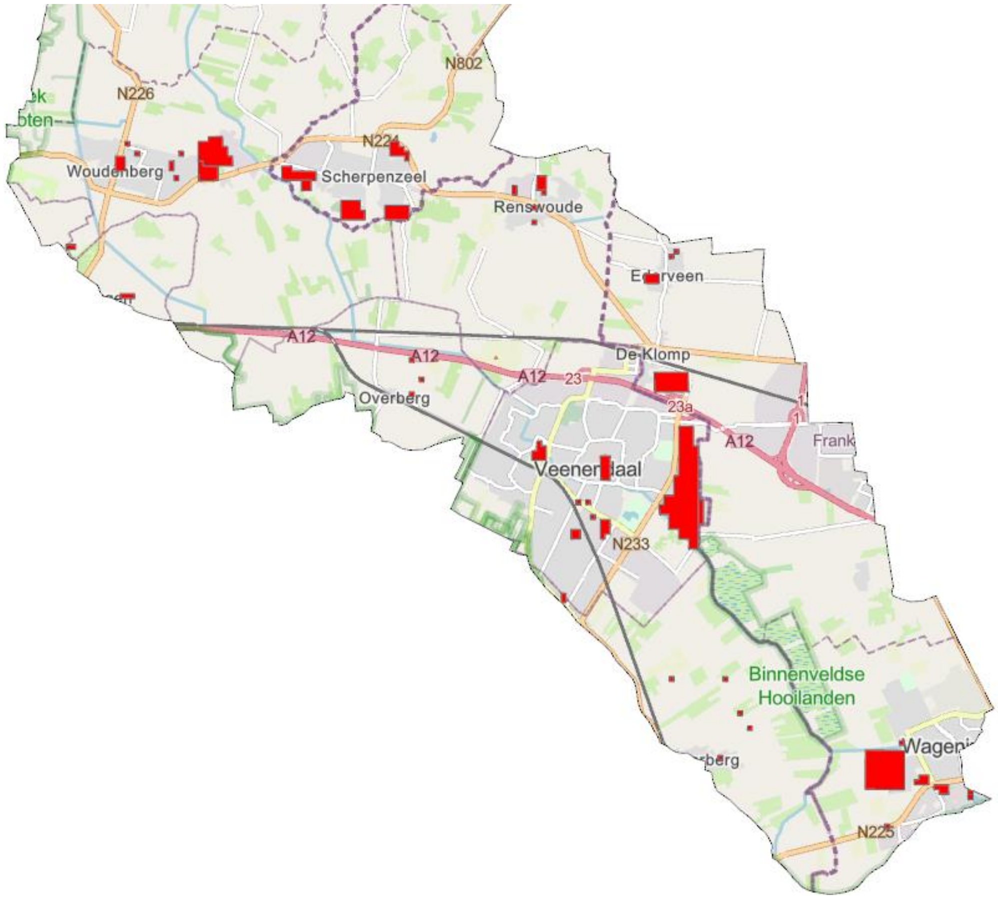

Figure B3: New spatial developments southern part case study 1 (Q1)

Appendix B3: Flood extent case study 1

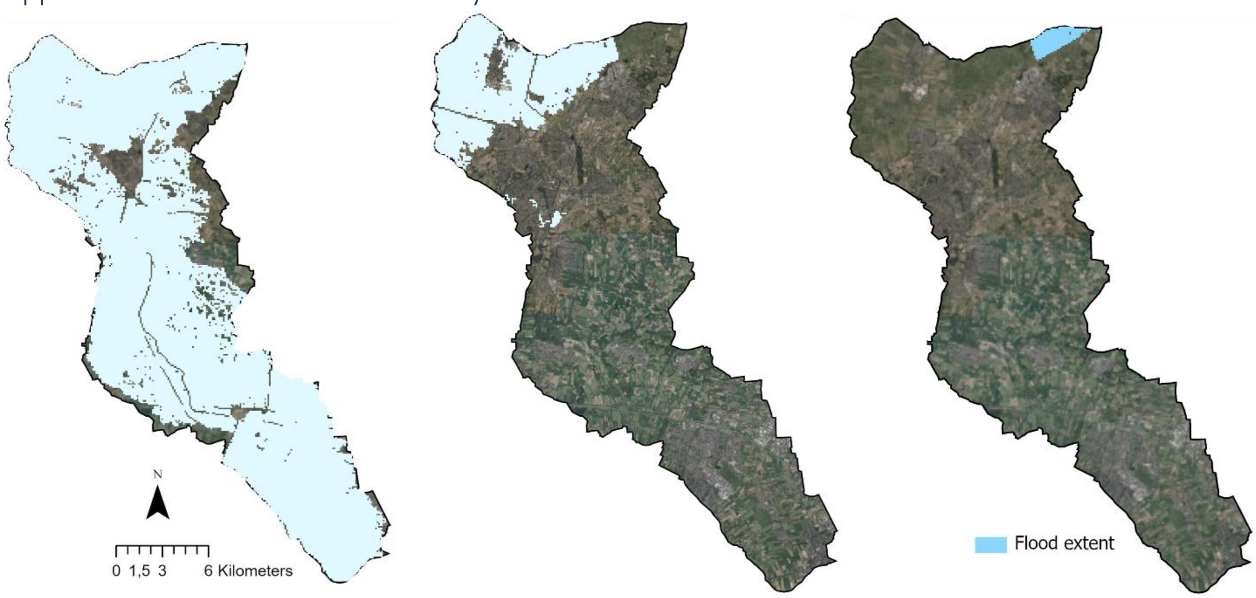

Figure B4 a) Flood extent 45-1 b) Flood extent 45-2 c) Flood extent 45-3

Appendix B4: SCBA alert flood safety standards

Table B2: Input data for SCBA alert standard derivation (Q1)

Variable	Value [unit]	Source
Evacuation fraction	0.43	Slootjes & Wagenaar (2016)
F_{TL}	0.8 [-]	Slootjes & Van der Most (2016a)
F_{WC}	0.2 [-]	
G	1.019 [-]	
$I(h_o)$ dike ring section 45-1	€14 million	Slootjes & Wagenaar (2016)
$I(h_o)$ dike ring section 45-2	€70 million	
$I(h_o)$ dike ring section 45-3	€3 million	
Length dike ring segment Eemdijk (45-2)	4.9 km	(Van der Scheer & Huting, 2012)
Length dike ring segment Oostdijk (45-2)	3.1 km	
Length dike ring segment Westdijk (45-2)	4.4 km	
Length dike ring segment Arkenheemse dijk (45-2)	5.1 km	
Length dike ring segment Slaagse dijk (45-2)	10.3 km	

Appendix C

Appendix C1: methodology research question 2

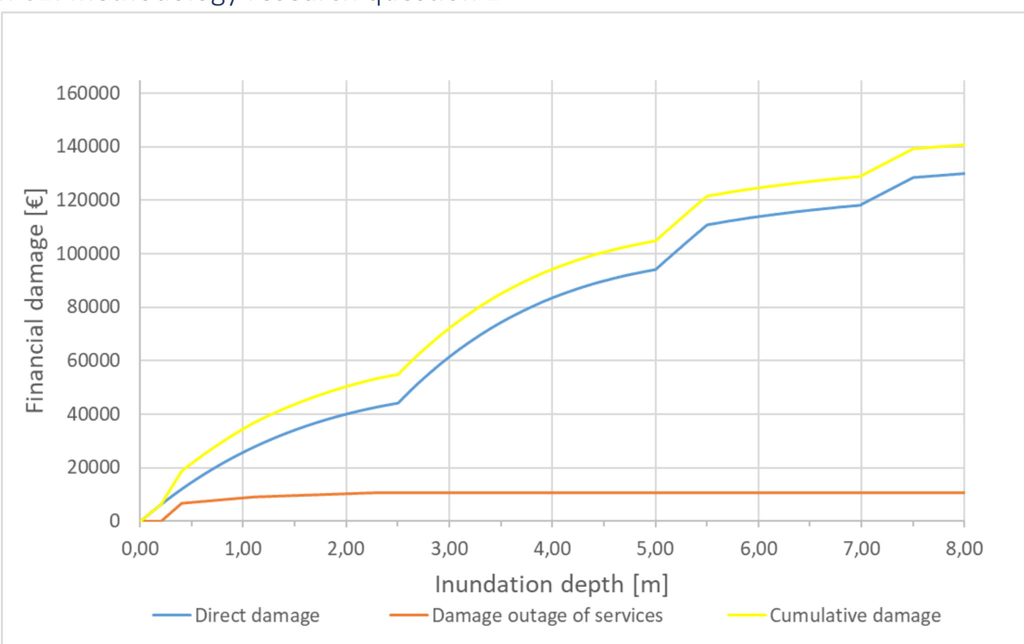

Figure C1: Total financial flood damage to apartments based on SSM2017

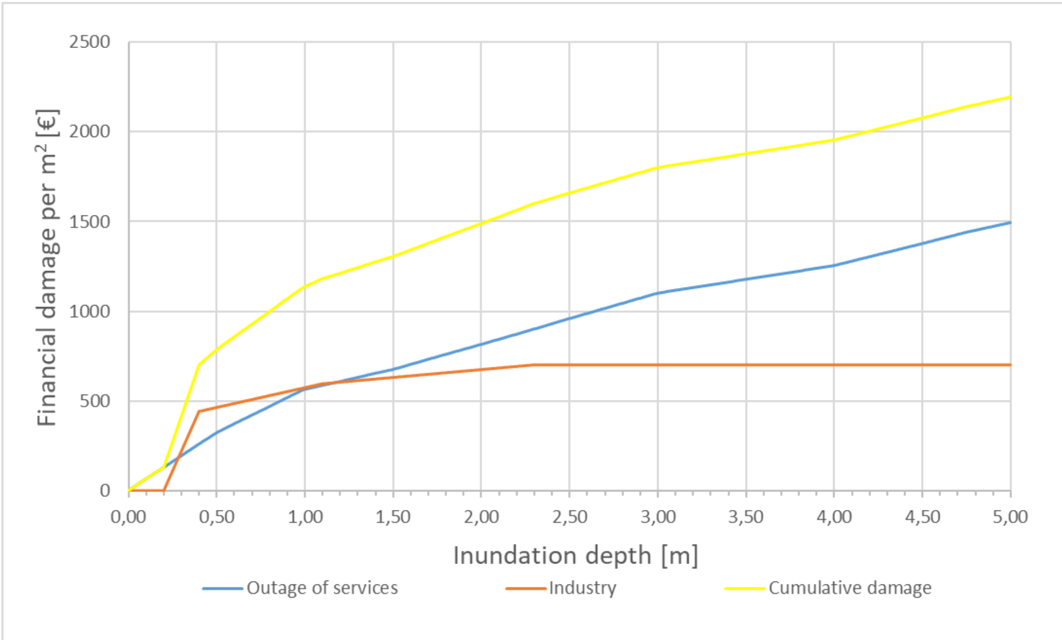

Figure C2: Total financial flood damage to industry based on SSM2017

Appendix C2: results spatial planning framework development

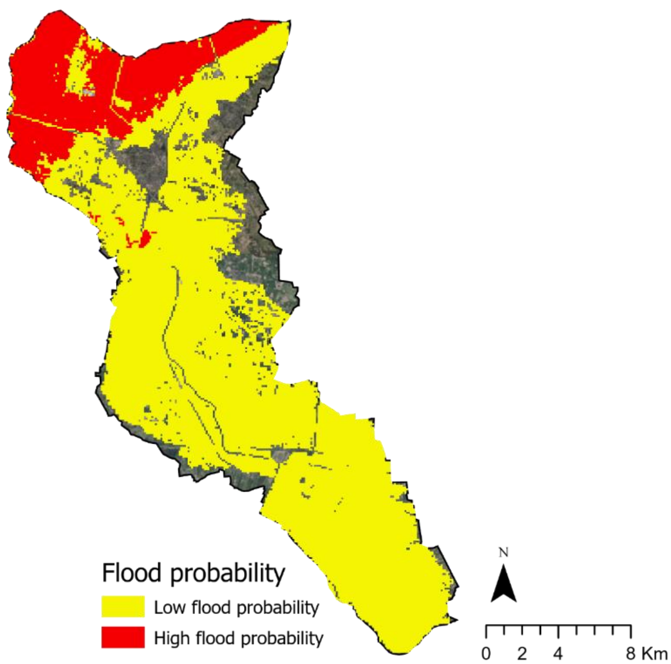

Figure C3: Flood probability dike ring area 45

Table C1: Classification for casualties

Classes	Mortality rate	Inundation depth rise rate <0.5 m/hour [m]	Inundation depth rise rate 0.5-4 m/hour [m]	Inundation depth rise rate >4 m/hour [m]
Not floodable	0%	0	0	0
Low	0 – 0.5%	0 – 1.76	0 – 1.76	0 – 1.76
Medium	0.5 – 1.2%	1.76 – 4.10	1.76 – 2.37	1.76 – 2.36
High	>1.2%	> 4.10	> 2.37	> 2.36

Table C2: All flood risk zone combinations

Flood risk zones	Flood pattern		Damage profile			
	Inundation depth	*Rise rate*	*Family homes*	*Apartments*	*Industry*	*Casualties*
1	Not floodable	Not floodable	Zero	Zero	Zero	Zero
2	Small	Small	Low	Low	Low	Medium
3	Medium	Small	Medium	Medium	Medium	High
4	Large	Small	Medium	High	Medium	Catastrophic
5	Extreme	Small	Catastrophic	Catastrophic	High	Catastrophic
6	Small	Medium	Low	Low	Low	Medium
7	Medium	Medium	Medium	Medium	Medium	High
8	Large	Medium	Medium	High	High	Catastrophic
9	Extreme	Medium	Catastrophic	Catastrophic	High	Catastrophic
10	Small	Large	Low	Low	Low	Medium
11	Medium	Large	Medium	Medium	Medium	High
12	Large	Large	Medium	High	High	Catastrophic
13	Extreme	Large	Catastrophic	Catastrophic	High	Catastrophic

Table C3: Basic spatial planning framework

Flood risk zone	Inundation depth	Rise rate	Damage to family homes	Damage to apartments	Casualty rates	Damage to industry
1	Not floodable	Not floodable	Zero	Zero	Zero	Zero
2	Small	All	Low	Low	Low	Medium
3	Medium	All	Medium	Medium	Medium	High
4	Large	Low	Medium	High	Medium	Catastrophic
5	Large	Medium, Large	Medium	High	High	Catastrophic
6	Extreme	All	Catastrophic	Catastrophic	High	Catastrophic

Appendix C3: Flood damage results framework validation

Table C4: Weighted 2050 flood damage ($D_{w,2050}$) for the basic framework validation (Q2)

Variant	$D_{w,2050}$ 45-1 [million €] *(additional damage)*	Reduction additional flood damage 45-1	$D_{w,2050}$ 45-2 [million €] *(additional damage)*	Reduction in additional flood damage 45-2	$D_{w,2050}$ 45-3 [million €]
Reference	57,370	-	366	-	14
Official planning	64,001 (+6,631/ 11.6%)	-	899 (+523/ 145.3%)	-	14
Full dike ring area	57,370	100%	366	100%	14
Municipality-Basic	59,273 (+1,903 /3.3%)	71.3%	698 (+332/ 90.6%)	36.5%	14
City outskirts	60,276 (+2,906 /5.1%)	56.2%	762 (+395/ 107.9%)	24.5%	14

Table C5: SCBA alert standards and economic flood risk basic framework case study 1 (Q2)

Variant ->	Reference	Official planning	Full dike ring area	Municipality	City outskirts
Alert standard 45-1 [yr[1]]	1/155,718	1/173,716	1/155,718	1/160,884	1/163,606
Alert standard 45-2 [yr[1]]	1/199	1/488	1/199	1/379	1/413
Alert standard 45-3 [yr[1]]	1/177	1/177	1/177	1/177	1/177
Economic flood risk 45-1 [million €/yr]	1.9	2.1 (+0.2)	1.9	2.0 (+0.1)	2.0 (+0.1)
Economic flood risk 45-2 [million €/yr]	3.7	9.0 (+5.7)	3.7	7.0 (+3.3)	7.6 (+3.9)
Economic flood risk 45-3 [million €/yr]	0.1	0.1	0.1	0.1	0.1

Table C6: Casualties case study 1 (Q2)

Variant ->fig	Casualties 45-1	Difference w.r.t. reference	Casualties 45-2	Difference w.r.t. reference	Casualties 45-3	Difference w.r.t. reference
Reference	1,257	-	2	-	0	-
Official planning	1,439	+182	9	+7	0	0
Full dike ring area-Basic & Extended	1,257	0	2	0	0	0
Municipality- Basic	1,298	+41	6	+4	0	0
Municipality-Extended	1,300	+44	6	+4	0	0
City outskirts - Basic & Extended	1,315	+58	5	+4	0	0

Table C7: Damage to family homes (Q2)

Variant	Damage to family homes 45-1 [million €]	Difference w.r.t. reference [million €]	Damage to family homes 45-2 [million €]	Difference w.r.t. reference [million €]	Damage to family homes 45-3 [million €]	Difference w.r.t. reference [million €]
Reference	4,256	-	18.0	-	0,1	-
Official planning	4,706	+450 (10.6%)	58.6	+40.7 (226.4%)	0,1	0
Full dike ring area – Basic & Extended	4,256	0	18.0	0	0,1	0
Municipality- Basic	4,322	+66 (1.6%)	37.8	+19.8 (110.3%)	0,1	0
Municipality - Extended	4,322	+66 (1.6%)	35.7	+17.7 (98.7%)	0,1	0
City outskirts – Basic & Extended	4,386	+130 (3.1%)	42.4	+24.4 (136%)	0,1	0

Table C8: Damage to apartments case study 1 (Q2)

Variant	Damage to apartments 45-1 [million €]	Difference w.r.t. reference [million €]	Damage to apartments 45-2 [million €]	Difference w.r.t. reference [million €]	Damage to apartments 45-3 [million €]	Difference w.r.t. reference [million €]
Reference	1,805	-	6.2	-	0,1	-
Official planning	2,224	+419 (23.2%)	25.6	+19.4 (311.1%)	0,1	0
Full dike ring area – Basic & Extended	1,805	0	6.2	0,0	0,1	0
Municipality- Basic	1,913	+108 (6.0%)	19.0	+12.8 (205.9%)	0,1	0
Municipality - Extended	1,919	+114 (6.3%)	20.8	+14.6 (234%)	0,1	0
City outskirts – Basic & Extended	1.951	+146 (8.1%)	19.4	+13.1 (211.2%)	0,1	0

Table C9: Damage to industry case study 1 (Q2)

Variant	Damage to industry 45-1 [million €]	Difference w.r.t. reference [million €]	Damage to industry 45-2 [million €]	Difference w.r.t. reference [million €]	Damage to industry 45-3 [million €]	Difference w.r.t. industry [million €]
Reference	4,200	-	12.3	-	0,1	-
Official planning	5,040	+840 (20%)	71.9	+59.6 (484.1%)	0,1	0

Full dike ring area - Basic & Extended	4,200	0	12.3	0	0,1	0
Municipality - Basic	4,540	+340 (8.1%)	62.6	+50.3 (409.1%)	0,1	0
Municipality - Extended	4,540	+340 (8.1%)	29.3	+17.0 (138%)	0,1	0
City outskirts - Basic & Extended	4,740	+540 (12.9%)	69.8	+57.5 (467.3%)	0,1	0

Appendix D

Appendix D1: methodology research question 3

Table D1: Input data SCBA alert standard derivation case study 2

Variable	Value [unit]	Source
Evacuation fraction	0.43	Slootjes & Wagenaar (2016)
F_{TL}	0.8 [-]	Slootjes & Van der Most (2016a)
F_{wc}	0.2 [-]	
G	1.019 [-]	
$I(h_o)$ dike ring section 35-1	€33.84 million	Slootjes & Wagenaar (2016)
$I(h_o)$ dike ring section 35-2	€87 million	
Length dike ring segment Keizersveer (35-1)	1.3 Km	(De Groot, 2014)
Length dike ring segment Overdiepsche Polder (35-1)	7.4 Km	
Length dike ring segment Capelsche Uiterwaard (35-1)	5.4 Km	
Length dike ring segment Wilhleminakanaal (35-2)	5.5 Km	
Length dike ring segment Donge (35-2)	5.3 Km	
Length dike ring segment Dombosch (35-2)	3.8 Km	

Table D2: Input data SCBA alert standard derivation case study 3

Variable	Value [unit]	Source
Evacuation fraction 15-1	0.46	Slootjes & Wagenaar (2016)
Evacuation fraction 15-2	0.08	
F_{TL}	0.8 [-]	Slootjes & Van der Most (2016a)
F_{wc}	0.2 [-]	
G	1.019 [-]	
$I(h_o)$ dike ring section 35-1	€17.48 million	Slootjes & Wagenaar (2016)
$I(h_o)$ dike ring section 35-2	€87 million	
Length dike ring segment Nieuwegeijn (15-1)	3.3 Km	(Boon, 2011)

Length dike ring segment IJsselstein (15-1)	7.3 Km	
Length dike ring segment Jaarsveld (15-1)	5.8 Km	
Length dike ring segment Lopik (15-1)	6.6 Km	
Length dike ring segment Krimpen a/d Lek (15-2)	7.7 Km	
Length dike ring segment Lekkerkerk (35-2)	6.4 Km	
Length dike ring segment Schoonhoven (35-2)	10.4 Km	

Appendix D2: results flood risk analysis case study 2 & case study 3

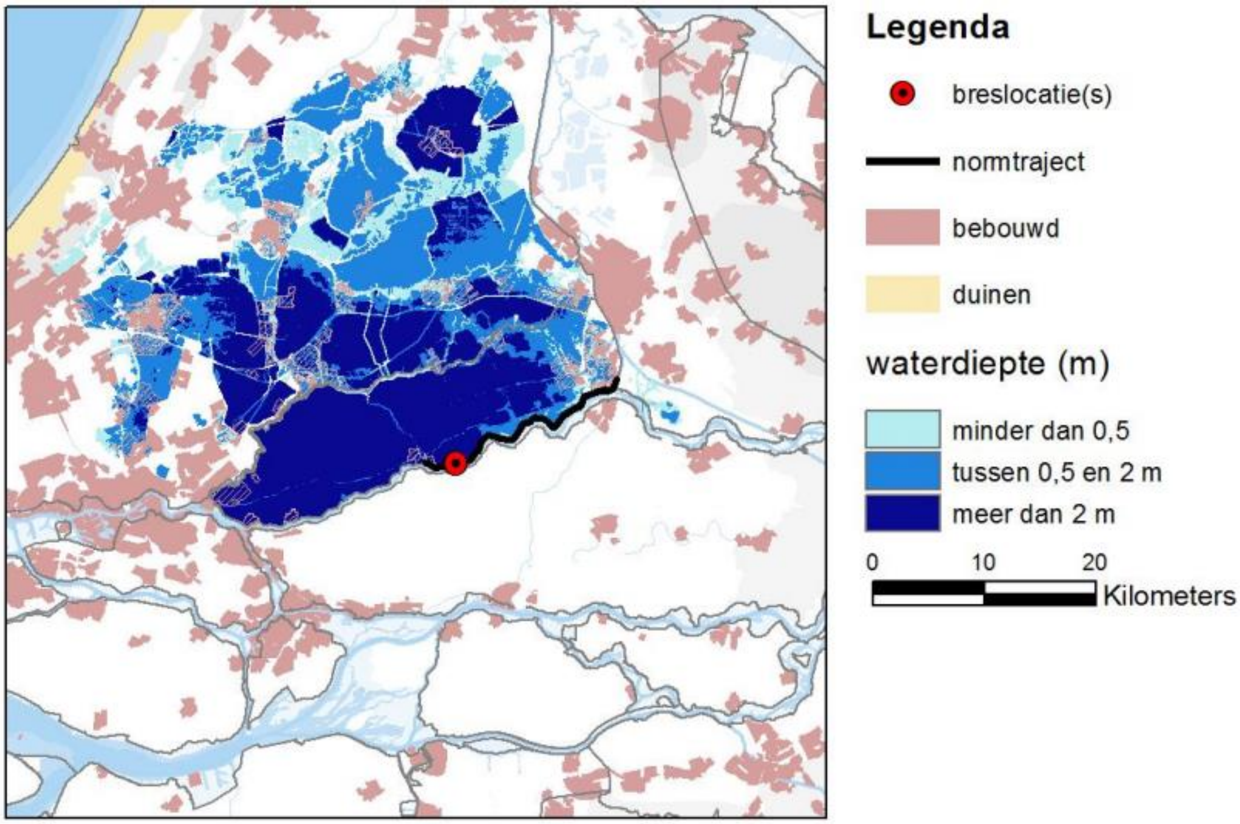

Figure D1: Flood extent dike ring area 15 (breach location Jaarsveld)

Table D3: Flood casualties (Q3)

Dike ring section	Casualties reference	Casualties official planning	Difference reference vs. official planning	Casualties framework	Difference reference vs. framework
35-1	105	112	+7	112	+7
35-2	46	48	+2	47	+1
15-1	1,626	1,709	+83	1,680	+54
15-2	873	907	+34	8,95	+22

Table D4: Financial flood damage to family homes (Q3)

Dike ring section	Flood damage reference [million €]	Flood damage official planning [million €]	Difference reference vs. official planning [million €]	Flood damage framework [million €]	Difference reference vs. framework [million €]
35-1	558	586	+28 (5.1%)	584	+27 (4.8%)
35-2	235	243	+7 (3.1%)	241	+5 (2.2%)
15-1	5,891	6,143	+252 (4.3%)	6047	+157 (2.7%)
15-2	3,643	3,784	+141 (3.9%)	3777	+135 (3.7%)

Table D5: Financial flood damage to apartments (Q3)

Dike ring section	Flood damage reference [million €]	Flood damage official planning [million €]	Difference reference vs. official planning [million €]	Flood damage framework [million €]	Difference reference vs. framework [million €]
35-1	121	142	+21 (17.6%)	136	+15 (12.5%)
35-2	27	31	+4 (15.4%)	30	+3 (10.5%)
15-1	1751	1873	+123 (7.0%)	1842	+91 (5.2%)
15-2	1065	1128	+63 (5.9%)	1103	+38 (3.6%)

Table D6: Financial flood damage to industrial objects (Q3)

Dike ring section	Flood damage reference [million €]	Flood damage official planning [million €]	Difference reference vs. official planning [million €]	Flood damage framework [million €]	Difference reference vs. framework [million €]
35-1	1,420	2,175	+755 (53.2%)	1,752	+333 (23.4%)
35-2	408	408	0	408	0
15-1	5,447	5,555	+109 (2.0%)	5,510	+63 (1.2%)
15-2	3,026	3,062	+36 (1.2%)	3,046	+20 (0.7%)

Appendix E: Conclusion

Table E1: Changes in housing stock selected municipalities case study 1, derived from CBS (2021)

Municipality	Housing stock July 2014	Housing stock start 2021	Difference 2014-2021	Residences planned 2021-2030
Bunschoten	7,867	8,550	683	2,340
Scherpenzeel	3,709	4,114	405	560
Leusden	12,389	13,229	840	825
Wageningen	19,236	18,086	-1,150	888
Amersfoort	64,445	68,809	4,364	9,160