Exploration of spatial adaptation strategies for mitigating future coastal flood risk in the Netherlands

Master Thesis

Hydraulic Engineering - Flood Risk

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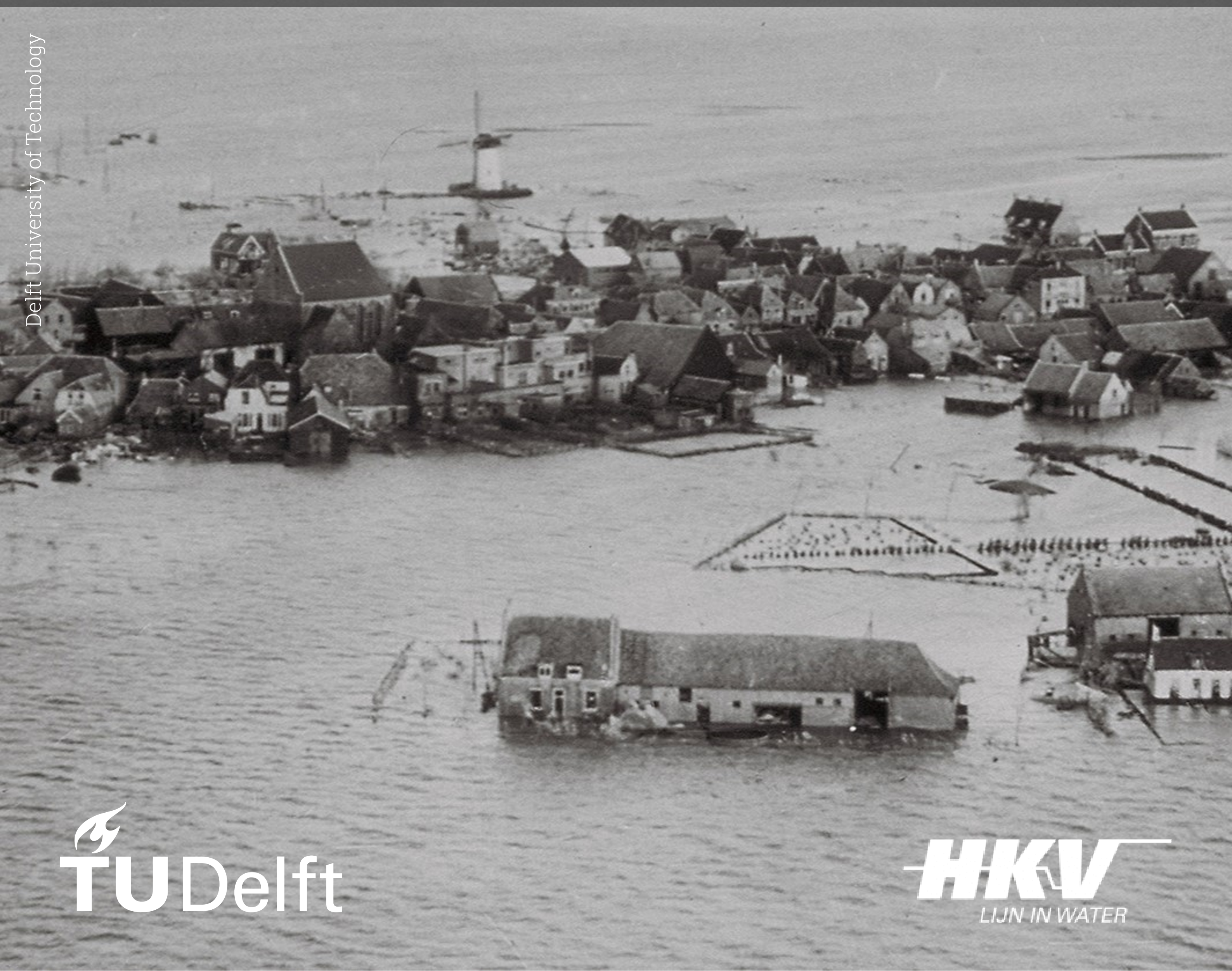

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HKV LIJN IN WATER

Exploration of spatial adaptation strategies for mitigating future coastal flood risk in the Netherlands

Master Thesis

by

Marloes Slokker

4708849

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday December 13, 2023 at 2:00 PM.

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Version:	December 6, 2023
Faculty:	Faculty of Civil Engineering and Geosciences, Delft

Cover: Watersnoodramp 1953 (PBL Planbureau voor de Leefomgeving)

Preface

This master's thesis serves as the concluding project for my master's in Hydraulic Engineering (Civil Engineering) at the Delft University of Technology. Over the past 9 months, I have enjoyed working on my thesis at the company HKV. The focus of my research has been to investigate the effectiveness of Plan B as a solution for mitigating future coastal flood risk in existing cities of the Netherlands, by comparing the performance of Plan B with the present strategy and other adapted spatial visions that consider the potential impacts of projected sea level rise.

With this preface, I would like to take the opportunity to express my gratitude to my committee. Firstly, Matthijs Kok, professor at the Delft University of Technology and the chair of this committee. I thank him for his enthusiasm, thoughtful input, and for providing interesting suggestions for this thesis. Next, I would like to extend special thanks to Bart Strijker. As my daily supervisor from HKV and the originator of this topic, I have experienced the collaboration to be very pleasant, despite his relocation to Sweden a few months ago. We have had many insightful discussions, and I have greatly benefited from his suggestions, appreciating his consistent involvement. He also assigned Cees Oerlemans as the second daily supervisor from HKV. Cees was a valuable addition to the committee for this master thesis. With his dedication and expertise in the field of flood risk, he was truly an asset, and I learned a lot from him. Additionally, I would like to thank Jakolien Leenders and Abe Klaas de Jong from HKV for their assistance with specific software. Finally, I want to express my gratitude to Joep Storms, an associate professor at the Delft University of Technology, for his contribution to this collaboration. Despite his expertise which is mainly in applied geology, his vision has added interesting perspectives to this research.

Last but not least, I would like to thank my family, friends and roommates for their support during this thesis and my student life in general. Although I am relieved that this time is coming to an end and I am ready for a next step, I am very sure that I will also miss this incredible time. Studying in Delft has brought me very insightful and valuable experiences, such as an internship at Witteveen+Bos and a multidisciplinary project in Uganda on the extension of the drinking water supply network. Finally, graduating on this topic at HKV was a great conclusion, and I aspire to continue to work in the field of flood risk towards a more sustainable future.

Marloes Slokker
Delft, December 2023

Abstract

Sea levels are expected to rise in the coming centuries, but there is increasing concern that this will happen at a faster rate than previously assumed because of factors such as accelerated ice melting in Antarctica. Coastal cities in the Netherlands are vulnerable to flooding and have an increased flood risk due to population growth and climate change, including sea level rise. Therefore, the Sea Level Rise Knowledge Program has been established. This program investigates the consequences of sea level rise and explores mitigation strategies for the protection and design of the Netherlands. These mitigation strategies include the categories 'protect-open' (which is the current strategy in the Netherlands), 'protect-closed', 'advance', and 'accommodate'. These strategies need further research for societal and technical feasibility, as they remain in an early stage of development (Haasnoot et al., 2019). This research therefore aims to examine the potential of one such conceptual idea in the category of accommodating: Plan B NL2200. This strategy envisions a Netherlands without dikes and focuses on adapting to sea level rise by shifting population and infrastructure to higher ground in the East. The Western coast transforms into a marine lagoon, while preserving existing cities ("Plan B: NL2200", 2020).

The research question reads: "How does the Plan B NL2200 approach (accommodate) perform as a solution for mitigating future coastal flood risk in existing cities, considering the projection of accelerated sea level rise, in comparison with the current strategy (protect) and alternative spatial adaptation strategies?"

This study examined flood risk levels for multiple (extreme) accelerated sea level rise scenarios (0, 1, 2, 4 and 6 meters) and a range of storm surge conditions (from T = 10 years up to T = 100,000 years). A probabilistic model is used to estimate the flood risk levels within coastal polders. This model is applied to two polders: an idealized coastal polder (a fictional case based on the characteristics of Walcheren) and Walcheren, an actual Dutch coastal polder.

The first part of this research focuses on the analysis of the idealized coastal polder. In this analysis, various spatial adaptation strategies are evaluated, including a plain dike-ring strategy, a secondary dike-ring strategy, a value protection dike-ring strategy, and a partitioned dike-ring strategy. Multiple configurations of these strategies have been analyzed. These configurations range from solely primary dike reinforcement to solely secondary dike reinforcement to complete dike reinforcement, and more. The objective is to assess the effectiveness of these strategies (and configurations) regarding the criteria spatial impact and mitigating flood risk, in terms of inundation depth and rate, given the future high water level scenarios. The findings of this analysis are implemented in the second part of this research: the case study on Walcheren.

For this case study on Walcheren, the various proposed spatial adaptation strategies are compared based on their level of flood risk mitigation, in terms of damage, casualties and affected people. One of the considered strategies is Plan B. For Walcheren, this means that the cities Middelburg and Vlissingen are protected separately through their own dike-ring. This reduces the dike-ring length compared to the primary dike-ring around Walcheren, which could potentially be advantageous from an investment point of view. Finally, the most cost-effective strategy can be identified by considering the lowest net present value, which combines investment costs and the expected annual damage, discounted to a present-day value.

The findings from the idealized coastal polder analysis indicate that all adaptation strategies are effective in mitigating flood risk, compared to a plain dike-ring strategy, as long as primary or complete dike reinforcement is implemented. The effectiveness of the various strategies for increasing sea levels does not change. In general, the secondary dike-ring strategy, value protection dike-ring strategy, and partitioned dike-ring strategy with complete dike reinforcement are the most favorable options, especially in providing enhanced protection to the city and reducing inundation depth and inundation rate

within the city across the multiple sea level rise scenarios. Of these three strategies, the value protection dike-ring strategy stands out as the preferred strategy, since the additional required embankment length is lower compared to the secondary dike-ring and partitioned dike-ring strategies.

The mentioned spatial adaptation strategies including complete reinforcement are evaluated in the case study of Walcheren. In addition, an extra configuration of the plain dike-ring strategy with an increased safety standard (lower failure probability), referred to as P2, is considered. Furthermore, two variants of the Plan B approach, B1 and B2, are examined. The final results of the Walcheren case study point out that, based on the total net present values, the plain dike-ring strategy with an increased safety standard (P2) stands out as the most cost-effective strategy when advocating for the preservation of the entirety of Walcheren. Second is the secondary dike-ring strategy, with a total net present value that is nearly a doubling compared to that of P2. The costliest strategy is Plan B (B1), due to its extreme flood risk. When the emphasis shifts to protecting only Middelburg and Vlissingen, the most favorable choice is also the plain dike-ring (P2) strategy, closely followed by the value protection dike-ring (including complete dike reinforcement) and the secondary dike-ring strategy.

Referring to the main research question, it can be concluded that, for the case study of Walcheren specifically, Plan B does not perform as the best strategy based on the set criteria. On the contrary, most of the other considered spatial adaptation strategies outperform the Plan B strategy. This study has shown that investments in the primary dike-ring prove more effective than those in the Plan B strategy at an equivalent safety level, attributed to both lower costs and risks. Although Plan B requires less dike length, its investment costs are higher due to building additional value protection dike-rings from scratch. In the event of a dike breach in Plan B, water distribution over a smaller area increases the inundation depth, elevating the risk compared to the primary dike-ring strategy. Furthermore, the primary dike-ring strategy has the advantage of not requiring land relinquishment, unlike the Plan B strategy. In addition to the primary dike-ring (P2) strategy, both the value protection dike-ring (complete dike reinforcement) and the secondary dike-ring strategy also outperform the Plan B strategies. Therefore, it can be concluded that the Plan B variants considered in this study are not the recommended solutions for mitigating future coastal flood risk in Middelburg and Vlissingen (or Walcheren), considering the projection of accelerated sea level rise, compared to alternative spatial adaptation measures.

Based on the outcomes of this study, it is recommended to maintain the current strategy of reinforcing the primary dikes while tightening safety standards, in order to protect Walcheren, including Middelburg and Vlissingen. Although the expectation is that this conclusion may hold for other Dutch coastal polders as well, the conclusions cannot be transferred directly to western cities in the Netherlands in general, since many (location-specific) assumptions possibly influence the results of this study. Examples of these location-specific assumptions are the contribution of rivers to the overall flood risk and the proportion of population and value in urban areas versus rural areas. For other polders in the Netherlands, it is therefore recommended to extend the methodology of this study for strategy comparison and flood risk assessment. Recommendations for further research include sensitivity analyses, other effects of sea level rise, exploration of more spatial adaptation strategies, optimization methods for dike reinforcement, and the societal aspects of the Plan B approach.

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Part I

Introduction and methodology

1 Introduction

The Netherlands has a long history of flooding, due to its low-lying topography and its location at the delta of several major rivers. Some of the most significant historical floods in the Netherlands include the St. Elizabeth's flood of 1421, the All Saints' flood of 1570, and the North Sea flood of 1953.

The St. Elizabeth flood was caused by a combination of heavy rainfall and a storm surge from the North Sea, which flooded large parts of the area and changed the course of several rivers (van der Meulen, 2018). The flood is estimated to have caused tens of thousands of fatalities as well as widespread damage to infrastructure and farmland in central Holland (De Kraker, 2006).

The All Saints' flood, also known as the 'Allerheiligenvloed', was caused by a combination of storm surges and a high tide that flooded a part of the Netherlands, resulting in thousands of fatalities and significant widespread destruction. Most of the polder regions of Flanders and the lowlands west of Bergen op Zoom, as well as areas on the right bank of the Oosterschelde and parts of central Zeeland, were affected by this flood (De Kraker, 2006).

The North Sea flood of 1953 was one of the most devastating floods in modern Dutch history. The flood was caused by a combination of the most severe storm surge ever recorded in the southeastern part of the North Sea; high tides; and a spring tide (De Kraker, 2006). This resulted in the flooding of Zeeland, a part of North Brabant, and a part of South Holland. During this flood, 4500 houses and buildings were destroyed, 200,000 ha of land were inundated and it claimed the lives of over 1,800 people (Slager, 2003). It also prompted the Dutch government to undertake a major flood protection program known as the Delta Works, which involved the construction of a network of dams, dikes, and storm surge barriers to protect against future floods (De Kraker, 2006) ("De Deltawerken", 2023).

The Delta Works in the Netherlands are managed using an adaptive delta management approach that allows for flexible responses to changing measurements and insights related to climate. Storm surge barriers were designed based on a maximum sea level rise within a certain period, but options for adaptation and replacement vary per barrier and depend on 12-yearly assessments. Additional measures are available if needed to keep the Delta Works in good condition and protect the low-lying areas of the Netherlands from floods and natural disasters ("De Deltawerken", 2023).

1.1. Motivation

It is an established fact that sea levels will experience a gradual increase over the next century and beyond. Moreover, several recent scientific publications have drawn a conclusion that the rise of sea levels may occur at a (much) faster rate than the assumptions made in the Delta Scenarios, which serve as the foundation for the Delta Program. This increased rate of sea level rise relates to newly discovered insights into the potential accelerated breaking and melting of land ice in Antarctica (Haasnoot et al., 2018). However, the precise magnitude and rate of this rise remain uncertain, as it depends on factors such as greenhouse gas emissions and therefore on international climate policy (DeConto & Pollard, 2016). Dutch policy aims to meet the targets set in the Paris Agreement, which seek to limit the global temperature increase to a maximum of 2°C. There is still much uncertainty about future emissions and the global warming and sea level rise associated with them. Because of the potentially large implications that such developments could have for the Netherlands and, consequently for the Delta Program, the scenario of extreme sea level rise is also considered. An extreme sea level rise could result from an emissions scenario leading to 4°C global temperature rise (Haasnoot et al., 2018).

Due to significant uncertainties in sea level rise, which may increase faster and more than previously assumed in the adaptive plan of the Delta Program, the Sea Level Rise Knowledge Program (Dutch: Kennisprogramma Zeespiegelstijging) has been established (Haasnoot et al., 2022).

The Sea Level Rise Knowledge Program is a collaborative effort between governments, companies, knowledge institutions, and civil society organizations to investigate the potential consequences of sea level rise for the Netherlands. The program examines a range of long-term scenarios and explores strategies for anticipating and mitigating the consequences. By providing valuable insights, the program allows for making informed decisions about protecting and designing the Netherlands ("Kennisprogramma Zeespiegelstijging", 2023).

1.2. Literature

This section provides an overview of the literature research conducted for this study. Relevant literature for this study includes the determination of flood risk in the Netherlands; the impacts of accelerated sea level rise; and possible adaptation strategies for the spatial planning of the Netherlands, according to the 'Sea Level Rise Knowledge Program'.

1.2.1. Flood risk

The definition of risk can vary depending on the context. In hydraulic engineering, flood risk takes into account both the probability of flooding and its potential impact (Kok et al., 2016). The probability of flooding is defined by determining the probability of a dike breach for each part of a levee system. The consequences of flooding are often expressed in terms of losses and fatalities and are determined for each dike breach. Then the flood risk is quantified as the product of probability and consequence (Vergouwe, 2014a). The probability of flooding and the associated consequences are combined for each part of the levee system. Together, this combination gives the flood risk (Vergouwe, 2014a). This is shown in figure 1.1.

Figure 1.1: Definition of flood risk (Vergouwe, 2014a)

The consequences of flooding are often defined as economic damage. However, risk encompasses more than just these factors. Flood risk can also be expressed in terms of other measures such as societal risk (probability of a large group of people losing their lives) and individual risk (probability of an individual dying). The Dutch approach to risk management considers three measures of risk: annual expected damage, individual risk, and societal risk. The most appropriate measure of risk depends on the specific factors and the perceived severity of the upcoming event (Kok et al., 2016).

Probability

VNK has computed the probability of failure for the failure mechanisms that can cause flood defenses to fail, for all levee systems in the Netherlands (Vergouwe, 2014a). The main failure mechanisms for levees are either driven by extreme hydraulic conditions or due to geotechnical failure. These main failure mechanisms are listed below:

- Overflow and overtopping
- Shearing of the landside slope
- Erosion due to revetment damage
- Piping, backward internal erosion

To calculate the failure probability of a levee system, it should first be divided into homogeneous stretches, and then the failure probability of each stretch can be determined (Vergouwe, 2014a).

To represent the levee performance, fragility curves can be used. A fragility curve expresses the relationship between the flood loading on the levee and the conditional probability of failure given that loading (Simm & Tarrant, 2018). Fragility curves differ from the relative reliability index because they are functions rather than point estimates, they treat loads deterministically and the probabilities are interpreted in absolute terms. Fragility curves provide a more comprehensive perspective on system reliability by conveying more information. The shape of a fragility curve describes uncertainty in the system's capacity to withstand a load or what load will cause the system to fail. If there is little uncertainty in capacity or demand, the fragility curve will be a step function. In complex systems, there is often uncertainty in the system's capacity to withstand a load, resulting in an S-shaped fragility curve (Schultz et al., 2010).

Consequences

Floods can be highly dangerous to human life and property and can cause widespread damage to society. The location of the breach, ground level, and land use in the area behind the flood defenses are crucial factors in determining the impact of a flood (De Moel et al., 2015). Raised landscape features, such as railways, roads, and regional defenses, can affect the flood's propagation patterns and the speed at which the area is submerged. Computer models are used to analyse different flood scenarios, including water depth, velocity, and rise rate, which are essential in determining the scale of losses and the number of fatalities that could occur as a result of a levee breach (Vergouwe, 2014a).

Flood risk in the Netherlands

VNK has assessed the flood risk in different parts of levee systems in the Netherlands by examining the probability of failure in specific areas such as levee sections, dunes, and hydraulic structures, and the potential consequences of such failures in terms of economic losses and fatalities. It is important to note that the level of risk may not be uniform across the entire levee system due to variations in probability and consequences. By identifying the key failure mechanisms and vulnerable areas, VNK has gained insights into how to best minimize flood risk through prevention strategies (Vergouwe, 2014a) (Vergouwe, 2014b).

Multi-layer safety

The Dutch government has introduced a flood safety policy to address future risks, with a focus on two main goals:

1. Improving physical safety by reinforcing numerous dikes and flood defenses
2. Mitigating potential consequences of flooding, through (sustainable) spatial planning and the revision of disaster plans.

This approach, which is a combination of protection and control is also known as 'multi-layer safety' (Dutch: meerlaagsveiligheid) (Dumbar, 2015) and consists of three layers. The first layer, 'protection', focuses on preventing floods through dikes and flood defenses. The development of new standards in terms of flooding probabilities is based on a cost-benefit analysis and a casualty assessment (basic safety) in the National Water Plan (Kolen & Kok, 2012). The second layer, '(sustainable) spatial planning', allows for the reduction of the impact of flooding by ensuring a more robust planning of urban areas and protecting vital and vulnerable functions. The third layer, 'disaster management', focuses on preparation for and management of floods through education, crisis management and evacuation (Dumbar, 2015) (Kolen et al., 2010). Effective disaster management can lead to increased safety for more individuals, through preventive evacuation. In addition, it enhances self-reliance (reducing the number of casualties) and such management can potentially prevent damage, including the evacuation of animals and movable goods (Kolen & Kok, 2012).

In figure 1.2, the visual representation of the multi-layer safety approach can be observed, with layers 1, 2, and 3 depicted from bottom to top, respectively. This research mainly focuses on the first two layers: 'protection' and '(sustainable) spatial planning'.

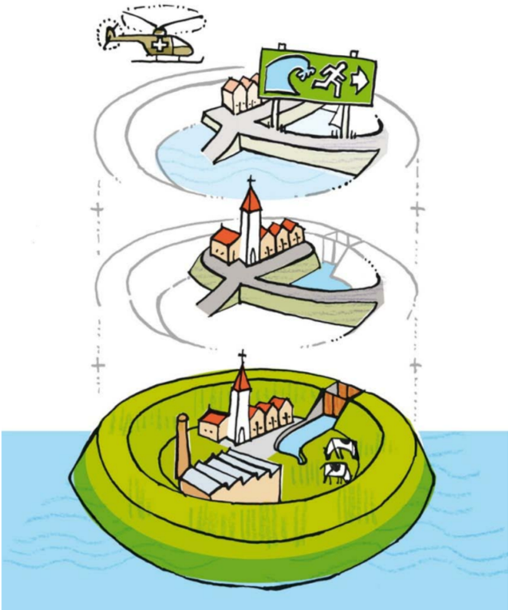


Figure 1.2: Multi-layer safety (Dutch: meerlaagsveiligheid) (Kolen & Kok, 2012)

1.2.2. Accelerated sea level rise

Until 2050, the projections of accelerated sea level rise do not differ much from the current Delta scenarios, which assume strong climate change. However, significant differences occur after 2050. The current scenarios for the Dutch Delta Program assume a sea level rise between 0.35 meters and 1 meter by 2100 (compared to the reference year 1995). However, new projections from KNMI suggest that the sea level could rise up to 2 meters by 2100, even if the goals of the Paris Agreement (a temperature increase of maximum 2°C in this century, RCP4.5) are met. In the case of a stronger global warming (with 4°C in 2100, RCP8.5), the sea level could rise to 3 meters by 2100 compared to 1995. These projections assume the occurrence of mechanisms that lead to an accelerated loss of ice mass in Antarctica and thus to an additional of sea level rise after 2100. The current upper limit of 1 meter from the Delta scenarios could be reached as early as 2070 (RCP8.5) or 2080 (RCP4.5) in the projections for accelerated sea level rise. Even after 2100, the sea level will continue to rise, possibly up to 5 to 8 meters by the year 2200 (Haasnoot et al., 2018). A consequence of sea level rise is that storm surge barriers will have to close more frequently and - in case of extreme values of sea level rise - eventually close completely. During large storms, more water will pass over the barriers more frequently.

1.2.3. Adaptation strategies

Deltares developed four strategies for the Netherlands that span the solution space for adapting to high sea level rise: protect-closed, protect-open, advance (seaward) and accommodate. All strategies largely correspond to the internationally recognized directions for adapting to high sea level rise (Haasnoot et al., 2019). A caricature of the four strategies is shown in figure 1.3. In practice, a combination of solution directions is most likely to be appropriate or desirable.

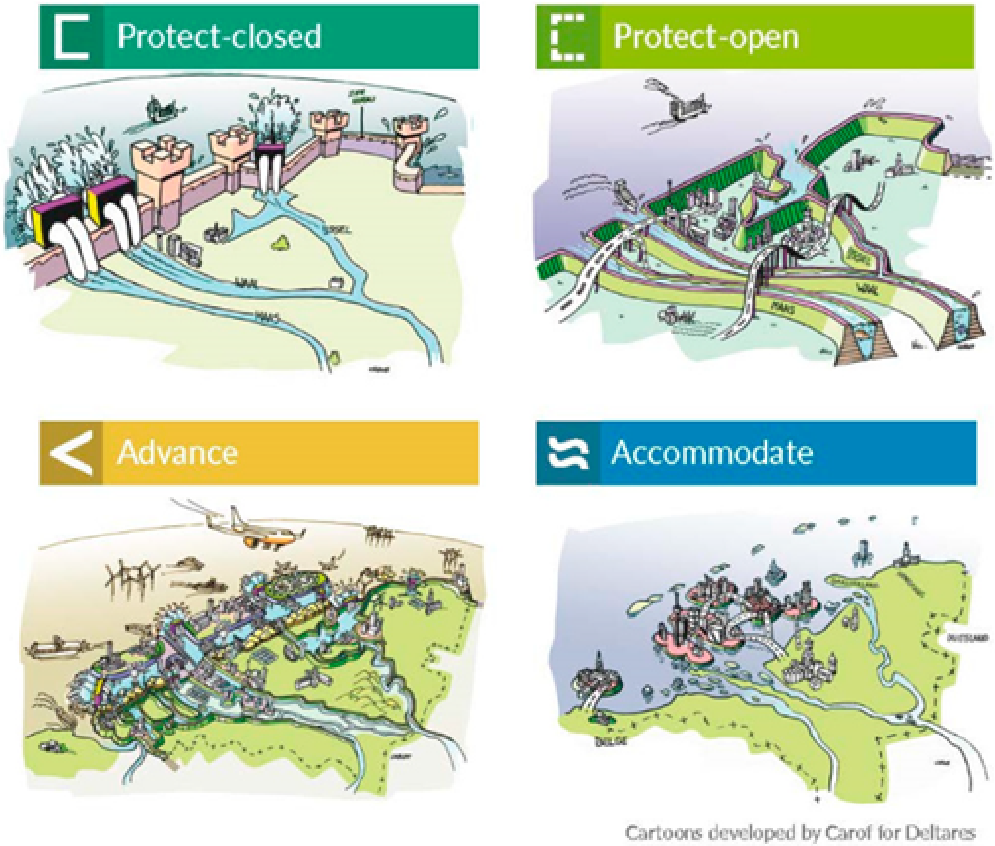


Figure 1.3: Adaptation strategies Deltares (Haasnoot et al., 2019)

Protect-closed

Protect-closed reduces the risk of consequences of sea level rise by protecting the coast against flooding and erosion. This can be accomplished by using both hard infrastructure and soft methods based on sediment or nature. In this closed variant, a solid water barrier is established that permanently closes the Netherlands off from the sea. This ensures that the water level in the rivers remains unaffected by the sea level and salt cannot infiltrate further into the delta. As a result, large pumps are needed to pump the rivers out to the North Sea (Haasnoot et al., 2019) (Haasnoot et al., 2022).

Protect-open

In the protect-open variant, the rivers remain connected to the sea. This solution reduces the risk of consequences of sea level rise in the delta by protecting not only the coast, but also the land along the rivers, which are still connected to the sea. In addition to coastal protection as in the closed variant, the open variant also includes storm surge barriers in the river estuaries that can be closed during high water levels, and additional protections such as dikes along the open rivers (Haasnoot et al., 2019) (Haasnoot et al., 2022).

Advance

Advance, or sea-ward, means creating higher land towards the sea in order to increase safety. This also creates more space for different things like housing, recreation, nature and energy provision. To do this, the current coastline can be moved out towards the sea by creating a new strip of land. This can include making a coastal lake or creating new islands (Haasnoot et al., 2019) (Haasnoot et al., 2022).

Accommodate

The main goal of accommodating, is to reduce vulnerability of houses and infrastructure by for example building houses on stilts or making them flood-resistant, but also by raising land or applying warning systems and spatial adaptation. For the Dutch delta, accommodating also means migration and planned relocation to higher elevated areas. This strategy is called 'living with water'. It is a way to make sure that vulnerable coastal areas are adapted such that they can continue to be utilized despite the rising sea level (Haasnoot et al., 2019) (Haasnoot et al., 2022).

1.2.4. Plan B NL2200

Plan B NL2200 is an adapted spatial vision for the future of the Netherlands developed by landscape architects and reacts to one of the adaptation strategies 'accommodate'. A map of the top view of the Netherlands according to this Plan B is presented in figure 1.4.

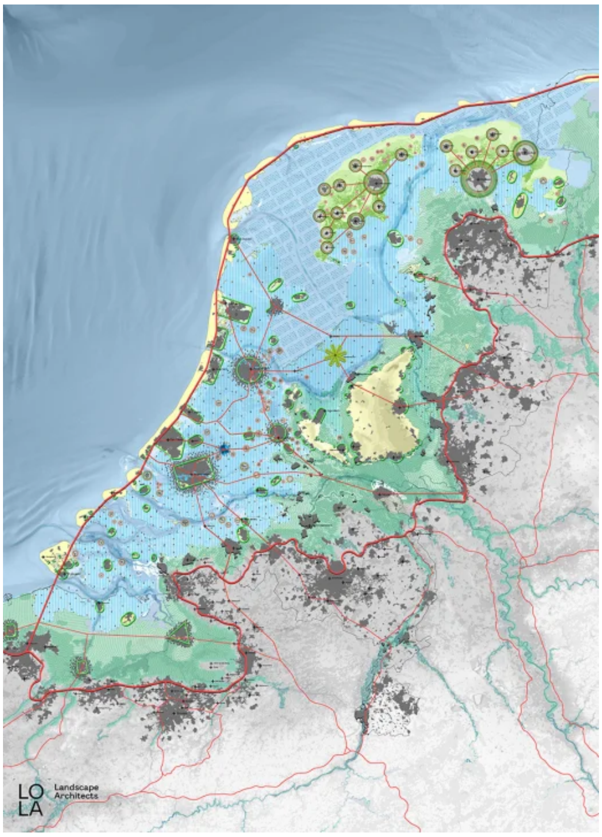


Figure 1.4: Plan B NL2200 ("Plan B: NL2200", 2020)

This plan is an initial exploration of a strategy to adapt to higher sea levels under an extreme but realistic scenario ("Plan B: NL2200", 2020): a rise of 6 meters by the year 2200 (De Winter et al., 2017). Dikes, dunes, dams and storm surge barriers won't be able to withstand these conditions. Therefore, Plan B proposes a Netherlands without dikes, where people live above sea level, rather than below it. It does not focus on constructing dikes and dams to keep the sea out. Instead, Plan B suggests using nature to create a new (and safer) Netherlands. However, living above sea level means shifting the coastline towards the eastern part of the country. This means that people living in the lower parts of the country will have to move to the east along with all the necessary facilities and infrastructure. This will create a new economic hub along the eastern coast. In this plan, the remainders of the western coast will be preserved and strengthened to create a marine lagoon. This lagoon will protect the historic cities and villages while also providing opportunities for various activities. Residents of 'Waterland', who are experienced in water management, will develop the lagoon for different purposes, including housing, fishing, aquaculture, recreation, nature and energy ("Plan B: NL2200", 2020).

Plan B NL2200 may seem alarming at first, but it does not have to be a defeat. It shows a bright future for the Netherlands, where people deal with water in a new way. Even if Plan A (the Paris Agreement) doesn't work out, the Netherlands can still survive by living with water and building with nature ("Plan B: NL2200", 2020).

Plan B versus present situation

The main difference between Plan B and the current spatial planning of the Netherlands is that Plan B generally does not include dikes or other forms of flood defenses. The sea water will rise to its natural level, which will result in the loss of areas of land. Additionally, a large number of people will need to relocate to higher ground or protected areas. In contrast to the current strategy, this implies that these areas will become even more densely populated than they already are.

An important similarity is that major Western cities such as Amsterdam, Rotterdam, The Hague and Utrecht, among others, will continue to exist in Plan B, without being rearranged compared to the present situation. Therefore, the present urban (built-up) areas will not disappear, but the cities will be protected, for instance through their own dike ring.

1.3. Problem statement

Coastal cities that are situated in deltaic regions are often vulnerable to floods due to their close proximity to rivers and sea, relatively low elevations, and land subsidence (De Moel et al., 2011). This applies to many Dutch cities, as a significant proportion of the Netherlands lies below sea level and major rivers have a direct route to the sea. This makes the country, and therefore the coastal cities, vulnerable to flooding (Vergouwe, 2014b). Since these cities experience continued population growth and economic development, the exposure to coastal flooding increases which enlarges the flood risk of these areas. As a consequence, protection against high water is and remains of vital importance for millions of Dutch citizens and the country's economy. To this end, the Netherlands is protected by over 3,500 kilometers of primary flood defenses, but maintenance of these measures in a delta is ongoing. In the forthcoming years and decades, the country must remain well protected, hence investments remain necessary. However, it is important to acknowledge that the impacts of climate change and the associated accelerated sea-level rise pose a threat to the future flood risk of the Netherlands (De Moel et al., 2011) (Vergouwe, 2014b).

Given the accelerated sea level rise and increasing future flood risks, the Sea Level Rise Knowledge Program has proposed multiple adaptation strategies for a revised spatial planning of the Netherlands, which were introduced in paragraph 1.2. However, these adaptation strategies are still at an early stage of development. While a few conceptual ideas have been formulated, it has not been thoroughly researched whether these ideas are realistic in terms of societal and technical feasibility. Therefore, this research is meant to conduct a more in-depth examination on the technical potential of one of the conceptual ideas developed in the context of accommodating.

The main goal of this research, corresponding to a revised and adapted spatial planning strategy of the Netherlands, is elaborated in more detail in the next paragraph 1.4.

1.4. Objective

The objective of this master thesis is to examine how Plan B ("Plan B: NL2200", 2020) performs as a solution in mitigating future coastal flood risk in Western cities of the Netherlands, and therefore enhance the future coastal flood safety in the Netherlands, in comparison with the present strategy and other adapted spatial visions that incorporate the potential impacts of the projected sea level rise.

This research is divided into two main parts. The first part explores various spatial adaptation strategies in idealized coastal polders, while the second part delves into the analysis of an actual Dutch coastal polder.

1.4.1. Context

This sub-paragraph aims to provide further clarification on the definitions of key features, such as flood risk and spatial adaptation measures, in this study. This is necessary as there may be multiple interpretations regarding their definitions.

Flood risk

Mostly, flood risk can be defined in terms of economic risk, societal risk or individual risk, as explained in paragraph 1.2. However, the first part of this research evaluates (fictional) scenarios of an idealized coastal polder, which makes it difficult to express the flood risk in terms of economic losses or fatalities.

Therefore, in this part of the research, flood risk will be defined as the probability of exposure to a specific water depth, due to a flooding. Hence, flood risk will be expressed in terms of flood exposure (De Moel et al., 2015). On the contrary, in the second part of this research, which delves into the analysis of a Dutch coastal polder, flood risk is defined in terms of damage, casualties and number of people affected by a flood.

Spatial adaptation measures

Varying approaches to spatial adaptation can have a significant impact on the flood risk of an area. Therefore, it is essential to consider the unique characteristics of a certain area to determine the most effective strategy to reduce flood risk. The spatial adaptation strategies considered in this research are retrieved from (Oost & Hoekstra, 2009) and listed below.

(a) A plain dike-ring area (no adaptation measures);

(b) A partitioned dike-ring area;

(c) A secondary dike in the dike-ring area, and

(d) A dike-ring with additional value protection.

The spatial adaptation strategies (a, b, c and d) are presented in figure 1.5 respectively.

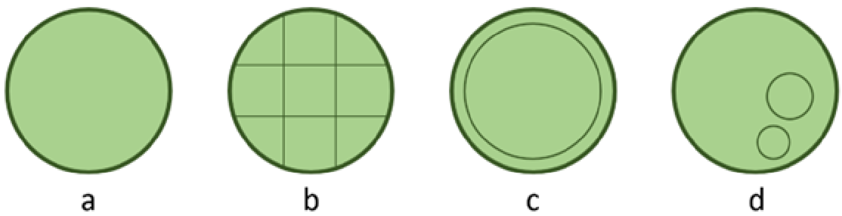


Figure 1.5: Spatial adaptation strategies

According to the above listed strategies, one form of spatial adaptation that will be considered in this research is compartmentalization. The use of compartmentalization measures can effectively reduce the extent of flooding or confine it to a limited area where the damage is minimized, thereby mitigating the impacts of a flood (Koks et al., 2014) (Oost & Hoekstra, 2009). To implement this type of adaptation strategy, existing "line elements" such as dikes, roads, and railways in the landscape can be upgraded to function as flood protection structures. Since these elements already have higher elevations, they can be easily transformed into secondary water defense structures (Koks et al., 2014).

1.4.2. Research question

Based on the objective of this project, the research question of this project is:

How does the Plan B NL2200 approach (accommodate) perform as a solution for mitigating future coastal flood risk in existing cities, considering the projection of accelerated sea level rise, in comparison with the current strategy (protect) and alternative spatial adaptation strategies?

An important note for this research is that explicit consideration is given to the influence of external factors, specifically sea water levels and sea level rise, on the primary flood defense and its effect on inundation within the polder. Flooding from within, such as rivers or intense precipitation events, is therefore not considered.

In order to answer the research question, the scope of this study is narrowed down to a single coastal polder area in the Netherlands. The choice for focusing on a coastal polder area in the Netherlands is motivated by the fact that the flood risk in such polders is predominantly determined by coastal flood inundation, with negligible contribution from rivers. Therefore, the direct impact from sea level rise on coastal flood inundation can be isolated.

Several sub questions that serve as a support to answer the research question are formulated below.

1. How do various spatial adaptation strategies influence the inundation depth (frequency) in idealized coastal polders compared to a plain dike-ring strategy, while accounting for the projected accelerated sea level rise?
2. What are effective spatial adaptation measures, considering the evaluation of spatial impact and mitigating flood risk, in idealized coastal polders?
3. What are potential design strategies for the Dutch coastal polder, taking into account the main principles of Plan B's adapted spatial vision as a foundation?
4. What is the effectiveness of various design strategies in reducing the expected future flood risk in the coastal polder, given the projected sea level rise, compared to the current strategy of the Dutch coastal polder?
5. What is the most cost-beneficial strategy for mitigating the future coastal flood risk in the Dutch coastal polder?

1.4.3. Case study: Walcheren

This research will be carried out by means of a case study. The selected case study area is the coastal polder area of Walcheren, which corresponds to the zone enclosed by dike-ring 29. The decision to focus on dike-ring 29 for this study allows for a focused and in-depth examination of the effects of coastal flood inundation on flood risk and the potential impact of future sea level rise. Next to that, this area is highly relevant to the research question in terms of reducing future coastal flood risk in Western cities of the Netherlands, since the cities Middelburg and Vlissingen are located in Walcheren. An elaborated area analysis of Walcheren is described in chapter 1.5.

According to the main principles of Plan B, Middelburg and Vlissingen will be protected, but the remaining parts of Walcheren will be reclaimed by the sea. Today, the residents in Middelburg and Vlissingen combined make up over 80% of the total population in Walcheren. Assuming this ratio will not change over time and residents of Middelburg and Vlissingen remain housed, this implies that approximately 20% of the population in Walcheren should move to higher ground or other protected areas, if Plan B would be put into action. This comes with moral complications, as this scenario creates significant pressure on the socio-economic environment. Therefore, it is important to plan the transition carefully. The sooner a relocation plan is established, the better it can be prepared for in terms of investments, housing, and other factors. For example, stimulation of employment in high land areas is one example of an effective strategy. However, the decision to migrate as a solution of 'accommodating' is unlikely to be driven by a political decision to leave a place of residence. Instead, extreme events with significant impacts are more likely to influence the decision of individuals and firms to relocate (Haasnoot et al., 2019). Although these societal factors play a significant role in the reflection of the feasibility of Plan B, they are not further considered in this study. Instead, this study only focuses on the determination of the most cost-beneficial strategy to redesign Walcheren according to the main principles of Plan B, with the goal to minimize future coastal flood risk.

1.5. Study area: Walcheren

In the past centuries, Zeeland has experienced multiple floods. After each flood, repair works were carried out to make the land habitable again and to protect it against future floods. After the 1953 North Sea flood, the Delta Commission was established to develop a plan to better protect the land against floods. The commission introduced a new safety philosophy that considers the costs of reducing the probability of flooding in relation to the reduction of the flood risk (Bossenbroek & Bardoel, 2014).

1.5.1. Location and schematization

Walcheren is located West in the province of Zeeland and consists of three municipalities: Middelburg, Veere and Vlissingen. Walcheren is surrounded by the North Sea, the Westerschelde, and the Veerse Meer (Vergouwe, 2014a), see figure 1.6. The eastern boundary of dike-ring 29 is defined by the separating dike with dike-ring 30 (Bossenbroek & Bardoel, 2014). Walcheren has a surface area of approximately 200 km^2 and a population of around 115,000 people (Vergouwe, 2014a). The combined population of Middelburg and Vlissingen covers more than 80% of the total population in Walcheren.

Figure 1.6: Location Walcheren (Bossenbroek & Bardoel, 2014)

The primary flood defense of the dike-ring area consists of various categories of water defenses (see figure 1.7). The dikes along the Veerse Meer fall under category C defenses, which provide indirect protection against external water. The other water defenses of the dike-ring are categorized as A defenses, which offer direct protection against external water.

The total length of the category A defenses is approximately 47.5 km (Vergouwe, 2014a). The boundary with dike-ring 30 is formed by 'dry' inner dikes that have a formal status as primary category C defenses (Bossenbroek & Bardoel, 2014).

Figure 1.7: Dike-ring 29 (Bossenbroek & Bardoel, 2014)

1.5.2. Flood scenarios

The calculated probability of flooding (for the A category defense) in the dike ring area is 1/1,000 per year. This calculated probability of flooding relates to the probability that a flood will occur somewhere in the dike ring area (Bossenbroek & Bardoel, 2014). The dike ring for the category A defense can be subdivided into 35 dike sections or 16 ring sections. These 16 ring sections are Vrouwenpolder, Oranjezon, Oostkapelle, Domburg, Noordduin, Westkapelle, Boudewijnskerke, Zoutelande, Dishoek, Vlissingen-Zwanenburg, Vlissingen Stad, Buitenhaven-West, Buitenhaven-Oost, Ritthem, Rammekens and Quarlespolder respectively (Bossenbroek & Bardoel, 2014). The annual failure probability per dike section is shown in figure 1.8. As can be seen in the figure, the overall failure probability per dike section in Walcheren is smaller than 1/10,000 per year.

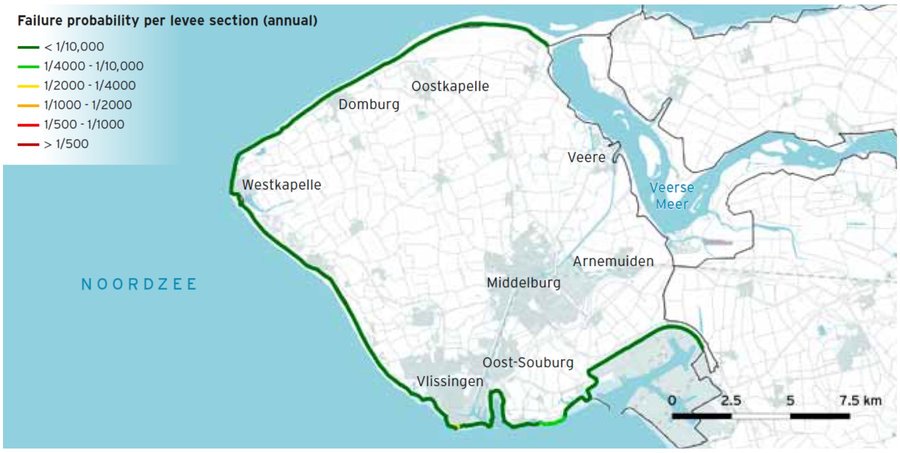


Figure 1.8: Failure probabilities of levee sections in dike-ring 29 (Vergouwe, 2014a)

However, for a few dike sections, the failure probability is somewhat larger. For example, near Vlissingen, there is a small dike section with a failure probability for overflow and wave overtopping of 1/2,500 per year. Next to that, a part of section Buitenhaven-Oost has a failure probability which is larger than 1/10,000 per year. The main failure mechanism is uplift and piping, for which the failure probability is 1/8,600 per year.

VNK has determined the flood scenarios for each of the dike ring sections. Multiple flood scenarios are described below: the most likely single dike breach; the most likely double dike breach; the most likely triple dike breach; and the maximum flood scenario.

Most likely single dike breach

The most likely single breach occurs in dike ring section 12 (Buitenhaven-West). The scenario probability is 1/2,500 per year. The damage in this scenario amounts to approximately 765 million euros, with 25 to 85 casualties (Bossenbroek & Bardoel, 2014).

Most likely double dike breach

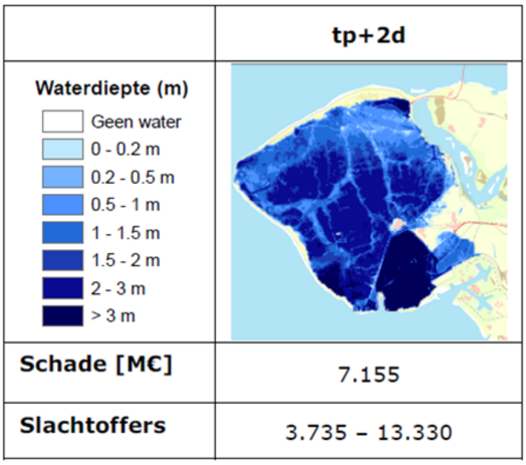
The most likely double breach involves breaches in dike ring sections 12 (Buitenhaven-West) and 13 (Buitenhaven-Oost). The scenario probability is 1/180,000 per year. The damage in this scenario amounts to approximately 1.2 billion euros, with 45 to 160 casualties (Bossenbroek & Bardoel, 2014).

Most likely triple dike breach

The most likely triple breach involves breaches in dike ring sections 6 (Westkapelle), 12 (Buitenhaven-West), and 15 (Rammekens). The scenario probability is 1/620,000 per year. The damage in this scenario amounts to approximately 1.6 billion euros, with 45 to 160 casualties (Bossenbroek & Bardoel, 2014).

Maximum flood scenario

The maximum water depth for a maximum flood scenario occurs for a worst-case inundation scenario for which all 16 dike breach locations break through. The maximum scenario primarily results from breaches occurring at ring sections 10 (Vlissingen-Zwanenburg) and 14 (Ritthem). The maximum water depths for this scenario are highest in the area between Vlissingen and Middelburg to the east of the Canal through Walcheren. The economical damage for this maximum scenario amounts to over 7 billion euros and the expected amount of victims is between 3,700 and 13,300, depending on the evacuation strategy (Bossenbroek & Bardoel, 2014). The inundation patterns for this maximum flood scenario are presented in figure 1.9.



	tp+2d
Waterdiepte (m) Geen water 0 - 0.2 m 0.2 - 0.5 m 0.5 - 1 m 1 - 1.5 m 1.5 - 2 m 2 - 3 m > 3 m	
Schade [M€]	7.155
Slachtoffers	3.735 – 13.330

Figure 1.9: Maximum flood scenario Walcheren (Bossenbroek & Bardoel, 2014)

1.5.3. Flood risk

The flood risk of the A-category defense has been determined by linking the calculated probability of the various flood scenarios to the consequences of these scenarios. The risk is expressed in terms of economic risk and casualty risk (Bossenbroek & Bardoel, 2014).

The expected value of the economic damage in Walcheren amounts to 0.2 million euros per year (Vergouwe, 2014a). In the calculated economic damage per scenario, the effect of relocating economic activity is always taken into account. The expected value of the economic damage is (considerably) lower than 10 euros per ha per year in most areas, but near the built-up areas, particularly Vlissingen, Middelburg, and Westkapelle, the expected values are locally one to two orders of magnitude higher: 10 to 100 or sometimes even 1,000 euros per ha per year (Bossenbroek & Bardoel, 2014).

The individual risk is the probability that an unprotected person who remains in the same location for a year will become a victim of a flood. The effect of evacuation is taken into account in the calculation of the local individual risk (Bossenbroek & Bardoel, 2014). Figure 1.10 shows the local individual risk in Walcheren based on this approach. As can be seen in the figure, the local individual risk is highest near and partly in Middelburg.

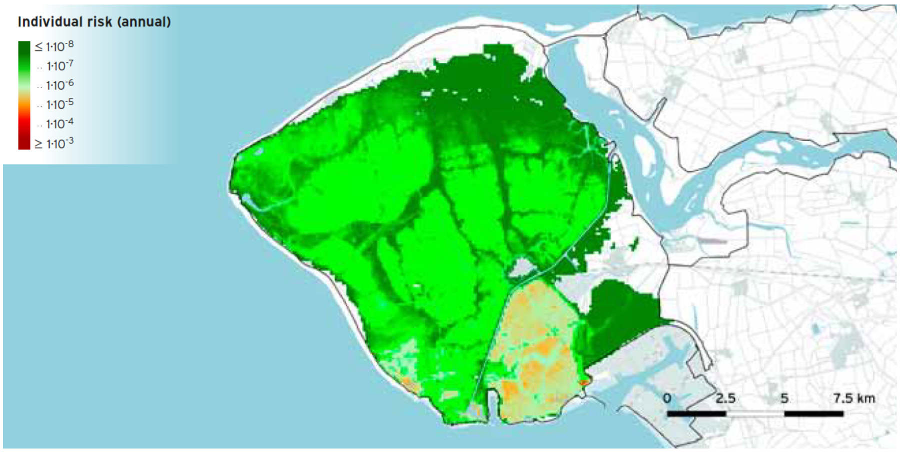


Figure 1.10: Individual risk in Walcheren (Vergouwe, 2014a)

1.6. Reading guide

The methodology of this research is described extensively in chapter 2. Next, the study is divided into two main sections. The first part analyzes an idealized coastal polder, with chapter 3 outlining the initial principles and assumptions for various spatial adaptation measures. Then, chapter 4 presents the results of the probabilistic model regarding polder inundation development and inundation frequency for all strategies. Chapter 5 includes an assessment of the various spatial adaptation strategies based on criteria such as spatial impact and flood risk. The second part of the research encompasses a case study of the Walcheren region. Chapter 6 outlines the design strategies for Walcheren, including their assumptions and starting points. Subsequently, chapter 7 compares the effectiveness of various design strategies when mitigating flood risk, followed by a cost-benefit analysis in chapter 8. The discussion in chapter 9 outlines the limitations of the research and its applicability in Dutch polders. Finally, chapter 10 presents the main conclusions of this study and provides recommendations for further research.

2
Methodology

In this chapter, the methodology used to answer the research question *"How does the Plan B NL2200 approach (accommodate) perform as a solution for mitigating future coastal flood risk in existing cities, considering the projection of accelerated sea level rise, in comparison with the current strategy (protect) and alternative spatial adaptation strategies?"* will be outlined. First, a general approach is provided outlining an overview of the necessary steps to address the research question. Subsequently, the paragraphs following after that elaborate on each step described in the approach.

2.1. Approach

In order to investigate how Plan B performs as a solution to reduce future coastal flood risk in Western cities of the Netherlands (particularly in Walcheren), the research can be subdivided into six steps, which are shortly described below. Step 1 and 2 describe starting points that serve as a foundation for the study. Subsequently, step 3 corresponds to the sub questions on idealized coastal polders, as formulated in 1.4.2. Lastly, steps 4, 5 and 6 correspond to the three sub questions formulated in 1.4.2 on a Dutch coastal polder, respectively. The six parts are elaborated in the following paragraphs.

1. Define multiple scenarios of future high water levels. Take into account various plausible scenarios of sea level rise and storm surge conditions.
2. Set up a probabilistic model for flood-inundation modeling of coastal polders. Set up the model such that it can be used for both the idealized coastal polder analysis as well as the case study area of Walcheren.
3. Determine the benefits and drawbacks of various spatial adaptation strategies of an idealized coastal polder. Therefore, design a simplified polder based on the characteristics of Walcheren and distinguish between several spatial adaptation measures. These measures should encompass different approaches to spatial organization and flood protection. Next, apply the probabilistic model to the idealized polder. This model is tested for the different spatial adaptation strategies and future high water levels. Investigate how various spatial adaptation measures influence the inundation depth (development) in an idealized coastal polder, compared to a plain dike-ring strategy. Set up an assessment to compare the different spatial adaptation strategies effectively. This framework should consider essential factors such as flood risk and spatial impact.
4. Propose multiple potential design strategies for the adapted spatial vision of Walcheren, taking into account the main principles of Plan B as a starting point. Use the findings derived from the assessment of the idealized polder as a source of inspiration and guidance for the design of these strategies.
5. Use the probabilistic model to determine the effectiveness of the different design strategies of Walcheren in reducing future coastal flood risk in the cities Middelburg and Vlissingen, by evaluating the damage and casualties. Therefore, first use the probabilistic approach for modeling the expected flood-inundated area and creating flood maps for the different scenarios of future

high water levels, while assuming certain values for levee failure probabilities. Apply the created flood maps to the Damage and Casualties Module and evaluate the effectiveness of the spatial adaptation strategies in terms of flood risk, compared to the current spatial planning strategy of Walcheren.

6. Analyse the results of the potential spatial adaptation design strategies for Walcheren regarding flood risk and quantify the most cost-beneficial solution for mitigating the future coastal flood risk in this coastal polder by evaluating the net present values.

2.2. Future high water levels

The first step of this research is to define multiple scenarios of future high water levels. Therefore, the projected sea level rise and storm surge conditions are considered.

2.2.1. Scenarios of sea level rise

A comparison between the Delta scenarios and the projection for accelerated sea level rise (RCP8.5) indicates that there will be no significant increase in sea level rise until the year 2050. Both the Delta scenarios and the accelerated sea level rise projection suggest a rise of approximately 0.4 meters by 2050, relative to the reference year of 1995. Additionally, the differences between the Delta scenarios and the projection for accelerated sea level rise become evident after the year 2050. According to the Delta scenarios, a rise of 1 meter could be attained by the year 2100. However, based on the median value of the RCP8.5 projection, this rise is anticipated to occur earlier, around 2080. Moreover, considering the upper values of the projection for accelerated sea level rise, a 1-meter rise is expected to be reached around 2070 (Haasnoot et al., 2018). According to the RCP8.5 projection, it is anticipated that there will be a sea level rise of 2 meters by the year 2100. In an extreme case of global warming (RCP8.5), this extreme trend continues and a sea level rise of 6 meters can be expected in the year 2200 (De Winter et al., 2017). The estimations of accelerated sea level rise according to the RCP8.5 projection closely fit the curve of the Marine Ice Cliff Instability model as presented in the latest KNMI scenarios (Bessembinder et al., 2023) (see figure 2.1). The Delta scenarios assume a more or less linear progression over time.

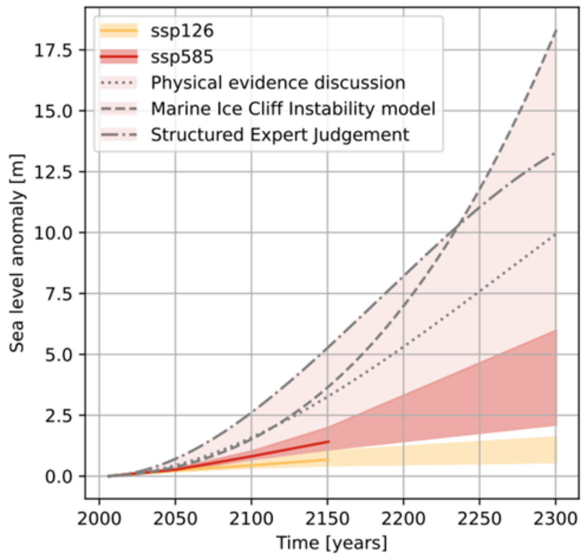


Figure 2.1: Sea level scenarios for the Netherlands until 2300 (Bessembinder et al., 2023)

In this study, a total of five sea level rise scenarios will be considered. Therefore, the accelerated sea level rise projection RCP8.5 is used as a baseline for the analysis. The sea level rise along the Dutch coastline according to both the Delta scenarios and the RCP8.5 projection are visually represented on a timeline in figure 2.2. First, a zero-scenario for 0 meters sea level rise will be created as a reference to represent the 'present' situation. It should be noted that the actual reference year of 0 meters sea level rise is 1995, but for the sake of simplicity it is assumed that the reference year is 2023 in this study. In order to enable a comparison between the inundation patterns of the present situation and scenarios of increasing sea level rise, two scenarios of relatively mild sea level rise will be evaluated in this study: one involving a rise of 1 meter by the year 2070, and the other involving a rise of 2 meters by the year 2100. It should be noted that these sea level rise scenarios, along with their corresponding years of occurrence, are indicative of the trend of extreme sea level rise. Nevertheless, these particular sea level rise scenarios are selected and considered 'relatively mild' based on the assumption that the current spatial planning might still (although not necessarily) be preserved and deemed sustainable until the specified years. However, it is important to note that the impact of 2 meter sea level rise on inundation depth within the polder, in comparison to 1 meter sea level rise, could be significant.

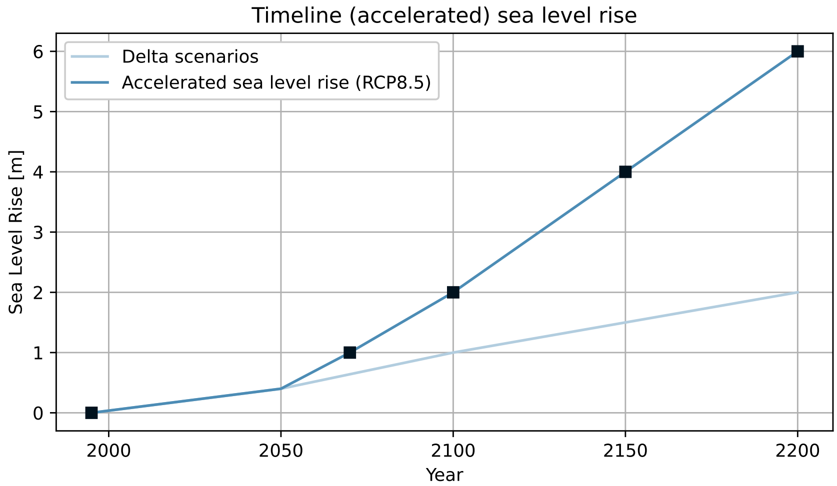


Figure 2.2: Timeline (accelerated) sea level rise (Dutch coast)

According to the accelerated sea level rise projection RCP8.5, an extreme but realistic sea level rise of 6 meters can be expected in the year 2200 (De Winter et al., 2017). For that reason, this value is the upper limit of sea level rise for this study. Lastly, a transitional scenario of 4 meters sea level rise by the year 2150 will be explored, based on interpolation between the years 2100 and 2200. For these extreme scenarios of sea level rise, the current dikes around Walcheren will most likely not be able to withstand the hydraulic loads and therefore a more technically feasible adapted spatial vision will have to be developed.

2.2.2. Scenarios of storm surge events

Hydra-NL is a probabilistic model that calculates the statistics of hydraulic loads (water level, wave conditions, wave overtopping) for the assessment of primary dikes and structures in the Netherlands. It is consistent with the Assessment and Design Instrumentation (Dutch: Beoordelings- en Ontwerpinstrumentarium (BOI)) ("Hydra-NL", 2023). Hydra-NL can be used to determine the representative future high water level scenarios for Walcheren, as the model calculates the water levels for different return periods for a selected location.

For any location, hydraulic calculations can be performed in Hydra-NL. For such a hydraulic calculation, the software automatically returns the estimated water levels for return periods of 10, 30, 100, 300, 1,000, 3,000, 10,000, 30,000 and 100,000 years. These water levels include the tide and storm surge. Therefore, this range of simulated storm surge events will be considered in this study.

In order to facilitate a qualitative comparison among the various storms, the results of the simulated events will be assessed using two primary categories of storm surge events:

- Frequent storm surges with a return period of 10 years. This translates into a water level with a probability of exceedance of 1/10 per year;

- Extreme storm surges with a return period of 10,000 years. This translates into a water level with a probability of exceedance of 1/10,000 per year.

The motivation for these categories of simulated events is based on frequent and extreme storms with return periods of 10 and 10,000 years respectively.

2.2.3. Water level exceedance frequency curve

The location in Walcheren where the normative design water level manifests is near Fort Rammekens and it is represented as a yellow dot in figure 2.3.

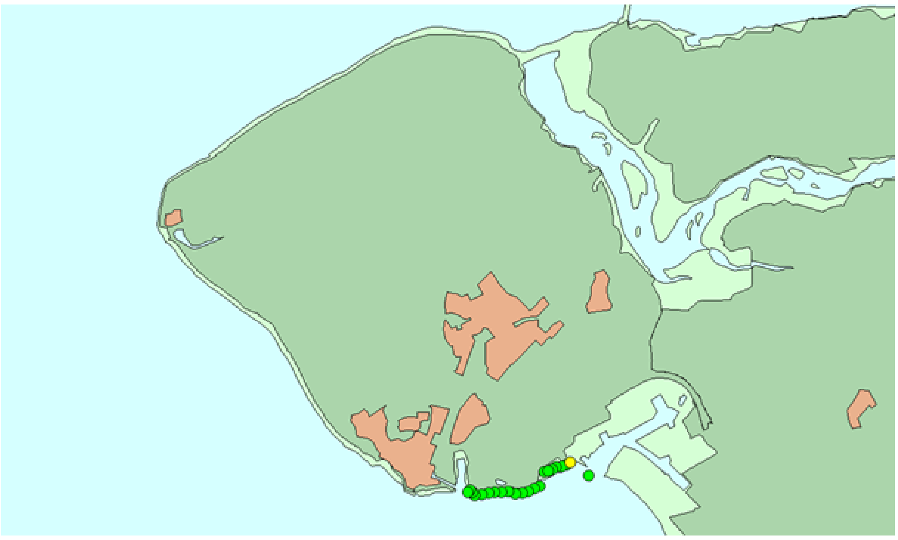


Figure 2.3: Location of normative water level in Walcheren (dike section 29-3 no. 2)

In order to make this research manageable, it is assumed that the water level at this specific location represents the entire area of Walcheren. This is a rather conservative, but safe assumption and simplification.

As described earlier, in the hydraulic calculations of Hydra-NL, the software automatically returns the estimated water levels (including tide and storm surge) for return periods of 10, 30, 100, 300, 1,000, 3,000, 10,000, 30,000 and 100,000 years. Based on these values, a water level exceedance frequency line can be set up for the current situation of 0 meters sea level rise. This is shown in figure 2.4.

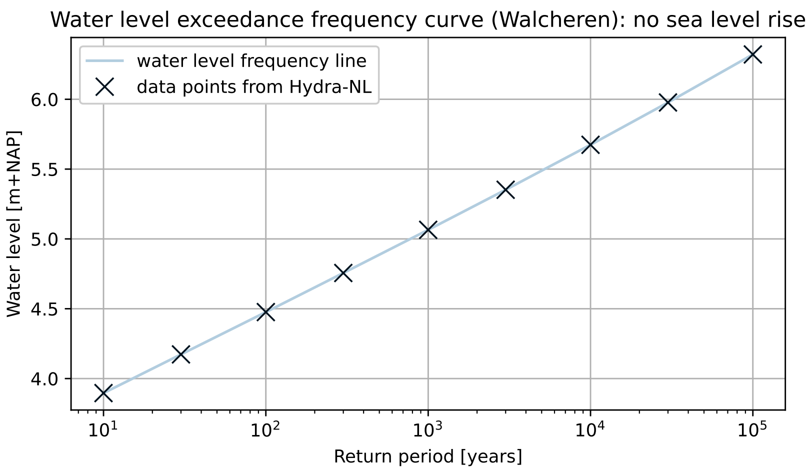


Figure 2.4: Water level frequency line (Walcheren) for 0 m sea level rise

As can be seen in the figure, a water level of around 3.90 m+NAP is expected to occur at least once every 10 years. This maximum water level is around 6.3 m+NAP for a return period of 100,000 years.

Hydra-NL allows for the implementation of up to 2 meters of sea level rise in hydraulic calculations. When considering a scenario of 1 meter of sea level rise, the results of the hydraulic calculations indicate that the model incorporates a straightforward 1-meter increase of the water levels for various return periods compared to the current (or zero) situation of 0 meters of sea level rise. This same principle applies to a scenario of 2 meters of sea level rise as well. This implies that the model does not account for changes in the magnitude and development of the tide and storm surges for an increasing sea level. Therefore, it can be concluded that the water level for a given return period and a certain scenario of sea level rise is the sum of the water level for that same return period in the zero situation and the magnitude of the sea level rise.

Based on this starting point, the water levels for various return periods of the scenarios of 4 and 6 meters of sea level rise can easily be calculated. Following the approach of the hydraulic calculations in Hydra-NL and assuming continuous values for subsequent scenarios of sea level rise, the water level exceedance frequency lines for the different sea level rise scenarios can be created, of which the plots are shown in figure A.1 in Appendix A.

2.2.4. Future high water level scenarios

Combining the different scenarios of sea level rise with the storm surge events, there are 45 possible future high water level scenarios in this research. These are the scenarios of 0, 1, 2, 4, and 6 meters sea level rise for storm surge events with return periods of 10, 30, 100, 300, 1,000, 3,000, 10,000, 30,000 and 100,000 years. Table 2.1 provides an overview of the potential future maximum water levels that can arise from various combinations of sea level rise and storm surge events.

Table 2.1: High water level scenarios - maximum water levels [m] (Hydra-NL)

		Storm surge event (Return period [years])								
		10	**30**	**100**	**300**	**1,000**	**3,000**	**10,000**	**30,000**	**100,000**
Sea level rise [m]	**0**	3.90	4.17	4.48	4.76	5.07	5.35	5.67	5.98	6.32
	1	4.90	5.17	5.48	5.76	6.07	6.35	6.67	6.98	7.32
	2	5.90	6.17	6.48	6.76	7.07	7.35	7.67	7.98	8.32
	4	7.90	8.17	8.48	8.76	9.07	9.35	9.67	9.98	10.32
	6	9.90	10.17	10.48	10.76	11.07	11.35	11.67	11.98	12.32

2.2.5. Temporal evolution of water levels

For a complete and comprehensive analysis, it is important to also consider the temporal evolution of the water levels (tide included) next to just the projected sea level rise and the maximum values of storm surges. Moreover, the storm duration is a relevant factor in sea level trends and should therefore also be considered. For this research, it is assumed that the storm duration for each of the simulated storm surge events is constant, approximately 40 hours.

The water level development tool provided by Rijkswaterstaat (Dutch: Waterstandsverlopen Tool) provides time-dependent water levels for all primary flood defenses, during the passage of a storm or flood wave. Given the reference location in figure 2.3, the temporal evolution of the water level for a specific maximum water level given a certain return period can be determined. The output of the water development tool is a time series of the development of the water level. These time series are created for each of the (future) high water level scenarios presented in table 2.1.

The water level development for the current situation (zero situation) of 0 meters sea level rise for frequent and extreme storms is shown in figure 2.5. The maximum water levels are depicted as black dots and correspond to the first row of values in table 2.1 for the return periods of 10 and 10,000 years respectively.

Similar water level development plots are made for the multiple scenarios of sea level rise. The temporal evolution of the water level for all return periods for a scenario of 0 meters sea level rise is shown in the plots in figure A.2 in Appendix A. For the scenarios of 1, 2, 4 and 6 meters sea level rise, the water level development plots for all return periods are presented in figures A.3, A.4, A.5 and A.6 respectively.

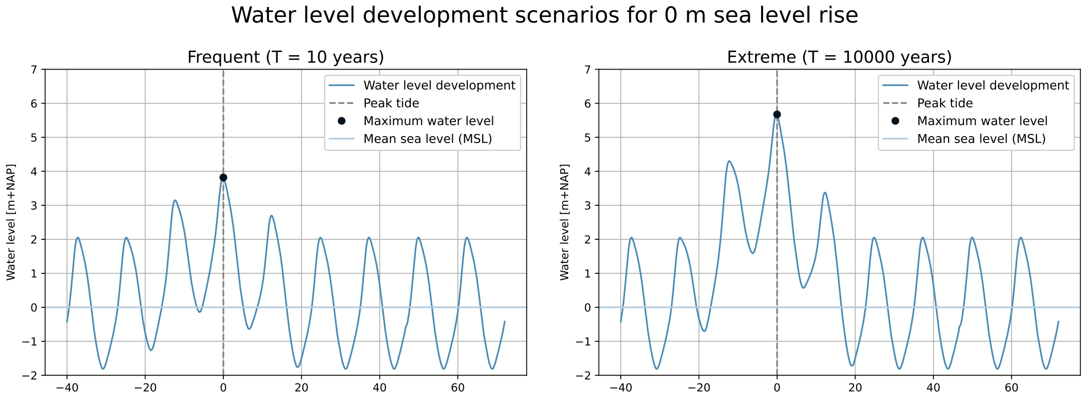


Figure 2.5: Water level development scenarios (Walcheren) for 0 m sea level rise

2.3. Probabilistic model

The exact time and location of a flood defense structure's failure is unknown due to numerous uncertain factors, including the structure's maximum loading and strength. Nevertheless, models and statistics can estimate the probability of failure for all possible combinations of uncertain load and strength. This probabilistic approach explicitly incorporates uncertainties about load and strength values in the assessment of levee safety (Vergouwe, 2014a). Therefore, the next action is to set up a probabilistic model. The probabilistic model considers the levee system explicitly by incorporating the failure probabilities of dike segments (which results in an expected number of breaches) and the influence on the inundation pattern of a polder (Rikkert et al., 2022).

2.3.1. Concise modeling approach

The required input for this probabilistic model are hydraulic conditions, polder characteristics, and embankment characteristics. The hydraulic conditions are determined by the sea level and the storm surge level for multiple return periods. Polder characteristics include topographic information like polder elevation and polder area size. Embankment characteristics include the number of breaches, breach width, breach level, breach moment and the length of the embankment. Then, the polder fill model can be used for inundation modelling, for which Python is applied. This is done for different possible storm events, or different scenarios of high water levels.

The probabilistic approach takes the maximum water level and the strength of individual dike segments, by means of fragility curves, as stochastic variables and other input variables as deterministic values. The estimated number of breaches is calculated based on fragility curves and embankment length, followed by inundation modeling to create inundation-frequency curves for the different storms with the resulting maximum water levels. Next to that, the model gives as output a database with flood maps (Rikkert et al., 2022). These flood maps are created with the help of QGIS and Python. A schematic overview of this modeling approach is shown in figure 2.6.

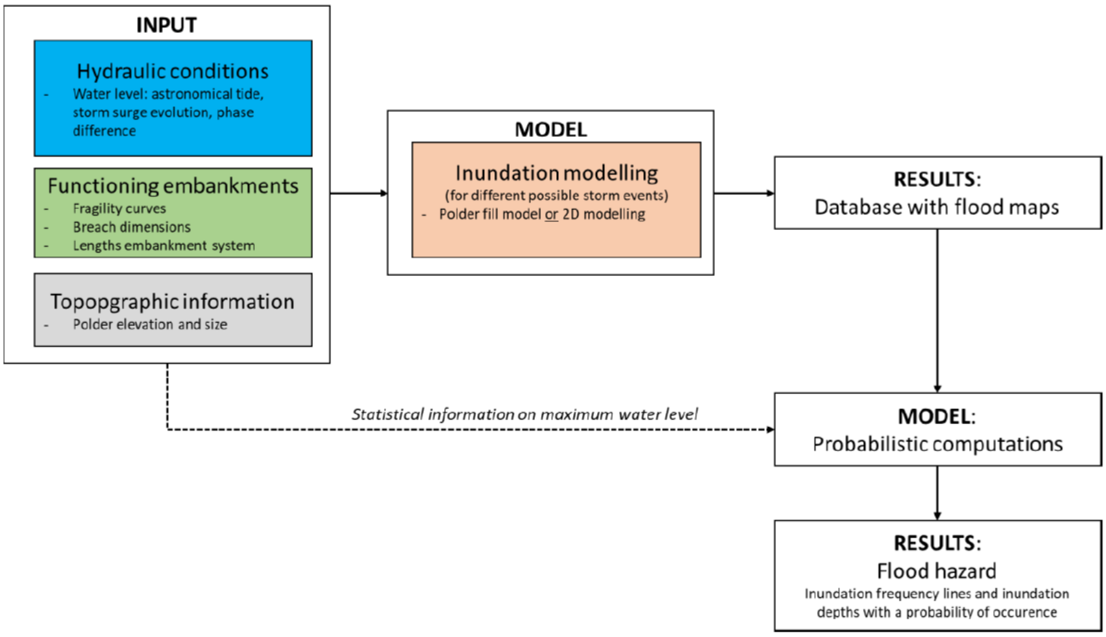


Figure 2.6: Modeling approach for inundation frequency lines and flood maps with a certain probability of occurrence (Rikkert et al., 2022)

2.3.2. Hydraulic conditions

The flood protection is subject to hydraulic loads, which are influenced by high water levels as a result of the astronomical tide (amplitude and mean sea level) as well as storm surges. When it comes to inundation of polders, the external water levels primarily determine the inundation patterns, while the impact of waves is negligible. For the probabilistic model, wave conditions are not taken into account. The high water levels that are considered are the result of the projected sea level rise and storm surges and are obtained by the superposition of the simulated surges and astronomical tide (Rikkert et al., 2022). The high water level scenarios considered for this research are presented in table 2.1. These scenarios are applied to both the idealized polder analysis and the case study of Walcheren.

2.3.3. Functioning of embankments

The probabilistic model requires polder and embankment characteristics. The idealized coastal polder is schematized based on the characteristics of Walcheren. The reference scenario, which represents a plain dike-ring strategy (no adaptation measures), is used as input. The polder can be simplified by representing it with an average polder elevation and a fixed polder area size. The idealized polder is assumed to be flat and circular. In this simplified case, it is assumed that the primary flood defense surrounds the entire idealized coastal polder, making it a circular island. In both analyses (idealized coastal polder and Walcheren), water enters the polder through dike breaches and distributes uniformly within the polder. The polder fill model subsequently computes the resultant inundation water depths within the polder.

Polder and embankment characteristics

The primary flood defense system (levee system 29), of both the idealized coastal polder and Walcheren, has a length of about 47.5 km and consists of 35 dike sections (Bossenbroek & Bardoel, 2014). Furthermore, the polder area is approximately 200 km^2 and the average polder elevation is 0 m+NAP. The annual flooding probability is 1/1,000. To simplify the representation of the polder, it is assumed that the dike sections are independent and have an equal failure probability.

For inundation modelling, the information regarding dike breaches is crucial. In this research, it is assumed that an instantaneous breach with a consistent width of 100 meters occurs when the water level reaches its maximum. The breach level aligns with the polder elevation. The occurrence of a certain number of breaches depends on the magnitude of the water level, which in its turn depends on the storm surge. Furthermore, it is assumed that there is a maximum of one breach per dike section. The total (maximum) possible number of breaches is therefore equal to the number of dike sections. The polder and breach characteristics are presented in table 2.2. The mean sea level is 0 m+NAP, which represents the current (zero) situation of 0 meters sea level rise.

Table 2.2: Polder characteristics of the idealized coastal polder and Walcheren (plain dike-ring strategy)

Description	Value
MSL	0 [m+NAP]
Number of breaches	dependent
Breach width	100 [m]
Breach level	0 [m+NAP] (polder level)
Breach moment	max. water level
Length dike-ring	47.5 [km]
Dike sections	35 [-]
Average polder area	200 [km^2]
Average polder elevation	0 [m+NAP]
Annual flooding probability	1/1,000

Fragility curve

The expected number of breaches can be determined by means of a fragility curve. The stability of an embankment during extreme storm conditions and wave conditions is largely determined by the outside water level of the sea. As the hydraulic load on the embankment increases, so does the probability of failure. Fragility curves are commonly employed to express the probability of failure as a function of the water level, making them a valuable tool. For the derivation of the fragility curve for the primary dike-ring, existing data on the failure probabilities of levee system 29 are used. This fragility curve is employed for the primary dike-ring of both the idealized coastal polder and Walcheren. Figure 2.7 illustrates the fragility curve for an individual dike section within this dike-ring, considering the cumulative effects of all failure mechanisms. This curve provides the conditional failure probabilities for water levels associated with a specific return period.

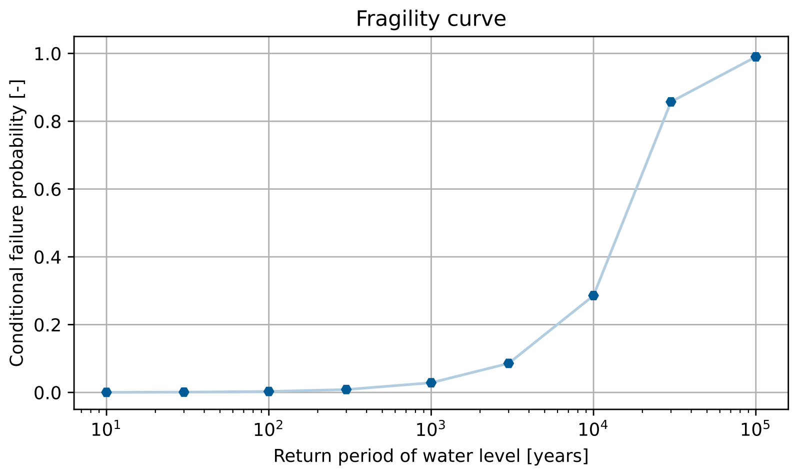


Figure 2.7: Fragility curve of an individual dike section

The fragility curve depicted in figure 2.7 is developed based on the zero situation: a scenario where there is no sea level rise (0 meters). For all failure mechanisms combined, the annual flooding probability of the polder is 1/1,000. Levee system 29 consists of 35 dike sections. Given the annual flooding probability of the polder of 1/1,000 and 35 equal independent dike sections, the annual failure probability of an individual dike section is estimated to be 1/35,000.

The expression representing the probability of occurrence of a certain water level in a year is given in equation 2.1.

$$P(H \geq h_T) = \frac{1}{T} \tag{2.1}$$

Applying this equation, the annual probability of occurrence for a water level with a return period of 100 years is determined as 1/100. Similarly, for a water level with a return period of 1,000 years, this probability is 1/1,000 per year, and so forth. Using the failure criterion of an individual embankment in combination with the annual probabilities of occurrence of water levels, the fragility curve can be constructed, by calculating the conditional failure probabilities according to equation 2.2. It should be noted though that this is not a mathematical truth, but rather an assumption of the progress of the fragility curve.

$$P(F|h) = \frac{P(F)}{P(h)} \tag{2.2}$$

In this (assumed) equation, P(F|h) is the (conditional) failure probability of an individual dike section given a certain water level. P(F) denotes the annual failure probability of an individual dike section and P(h) is the probability of occurrence of a certain water level in a year, which is P(H $\geq$ h$_T$). An example calculation of the conditional failure probability of an individual dike section given a water level with a return period of 10,000 years is shown in equation 2.3.

$$P(F|h = 5.67) = \frac{1}{35000} / \frac{1}{10000} = 0.286 \tag{2.3}$$

Using this method, the estimated conditional failure probability of a dike section would be greater than 1 given a water level with a return period of 100,000 years. However, probabilities cannot exceed 1, showing the mathematical incorrectness of this equation. Therefore, the failure probability for this return period is estimated to be 0.99 instead.

Under the assumption that the probability of flooding remains the same for scenarios with increasing sea level rise, and thus levees will need to be reinforced, the fragility curves are expected to appear identical for different scenarios. It should be noted that this does not necessarily imply that the flood risk levels are similar, as the inflow of water through the breach can be larger with increasing sea levels. However, if the current levees are not strengthened and sea levels continue to rise, the fragility curves for different scenarios of sea level rise are expected to be according to figure B.1. As the figure shows, for a scenario of 2 meters sea level rise or higher, the conditional failure probability of an individual dike section is approximately 1 for all return periods. This can be explained by the fact that the water level with a return period of 100 years for a scenario of 2 meters sea level rise is higher than the water level with a return period of 100,000 years for a scenario of 0 meters sea level rise.

Expected number of breaches

In this study, it is assumed that all individual dike sections within the dike-ring have the same fragility curve and characteristics, and are mutually independent.

In order to estimate the probability of multiple breaches occurring at a given water level, it is necessary to know the total number of individual dike sections, as well as the conditional probability of failure for each section at that specific water level, which can be obtained from the fragility curve. Since the dike sections are assumed to be independent, the binomial distribution can be applied (Rikkert et al., 2022). By using the fragility curve for an individual dike section, the probability of multiple dike section failures during a specific event can be determined by applying equation 2.4.

$$P(X = k) = \binom{n}{k} \cdot p^k \cdot (1-p)^{n-k} \tag{2.4}$$

In this equation, *P(X = k)* is the probability of *k* dike breaches within *n* individual dike sections, $\binom{n}{k}$ is the number of combinations and *p* is the failure probability of an individual dike section.

For a scenario of 0 meters sea level rise, the results of the binomial distribution are presented in figure 2.8 for frequent and extreme storms with corresponding return periods of T = 10 and T = 10,000 years respectively. The expected number of breaches for each possible event can be calculated by multiplying the conditional failure probability given a certain water level with the total number of individual dike sections.

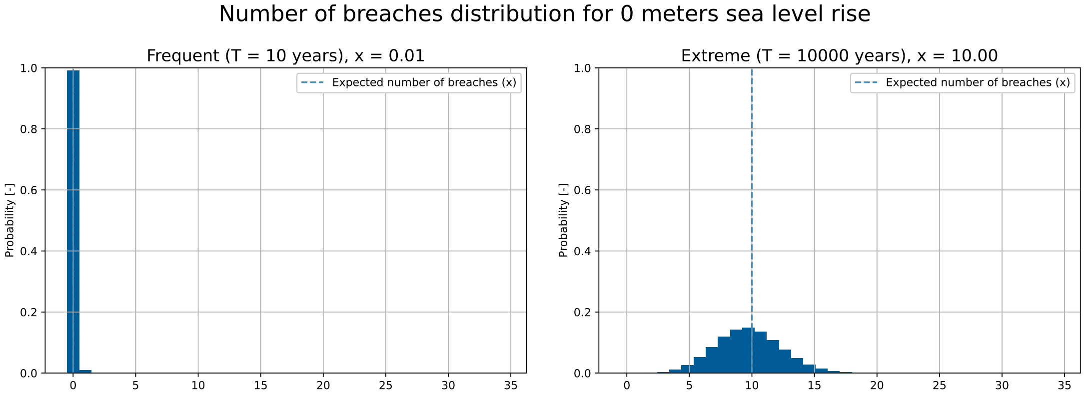


Figure 2.8: Histograms: distribution of number of breaches for a scenario of 0 meters sea level rise

As follows from the fragility curve, the failure probability of an individual dike section is approximately 0 for frequent water levels (return period of T = 10 years). Therefore, the expected number of dike breaches is x = 0.01. For extreme water levels with a return period of T = 10,000 years, the failure probability of an individual dike section is approximately 0.3, resulting in an expected number of dike breaches of x = 10 (see figure 2.8). The histograms of the distribution of the number of breaches for all return periods are presented in figure B.2. From this figure, it can be derived that the expected number of breaches for a water level with a return period of T = 1,000 years is x = 1. This is in line with the annual flooding probability of the polder, which is 1/1,000.

The expected number of breaches for the primary dike-ring of the idealized polder or Walcheren can be plotted against the return periods of the storm surges. This is shown in figure 2.9.

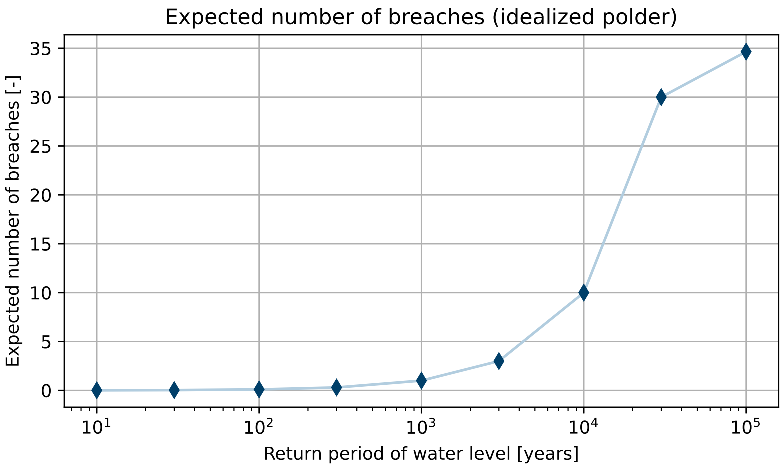


Figure 2.9: Expected number of breaches (idealized polder and Walcheren)

As Hydra-NL supports the calculation of water levels for multiple return periods, these are all included in the figure. This information can be used to perform calculations for the inundation of the idealized coastal polder and Walcheren. This is further explained in the next sub section on breach discharge modelling of the polder fill model.

2.3.4. Topographic information

Accurate elevation data is essential for flood simulation, as flooding can only occur in areas where the ground level is lower than the water level. To create flood maps, an inundation model relies on elevation data as input. However, it is crucial that the vertical reference datum of the elevation aligns with the water levels being modeled to ensure accurate predictions (Rikkert et al., 2022).

For the analysis of the idealized coastal polder, it is assumed that the polder has an average fixed elevation of 0 m+NAP. For the case study in Walcheren, the digital elevation model (DEM) used is called AHN (Dutch: Actueel Hoogtebestand Nederland), an elevation dataset which is specific to the Netherlands. With this elevation data and the (flood) water level predictions obtained from the probabilistic model, flood maps can be created using tools like the Geographic Information System (GIS) software QGIS and the programming language Python.

2.3.5. Polder fill model

The polder fill model (Rikkert et al., 2022) offers a tool for estimating the polder inundation in the event of one or multiple dike breaches. In this research, the focus is on inundation modelling as a result of high water levels. The impact of waves during storm surge conditions is neglected. The model consists of two components:

1. The flood volume calculation and
2. The storage curve for flood volume distribution within the polder.

The storage is derived from the polder's digital elevation map by calculating how much water the polder can store as water levels rise. A flood extent curve can be determined in the same way, by calculating how much of the polder area will be inundated for each water level in the polder. The calculation of the flood volume is obtained from an analytical model. This model computes the breach discharge that depends on the dimensions of the breach, hydraulic conditions, and a simplified topography of the polder (average polder size and average polder height).

In the analytical model, water passes through the breach and enters a confined polder with a surface area A_{pol}. The polder is schematized as a bucket with a flat or straight bottom, with its height and surface area based on the average dimensions of the polder. The flood protection system is designed to withstand hydraulic loads (high water levels) and protects the low-lying polder area. Prior to the breach being completely flooded, the average rate at which the water level in the polder rises can be determined using equation 2.5.

$$Q_{br} = m \cdot \frac{2}{3} \cdot W_{br} \cdot \sqrt{\frac{2}{3} \cdot g} \cdot (h_{out} - \eta_{br})^{\frac{3}{2}} \tag{2.5}$$

In this equation, Q_{br} is the discharge through the breach in [m^3/s], m is the discharge coefficient [-], W_{br} is the breach width in [m] for which an instantaneous value of 100 m is assumed. Furthermore, η_{br} is the bottom level of the breach [m+NAP] and h_{out} is the outside water level in [m+NAP]. As follows from the equation, the breach discharge is directly proportional to the width of the breach. The outside water level in relation to the breach level plays a significant role as it is raised to the power $\frac{3}{2}$ (Rikkert et al., 2022).

As the polder inundates, the water levels within the polder rise (also known as bathtub filling), which in its turn affects the breach discharge. When the difference between the water level inside the polder and the breach level (h_{pol} - η_{br}) is larger than $\frac{2}{3}$ of the value of the outside water level relative to the breach level (h_{out} - η_{br}), the flow is influenced by the water level downstream. This leads to sub-critical flow or drowned breach flow. In general, when the breach flow becomes drowned, it results in a decrease in the breach discharge. Under these conditions, the breach discharge is calculated according to equation 2.6.

$$Q_{br} = c \cdot W_{br} \cdot (h_{pol} - \eta_{br}) \sqrt{2 \cdot g \cdot (h_{out} - h_{pol})} \tag{2.6}$$

In this equation, c is the discharge coefficient [-] and h_{pol} is the polder water level in [m+NAP] (Rikkert et al., 2022).

The calculated (maximum) flood volume as a result of the breach discharge and time can be transformed into a flood map by making use of the storage curve and flood extent curve specific to the area. The storage curve represents the polder water level as a function of the flood volume, while the flood extent curve expresses the flood extent as a function of the flood volume. When the flood volume is calculated with the polder fill model, the water level in the polder and the flooded area can be derived (Rikkert et al., 2022). The storage curve and flood extent curve for Walcheren, obtained from the probabilistic model, are presented in figure 2.10.

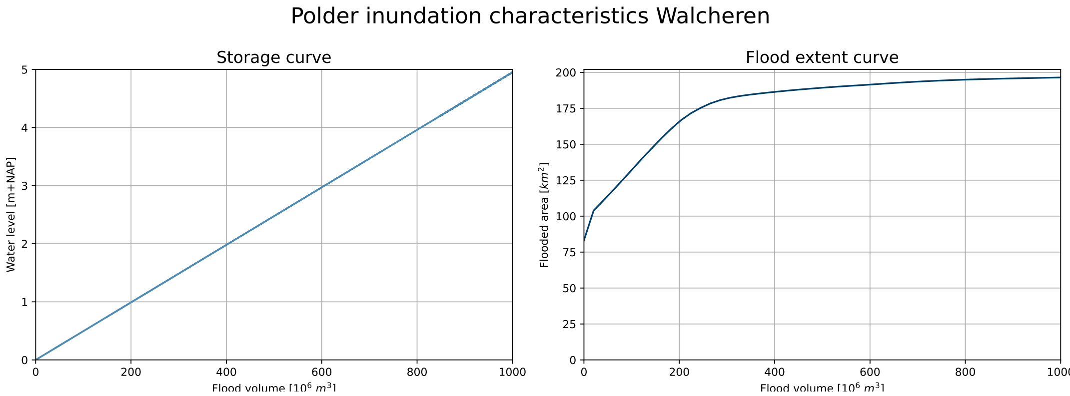


Figure 2.10: Storage curve (left) and flood extent curve (right) for Walcheren

As the storage curve shows, there is a linear relationship between the flood volume and the water level. This is due to the assumption that the breaches are instantaneous with a width of 100 meters. The flood extent curve shows that for the smallest volume, the flooded area exceeds 75 km^2. This is due to the fact that at least 75 km^2 of Walcheren lies below mean sea level. However, for the idealized polder, both relationships are linear. The flood volume's linear correlation with the water level can be attributed to the assumption of instantaneous dike breaches. Similarly, the flood volume's linear relationship with the flooded area is a consequence of the polder maintaining a consistently fixed average elevation.

2.3.6. Results

The final output of the model is a database of flood hazards and flood maps. For the idealized polder analysis, the results are mainly defined by the flood hazards, consisting of inundation frequency lines and inundation depths with a certain probability of occurrence. For the case study of Walcheren, the flood maps as a result of the flood hazards are the most crucial outputs of the probabilistic model.

Idealized coastal polder versus Walcheren

The similarities and differences between the methodology of the idealized coastal polder analysis and the case study of Walcheren are summarized in table 2.3.

The most important differences between the probabilistic approach applied to the idealized coastal polder and Walcheren are the topographic infomation and the output. In the idealized coastal polder scenario, the entire polder assumes a consistent, fixed average elevation, while Walcheren's topographic data varies greatly by location and is determined by AHN. The detailed topographic data provided for Walcheren strongly influences the variation of water depths in the polder as a result of an inundation. The flood maps (in combination with inundation rate) of Walcheren that are the output of the probabilistic model are crucial for determining the expected damage and number of casualties in an area. Using this detailed information in combination with a calculation of the investment costs for each strategy of Walcheren, a cost-benefit analysis can be conducted in order to determine the most cost-effective strategy. For the idealized coastal polder, the evaluation of the most effective strategy is conducted by means of a qualitative assessment covering crucial aspects such as spatial impact and flood risk.

Table 2.3: Methodology idealized coastal polder versus Walcheren

	Idealized coastal polder	**Walcheren**
Hydraulic conditions	Future high water level scenarios	Future high water level scenarios
Functioning of embankments	Fragility curve	Fragility curve
Topographic information	Fixed elevation (0 m+NAP)	AHN
Inundation modeling	Polder fill model	Polder fill model
Output (probabilistic model)	Inundation-frequency lines	Inundation-frequency lines Flood maps
Expression of flood risk	Inundation depth [m] Inundation rate [m/h]	Damage [€] Casualties [-]
Evaluation of strategies	Qualitative assessment	Cost-benefit analysis

2.4. Flood risk in idealized coastal polders

As a next step of this research, multiple strategies of an idealized coastal polder will be designed for the area of interest, Walcheren. In the context of this idealized coastal polder, the probabilistic approach is employed in combination with the polder fill inundation model.

2.4.1. Spatial adaptation strategies

This study focuses on various spatial adaptation strategies of a coastal polder in order to identify the most effective approach for mitigating future coastal flood risks. The evaluation criteria for determining the best strategy include minimizing the exposed water depth, and therefore reducing damage and minimizing the potential loss of life.

It is assumed that there is one city in the idealized coastal polder polder, where all residents and economic activities of the polder are concentrated. For the protection of this city, the multiple spatial adaptation strategies as described in the introduction, can be applied on this specific idealized coastal polder, which is shown in figure 2.11.

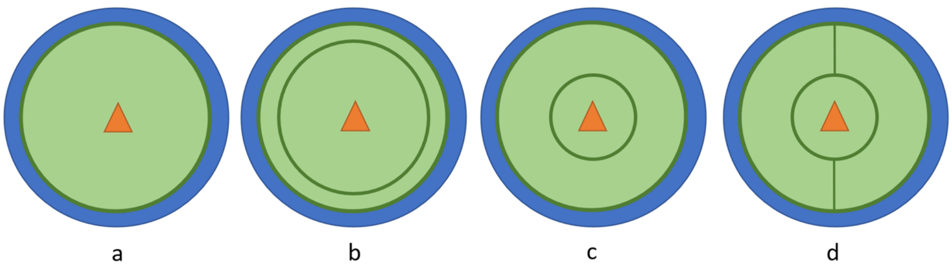


Figure 2.11: Spatial adaptation strategies idealized coastal polder

The first strategy (*a*) represents the baseline scenario: a plain dike-ring without adaptation measures. Strategies *b* and *c* are similar, with as main difference the location of the secondary dike-ring. In strategy *b*, the secondary dike-ring is positioned near the primary dike-ring, whereas in strategy *c*, the secondary dike-ring is located near the city and serves as direct additional value protection. Lastly, strategy *d* is a partitioned dike-ring and represents compartmentalization of the coastal polder.

The spatial adaptation strategies illustrated in figure 2.11 are mostly applicable to mild scenarios of sea level rise. In more extreme scenarios of sea level rise, according to the main design principles of Plan B, the primary flood defense disappears and the city's protection becomes more site-specific and direct. In such cases, the strategies as presented in figure 2.11 can be modified to account for adapted areas and adjust the dimensions of flood defenses and/or dike-rings accordingly.

The probabilistic approach combines all different water level and embankment breach events, which results in inundation frequency lines (which can be used to visualize the probability of flood depths at a certain location and provide the flood hazard at one location) at specific locations (Rikkert et al., 2022). Then, using the probabilities of occurrence of future water level scenarios and inundation depths corresponding to various spatial adaptation strategies, the influence of these strategies on the flood risk of the idealized coastal polder can be determined.

2.4.2. Assessment of spatial adaptation strategies

In order to review how the different spatial adaptation strategies influence the spatial impact and flood risk of an idealized coastal polder, a qualitative assessment can be set up. This assessment consists of two criteria for spatial impact and two criteria for flood risk and are listed below:

- Spatial impact
  - Protected land (enhanced)
  - Embankment length
- Flood risk
  - Inundation depth
  - Inundation rate (evacuation time)

The two criteria for spatial impact are: protected land (enhanced) and embankment length. The criterion of 'protected land (enhanced)' takes into account the land area protected according to the strategy and which part of the polder receives enhanced protection. It assesses the area that can be protected with a particular strategy and the potential impact it may have on social and economic aspects associated with relinquishing land areas. The criterion 'embankment length' evaluates the dike length that is needed to protect a specific part of the polder. For instance, a secondary dike-ring involves a significant increase in dike length, which requires considerable time for construction. This makes it an intensive intervention. In addition, a secondary dike-ring requires a part of the space in the polder, which makes it a relevant criterion for spatial impact. Moreover, it is directly linked to financial costs. The greater the dike length (and consequently the volume), the higher the associated expenses.

The two criteria for flood risk are: inundation depth and inundation rate (evacuation time). For the 'inundation depth' criterion, a comparison between various spatial adaptation strategies can be made by analyzing the inundation depths for the multiple sea level rise scenarios and return periods of water levels. For instance, compartmentalization measures can impact the inundation depth within the protected area of the polder compared to the plain situation without such measures, and therefore influence the flood risk. Finally, the criterion 'inundation rate (evacuation time)' should be considered. For this criterion, the polder inundation development is evaluated with particular emphasis on the time required to reach the maximum inundation depth. If a particular spatial adaptation strategy has a positive impact on the inundation rate within the polder, this can result in more evacuation time, allowing people to evacuate in advance before the area is completely flooded. This, in turn, positively influences the individual flood risk.

For the assessment of the various spatial adaptation strategies, a trade-off between the different criteria can be made to determine the most desirable and overall beneficial strategy.

2.5. Design strategies for spatial adaptation of Walcheren

There are multiple options for spatial adaptation measures of Walcheren, taking into account the projected sea level rise. Since the cities of Middelburg and Vlissingen are situated within Walcheren, it is desirable to protect these areas. However, in the distant future, it might not be feasible to preserve all of Walcheren, hence part of Plan B includes returning land to the sea. Therefore, considering the aim of reducing flood risks, it is crucial to make deliberate and conscious decisions.

In advocating for the preservation of Middelburg and Vlissingen and applying the strategies elaborated for the idealized coastal polder, the design strategies of Walcheren include:

- A plain dike-ring, protecting Middelburg and Vlissingen (current strategy, no adaptation measures).
- A secondary dike-ring, ensuring enhanced protection of Middelburg and Vlissingen.
- Two value protection dike-rings, ensuring enhanced protection of Middelburg and Vlissingen, separately.
- A partitioned dike-ring, ensuring enhanced protection of Middelburg and Vlissingen by means of compartmentalization measures.

These design strategies will be further elaborated in more detail based on the results of the influence of spatial adaptation strategies on the flood risk in an idealized polder. Based on these strategies, it is possible to differentiate between various norms of the dike rings and to vary the probability of failure to investigate the influence of it on the effect of flood inundation.

2.6. Effectiveness of design strategies in reducing flood risk

In this part of the research, the effectiveness of the various design strategies regarding the mitigation of future coastal flood risk in the Dutch coastal polder Walcheren will be evaluated.

2.6.1. Application of probabilistic model to spatial adaptation strategies

In order to evaluate the effectiveness of various design strategies in mitigating flood risk while accounting for the projected sea level rise, the proposed design strategies for Walcheren based on the considered spatial adaptation strategies of the idealized coastal polder, as well as the current spatial planning of Walcheren are considered as separate scenarios.

The probabilistic model can be used to identify the future flood risks in the coastal polder Walcheren, for each design strategy. Based on the probabilistic model, the expected flood-inundated area is modeled for all scenarios, while assuming constant dike failure probabilities for the projected sea level rise as explained in paragraph 2.2. The model is executed to evaluate the different scenarios of future high water levels. The given probabilities of occurrence in combination with the modeled flood maps for the different scenarios are key for qualification and quantification of the effectiveness of the design strategies in mitigating future coastal flood risk in Walcheren.

The flood maps generated for the plain dike-ring strategy of Walcheren by the model can be compared to the flood maps of LIWO. LIWO (Dutch: Het Landelijk Informatiesysteem Water en Overstromingen) or, The National Water and Flood Information System, contains map layers for professionals involved in (preparing for) floods in the Netherlands. LIWO contains a database with maps of the Netherlands, including the 'maximum flood depth Netherlands'. Overall, the flood maps generated by the model match those of LIWO quite well. However, for extremely low probabilities, the model tends to underestimate water depths near Middelburg and Vlissingen, whereas it overestimates the inundation in and around Arnemuiden. A more detailed elaboration is described in Appendix D.1.

The quantification of the effectiveness of the design strategies in Walcheren can be explored by applying the Damage and Casualties Module, which is further explained in paragraph 2.6.2. Based on the results of the Damage and Casualties Module, the effectiveness of Plan B in mitigating future flood risk in Walcheren compared to the current strategy and alternative adapted spatial visions can be investigated.

2.6.2. Damage and Casualties Module (SSM)

The Damage and Casualties Module, known as SSM (Schade- en Slachtoffermodule), allows for the calculation of damage and casualties resulting from floods. This is carried out according to a national standard methodology. With SSM, it is possible to compute various consequences of flooding for each simulation of a Dutch flood event. Examples include determining the number of (vulnerable) objects and residents affected, estimating potential damage, and assessing potential casualties. The application is particularly suitable for large-scale deep inundations originating from the main water system ("Schade- en Slachtoffer Module", n.d.).

For each design strategy, the flood maps created for the multiple high water level scenarios are used as input files for the Damage and Casualties Module. This module is applied to calculate the damage and determine the number of casualties. To run this module, a flood map is essential as input. The inclusion of an inundation rate file is optional, but it results in a (slightly) more realistic estimation of the number of potential casualties. Therefore, the inundation rate is included.

The output of the Damage and Casualties Module consists of multiple files, of which one excel file containing information on the total damage and victims. In this excel file, the fist summary table provides the total damage, the total number of casualties (excluding evacuation), and the total number of affected individuals (residents in the flooded area). The second summary table offers an estimate of the expected number of casualties when a preventive evacuation strategy is employed or a vertical evacuation strategy is implemented. The damage section presents the total damage and the number of objects or areas that have been inundated (> 2 cm of water) for each category. A category may be further subdivided into two or three subcategories. For example, within the inland dike method, the category of businesses includes a cost component for direct damage and business interruption. Homes are divided into four subcategories, and each subcategory is further segmented by damage to personal property, structural damage, and damage resulting from the loss of residential services (Heymen, 2023).

2.6.3. Expected annual risk

The results generated by the Damage and Casualties Module (SSM), consisting of damage, casualties, and the number of individuals affected by the flood, are valuable for assessing the effectiveness of spatial adaptation strategies. This evaluation involves calculating the expected annual risk associated with each of these strategies, which can then be further broken down into the three specified categories: damage, casualties, and the people affected by the flood.

Expected annual damage

The expected annual damage (EAD) represents the average amount of money one would expect to spend each year if all potential monetary damages from different hazards were evenly spread out over time, regardless of their severity or probability of occurrence. However, it is important to note that this does not imply that each year will produce identical damages caused by natural hazards. Instead, some years may experience significant damages, while others will have minimal damages ("Colorado Water Conservation Board", 2020). Expected annual damages are often presented as an estimate based on a single event and its associated probability. For instance, when assessing flood damages, it's common to focus on the 1% probability event, often referred to as the 100-year flood. In that scenario, if only 100-year floods caused damage, the expected annual damage would simply be 1% of the damage magnitude for that specific event. However, this simplistic approach oversimplifies the reality of multiple hazard probabilities and varying damage levels ("Colorado Water Conservation Board", 2020).

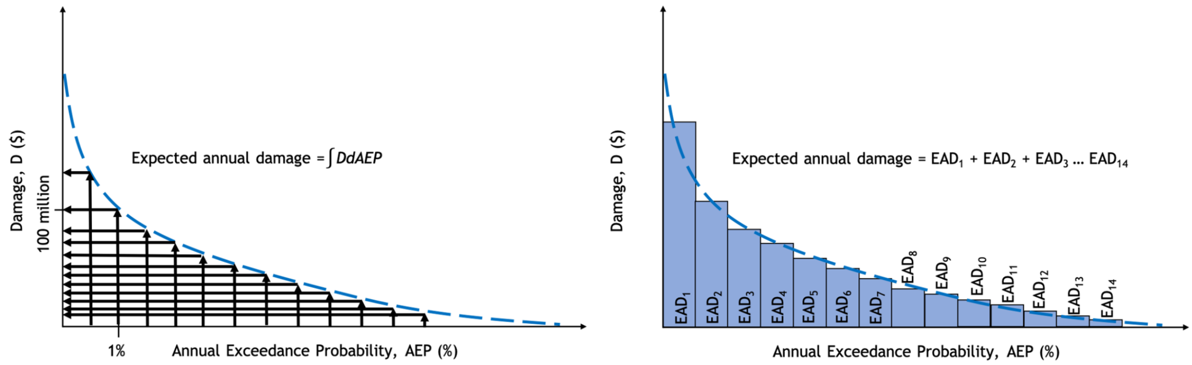
In reality, there are numerous probabilities and damage levels to consider. A more accurate calculation of expected annual damages incorporates all probabilities and their respective damage potentials. This entails accounting for the impacts of both rarer, more costly events and more frequent ones that may not result in significant damages (see figure 2.12, 2.12a).

The expected annual damage (EAD) of any given year is the integration of the flood risk density curve over all probabilities (Olsen et al., 2015). Denoted by D the damage which occurs at the event with annual exceedance probability AEP (%). The EAD can then be expressed according to equation 2.7.

$$EAD = \int D d\, AEP \tag{2.7}$$

To arrive at a more comprehensive expected annual damage value, the damage-probability data can be split up into smaller increments and then summed together (see figure 2.12b). The expected annual damage (EAD) is then according to equation 2.8.

$$EAD = EAD_1 + EAD_2 + EAD_3 + ... + EAD_n \tag{2.8}$$



(a) Expected annual damage (integral) **(b)** Expected annual damage (summation)

Figure 2.12: Calculation of expected annual damage (“Colorado Water Conservation Board”, 2020)

In summary, the expected annual damage, when factoring in all damages and probabilities, exceeds the estimate derived from a single probability event. This research uses an approach that considers damages across multiple probability levels, providing a broader perspective on financial impacts.

Expected annual casualties and affected people

The expected annual casualties and affected people can be determined using the same approach applied for estimating the expected annual damage. For this calculation, multiple probability levels are considered. Similar calculations can be performed for the expected annual casualties and the expected annual affected people as described by equation 2.8.

2.7. Cost-benefit analysis

In the final part of this research, a cost-benefit analysis of the proposed design strategies for Walcheren is conducted. This analysis implicitly covers all criteria considered in the assessment of the idealized coastal polder, which include the spatial impact and flood risk. Through this analysis, it becomes clear how the various spatial adaptation strategies compare not only to the plain dike-ring approach but also to one another. Ultimately, this enables the identification of the most cost-beneficial strategy.

Multiple proposed design strategies for Walcheren, including the secondary dike-ring, value protection dike-ring and compartmentalization strategies, require additional embankment length and volume when compared to the plain dike-ring approach. Therefore, the investment costs of these strategies exceed those of sole reinforcement of the plain dike-ring. However, the expectation is that these additional protection measures will reduce damage and the number of casualties when a flood occurs. Therefore, a fair trade-off should be made between the costs (investment) and the risk (damage). This emphasizes the need for a cost-benefit analysis.

2.7.1. Investment costs

The ’extra’ investment costs of the spatial adaptation strategies compared to the plain dike-ring strategy, are calculated based on a standard dike profile with a 1:3 slope. The crest height of this dike can be determined based on the hydraulic load level (Dutch: hydraulisch belastingniveau, HBN) given a certain return period and magnitude of sea level rise. It is assumed that the additional dikes (secondary dike-ring, value protection dike-rings and partition elements) have a crest width of 10 meters, irrespective of the height. An example of such a dike profile is presented in figure 2.13.

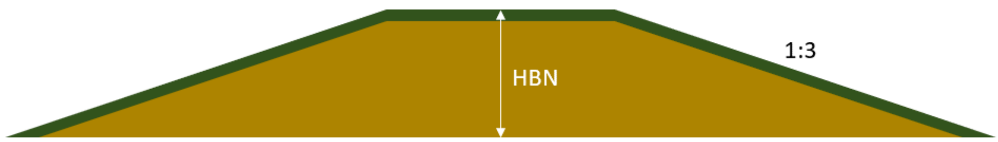


Figure 2.13: Standard dike profile with 1:3 slope applied for additional dikes

This standard dike profile consists of a core layer and a top layer. It is assumed that the top layer is a grass cover with a constant thickness of 0.30 meters. Using unit prices and the mentioned assumptions of dimensions of the core layer and the top layer, the costs of a cubic metre dike (reinforcement) can be calculated. The unit prices are shown in table 2.4. In this way, knowing the total dike length, the total investment costs for each strategy can be determined.

In reality, initial costs and land acquisition costs should be taken into consideration as well, but in this research, these costs are not explicitly included. However, in KOSWAT, storage factors are employed to convert direct construction costs into investment costs following the standard system for cost estimates, also known as the SSK methodology (Dutch: Standaardsystematiek voor Kostenramingen) (Deltares, 2016). The storage factor used in this study is 1.6, which is valid for soil measures (Dutch: grondmaatregelen), since it is assumed that the dike is constructed fully based on soil types. This storage factor is based on a 'normal' level of complexity and does not include VAT (Deltares, 2016).

Table 2.4: Unit prices (KOSWAT) (Deltares, 2016)

Activity	Costs [€/m^3]
Supply + processing topsoil	12.00
Supply + processing underlayer	17.49
Supply + processing core material	10.56
Use as top layer in profile	5.74
Use as core material in profile	4.45
Disposal of excess material	6.79

2.7.2. Damage (risk)

Flood damage will increase over time due to economic and demographic growth. Water level rise and dike increase may also increase the extent of flood damage. The formula for flood damage at time t used in optimisation is according to equation 2.9 (Deltares, 2011).

$$V(t) = V(0)e^{\gamma t}e^{\psi \eta t}e^{\zeta(H(t)-H(0))} \tag{2.9}$$

In this equation,

- V(t) is the flood damage [M€] as a function of time
- V(0) is the flood damage [M€] at time 0 (no dike reinforcement)
- γ is the rate [%/year] of economic growth (*gamma*)
- ψ is the parameter for extra damage [1/cm] due to water level rise (*psi*)
- η is the structural increase [cm/year] in relative water levels (*eta*)
- ζ is the increase rate [1/cm] of damage per cm dike reinforcement (*zeta*)

For the calculation of flood damage, all parameters are set at 0, except for the rate of economic growth (γ), which is 1.9% per year (Deltares, 2011). The remaining equation 2.10 can be applied to calculate the flood damage in any year up to 2200 for all spatial adaptation strategies.

$$V(t) = V(0)e^{0.019t} \tag{2.10}$$

In this research, the main focus is on sea level rise, so therefore it would be expected to take into account the parameter for extra damage due to water level rise (ψ). However, when calculating flood damage for a specific year (see equation 2.10), V(0) denotes the expected annual damage as computed by equation 2.8. It should be noted that this value varies across different sea level rise scenarios and is interpolated between the associated years, so therefore the extra damage due to water level rise is integrated into the flood damage calculation, yet in a different way. Likewise, the height of the dikes is adjusted to account for the increasing sea levels. The expected annual damage calculated for varying sea levels (according to equation 2.8) therefore also implicitly accounts for the increase rate of damage per cm dike reinforcement (ζ).

2.7.3. Net present value (NPV)

To determine the most cost-effective strategy, a comprehensive cost-benefit analysis can be conducted for each strategy. This is done by determining the Net Present Value (NPV) for each spatial adaptation strategy.

The Net Present Value (NPV) method is a widely used and advanced economic evaluation technique. It involves the process of discounting all future cash flows, including both incoming and outgoing funds associated with the innovation project, using a predetermined discount rate. These discounted cash flows are then summed (see equation 2.11) to determine the overall value (Žižlavskỳ, 2014).

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t} \tag{2.11}$$

In this equation, *NPV* [€] is the net present value. NCF_t [€] is the net cash flow generated by the innovation project in year *t* and *r* [%] is the discount rate.

Discount rate

The role of the discount rate in social cost-benefit analyses (SCBAs, Dutch: MKBA's) is to correctly value future costs and benefits to determine the expected social value of a project. An investment is only socially profitable if it generates additional welfare and the present value of future benefits exceeds the costs. The discount rate can also be understood as the return requirement to be placed on a public investment or project from a societal point of view. The discount rate is a percentage by which expected future costs and benefits are discounted back to the base year of the project. For social cost-benefit analyses, a discount rate of 2.25% is recommended, composed of a risk-free part of -1% and a risk premium of 3.25%. The rates are inflation-adjusted: they apply to analyses prepared in constant prices. Importantly, these rates remain constant throughout the entire duration of the project analysis (Werkgroep, 2020).

Total costs

For each of the spatial adaptation strategies, the NPV can be calculated for the investment costs and the damage costs, separately. The total NPV comprise both the investment and damage (risk), see equation 2.12.

$$NPV_T = NPV_I + NPV_V \tag{2.12}$$

In this equation, NPV_T is the total NPV [€], NPV_I is the NPV of the investment costs [€] and NPV_V is the NPV of the risk (damage) [€].

2.7.4. Expected annual costs per capita

The total expected annual costs per capita of Walcheren can be computed by summing the expected annual expenses, which comprise both the investments costs and the expected risk.

For all strategies, the total investment costs can be distributed evenly over the entire period from the present day up to the year 2200, and then divided by the total number of inhabitants. It is assumed that the population is constant over this period. The expected risk per year is summed over the full duration until 2200 and then divided by both the total duration (until 2200) and total population to calculate the average expected annual risk per individual.

Part II

Idealized coastal polder

3

Starting points design strategies

This chapter describes the various starting points of the four main (spatial adaptation) strategies of the idealized coastal polder: the plain dike-ring strategy, the secondary dike-ring strategy, the value protection dike-ring strategy, and the partitioned dike-ring strategy. Subsequently, multiple configurations are developed for these strategies.

3.1. Plain dike-ring

The initial strategy and baseline scenario of the idealized coastal polder is a plain dike-ring. This plain dike-ring consists of 35 independent individual dike sections. The polder characteristics are according to table 2.2. The fragility curve for each individual dike section and the total expected number of dike breaches in the idealized coastal polder were determined and elaborated in section 2.3.

Two configurations can be distinguished for the plain dike-ring of the idealized coastal polder: dike reinforcement (R) or no dike reinforcement (NR). In the current or zero situation (0 meters sea level rise), the flooding probability of the coastal polder is 1/1,000 per year. Under the condition that the dikes will be reinforced for varying sea level rise scenarios, it is assumed that the annual flooding probability of the coastal polder remains 1/1,000, regardless of the magnitude of sea level rise; although it should be noted that the flood risk levels are not necessarily similar, as the inflow of water through breaches can be larger for increasing sea levels. However, if the dikes will not be reinforced, this will have a significant impact on the flooding probability of the coastal polder for the different scenarios of sea level rise. This flooding probability will increase as the sea level rises.

A cross-section of the two configurations of no dike reinforcement and dike reinforcement are visually schematized in figure 3.1.

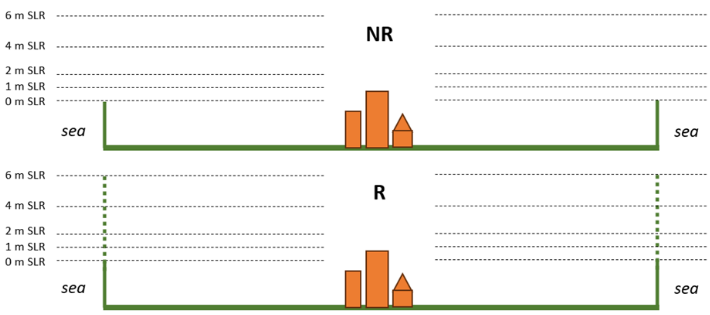


Figure 3.1: Plain dike-ring scenarios: no reinforcement (NR) and reinforcement (R)

3.2. Secondary dike-ring

An example of a spatial adaptation strategy of the idealized coastal polder is a secondary dike-ring. In this strategy, the secondary dike-ring is located near the primary dike-ring, but has a distance such that the area between the primary and secondary dike-ring serves as a buffer area when a dike breach occurs in the primary dike-ring.

3.2.1. Assumptions

In this strategy, the primary dike-ring has the characteristics of the plain dike-ring, as described in section 3.1. Based on these characteristics, some starting points for the secondary dike-ring are constructed. The primary dike-ring has a length of 47.5 km and consists of 35 dike sections. Given a total length of the secondary dike-ring of approximately 40 km and the average length of the dike sections of the primary dike-ring, the secondary dike-ring has approximately 30 dike sections. The inside polder has an area of 125 km^2. Given that the total area of the idealized polder is 200 km^2, the outer ring area is 75 km^2. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 3.1.

Table 3.1: Idealized polder characteristics - Secondary dike-ring

Description	Primary dike-ring	Secondary dike-ring
MSL	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent
Breach width	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level
Length dike-ring	47.5 [km]	40 [km]
Dike sections	35 [-]	30 [-]
Average polder area	75 [km^2]	125 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	< 1/1,000

In the reference situation of 0 meters sea level rise, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probability of the secondary dike-ring is smaller. It is assumed that the primary and secondary dike-rings have the same characteristics and the same height. The only difference is the perimeter, and therefore the number of dike sections is smaller for the secondary dike-ring.

In this research, three configurations are distinguished for the secondary dike-ring of the idealized coastal polder: primary dike reinforcement (PR), secondary dike reinforcement (SR), and complete reinforcement (CR, both primary and secondary dike-rings). Initially, in the reference scenario of no sea level rise, the primary and secondary dike-rings obtain the same characteristics and height. However, for increasing sea levels, the characteristics of the primary and secondary dike-ring may vary, depending on the type of configuration. In the case of primary dike reinforcement, the annual failure probability of the primary dike-ring remains constant for all sea level rise scenarios, whereas the secondary dike-ring has a failure probability based on a scenario of 0 meters sea level rise. On the other hand, the configuration of secondary dike reinforcement indicates the exact opposite. Conversely, when implementing complete reinforcement, both the primary and secondary dike-rings will undergo reinforcement, with adjustments in height for all sea level rise scenarios. A cross-section of the three configurations of primary, secondary and complete dike reinforcement are visually represented in figure 3.2.

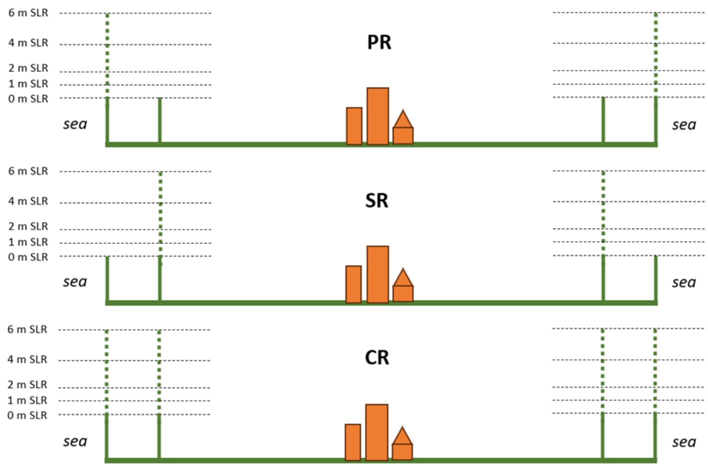


Figure 3.2: Secondary dike-ring scenarios: primary dike reinforcement (PR), secondary dike reinforcement (SR) and complete dike reinforcement (CR)

3.2.2. Primary (outer) dike reinforcement

In the scenario of primary dike reinforcement, it is assumed that the flooding probability remains 1/1,000 per year, irrespective of the magnitude of sea level rise, given that the primary dike-ring will be strengthened to accommodate different sea level rise scenarios. To this point, the scenario is exactly the same as the plain dike-ring with dike reinforcement. However, in this particular scenario, there is a secondary dike-ring and it is assumed that this dike will not undergo any reinforcement. The annual flooding probability of the secondary dike-ring for the zero situation (no sea level rise) is <1/1,000 per year, but the conditional failure probability for an individual dike section changes significantly for increasing scenarios of sea level rise. As a consequence, the expected number of breaches increases and therefore the total flooding probability of the coastal polder as well.

In the event of a dike breach in the primary dike-ring, the outside polder area becomes inundated and reaches a certain inundation depth, where-after one (or multiple) dike section(s) of the secondary dike-ring potentially fail(s). While the secondary dike-ring maintains the same failure probability as the primary dike-ring in the reference scenario, it increases for higher sea level rise scenarios. Therefore, in order to associate the maximum water levels in the outer polder with the return periods that correspond to the water levels observed at sea in the zero situation (0 meters of sea level rise), interpolation is employed. Furthermore, it is assumed that the polder inundation in the inside polder, where the city is located, levels out with the outside polder inundation for water levels in the outer polder exceeding 7.5 m+NAP.

3.2.3. Secondary (inner) dike reinforcement

In the scenario of secondary dike reinforcement, it is assumed that the annual flooding probability of the dike is <1/1,000, irrespective of the magnitude of sea level rise, given that the secondary dike-ring will be strengthened to accommodate different sea level rise scenarios.

However, in this particular scenario, it is assumed that the primary dike-ring will not undergo any reinforcement. The annual flooding probability of the primary dike-ring for the zero situation is 1/1,000, but the conditional failure probability for an individual dike section changes significantly for increasing scenarios of sea level rise. As a consequence, the expected number of breaches increases and therefore the total flooding probability of the coastal polder as well. In this scenario, for maximum water levels at sea exceeding 7.5 meters, the initial outside polder inundation at t = 0 is equivalent to the sea water level. From this moment, the annual failure probability of the value protection dike-ring is equivalent to 1/1,000.

3.2.4. Complete dike reinforcement

In the scenario of complete dike reinforcement for the secondary dike-ring strategy, it is assumed that the annual flooding probability of the primary dike is constant at 1/1,000 and the annual flooding probability of the secondary dike is <1/1,000, irrespective of the magnitude of sea level rise, given that both dike-rings will be strengthened to accommodate different sea level rise scenarios. Therefore, the primary and secondary dike-rings have the same characteristics and the same height for all scenarios of sea level rise.

3.3. Value protection dike-ring

The value protection dike-ring strategy of the idealized coastal polder is very much like that of the secondary dike-ring, but with one crucial difference. Unlike the secondary dike-ring, which is situated near the primary dike-ring, the value protection dike-ring is positioned closer to the city. This distinction has an impact on the inside and outside areas of the polder. The inside polder now has an area of 50 km^2. Given that the total area of the idealized polder is 200 km^2, the outer ring area is 150 km^2.

In this strategy, the primary dike-ring has the characteristics of the plain dike-ring, as described in section 3.1. Based on these characteristics, some starting points for the additional value protection dike-ring are constructed. The primary dike-ring has a length of 47.5 km and consists of 35 dike sections. Given a total length of the value protection dike-ring of approximately 26 km and the average length of the dike sections of the primary dike-ring, the secondary dike-ring has approximately 20 dike sections. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 3.2.

In the reference situation of 0 meters sea level rise, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probability of the secondary dike-ring is smaller. It is assumed that the primary and secondary dike-rings have the same characteristics and the same height. The only difference is the perimeter, and therefore the number of dike sections is smaller for the secondary dike-ring.

Table 3.2: Idealized polder characteristics - Value protection (secondary) dike-ring

Description	Primary dike-ring	Secondary dike-ring
MSL	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent
Breach width	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level
Length dike-ring	47.5 [km]	26 [km]
Dike sections	35 [-]	20 [-]
Average polder area	150 [km^2]	50 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	< 1/1,000

Three configurations are distinguished for the secondary value protection dike-ring of the idealized coastal polder: primary dike reinforcement (PR), secondary dike reinforcement (SR), and complete reinforcement (CR, both primary and secondary dike-rings). A cross-section of the three configurations of primary, secondary and complete dike reinforcement are visually represented in figure 3.3.

The principles of the three different configurations (PR, SR and CR) are essentially the same as those for the secondary dike-ring strategy, with the sole difference being the location of the value protection (or secondary) dike-ring. The most important assumption for the SR configuration of the value protection dike-ring strategy is that the primary dike-ring will not be reinforced, which makes it an example of the Plan B strategy.

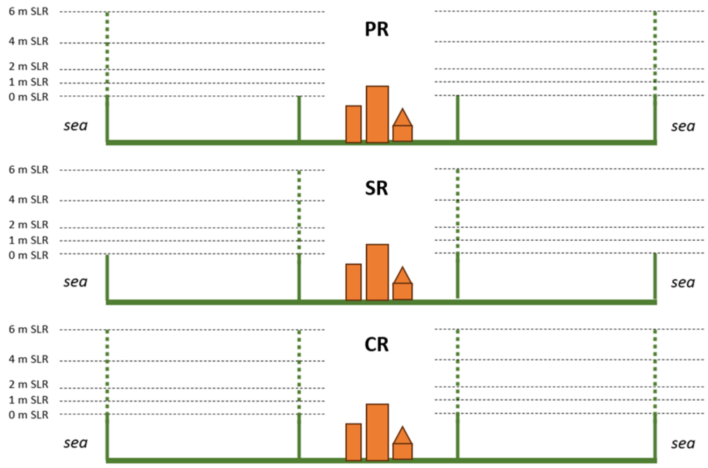


Figure 3.3: Value protection dike-ring scenarios: primary dike reinforcement (PR), secondary dike reinforcement (SR) and complete dike reinforcement (CR)

3.4. Partitioned dike-ring

The final spatial adaptation strategy considered for this idealized coastal polder is a partitioned dike-ring, also known as compartmentalization. In this strategy, the polder has a primary dike-ring, a (secondary) value protection dike-ring and two partition elements. The inside polder area is 50 km^2, as for the value protection strategy. The partition elements split the outside polder area in two equal parts. Therefore, the partitioned areas are 75 km^2 each.

3.4.1. Assumptions

In this strategy, the primary dike-ring has the characteristics of the plain dike-ring, as described in section 3.1, and the secondary dike-ring has the characteristics of the value protection dike-ring, as described in 3.3. In addition, there are two partition elements. Based on the primary and secondary dike-ring characteristics, some starting points for the additional partition elements are constructed. The primary dike-ring has a length of 47.5 km and consists of 35 dike sections. Given the length of a single partition element of approximately 4 km and the average length of the dike sections of the primary dike-ring, the total partition length is 8 km and the partition elements together have 6 dike sections. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 3.3.

Table 3.3: Idealized polder characteristics - Partitioned dike-ring

Description	Primary dike-ring	Secondary dike-ring	Partitions
MSL	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent	dependent
Breach width	100 [m]	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level	max. water level
Length dike-ring	47.5 [km]	26 [km]	8 [km]
Dike sections	35 [-]	20 [-]	6 [-]
Average polder area	150 [km^2]	50 [km^2]	-
Average polder elevation	0 [m+NAP]	0 [m+NAP]	-
Annual failure probability	1/1,000	<1/1,000	<1/1,000

In the reference situation of 0 meters sea level rise, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probabilities of the secondary dike-ring and partition elements are smaller. It is assumed that the primary and secondary dike-rings have the same characteristics and the same height. The only difference is the perimeter, and therefore the number of dike sections is smaller for the secondary dike-ring. The partitions are assumed to have a variable height, dependent on the scenario.

Two configurations are distinguished for the partitioned dike-ring of the idealized coastal polder: partition investment (PI), and city protection (CP). For the partitioned dike-ring strategy, both the primary and secondary dike-rings will undergo reinforcement, with adjustments in height for all sea level rise scenarios. To this point, this strategy aligns with the secondary value protection dike-ring strategy with complete dike reinforcement. In the case of partition ivestment, the annual failure probability of the partitions is always smaller than the secondary dike-ring. On the other hand, the configuration of city protection indicates that the annual failure probability of the partitions is always larger than the secondary dike-ring. The cross-sections of the two configurations of partition investment and city protection are visually represented in figure 3.4.

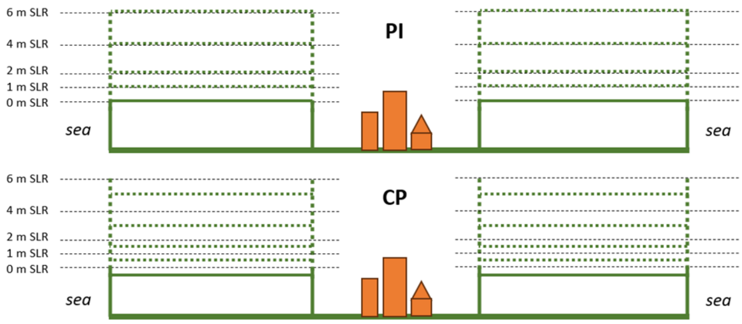


Figure 3.4: Partitioned dike-ring scenarios: partition investment (PI) and city protection (CP)

3.4.2. Partition investment

In the scenario of partition investment for the partitioned dike-ring strategy, it is assumed that the annual flooding probability of the primary dike is constant at 1/1,000 and the annual flooding probability of the secondary dike is constant at <1/1,000, irrespective of the magnitude of sea level rise, given that both dike-rings will be strengthened to accommodate different sea level rise scenarios. Therefore, the primary and secondary dike-rings have the same characteristics and the same height for all scenarios of sea level rise. The partitions also have a constant flooding probability of <1/1,000, while the characteristics and height of these dikes are different from the primary and secondary dike-ring. In this scenario, the partitions are slightly higher than the secondary dike-ring (hence partition investment). Therefore, it is assumed that the secondary dike-ring will fail before the partitions fail.

Furthermore, in this particular situation, it is assumed that when the return period of a water level is equal to or less than T = 10,000 years, the breach(es) of the primary dike lead(s) to flooding in a single compartment. However, for extreme water levels exceeding a return period of T = 10,000 years, it is assumed that the breaches in the primary dike-ring are distributed more evenly, resulting in identical flooding patterns and conditions as those observed in strategy *c* (value protection).

3.4.3. City protection

In the scenario of city protection for the partitioned dike-ring strategy, it is assumed that the primary and secondary dike-rings have the same characteristics, flooding probabilities and heights as described for the scenario of partition investment. The partitions have a constant flooding probability of <1/1,000, while the characteristics and height of these dikes are different from the primary and secondary dike-ring. In this scenario, the partitions are lower in height and have a larger flooding probability than the secondary dike-ring. Therefore, it is assumed that the partitions will fail before the secondary dike-ring fails.

Also in this particular situation, it is assumed that when the return period of a water level is equal to or less than T = 10,000 years, the breach(es) of the primary dike first lead(s) to flooding in a single compartment. However, when the return period of a water level exceeds T = 10,000 years, it is assumed that the breaches in the primary dike-ring are distributed more evenly, resulting in identical flooding patterns and conditions as those observed in strategy *c* (value protection).

4

Results of design strategies

This chapter plays a central role in addressing the first sub-question of this study: "How do various spatial adaptation strategies influence the inundation depth and frequency in idealized coastal polders compared to a plain dike-ring strategy, while accounting for the projected accelerated sea level rise?"

4.1. Plain dike-ring

In this paragraph, topics such as the polder inundation development and inundation frequency are discussed for the plain dike-ring strategy. Therefore, both configurations of no dike reinforcement (NR) and dike reinforcement (R) are considered. The polder inundation development is presented for a scenario of 2 meters sea level rise by the year 2100. Additionally, the inundation frequency lines are depicted for multiple sea level rise scenarios and various return periods of water levels and a comparison is made between the inundation depths of both configurations.

4.1.1. Polder inundation development

The polder inundation development scenarios for frequent and extreme storm surges, in case of a plain dike-ring strategy and 2 meters sea level rise are shown in figure 4.1.

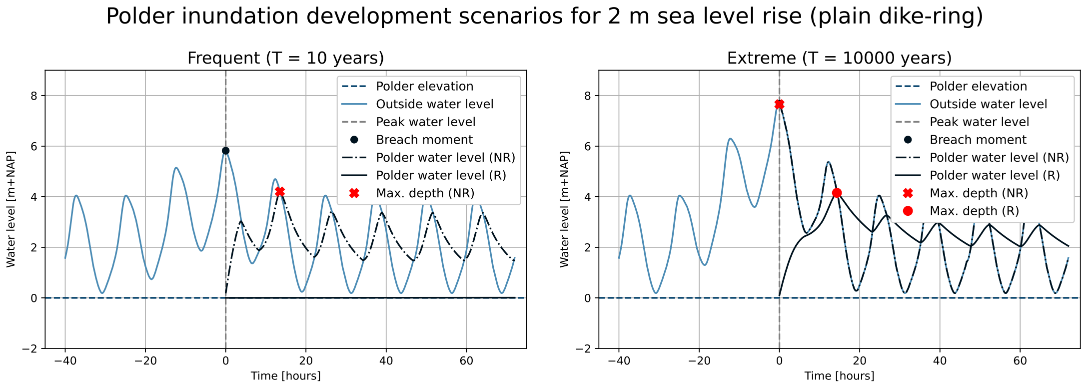


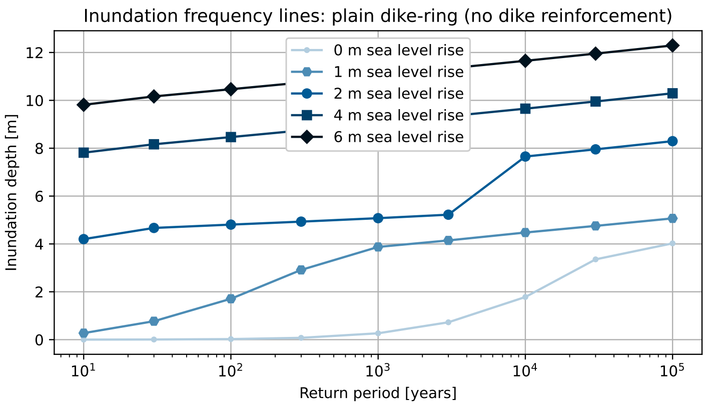
Figure 4.1: Polder inundation development for a plain dike-ring strategy for 2 meters sea level rise

Without dike reinforcement (NR), the fragility curve for an individual dike section changes significantly for increasing scenarios of sea level rise. As a consequence, the expected number of breaches increases and therefore the flooding probability of the coastal polder as well. The maximum inundation in the polder can reach up to 4 meters as a result of frequent storms (every 10 years), by the end of this century. For more extreme storm surges, the maximum polder water levels are increasing and the moment of maximum inundation is reached earlier (see figure 4.1). The rate of water level rise is significantly faster in more extreme situations due to the higher number of breaches occurring. For maximum water levels exceeding 7.5 meters, the initial polder inundation at t = 0 is equivalent to that of the sea water level, which is the case for extreme storms according to figure 4.1. This assumption arises from the expectation that the dike already fails, when the sea water level exceeds a certain critical value (of around 6 m+NAP), before the maximum water level (7.5 m+NAP or higher) is reached. However, the expectation is that reinforcing the dikes (R) until the end of this century will be highly effective for frequent storms, as the maximum expected inundation after 72 hours is negligible compared to a maximum inundation of over 4 meters without dike reinforcement (see figure 4.1). However, during extreme storms, the maximum polder inundation can still reach up to 4 meters after approximately 15 hours. Although this is approximately 4 meters lower compared to the situation without dike reinforcement, this inundation represents a doubling of the expected inundation for extreme storms at 0 meter sea level rise. For the projection of the accelerated sea level rise, this indicates that primary dike reinforcement has a substantial impact on reducing inundation during extreme events, but there is still a considerable risk to be managed.

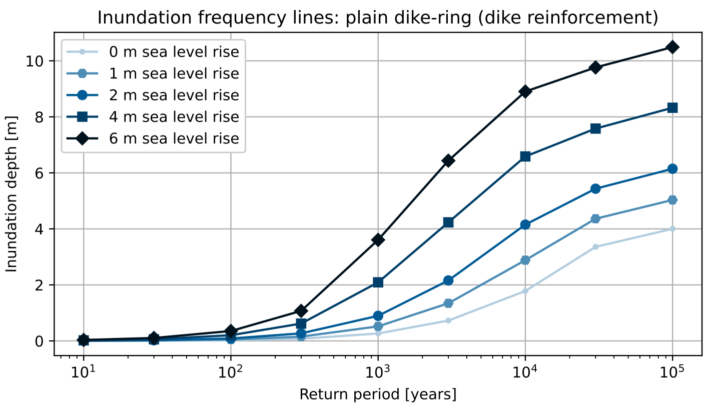
The polder inundation development plots for a plain dike-ring strategy without dike reinforcement (NR) for all return periods and sea level rise scenarios (0, 1, 2, 4, and 6 meters) are presented in figures C.1, C.2, C.3, C.4 and C.5 respectively. For a plain dike-ring strategy with dike reinforcement (R), these plots can be observed in figures C.6, C.7, C.8, C.9 and C.10 respectively.

4.1.2. Inundation frequency

The inundation frequency lines for a plain dike-ring without dike reinforcement (NR) and dike reinforcement (R) are shown in figures 4.2a and 4.2b respectively. In these figures, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level.



(a) no dike reinforcement (NR)



(b) dike reinforcement (R)

Figure 4.2: Inundation frequency lines for an idealized coastal polder with a plain dike-ring

For a plain dike-ring without dike reinforcement (NR), the maximum inundation depths in the polder vary significantly among the various scenarios of sea level rise, for the different return periods (see figure 4.2a). This can be explained by the fact that the maximum water levels for the different scenarios of sea level rise are linked to a new return period. This correlation is derived from the scenario with no sea level rise (0 meters). To clarify with an example, consider a storm surge with a return period of 100 years in a situation with 2 meters sea level rise. In this case, the resulting maximum water level would be higher than the water level resulting from a storm surge with a return period of 100,000 years and no meters sea level rise. When re-linking this maximum water level for a scenario of 2 meters sea level rise to a new return period, using the scenario with no sea level rise as a basis, it automatically indicates a water level with a return period of 100,000 years. Therefore, the maximum inundation depth in the polder is higher for this combination (see figure 4.2a).

The maximum inundation depths in the situation of dike reinforcement (R) are clearly different than for the situation without dike reinforcement. The inundation depths of the different sea level rise scenarios are comparable for low return periods, but are more widespread for increasing return periods (see figure 4.2b). The dike reinforcement implies that the fragility curve and expected number of breaches according to figures 2.7 and 2.9 respectively, are valid for all sea level rise scenarios. The increasing inundation depth for increasing return periods, is due to the volume of water that enters the polder which increases as a result of a higher number of dike breaches. The diverging effect for increasing return periods among the various sea level rise scenarios can be explained by the fact that the volume of water entering the polder also increases for higher water levels.

The inundation depths for the two configurations of the plain dike-ring strategy can be compared directly for the various scenarios of sea level rise. In figure 4.3, the inundation depth for the configuration with dike reinforcement relative to no dike reinforcement is presented. Next to the frequent (T = 10 years) and extreme (T = 10,000 years) storms, two storm surges (with return periods of 100 and 1,000 years) are added for a more complete and comprehensive analysis.

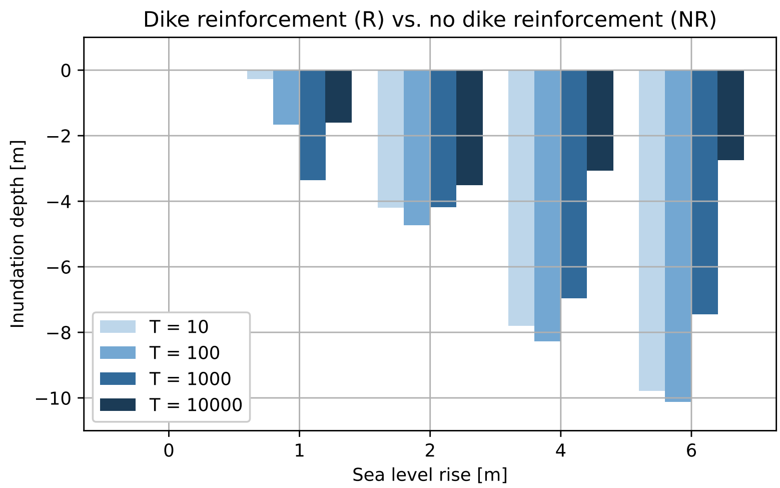


Figure 4.3: Inundation depth comparison: dike reinforcement (a-R) vs. no dike reinforcement (a-NR) for a plain dike-ring

There is no difference between the configurations for the scenario of 0 meters sea level rise. As this scenario serves as the reference or baseline, both configurations are identical since the norm of the dike-ring remains the same. However, for scenarios with increasing sea level rise, reinforcing the dike-ring can significantly reduce the inundation depth compared to the scenario without reinforcement. Even with a sea level rise of just 1 meter, the implementation of reinforcement measures can lead to a reduction in polder inundation depth by nearly 2 meters for a sea water level with a return period of 100 years (see figure 4.3). In scenarios where the sea level rises by 2 meters or more, it is evident that dike reinforcement measures are more effective in mitigating inundation during frequent storms compared to extreme storms. The most significant reduction in inundation depth occurs in the case of storm surges with a return period of 100 years (see figure 4.3).

4.2. Secondary dike-ring

This paragraph describes the main aspects of the secondary dike-rings strategy, with particular focus on the polder inundation development and the analysis of inundation frequency. Therefore, three key configurations are considered: primary dike reinforcement (PR), secondary dike reinforcement (SR) and complete dike reinforcement (CR). In a more specific context, the polder inundation development is illustrated for a scenario of 2 meters sea level rise by the year 2100. Additionally, a comparison is made between the inundation depths of the three configurations, compared to the plain dike-ring strategy, for multiple sea level rise scenarios and various return periods.

4.2.1. Polder inundation development

The polder inundation development scenarios for frequent and extreme storm surges, in case of a secondary dike-ring strategy and 2 meters sea level rise are shown in figure 4.4.

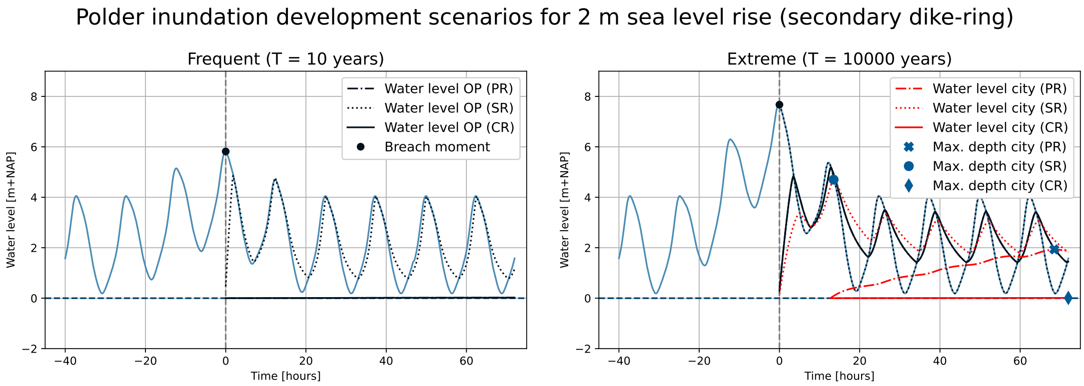


Figure 4.4: Polder inundation development for a secondary dike-ring for 2 meters sea level rise

In case of 2 meters sea level rise by the end of this century, a secondary dike-ring is redundant when considering frequent storms and primary dike reinforcement (PR) or complete dike reinforcement (CR). This is proven by the left graph in figure 4.4, where the inundation within both the outside polder (OP) and inside polder (city) area are negligible. In contrast, the secondary dike-ring does provide added value for the configuration of solely secondary dike reinforcement (SR), since the inundation in the outside polder (OP) is nearly aligned with the outside water level, whereas the inundation within the city is negligible.

For more extreme storms, a secondary dike-ring, even without reinforcement compared to the reference situation (no sea level rise), can provide considerable added value. In comparison to the plain dike-ring strategy, the secondary dike-ring strategy, with solely primary dike reinforcement (PR), can reduce the maximum inundation of the city within the polder by 2 meters. Moreover, this strategy substantially prolongs the time required to reach this maximum inundation from 15 hours to approximately 70 hours (see figure 4.4). However, the secondary dike-ring strategy with solely secondary dike reinforcement (SR) leads to a higher maximum inundation depth within the polder compared to the plain dike-ring strategy with dike reinforcement. For extreme storms, complete dike reinforcement (CR) proves to be the most effective configuration, as the maximum inundation of the city within the polder is approximately 0 meters. This is a significant reduction compared to the plain dike-ring strategy. These findings highlight the potential benefits of the secondary dike-ring strategy with primary dike reinforcement (PR) or complete dike reinforcement (CR), particularly during extreme storm events.

The polder inundation development plots for primary dike reinforcement (PR) for all sea level rise scenarios (0, 1, 2, 4, and 6 meters) are presented in figures C.11, C.12, C.13, C.14 and C.15 respectively. For a situation with solely secondary dike reinforcement (SR), these plots are illustrated in figures C.16, C.17, C.18, C.19 and C.20 respectively. For complete dike reinforcement (CR), these plots can be observed in figures C.21, C.22, C.23, C.24 and C.25 respectively.

4.2.2. Inundation frequency

The inundation frequency graphs created for the plain dike-ring strategy as presented in figure 4.2 are also created for the three configurations of the secondary dike-ring strategy. For the configuration of solely primary dike reinforcement (PR), these inundation frequency lines are elaborated in Appendix C and presented in figure C.52. For the configurations of solely secondary dike reinforcement (SR) and complete dike reinforcement (CR) these inundation frequency lines can be observed in figures C.53 and C.54 respectively. These figures offer a comparative analysis of inundation frequency (considering multiple sea level rise scenarios and storm surge events) across the various dike-ring strategies, providing valuable insights into the effectiveness of each configuration in managing inundation events.

The inundation depths for the three configurations (primary, secondary or complete dike reinforcement) of the secondary dike-ring strategy can be compared directly to the plain dike-ring strategy (with dike reinforcement) for the various scenarios of sea level rise. This is illustrated in figure 4.5.

Until the end of the century, for mild sea level rise scenarios (0, 1 or 2 meters), the implementation of a secondary dike-ring proves to be beneficial for all three configurations, mostly for extreme storm surges, when compared to the plain dike-ring strategy with dike reinforcement. However, in all three configurations, the added value of the secondary dike-ring (compared to the plain dike-ring strategy with dike reinforcement) can be neglected for frequent storm surges with return periods of 10 years and is low for storm surges with a return period of 100 years (see figure 4.5).

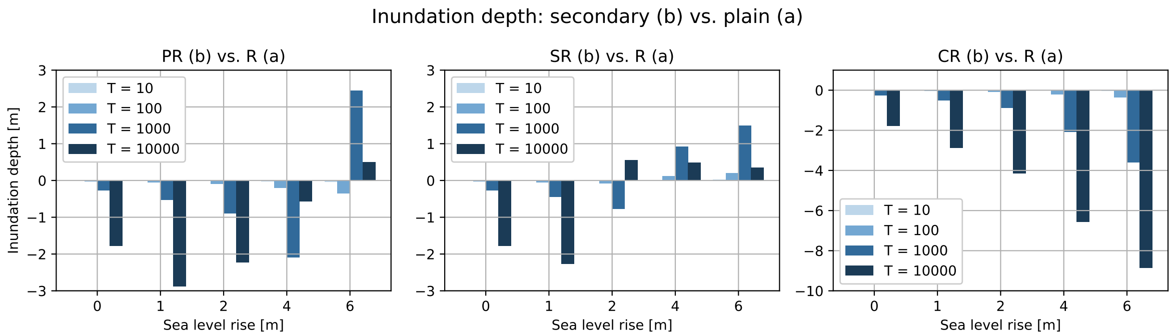


Figure 4.5: Inundation depth comparison: left figure: primary dike reinforcement (b-PR) versus plain dike reinforcement (a-R); middle figure: secondary dike reinforcement (b-SR) versus plain dike reinforcement (a-R); right figure: complete dike reinforcement (b-CR) versus plain dike reinforcement (a-R)

The benefits of the secondary dike-ring strategy with solely primary dike reinforcement, demonstrate a turning point for storm surges with return periods of T = 1,000 years and higher, at a scenario of 6 meters sea level rise. Conversely, when considering solely secondary dike reinforcement, this turning point is already visible at 2 meters sea level rise, specifically for extreme surges with a return period of 10,000 years (see figure 4.5).

When compared to a plain dike-ring strategy, the secondary dike-ring strategy with complete dike reinforcement consistently proves to be more effective, particularly in dealing with storm surges with return periods of T = 1,000 years and T = 10,000 years. Notably, in all considered scenarios in this analysis, the inundation depth can be reduced to zero, even for extreme storm surges. This highlights the potential for effective flood mitigation.

4.3. Value protection dike-ring

This section delves into two important aspects of the value protection dike-ring strategy: polder inundation development and inundation frequency analysis. The examination considers three configurations: primary dike reinforcement (PR), secondary dike reinforcement (SR), and complete dike reinforcement (CR). Specifically, the focus lies on polder inundation development within the context of a 2-meter sea level rise by the year 2100. Additionally, the differences in inundation depths among these three configurations compared to the reference strategy are evaluated across various sea level rise scenarios and multiple return periods.

4.3.1. Polder inundation development

The polder inundation development scenarios for frequent and extreme storm surges, in case of a secondary value protection dike-ring strategy and 2 meters sea level rise are shown in figure 4.6.

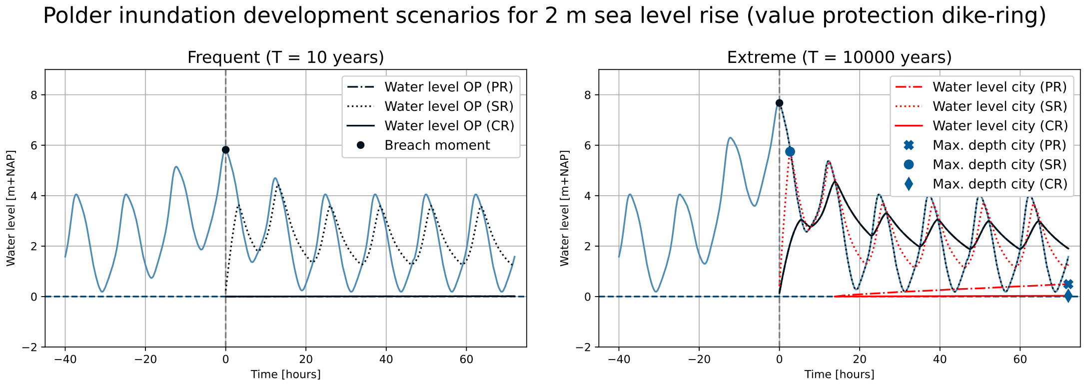


Figure 4.6: Polder inundation development for a value protection dike-ring for 2 meters sea level rise

If a sea level rise of 2 meters occurs by the end of this century, the need for implementing a (secondary) value protection dike-ring depends on the specific strategy chosen for dealing with frequent storms. Three configurations are considered: primary dike reinforcement (PR), secondary dike reinforcement (SR) and complete dike reinforcement (CR).

The left graph in figure 4.6 provides valuable insight, showing that in the case of either PR or CR, there is no inundation within both the outside and inside polder areas. This suggests that in such scenarios, the secondary value protection dike-ring may not be necessary. On the contrary, when considering solely secondary dike reinforcement (SR), the secondary dike-ring exhibits clear advantages in mitigating the impact of frequent storms in the city.

When dealing with more extreme storms, even without additional reinforcement compared to the reference situation with no sea level rise, a (secondary) value protection dike-ring can offer substantial benefits. In comparing the value protection dike-ring strategy with solely primary dike reinforcement to the plain dike-ring approach, the maximum inundation of the city within the polder can be reduced by at least 3 meters. Furthermore, this strategy significantly prolongs the time required to reach this maximum inundation, extending it from approximately 15 hours to 72 hours, as can be observed in figure 4.6. Nevertheless, in the scenario of extreme storms, the secondary value protection dike-ring strategy with solely secondary dike reinforcement (SR) may lead to a higher maximum inundation depth within the polder when compared to the plain dike-ring strategy with dike reinforcement. This outcome is explained by the fact that, during the breach moment, the water level in the outside polder area aligns directly with the sea water level. Consequently, the water entering through the breaches of the secondary dike-ring spreads evenly throughout the inside polder, covering a smaller area compared to the area impacted by the plain dike-ring strategy. For extreme storm surges, the implementation of a value protection dike-ring with complete dike reinforcement (CR) demonstrates significant added value, as shown in figure 4.6. The maximum inundation of the city within the polder is approximately 0 meters, a substantial reduction compared to the plain dike-ring strategy with dike reinforcement. These findings emphasize the potential advantages of implementing the value protection dike-ring strategy with primary dike reinforcement (PR) or complete dike reinforcement (CR), particularly in mitigating the impacts of extreme storm events.

The plots depicting polder inundation development for various sea level rise scenarios (0, 1, 2, 4, and 6 meters) with different dike reinforcement strategies are presented in the following figures:

1. For primary dike reinforcement (PR), refer to figures C.26, C.27, C.28, C.29, and C.30 respectively.
2. In the case of solely secondary dike reinforcement (SR), these plots are illustrated in figures C.31, C.32, C.33, C.34, and C.35 respectively.

3. For complete dike reinforcement (CR), the corresponding plots are available in figures C.36, C.37, C.38, C.39, and C.40 respectively.

4.3.2. Inundation frequency

The inundation frequency graphs, initially developed for the plain dike-ring strategy and displayed in figure 4.2, have also been generated for the three different configurations of the value protection dike-ring strategy. Specifically, for the scenario involving solely primary dike reinforcement (PR), these inundation frequency curves are elaborated in more detail in Appendix C and are visually represented in figure C.55. As for the configurations employing solely secondary dike reinforcement (SR) and complete dike reinforcement (CR), the corresponding inundation frequency lines can be observed in figures C.56 and C.57, respectively.

The inundation depths for the three configurations (primary, secondary or complete dike reinforcement) of the secondary value protection dike-ring strategy can be compared to the plain dike-ring strategy (with dike reinforcement) for the various scenarios of sea level rise. This is illustrated in figure 4.7. The overall findings are quite similar to that of the secondary dike-ring strategy.

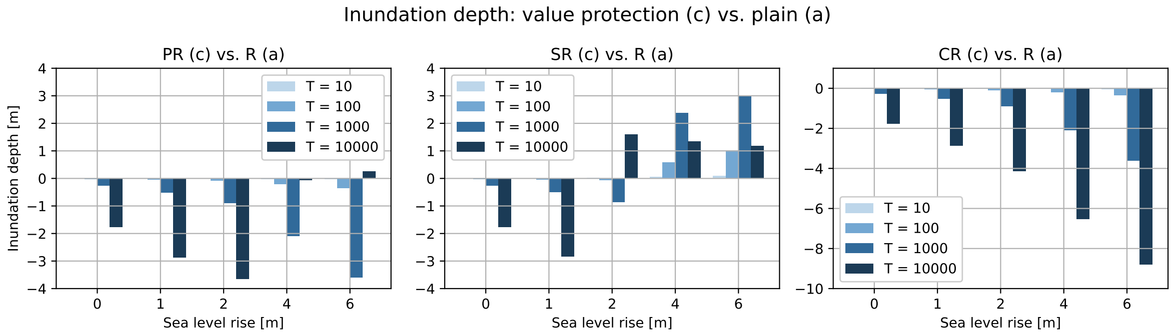


Figure 4.7: Inundation depth comparison: primary dike reinforcement (c-PR) versus plain dike reinforcement (a-R) (left figure); secondary dike reinforcement (c-SR) versus plain dike reinforcement (a-R) (middle figure); and complete dike reinforcement (c-CR) versus plain dike reinforcement (a-R) (right figure)

Until the end of the century, for mild sea level rise scenarios (0, 1 or 2 meters), the implementation of a value protection dike-ring proves to be beneficial for all three configurations, just like the secondary dike-ring strategy. These advantages are most pronounced during storm surges, particularly those with return periods of 1,000 and 10,000 years, when compared to the plain dike-ring strategy with dike reinforcement. However, across all three configurations, the contribution of the value protection dike-ring, as compared to the plain dike-ring strategy with dike reinforcement, remains minimal for frequent storm surges, characterized by return periods of 10 years. Its impact is relatively low even for storm surges with a return period of 100 years (see figure 4.7).

The benefits of the (secondary) value protection dike-ring strategy, coupled with solely primary dike reinforcement, reveal a subtle turning point in the context of a 6-meter sea level rise scenario, particularly during extreme storm surges with a return period of 10,000 years. Conversely, when considering solely secondary dike reinforcement, this turning point becomes apparent at a sea level rise of 2 meters, specifically for extreme surges with a return period of 10,000 years, as illustrated in figure 4.7.

Compared to a plain dike-ring strategy, the value protection dike-ring strategy with complete dike reinforcement consistently proves to be more effective, particularly when confronted with storm surges characterized by return periods of T = 1,000 years and T = 10,000 years. Notably, in all scenarios considered within this analysis, the inundation depth can be reduced to nearly zero, even for extreme storm surges. This highlights the potential for effective flood mitigation.

4.4. Partitioned dike-ring

This section provides an analysis of the inundation depth for the value protection dike-ring strategy, with a particular focus on polder inundation development and the analysis of inundation frequency.

The examination is centered around two configurations: partition investment (PI) and city protection (CP). The polder inundation development is presented for a scenario of 2 meters sea level rise by the year 2100. Additionally, a comparative analysis is conducted to evaluate the difference in inundation depths between the two configurations and reference strategy, for multiple sea level rise scenarios and various return periods.

4.4.1. Polder inundation development

The polder inundation development scenarios for frequent and extreme storm surges, in case of a partitioned dike-ring strategy with complete dike reinforcement and 2 meters sea level rise are shown in figure 4.8.

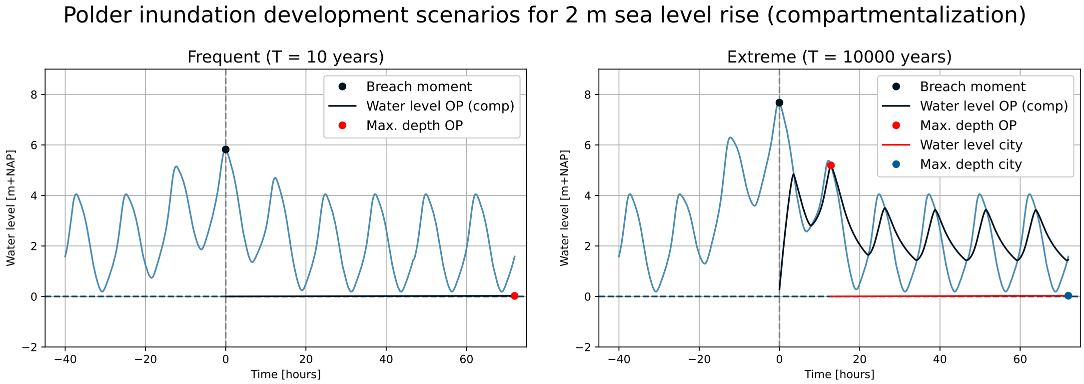


Figure 4.8: Polder inundation development for a partitioned dike-ring (complete dike reinforcement) for 2 meters sea level rise

Considering frequent storm surges under a projected 2-meter accelerated sea level rise by 2100, the partitioned dike ring strategy with partition investment (PI) or city protection (CP) does not offer any additional advantages when compared to the plain dike-ring strategy with dike reinforcement, similar to the secondary dike-ring and value protection dike-ring strategies. This conclusion is derived from the observation that there is no water inflow in any section of the polder situated behind the primary dike-ring (see figure 4.8). On the contrary, for extreme storm surges, the partitioned dike-ring with partition investment (PI) or city protection (CP) effectively ensures that the inundation depth within the city is mitigated to 0 meters, even up to 72 hours after the peak of the storm surge. However, it is essential to note that in the case of extreme storm surges with a return period of 10,000 years, the partitioned dike-ring strategy with partition investment or city protection may not necessarily provide added value compared to the secondary and value protection dike-ring strategies, both of which involve complete dike reinforcement, as the inundation depth within the city remains at approximately 0 meters for all of these configurations.

The polder inundation development plots for the partition investment strategy (PI) for all sea level rise scenarios (0, 1, 2, 4, and 6 meters) are presented in figures C.41, C.42, C.43, C.44 and C.45 respectively. For the city protection strategy (CP), these plots are illustrated in figures C.46, C.47, C.48, C.49 and C.50 respectively.

4.4.2. Inundation frequency

The inundation frequency graphs, originally developed for the plain dike-ring strategy and presented in figure 4.2, have also been extended for the two configurations of the partitioned dike-ring strategy. In particular, for the scenario involving partition investment (PI), these inundation frequency curves are elaborated in more detail in Appendix C and are visually represented in figure C.58. Likewise, for the city protection (CP) configuration, the corresponding inundation frequency lines can be observed in figure C.59.

The inundation depths for the two configurations (city protection or partition investment) of the partitioned dike-ring strategy can be compared to the plain dike-ring strategy (with dike reinforcement) for the various scenarios of sea level rise. This is illustrated in figure 4.9. For both configurations, the added value of the partitioned dike-ring (compared to the plain dike-ring strategy with dike reinforcement) can be neglected for frequent storm surges with return periods of 10 years and is very low for storm surges with a return period of 100 years (see figure 4.7). However, the implementation of a partitioned dike-ring proves to be beneficial for both configurations in the case of storm surges with return periods of 1,000 and 10,000 years, when compared to the plain dike-ring strategy with dike reinforcement. Notably, in all considered scenarios in this analysis, the inundation depth can be reduced to (almost) zero, even for extreme storm surges. This highlights the potential for effective flood mitigation.

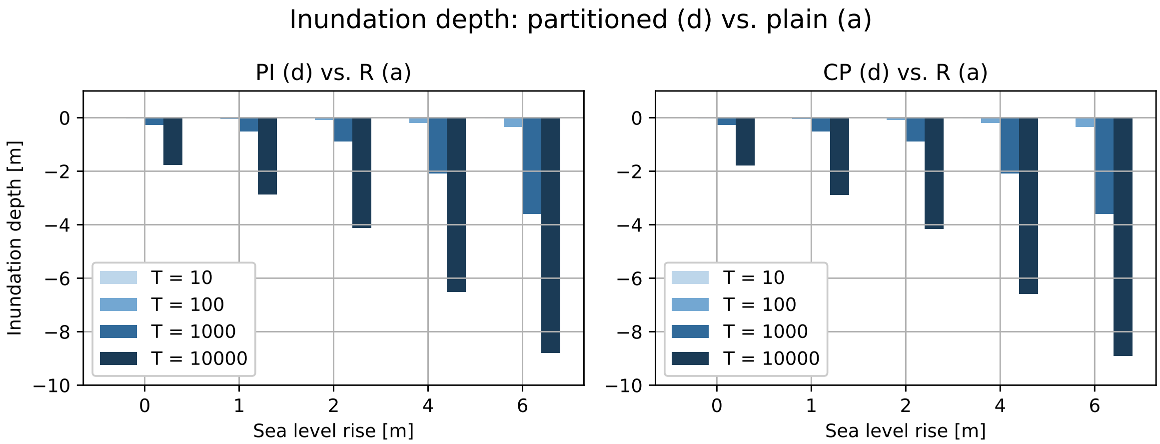


Figure 4.9: Inundation depth comparison: partition investment (d-PI) versus plain dike reinforcement (a-R) (left figure); and city protection (d-CP) versus plain dike reinforcement (a-R) (right figure)

5

Evaluation of design strategies

The assessment explores different spatial adaptation strategies for spatial impact and flood risk management. These strategies include the plain dike-ring, secondary dike-ring, value protection, and partitioned dike-ring approaches. This study examines the effects of these strategies on (enhanced) protected land and embankment lengths, as well as their impact on reducing inundation depth and inundation rate. Through this assessment, this chapter plays a central role in addressing the second sub-question concerning idealized coastal polders: ”What are effective spatial adaptation measures in idealized coastal polders, considering the evaluation of spatial impact and mitigating flood risk?”

5.1. Spatial impact

The first category of the assessment is spatial impact. This category consists of two criteria: available (enhanced protected) land and embankment length. The (enhanced) protected land refers to the area of land preserved that has been subjected to enhanced protection measures within each spatial adaptation strategy relative to the reference scenario, a plain dike-ring. The embankment length criterion measures the additional length of embankments needed for each spatial adaptation strategy, compared to the plain dike-ring strategy.

5.1.1. Protected land (enhanced)

An overview with the protected land for each of the spatial adaptation strategies is presented in table 5.1. In the case of the plain dike-ring strategy, there are no enhanced protection measures, as this is the reference scenario. However, with the secondary dike-ring strategy, approximately 63% of the original coastal polder is retained as a well protected area. On the other hand, both the value protection dike-ring and the partitioned dike-ring strategies result in 25% of the initial polder area being well protected. It is important to highlight that in the scenario of complete reinforcement of all strategies, the probability of primary dike-ring failure remains the same across each strategy. In the case of a secondary, value protection, and partitioned dike-ring, although the preserved area (the area in which the city is located) is smaller, the city receives enhanced protection compared to the plain dike-ring strategy.

Table 5.1: Protected land (enhanced) spatial adaptation strategies

	Protected area [km^2]	**Enhanced protected area [km^2]**	**Percentage [%]**
Plain dike-ring	200	0	0
Secondary dike-ring	200	125	62.5
Value protection dike-ring	200	50	25
Partitioned dike-ring	200	50	25

5.1.2. Embankment length

Table 5.2 shows the embankment lengths needed for different spatial adaptation strategies. Looking at the table, it is evident that the secondary dike-ring strategy requires the most additional dike length, followed by the partitioned dike-ring strategy. The value protection dike-ring strategy, on the other hand, requires the least extension in dike length, compared to the plain dike-ring strategy.

When considering the complete reinforcement of dikes for all strategies, it is necessary to make these dikes higher and wider, resulting in a significant increase in volume. This, in turn, has a direct impact on the associated costs for implementing the various strategies. It is important to take this into account, especially when there is a limited budget available.

Table 5.2: Embankment length spatial adaptation strategies

	Primary [km]	Secondary [km]	Partition [km]	Total [km]
Plain dike-ring	47.5	-	-	**47.5**
Secondary dike-ring	47.5	40	-	**87.5**
Value protection dike-ring	47.5	26	-	**73.5**
Partitioned dike-ring	47.5	26	8	**81.5**

5.2. Flood risk

The second category of the assessment is flood risk. This category consists of two criteria: flood inundation depth and inundation rate (evacuation time). The predicted inundation depths for each spatial adaptation strategy are compared visually. The assessment also considers the evacuation time available until an inundation depth of 1 meter is reached in the city.

5.2.1. Inundation depth

The effectiveness of the various spatial adaptation strategies compared to the reference strategy (R), in terms of reducing the inundation depth for frequent storms (T = 10 years), is nearly negligible. The only effectiveness achieved is the reinforcement of the plain dike ring as opposed to no reinforcement. For all other strategies, the anticipated inundation depth is nearly 0 meters, across all sea-level rise scenarios (see figure 5.1).

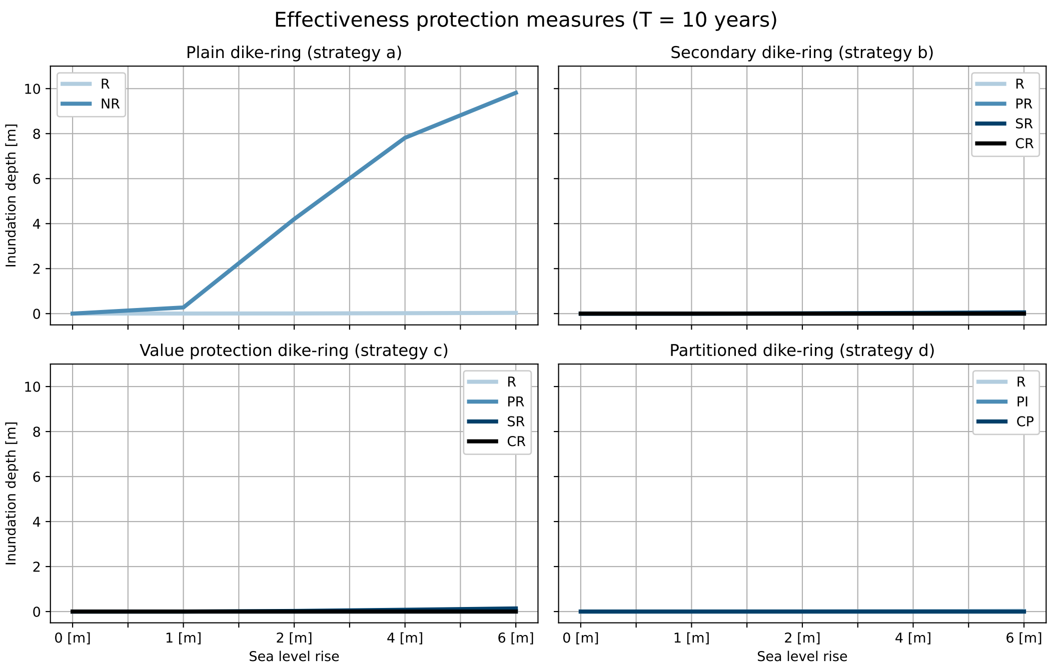


Figure 5.1: Comparison inundation depth spatial adaptation strategies for frequent storms (T = 10 years)

However, for extreme storms (T = 10,000 years), the added value of a secondary, value protection, or partitioned dike-ring is significant, compared to a plain dike-ring strategy with dike reinforcement (reference strategy, R).

The implementation of a secondary dike-ring strategy with solely primary dike reinforcement results in a reduction of the inundation depth within the city in nearly all sea-level rise scenarios, particularly for a sea-level rise up to 2 meters (see figure 5.2). However, starting from a 2-meter sea-level rise, by the end of this century, a secondary dike-ring with solely secondary dike reinforcement no longer provides added value compared to the plain dike-ring (with dike reinforcement), and the predicted inundation depth becomes larger (see figure 5.2). On the other hand, complete dike reinforcement of the secondary dike-ring strategy reduces the inundation depth to approximately zero meters in all sea-level rise scenarios. For a value protection dike-ring, the results of the multiple configurations are similar to that of the secondary dike-ring, but with slightly larger variations compared to the reference strategy (R). Both configurations of a partitioned dike-ring result in an inundation depth within the city of approximately zero meters (see figure 5.2).

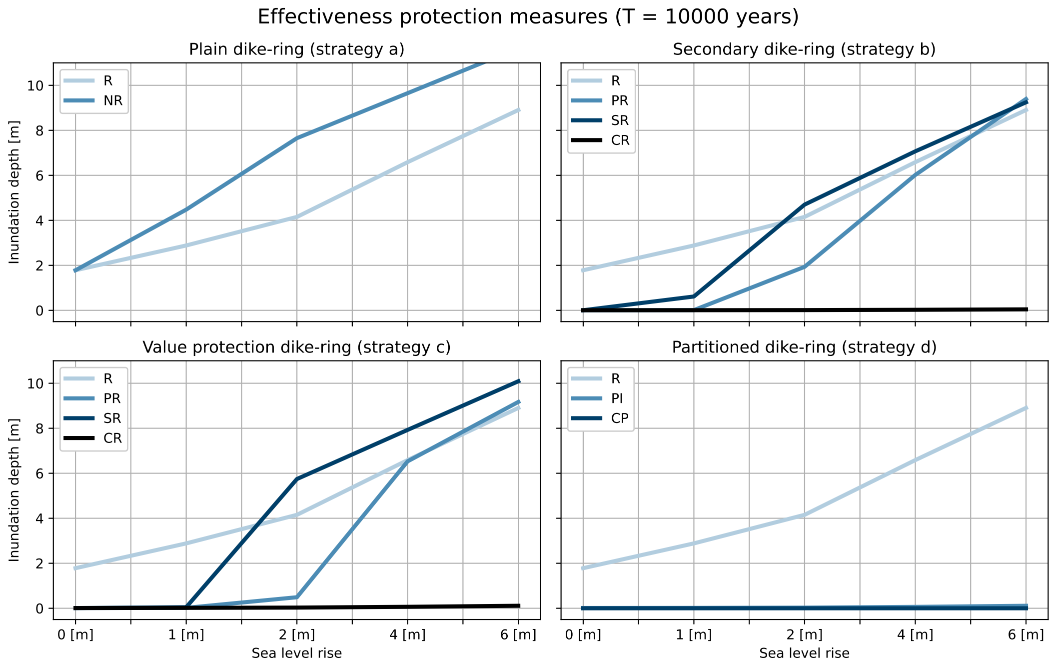


Figure 5.2: Comparison city inundation depth of spatial adaptation strategies for extreme storms (T = 10,000 years)

5.2.2. Inundation rate (evacuation time)

For the inundation rate, the polder inundation development is evaluated with particular emphasis on the time it takes until the inundation depth in the city exceeds 1 meter. If a particular spatial adaptation strategy has a positive impact on the inundation rate within the polder, this can result in more evacuation time, allowing people to evacuate in advance before the area is completely flooded. This, in turn, can positively influence the individual flood risk.

The average inundation rate [m/h] within the polder caused by frequent storms occurring with a 10-year return period can be determined for the various spatial adaptation strategies and configurations. Generally, the inundation rate remains close to 0 m/h regardless of the chosen strategy or the magnitude of sea level rise (see table 5.3). Therefore, the time until 1 meter inundation depth is reached is generally large or even toward infinity (see table 5.4). However, an exception is observed in the case of the plain dike-ring strategy without dike reinforcement. For this configuration, the average inundation rate increases significantly when the sea level rises by 2 meters or more (see table 5.3). As a consequence, 1 meter inundation depth in the city is reached after less than an hour (see table 5.4).

Table 5.3: Average inundation rate [m/h] for frequent storms (T = 10 years)

	a		b			c			d	
	R	NR	PR	SR	CR	PR	SR	CR	PI	CP
0 [m+NAP]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 [m+NAP]	<0.01	<0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2 [m+NAP]	<0.01	0.31	0.00	<0.01	0.00	0.00	<0.01	0.00	0.00	0.00
4 [m+NAP]	<0.01	>5	0.00	<0.01	0.00	0.00	<0.01	0.00	0.00	0.00
6 [m+NAP]	<0.01	>5	0.00	<0.01	0.00	0.00	<0.01	0.00	0.00	0.00

Table 5.4: Evacuation time (until inundation depth exceeds 1 meter) for frequent storms (T = 10 years)

	a		b			c			d	
	R	NR	PR	SR	CR	PR	SR	CR	PI	CP
0 [m+NAP]	>>72	>>72	>>72	>72	>>72	>>72	>72	>>72	>>72	>>72
1 [m+NAP]	>>72	>72	>>72	>72	>>72	>>72	>72	>>72	>>72	>>72
2 [m+NAP]	>>72	<1	>>72	>72	>>72	>>72	>72	>>72	>>72	>>72
4 [m+NAP]	>>72	<1	>>72	>72	>>72	>>72	>72	>>72	>>72	>>72
6 [m+NAP]	>>72	<1	>>72	>72	>>72	>>72	>72	>>72	>>72	>>72

The average inundation rate increases for storms with higher return periods, such as extreme storms with a 10,000-year return period. Compared to the plain dike-ring strategy with dike reinforcement, the addition of a secondary, value protection or partitioned dike-ring can reduce the inundation rate to nearly 0 m/h for a sea level rise up to 1 meter for all configurations, and to some extent for rises up to 2 meters. By implementing complete dike reinforcement of the secondary and value protection dike-ring strategies, the inundation rate can be effectively mitigated to nearly 0 m/h, even when facing a significant sea level rise of 6 meters. This applies to the partitioned dike-ring configurations as well (see table 5.5). For extreme storms, the time until the inundation depth in the city exceeds 1 meter is only 3 hours for a plain dike-ring strategy in a situation with no sea level rise. Table 5.6 shows that to this extent, the secondary and value protection dike-ring strategies as well as the partitioned dike-ring strategy are effective mitigation measures, since the evacuation time for these strategies is generally higher compared to the reference scenario (R).

Table 5.5: Average inundation rate [m/h] for extreme storms (T = 10,000 years)

	a		b			c			d	
	R	NR	PR	SR	CR	PR	SR	CR	PI	CP
0 [m+NAP]	0.12	0.12	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00
1 [m+NAP]	0.20	1.49	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.00
2 [m+NAP]	0.30	>5	0.03	0.35	<0.01	<0.01	2.15	<0.01	<0.01	0.00
4 [m+NAP]	0.48	>5	0.41	0.54	<0.01	0.45	3.17	<0.01	<0.01	0.00
6 [m+NAP]	0.67	>5	0.77	0.73	<0.01	0.71	4.32	<0.01	<0.01	0.00

Table 5.6: Evacuation time (until inundation depth exceeds 1 meter) for extreme storms (T = 10,000 years)

	a		b			c			d	
	R	NR	PR	SR	CR	PR	SR	CR	PI	CP
0 [m+NAP]	3	3	>72	>72	>72	>72	>72	>72	>72	>>72
1 [m+NAP]	2	<1	>72	>72	>72	>72	>72	>72	>72	>>72
2 [m+NAP]	1.5	<1	38	1	>72	>72	<1	>72	>72	>>72
4 [m+NAP]	1	<1	13	<1	>72	13	<1	>72	>72	>>72
6 [m+NAP]	<1	<1	12	<1	>72	13	<1	>72	>72	>>72

5.3. Overall assessment

This part of the study examines the effects of multiple spatial adaptation strategies on (enhanced) protected land and embankment lengths, as well as their impact on reducing inundation depth and inundation rate. The findings reveal that the different strategies result in varying levels of land protection and embankment lengths. Additionally, implementing additional dikes can significantly reduce inundation depth and inundation rate, providing protection against extreme sea level rise. This highlights the importance of effective flood risk management measures.

In order to answer the sub-question ”What are effective spatial adaptation measures in idealized coastal polders, considering the evaluation of spatial impact and mitigating flood risk?”, a multi-criteria assessment is presented in table 5.7. In this assessment, the spatial adaptation strategies which include the plain dike-ring strategy, secondary dike-ring strategy, value protection dike-ring strategy and partitioned dike-ring strategy are defined as ’a’, ’b’, ’c’ and ’d’ respectively. The assessment involves a qualitative evaluation of the specified criteria, categorized into five rating classes ranging from low to high: ’- -’, ’-’, ’0’, ’+’ and ’+ +’. The plain dike-ring strategy with dike reinforcement (R) is rated as neutral (0) across all criteria, since this strategy is considered the reference strategy. The other strategies are qualitatively assessed relative to this reference strategy. Both the secondary dike-ring strategy and value protection dike-ring strategy with either primary dike reinforcement (PR) or complete dike reinforcement (CR) achieve a final score of ’+’, relative to the plain dike-ring. Likewise, both configurations of the partitioned dike-ring have a ’+’ rating. However, the configurations with secondary dike reinforcement (SR) within both the secondary dike-ring strategy and the value protection dike-ring strategy perform less favorable when compared to the reference strategy.

Table 5.7: Multi-criteria assessment of spatial adaptation strategies in an idealized coastal polder

		a		b			c			d	
Main criteria	***Sub criteria***	**R**	**NR**	**PR**	**SR**	**CR**	**PR**	**SR**	**CR**	**PI**	**CP**
Spatial impact	**Protected land (enhanced) [km^2]**	0	- -	+	0	+ +	+	0	+ +	+ +	+ +
	Embankment length [m]	0	0	-	-	- -	-	-	- -	- -	- -
Flood risk	**Inundation depth [m]**	0	- -	+	-	+ +	+	-	+ +	+ +	+ +
	Inundation rate [m/h]	0	- -	+	-	+ +	+	-	+ +	+ +	+ +
Total		**0**	**- -**	**+**	**-**	**+**	**+**	**-**	**+**	**+**	**+**

In general, the spatial adaptation strategies ’b’, ’c’ and ’d’ with complete dike reinforcement are the most favorable options, especially in providing enhanced protection to the city and reducing inundation depth and inundation rate within the city across the multiple sea level rise scenarios. Of these three strategies, the value protection dike-ring strategy stands out as the preferred strategy, since the additional required embankment length (and volume) is lower compared to the secondary dike-ring and partitioned dike-ring strategies. In the context of applying the mentioned strategies to a real Dutch coastal polder, such as Walcheren, the strategies with complete dike reinforcement are suggested to analyse in more detail. The configuration involving solely secondary dike reinforcement (SR) within the value protection dike-ring strategy, which represents Plan B, may not appear the most promising choice based on the obtained results. However, this specific configuration will be considered for Walcheren in order to assess its effects on the Dutch coastal polder. In addition, a similar configuration, but with a stricter norm, will also be taken into consideration. This aspect aims to explore how a stricter norm can influence the overall outcome and performance of the strategy.

Part III

Walcheren

6

Design strategies for Walcheren

This chapter focuses on the following sub-question: ”What are potential design strategies for the Dutch coastal polder (Walcheren), taking into account the main principles of Plan B’s adapted spatial vision as a foundation?”

6.1. Introduction

The visual representation of the four design strategies (plain dike-ring, secondary dike-ring, value protection dike-ring and compartmentalization) implemented on Walcheren can be observed in figure 6.1.

(a) Plain dike-ring

(b) Secondary dike-ring

(c) Value protection dike-ring

(d) Compartmentalization

Figure 6.1: Potential design strategies for the future spatial adaptation of Walcheren

The main principles of Plan B's adapted spatial vision of the Netherlands revolve around the preservation of Western cities. Therefore, the strategies are designed such, to offer enhanced protection to the cities Middelburg and Vlissingen. For the multiple spatial adaptation strategies, the results of the idealized polder analysis pointed out that complete dike reinforcement is highly effective in mitigating flood risk and therefore this case study mostly focuses on the detailed elaboration of these specific configurations.

6.2. Plain dike-ring

The reference scenario and current strategy of Walcheren is a plain dike-ring (see figure 6.1a). This plain dike-ring is a primary water defense and consists of 35 independent individual dike sections. For sake of simplicity, it is assumed that these 35 dike sections are identical, meaning that they are equally long and have the same failure probability. It should be noted that this is not the case in reality. It is assumed that a single or multiple dike breach(es) result(s) in the water spreading out evenly over the polder. The polder characteristics of the reference strategy are according to 'Plain dike-ring (P1)' in table 6.1. Additionally, another configuration is considered, with an increased safety standard: 'Plain dike-ring (P2)'.

Table 6.1: Characteristics Walcheren - Plain dike-ring

Description	Plain dike-ring (P1)	Plain dike-ring (P2)
MSL	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent
Breach width	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level
Length dike-ring	47.5 [km]	47.5 [km]
Dike sections	35 [-]	35 [-]
Average polder area	202 [km^2]	202 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	1/10,000

In the context of various sea level rise scenarios, the characteristics described in table 6.1 above are valid. The only variable is the mean sea level (MSL), which assumes the magnitude of sea level rise as its value. Irrespective of the sea level rise considered, the annual failure probability for the primary dike-ring remains constant at 1/1,000 or 1/10,000 for strategy P1 or P2 respectively. This implies that measures should be taken to adapt the primary dike-ring to the rising sea levels, in order to ensure compliance with the established norm. The value of 1/1,000 per year is the lower limit of the normative path (Dutch: normtraject), which is section 29-1. It is assumed that this failure probability is fully derived from the failure mechanism 'height', which is the normative failure mechanism considered in this study. Based on these characteristics, it can be observed that the principles for the (reference) plain dike-ring (P1) of Walcheren align with the same strategy applied to the idealized polder. Consequently, the input for the model is also nearly identical. Therefore, similar outcomes can be expected.

6.3. Secondary dike-ring

In this strategy, the secondary dike-ring is located at a certain distance behind the primary dike-ring such that the area between the primary and secondary dike-ring serves as a buffer area when a dike breach occurs in the primary dike-ring. The shape of this secondary dike-ring is selected without specific constraints, but it is designed in a way to ensure that about half of the polder area is behind the secondary dike-ring. Middelburg and Vlissingen receive enhanced protection, since both cities are located in the area behind the secondary dike-ring (see figure 6.1b), which is referred to as the inside polder. This inside polder has an area of 91 km^2. Given that the total area of the idealized polder is 202 km^2, the 'outside' polder area is 111 km^2. In this strategy, the primary dike-ring has the characteristics of the plain dike-ring. Given a total length of the secondary dike-ring of approximately 39.2 km and the average length of the dike sections of the primary dike-ring, the secondary dike-ring has approximately 29 dike sections. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 6.2.

One interesting feature of this strategy is that the secondary dike-ring is very close to the primary dike-ring around Vlissingen. The reason behind this is to offer better protection to the cities, with a particular focus on Middelburg and Vlissingen. Given this setup, it is assumed that a dike breach in the primary dike-ring near Vlissingen will not directly result in the flooding of Vlissingen.

For any sea level rise scenario, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probability of the secondary dike-ring is smaller. It is assumed that the primary and secondary dike-rings have the same characteristics and the same height. The only difference is the perimeter or length, and therefore the number of dike sections is smaller for the secondary dike-ring. The dimensions of both the secondary dike-ring and the inside polder area of Walcheren differ from those of the idealized polder, leading to a variance in the model's input.

Table 6.2: Characteristics Walcheren - Secondary dike-ring

Description	**Primary dike-ring**	**Secondary dike-ring**
MSL	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent
Breach width	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level
Length dike-ring	47.5 [km]	39.2 [km]
Dike sections	35 [-]	29 [-]
Average polder area	111 [km^2]	91 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	< 1/1,000

6.4. Value protection dike-ring

The value protection dike-rings are positioned close to the cities Middelburg and Vlissingen (see figure 6.1c). The enhanced protected inside polders (Middelburg and Vlissingen) have an area of 18 and 15 km^2 respectively. The shapes of the dike-rings are chosen arbitrarily, but with the primary goal of ensuring separate protection for the cities. Given that the total area of the idealized polder is 202 km^2, the outside polder area then is 169 km^2.

6.4.1. Complete dike reinforcement

In this strategy, the primary dike-ring has the characteristics of the plain dike-ring. Given that the total length of the value protection dike-ring of Middelburg is approximately 16.5 km, this value protection dike-ring has approximately 12 dike sections, based on previous explained starting points. For the value protection dike-ring of Vlissingen, this is a length of 17 km consisting of 13 dike sections. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 6.3.

Table 6.3: Characteristics Walcheren - Value protection dike-ring

Description	**Primary dike-ring**	**Middelburg**	**Vlissingen**
MSL	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent	dependent
Breach width	100 [m]	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level	max. water level
Length dike-ring	47.5 [km]	16.5 [km]	17 [km]
Dike sections	35 [-]	12 [-]	13 [-]
Average polder area	169 [km^2]	18 [km^2]	15 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	<1/1,000	<1/1,000

As for the secondary dike-ring strategy, an interesting feature of the value protection strategy is that one of the dike-rings is very close to the primary dike-ring around Vlissingen. The reason behind this is to offer better protection to Vlissingen. Given this setup, it is assumed that a dike breach in the primary dike-ring near Vlissingen will not directly result in the flooding of Vlissingen.

In the case of complete dike reinforcement, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probability of the value protection dike-rings is smaller, for all scenarios of sea level rise. It is assumed that the primary and value protection dike-rings have the same characteristics and the same height. The only difference is the perimeter, and therefore the number of dike sections is smaller for the value protection dike-rings.

6.4.2. Plan B

The value protection strategy can, in a way, be seen as a design example of Plan B. However, it's important to note that this value protection strategy for Walcheren assumes a complete dike reinforcement of both the primary and secondary dike-rings, in contrast to Plan B, which entails no primary dike reinforcement and relies solely on local protection measures. Since the goal is to investigate how Plan B compares to the current strategy and alternative spatial adaptation strategies, two variations of Plan B are considered.

In the first variant (B1), the value protection dike-rings have a failure probability of less than 1/1,000 per year, while in the second variant (B2), this failure probability is less than 1/10,000 per year. These failure probabilities arise from the water levels at sea and the design of dikes is determined by the corresponding hydraulic load levels. It should be noted that these failure probabilities change in response to rising sea levels. Up to 2 meters sea level rise, the primary dike-ring might still afford some protection, resulting in failure probabilities that remain less than 1/1,000 per year or less than 1/10,000 per year, for variant B1 and B2 respectively. However, for sea level rises exceeding 2 meters, it is anticipated that the area of Walcheren around Middelburg and Vlissingen will be submerged, leaving the value protection dike-rings directly exposed to the sea. In such circumstances, the failure probabilities for the two variants become equivalent to 1/1,000 per year and 1/10,000 per year, respectively. The value protection dikes around Middelburg and Vlissingen are reinforced and adapted in order to establish the norm and withstand the impacts of sea level rise.

6.5. Compartmentalization

The final spatial adaptation strategy considered for Walcheren is a partitioned dike-ring, also known as compartmentalization (see figure 6.1d). In this strategy, the polder has a primary dike-ring and several partition elements. The partition elements split Walcheren into five compartments, as can be seen in figure 6.2.

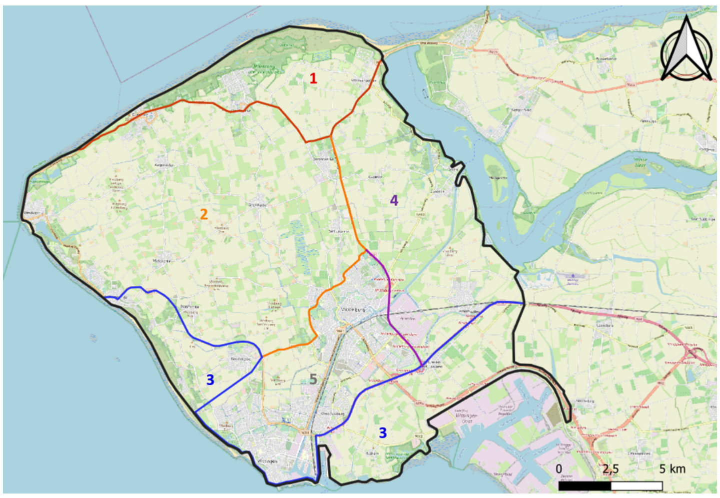


Figure 6.2: Compartmentalization of Walcheren

In this figure, the colors indicate which partition elements are part of which compartment. The largest part of the partition elements are pre-existing linear features, specifically roads in the current landscape. The reason to use these pre-existing line elements as the partition dividers is because of two key factors. Firstly, it has proven to be a cost-effective approach and secondly, by utilizing these pre-existing routes as partition elements, there is efficient access to all compartments within the region.

6.5.1. Compartment characteristics

In this strategy, the primary dike-ring has the characteristics of the plain dike-ring. Based on the primary dike-ring characteristics, some starting points for the additional partition elements are constructed. The primary dike-ring has a length of 47.5 km and consists of 35 dike sections. Given the lengths of the partition elements and the average length of a dike section, the number of dike sections for the partition elements can be determined. The polder characteristics for the zero situation of 0 meters sea level rise are presented in table 6.4 and 6.5.

Table 6.4: Characteristics Walcheren - Partitioned dike-ring (part 1)

Description	Primary dike-ring	Compartment 1	Compartment 2
MSL	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent	dependent
Breach width	100 [m]	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level	max. water level
Length dike-ring	47.5 [km]	14.6 [km]	11.2 [km]
Dike sections	35 [-]	11 [-]	8 [-]
Average polder area	-	20 [km^2]	81 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Annual failure probability	1/1,000	<1/1,000	<1/1,000

Table 6.5: Characteristics Walcheren - Partitioned dike-ring (part 2)

Description	Compartment 3	Compartment 4	Compartment 5
MSL	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Number of breaches	dependent	dependent	dependent
Breach width	100 [m]	100 [m]	100 [m]
Breach level	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)	0 [m+NAP] (polder level)
Breach moment	max. water level	max. water level	max. water level
Length dike-ring	27.6 [km]	5 [km]	-
Dike sections	20 [-]	4 [-]	-
Average polder area	33 [km^2]	38 [km^2]	30 [km^2]
Average polder elevation	0 [m+NAP]	0 [m+NAP]	0 [m+NAP]
Annual failure probability	<1/1,000	<1/1,000	<1/1,000

Similar to the secondary dike-ring and value protection dike-ring strategies, one of the partition elements is closely aligns with the primary dike-ring around Vlissingen. The reason behind this is to enhance the protection of Vlissingen. Consequently, it is assumed that a dike breach in the primary dike-ring near Vlissingen will not directly result in the flooding of Vlissingen. Instead, the water will be distributed evenly across compartment 3, spanning both its left and right sides.

For all scenarios of sea level rise, the annual failure probability of the primary dike-ring is 1/1,000, whereas the annual failure probabilities of the partition elements are smaller. It is assumed that the primary dike-ring and partition elements have the same characteristics and the same height. The only difference is the length, and therefore the number of dike sections is larger for all partition elements combined.

6.5.2. Dike breach locations

For the preceding strategies (plain dike-ring, secondary dike-ring and value protection dike-ring), the location of the dike breach(es) in the primary dike-ring is irrelevant in this approach, due to the assumption of proportional distribution of water in the area. However, the location of a dike breach does hold significance in the compartmentalization strategy, since compartmentalization limits the evenly distribution of water in this regard. The primary dike-ring follows the characteristics of the plain dike-ring, as previously described. Based on the annual failure probability of 1/1,000, the dike-ring possesses a specific fragility curve. According to this fragility curve, a single dike breach occurs during a storm with a return period of 1,000 years. In the case of a storm with a return period of 3,000 years, there would be three dike breaches, and so on. Based on the assumptions presented in VNK2 (Vergouwe, 2014a), it is expected that a single dike breach will occur in compartment 3. In the event of a triple dike breach, compartments 2 and 3 are affected. For extreme storms with return periods of 10,000 years and beyond, it is anticipated that sea water entering the polder through the corresponding ten dike breaches will distribute evenly across Walcheren.

7

Effectiveness of design strategies

This chapter plays an important role in addressing the sub-question: ”What is the effectiveness of various design strategies in reducing the expected future flood risk in the coastal polder, given the projected sea level rise, compared to the current strategy of the Dutch coastal polder?” The answer to this question can be achieved by evaluating the effectiveness of the various proposed design strategies for Walcheren in terms of mitigating flood risk, encompassing factors such as damage, casualties and number of individuals affected by a flood.

7.1. Plain dike-ring

For the plain dike-ring strategy, two configurations are considered: P1 and P2. For configuration P1, it is assumed that the dike is reinforced along with the sea level rise to ensure that the annual failure probability remains at a constant value of 1/1,000. Configuration P2 assumes an annual failure probability of the primary dike-ring that remains constant at a value of 1/10,000. In this paragraph, the polder inundation is displayed and the effect of the inundation is represented in terms of damage and casualties.

7.1.1. Polder inundation (frequency)

The model input of the plain dike-ring strategy (P1) of Walcheren is nearly identical to that of the same strategy applied to the idealized polder. Therefore, the polder inundation shows similar results. The inundation frequency lines for configurations P1 and P2 of the plain dike-ring strategy of Walcheren are shown in the left and right graph of figure 7.1 respectively. In these graphs, each data point represents the maximum (average) polder inundation corresponding to a specific combination of sea level rise and storm surge water level.

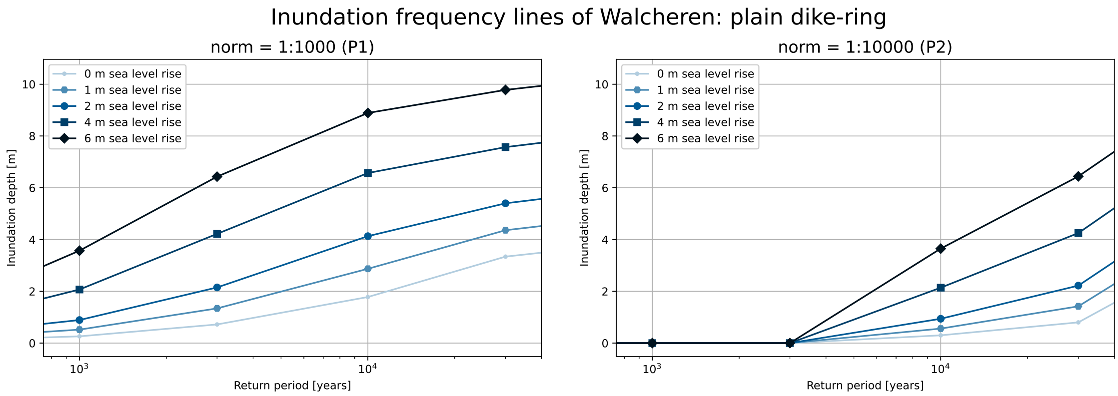


Figure 7.1: Inundation frequency lines for Walcheren with a plain dike-ring

It should be noted that the inundation-frequency lines do not include the full range of return periods. For configuration P1, the expected number of breaches calculated based on the fragility curve is below one (n < 1) for storms occurring more frequently than once every 1,000 years. Consequently, the inundation-frequency lines and flood maps are exclusively generated for scenarios where the expected number of breaches, when rounded to the nearest integer, equals at least one. Therefore, the lower limit is T = 1,000 years. Storms with a return period of T = 100,000 years are excluded from further consideration for Walcheren due to their extreme rarity. The contribution of these storms to the flood risk (expected annual damage) is nearly negligible, and therefore these storms are considered irrelevant. Instead, the upper limit considered for the flood maps is set at T = 30,000 years. In this extreme scenario, according to the model, 30 out of 35 dike sections experience breaches, resulting in an extreme inundation pattern.

Overall, the impact of a flooding for a given return period increases significantly for rising sea levels. The diverging effect for increasing return periods can be explained by the fact that the volume of water that enters the polder increases due to a higher number of dike breaches, which was derived from the fragility curve. By increasing the safety standard for the primary dike-ring from a failure probability of 1/1,000 per year to 1/10,000 per year, it is anticipated that the dike-ring will be resilient against storms with return periods below 10,000 years. This leads to a significant reduction of the expected inundation (frequency) of the polder, as compared to a dike-ring with a failure probability of 1/1,000 per year (see figure 7.1).

The flood maps of Walcheren for a plain dike-ring strategy (P1) for all sea level rise scenarios (0, 1, 2, 4 and 6 meters) are presented in appendix D in figures D.9, D.10, D.11, D.12 and D.13 respectively. These flood maps provide a visual representation of how the inundation is distributed across the area. The maximum polder inundation values presented in figure 7.1 represent the average inundation water levels [m+NAP] of the polder. For relatively low average inundation water levels, only the low-lying parts are inundated, leaving other regions unaffected (see figure D.9, T = 1,000 years). However, for very high (average) inundation water levels, nearly the entire polder area is flooded, often also resulting in large water depths (see figure D.9, T = 30,000 years). For configuration P2 of the plain dike-ring strategy, the flood maps for all sea level rise scenarios (0, 1, 2, 4 and 6 meters) are presented in appendix D in figures D.14, D.15, D.16, D.17 and D.18 respectively.

7.1.2. Damage and casualties

The damage in Walcheren, for a plain dike-ring strategy for both configurations P1 and P2, as a result of all flooding scenarios are presented in table 7.1. As the inundation-frequency lines and the flood maps clearly show, the inundation depth (for a specific flooding event) increases significantly for rising sea levels. This results in increasing damage levels as well.

Table 7.1: Damage (D) in euros (10^9) in Walcheren for a plain dike-ring strategy

	Return period [years]							
	T = 1,000		**T = 3,000**		**T = 10,000**		**T = 30,000**	
Sea level rise [m]	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**
0	2.5	0	6.4	0	10	3.1	16	6.9
1	5.2	0	9	0	14	5.5	21	9.2
2	7.5	0	11	0	20	7.7	23	11
4	11	0	20	0	23	11	24	20
6	17	0	23	0	24	17	24	23

The analysis of configuration P1 of the plain dike-ring strategy (see table 7.1) reveals that the damage resulting from a storm with a low probability of occurrence of 1/1,000 per year, under a scenario with 6 meters sea level rise, surpasses the damage caused by a storm with an extremely low annual occurrence probability of 1/30,000 for the current situation (0 meters sea level rise). Furthermore, in the case of a storm with a low annual probability of occurrence of 1/1,000, the damage increases nearly sevenfold when considering a scenario with 6 meters sea level rise, compared to the current situation with 0 meters sea level rise. However, a plain dike-ring strategy with a safety standard of 1/10,000 can significantly reduce the damage in Walcheren, especially for storms with return periods up to T = 3,000 years. The damage levels for the multiple flood scenarios as desribed in table 7.1 are also visually represented in figure 7.2. In this figure, a comparison of the damage observed for configuration P2 relative to configuration P1 in Walcheren is presented for rural areas as well as in Middelburg and Vlissingen combined.

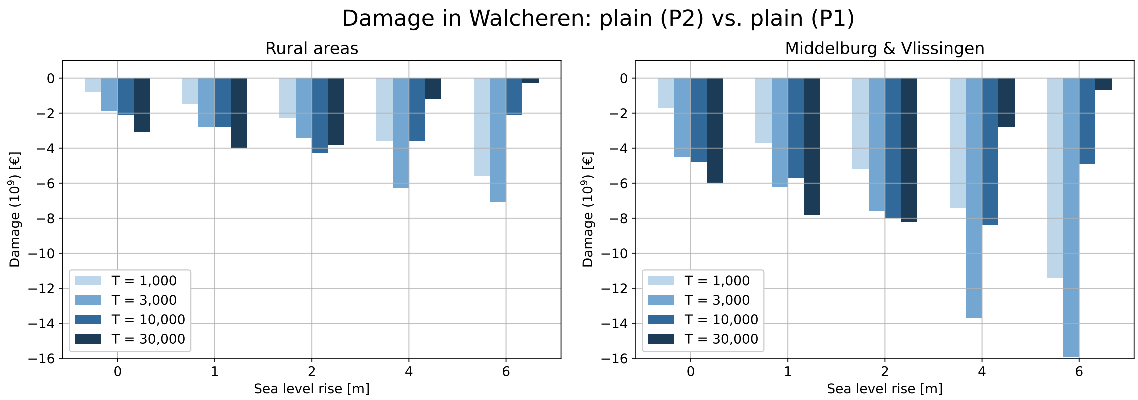


Figure 7.2: Damage comparison in Walcheren: plain dike-ring (P2) vs. plain dike-ring (P1)

Next to an increase in damage for rising sea levels, the number of casualties also increase in Walcheren for a plain dike-ring strategy (see table 7.2). Considering configuration P1, for a storm with a return period of T = 1,000 years, the number of casualties increases by more than 18-fold for a 6-meter sea level rise scenario compared to the current situation (0 meters sea level rise). In addition, considering a storm with a return period of T = 30,000 years, the number of casualties is over 22 times larger in a 6-meter sea level rise scenario compared to the situation with 0 meters sea level rise (see table 7.2). The extreme number of casualties calculated for extreme storms can be declared by the fact that the inundation rate for these scenarios is significantly higher compared to the other storms. Increasing the safety standard (configuration P2) can lead to a significant reduction of the expected number of casualties. Even in case of extreme storms with a return period of T = 30,000 years, the expected number of casualties for a 6-meter sea level rise scenario is lower than the casualties observed in the current situation with no sea level rise for P1 (see table 7.2).

Table 7.2: Number of casualties (C) [-] in Walcheren for a plain dike-ring strategy (no evacuation)

	Return period [years]							
	T = 1,000		T = 3,000		T = 10,000		T = 30,000	
Sea level rise [m]	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**
0	66	0	224	0	610	79	4,024	253
1	153	0	448	0	1,016	167	14,855	477
2	285	0	737	0	1,484	303	32,339	762
4	709	0	1435	0	2,322	734	61,317	1,444
6	1,222	0	2116	0	7,896	1,248	90,446	2,119

7.2. Secondary dike-ring

For the secondary dike-ring strategy, it is assumed that both the primary and secondary dikes are reinforced along with the sea level rise to ensure that the annual failure probabilities remain at a constant value of 1/1,000 and <1/1,000 respectively. In this paragraph, the polder inundation is described and the effect of the inundation is represented in terms of damage and casualties.

7.2.1. Polder inundation (frequency)

The implementation of a secondary dike-ring can lead to varying inundation patterns across different locations within Walcheren. For example, a location outside the secondary dike-ring area such as

Westkapelle is expected to experience more significant inundation compared to Middelburg or Vlissingen. The inundation in Westkapelle is slightly larger for this secondary dike-ring strategy compared to the plain dike-ring strategy (P1). This can be explained by the fact that the volume of water entering the polder distributes over a smaller area, resulting in a larger water depth. On the contrary, Middelburg and Vlissingen experience considerable less inundation compared to the plain dike-ring strategy. For all the considered return periods and sea level rise scenarios, the inundation depth in Middelburg and Vlissingen is lower for the secondary dike-ring strategy than for the plain dike-ring strategy. The polder inundation frequency graphs for a secondary dike-ring strategy can be observed in figure D.4. The inundation of Westkapelle is shown in the left graph, whereas the inundation of Middelburg and Vlissingen is presented in the right graph.

The flood maps of Walcheren for a secondary dike-ring strategy for all sea level rise scenarios (0, 1, 2, 4 and 6 meters) are presented in appendix D in figures D.19, D.20, D.21, D.22 and D.23 respectively.

7.2.2. Damage and casualties

The graphical representation of the (expected) damage in Walcheren observed for a secondary dike-ring strategy compared to a plain dike-ring strategy (P1), encompassing both rural areas and Middelburg and Vlissingen, is presented in figure 7.3.

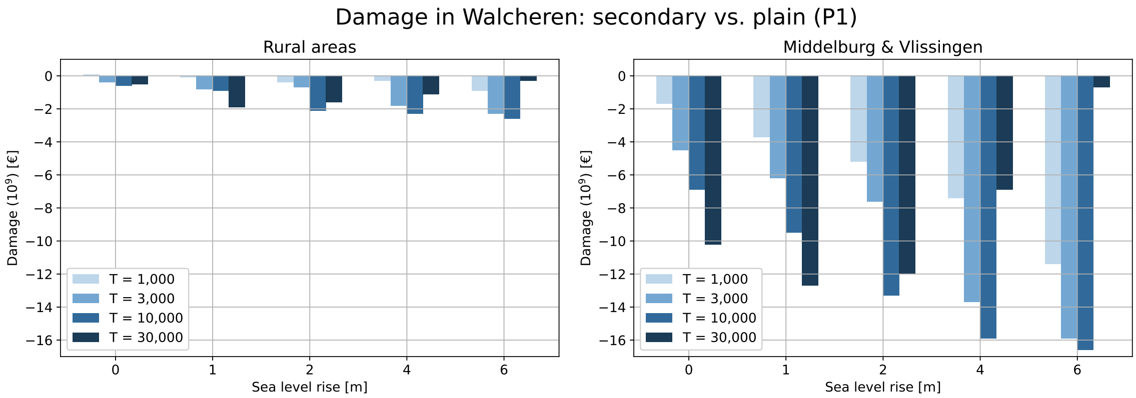


Figure 7.3: Damage comparison in Walcheren: secondary dike-ring vs. plain dike-ring (P1)

The implementation of a secondary dike-ring results in a reduction of damage levels within the rural areas as well as within the cities, primarily noticeable in cases of extreme storms with return periods of T = 30,000 years for sea level rise scenarios up to 2 meters. This reduction in damage is also significant for storms with return periods of T = 10,000 and lower in scenarios involving sea level rise of 4 or 6 meters (see figure 7.3). Despite the fact that the inundation depths in the outer polder (rural) area are higher in comparison to the plain dike-ring strategy, the observed damage is lower. This can be explained by the delineation of the rural area. This area is defined as the entirety of Walcheren except for Middelburg or Vlissingen. However, for the secondary dike-ring strategy, a large part of the rural area is also located behind the secondary dike-ring, thus mitigating damage levels. In Middelburg and Vlissingen, the damage levels are even reduced to 0 [€] across all sea level rise scenarios, for storms with return periods of T = 10,000 years and lower.

The total number of casualties in Walcheren for a secondary dike-ring strategy, as a result of all flooding scenarios are presented in table 7.3. Overall, the number of casualties in Walcheren is reduced with the implementation of a secondary dike-ring, compared to a plain dike-ring strategy (P1). The affected area is greatly reduced by this measure and therefore the number of casualties is also reduced. In the context of extreme storms (T = 30,000 years), there is a notable rise in the number of casualties, primarily due to the impact these storms have on the cities Middelburg and Vlissingen. The rate at which inundation occurs is a crucial factor contributing to this effect.

Table 7.3: Number of casualties (C) [-] in Walcheren for a secondary dike-ring strategy (no evacuation)

	Return period [years]			
Sea level rise [m]	**T = 1,000**	**T = 3,000**	**T = 10,000**	**T = 30,000**
0	22	55	143	5,295
1	48	102	213	10,753
2	86	157	282	15,410
4	197	272	715	20,487
6	320	384	1,843	21,429

7.3. Value protection dike-ring

For the value protection dike-ring strategy, three configurations are considered. The first scenario is complete reinforcement, which implies that both the primary and value protection dikes are reinforced along with the sea level rise to ensure that the annual failure probabilities remain at a constant value of 1/1,000 and <1/1,000 respectively. The other configurations are two variants of Plan B: B1 (1/1,000) and B2 (1/10,000). In this paragraph, the polder inundation (frequency) is described for all configurations and the effect of the inundation is represented in terms of damage and casualties.

7.3.1. Polder inundation (frequency)

The introduction of value protection dike-ring system results in varying inundation patterns across different locations within Walcheren. For instance, locations lying outside the value protection dike-ring areas, like Westkapelle, are expected to experience more significant inundation compared to Middelburg or Vlissingen.

In case of complete dike reinforcement of the value protection dike-rings, the inundation levels in rural areas, represented by places like Westkapelle, closely resemble those observed in the plain dike-ring strategy. In contrast, Middelburg and Vlissingen experience considerable less inundation compared to the plain dike-ring strategy. Across all the considered return periods and scenarios of sea level rise, the inundation depth in Middelburg and Vlissingen is consistently lower for the value protection dike-ring strategy in comparison to the plain dike-ring strategy. This can be observed in figure D.5.

However, when considering the Plan B scenarios, the inundation levels in the rural areas increase significantly compared to the plain dike-ring strategy. This escalation can be attributed to the absence of primary dike-ring reinforcement, resulting in more severe inundation, particularly for increasing sea levels (see figures D.6 and D.7). In the context of providing (enhanced) protection for Middelburg and Vlissingen, Plan B (B1) demonstrates a marginal advantage over a plain dike-ring strategy when dealing with sea levels up to 2 meters, particularly for storms with return periods of T = 3,000 or lower. However, for sea levels exceeding 2 meters, the inundation observed in Middelburg and Vlissingen is higher than for the plain dike-ring strategy (P1). Considering the alternative B2 scenario of Plan B, the inundation in Middelburg and Vlissingen can be reduced significantly across all sea level rise scenarios for storms with return periods of T = 3,000 years and lower, when compared to the plain dike-ring strategy. However, when confronted with storms that have return periods exceeding T = 10,000 years, the extent of inundation becomes more significant at sea levels of 2 meters and beyond.

The flood maps, which illustrate the maximum inundation scenarios for Walcheren under the conditions of value protection dike-rings for all sea level rise scenarios (0, 1, 2, 4 and 6 meters) are presented in appendix D in figures D.24, D.25, D.26, D.27 and D.28 respectively, in case of complete dike reinforcement. For Plan B (B1), these flood maps can be observed in figures D.29, D.30, D.31, D.32 and D.33 respectively. The corresponding flood maps for the Plan B (B2) scenario are shown in figures D.34, D.35, D.36, D.37 and D.38 respectively.

7.3.2. Damage and casualties

The damage levels in the rural areas and cities of Walcheren under the conditions of a value protection dike-ring strategy are illustrated in figures 7.4 and 7.5 respectively. It can be observed that the damage levels in the rural areas are higher when value protection dike-rings are employed, as opposed to the plain dike-ring strategy. This is valid across all three configurations: complete dike reinforcement, Plan

B (B1) and Plan B (B2). The damage levels in the rural areas observed for the value protection dike-ring strategy exceeding that of the plain dike-ring strategy is in line with the observed inundation in the rural areas.

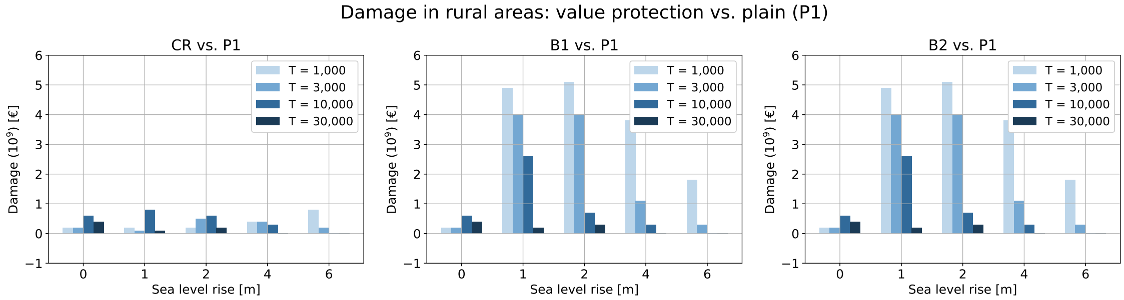


Figure 7.4: Damage comparison in rural areas of Walcheren: value protection dike-ring (CR, B1, B2) vs. plain dike-ring (P1)

However, in the cities of Walcheren, the presence of a value protection dike-ring appears to be highly effective as the damage levels are strongly reduced compared to the plain dike-ring strategy. This is valid, mainly for the configurations complete reinforcement (CR) and Plan B (B2). For the configuration Plan B (B1), the damage levels in Middelburg and Vlissingen are strongly reduced for scenarios of sea level rise up to 2 meters. However, a turning point can be observed at a sea level rise of 2 meters, specifically for extreme storms with a return period of 10,000 years or higher (as illustrated in figure 7.4).

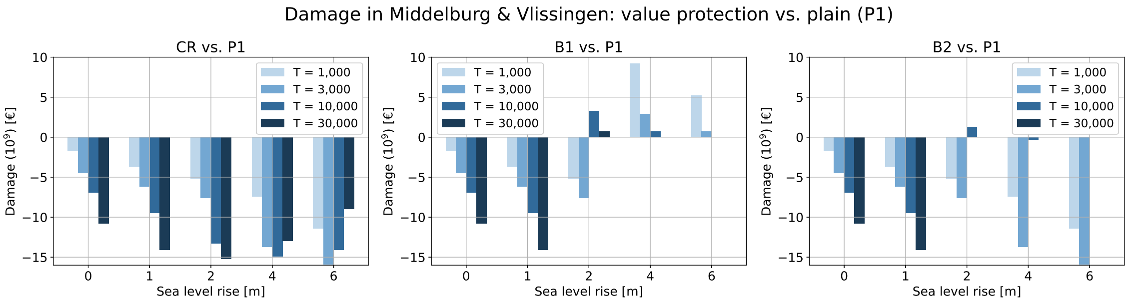


Figure 7.5: Damage comparison in Middelburg and Vlissingen: value protection dike-ring (CR, B1, B2) vs. plain dike-ring (P1)

The total number of casualties in Walcheren for a value protection dike-ring strategy, as a result of all flooding scenarios are presented in table 7.4. Overall, the number of casualties is reduced with the implementation of a value protection dike-ring with complete reinforcement, compared to the plain dike-ring strategy (P1). The affected area is reduced by this measure, consequently leading to a decrease in the number of casualties. In the context of extreme storms, the number of casualties increases significantly, primarily due to the impact these storms have on the cities Middelburg and Vlissingen. The rate at which inundation occurs is a crucial factor contributing to this effect.

Table 7.4: Number of casualties (C) [-] in Walcheren for a value protection dike-ring strategy (no evacuation)

	Return period [years]											
Sea level rise [m]	**T = 1,000**			**T = 3,000**			**T = 10,000**			**T = 30,000**		
	CR	**B1**	**B2**	**CR**	**B1**	**B2**	**CR**	**B1**	**B2**	**CR**	**B1**	**B2**
0	21	0	0	69	0	0	189	0	0	2,258	0	0
1	49	0	0	135	0	0	302	0	0	6,993	0	0
2	93	0	0	219	0	0	425	6,522	663	12,457	11,861	8,784
4	228	2,028	0	408	3,972	0	732	83,242	1,839	22,508	83,347	49,720
6	392	5,606	0	589	66,837	0	2,558	83,388	6,356	31,779	83,389	71,479

When considering the Plan B scenarios, it is assumed that people have moved out of the rural areas.

Therefore, the population of Walcheren considered for these scenarios is the population of Middelburg and Vlissingen combined. This adds up to a total of 83,389 inhabitants, according to the Damage and Casualties Module (SSM), compared to a total of 115,300 in Walcheren. The results of the Plan B (B1) scenario show that for a sea level rise of up to 2 meters, the number of casualties can be reduced to 0. However, for sea level rise scenarios of 4 meters or higher, almost the entire population dies as a consequence of a storm with a return period exceeding 10,000 years (see table 7.4). In the case of the Plan B (B2) scenario, while the impact is less extreme, it remains notably significant. It should be noted though that the number of casualties is determined for a situation without evacuation.

7.4. Compartmentalization

For the partitioned dike-ring strategy (compartmentalization), it is assumed that the primary and partition element dikes are reinforced along with the sea level rise to ensure that the annual failure probabilities remain at a constant value of 1/1,000 and <1/1,000 respectively. In this paragraph, the polder inundation (frequency) is described and the effect of the inundation is represented in terms of damage and casualties.

7.4.1. Polder inundation (frequency)

Compartmentalization of Walcheren results in varying inundation patterns across different locations within Walcheren. As an example, locations lying outside the enhanced protected areas, like Westkapelle, are expected to experience more significant inundation compared to Middelburg or Vlissingen. The inundation levels in rural areas, represented by a village such as Westkapelle, are lower than those observed in the plain dike-ring strategy (P1). However, it should be noted that Westkapelle does not represent the entire rural area of Walcheren. Due to the compartmentalization measures, the inundation depth across different compartments varies. Overall, Middelburg and Vlissingen experience considerable less inundation compared to the plain dike-ring strategy, specifically for storms with return periods of T = 10,000 and below. This can be observed in figure D.8.

The flood maps, which illustrate the maximum inundation scenarios for Walcheren under the conditions of a partitioned dike-ring (compartmentalization) for all sea level rise scenarios (0, 1, 2, 4 and 6 meters) are presented in appendix D in figures D.39, D.40, D.41, D.42 and D.43 respectively.

7.4.2. Damage and casualties

The damage levels in the rural areas and cities of Walcheren under the conditions of compartmentalization are illustrated in the left and right graph of figure 7.6 respectively. It can be observed that the damage levels in the rural areas are generally lower when compartmentalization measures are employed, as opposed to the plain dike-ring strategy. In addition, for the cities Middelburg and Vlissingen, the observed damage under compartmentalization measures is also reduced (for storms with return periods up to 10,000 years) and notably, with rising sea levels, the disparity in inundation depth between the compartmentalization strategy and plain dike-ring (P1) increases, proving the effectiveness of the compartmentalization measures.

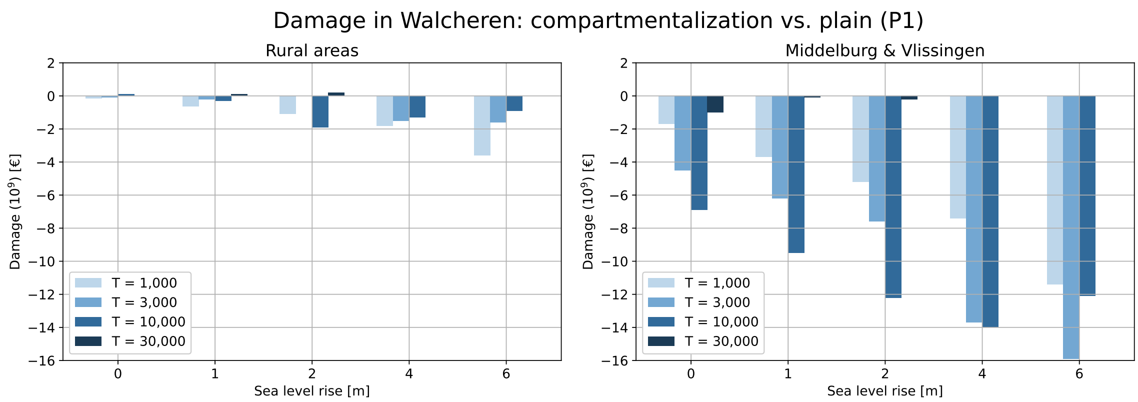


Figure 7.6: Damage comparison in Walcheren: compartmentalization vs. plain dike-ring (P1)

The total number of casualties in Walcheren for a partitioned dike-ring strategy, as a result of all flooding scenarios are presented in table 7.5. Overall, the number of casualties in Walcheren is reduced with the implementation of compartmentalization measures, compared to a plain dike-ring strategy (P1). The affected area is reduced by this measure and therefore the number of casualties is also reduced.

Table 7.5: Number of casualties (C) [-] in Walcheren for a compartmentalization strategy (no evacuation)

	Return period [years]			
Sea level rise [m]	**T = 1,000**	**T = 3,000**	**T = 10,000**	**T = 30,000**
0	21	66	193	4,752
1	40	117	596	7,229
2	60	181	1,204	7,558
4	104	323	2,165	10,111
6	148	458	3,898	10,537

7.5. Expected annual risk

The spatial adaptation strategies can be directly compared to one another in terms of effectiveness by assessing the expected annual risk. When evaluating the expected annual risk, the focus is on three key categories: damage, casualties and the number of people affected.

Consider the current situation: a plain dike-ring strategy (P1) with 0 meters sea level rise. In this context, the model predicts an expected annual damage of 3.00 million euros for the combined areas of Middelburg and Vlissingen (see equation 7.1).

$$EAD_{P1} = \frac{10.8 \cdot 10^9}{30,000} + 6.9 \cdot 10^9 \cdot 6.67 \cdot 10^{-5} + 4.5 \cdot 10^9 \cdot 2.33 \cdot 10^{-4} + 1.7 \cdot 10^9 \cdot 6.67 \cdot 10^{-4} = 3.00 \cdot 10^6 \quad (7.1)$$

Similarly, the expected annual damage is calculated for the rural area of Walcheren. This process is repeated for all spatial adaptation strategies and various sea level rise scenarios. Additionally, the same calculations can be performed for the expected annual number of casualties in Walcheren and the expected annual number of people affected by a flood in Walcheren. For the specific considered strategy at 0 meters sea level rise, the expected annual number of casualties in Walcheren is estimated to be 0.27 [-] (see equation 7.2).

$$EAC_{P1} = \frac{4,024}{30,000} + 610 \cdot 6.67 \cdot 10^{-5} + 224 \cdot 2.33 \cdot 10^{-4} + 66 \cdot 6.67 \cdot 10^{-4} = 0.27 \quad (7.2)$$

Likewise, the expected annual number of people affected by a flood in Walcheren for the current situation with 0 meters sea level rise is estimated at 113 [-] (see equation 7.3).

$$EAP_{P1} = \frac{115,000}{30,000} + 114,200 \cdot 6.67 \cdot 10^{-5} + 113,500 \cdot 2.33 \cdot 10^{-4} + 112,900 \cdot 6.67 \cdot 10^{-4} = 113 \quad (7.3)$$

When considering all strategies and sea level rise scenarios, the assessment of the expected annual risk is illustrated in figure 7.7.

Regarding the mitigation of expected annual damage in Middelburg and Vlissingen, it is evident that any strategy, compared to the plain dike-ring strategy (P1), is highly effective for a sea level rise up to 2 meters. However, for a sea level rise exceeding 4 meters, the effectiveness of the Plan B (B1) strategy diminishes compared to P1, whereas all other strategies consistently demonstrate significant reductions in damage in these cities, when compared to P1.

Focusing on the expected annual damage in the rural area of Walcheren, strategies such as the plain dike-ring (P2), secondary dike-ring and compartmentalization prove to be more effective than the reference strategy (P1). Notably, the plain dike-ring (P2) stands out as the most effective solution. For this strategy, even in a scenario of 6 meters sea level rise, the expected annual damage in the rural area is expected to remain below 1 million euros, which is a big contrast to the approximately 9 million euros projected for the P1 strategy (see figure 7.2).

Furthermore, when it comes to the casualties, all strategies, except for Plan B (B1), are effective in reducing the expected annual number of casualties, in comparison to the plain dike-ring strategy (P1). Once again, strategy P2 proves to be the most effective choice.

Overall, the plain dike-ring (P2) strategy consistently proves to be the most effective strategy in mitigating flood risk, in terms of damage, casualties and the number of people affected.

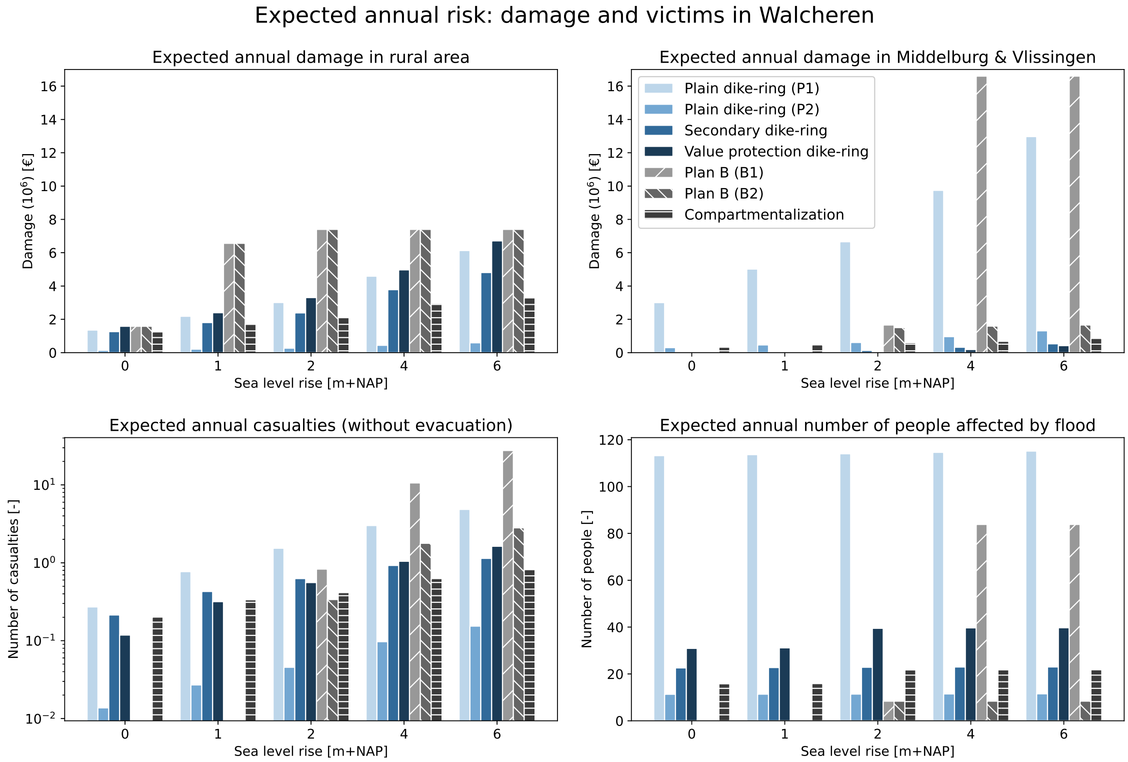


Figure 7.7: Expected annual flood risk in Walcheren (damage, casualties and affected people) (RCP8.5 sea level rise projections up to 2200)

8

Cost-benefit analysis

This chapter addresses the final sub-question of this study: ”What is the most cost-beneficial strategy for mitigating the future coastal flood risk in the Dutch coastal polder?” To answer this research question, a cost-benefit analysis is conducted, considering all spatial adaptation strategies, accounting for investment costs and expected damage.

8.1. Investment costs

For the determination of the investment costs, the dike volume should be calculated, based on the standard dike profile with a slope of 1:3. The initial step in this process is establishing the crest height of the dike, which varies depending on the sea level magnitude and the safety standard. The crest heights (HBN) of dikes for multiple sea level rise scenarios are presented in table 8.1, considering safety standards (or norms) of 1/1,000 as well as 1/10,000.

Table 8.1: Crest heights (HBN) [m+NAP] of dikes for multiple sea level rise scenarios

		Crest height [m+NAP]	
		norm 1:1,000	**norm 1:10,000**
Sea level rise [m]	**0**	5.58	6.47
	1	6.58	7.47
	2	7.58	8.47
	4	9.58	10.47
	6	11.58	12.47

As a next step, the required dike volume is computed for a specific strategy. For simplicity, it is assumed that the primary dike-ring of Walcheren has a standard dike profile with an average height of 5.58 m+NAP. Therefore, it needs to be reinforced to accommodate rising sea levels. An example calculation for determining the required additional dike volume for a plain dike-ring strategy (P1), using a safety standard of 1/1,000 in a scenario with 1 meter sea level rise, is given in equations 8.1 and 8.2.

$$\Delta V_{1,P1} = V_{1,P1} - V_{0,P1} \tag{8.1}$$

$$V_{1,P1} = (2 \cdot \frac{1}{2} \cdot HBN_1 \cdot (3 \cdot HBN_1) + CW \cdot HBN_1) \cdot L_{P1} \tag{8.2}$$

In these equations, $\Delta V_{1,P1}$ represents the additional dike volume required for a sea level rise of 1 meter for a plain dike-ring strategy (P1) relative to the existing dike. HBN_1 is the hydraulic load level (or crest height) for 1 meter sea level rise and L_{P1} is the length of the primary dike-ring. CW is the crest width [m] of the dike and has a constant value of 10 meters. Filling out equation 8.2, the dike volume necessary for 1 meter sea level rise is 9.30 million cubic meters. Similarly, the dike volume for 0 meters sea level rise (that is already existing) is approximately 7.10 million cubic meters. This results in an additional required dike volume of approximately 2.21 million cubic meters. The dike consists of a core material part and a top layer. The top layer is a grass cover with a thickness of 0.30 m. Therefore, the core dike volume is approximately 2.12 million cubic meters and the grass volume is 85.5 thousand cubic meters. This situation is visually represented and schematized in figure 8.1.

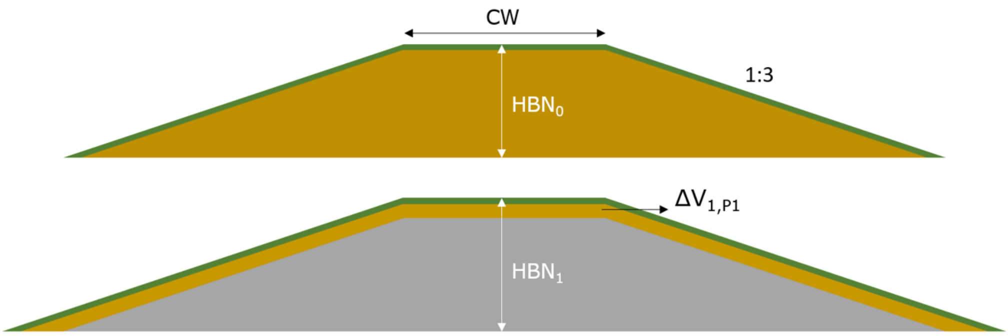


Figure 8.1: Schematization (cross-section) of additional dike volume $\Delta V_{1,P1}$

Consequently, by employing the unit prices for the core material and top layer and considering a storage factor (Dutch: opslagfactor) of 1.6, the investment costs for this scenario are estimated to be 53 million euros (see equation 8.3).

$$I_{1,P1} = 1.6 \cdot (2.12 \cdot 10^6 \cdot 15.01 + 85.5 \cdot 10^3 \cdot 17.74) = 53 \cdot 10^6 [€] \tag{8.3}$$

Similarly, the investment costs are calculated for the other sea level rise scenarios and all spatial adaptation strategies. The investment costs per strategy for the multiple sea level rise scenarios are displayed in table 8.2. These values represent the investment costs for a specific scenario compared to the current situation. Over the long term, in the scenario of 6 meters sea level rise, it appears that Plan B (B1) is the least expensive option, while compartmentalization stands out as the most expensive alternative.

Table 8.2: Investment costs (10^6) in euros of spatial adaptation strategies applied to Walcheren

	Investment costs [M€]						
Sea level rise [m]	**Plain (P1) dike-ring**	**Plain (P2) dike-ring**	**Secondary dike-ring**	**Value protection dike-ring**	**Plan B B1**	**Plan B B2**	**Partitioned dike-ring**
0	0	47	143	122	122	155	213
1	53	107	240	213	160	197	332
2	114	173	350	316	202	244	466
4	255	326	608	556	302	352	781
6	423	507	915	844	420	479	1,156

8.2. Damage (risk)

The expected damage resulting from all spatial adaptation strategies is calculated for each year up to 2200, as illustrated in figure 8.2. In general, an exponential growth of the expected damage can be observed over time, for all strategies. However, a decline in damage occurs for all strategies (with exception of the reference strategy P1) in the year 2050, since it is assumed that the initial investments are scheduled by that time. The exponential trend leads back to the assumption of an annual economic growth rate of the area of 1.9%.

When considering the expected damage in Walcheren, it appears that the plain dike-ring (P2) strategy emerges as the most optimal choice. However, when focusing on the damage in only the cities Middelburg and Vlissingen, it appears that the secondary dike-ring, value protection dike-ring and compartmentalization strategies outperform P2 in terms of damage reduction.

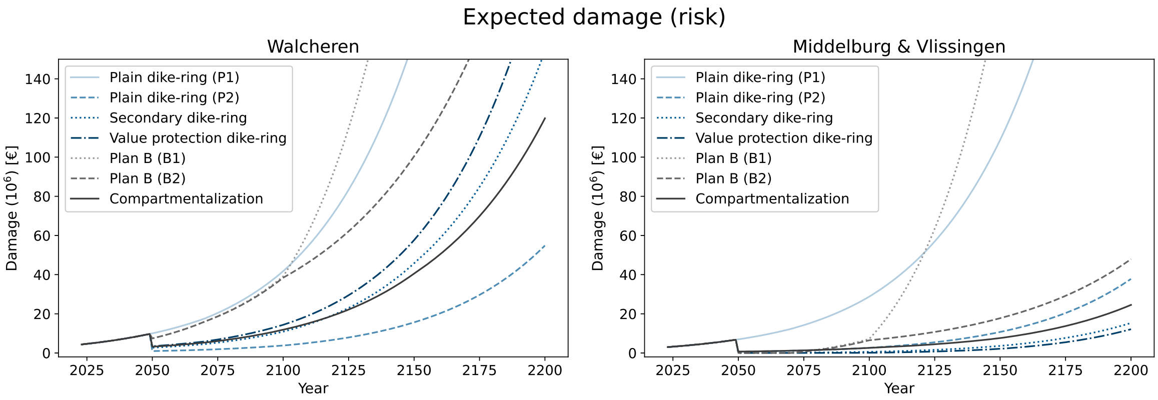


Figure 8.2: Expected damage (risk) over time for spatial adaptation strategies (RCP8.5 sea level rise projections up to 2200)

8.3. Net present value (NPV)

The timeline assigned to the (accelerated) sea level rise scenarios is important to take into consideration when it comes to scheduling investments. The sea level could rise up to 1 meter by the year 2070, and by the end of this century, in 2100, an extreme yet plausible scenario of a 2-meter sea level rise will not be unthinkable. In this research, it is assumed that no significant action is taken until 2050. Then, in 2050, the investment for 1 meter sea level rise is scheduled. Similarly, in the year 2070, investments will be initiated to be safe for 2 meters sea level rise, which can be expected in 2100. Likewise, in 2100, an investment will be made to account for 4 meters sea level rise, which might occur in 2150, and so forth.

The timing of investments has a significant impact on the net present value, which becomes evident through the discount rate. With a discount rate of 2.25% (already adjusted for inflation), investments associated with specific years can be discounted to determine their net present value as of today.

As indicated in table 8.2, the investment required to meet the 1-meter sea level rise standard for a partitioned dike-ring strategy currently amounts to €332 million when assuming that this investment is made in a single installment, without prior investment for the present 0-meter sea level situation. The assumption here is that this investment will occur in 2050. The net present value for this investment is approximately €182 million, and can be calculated using equation 8.4. In this equation, NPV$_{I,C,1}$ represents the net present value of the investment costs if they were to be done in 2050 for a compartmentalization strategy designed for a 1-meter sea level rise.

$$NPV_{I,C,1} = \frac{332 \cdot 10^6}{(1 + 0.0225)^{27}} = 182.1 \cdot 10^6 [€] \tag{8.4}$$

In the year 2050, following the implementation of the compartmentalization strategy to meet the 1-meter sea level rise standard, the expected damage is reduced to approximately €0.69 million, accounting for economic growth. The net present value of the expected damage for this specific strategy amounts to €0.38 million (see equation 8.5). In this context, NPV$_{V,C,1}$ represents the net present value of expected damage in 2050 for a compartmentalization strategy.

$$NPV_{V,C,1} = \frac{0.69 \cdot 10^6}{(1 + 0.0225)^{27}} = 0.38 \cdot 10^6 [€] \tag{8.5}$$

The total net present value is the sum of the net present value for investment costs and the net present value for damages. For a compartmentalization strategy in the year 2050, this overall net present value sums up to approximately €182.5 million. Similarly, the net present value is calculated for each year and all strategies, which is presented in figure 8.3. The high peaks correspond to the investment costs. In this figure, the difference between the various design strategies is difficult to distinguish. Therefore, a zoomed in version of the graphs is shown in figure 8.4.

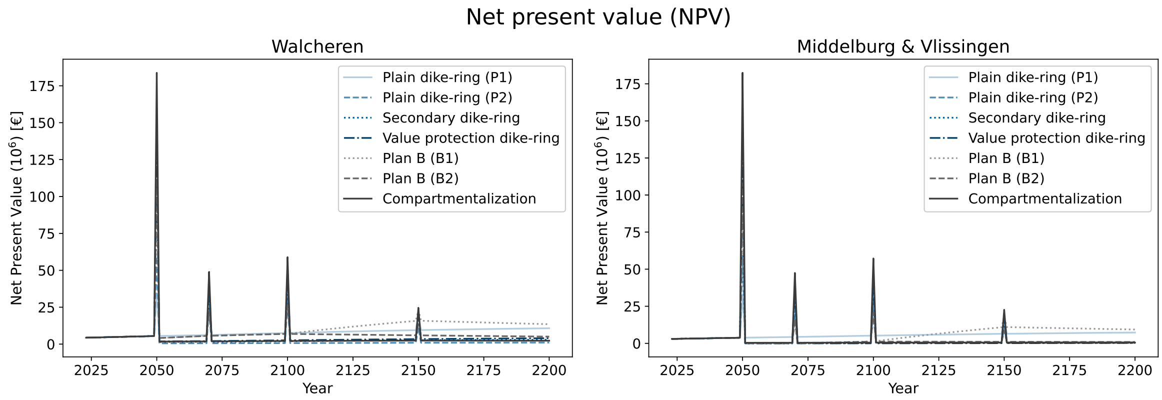


Figure 8.3: Net present value (NPV) for spatial adaptation strategies (RCP8.5 sea level rise projections up to 2200)

As figure 8.4 shows, a significant difference of the NPV over the years can be observed between the entirety of Walcheren or only the cities Middelburg and Vlissingen. In the case of Walcheren as a whole, most strategies show a gradual increase in NPV as time progresses. Conversely, in Middelburg and Vlissingen, the NPV remains relatively consistent over time for the majority of the strategies.

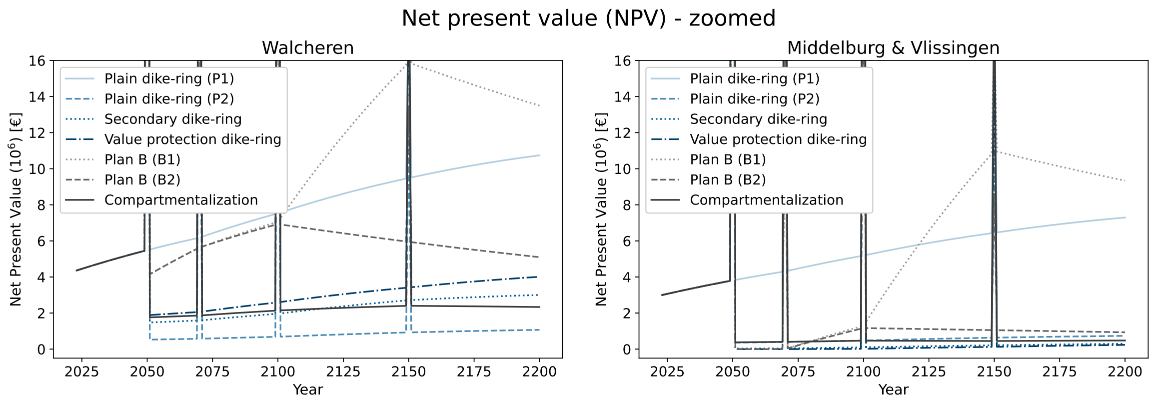


Figure 8.4: Net present value (NPV) for spatial adaptation strategies (zoomed) (RCP8.5 sea level rise projections up to 2200)

It is challenging to distinguish the strategies based on the peaks illustrated in figure 8.3. To address this, the net present values of the investment costs of the various strategies for the years 2050, 2070, 2100 and 2150 are shown in figure 8.5, separately.

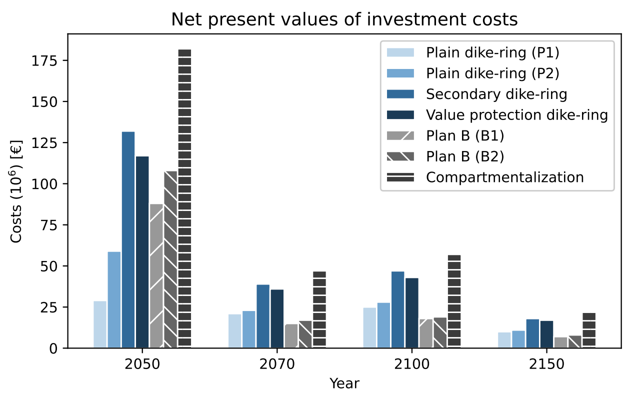


Figure 8.5: NPV of investment costs for spatial adaptation strategies (RCP8.5 sea level rise projections up to 2200)

From this figure it becomes evident that the compartmentalization strategy requires the highest net present investment costs, followed by the secondary dike-ring strategy and the value protection dike-ring strategy. In contrast, the plain dike-ring strategies generally have overall lower costs. The Plan B options require large investment costs for the initial investment (in 2050), but after this year, the investment costs are relatively low compared to other strategies.

To determine the overall most cost-effective strategy, the net present values (NPVs) are aggregated over the entire analysis period (from the current year up to 2200). The collective net present values for all spatial adaptation strategies are presented in table 8.3. This table makes a clear distinction between Walcheren and the combined region of Middelburg and Vlissingen.

When prioritizing the safety of the entire area of Walcheren, the plain dike-ring (P2) strategy seems the optimal choice due to its favorable balance between investment costs and risk, resulting in the lowest total net present value. When focusing on the protection of Middelburg and Vlissingen, the plain dike-ring (P2) strategy also proves to be the most favorable option. It is closely followed by the value protection dike-ring strategy, characterized by complete dike reinforcement, the secondary dike-ring strategy and the Plan B (B2) strategy.

Table 8.3: Net present values (10^6) [€] of spatial adaptation strategies (RCP8.5 sea level rise projections up to 2200)

	Walcheren			**Middelburg & Vlissingen**		
	Investment	**Risk**	**Total**	**Investment**	**Risk**	**Total**
Plain dike-ring (P1)	86	1,402	**1,488**	86	960	**1,046**
Plain dike-ring (P2)	120	255	**375**	120	176	**296**
Secondary dike-ring	235	481	**716**	235	116	**351**
Value protection dike-ring	213	584	**797**	213	105	**319**
Plan B (B1)	128	1,750	**1,877**	128	944	**1,072**
Plan B (B2)	152	1,021	**1,173**	152	216	**367**
Compartmentalization	308	464	**772**	308	159	**468**

8.4. Expected annual costs per capita

In addition to the calculated net present values, the expected annual costs per captia are also determined for the various strategies. These costs are split into investment costs and risks. In this context, the investment costs and risks are not discounted. Inflation is not taken into account, but economic growth is considered for damage costs. Both total investment costs and total damage costs are divided over the entire period (from now until 2200) and the total population. The annual costs per capita are presented in table 8.4. The values provided in this table indicate that the risks play a more substantial role in the overall expected annual costs in comparison to the net present values outlined in table 8.3. This highlights the significant influence that the timing of investments and the discount rate have on the estimated costs.

Table 8.4: Expected annual costs [€] per inhabitant for spatial adaptation strategies (RCP8.5 sea level rise projections up to 2200)

	Walcheren			**Middelburg & Vlissingen**		
	Investment	**Risk**	**Total**	**Investment**	**Risk**	**Total**
Plain dike-ring (P1)	21	1,076	**1,097**	29	1,013	**1,042**
Plain dike-ring (P2)	25	113	**138**	34	108	**142**
Secondary dike-ring	45	308	**352**	62	44	**106**
Value protection dike-ring	41	398	**439**	57	32	**89**
Plan B (B1)	28	2,052	**2,081**	28	1,331	**1,359**
Plan B (B2)	32	878	**911**	32	157	**189**
Compartmentalization	57	265	**322**	78	79	**157**

Another noticeable observation is that the investment costs for Walcheren are not the same as those for Middelburg and Vlissingen. This discrepancy arises from the fact that for Middelburg and Vlissingen, the investment costs per capita are based on the residents of Middelburg and Vlissingen alone, rather than the entire Walcheren region. The results reveal that for safeguarding the entirety of Walcheren, the plain dike-ring (P2) strategy stands out as the most economical choice. On the other hand, when focusing on the protection of Middelburg and Vlissingen, the value protection dike-ring strategy emerges as the most economical option, followed by the secondary dike-ring strategy, and then the plain dike-ring (P2) strategy.

Part IV

Discussion, conclusion and recommendations

9 Discussion

The technical and economic performance of multiple spatial adaptation strategies as a solution for mitigating future coastal flood risk in existing cities, in comparison with the current strategy, have been examined. In this study, the projection of accelerated sea level rise (RCP8.5) is considered. This chapter provides an extensive description of the limitations of the research and delineates the potential applicability of this study within Dutch coastal polders.

9.1. Limitations

This research is narrowly scoped, leaving certain aspects unexamined. Therefore, this section delves into the limitations of the study, including an overview of the numerous assumptions made which could possibly affect the results. The assumptions are categorized into four groups: general assumptions, future high water levels, the idealized coastal polder analysis and the case study of Walcheren.

9.1.1. General

This study primarily examines the impact of (accelerated) sea level rise scenarios on flood risk in Dutch coastal polders, with specific focus on a case study: Walcheren. This research does not include internal influences such as heavy precipitation or river floodings. The flooding patterns in Walcheren are predominantly determined by processes at sea and the influence of rivers is negligible, but the effects of heavy precipitation could still influence the flooding patterns. However, since accelerated sea level rise could lead to meters of inundation depth within the polder, the contribution of heavy precipitation might be negligible compared to the coastal flood risk.

Furthermore, a large part of the Netherlands is experiencing subsidence. This involves the gradual lowering of ground levels compared to a fixed reference point such as the Normaal Amsterdams Peil (NAP). Land subsidence is not included in this study, but it does affect flood risk, as land is descending in relation to the sea level. The influence of sea level rise further increases this flood risk. In certain areas of Walcheren, land subsidence occurs at a rate of 3 millimeters per year (Bos & Bosch, 2008). Considering that the timeline of this study extends to the year 2200, it becomes evident that, in comparison to the present situation, over half a meter subsidence can be anticipated by the end of next century. This underscores the increase of relative sea level rise. Importantly, even in the scenario of an accelerated sea level rise of 6 meters projected for 2200, land subsidence continues to play a significant role. Additionally, to maintain dry grounds, excess water from the polder must be pumped out. The challenge of doing so is becoming more significant due to rising sea levels, land subsidence, and elevated dikes, resulting in an increase in pumping costs.

9.1.2. Future high water levels

The selected range of future high water levels plays a significant role in the model's input parameters and therefore on the final results. In this research, it is assumed that sea level rise and storm surge levels are mutually independent. However, in reality, the extent of sea level rise might have a positive impact on storm surge water levels. For an open coastline, the additional storm surge level, compared to the (tidal) sea level, can be calculated according to equation 9.1 (Van der Linden, 1999).

$$\Delta h = \sqrt{2\kappa \frac{u^2}{g} F \cos\phi + h^2} - h \quad (9.1)$$

In this equation, Δh represents the storm set-up [m] and h is the water depth [m]. Although this equation is not always applicable due to the non-uniform nature of open coast scenarios and variable water depths (Van der Linden, 1999), it does illustrate how an increase in water depth leads to a reduction of storm set-up. This implies that sea level rise might indeed result in a decrease in storm surge levels, which would be a favorable outcome.

Another conservative assumption is the selected normative location of the reference water level, situated close to Fort Rammekens. The water levels vary along the coastline of Walcheren, and there is a possibility that the maximum observed water levels could be lower than the initial assumptions. This, in turn, might result in slightly less extreme outcomes.

The main driver for the future high water level scenarios is the accelerated sea level rise. The projection of this accelerated sea level rise over time is an estimate, subject to potential variation. These accelerated sea level rise scenarios are extreme, and although they are plausible, the probability of their occurrence is relatively small. It is more probable that sea level rise will occur at a less accelerated pace. In this instance, the scenarios observed up to a 6-meter sea level rise should be considered over a more extended timeframe. Alternatively, if the timeline is fixed, the sea level rise by 2200 would be lower. This would result in outcomes that are less extreme, and more favorable.

In contrast, the timeframe up to 2200 could also be considered as a limitation. Taking into account the new climate scenarios, with particular focus on the accelerated sea level rise scenarios according to the Marine Ice Cliff Instability Model (Bessembinder et al., 2023) as discussed in this research, the expected sea level rise could reach approximately 17.5 meters by the year 2300. This represents an additional 11.5 meters of sea level rise compared to the previous century. In other words, in this 100-year period, sea level rise is expected to increase by approximately twice as much as the total rise in the preceding 200 years. Against such a water level, almost no feasible reinforcement measures could be effective. This is because the additional amount of dike volume required would be extremely large, multiplying the costs by a factor of four when compared to a scenario with a six-meter sea level rise in the previous century, based on an annual failure probability of the dike-ring of 1/10,000. However, to prevent the immediate and complete flooding of an area in case of (extreme) storms, the safety standard of the dike-ring must become extremely strict. This would result in even higher dikes. Given the extremely high dikes, the pumping of excess water in the polder to the sea becomes increasingly challenging. If the mentioned extended timeframe were to be considered, it could therefore lead to entirely different outcomes and raise numerous questions.

9.1.3. Idealized coastal polder

The idealized coastal polder analysis considers four spatial adaptation strategies: a plain dike-ring, a secondary dike-ring, a value protection dike-ring and a partitioned dike-ring. Within the scope of these mentioned strategies, multiple configurations are analyzed, ranging from solely primary dike reinforcement to solely secondary dike reinforcement to complete dike reinforcement, and more. It is worth noting that these configurations consistently assume a safety standard of 1/1,000 for the dikes (in the case of reinforcement). Varying this safety standard could lead to different outcomes; for instance, a higher safety standard would likely result in reduced inundation.

The above mentioned assumption is related to a specific fragility curve that was adopted for any dike section. A higher safety standard would influence the fragility curve, reducing the number of expected dike breach locations. The shape of the fragility curve in this study is an assumption, since the exact moment of failure of a dike section is unknown. However, the results of the model are highly sensitive to this assumption. A different type of fragility curve could significantly impact the extent of inundation for storms with specific return periods. The assumption in this study is a gradual progression, because it is unknown when exactly (a part of) the dike-ring will fail, and therefore accounts for uncertainty. If the fragility had a steeper gradient, such as a step function, the moment of failure would be more certain. For the idealized polder and Walcheren, the probability of failure for a single independent dike section is 1/35,000 per year. With a step function, the conditional failure probability of a dike section in case of water levels occurring more frequently than once every 35,000 years would be zero. For all water levels occurring once every 35,000 years or less frequently, the conditional failure probability of a dike section would be one. This would lead to considerable less extreme outcomes. The elimination of uncertainty, however, tends to significantly underestimate the actual situation.

Furthermore, the volume of water entering the polder is directly proportional to the width of the dike breach. Consequently, the choice of the dike breach width has a strong influence on the volume of water entering the polder and therefore also the inundation water level in the polder. Additionally, it is assumed that each dike section experiences a maximum of one dike breach, though it is possible for multiple breaches to occur within a single dike section. These assumptions influence the polder inundation development of the idealized coastal polder, particularly for storms with relatively lower return periods.

In addition to the dike breach width, which significantly influences the development of inundation water levels in the polder, the timing of the dike breach is also crucial. In this research, it is assumed that a dike breach occurs at the maximum peak sea water level. In reality, if the dike breach were to occur after this maximum peak, a less severe level of inundation is expected. However, if a dike breach would occur before reaching the maximum peak water level, this would lead to a significant increase in the inundation water level within the polder compared to the results observed in this study, particularly for storms with relatively lower return periods that result in only a few dike breaches. For extreme storms with relatively higher return periods that result in many dike breaches (> 10), it is questionable if this effect contributes as much to the inundation depth within the polder, since these storms already lead to extreme inundation patterns and extreme damage for the considered timing of the dike breaches in this study.

9.1.4. Walcheren

The primary flood defense system of Walcheren consists of both dikes and dunes and there are multiple regional flood defenses. However, in this research, for simplicity, it is assumed that the primary flood defense consists of only a dike system and there are no regional flood defenses. In this research, the primary dike-ring has 35 equally long dike sections, with each the same failure probability. This is a valid starting point, assuming that the water entering the polder is uniformly distributed throughout the entire polder. However, in reality, the flooding patterns may appear different, and the location of dike breaches, along with the specific failure probability for each dike segment, will play a significant role. In particular, for storms with a low probability of occurrence (T < 3,000 years), where the expected number of dike breaches is low, it is highly probable that the flood pattern will be more localized rather than a uniform distribution across the area. To this extent, the presence of regional flood defenses also influence the (localization of) inundation patterns. This aligns with the results as presented in the VNK2 report (Bossenbroek & Bardoel, 2014). For rare or extreme storms with an extremely low probability of occurrence (T > 10,000 years), where the expected number of dike breaches is high, the expectation of a uniform distribution becomes more plausible. Although the assumption of a uniform water distribution in the polder has its constraints, the results of the model show a relatively close correlation with the LIWO database maps. This is the case for storms with a low probability of occurrence (T = 1,000 years) as well as storms with an extremely low probability of occurrence (T = 30,000 years), indicating the overall utility of the model.

Just as with the analysis of the idealized coastal polder, the width of the dike breach can have a significant impact on the inundation patterns within the polder. In this research, all dike breaches are assumed to occur instantaneously, with a consistent width of 100 meters. However, in reality, dike breaches are likely to grow over time. The expansion of a dike breach would affect the volume of water entering the polder for a specific time step. During the initial hours, it is probable that the volume of water entering the polder will be less than the estimation in this study, but will continue to grow in time. It is unclear what the exact effect would be on the temporal development of the polder inundation and, consequently, on the maximum polder inundation. However, the expectation is that the inundation rate, particularly during the initial hours, will be less severe than the results obtained in this study. This will most likely have a positive impact on the expected number of casualties.

The final maximum polder inundation values for multiple scenarios translated into flood maps are used as an input for the Damage and Casualties Module. This module returns the damage and casualties for a specific flood event. The estimated damage is quite accurate based on the input file (flood map) provided, as the database of the Damage and Casualties Module contains detailed objects of the area. The estimated number of casualties, on the other hand, is less accurate. Although an inundation rate file is used in the calculations, the assumption of a uniform distribution across the entire area leads to a somewhat unreliable estimate, which might even be an overestimate. However, this estimation is superior to a calculation that ignores the inundation rate entirely, since this would result in a significant underestimation of casualties. It is essential to note that this analysis considers a scenario without evacuation measures, making it a conservative assumption. The implementation of evacuation strategies could further reduce the number of casualties.

For the cost-benefit analysis, the calculated total costs result from a combination of investment costs and expected damage. The investment costs, which are a rough estimate, depend on multiple factors. For the primary dike and additional dikes, a standard dike profile including crest width is assumed. However, in reality, the primary dike-ring has a different profile compared to this standard profile. Certain existing dikes already exceed the necessary hydraulic load level (Dutch: HBN) for specific sea level rise scenarios. As a consequence, the additional required dike volume (and, by extension, the investment costs) might be lower than calculated, resulting in more favorable outcomes. However, the actual investment costs could be higher due to potential constraints such as insufficient available space and the necessity for additional structures like cofferdams. Moreover, acquiring parcels of land involves additional expenses, and there might be other overlooked initial costs. Consequently, the overall expenses may exceed the current estimates significantly. The expected damage, on the other hand, is an overestimation of reality. In the analysis considered, investments are made a certain number of years in advance to align with an expected corresponding sea level rise scenario. Consequently, in reality, the risk decreases shortly after an investment is completed. This aspect is not included in the analysis, leading to conservative outcomes. Including this element would result in more favorable outcomes.

Finally, in the Plan B approach, the dike-rings of Western cities, including those of Middelburg and Vlissingen, are directly exposed to the sea water level. The Plan B approach (“Plan B: NL2200”, 2020) suggests strengthening the remainders of the Western coast and creating a marine lagoon. If this plan were to be implemented, the extreme water levels caused by storm surges are expected to be observed mainly along the protected Western coast and the impacts along the dike-rings of the cities may also be significant due to the relation between water depths and storm surges according to equation 9.1. However, waves along the coastlines of the Western cities can be dampened due to the remainders of the Western coast and there is a possibility that the storm surge might be less significant due to an interruption of the fetch. Therefore, the flooding probability could be (significantly) lower and consequently, the flood risk in the cities as well.

9.2. Reflection on literature

The results of the model can be compared to the available information from the report of VNK2 (Veiligheid Nederland in kaart) (Bossenbroek & Bardoel, 2014) on flood risk in Walcheren (levee system 29). According to the analysis of VNK2, the expected value of economic damage is 0.2 million euros per year. For a scenario of 0 meters of sea level rise and a plain dike-ring strategy, the model calculates an expected value of 4.36 million euros of damage per year. This demonstrates that the model significantly overestimates the damage compared to the data in VNK2. As mentioned earlier, the model implements a specific fragility curve for any dike section (without differentiating between failure probabilities of different dike sections) and the model does not take into account the regional defenses present in the area. The assumption of the specific fragility curve in combination with uniform distribution of water across the area therefore most likely lead to an overestimation of the expected value of annual damage.

As expected and also previously demonstrated by other studies, adaptation measures have a positive impact on flood risk reduction in cities. In this research, the results of the Walcheren case study show that upgrading the safety standard of the primary defenses is most effective in reducing flood risk. This aligns with conclusions from a study on coastal floods in Belgium (Koks et al., 2014). Likewise, the conclusions described in the Walcheren report of VNK (Bossenbroek & Bardoel, 2014) claim that taking measures at the three weakest dike sections can reduce the annual flooding probability of Walcheren from 1/1,000 to 1/4,300. Improving the ten worst dike sections decreases the flooding probability to 1/28,700 per year.

In the Walcheren case study of this research, the second most effective strategy in reducing flood risk in terms of minimizing casualties is the implementation of a secondary dike-ring strategy. This favorable outcome also aligns with conclusions from a previous study by DHV (Oost & Hoekstra, 2009).

9.3. Applicability in Dutch polders

The objective of this research is mitigating future coastal flood risk. The methodology employed in this research is useful for conducting an initial and rough evaluation of various spatial adaptation strategies in (other) coastal polders in the Netherlands, for example the dike-ring 14 region.

Although the methodology in this research has potential, directly applying the findings from the case study of Walcheren to other Dutch coastal polders would be imprudent. The results are based on multiple assumptions, one of which relates to the water levels observed at sea, that can vary across different regions in the Netherlands. Therefore, it is crucial to consider the specific sea level conditions for the associated coastal polder. Moreover, in other coastal polders, additional factors may affect the overall flood risk. For example, the total flood risk of Walcheren is (almost) entirely caused by the coastal flood risk, while the influence of rivers is negligible. This choice is logical when assessing the effects of sea level rise in Walcheren. However, in other Dutch coastal polders, rivers may significantly contribute to the overall flood risk, emphasizing the need for a separate examination.

The model utilizes a highly simplified representation, assuming an average polder height. This approach is generally suitable when there are relatively few differences in elevation within the area, such as Walcheren. However, when there is significant variation in elevation, which could be the case for other Dutch polders, the estimation of water levels within the polder becomes imprecise and can deviate substantially from reality. Furthermore, Walcheren is not necessarily a representative location in terms of reflection of the (distribution of the) Dutch population. Walcheren (dike-ring 29) has a population of about 115,000 people, which is relatively small compared to, for example, the area covered by dike-ring 14. Large cities such as The Hague, Leiden, Haarlem, large parts of both Amsterdam and Rotterdam and more are situated in this area. The population in this area adds up to approximately 3.6 million and about 65% of the economy of the Netherlands is situated in this area (Vergouwe, 2014a). The consequences of a flood in this area would therefore be significantly worse than in Walcheren, both in terms of damage and casualties. As a result, this area requires enhanced protection, and the safety standards in the current situation are also much stricter. Given the complexity and value of this area, a separate comprehensive analysis for dike-ring area 14 should be conducted. If this amount of people and this share of the economy were to be situated in Walcheren, and the urban versus rural distribution remained the same, it means that the value and population in the cities of Middelburg and Vlissingen would increase substantially. The risk could therefore raise increased contribution to the total expected costs relative to the investment costs, and protecting the cities would become even more important. Based on (adjusted) results, a different strategy might be preferred.

When briefly reflecting on the conduct of this study, it can be affirmed that, as long as location-specific assumptions are critically re-evaluated, the methodology of this study can be applied to other coastal polders in the Netherlands for an initial assessment.

10

Conclusion and recommendations

10.1. Conclusions

The main research question of this research reads: ”How does the Plan B NL2200 approach (accommodate) perform as a solution for mitigating future coastal flood risk in existing cities, considering the projection of accelerated sea level rise, in comparison with the current strategy (protect) and alternative spatial adaptation strategies?” In order to address this research question, this study was divided into two main parts. The main research question has been subdivided into several sub-questions. Of these, two sub-questions relate to the first part of the research, which predominantly focuses on the exploration of multiple spatial adaptation strategies in the analysis of idealized coastal polders. The three remaining sub-questions apply to a specific case study, Walcheren, which is the second part of the research. The findings derived from the idealized coastal polder analysis have been employed in this part of the research.

10.1.1. Idealized coastal polder

In the first part of the research, the idealized coastal polder analysis, various spatial adaptation strategies have been studied. The reference (or baseline) scenario is a plain dike-ring strategy, which represents the present situation. In this situation, the polder is protected by means of (solely) a primary dike-ring with an annual failure probability of 1/1,000. In addition to this reference strategy, a secondary dike-ring strategy, a value protection dike-ring strategy and a partitioned dike-ring strategy have been considered, in order to provide enhanced protection for the city in the idealized polder. For the final assessment of the idealized coastal polder, multiple configurations of these strategies have been analyzed. These configurations range from solely primary dike reinforcement to solely secondary dike reinforcement to complete dike reinforcement, and more. Primary dike reinforcement maintains a constant annual failure probability of 1/1,000 by reinforcing and elevating the primary dike-ring. Similarly, secondary dike reinforcement applies the same principle to the secondary dike-ring, while complete dike reinforcement involves equal elevation of both the primary and secondary dike-rings.

The first sub-question that associates with the idealized coastal polder analysis reads: ”How do various spatial adaptation strategies influence the inundation depth (frequency) in idealized coastal polders compared to a plain dike-ring strategy, while accounting for the projected accelerated sea level rise?”

The results of the idealized coastal polder analysis reveal that the implementation of a secondary or value protection dike-ring, with any type of reinforcement leads to a reduction of the inundation depth within the city of the polder for mild sea level rise scenarios up to 2 meters, in comparison to the reference strategy. However, when the sea level rise exceeds 2 meters, the configurations with solely secondary dike reinforcement lead to an increase of inundation depth within the city, compared to a plain dike-ring strategy. Overall, the other types of reinforcement (solely primary dike reinforcement or complete dike reinforcement) lead to a reduction of inundation in the city. For the scenarios with complete dike reinforcement, this inundation depth can be reduced to zero, even for sea level rise scenarios up to 6 meters and (extreme) storms with return periods of up to T = 10,000 years. The implementation of a partitioned dike-ring always leads to a reduction of inundation depth in the city, compared to the reference strategy, since this strategy assumes complete dike reinforcement.

The second sub-question of the idealized coastal polder analysis is: ”What are effective spatial adaptation measures, considering the evaluation of spatial impact and mitigating flood risk, in idealized coastal polders?”

The multi-criteria assessment of the spatial adaptation strategies in an idealized coastal polder, considering the evaluation of the criteria ’spatial impact’ and ’flood risk’, reveals that, compared to the reference strategy, all adaptation measures are effective as long as primary or complete dike reinforcement is applied. The effectiveness of the various strategies does not change for increasing sea levels. In general, the secondary dike-ring strategy, value protection dike-ring strategy and partitioned dike-ring strategy with complete dike reinforcement are the most favorable options, especially in providing enhanced protection to the city and reducing inundation depth and inundation rate within the city across the multiple sea level rise scenarios. Of these three strategies, the value protection dike-ring strategy stands out as the preferred strategy, since the additional required embankment length (and volume) is lower compared to the secondary dike-ring and partitioned dike-ring strategies.

10.1.2. Walcheren

The conclusions on the idealized coastal polder analysis lead to the second part of the research, which focuses on the case study of Walcheren. One of the sub-questions relating to this part of the research is: ”What are potential design strategies for the Dutch coastal polder, taking into account the main principles of Plan B’s adapted spatial vision as a foundation?” The main principles of Plan B’s adapted spatial vision of the Netherlands revolve around the preservation of Western cities. Therefore, the adaptation strategies have been designed such, to provide enhanced protection for the cities Middelburg and Vlissingen. For the multiple spatial adaptation strategies, it has been concluded from the idealized polder analysis that complete dike reinforcement turns out to be most effective in mitigating flood risk and therefore this case study mostly focused on the detailed elaboration of these specific configurations. Similar to the idealized polder, for Walcheren, a plain dike-ring with an annual failure probability of 1/1,000 serves as the reference strategy. In addition to this reference strategy, a secondary dike-ring strategy, a value protection dike-ring strategy and a partitioned dike-ring strategy (all with complete dike reinforcement) have been considered. Furthermore, several additional strategies have been taken into account. For example, a plain dike-ring (P2) with an elevated safety standard of 1/10,000 has been added to the analysis as well as two variants of the Plan B approach: B1 and B2. The difference between these variants lies in the safety standards, with variant B1 adopting a safety standard of 1/1,000, and variant B2 implementing an elevated norm of 1/10,000.

The next sub-question on the Walcheren analysis is: ”What is the effectiveness of various design strategies in reducing the expected future flood risk in the coastal polder, given the projected sea level rise, compared to the current strategy of the Dutch coastal polder?”

The assessment of various design strategies in mitigating the expected future flood risk in Walcheren involved an analysis of the expected annual damage, casualties and the number of affected people for each strategy. In the context of expected annual damage, a distinction was made between the rural areas of Walcheren and the cities Middelburg and Vlissingen combined. Taking into account both the expected annual damage in Middelburg and Vlissingen and the expected annual casualties in Walcheren (without evacuation), it becomes evident that all adaptation strategies, with the exception of Plan B (B1), outperform the reference strategy (plain dike-ring, P1) up to a sea level rise of 6 meters. This highlights the effectiveness of these strategies. Moreover, when considering the expected number of affected people, Plan B (B1) also outperforms the reference strategy. This can be explained by the fact that in case of a Plan B strategy, people reside exclusively in the cities, resulting in a smaller population. In the context of mitigating the overall expected annual flood risk, in terms of damage, casualties and the number of people affected, the plain dike-ring (P2) strategy with its increased safety standard consistently proves to be the most effective strategy. This effectiveness can be clarified by the fact that the annual failure probability of the dike-ring is set at 1/10,000, implying that flood events are not anticipated for storms with return periods below T = 10,000 years. Given that the expected risk is primarily influenced by more frequently occurring storms, its contribution to the overall expected annual risk is relatively lower compared to other strategies.

Finally, the last sub-question reads: "What is the most cost-beneficial strategy for mitigating the future coastal flood risk in the Dutch coastal polder?"

In the cost-benefit analysis, the net present values have been calculated for the various spatial adaptation strategies, based on the projections of RCP8.5 (accelerated) sea level rise up to 2200. When prioritizing the safety of the entire area of Walcheren, the plain dike-ring (P2) strategy stands out as the optimal strategy due to its favorable balance between investment costs and risk, resulting in the lowest total NPV of 375 million euros. Following is the secondary dike-ring strategy, with a total NPV of 716 million euros, which is nearly a doubling. Compared to P2, the investment costs for this strategy are a little under twice as large, and the risk also approximately doubles. The 'costliest' strategy is Plan B (B1), with a total NPV of 1,877 million euros. This is primarily due to the extreme risk. When the emphasis shifts to protecting only Middelburg and Vlissingen, the most favorable choice is also the plain dike-ring (P2) strategy, with a total NPV of 296 million euros. However, this strategy is closely followed by the value protection dike-ring including complete dike reinforcement (NPV = 319 million euros) and the secondary dike-ring strategy (NPV = 351 million euros). Once again, Plan B (B1) is the most expensive strategy, due to its high risk, resulting in a total NPV of 1,072 million euros.

In evaluating the expected annual costs per capita and emphasizing the safety of the entire Walcheren area, the plain dike-ring (P2) strategy once again emerges as the optimal choice, resulting in a total of 138 euros per year. Following closely is the compartmentalization strategy, adding up to a total expense of 322 euros per year, which is more than twice as much. However, when prioritizing the protection of only Middelburg and Vlissingen, the value protection dike-ring strategy including complete reinforcement, estimated at 89 euros per inhabitant per year, emerges as the most cost-effective option. It is followed by the secondary dike-ring strategy (106 euros) and the plain dike-ring (P2) strategy (142 euros). When considering the overall expected annual costs per capita, risks play a more significant role compared to net present values, leading to different preferred strategies in certain scenarios. This highlights the substantial impact of investment timing and discount rates on the estimated costs.

10.1.3. General conclusion

Having the answers to all the sub-questions enables the addressing of the central research question:

How does the Plan B NL2200 approach (accommodate) perform as a solution for mitigating future coastal flood risk in existing cities, considering the projection of accelerated sea level rise, in comparison with the current strategy (protect) and alternative spatial adaptation strategies?

This question can be directly answered when examining the cities of Middelburg and Vlissingen. As revealed by the results of the Walcheren case study, the Plan B (B1) strategy, employing the same safety standard as the current plain dike-ring (P1) strategy, results in a higher Net Present Value (NPV) compared to the present strategy. On the contrary, the Plan B (B2) strategy, with an elevated safety standard compared to the current strategy, results in a substantially lower NPV. However, tightening the safety standard of the primary dike-ring (P2) to match that of the local dike-rings in strategy B2 leads to a reduced NPV. In other words, it can be concluded that investments in the primary dike-ring are more effective than investments in the Plan B strategy at an equivalent safety level. This is related, on the one hand, to lower investment costs and, on the other hand, also to lower risks. Despite the fact that Plan B requires less dike length than the primary dike-ring, the investment costs are still higher for Plan B. This is due to the fact that these 'additional' value protection dike-rings need to be built from scratch. As a result, the initial investment costs are high. Furthermore, despite the equal failure probabilities, when a dike breach occurs in the Plan B strategy, the volume of water that enters the polder distributes over a smaller area, resulting in a larger inundation depth and consequently elevating the risk compared to the primary (plain) dike-ring strategy. Moreover, investments in the primary dike-ring also hold a major advantage in that no land is relinquished or surrendered, unlike the Plan B strategy. In addition to the primary dike-ring (P2) strategy, both the value protection dike-ring (complete dike reinforcement) and the secondary dike-ring strategy also outperform the Plan B strategies. Therefore, it can be concluded that the Plan B variants considered in this study are not the recommended solutions for mitigating future coastal flood risk in Middelburg and Vlissingen, considering the projection of accelerated sea level rise, in comparison to alternative spatial adaptation measures.

Drawing a conclusion becomes challenging when a broader perspective is considered, specifically

Western cities in the Netherlands in general. This is due to the fact that, for other locations, the results could be influenced by factors such as the contribution of rivers to the overall flood risk and the proportion of population and value in urban areas versus rural areas. When the population and value in specific cities are significantly higher, these cities might require (additional) special protection, which could lead to a preference for an alternative strategy and consequently different conclusions. Therefore, additional research is recommended.

The results of this study have demonstrated that varying the safety standards of the dikes has a substantial impact on the performance of a certain strategy. The optimal safety standard for the Plan B strategy remains undetermined (as of now). So far, the results of this study indicate that primary reinforcement at a higher safety level is the preferred approach, even in the present situation. In the present situation, this is a contradictory result, as one would expect that the existing strategy and safety standards are the preferred choices in the current situation; otherwise, they would not have been selected initially. This indicates that certain assumptions indeed have a strong influence on the results, particularly an overestimation of the risk, and therefore, on the conclusions. As a result, it is recommended to further investigate the optimal safety standard from a cost-benefit perspective. From a cost perspective, it makes sense that the primary dike-ring strategy at a higher safety level is the preferred approach, since this primary dike already exists, demanding relatively lower investment costs compared to some other strategies. If Plan B were to be implemented, a careful selection must be made regarding which Western cities in the Netherlands should receive localized protection. Theoretically, individually safeguarding all these separate cores could result in a greater required dike length than the existing primary dike. This would significantly increase the total investment costs in comparison to the current strategy which focuses on strengthening the existing primary dikes in the Netherlands.

10.2. Recommendations

The issues considered in the discussion highlight opportunities for additional research on, among others, the effects of sea level rise. This section outlines policy recommendations, indicating the recommendations derived from the findings of this study for the authorities responsible for water safety in the Netherlands, as well as recommendations for further research directions.

10.2.1. Policy recommendations

Based on the findings of this study, it is recommended to continue the current strategy for the specific situation in Walcheren, which involves reinforcing the primary dikes. It is explicitly emphasized that it is essential to increase the safety standards. Protecting at a higher safety level, specifically at an annual failure probability of 1/10,000, ensures that storms with return periods of T = 1,000 years or T = 3,000 years will not lead to flooding of the polder. Extreme storms with return periods exceeding 10,000 years may still result in inundation, but these storms have only a small contribution to the overall annual risk.

It has been demonstrated that, even under a scenario of 6 meters of sea level rise (anticipated in the year 2200 under the assumption of accelerated sea level rise), the expected annual damage, casualties, and the number of affected people remain minimal throughout the entire area. In other words, the flood risk in Walcheren, for this strategy (P2), is low. However, the probability of experiencing such a rapid increase in sea levels is low, since this is a very extreme scenario. Therefore, it is recommended to explore alternative, less extreme sea level rise scenarios. For example, 1 meter sea level rise by the end of this century in 2100 and 2 meters sea level rise by 2200 could be examined, which (although this is not the expectation) might lead to different conclusions. Adjusting the safety standard of the primary dike-ring allows for the identification of the optimal balance between investment costs and risks.

In addition, when considering the entirety of the Netherlands, it is challenging to conclusively say if the mentioned strategy is generally the best strategy, as outcomes and, consequently, the determination of the preferred strategy depend on location-specific circumstances and conditions. It is recommended to apply the established method in this study to other polders, in order to compare different strategies and investigate their impact on flood risk. Although the expectation is that the mentioned strategy will likely emerge as the best, it cannot be ruled out that another strategy may perform better in a different area.

10.2.2. Further research

The recommendations for further research include sensitivity analyses, the effects of sea level rise, spatial adaptation strategies, optimisation methods and the societal aspects of the Plan B approach.

Sensitivity analyses

As described in the discussion, this study relies on several assumptions that influence the results. The exact extent to which these assumptions affect the results remain uncertain, emphasizing the importance of conducting various sensitivity analyses.

For instance, an extensive examination of how land subsidence affects flood risk in Walcheren or other coastal polders in the Netherlands would provide relevant insights. Additionally, it could be valuable to perform a sensitivity analysis to explore the extent to which sea level rise may potentially exert a (reduced) effect on storm surge levels, whether significant differences are anticipated, or if the effect is negligible, and how this, in turn, affects inundation patterns. Besides, it is advisable to incorporate regional defenses into the model to examine whether this leads to a more precise estimation of reality. Furthermore, it is essential to investigate the effect of both the timing of the dike breach and the evolution of the breach width over time on the inundation patterns, and consequently, the extent of damage and casualties within the polder. Moreover, the fragility curve employed in this research significantly influences the results, emphasizing the need to explore various types and progressions of fragility curves and assess their impact on flood risk and potential conclusions.

Finally, gaining a deeper understanding of investment costs would lead to a more accurate estimation of net present values, allowing for a more informed decision in the selection of a preferred strategy.

Effects of sea level rise

In this research, the effects of sea level rise on flood risk in the Netherlands are considered. However, sea level rise affects not only the flood risk, but also salinity, and therefore it influences the freshwater supply in the Netherlands. During periods of high sea water levels and low river discharges, saltwater intrusion extends further inland, leading to increased groundwater pressure and hence an increase in saltwater seepage. This, in turn, affects the demand for freshwater for flushing the polder water system (Haasnoot et al., 2018). These aspects are not considered in this study, but they are crucial to include for a comprehensive evaluation. Consequently, it is recommended to investigate the effects of various adaptation strategies on salinity in the Netherlands. For instance, should Plan B be put into action, a significant part of the Netherlands would be reclaimed by the sea. This would result in a substantial inland extension of saltwater intrusion.

Furthermore, if this study were to be applied to other coastal polders, it would be recommended to investigate the impact of sea level rise on river water levels. A higher sea level, particularly in the case of open storm surge barriers, results in a proportionate elevation of water levels in the sea-dominated section of the lower river region. However, even further upstream, a higher sea level can affect water levels due to the 'backwater effect' (Haasnoot et al., 2018). Sea level rise also affects the closure frequencies of storm surge barriers. At a 2-meter sea level rise (projected for 2100 according to accelerated sea level rise scenarios), there is such a significant increase in the closure frequency of the Maeslant barrier and Oosterschelde barrier under the current closure criteria that they are almost continuously closed. Consequently, numerous structures will need to be adjusted or replaced (Haasnoot et al., 2018). A follow-up study could therefore be to investigate what the exact consequence would be on the closure frequency of the Maeslant barrier and what would be the costs to adjust or replace the barrier for multiple sea level rise scenarios.

Spatial adaptation strategies

Both the idealized coastal polder analysis and the case study of Walcheren of this study consider four spatial adaptation strategies: a plain dike-ring, a secondary dike-ring, a value protection dike-ring and a partitioned dike-ring. It is important to acknowledge that this selection is, in a way, a limitation, as there exist more strategies that could have been added to the analysis. The mentioned strategies are mainly measures that match the category 'protect', whereas Plan B is a design example that aligns with the category 'accommodate'. In this analysis, the category 'advance' (sea-ward) is not considered. To ensure a more complete and comprehensive analysis, the inclusion of a spatial adaptation strategy from this category could enrich the analysis and could possibly lead to different conclusions.

Optimisation

If the sea level rises and the flooding probability (or safety standard) of the area remains constant, the overall flood risk increases. This is because the extent of inundation (and consequently, damage and casualties) becomes more extreme, and risk is a product of probability and consequence. In this study, the safety standard has generally remained constant at 1/1,000. An exception is the elevated safety standard of 1/10,000 in strategies P2 and B2. Due to these constant safety standards, the dike height in this research has been predetermined. Based on this assumption, the primary objective was to identify the most favorable strategy, resulting in the least total net present value. However, a different research could lay focus on finding the optimal additional dike height for a specific strategy. This optimal value is the minimum value of the sum of investment costs and expected damage (see figure 10.1). Subsequently, this minimum value reveals the optimal required additional dike height. Likewise, the various adaptation strategies can be evaluated based on these total costs.

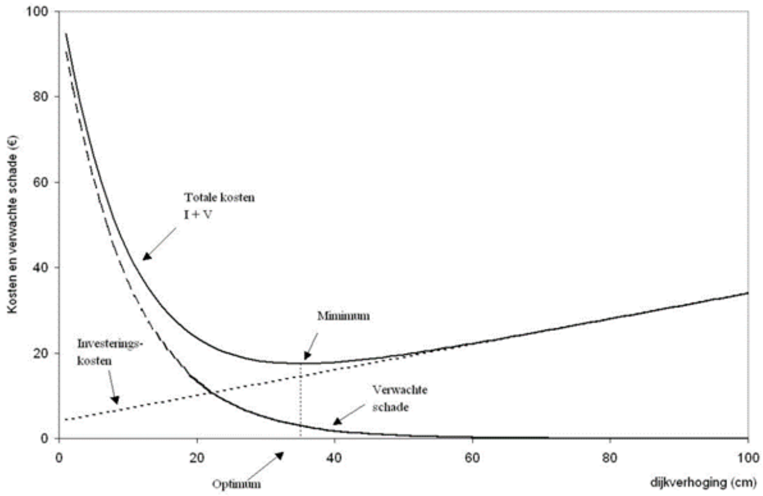


Figure 10.1: General principle of the social cost-benefit analysis (Deltares, 2011)

Furthermore, a form of optimization involves mitigating the consequences. This means that interventions can be made in spatial planning. This can be achieved, for example, by primarily organizing land use in more vulnerable areas, while economic activities and housing mainly take place in cities, which are the better-protected areas. In essence, Plan B aligns with this approach and, with an eye on the future, also has a plan for adaptive construction. A follow-up study could explore and provide more details on implementing these aspects.

Societal (social) aspects of Plan B

In the Plan B strategy, Western cities in the Netherlands will be protected, while the remaining low-lying areas of the polders will be reclaimed by the sea. Although a substantial portion of the population resides in these (Western) cities, a significant percentage also lives outside these urban areas. Therefore, if Plan B were to be implemented, many people would be forced to relocate to higher ground or other protected areas. This presents moral complexities, as such a scenario places substantial pressure on the socio-economic environment. This research, however, primarily focused on the technical aspects. Therefore, a follow-up study could delve into the societal and social aspects of this strategy.

Establishing a relocation plan as early as possible allows for better preparation in terms of investments, housing, and other critical factors. For instance, stimulating employment opportunities in higher-lying regions is one effective approach. However, the decision to migrate as a solution of 'accommodating' is unlikely to be solely determined by a political decision to leave a place of residence. Instead, it is more probable that individuals and businesses will be influenced by extreme events with significant impacts when deciding to relocate (Haasnoot et al., 2019).

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Part V

Appendices

A

Future high water levels

A.1. High water level scenarios

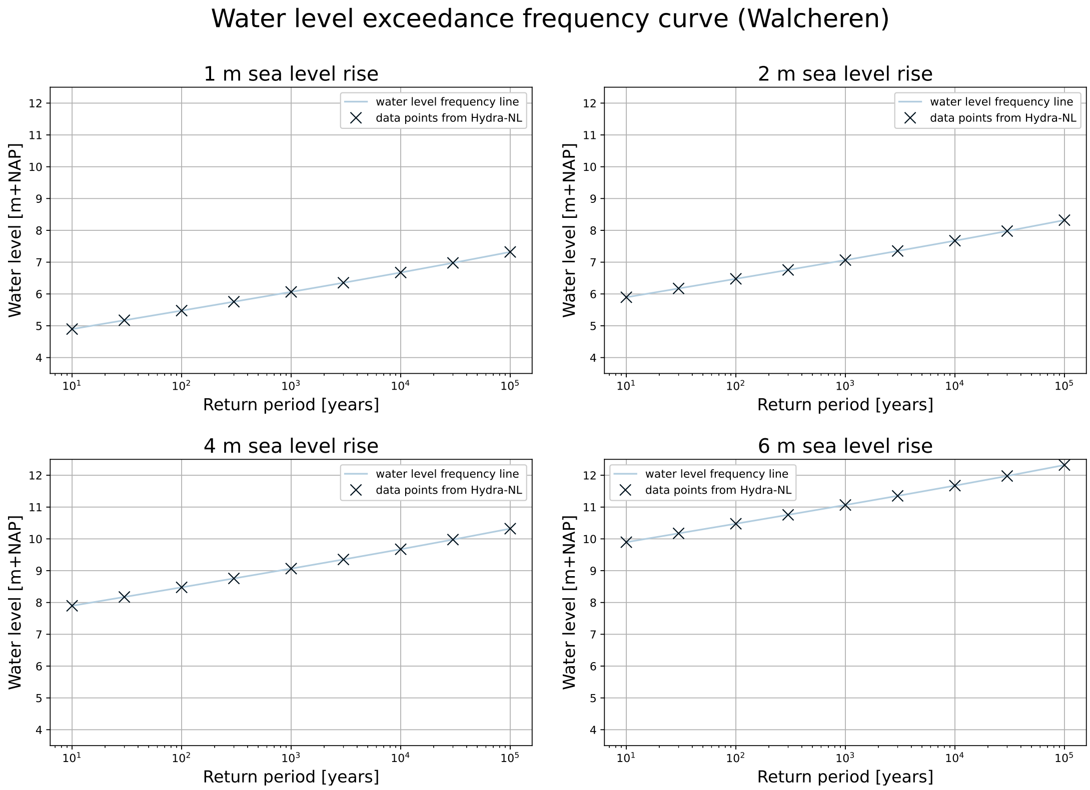


Figure A.1: Water level frequency lines for future high water level scenarios (Walcheren)

A.2. Water development scenarios

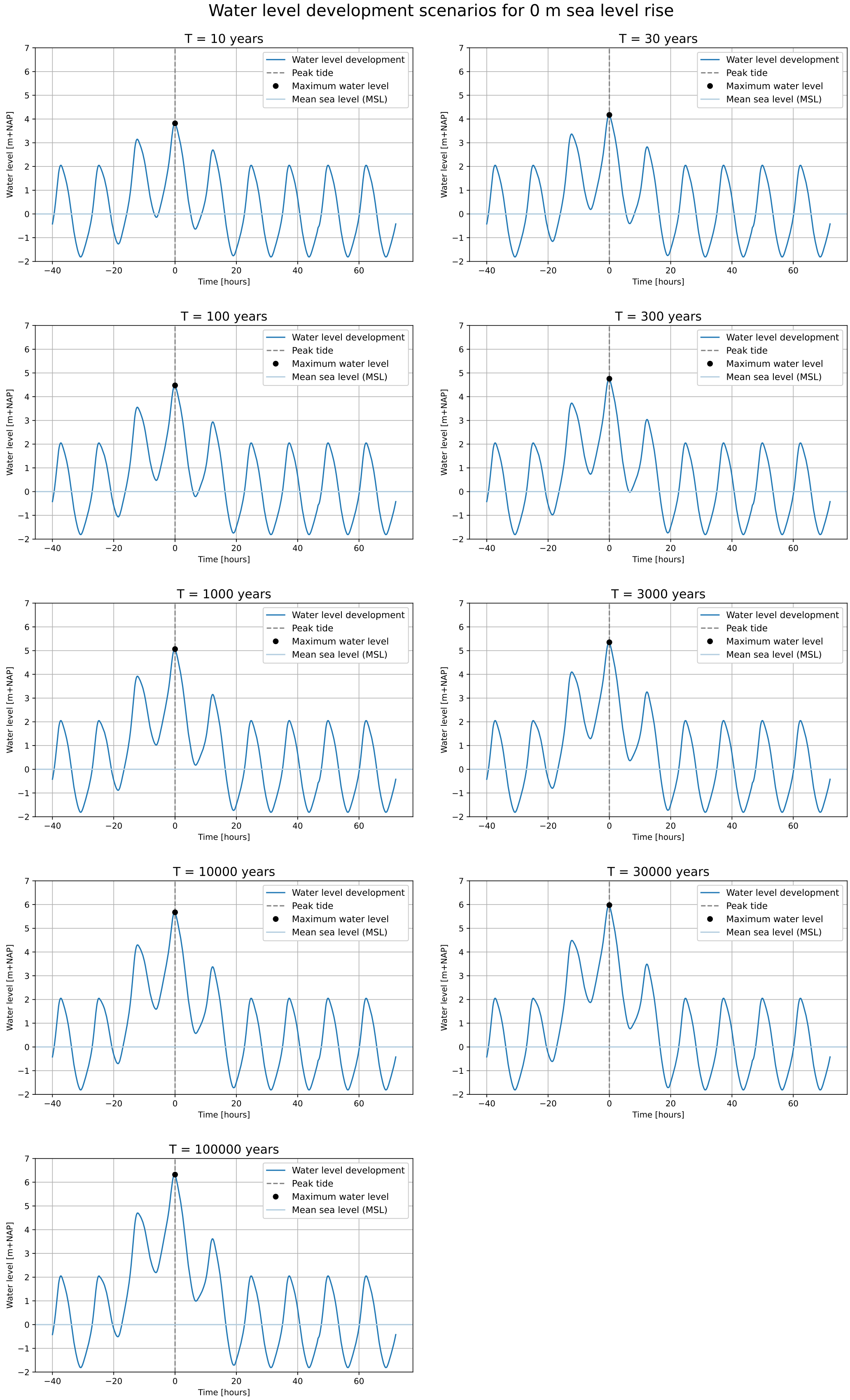


Figure A.2: Water level development scenarios (Walcheren) for 0 m sea level rise

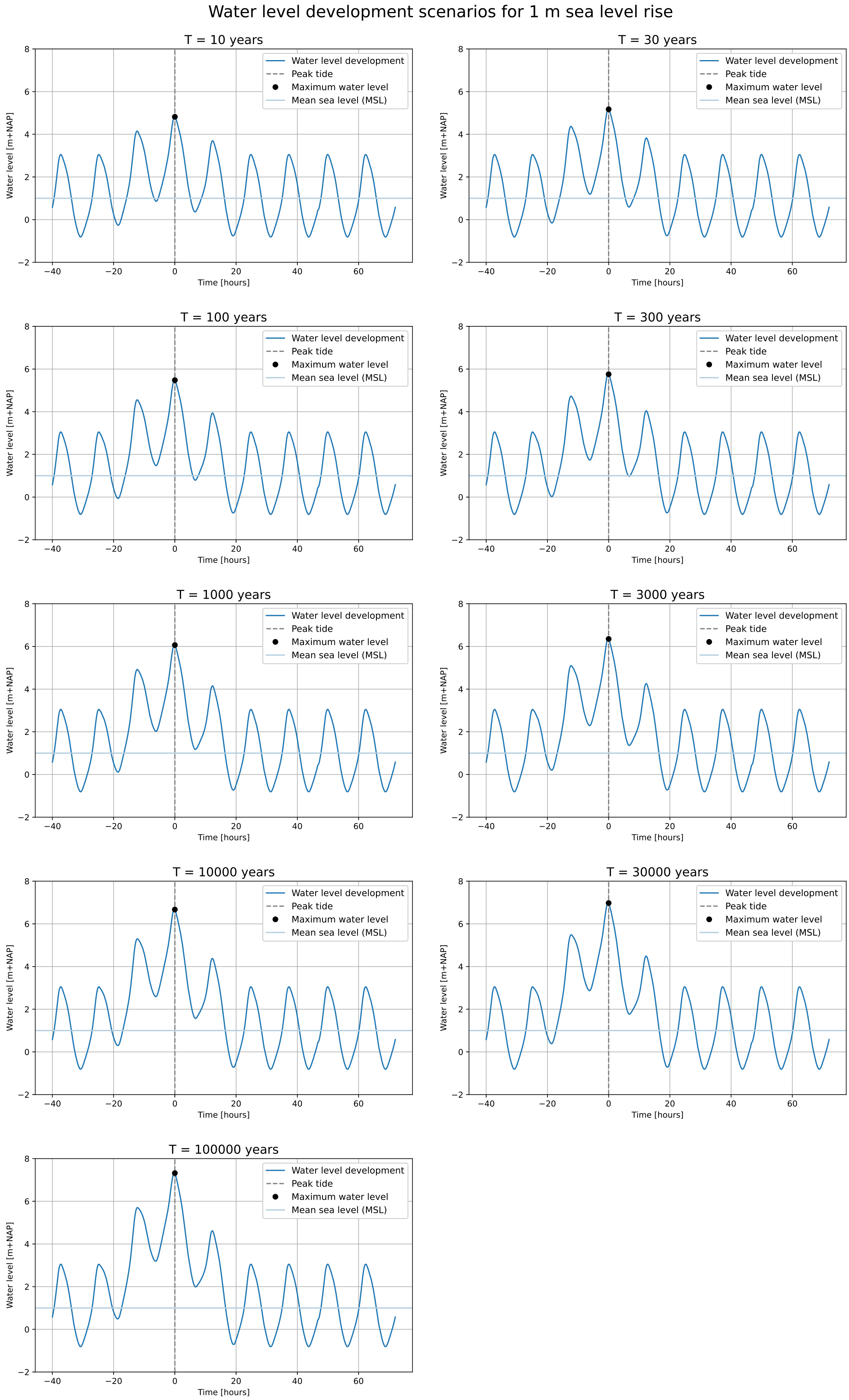


Figure A.3: Water level development scenarios (Walcheren) for 1 m sea level rise

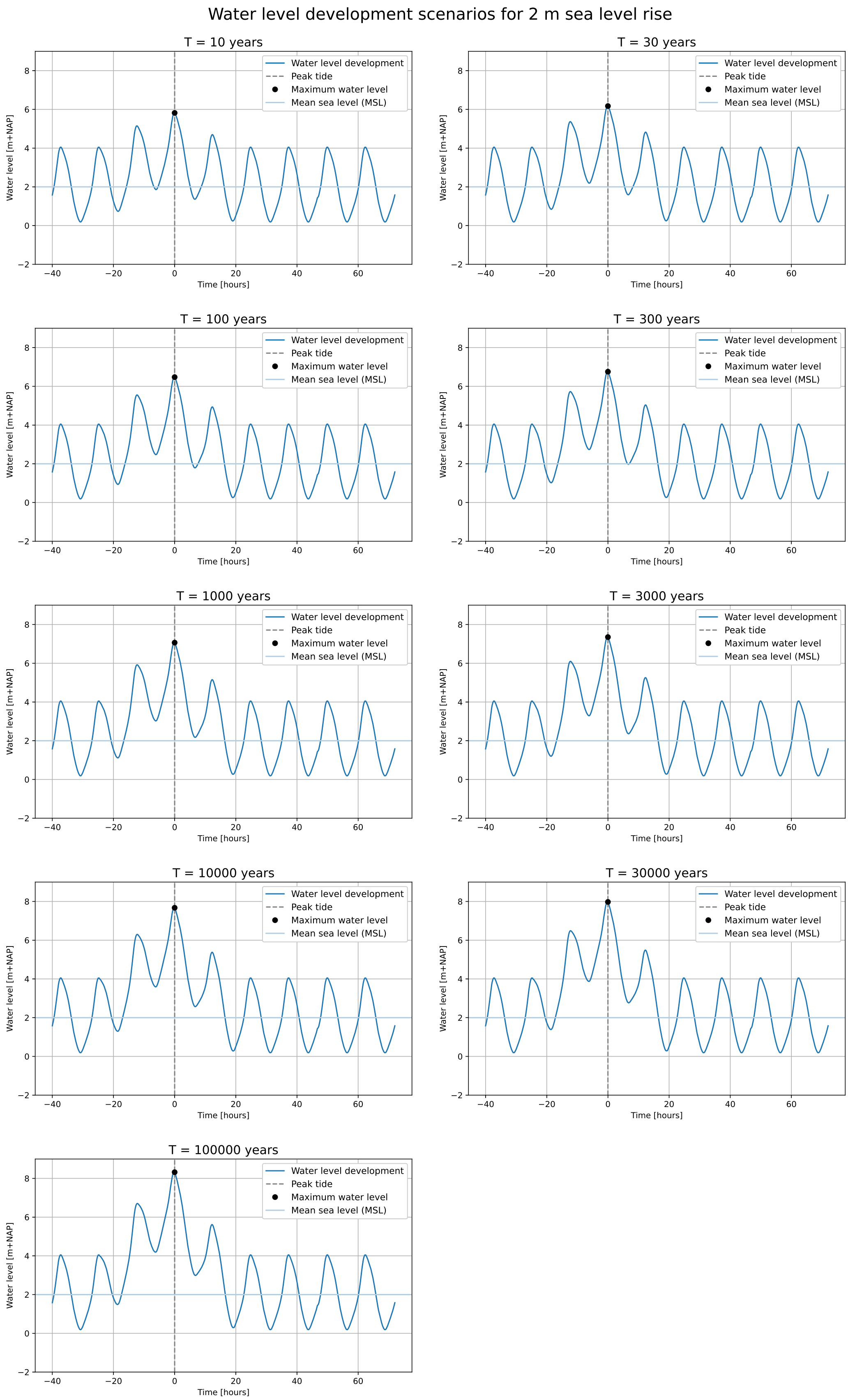


Figure A.4: Water level development scenarios (Walcheren) for 2 m sea level rise

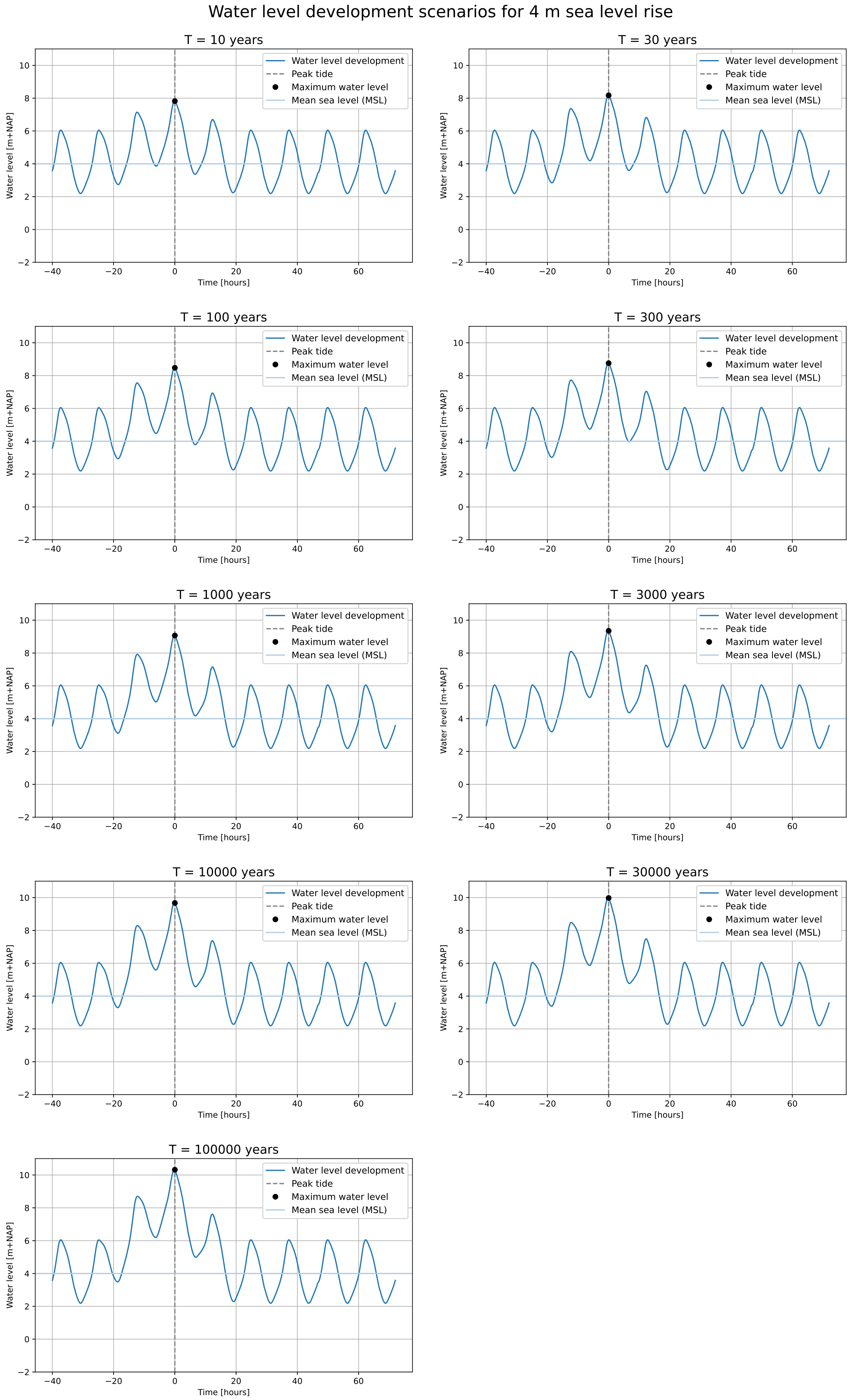


Figure A.5: Water level development scenarios (Walcheren) for 4 m sea level rise

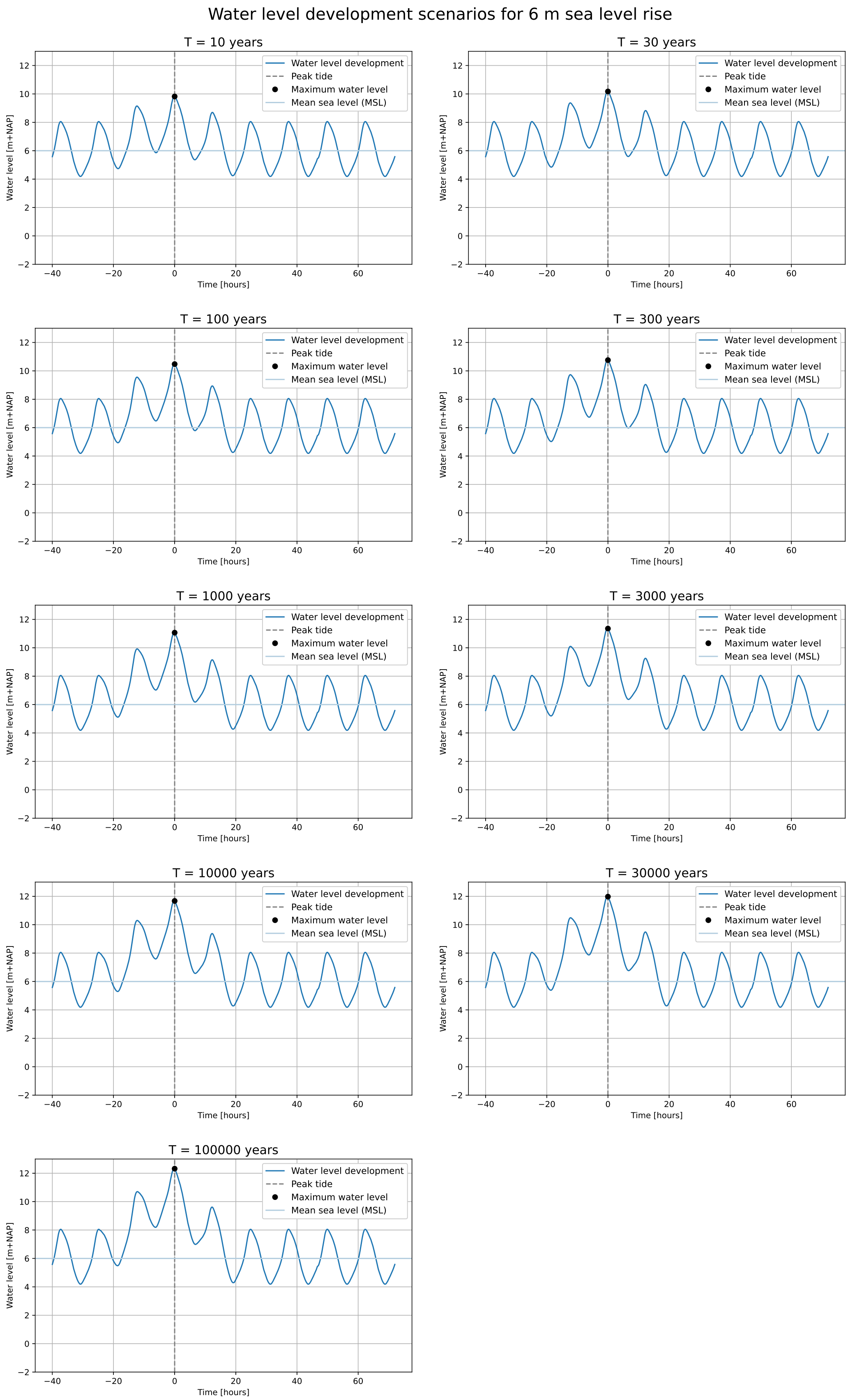


Figure A.6: Water level development scenarios (Walcheren) for 6 m sea level rise

B

Probabilistic approach

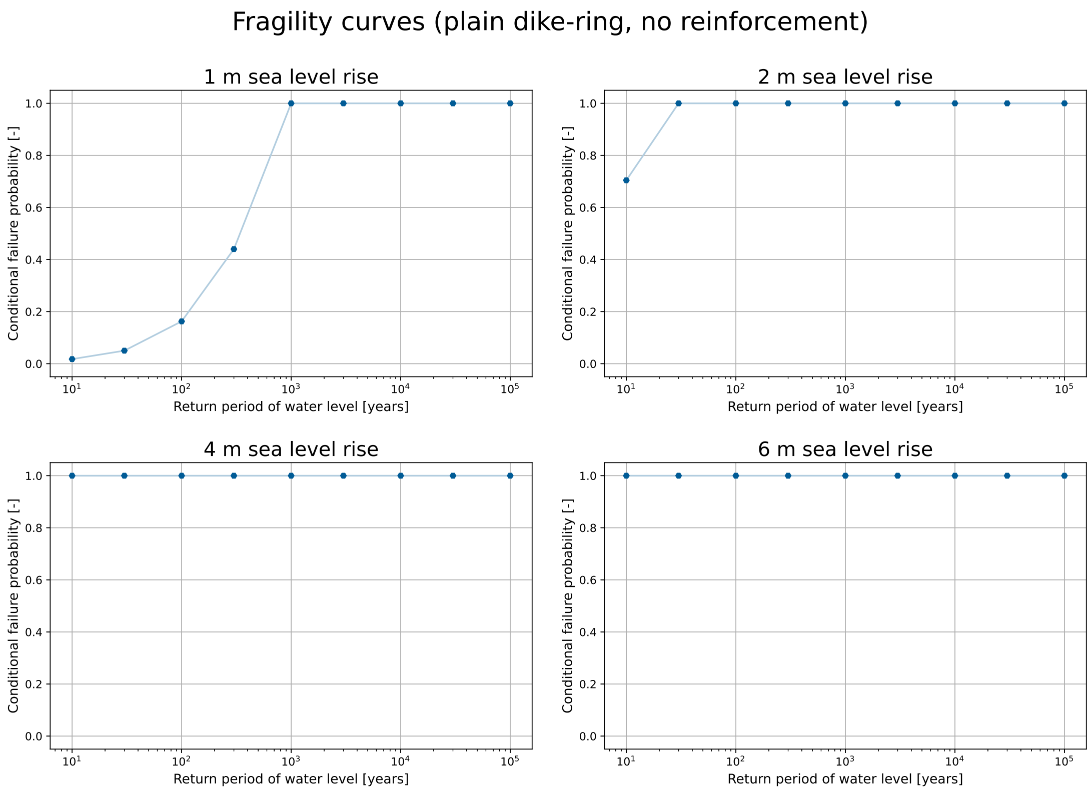


Figure B.1: Fragility curves scenarios

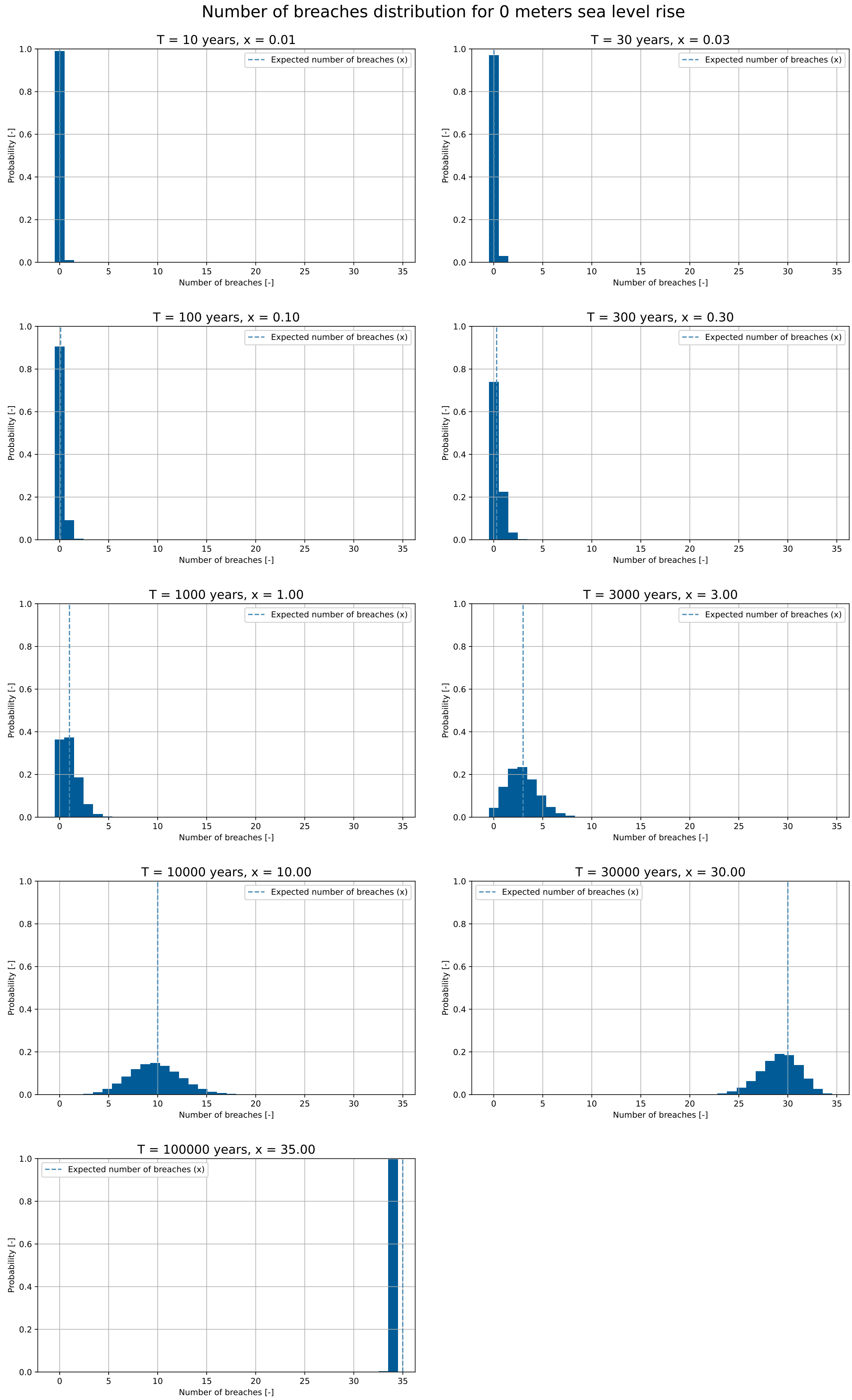


Figure B.2: Histograms: distribution of number of breaches for a scenario of 0 meters sea level rise

C

Idealized coastal polder

C.1. Polder inundation development of spatial adaptation strategies

C.1.1. Plain dike-ring

No dike reinforcement

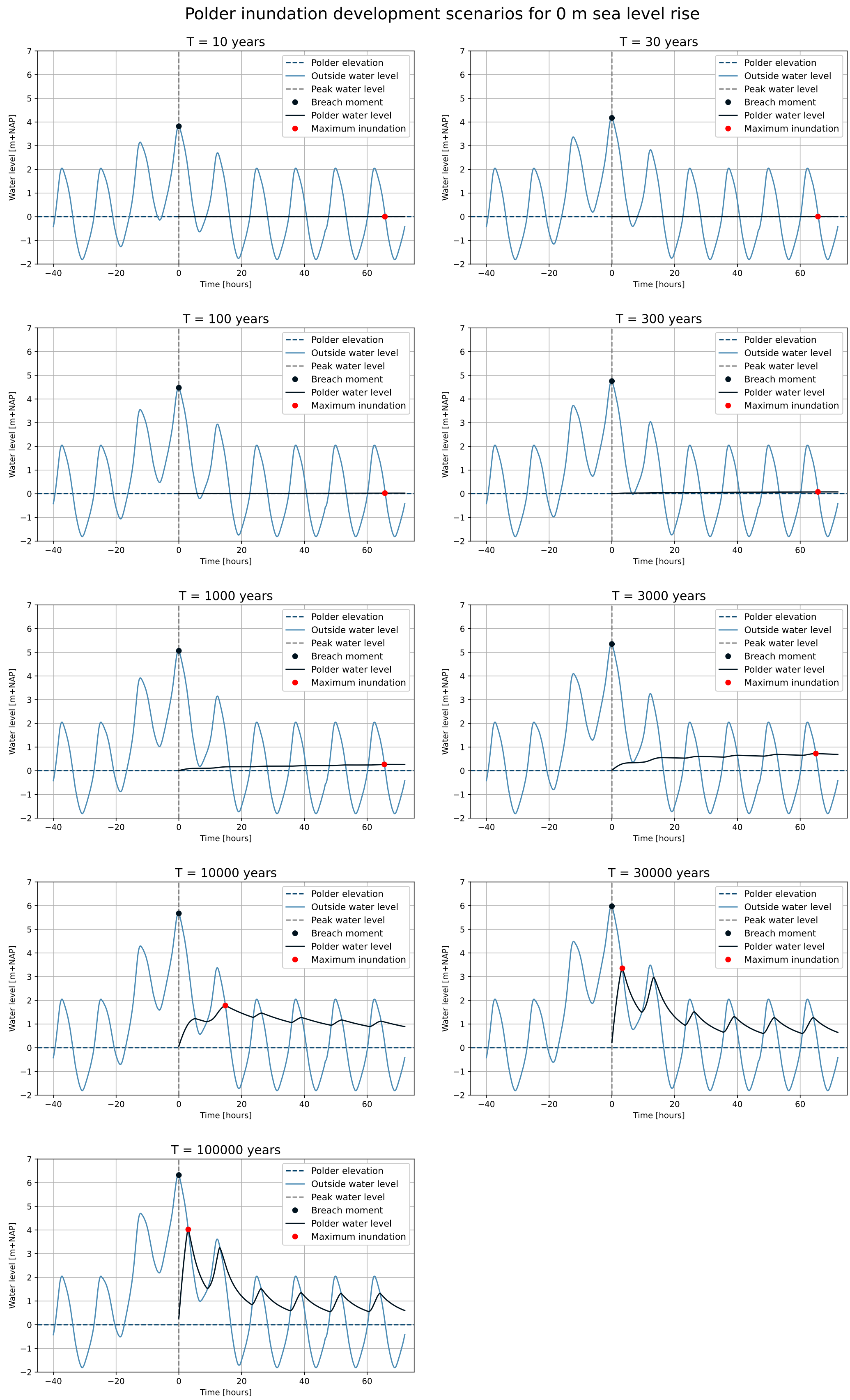


Figure C.1: Polder inundation development for 0 meter sea level rise (plain dike-ring strategy)

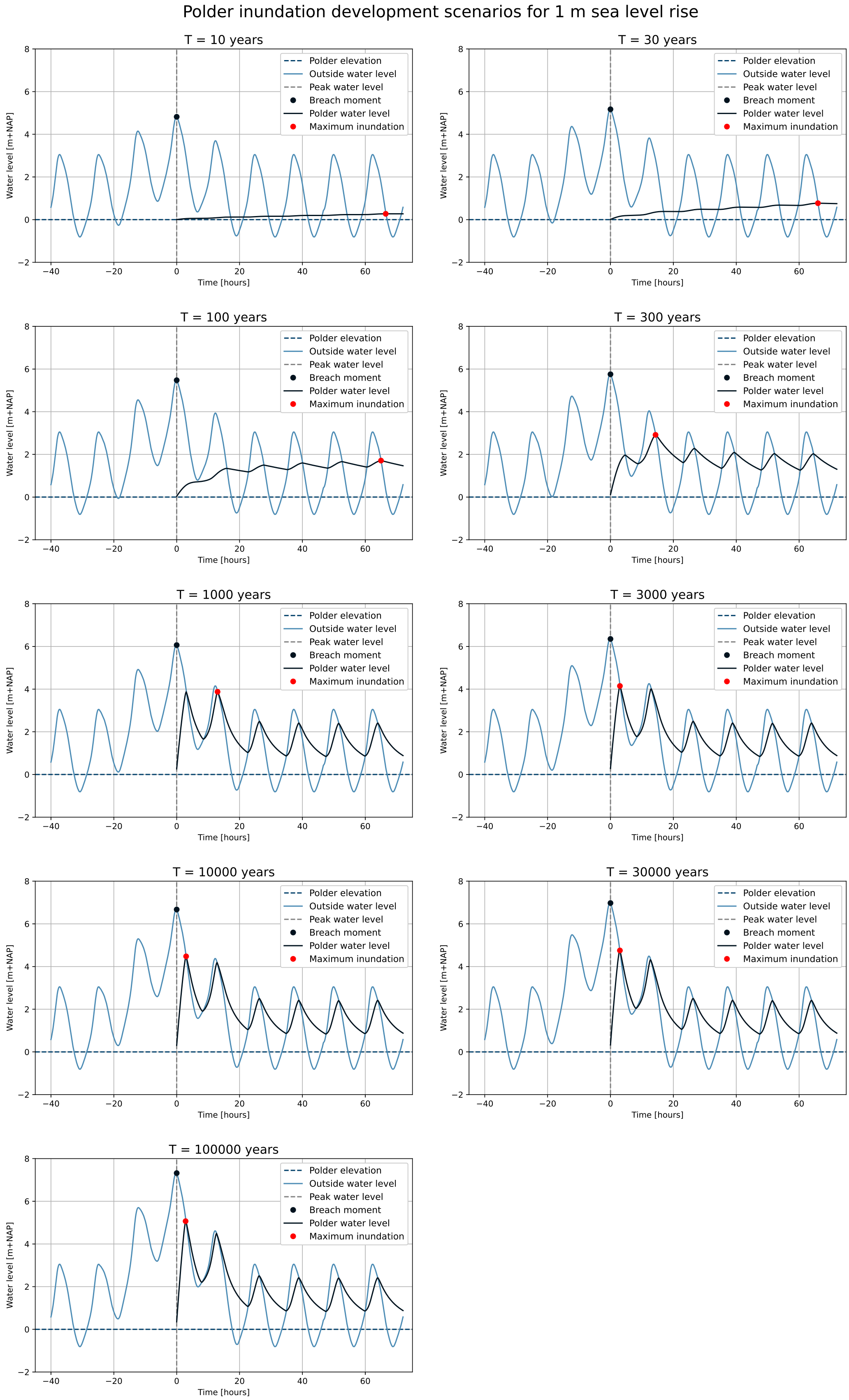


Figure C.2: Polder inundation development for 1 meter sea level rise (no dike reinforcement) (plain dike-ring strategy)

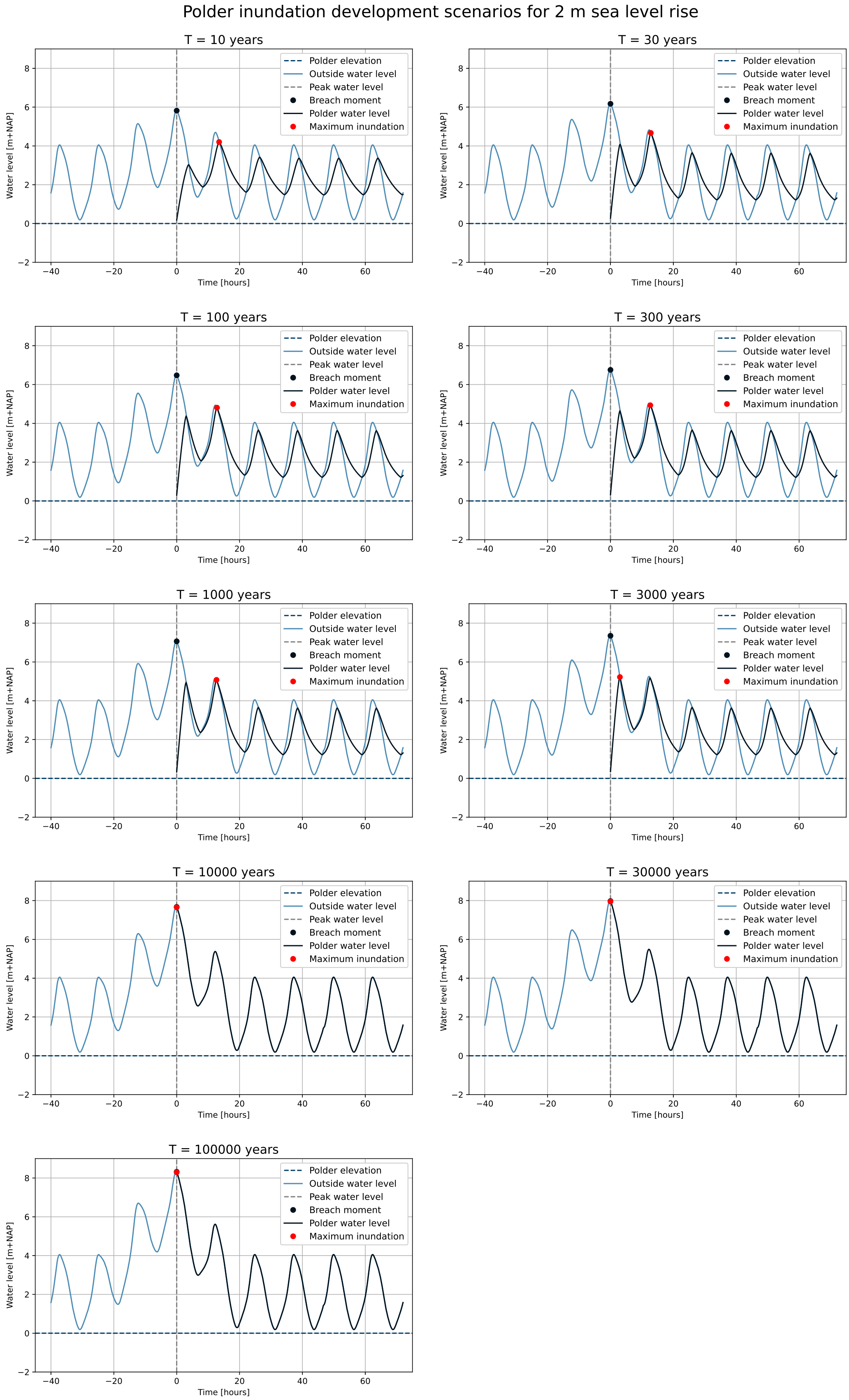


Figure C.3: Polder inundation development for 2 meter sea level rise (no dike reinforcement) (plain dike-ring strategy)

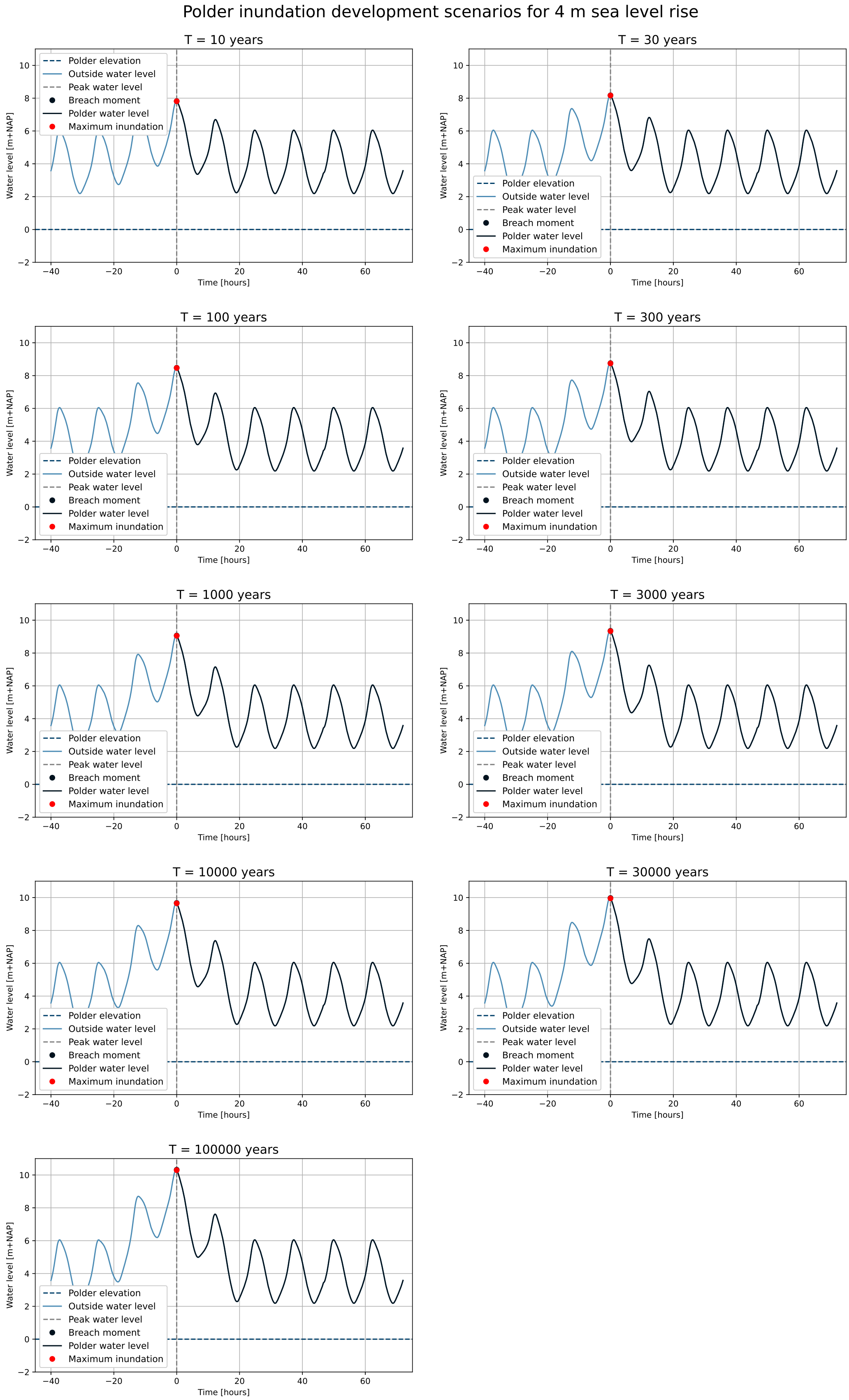


Figure C.4: Polder inundation development for 4 meter sea level rise (no dike reinforcement) (plain dike-ring strategy)

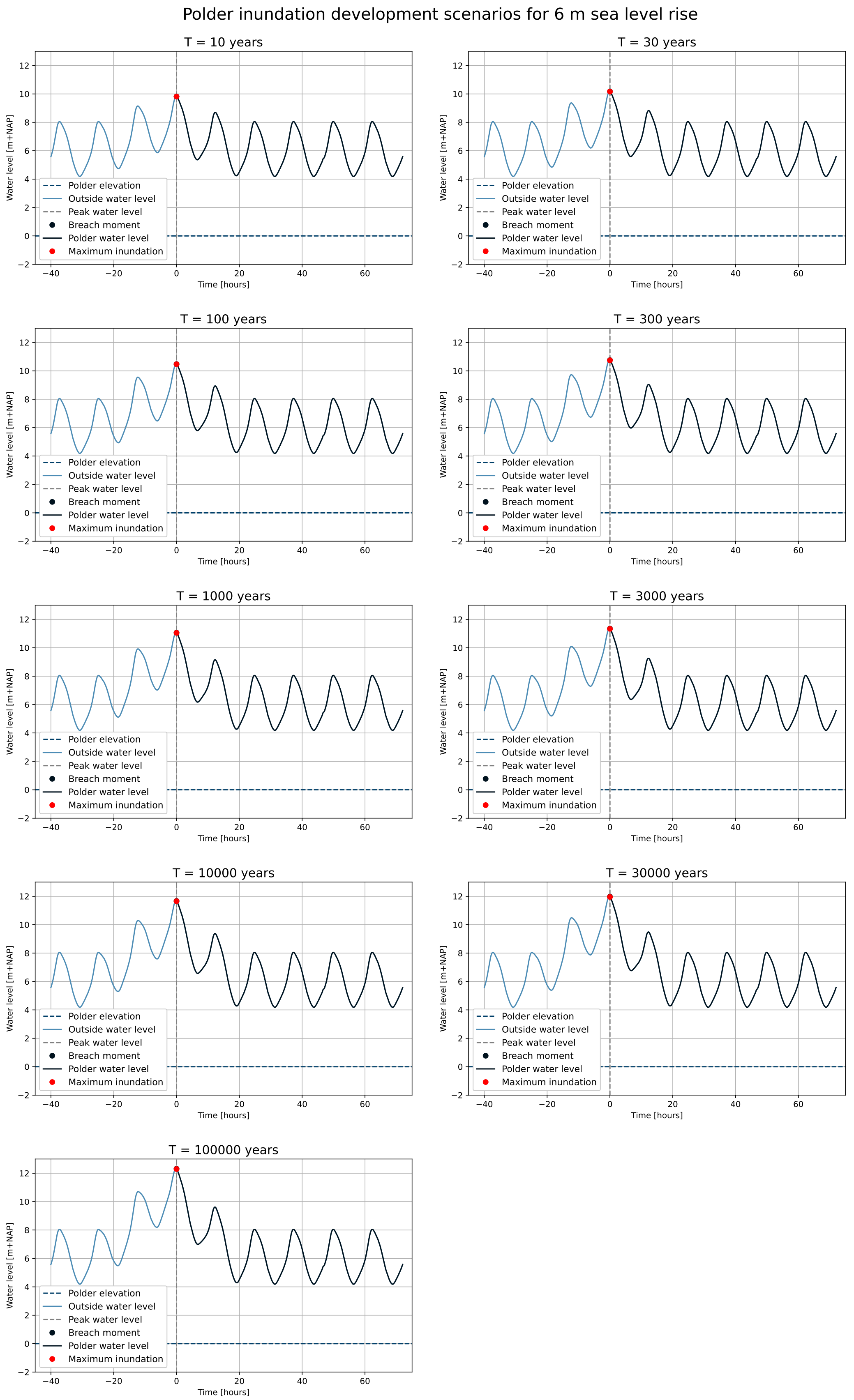


Figure C.5: Polder inundation development for 6 meter sea level rise (no dike reinforcement) (plain dike-ring strategy)

Dike reinforcement

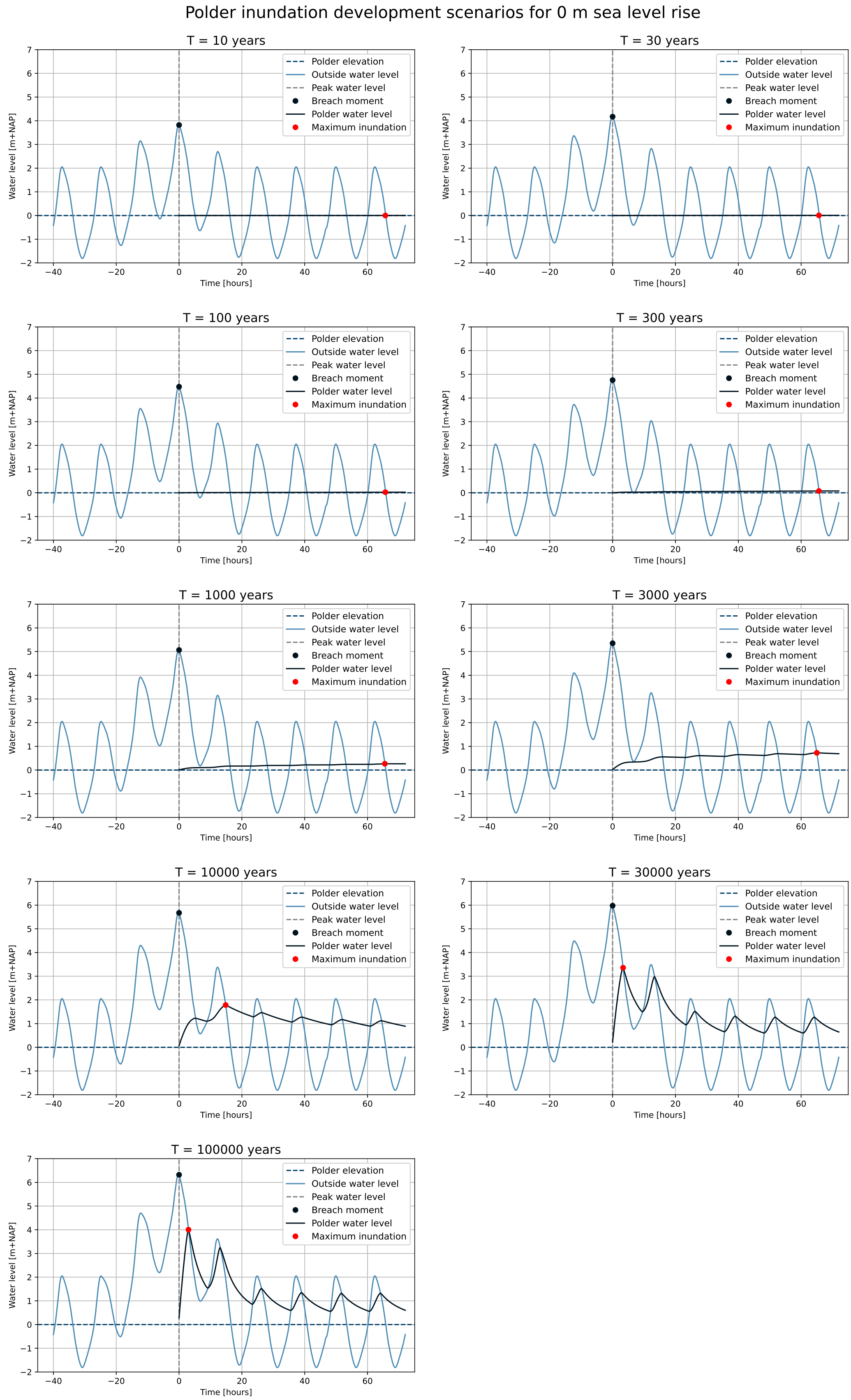


Figure C.6: Polder inundation development for 0 meter sea level rise (plain dike-ring strategy)

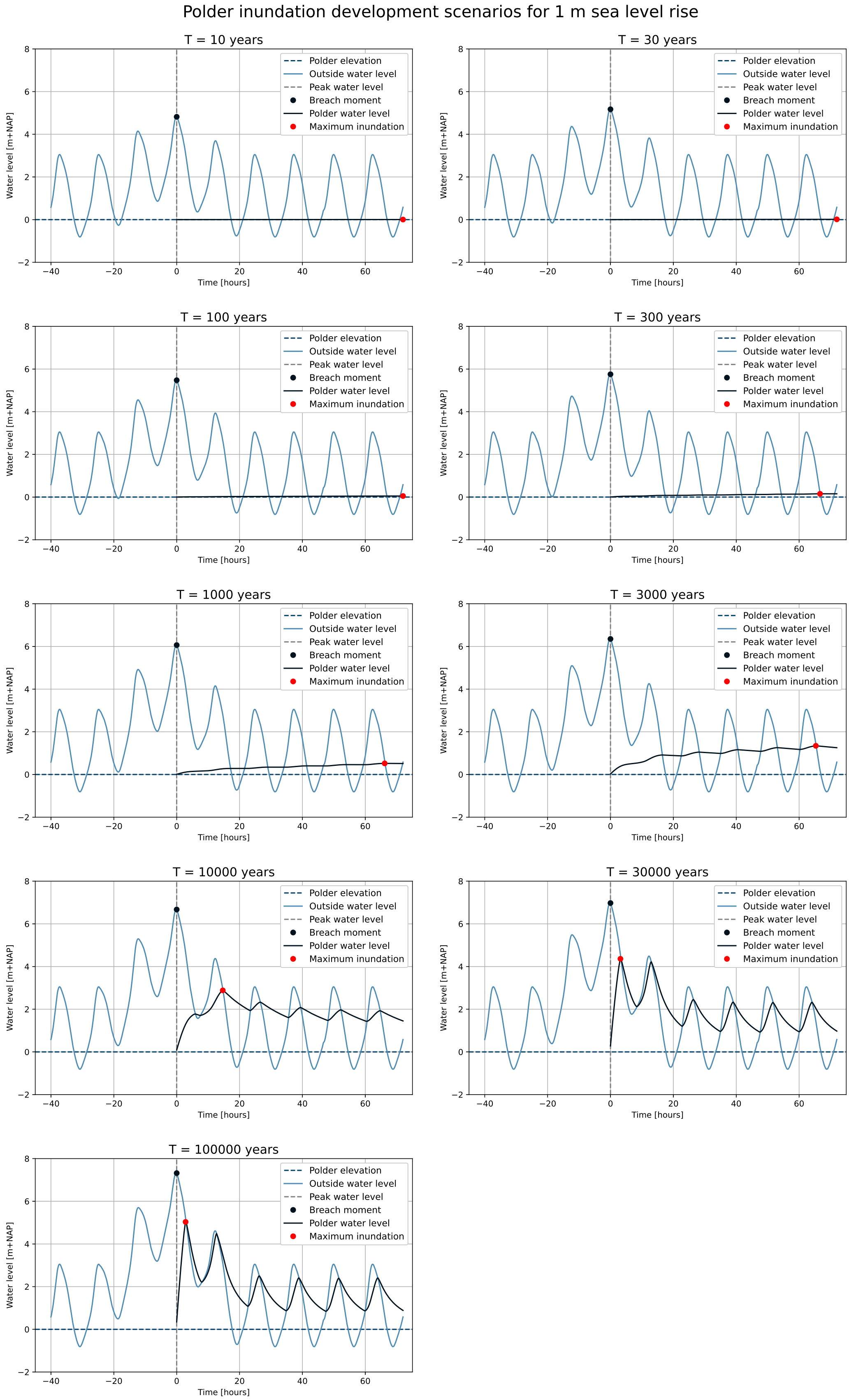


Figure C.7: Polder inundation development for 1 meter sea level rise (dike reinforcement) (plain dike-ring strategy)

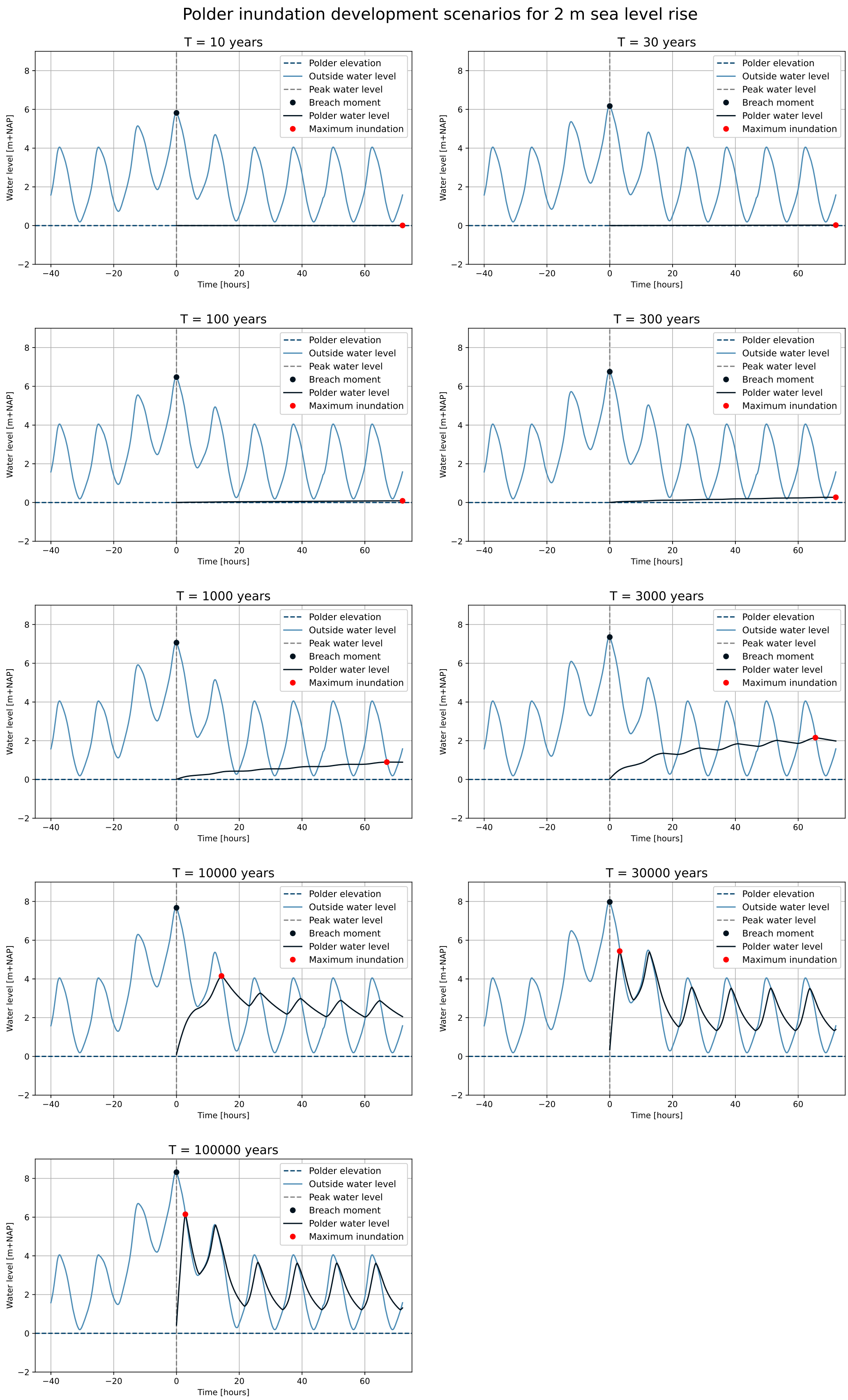


Figure C.8: Polder inundation development for 2 meter sea level rise (dike reinforcement) (plain dike-ring strategy)

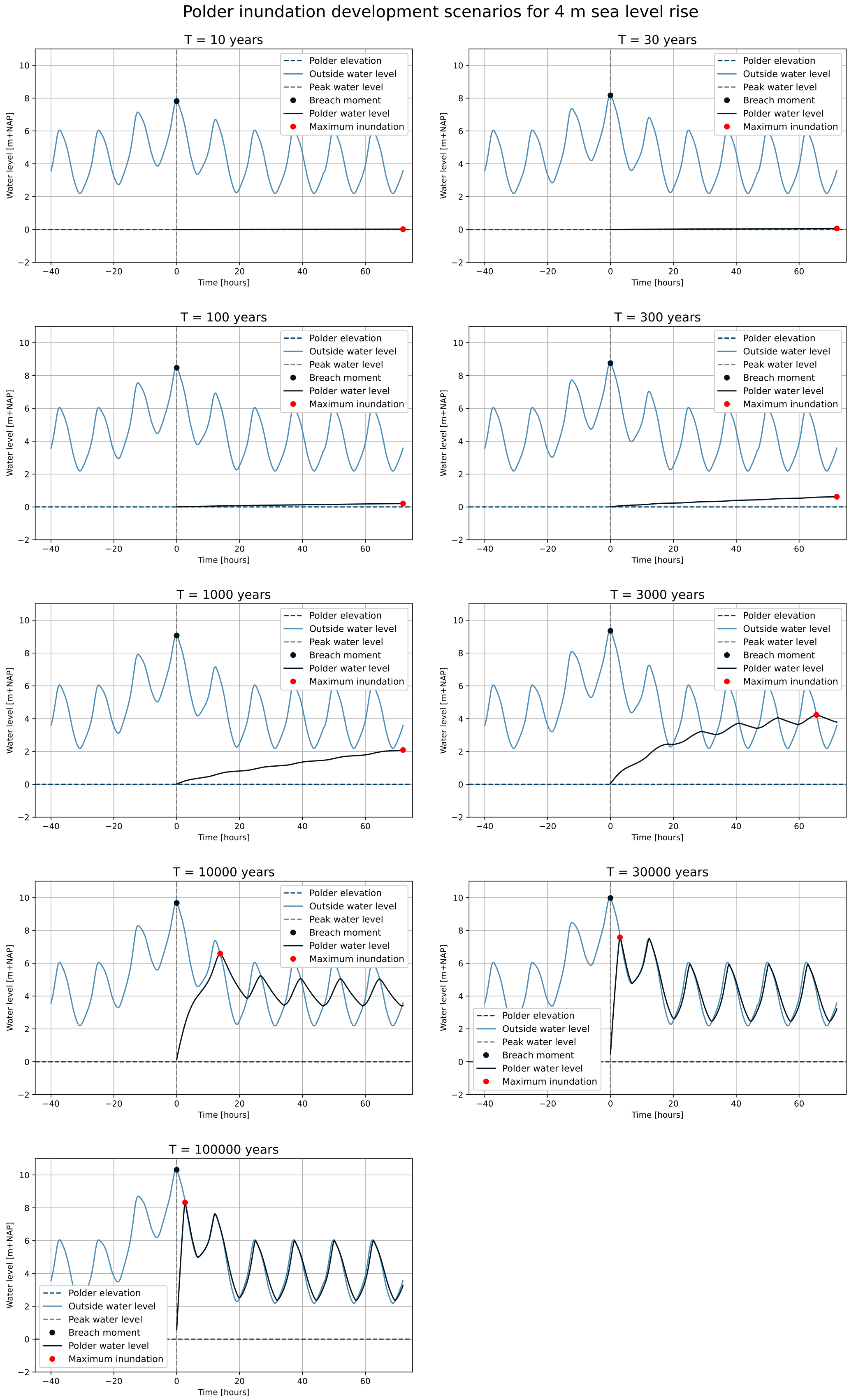


Figure C.9: Polder inundation development for 4 meter sea level rise (dike reinforcement) (plain dike-ring strategy)

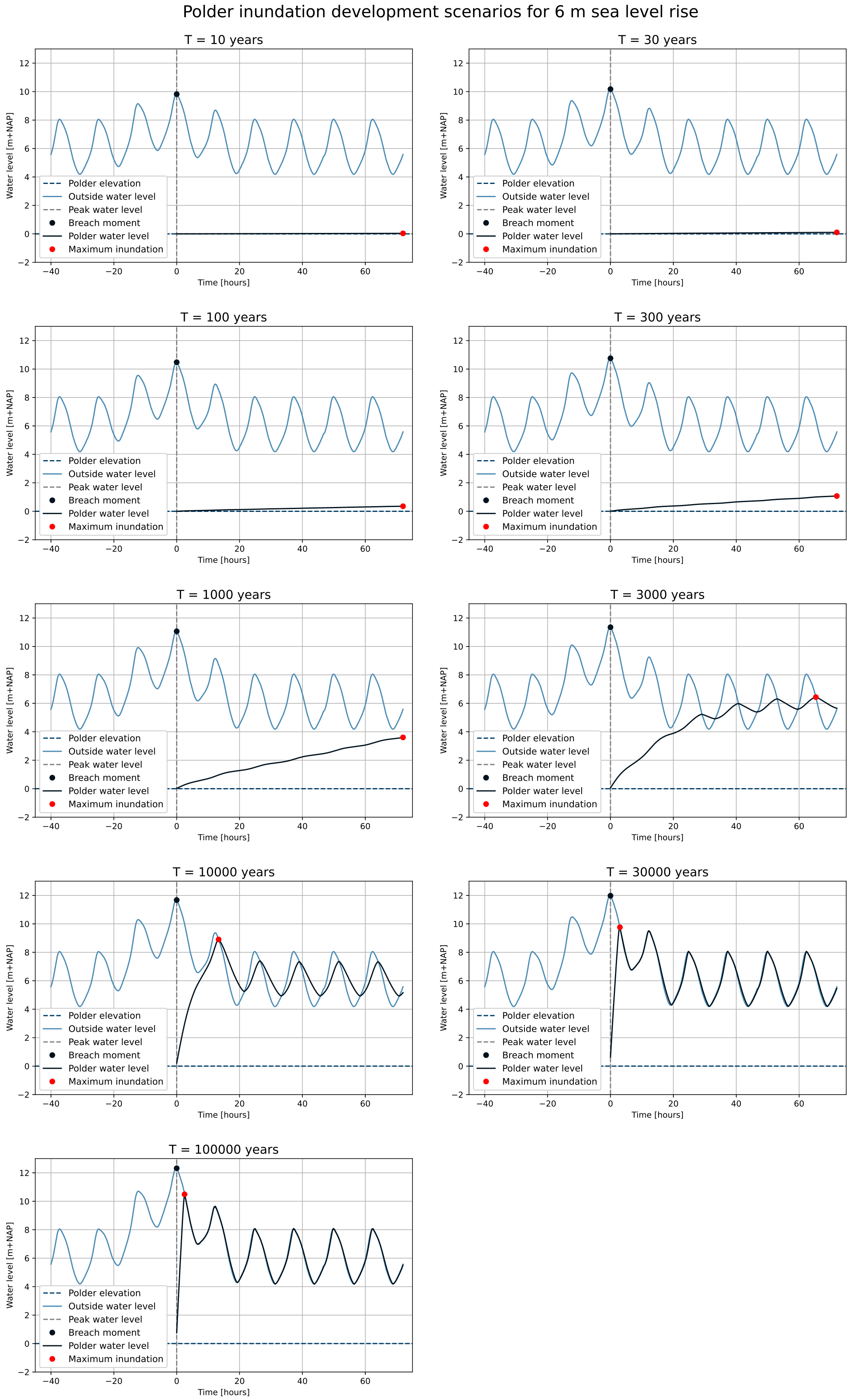


Figure C.10: Polder inundation development for 6 meter sea level rise (dike reinforcement) (plain dike-ring strategy)

C.1.2. Secondary dike-ring

Primary (outer) dike reinforcement

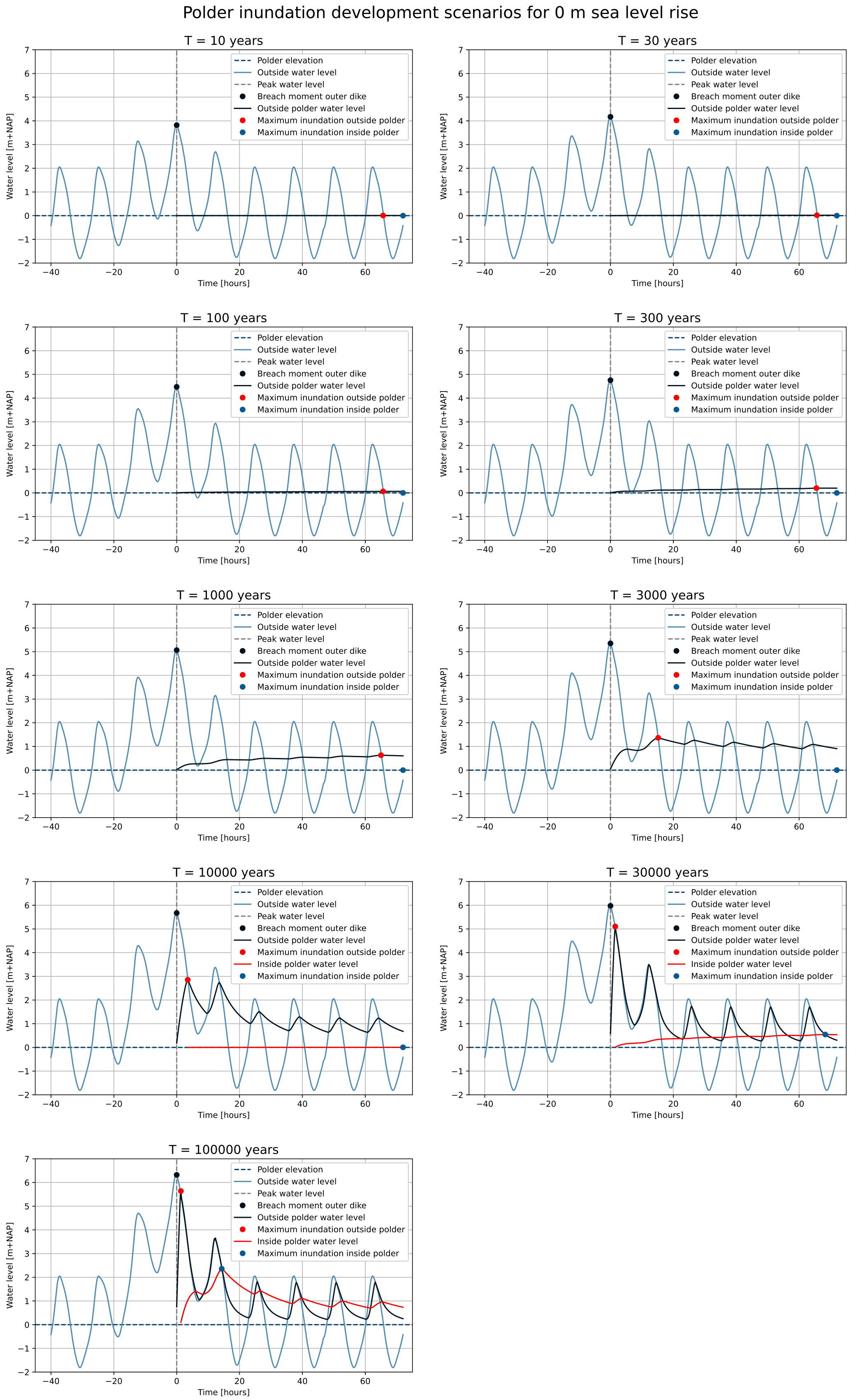


Figure C.11: Polder inundation development for 0 meter sea level rise (primary dike reinforcement) (secondary dike-ring strategy)

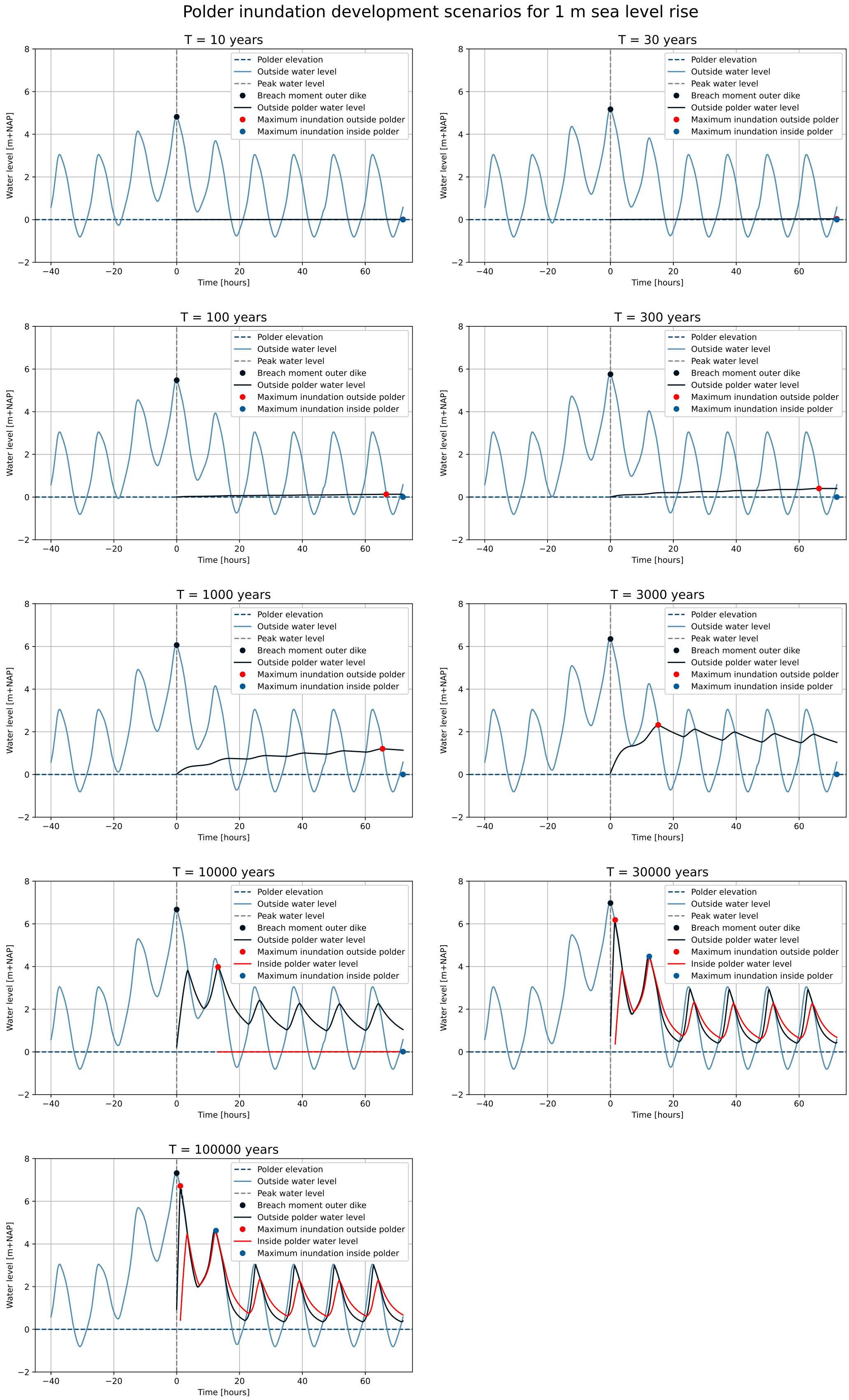


Figure C.12: Polder inundation development for 1 meter sea level rise (primary dike reinforcement) (secondary dike-ring strategy)

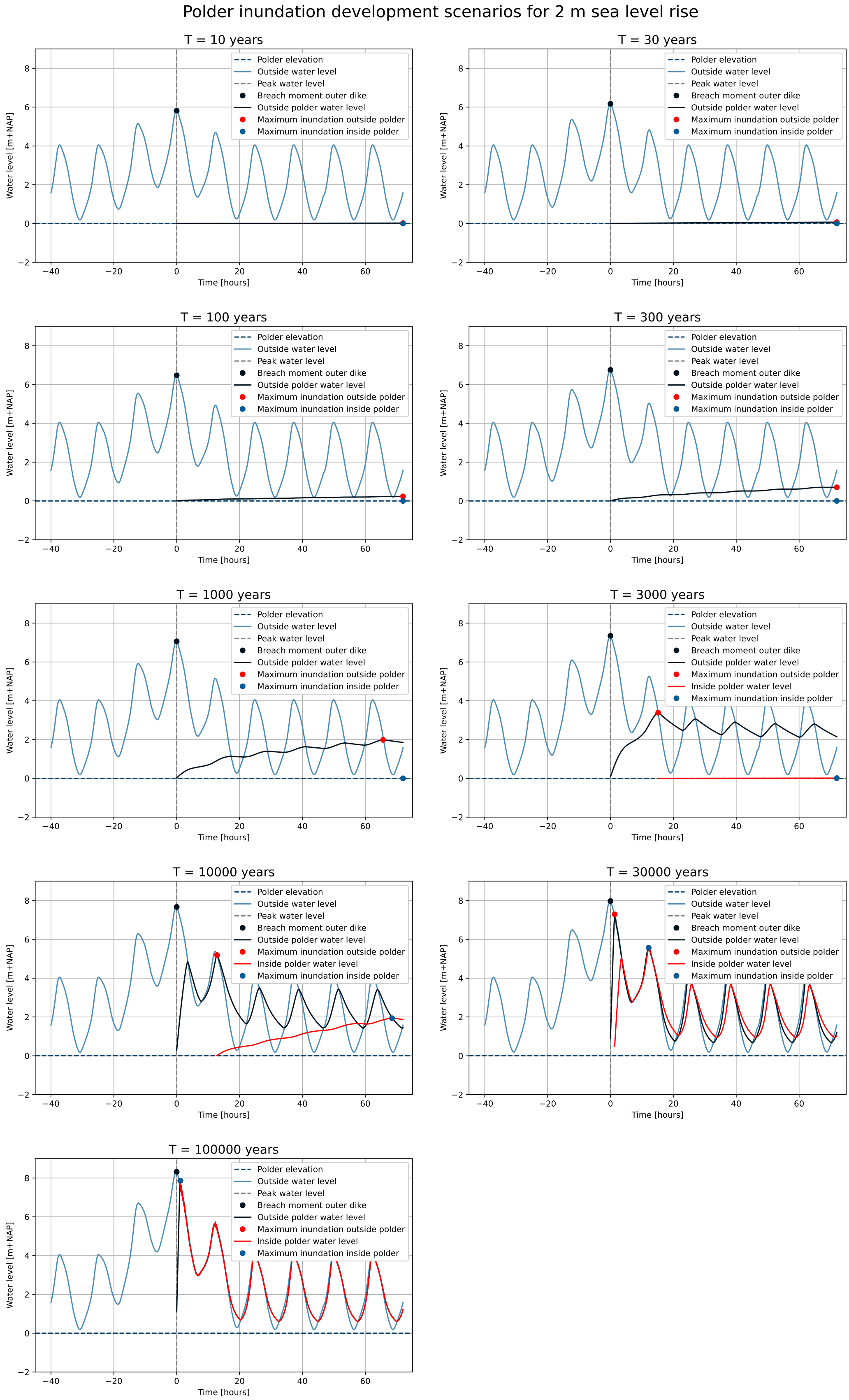


Figure C.13: Polder inundation development for 2 meter sea level rise (primary dike reinforcement) (secondary dike-ring strategy)

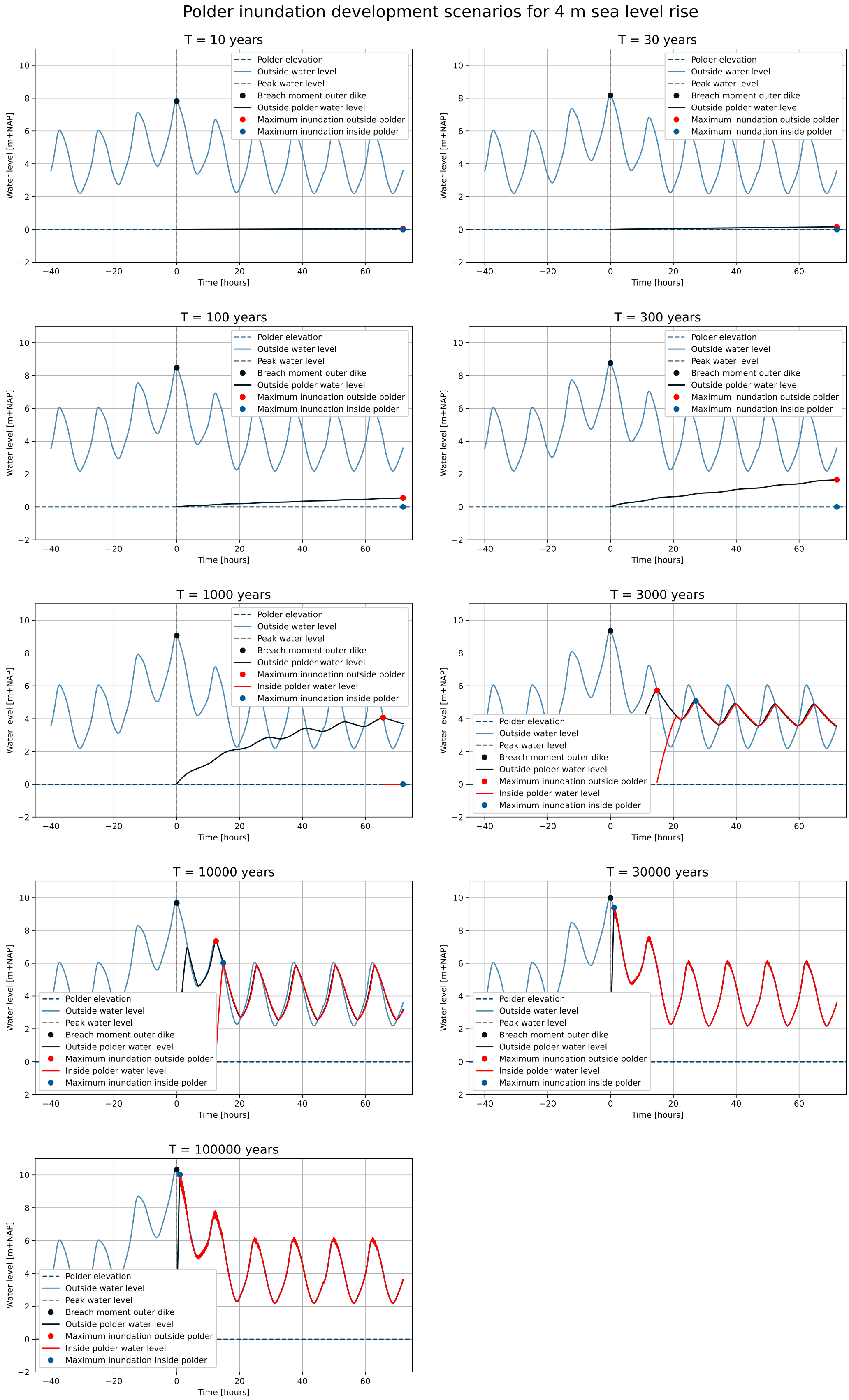


Figure C.14: Polder inundation development for 4 meter sea level rise (primary dike reinforcement) (secondary dike-ring strategy)

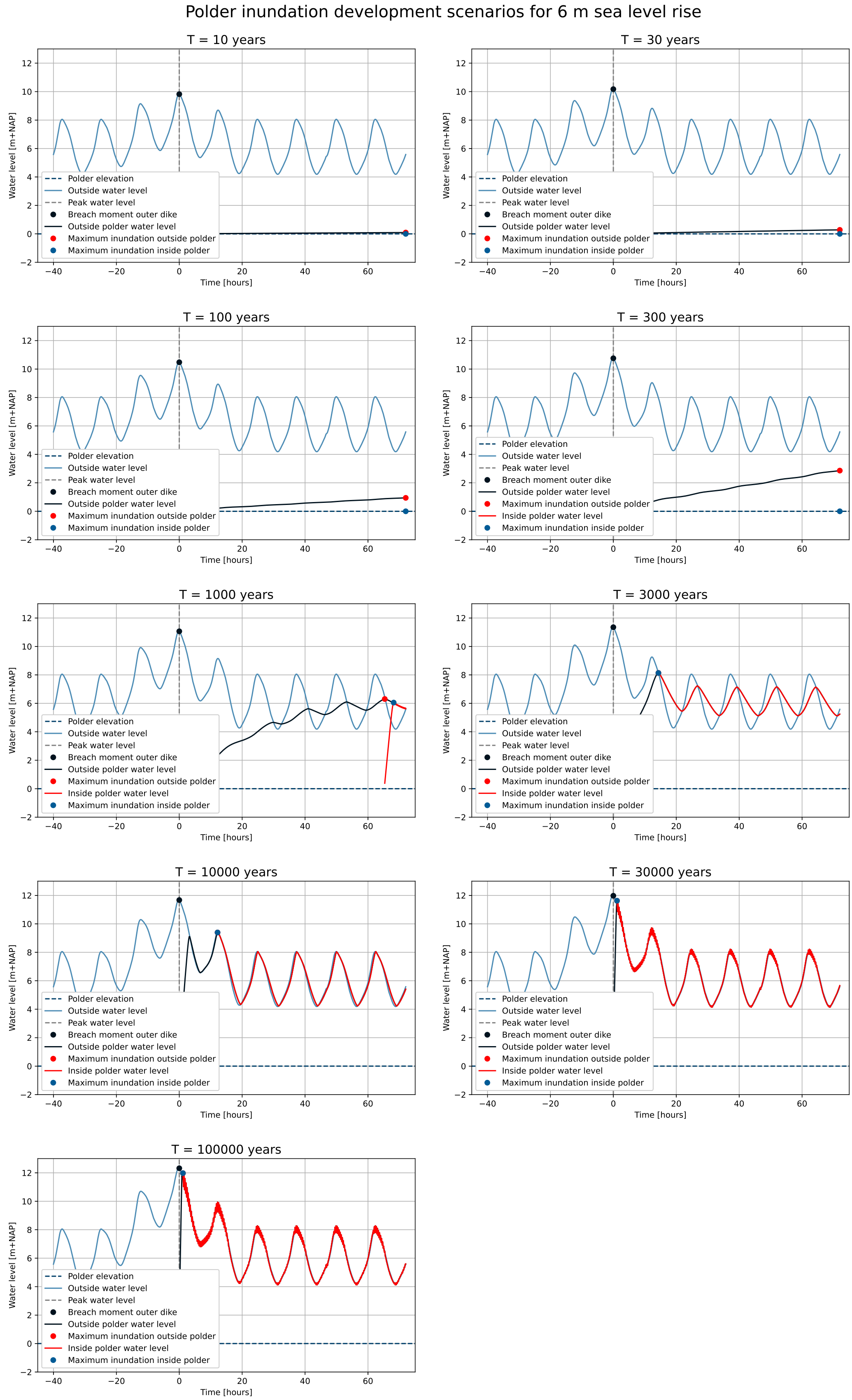


Figure C.15: Polder inundation development for 6 meter sea level rise (primary dike reinforcement) (secondary dike-ring strategy)

Secondary (inner) dike reinforcement

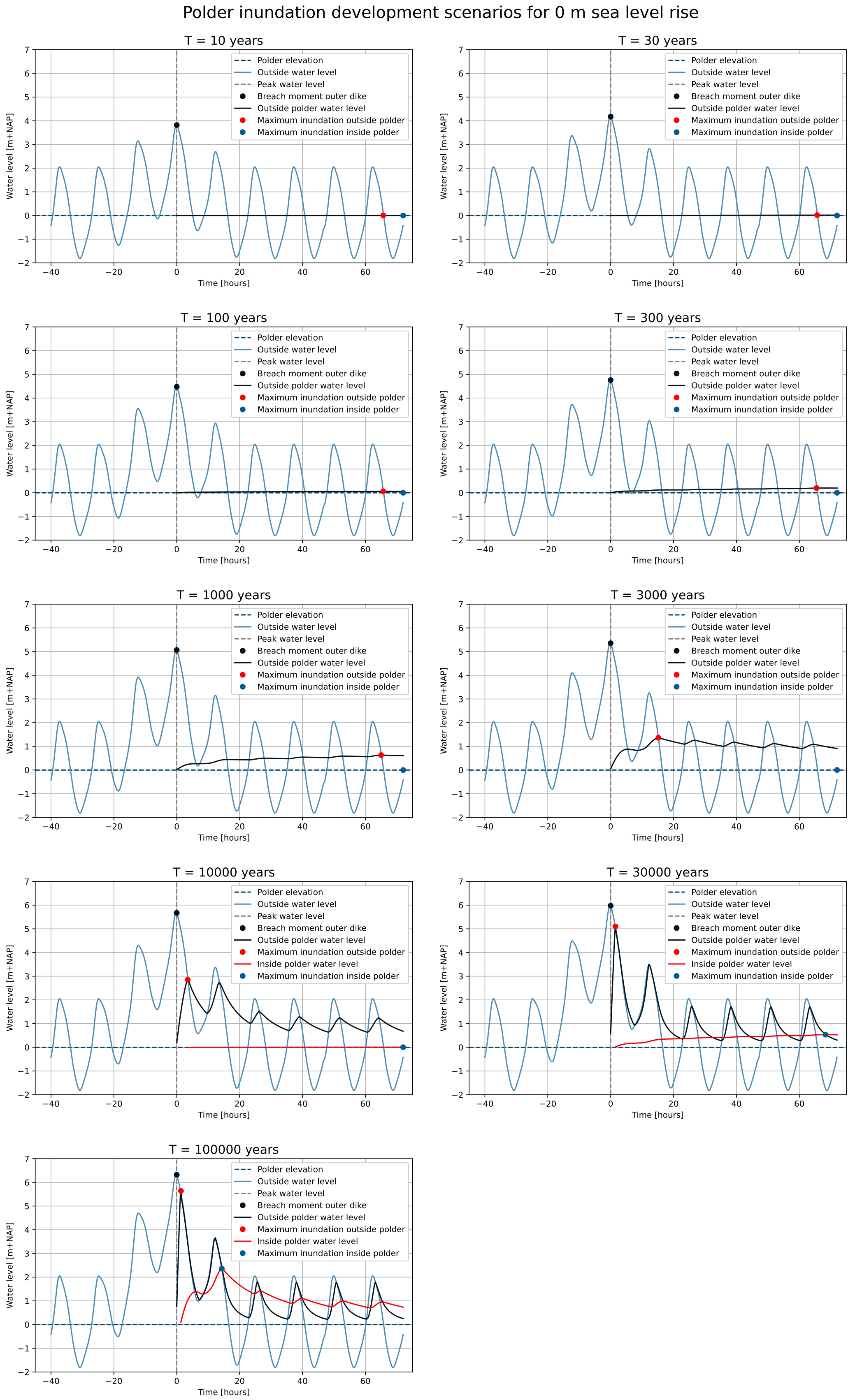


Figure C.16: Polder inundation development for 0 meter sea level rise (secondary dike reinforcement) (secondary dike-ring strategy)

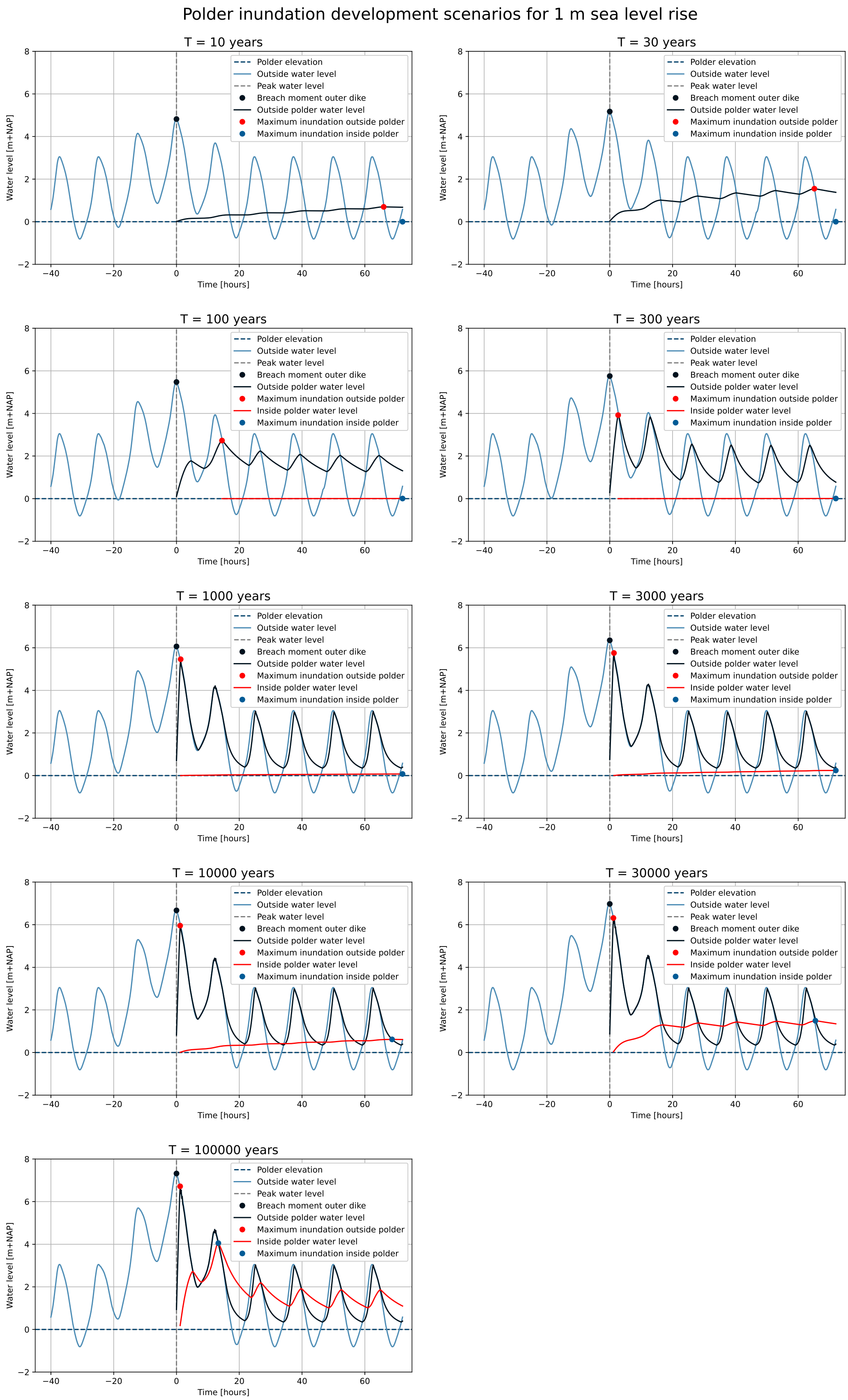


Figure C.17: Polder inundation development for 1 meter sea level rise (secondary dike reinforcement) (secondary dike-ring strategy)

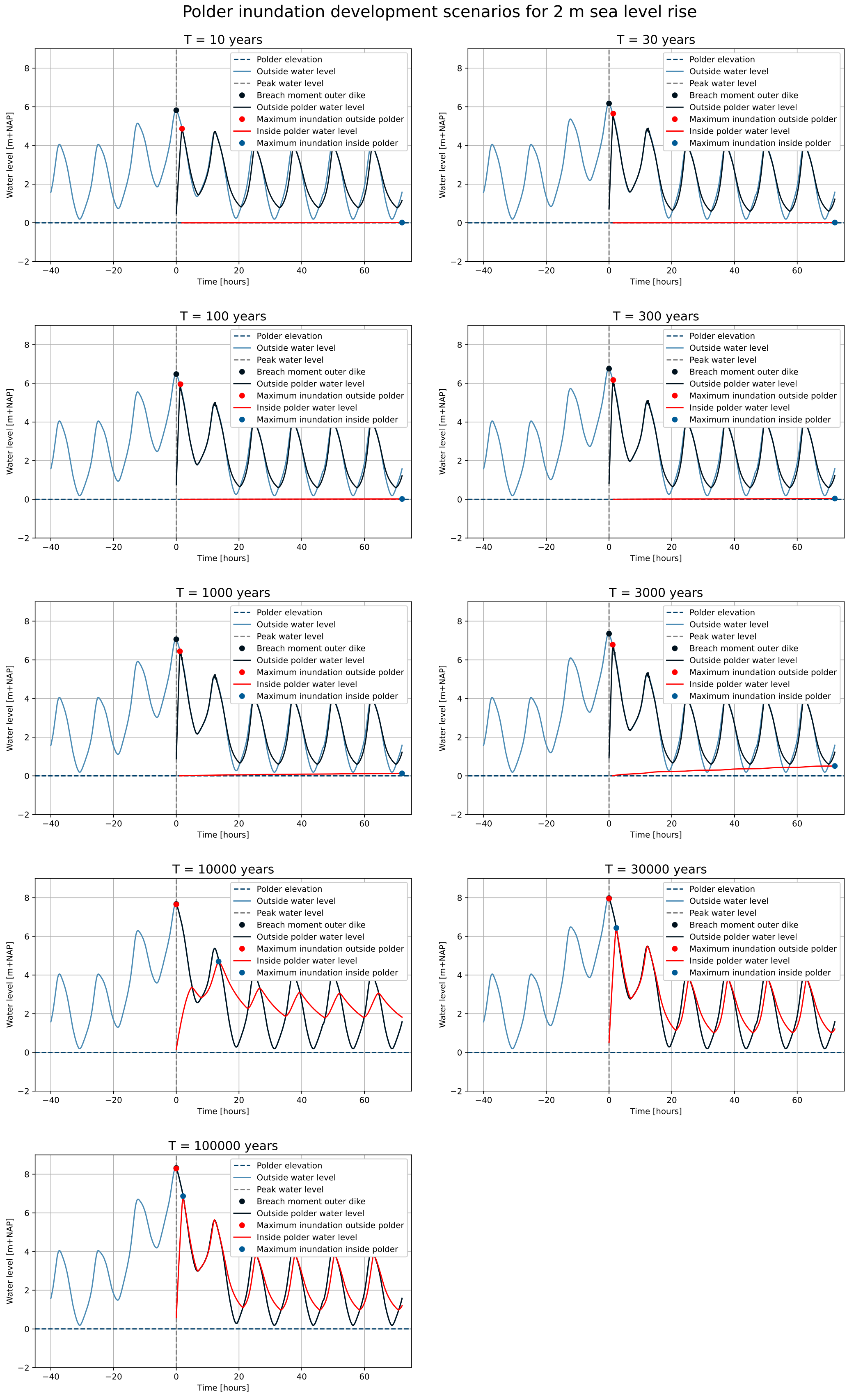


Figure C.18: Polder inundation development for 2 meter sea level rise (secondary dike reinforcement) (secondary dike-ring strategy)

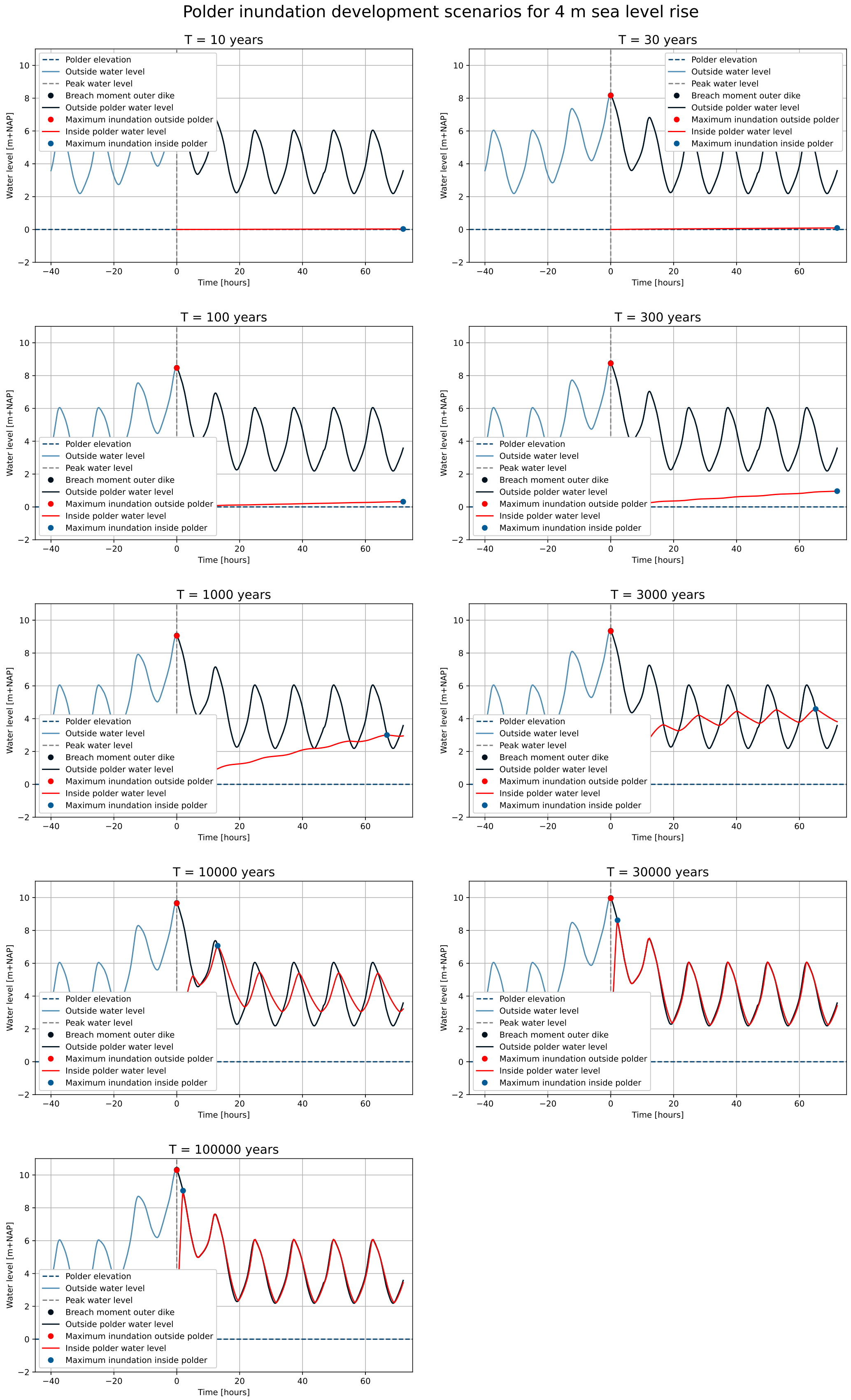


Figure C.19: Polder inundation development for 4 meter sea level rise (secondary dike reinforcement) (secondary dike-ring strategy)

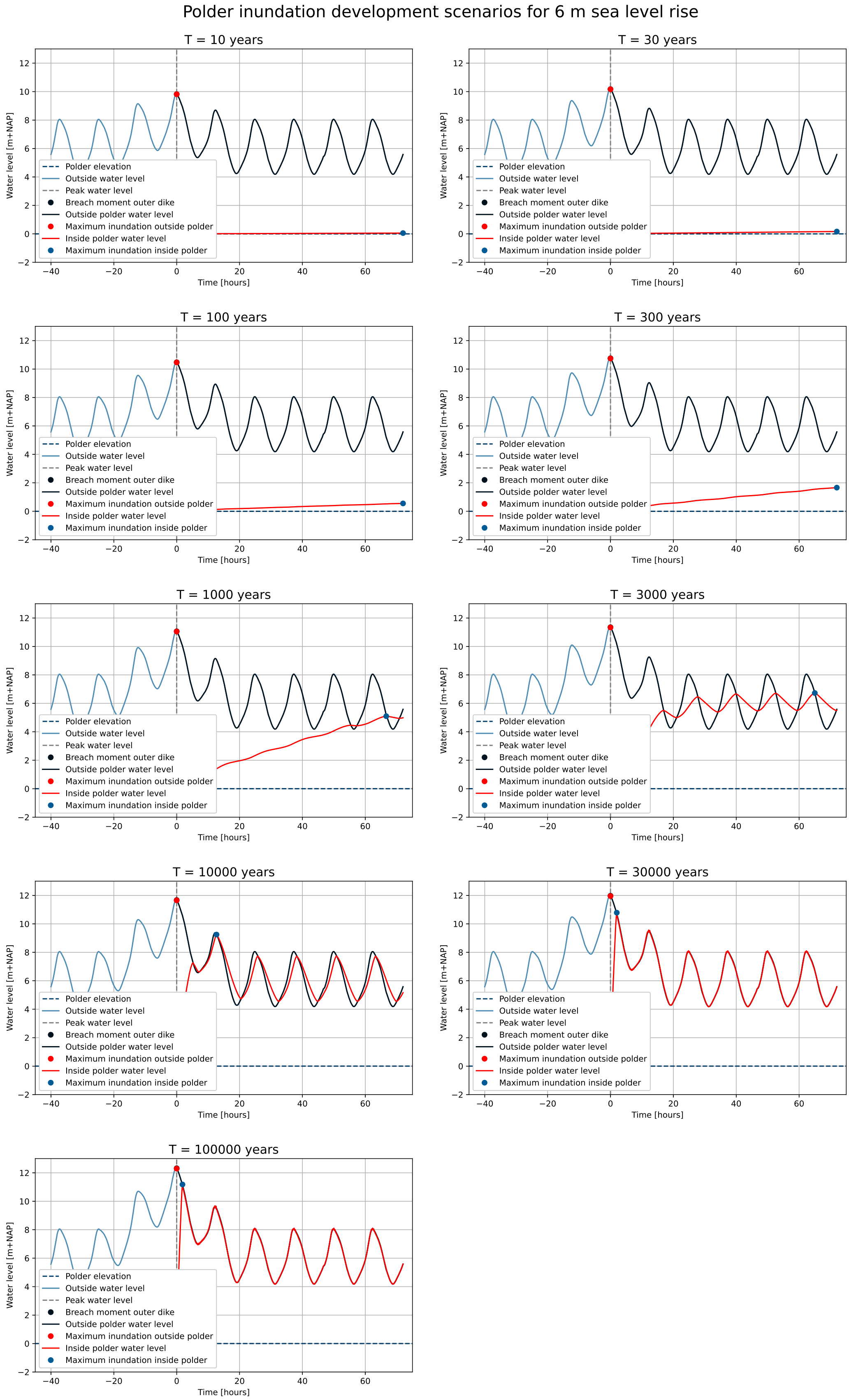


Figure C.20: Polder inundation development for 6 meter sea level rise (secondary dike reinforcement) (secondary dike-ring strategy)

Complete dike reinforcement

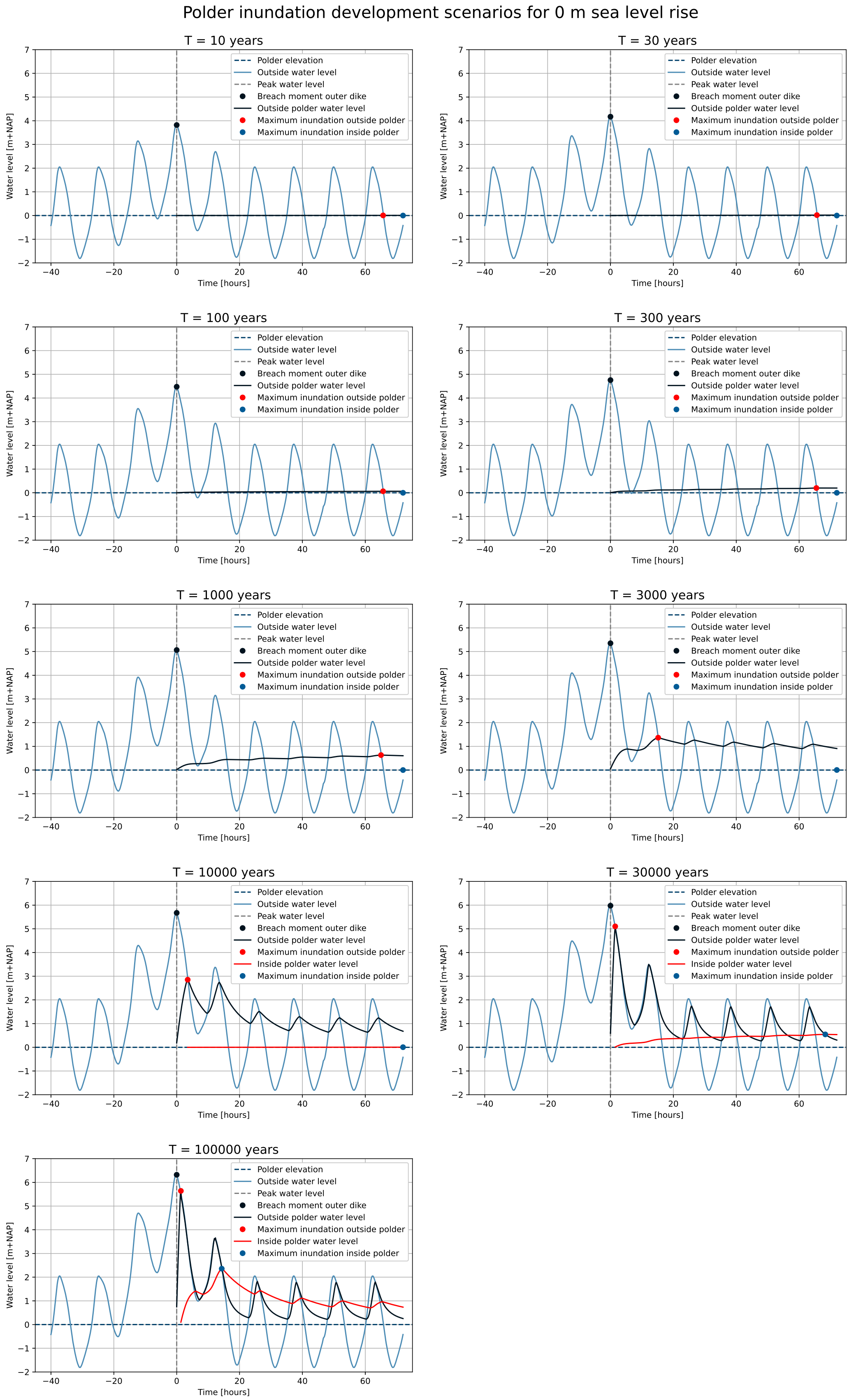


Figure C.21: Polder inundation development for 0 meter sea level rise (complete dike reinforcement) (secondary dike-ring strategy)

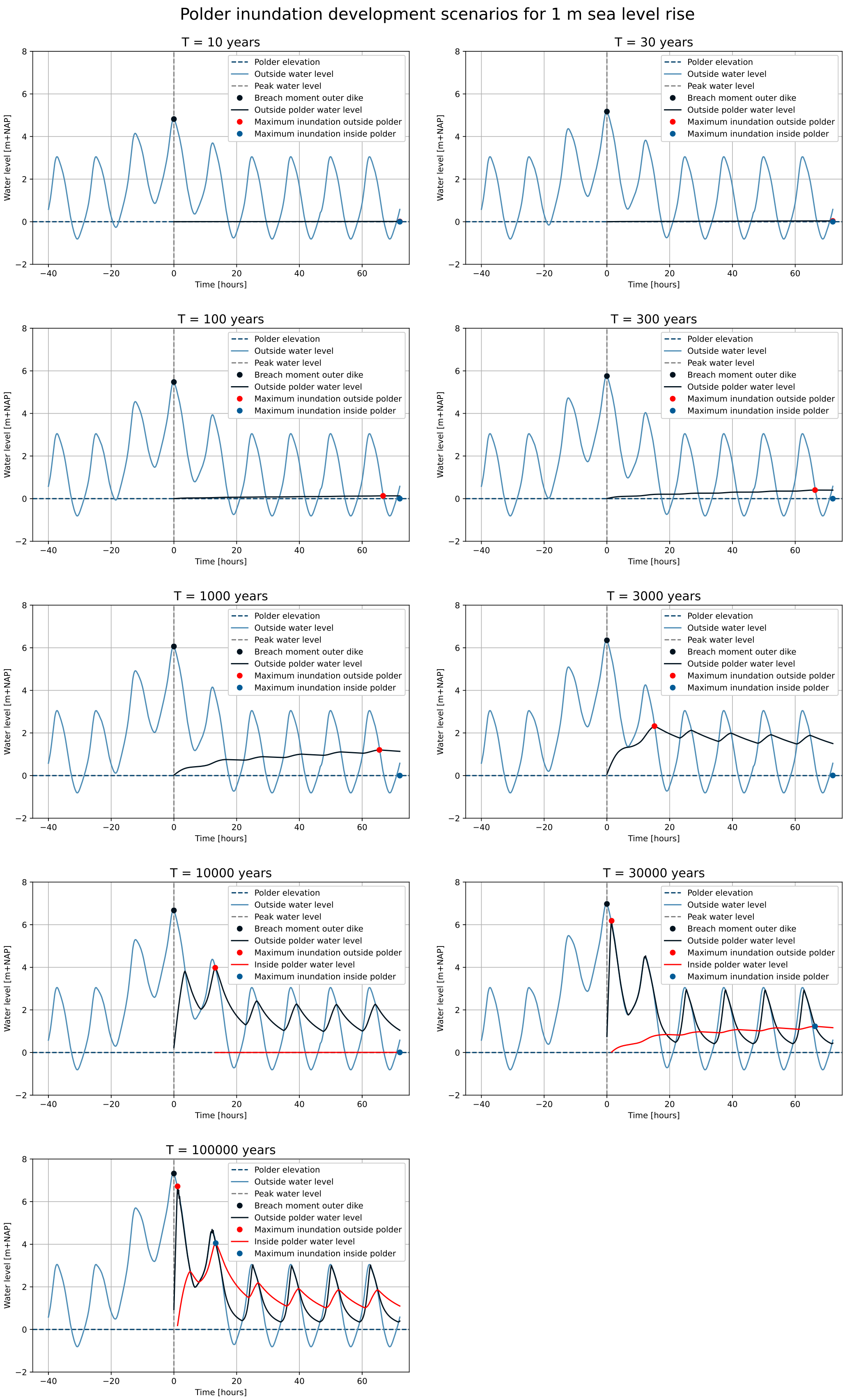


Figure C.22: Polder inundation development for 1 meter sea level rise (complete dike reinforcement) (secondary dike-ring strategy)

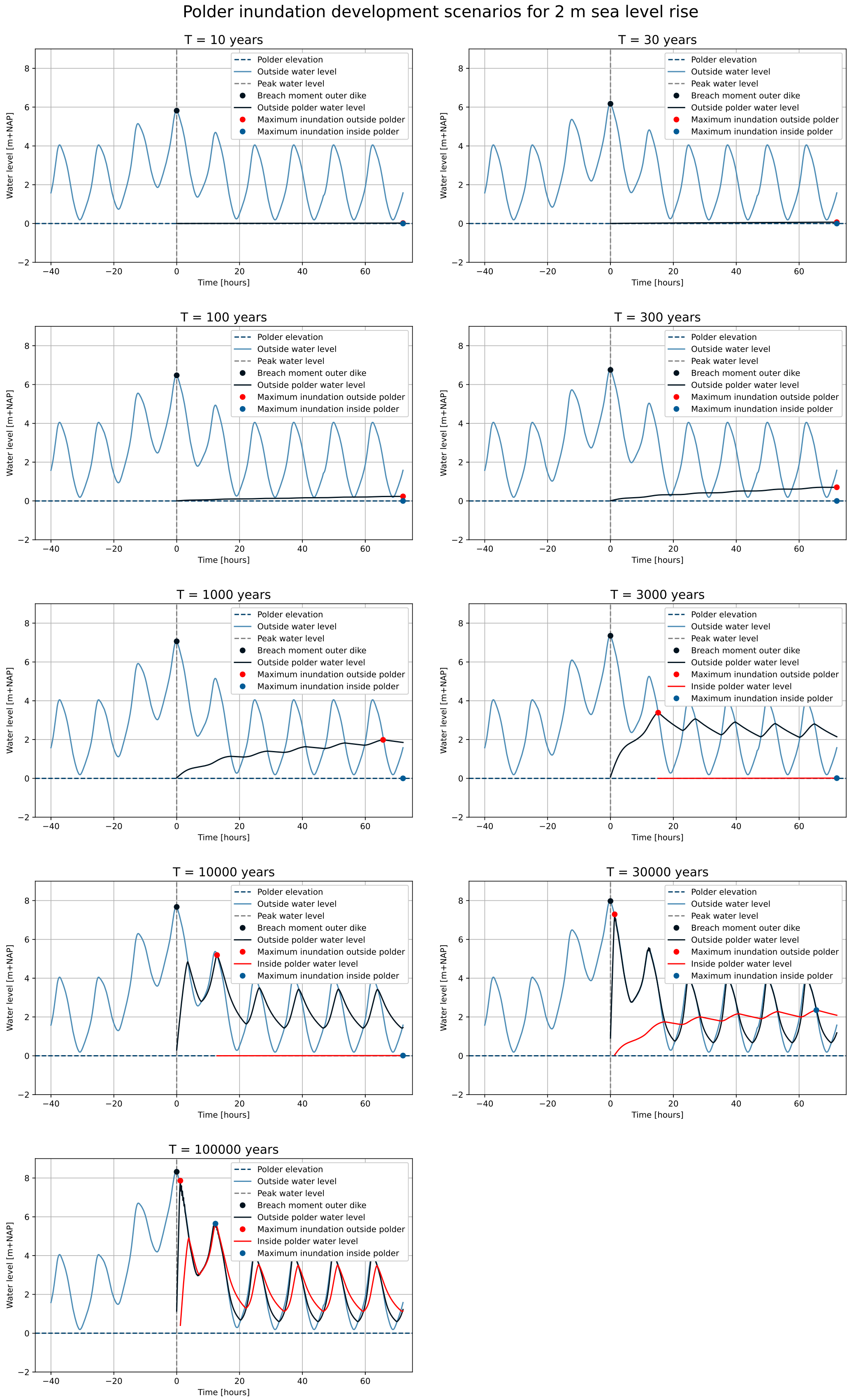


Figure C.23: Polder inundation development for 2 meter sea level rise (complete dike reinforcement) (secondary dike-ring strategy)

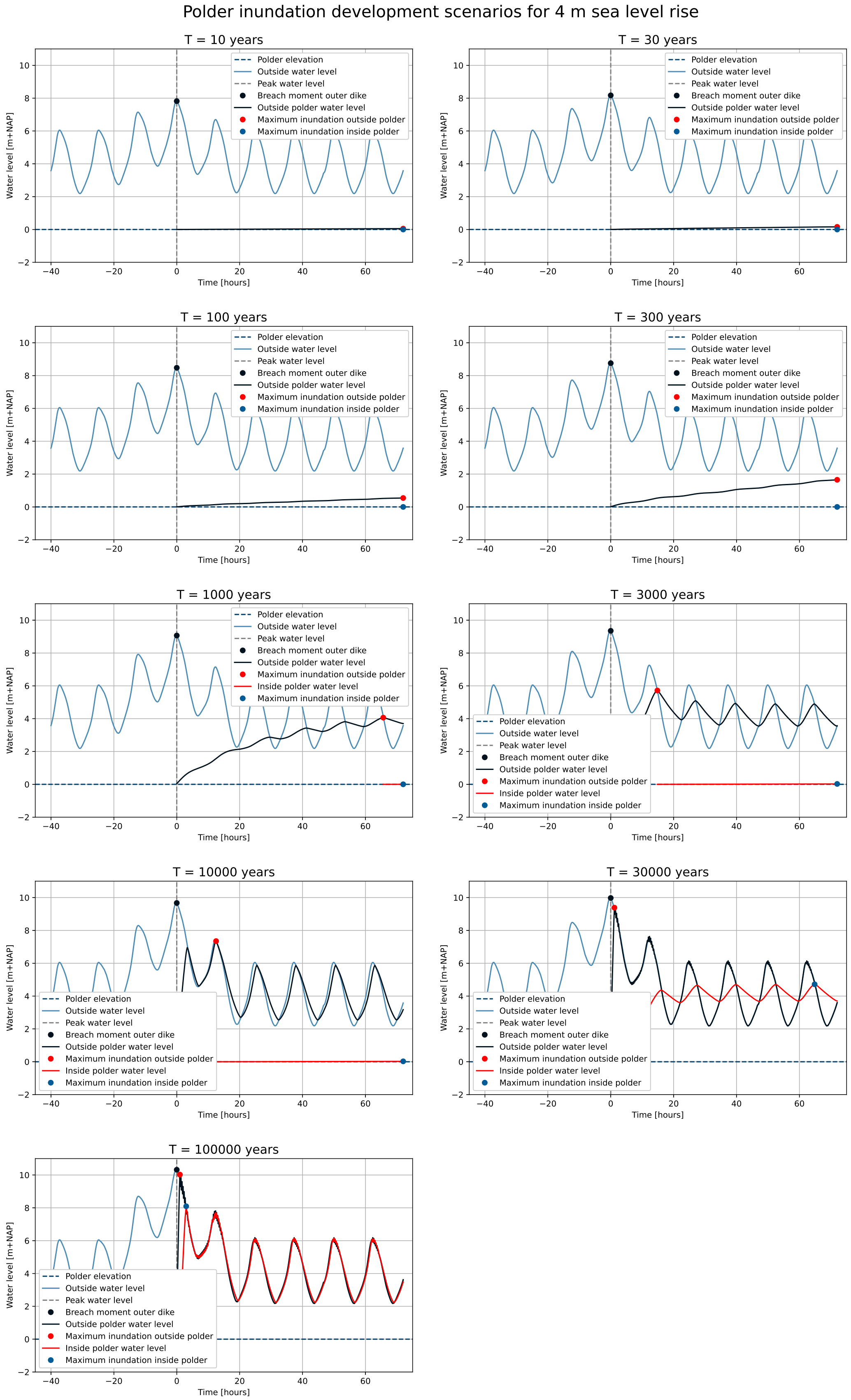


Figure C.24: Polder inundation development for 4 meter sea level rise (complete dike reinforcement) (secondary dike-ring strategy)

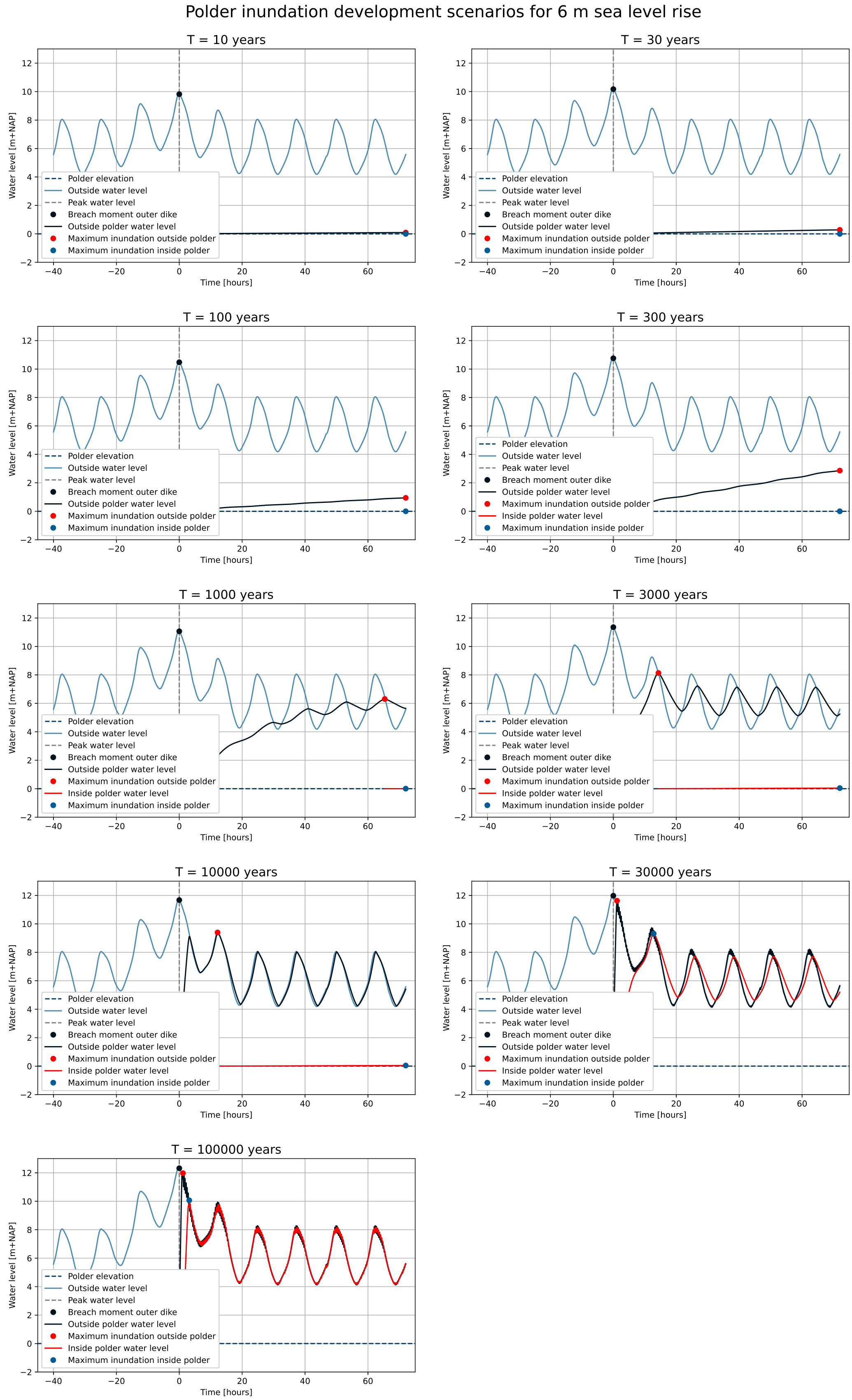


Figure C.25: Polder inundation development for 6 meter sea level rise (complete dike reinforcement) (secondary dike-ring strategy)

C.1.3. Value protection (secondary) dike-ring

Primary (outer) dike reinforcement

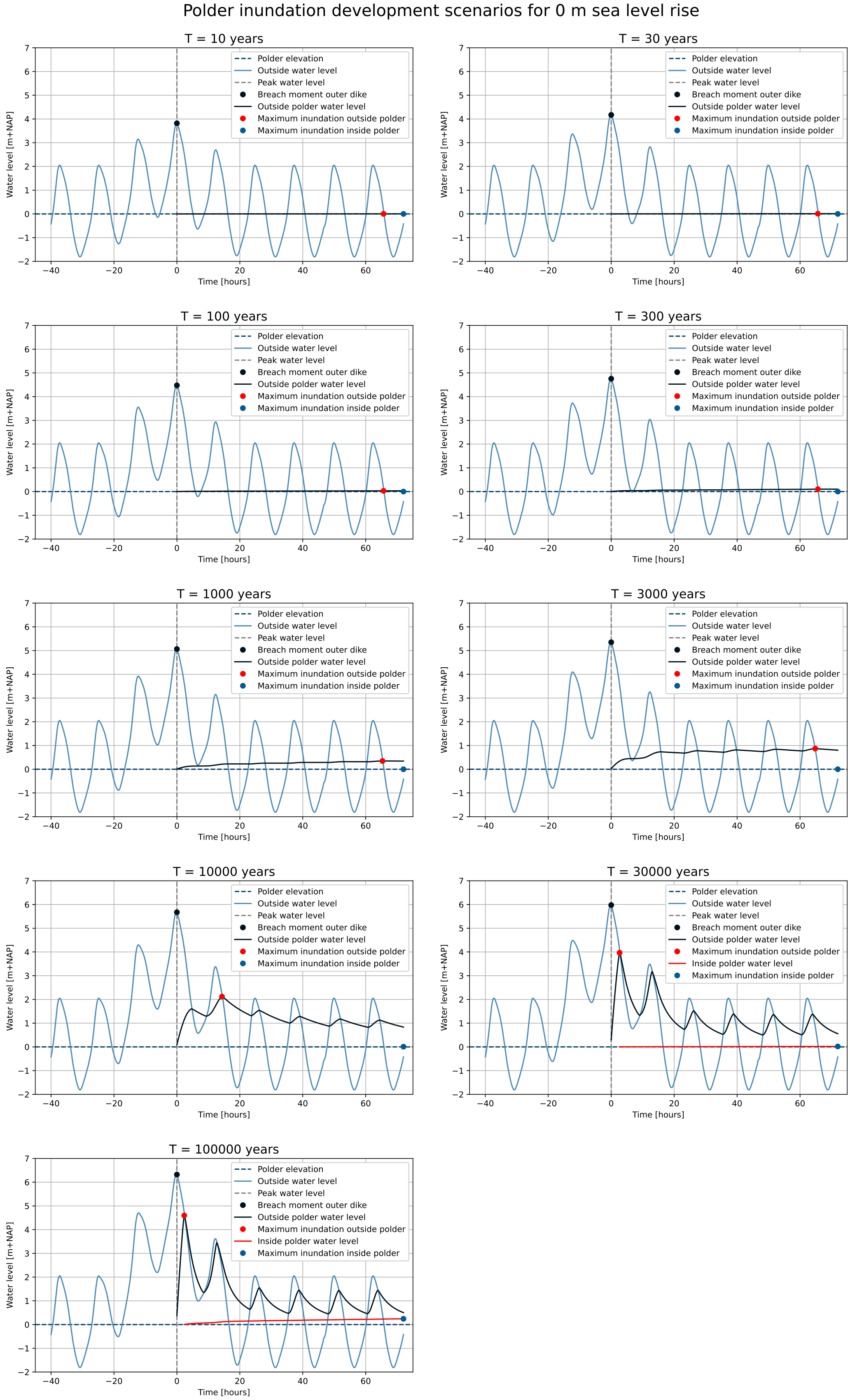


Figure C.26: Polder inundation development for 0 meter sea level rise (primary dike reinforcement) (value protection dike-ring strategy)

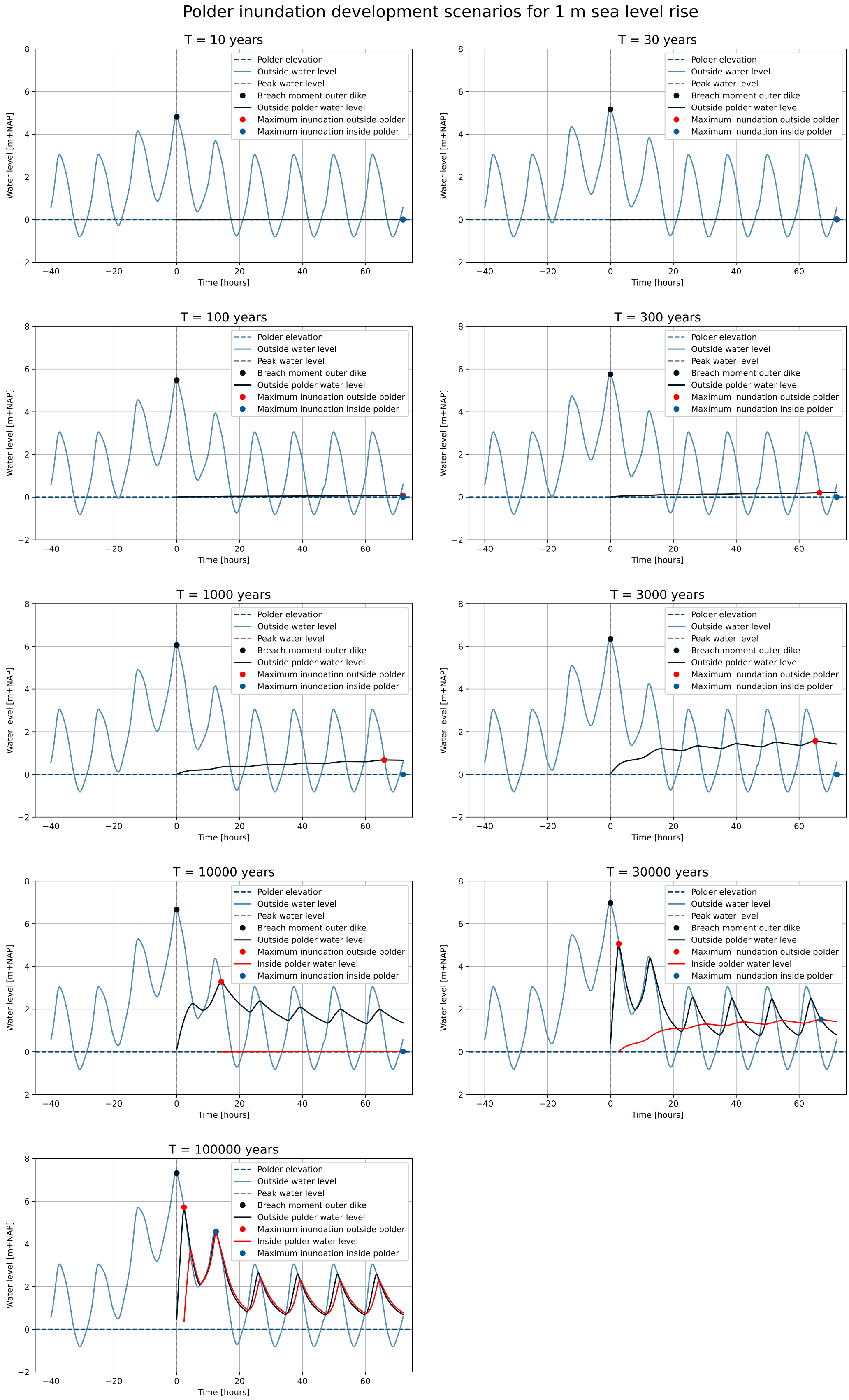


Figure C.27: Polder inundation development for 1 meter sea level rise (primary dike reinforcement) (value protection dike-ring strategy)

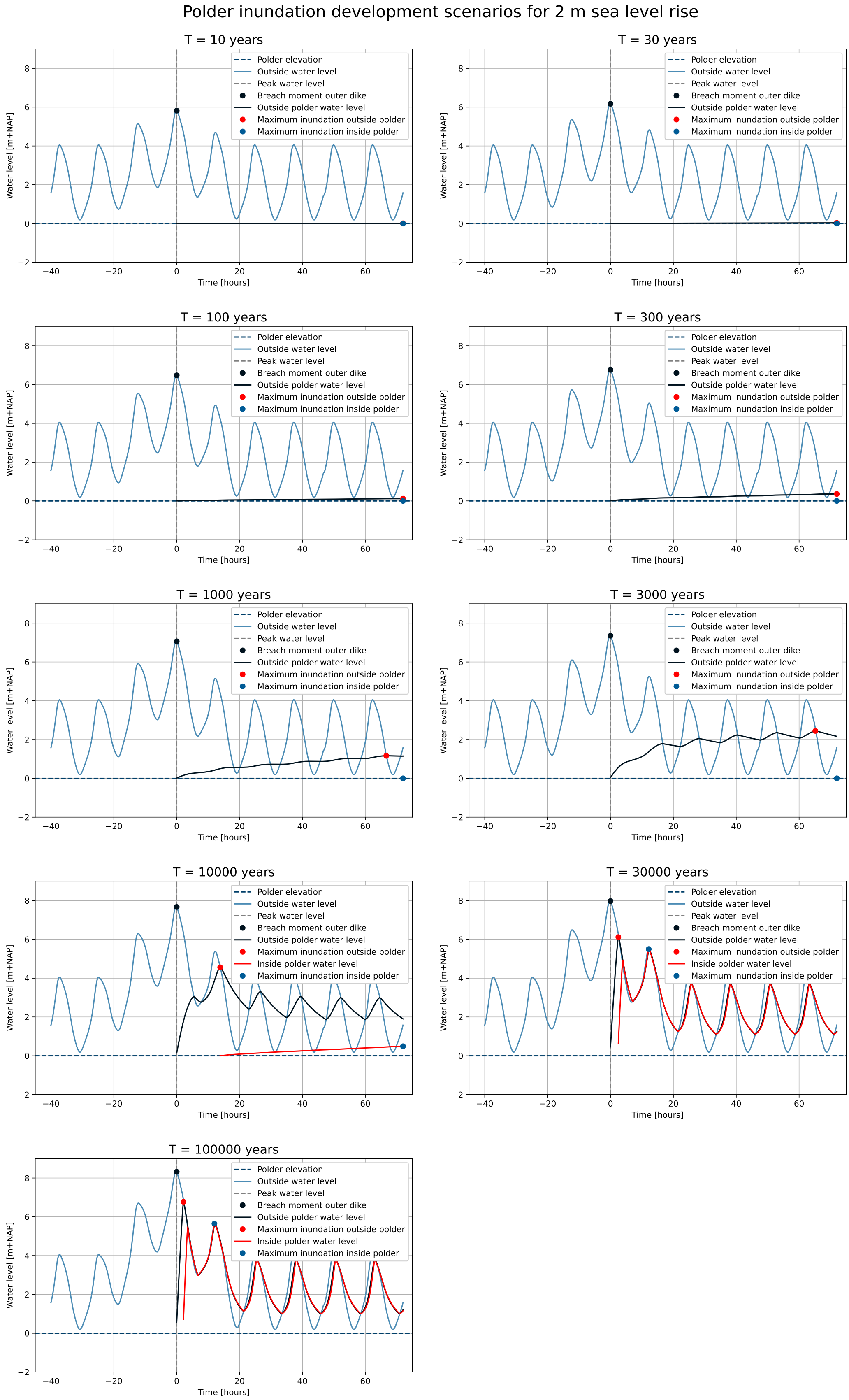


Figure C.28: Polder inundation development for 2 meter sea level rise (primary dike reinforcement) (value protection dike-ring strategy)

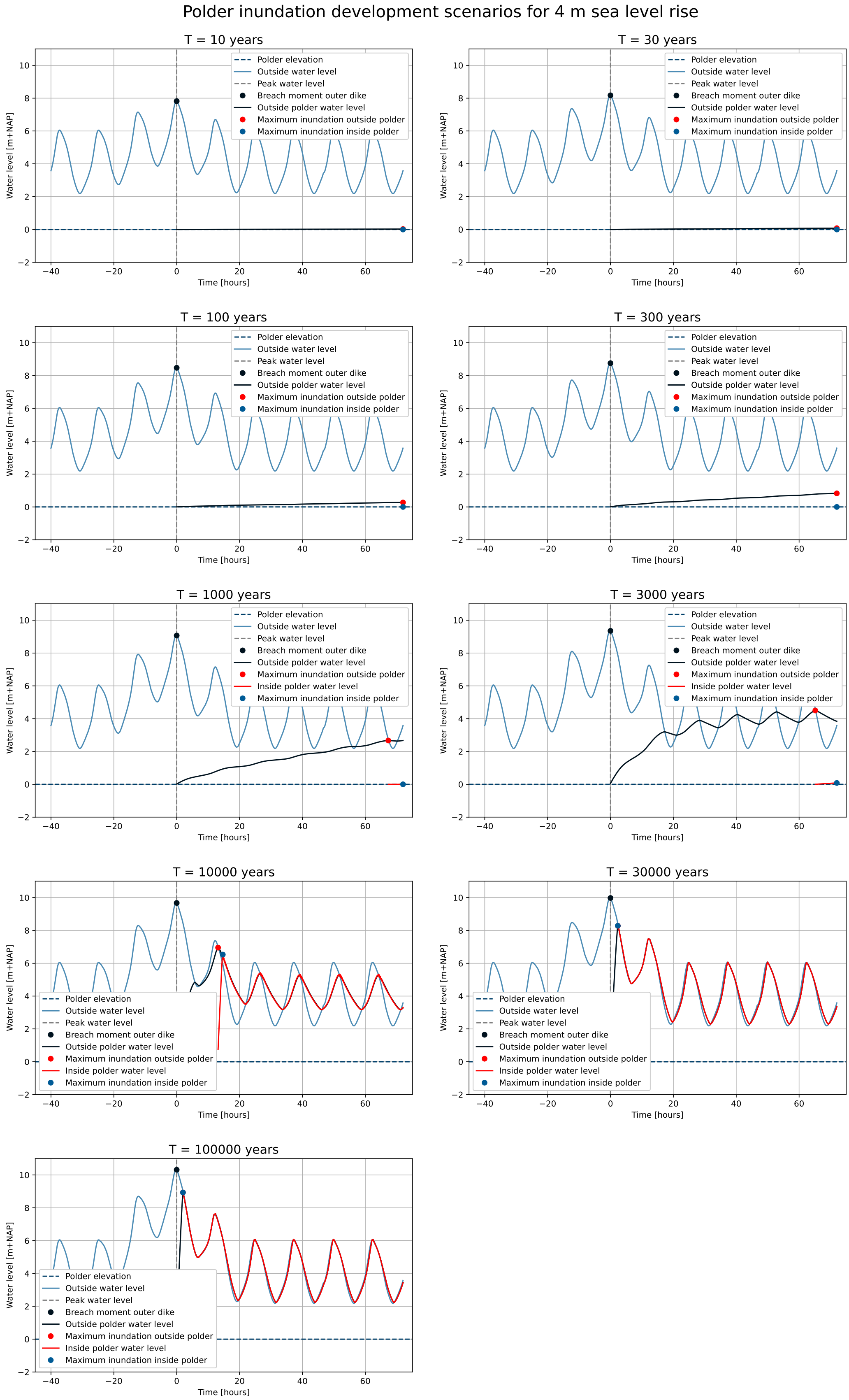


Figure C.29: Polder inundation development for 4 meter sea level rise (primary dike reinforcement) (value protection dike-ring strategy)

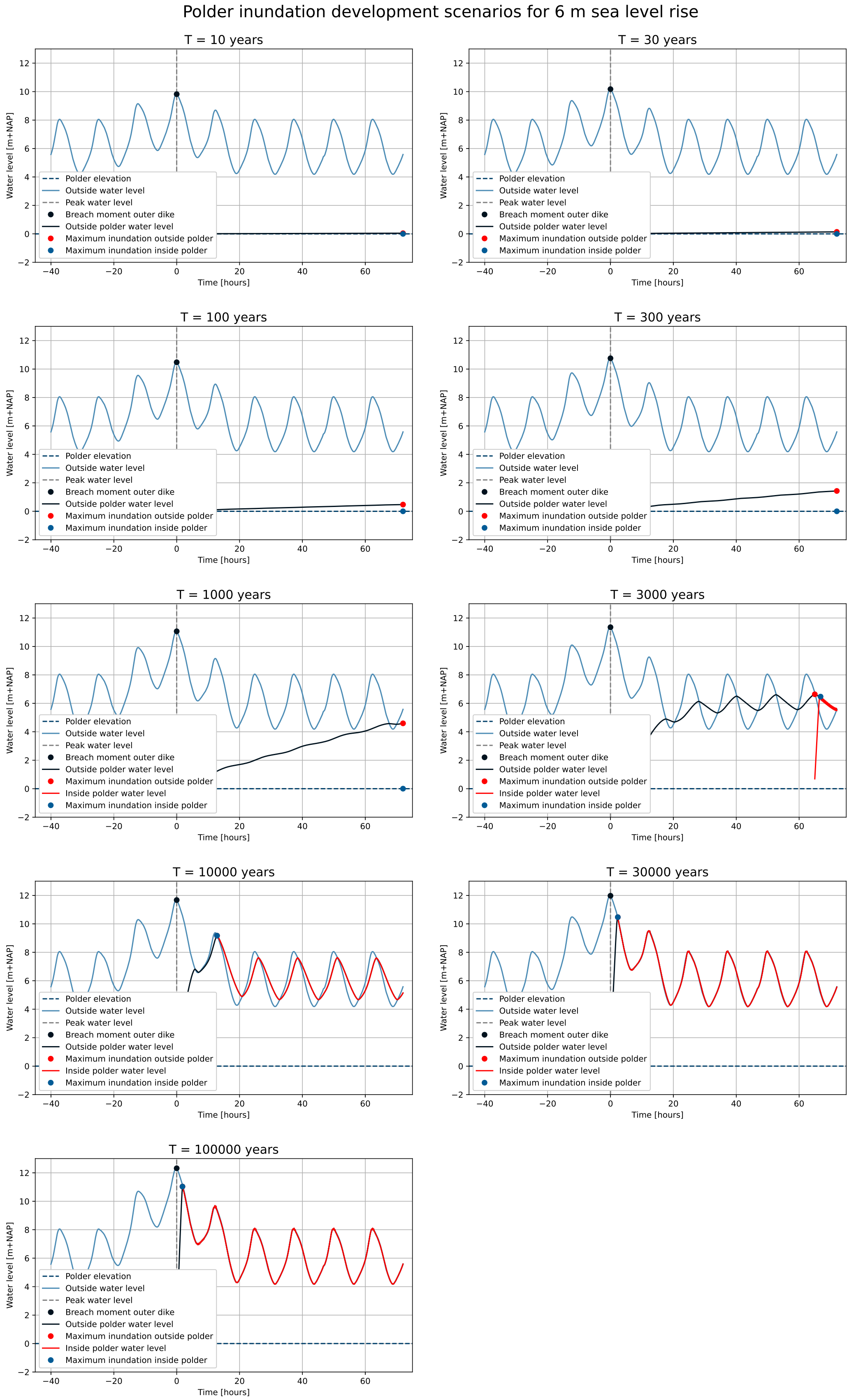


Figure C.30: Polder inundation development for 6 meter sea level rise (primary dike reinforcement) (value protection dike-ring strategy)

Secondary (inner) dike reinforcement

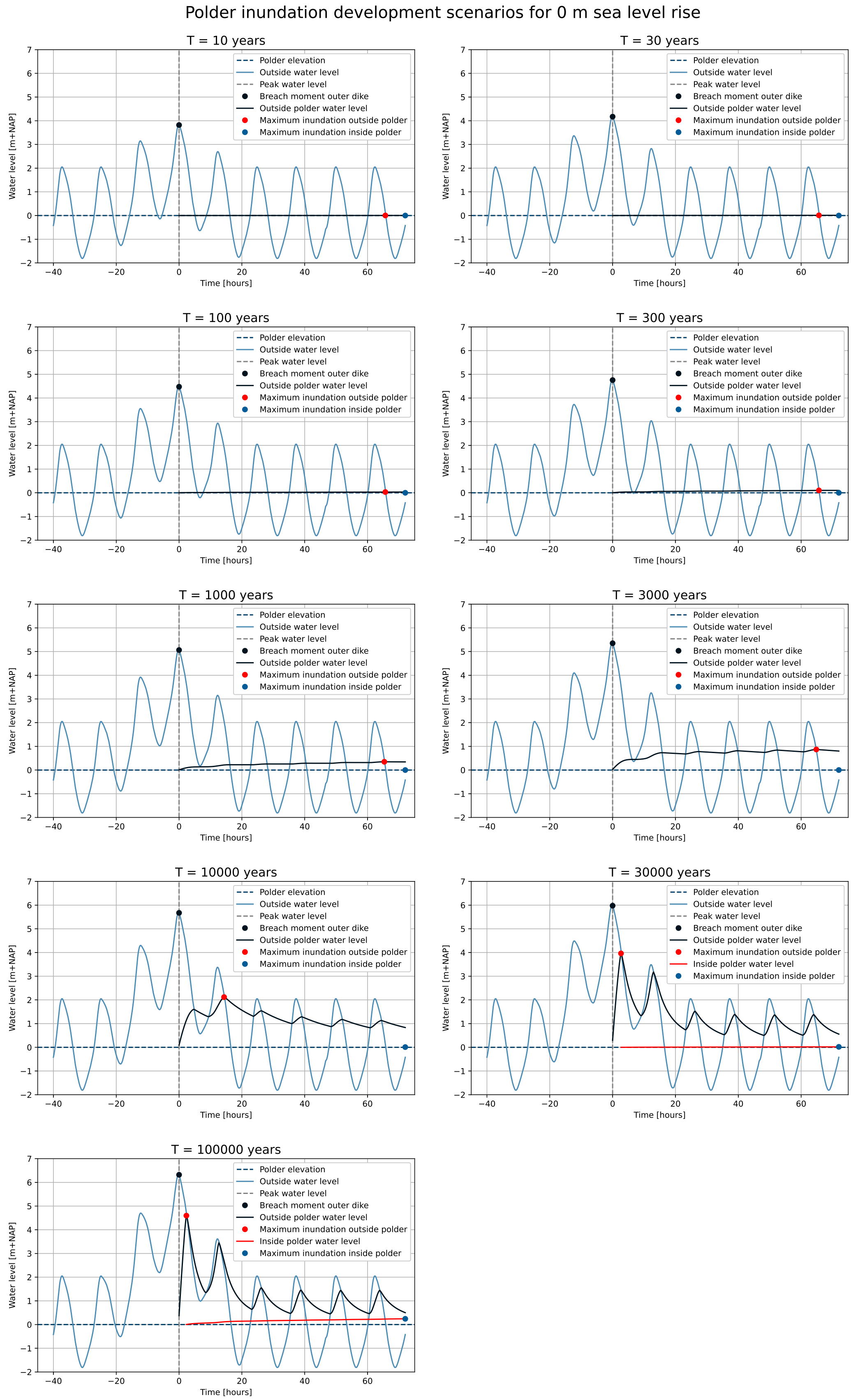


Figure C.31: Polder inundation development for 0 meter sea level rise (secondary dike reinforcement) (value protection dike-ring strategy)

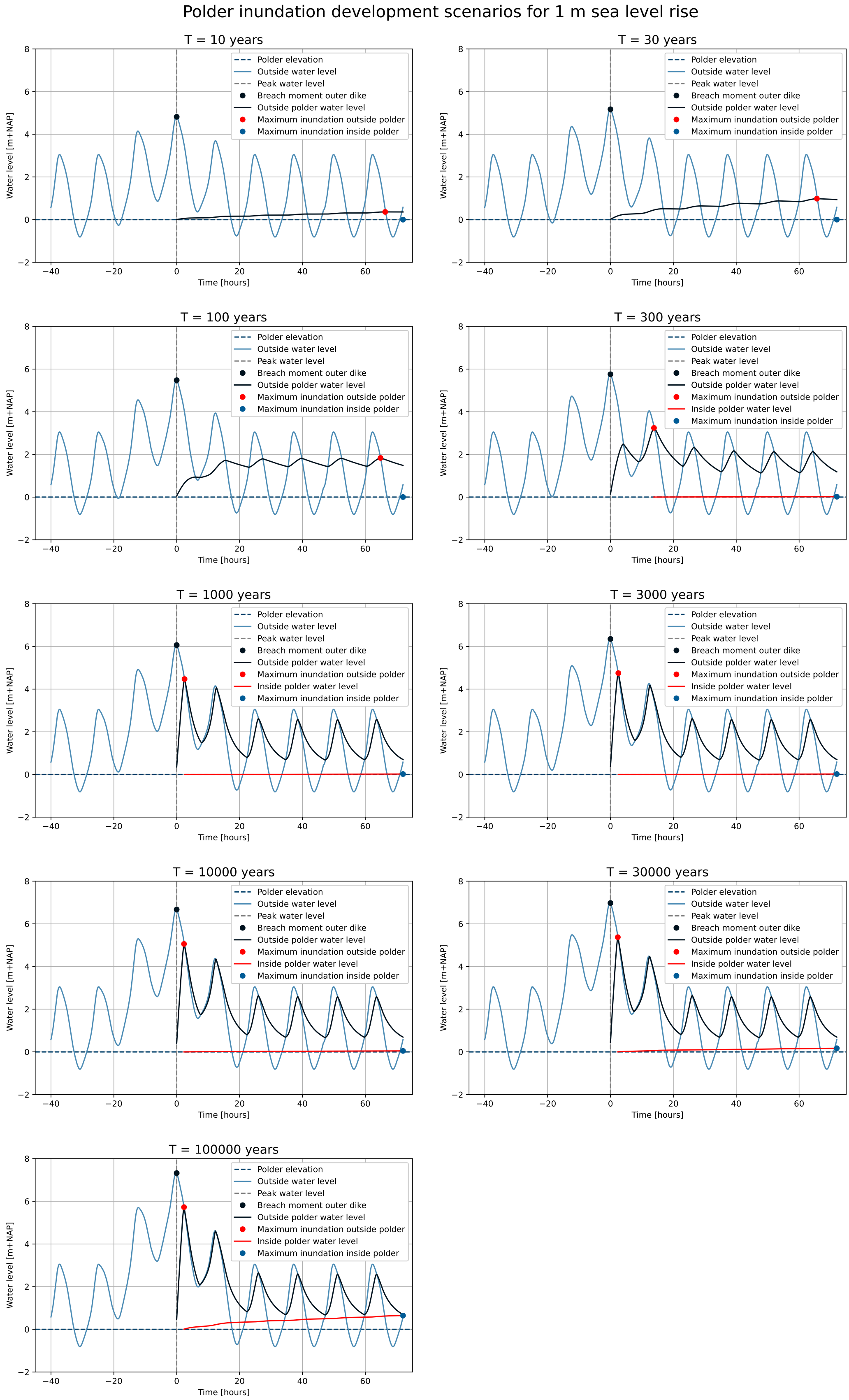


Figure C.32: Polder inundation development for 1 meter sea level rise (secondary dike reinforcement) (value protection dike-ring strategy)

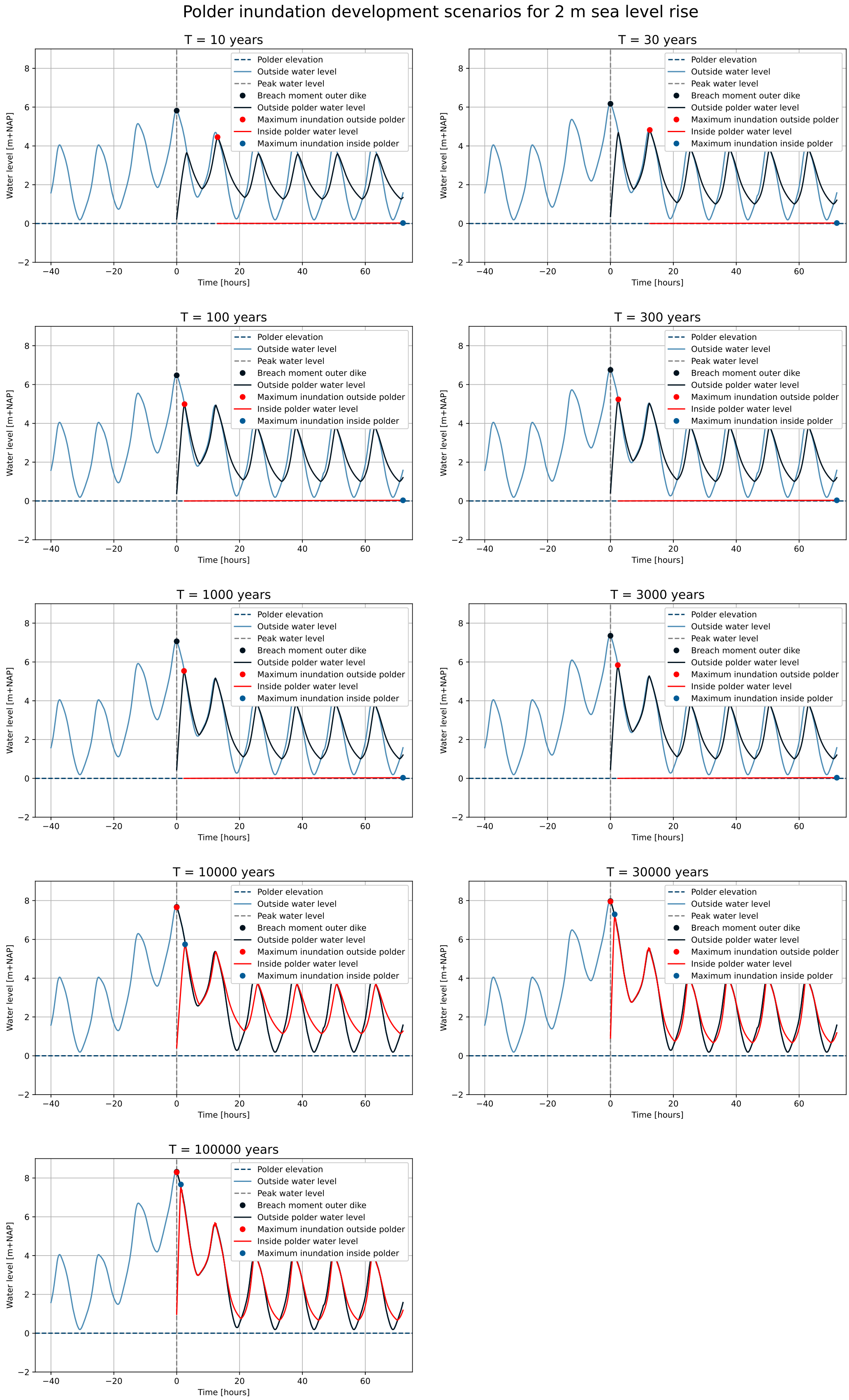


Figure C.33: Polder inundation development for 2 meter sea level rise (secondary dike reinforcement) (value protection dike-ring strategy)

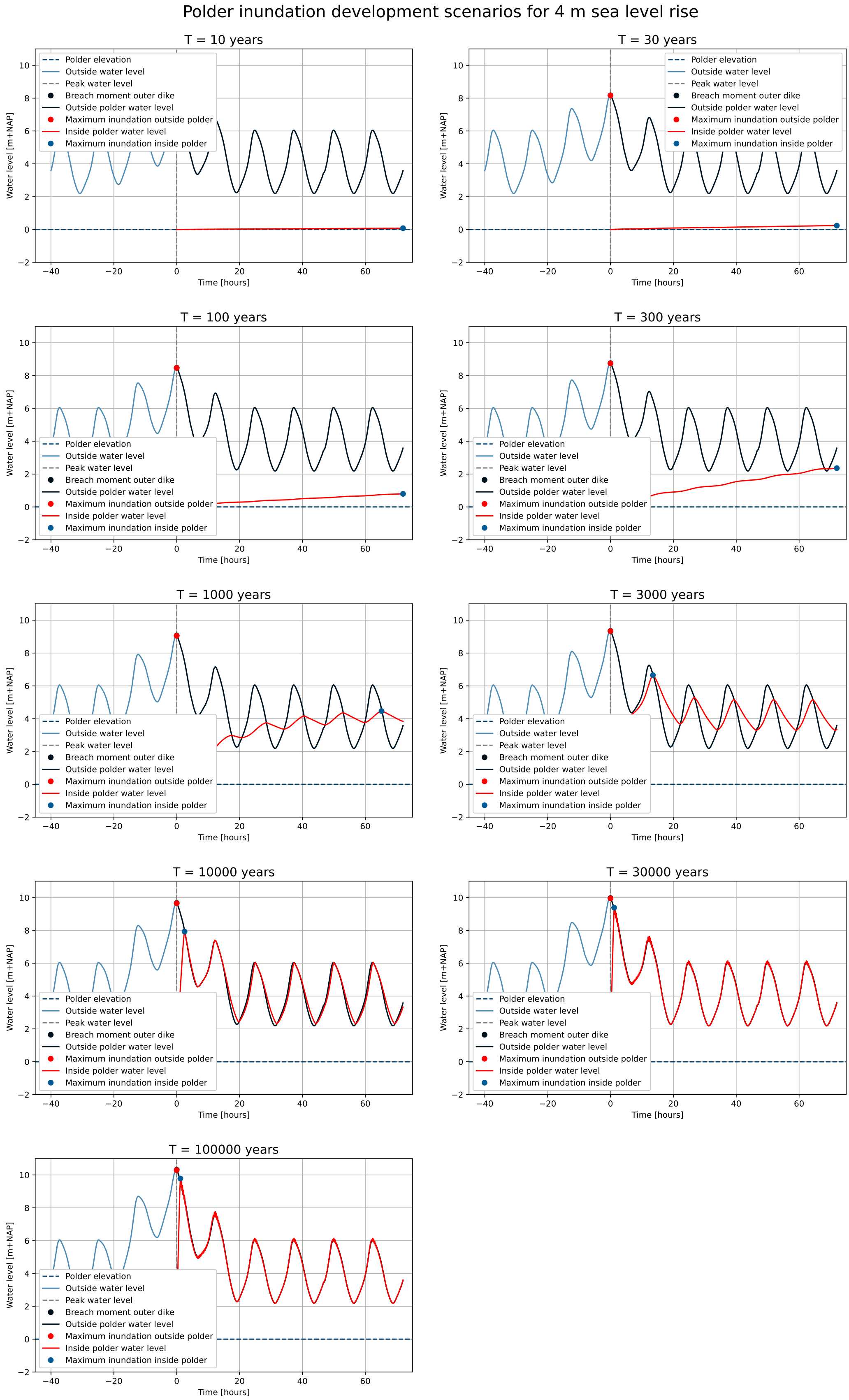


Figure C.34: Polder inundation development for 4 meter sea level rise (secondary dike reinforcement) (value protection dike-ring strategy)

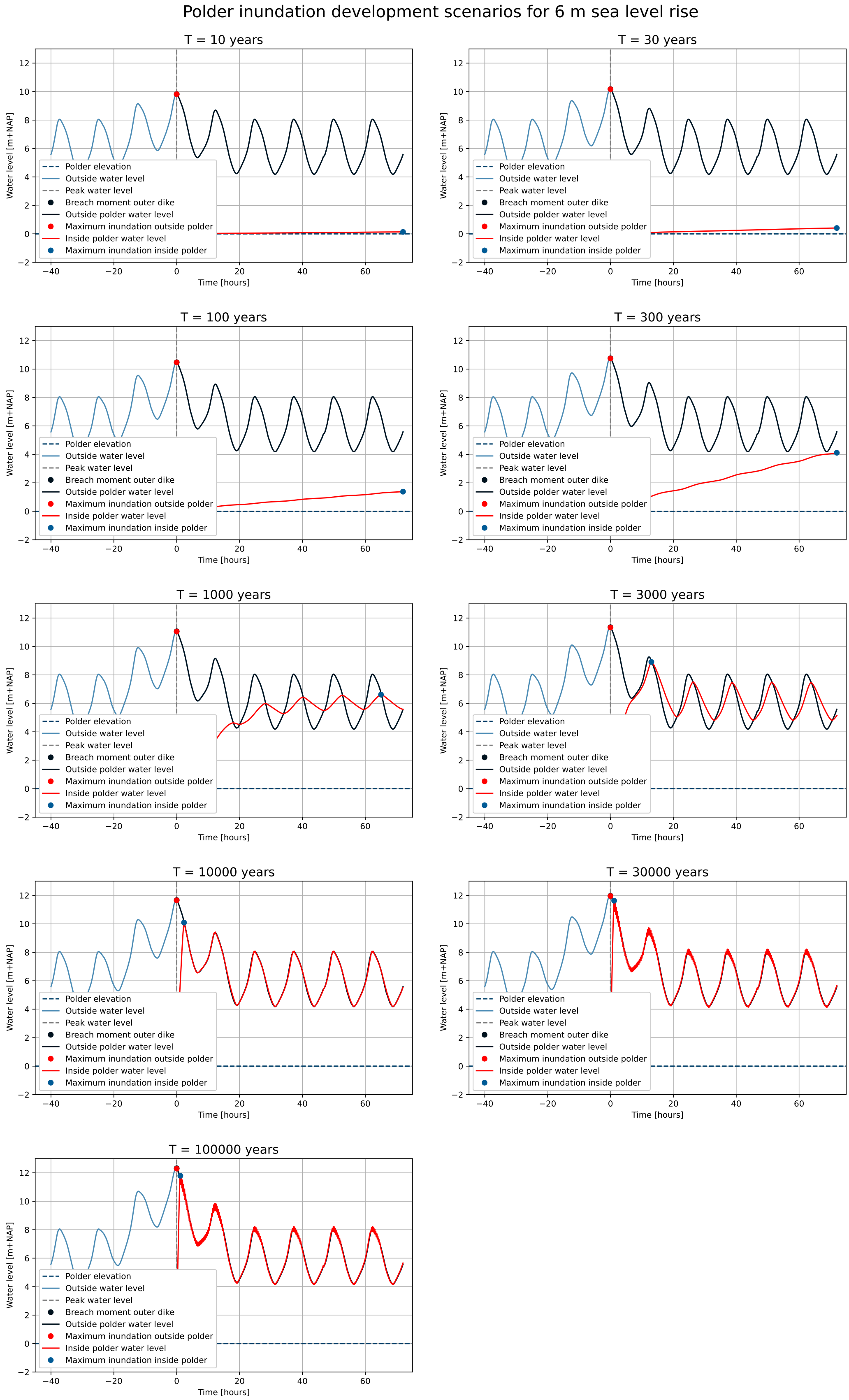


Figure C.35: Polder inundation development for 6 meter sea level rise (secondary dike reinforcement) (value protection dike-ring strategy)

Complete dike reinforcement

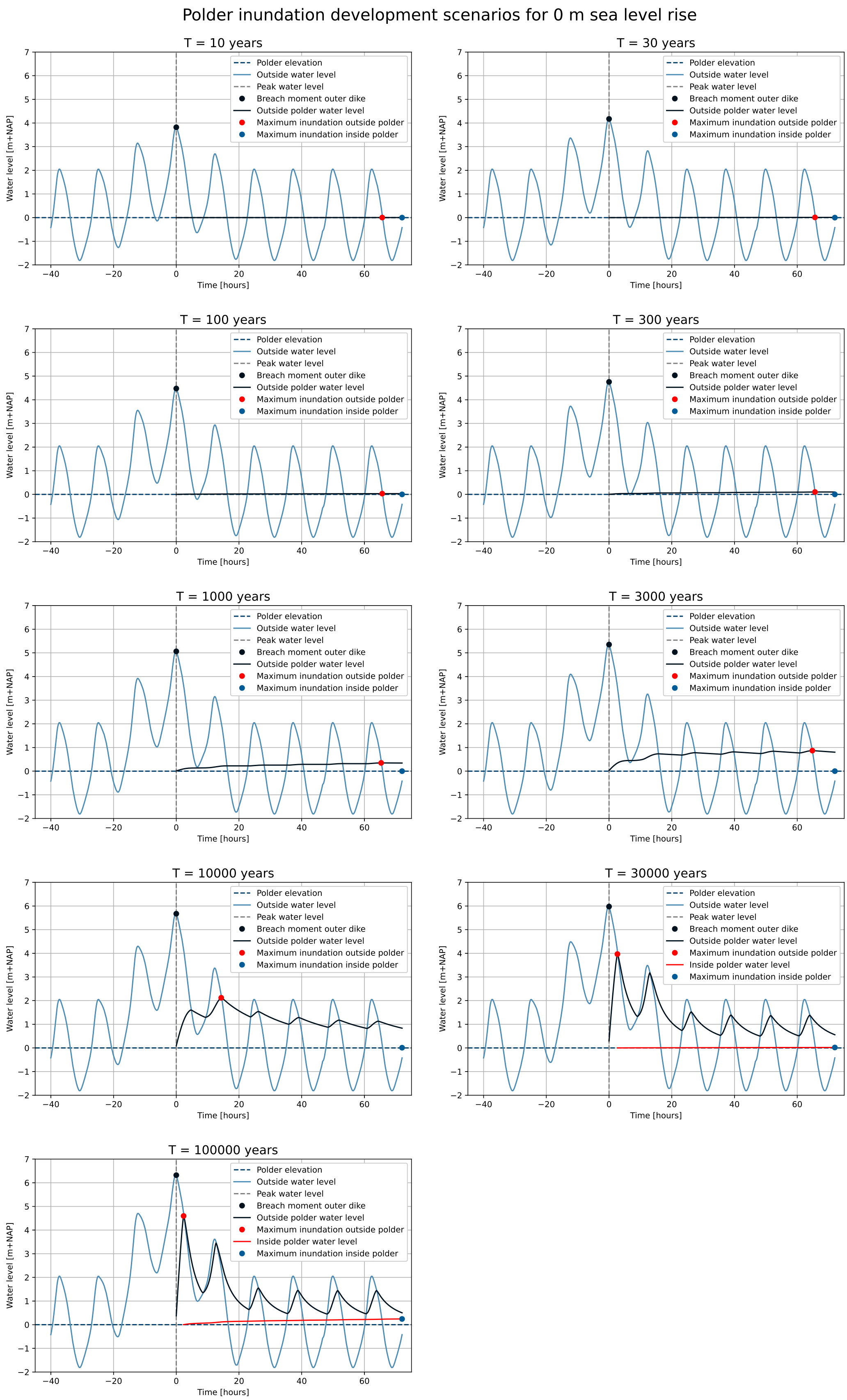


Figure C.36: Polder inundation development for 0 meter sea level rise (complete dike reinforcement) (value protection dike-ring strategy)

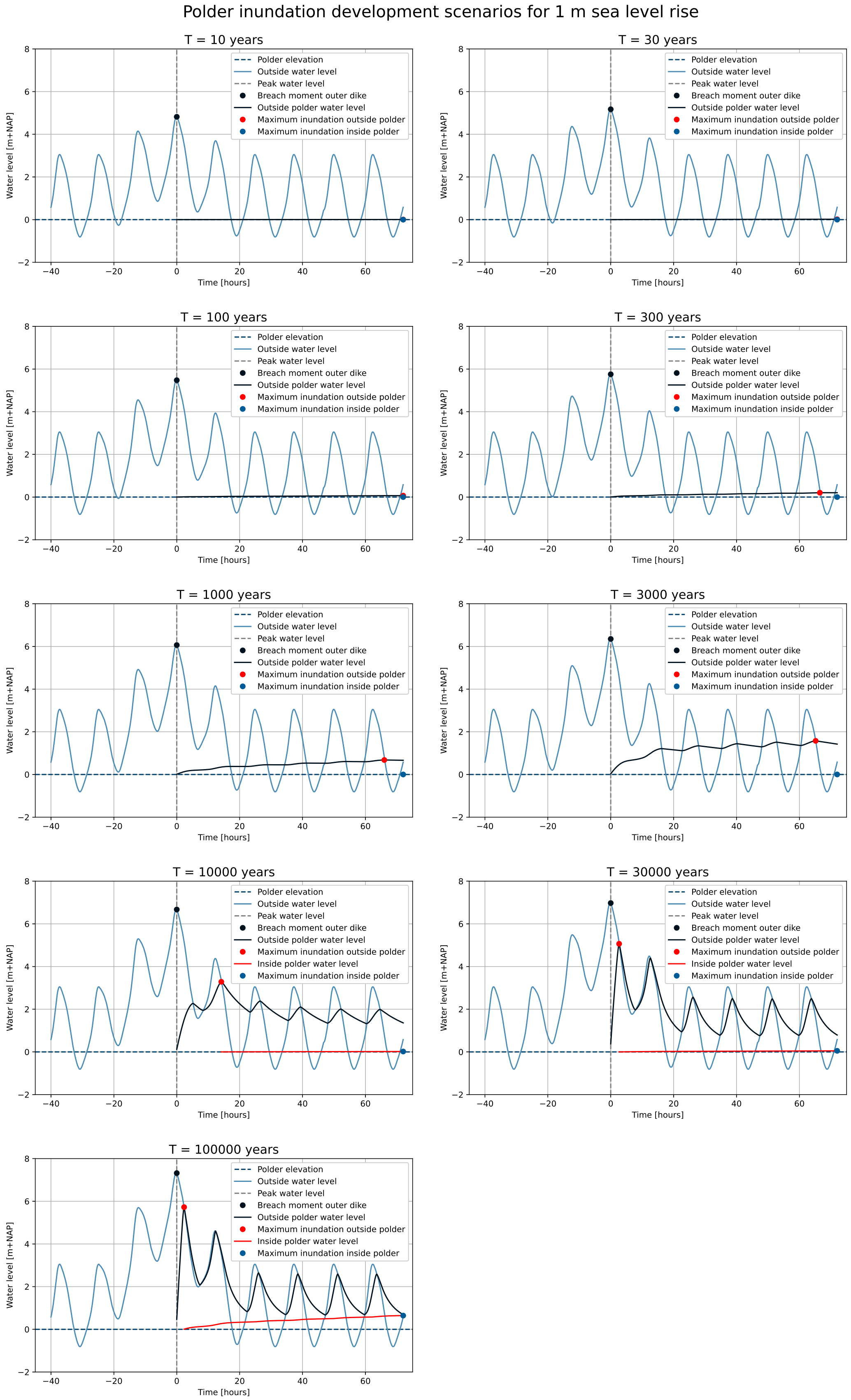


Figure C.37: Polder inundation development for 1 meter sea level rise (complete dike reinforcement) (value protection dike-ring strategy)

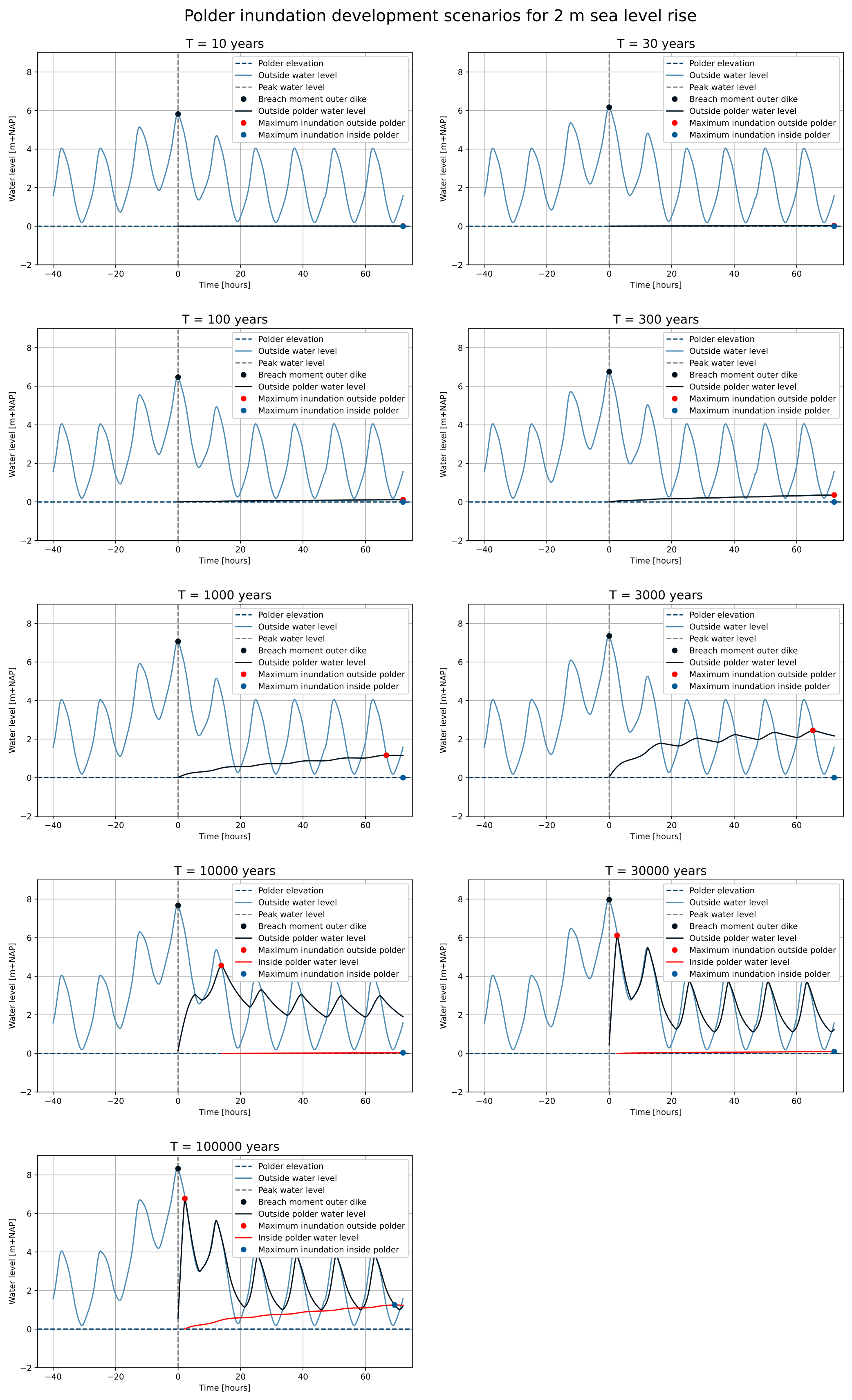


Figure C.38: Polder inundation development for 2 meter sea level rise (complete dike reinforcement) (value protection dike-ring strategy)

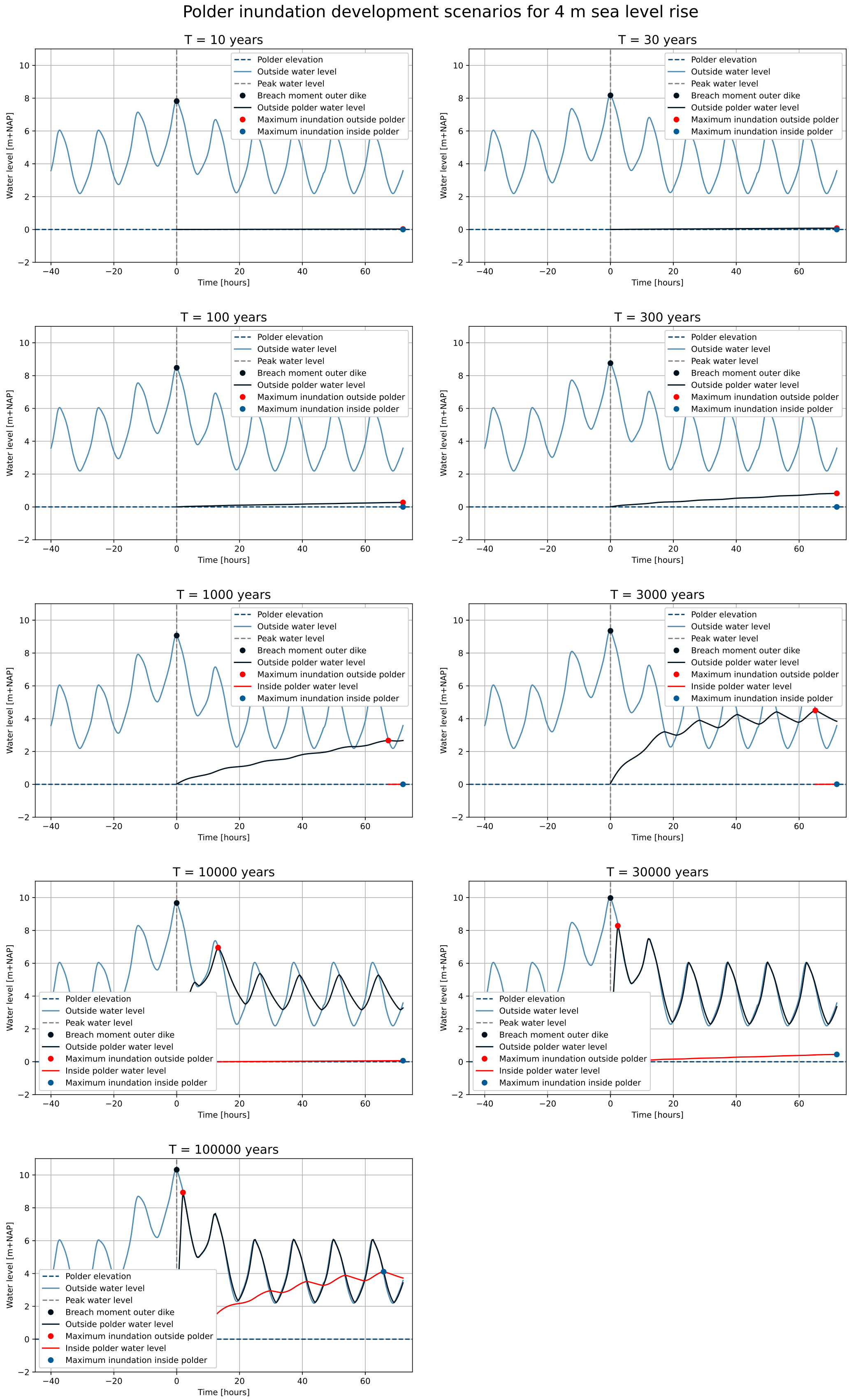


Figure C.39: Polder inundation development for 4 meter sea level rise (complete dike reinforcement) (value protection dike-ring strategy)

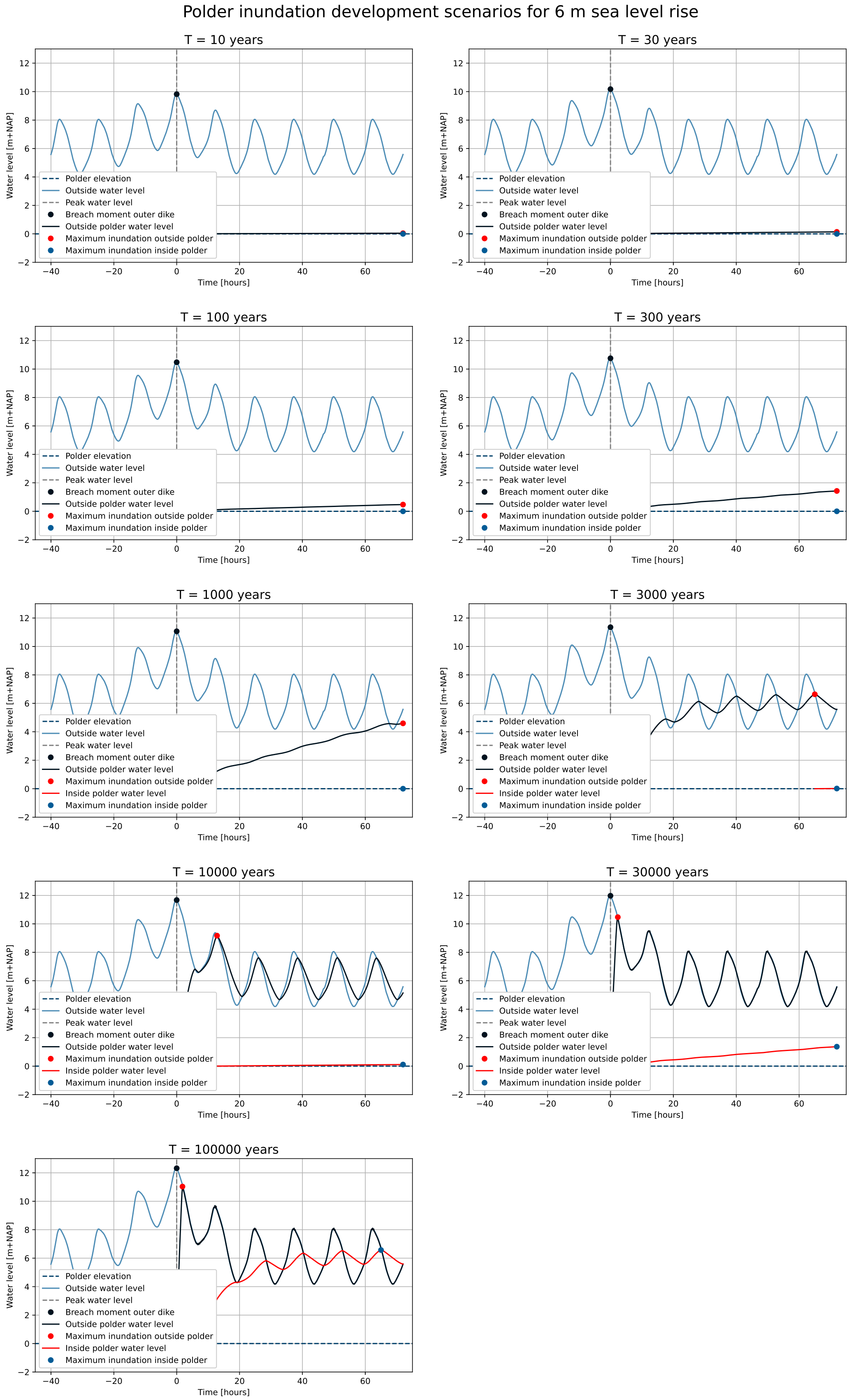


Figure C.40: Polder inundation development for 6 meter sea level rise (complete dike reinforcement) (value protection dike-ring strategy)

C.1.4. Partitioned dike-ring (compartmentalization)

Partition investment

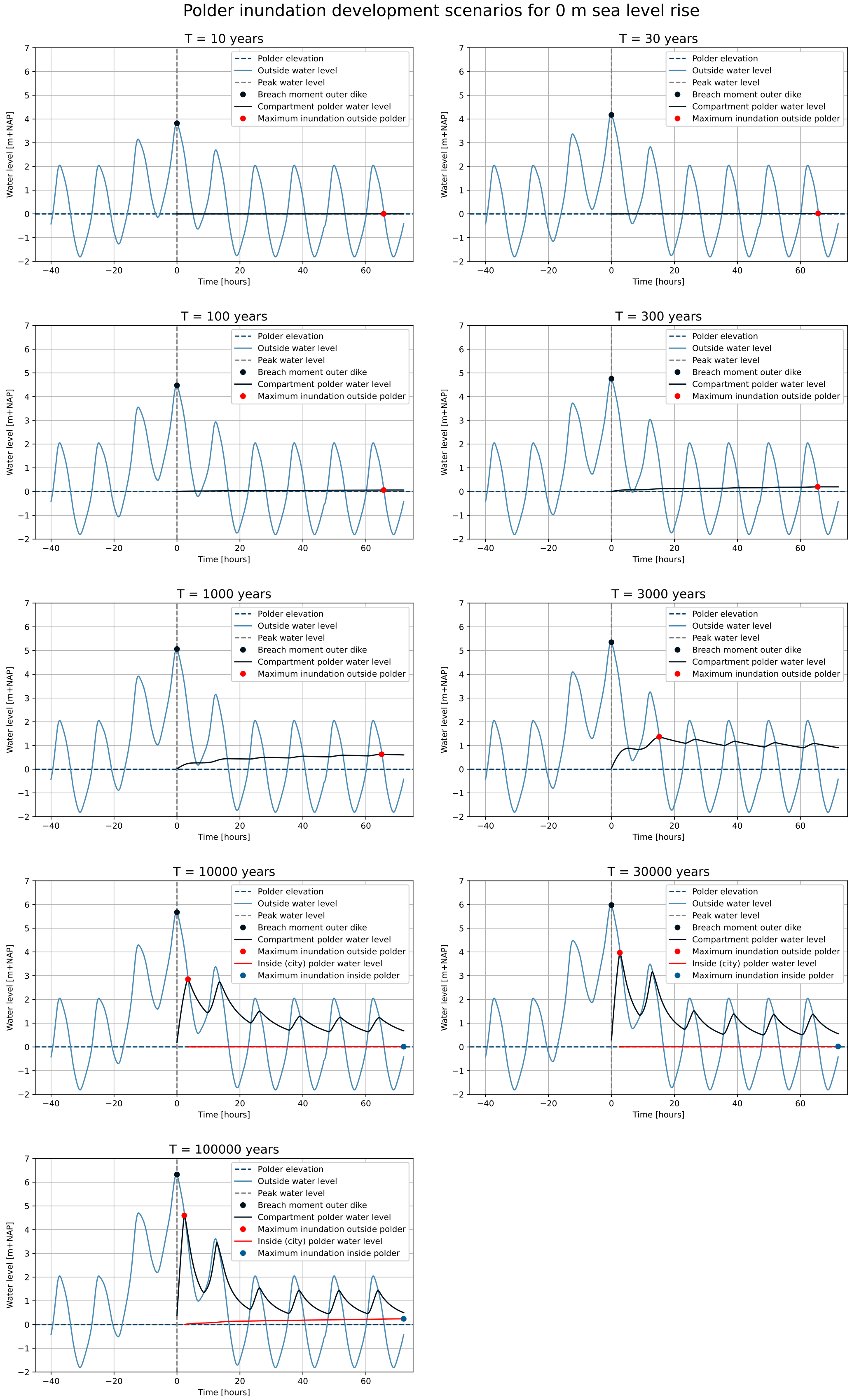


Figure C.41: Polder inundation development for 0 meter sea level rise (complete dike reinforcement and partition investment) (compartmentalization strategy)

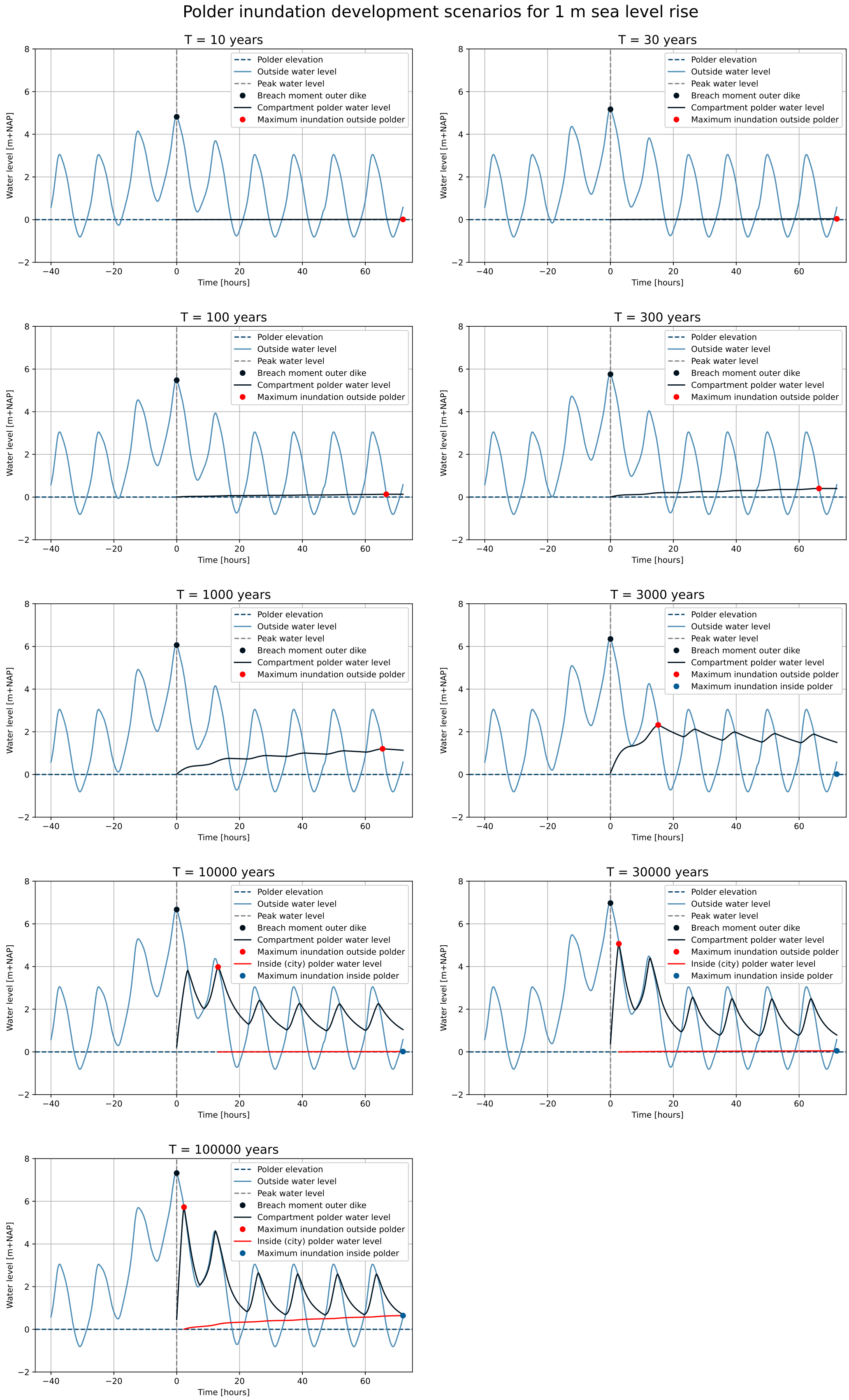


Figure C.42: Polder inundation development for 1 meter sea level rise (complete dike reinforcement and partition investment) (compartmentalization strategy)

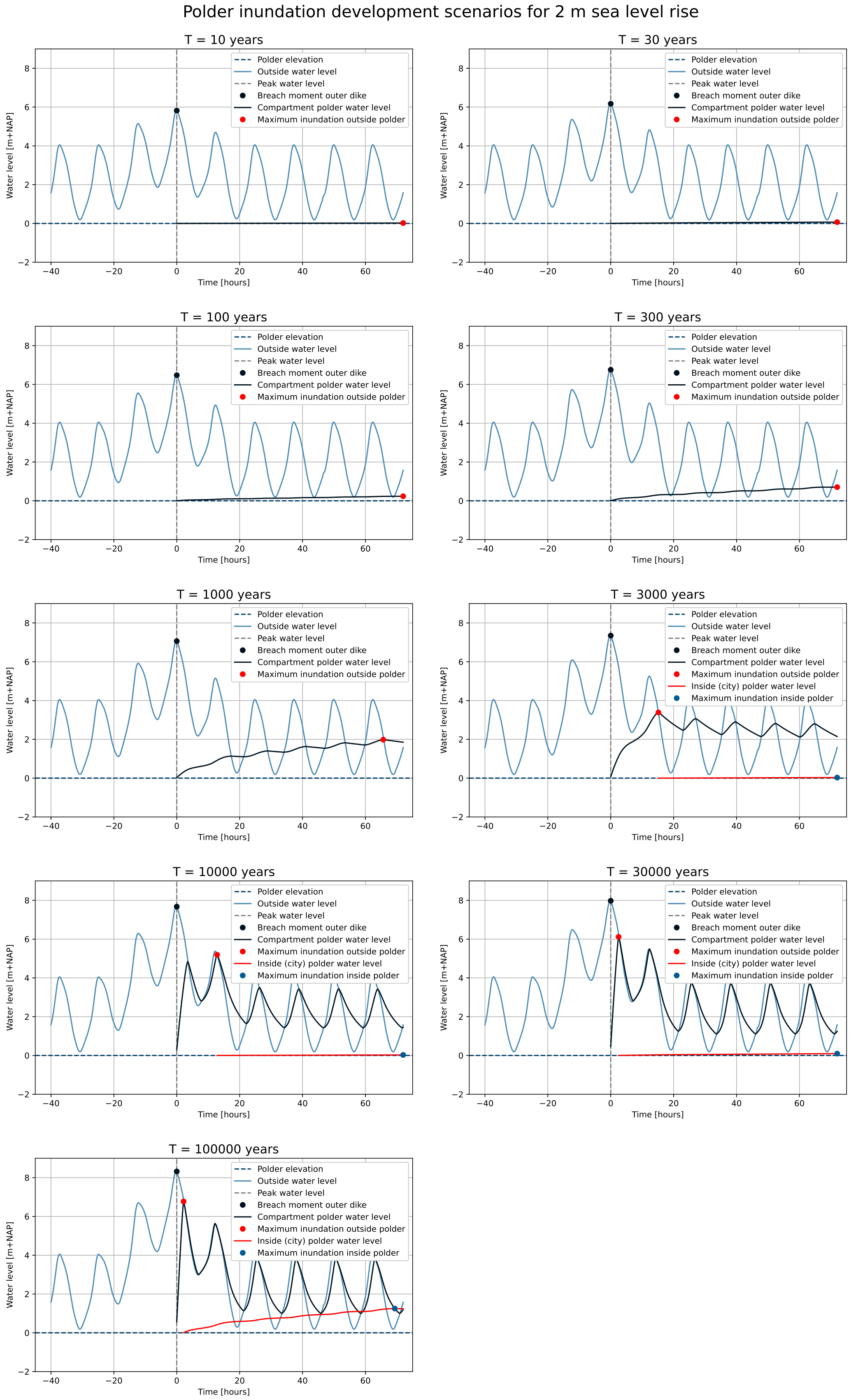


Figure C.43: Polder inundation development for 2 meter sea level rise (complete dike reinforcement and partition investment) (compartmentalization strategy)

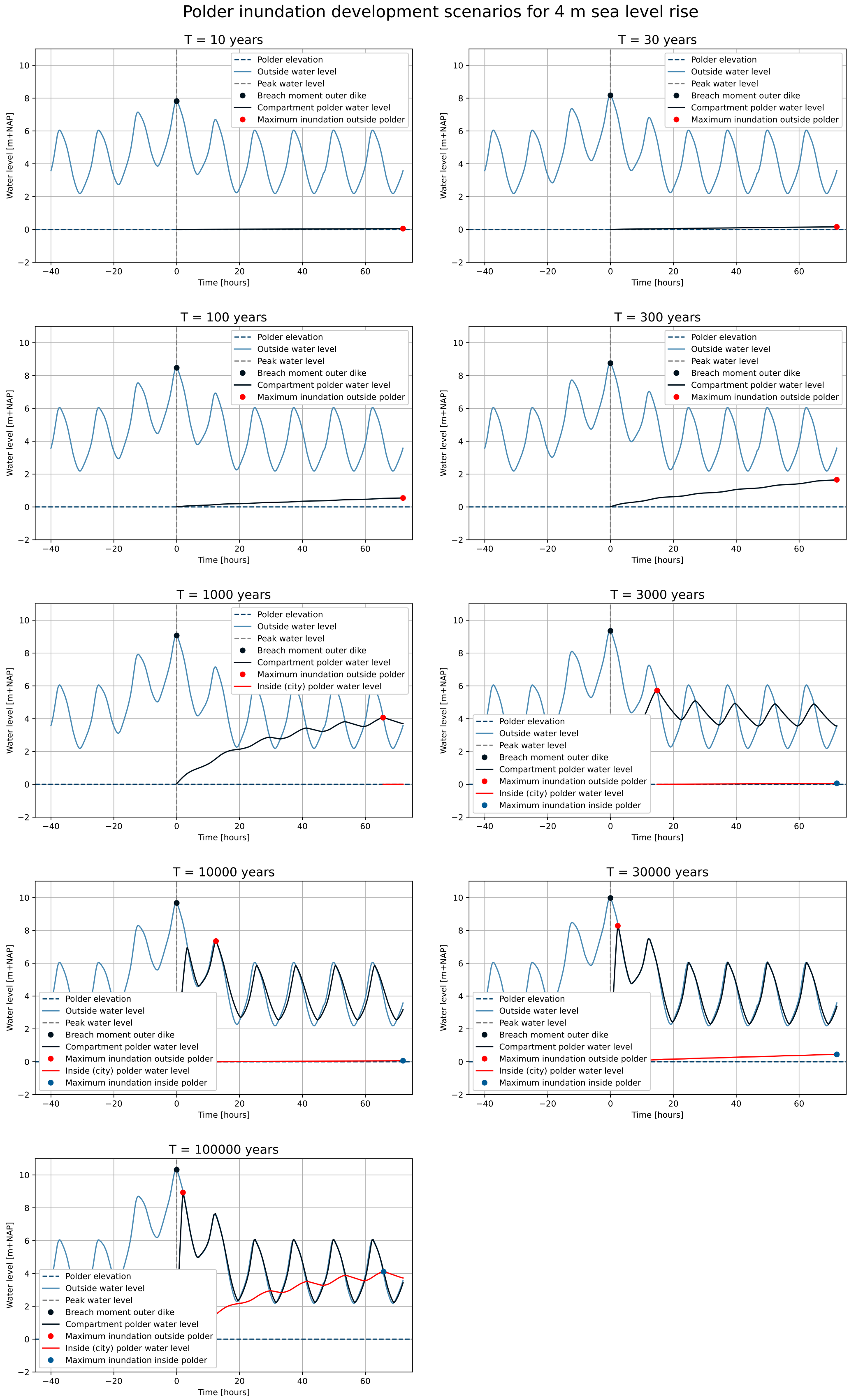


Figure C.44: Polder inundation development for 4 meter sea level rise (complete dike reinforcement and partition investment) (compartmentalization strategy)

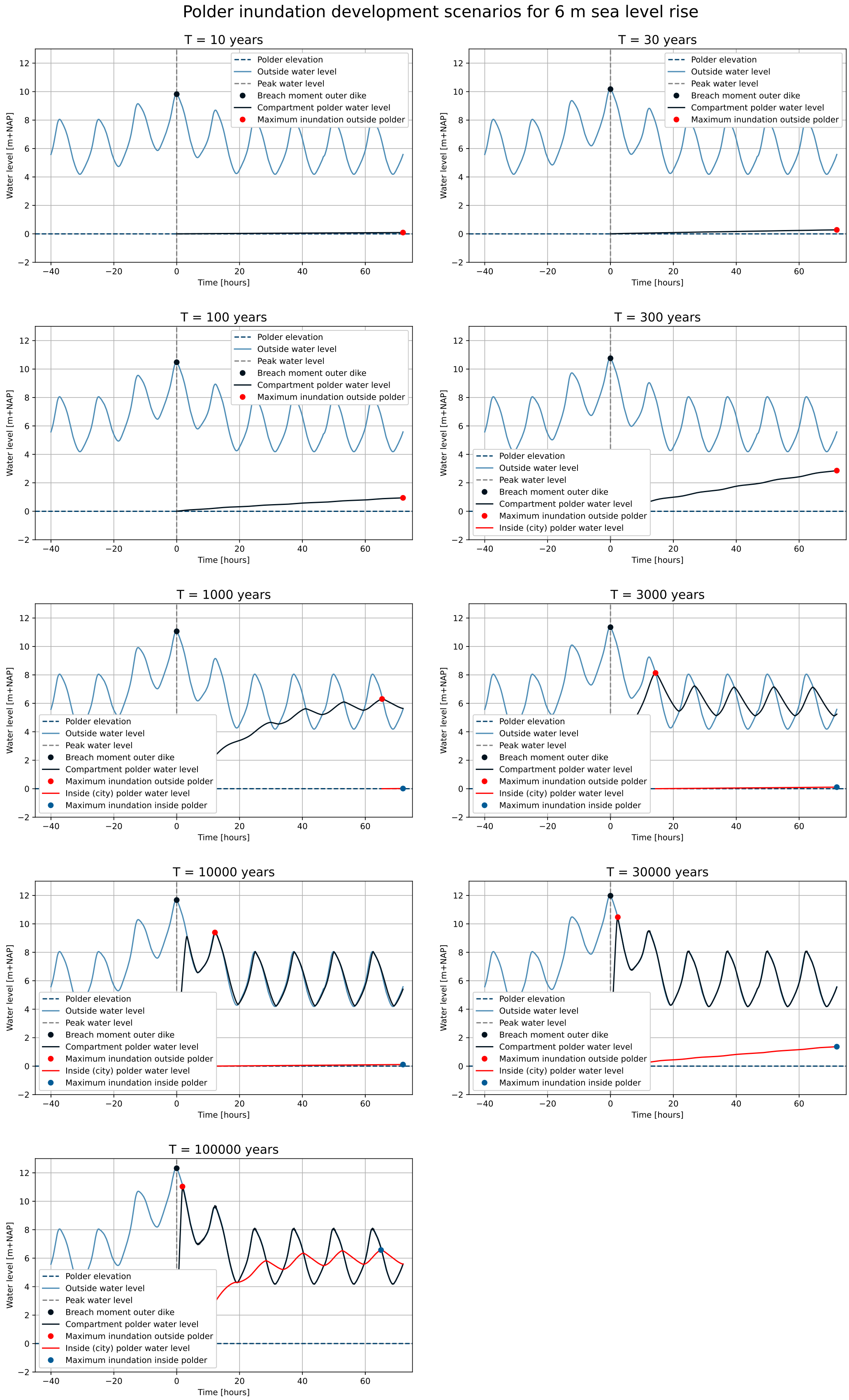


Figure C.45: Polder inundation development for 6 meter sea level rise (complete dike reinforcement and partition investment) (compartmentalization strategy)

City protection

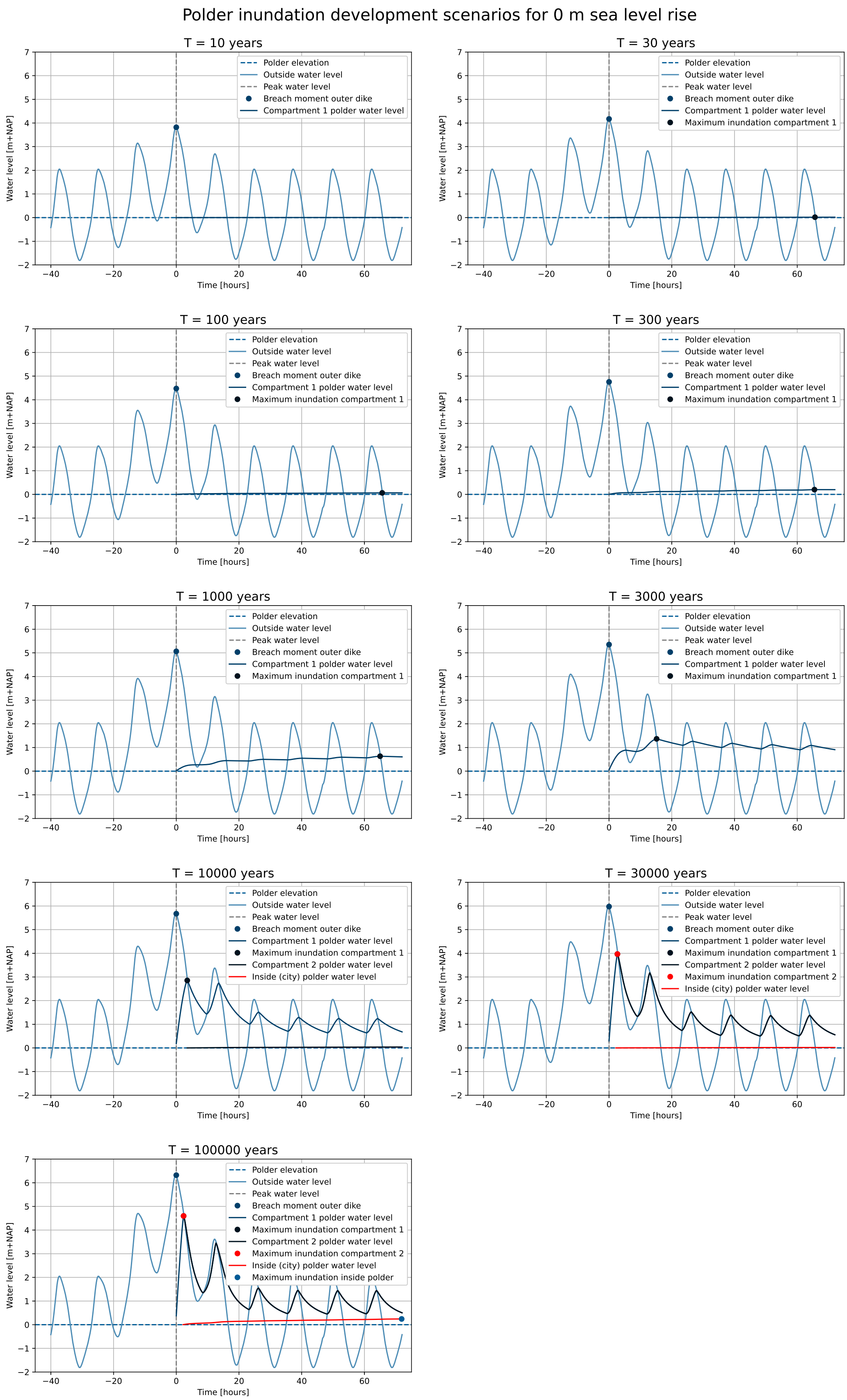


Figure C.46: Polder inundation development for 0 meter sea level rise (complete dike reinforcement and city protection) (compartmentalization strategy)

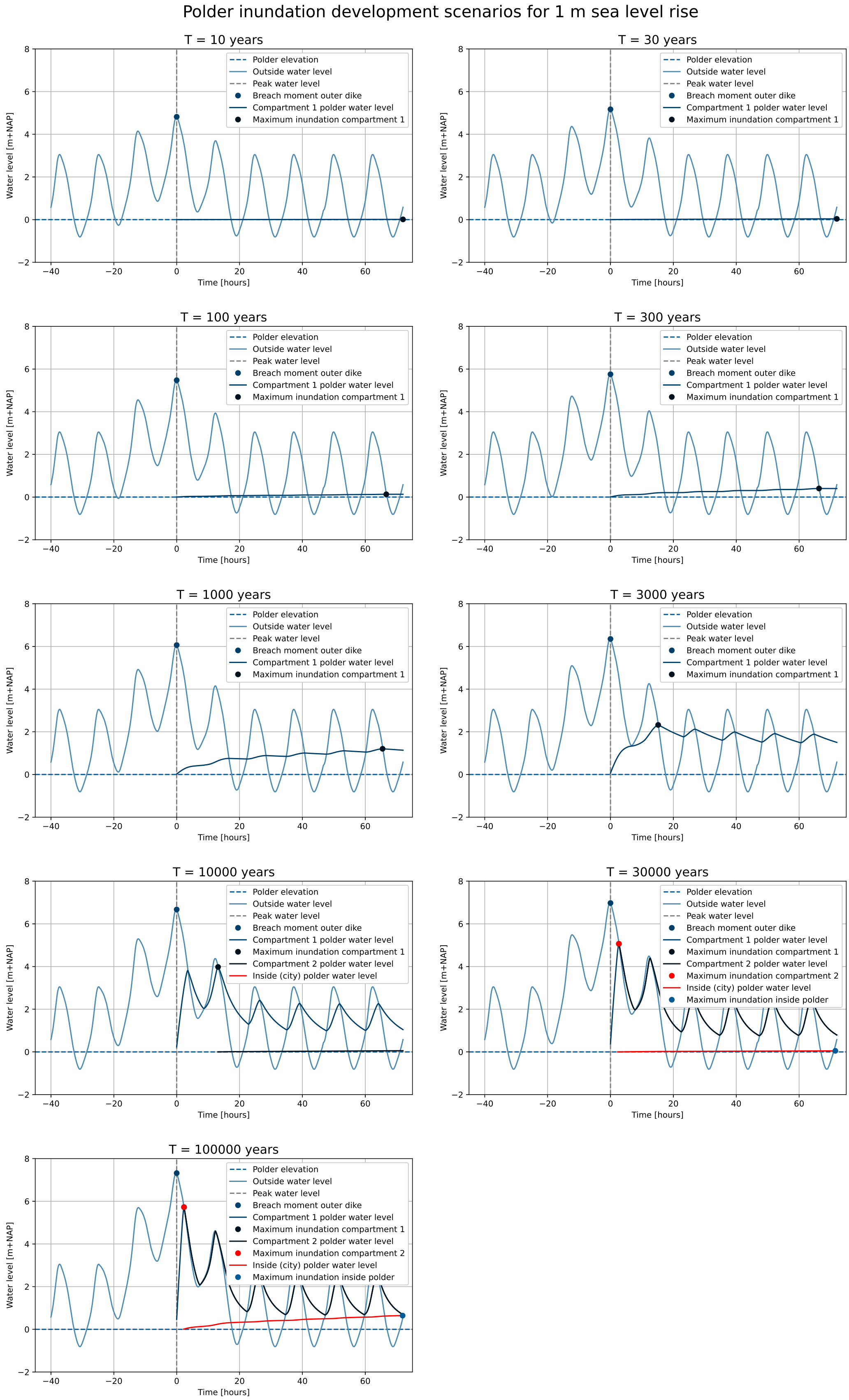


Figure C.47: Polder inundation development for 1 meter sea level rise (complete dike reinforcement and city protection) (compartmentalization strategy)

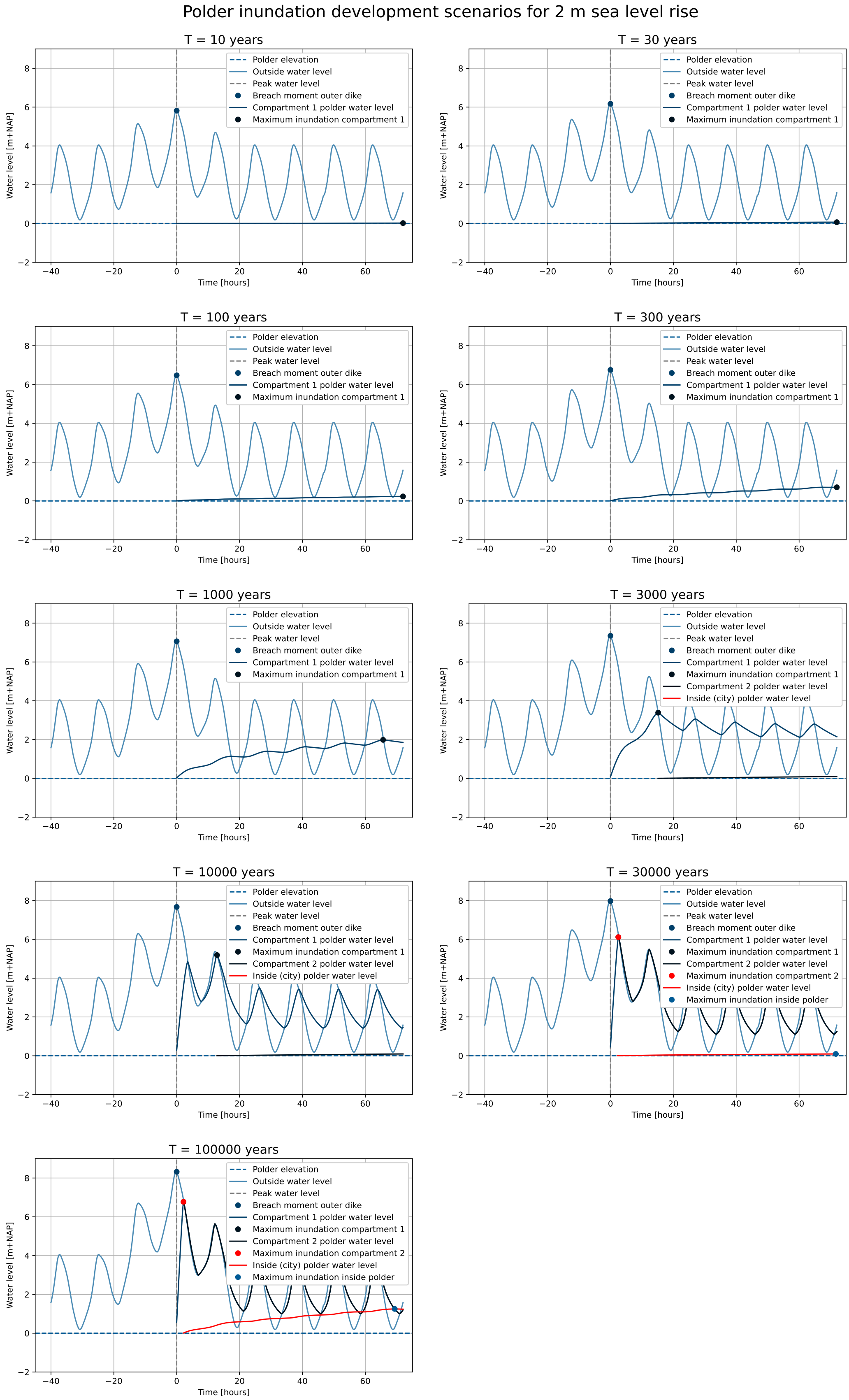


Figure C.48: Polder inundation development for 2 meter sea level rise (complete dike reinforcement and city protection) (compartmentalization strategy)

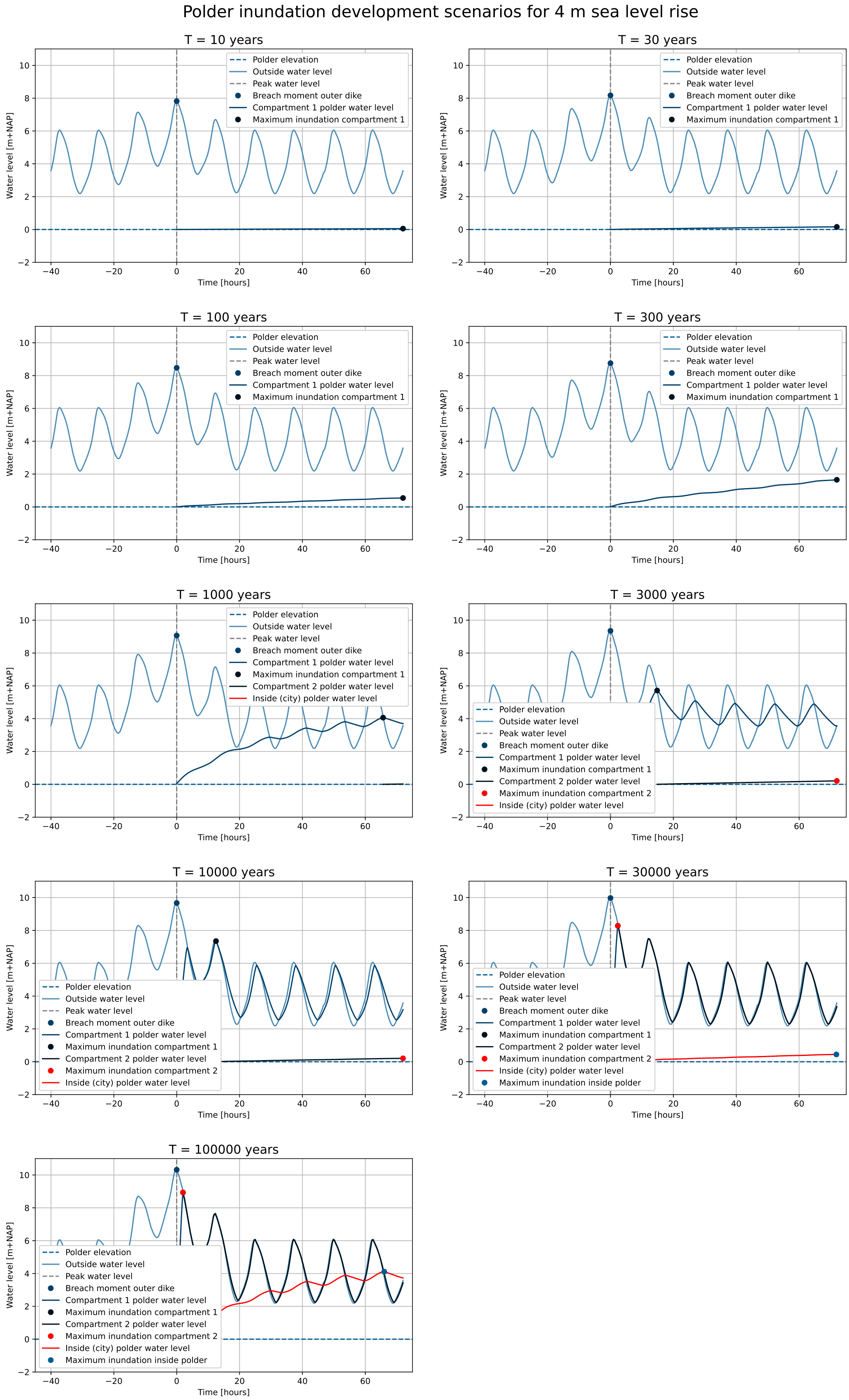


Figure C.49: Polder inundation development for 4 meter sea level rise (complete dike reinforcement and city protection) (compartmentalization strategy)

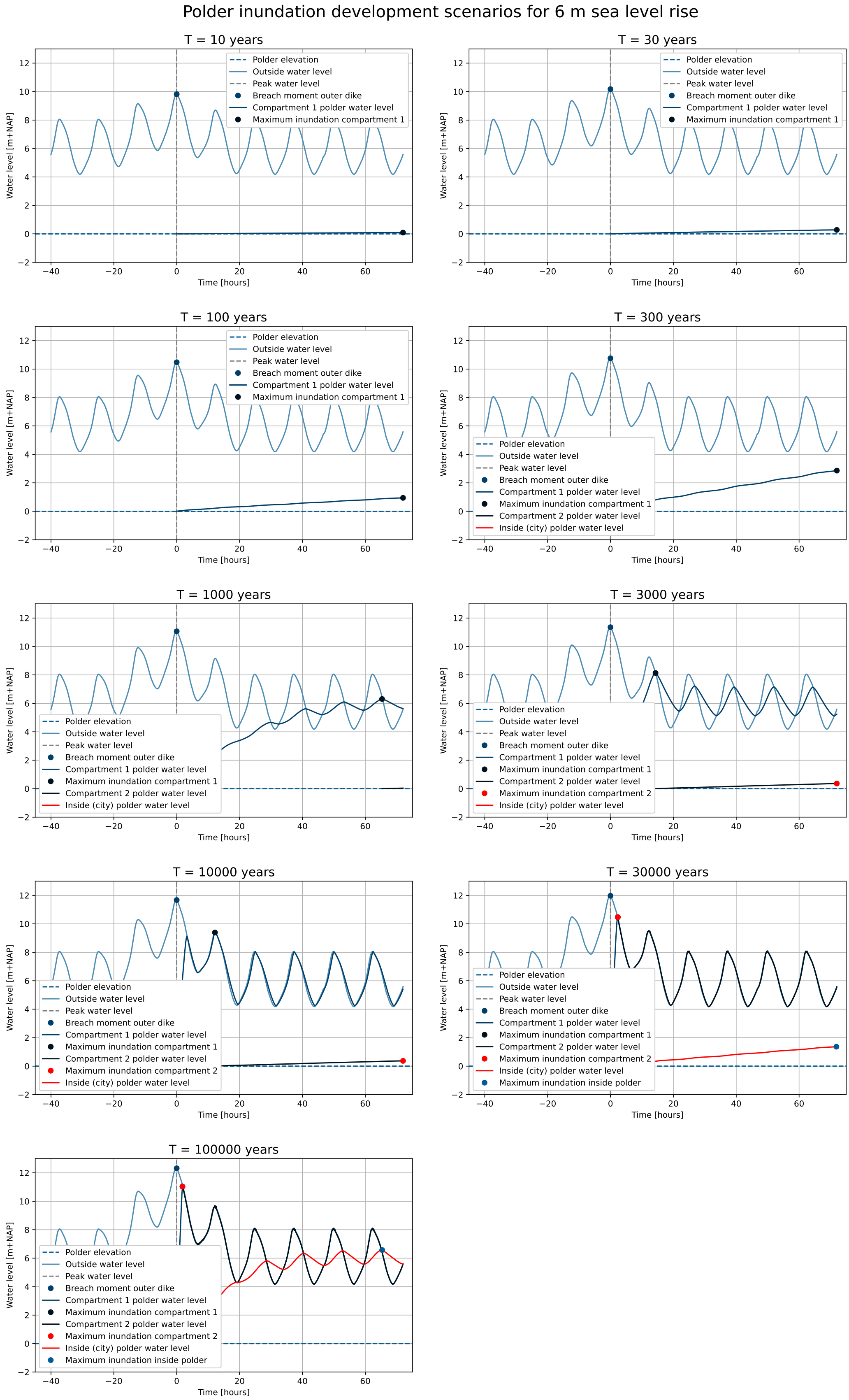
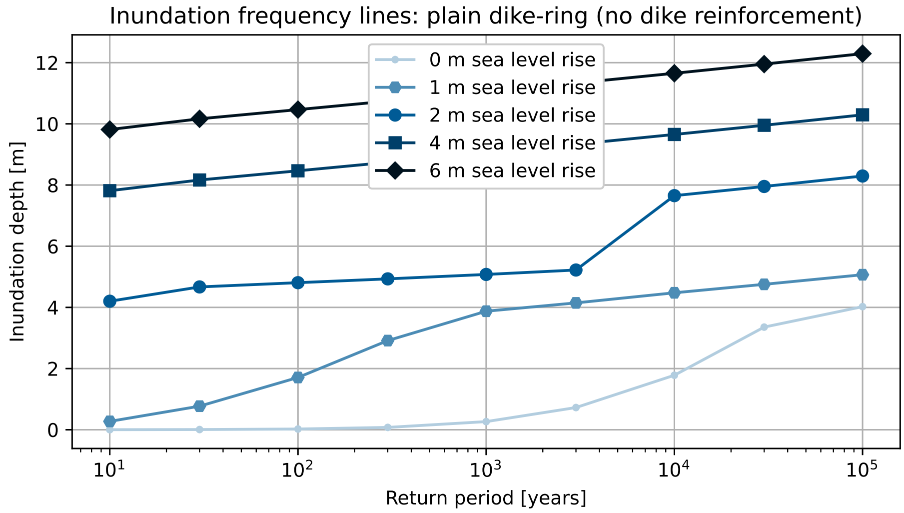


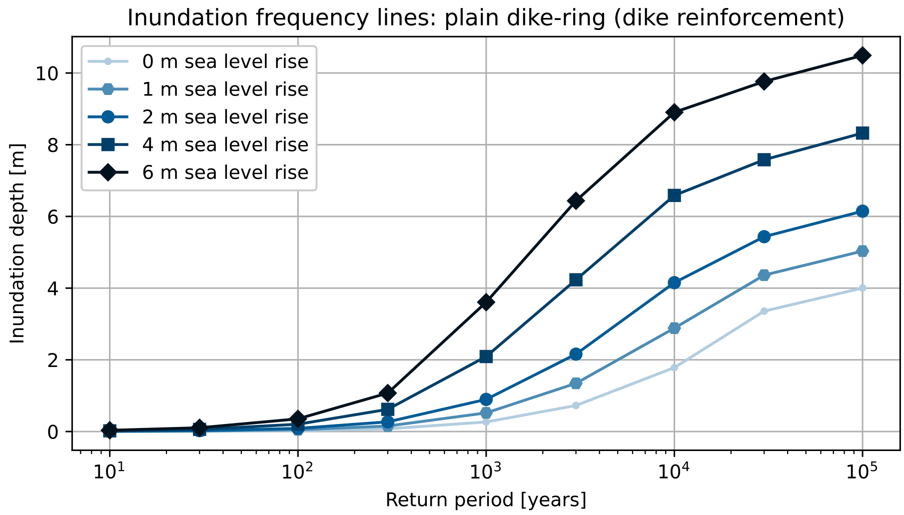
Figure C.50: Polder inundation development for 6 meter sea level rise (complete dike reinforcement and city protection) (compartmentalization strategy)

C.2. Inundation frequency lines

C.2.1. Plain dike-ring



(a) no dike reinforcement (NR)



(b) dike reinforcement (R)

Figure C.51: Inundation frequency lines for an idealized coastal polder with a plain dike-ring

C.2.2. Secondary dike-ring

Primary (outer) dike reinforcement

The inundation frequency lines for a secondary dike-ring with primary dike reinforcement are shown in figure C.52. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.11, C.12, C.13, C.14 and C.15.

The secondary dike-ring with primary dike reinforcement is most valuable for scenarios of mild sea level rise (0, 1 and 2 meters) and mostly for lower return periods. Overall, in the lower range of return periods, implementation of this strategy results in lower inundation depths compared to the plain dike-ring strategy with dike reinforcement. However, when considering a scenario of for instance 6 meters sea level rise in combination with a storm surge with a return period of T = 1,000 years, the expected maximum inundation depth is higher in the presence of a secondary dike-ring compared to a plain dike-ring (see figure C.52 versus 4.2b). This can be explained by the fact that the water that enters the polder through breaches in a plain dike-ring area spreads out evenly over a larger area compared to the situation with a secondary dike-ring. In case of the secondary dike-ring, the water spreads out over the area between the primary and secondary dike-ring. Therefore, for a plain dike-ring, the estimated maximum inundation depth is reached after 72 hours, which is the maximum time frame in this study. Looking at the polder inundation development for T = 1,000 years in figure C.10, the expectation is that the polder inundation will grow further in time. However, for the strategy including a secondary dike-ring, the maximum inundation in the outside polder is reached after approximately 65 hours, after which the inside polder almost immediately levels out with the outside polder water level, as shown in figure C.15.

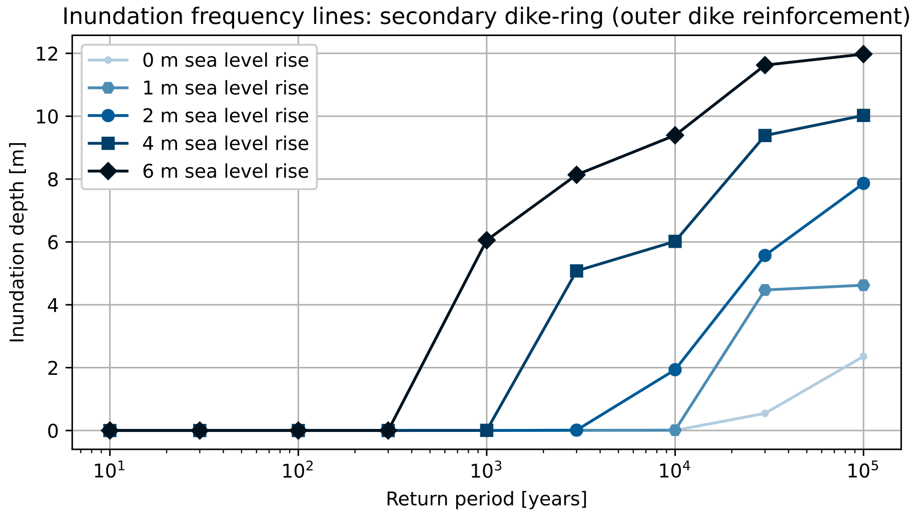


Figure C.52: Inundation frequency lines for a secondary dike-ring (primary dike reinforcement)

Secondary (inner) dike reinforcement

The inundation frequency lines for a secondary dike-ring with secondary (inner) dike reinforcement are shown in figure C.53. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.16, C.17, C.18, C.19 and C.20.

The secondary dike-ring with secondary dike reinforcement proves to be most beneficial in scenarios of low sea level rise (0 and 1 meters), across the full range of storm surge scenarios. However, as the end of this century approaches (2 meters sea level rise), the secondary dike-ring strategy with secondary dike reinforcement retains its value primarily for storm surges with return periods below 10,000 years. In the case of extreme sea level rise (4 or 6 meters), the secondary dike-ring with solely secondary dike reinforcement demonstrates some advantage for 'frequent' storm surges with a return period of 100 years or lower. However, for scenarios of extreme sea level rise and storm surges with return periods of 1,000 years or higher, the inundation depths become so high that the secondary dike-ring is ineffective in providing added value (see figure C.53).

Based on these observations, it can be stated that the effectiveness of the secondary dike-ring with secondary dike reinforcement varies based on the level of sea level rise and the magnitude of storm surges. The secondary dike-ring offers significant advantages in low sea level rise scenarios and frequent storm surge events, but its added value diminishes in scenarios of extreme sea level rise and less frequent, more severe storm surges.

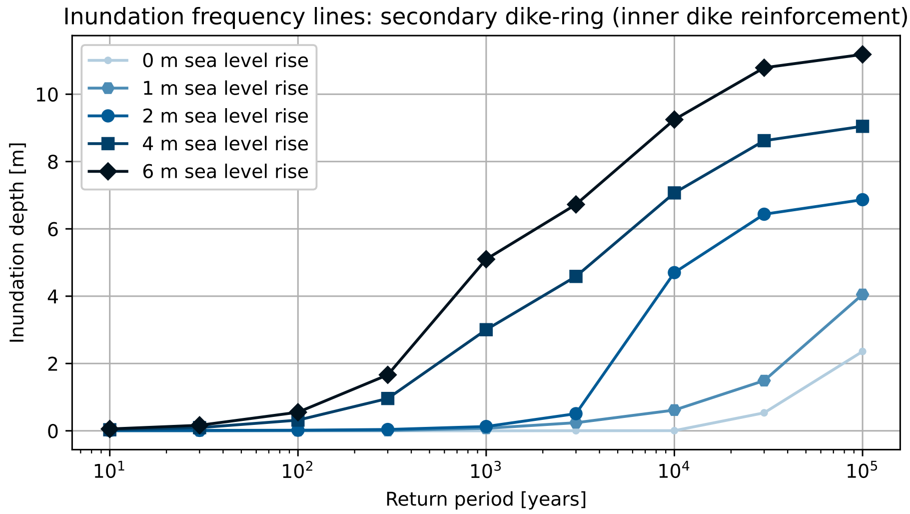


Figure C.53: Inundation frequency lines for a secondary dike-ring (secondary dike reinforcement)

Complete dike reinforcement

The inundation frequency lines for a secondary dike-ring with complete dike reinforcement are shown in figure C.54. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.21, C.22, C.23, C.24 and C.25.

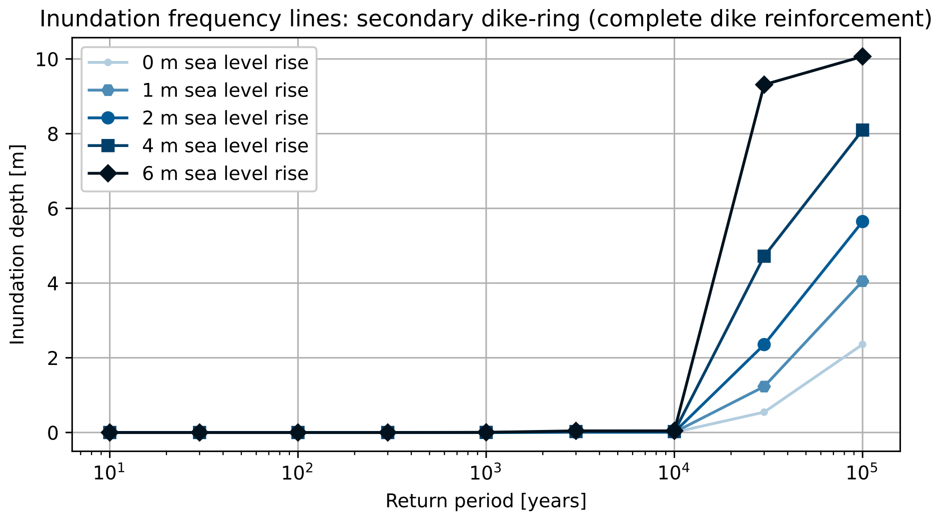


Figure C.54: Inundation frequency lines for a secondary dike-ring (complete dike reinforcement)

The secondary dike-ring with complete reinforcement holds significant value across all scenarios of sea level rise, even for extreme storm surges with return periods equal to or lower than T = 10,000 years. In such cases, the inundation depth in the city located within the polder remains at 0 meters, regardless of the level of sea level rise (see figure C.54). This illustrates the effectiveness of the secondary dike-ring strategy in offering complete protection against storm surges with moderate to extreme return periods.

However, for water levels with return periods higher than T = 10,000 years, the inundation depth is still manageable in case of low sea level rise scenarios (0 or 1 meters), but by the end of this century and beyond (2 meters sea level rise and more), the expected inundation depth becomes extreme and challenging to manage (see figure C.54).

C.2.3. Value protection dike-ring

Primary (outer) dike reinforcement

The inundation frequency lines for a value protection dike-ring with primary dike reinforcement are shown in figure C.55.

In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.26, C.27, C.28, C.29 and C.30.

Similar to the secondary dike-ring strategy, the secondary value protection dike-ring with primary dike reinforcement is most valuable for scenarios of mild sea level rise (0, 1 and 2 meters) and mostly for lower return periods. Overall, in the lower range of return periods, implementation of this strategy results in lower inundation depths compared to the plain dike-ring strategy with dike reinforcement. For extreme scenarios of sea level rise (4 and 6 meters), the inundation depths of the secondary value protection dike-ring strategy with primary dike reinforcement are quite similar to that of the plain dike-ring strategy with dike reinforcement for return periods larger than 1,000 years.

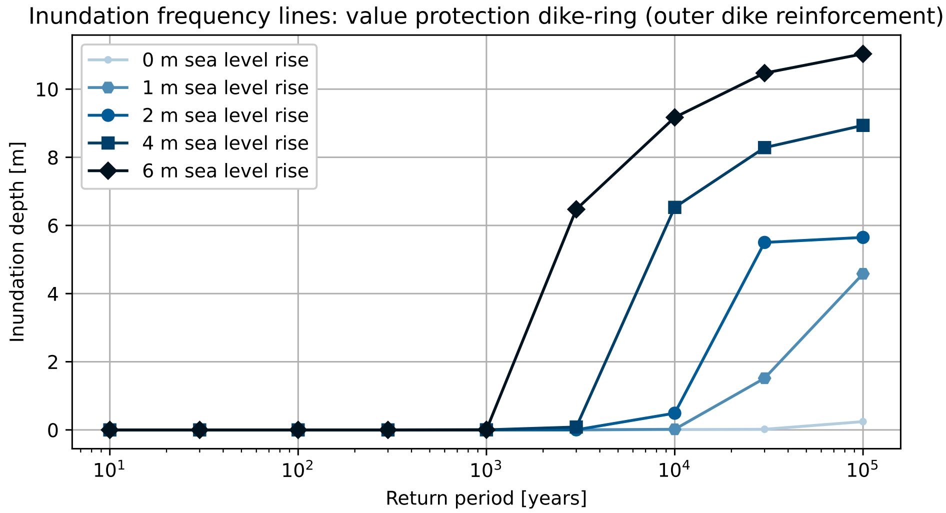


Figure C.55: Inundation frequency lines for a (secondary) value protection dike-ring (primary dike reinforcement)

Secondary (inner) dike reinforcement (Plan B)

The inundation frequency lines for a secondary value protection dike-ring with secondary dike reinforcement are shown in figure C.56. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.31, C.32, C.33, C.34 and C.35.

Similar to the secondary dike-ring strategy with secondary dike reinforcement, the secondary value protection dike-ring with secondary dike reinforcement proves to be most beneficial in scenarios of low sea level rise (0 and 1 meters), across the entire range of storm surge scenarios. However, as the sea level rise reaches 2 meters by the end of this century, the effectiveness of the secondary dike-ring strategy with secondary dike reinforcement is primarily retained for storm surges with return periods below 10,000 years. The abrupt rise in inundation depth observed in the scenario with 2 meters sea level rise (see figure C.56) can be attributed to the maximum sea water level exceeding the critical threshold of 7.5 m+NAP. Consequently, it is assumed that the water level in the outside polder area matches the sea water level. As a result, the expected number of breaches in the secondary value protection dike-ring increases, leading to a corresponding increase in the inundation depth.

In cases of extreme sea level rise (4 or 6 meters), the secondary value protection dike-ring with solely secondary dike reinforcement demonstrates some advantage for storm surges considered 'frequent' with a return period of 100 years or lower. Nevertheless, for scenarios involving extreme sea level rise and storm surges with return periods of 1,000 years or higher, the inundation depths become so substantial that the secondary dike-ring becomes ineffective in providing added value (see figure C.56).

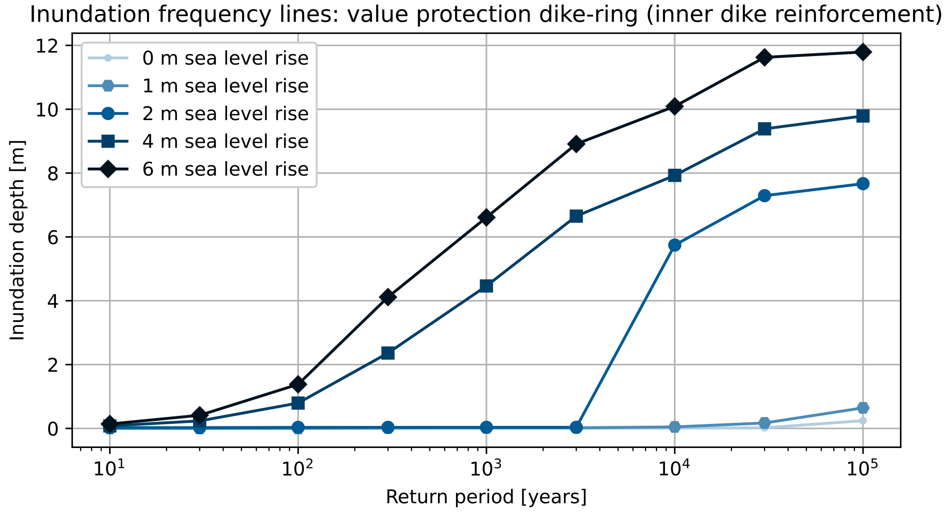


Figure C.56: Inundation frequency lines for a (secondary) value protection dike-ring (secondary dike reinforcement)

The findings from this analysis indicate that the effectiveness of the secondary value protection dike-ring with secondary dike reinforcement varies based on the level of sea level rise and the magnitude of storm surges. Under the assumption that the primary dike is not reinforced, the secondary dike-ring offers significant advantages in low sea level rise scenarios and frequent storm surge events, but its added value diminishes in scenarios of extreme sea level rise and less frequent, more severe storm surges.

Complete dike reinforcement

The inundation frequency lines for a secondary value protection dike-ring with complete dike reinforcement are shown in figure C.57. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.36, C.37, C.38, C.39 and C.40.

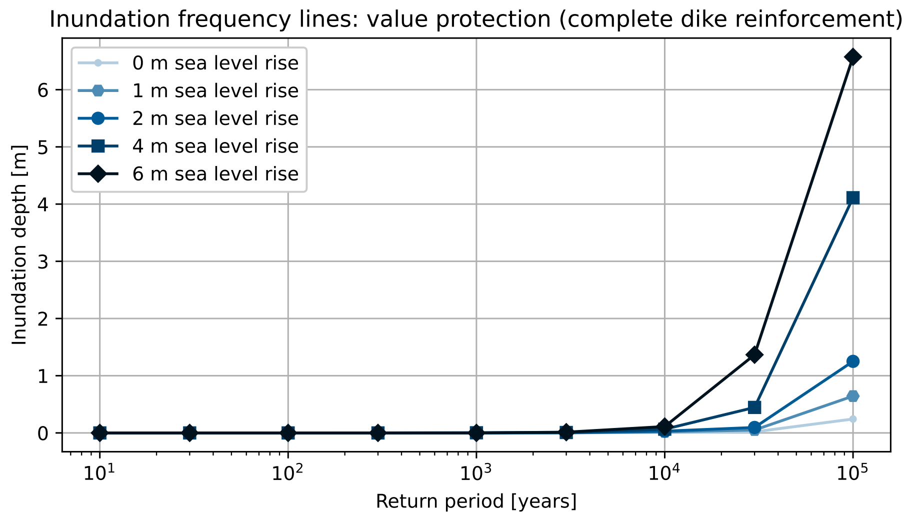


Figure C.57: Inundation frequency lines for a secondary value protection dike-ring (complete dike reinforcement)

The secondary value protection dike-ring with complete reinforcement holds significant value across all scenarios of sea level rise, even for extreme storm surges with return periods equal to or lower than T = 10,000 years. In such cases, the inundation depth in the city located within the polder remains at values of around 0 meters, regardless of the level of sea level rise (see figure C.57). This illustrates the effectiveness of the secondary value protection dike-ring strategy in offering complete protection against storm surges with moderate to extreme return periods.

For very extreme storm surges with return periods of T = 100,000 years, the inundation depth is even manageable in case of mild sea level rise scenarios (0, 1 or 2 meters). Then, for more extreme sea level rise scenarios (4 or 6 meters), the expected inundation depth becomes extreme and challenging to manage (see figure C.57).

C.2.4. Partitioned dike-ring

Partition investment

The inundation frequency lines for a partitioned dike-ring with complete dike reinforcement and partition investment are shown in figure C.58. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.41, C.42, C.43, C.44 and C.45.

Similar to the secondary value protection dike-ring with complete reinforcement, the partitioned dike-ring strategy with partition investment demonstrates considerable efficiency in all scenarios of sea level rise, even for extreme storm surges with return periods equal to or lower than T = 10,000 years. In such instances, the inundation depth within the city situated within the polder remains at values of approximately 0 meters, irrespective of the magnitude of sea level rise (see figure C.58).

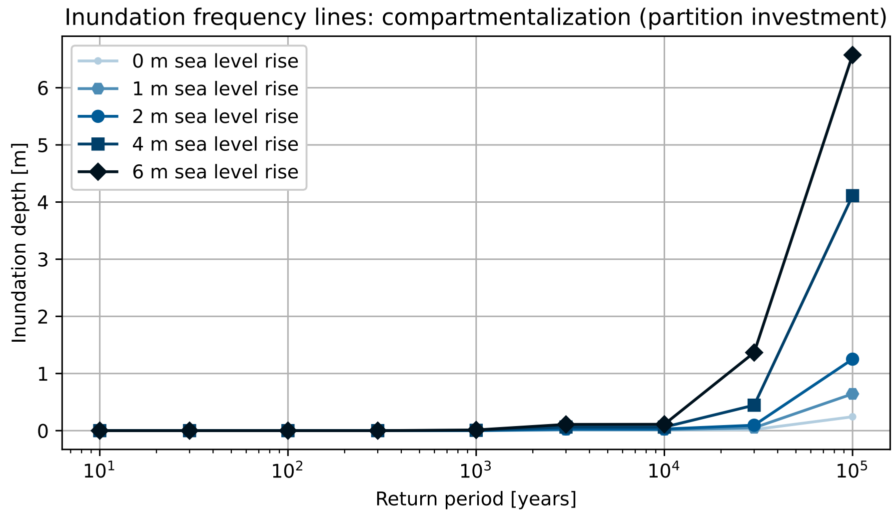


Figure C.58: Inundation frequency lines for a partitioned dike-ring (complete dike reinforcement) with partition investment

City protection

The inundation frequency lines for a partitioned dike-ring with complete dike reinforcement and city protection are shown in figure C.59. In the figure, each data point represents the maximum polder inundation corresponding to a specific combination of sea level rise and storm surge water level. These values align with the maximum polder inundation values as presented in figures C.46, C.47, C.48, C.49 and C.50.

For a partitioned dike-ring strategy with city protection, the inundation depth of the city can be reduced to 0 meters for all scenarios of sea level rise, for extreme storm events with return periods equal to or below T = 10,000 years.

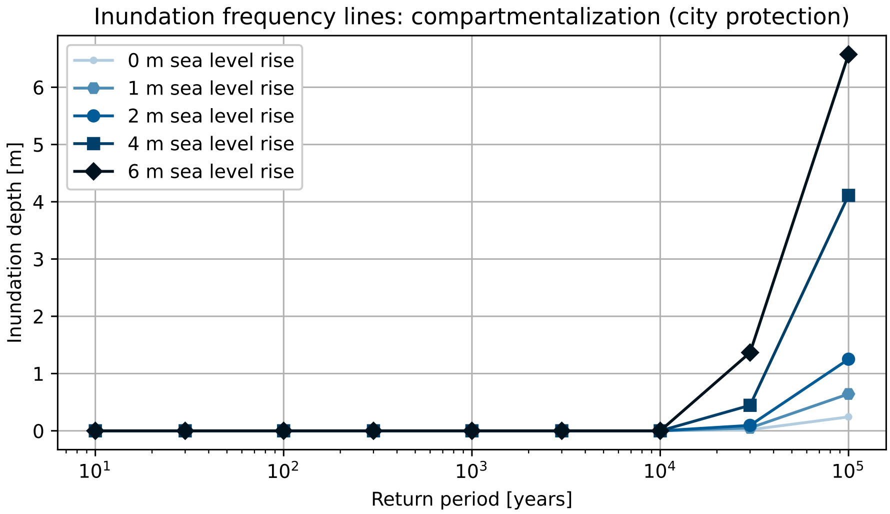


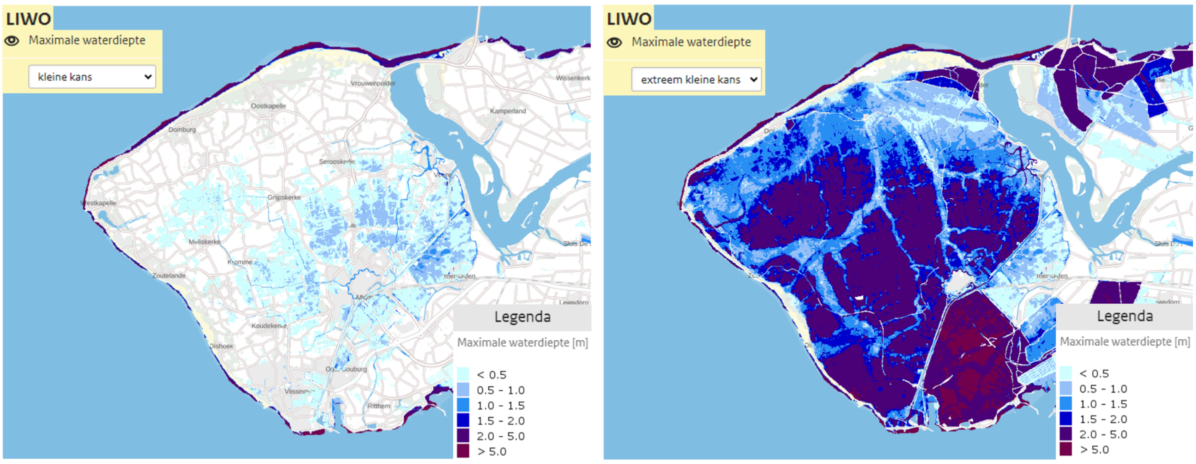
Figure C.59: Inundation frequency lines for a partitioned dike-ring with city protection (complete dike reinforcement)

D

Walcheren

D.1. LIWO

The National Water and Flood Information System, also known as LIWO (Dutch: Het Landelijk Informatiesysteem Water en Overstromingen) contains map layers for professionals involved in (preparing for) floods in the Netherlands. LIWO contains a database with maps of the Netherlands, including the maximum flood depth Netherlands (Dutch: Maximale overstromingsdiepte Nederland). Figure D.1 displays the maximum flood depth maps for Walcheren, showing both the maximum water depth with a low probability (figure D.1a) and the maximum water depth with an extremely low probability (figure D.1b).



(a) Low probability

(b) Extremely low probability

Figure D.1: LIWO flood maps

The probability classes as defined by LIWO are quantified as follows:

- High probability: >1/30 per year
- Medium probability: 1/30 to 1/300 per year
- Low probability: 1/300 to 1/3,000 per year
- Very low probability: 1/3,000 to 1/30,000 per year
- Extremely low probability: <1/30,000 per year

The flood maps generated by the model for a plain dike-ring strategy under current sea level conditions (0 meters sea level rise) can be compared to those provided by LIWO. The scenario of the plain dike-ring strategy with a return period of T = 1,000 years closely approximates the low-probability scenario in LIWO (see figure D.2), consistent with the defined probability class by LIWO. Meanwhile, for LIWO's extremely low-probability scenario, the corresponding match is found in the plain dike-ring strategy scenario with a return period of T = 30,000 years (see figure D.2), fitting within the given probability class as well.

Subtle differences can be observed when comparing the flood maps from LIWO to the model, particularly in scenarios with extremely low probabilities (T = 30,000 years). For example, the model tends to underestimate water depths in the area encompassing Vlissingen Oost-Souberg and Middelburg-Zuid (located between longitudes 30,000 and 35,000, and latitudes 386,000 and 392,000), while it tends to overestimate inundation in and around Arnemuiden. A crucial feature lacking in the model is the incorporation of regional flood defenses, which accounts for the observed variations in flood depths between LIWO and the model in these mentioned areas. However, for this research, overall the model provides a satisfactory approximation of flood depths in Walcheren for a preliminary assessment.

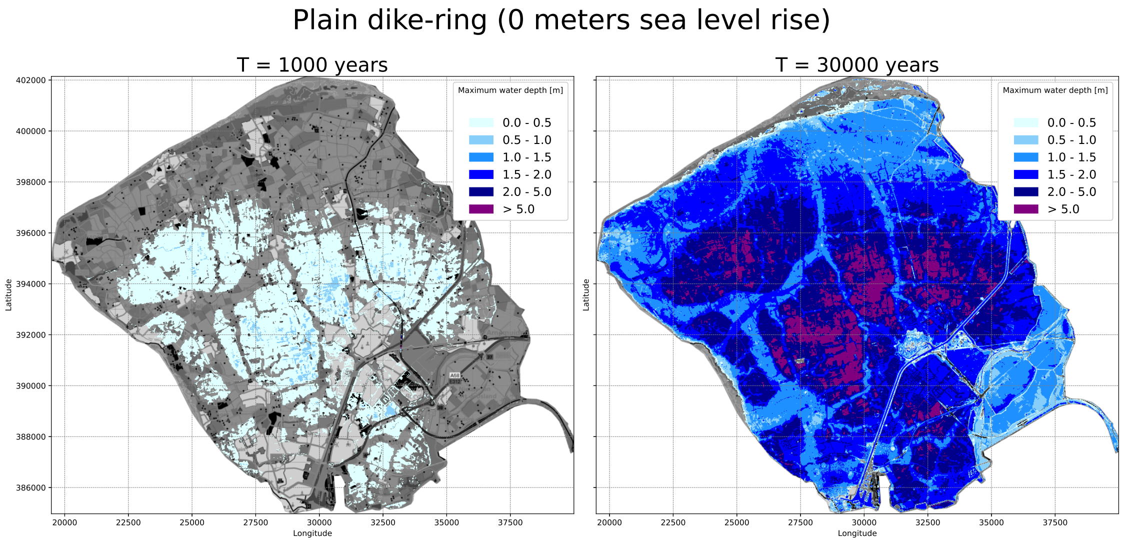


Figure D.2: Inundation of Walcheren for 0 meters sea level rise (plain dike-ring)

D.2. Polder inundation (frequency)

D.2.1. Plain dike-ring

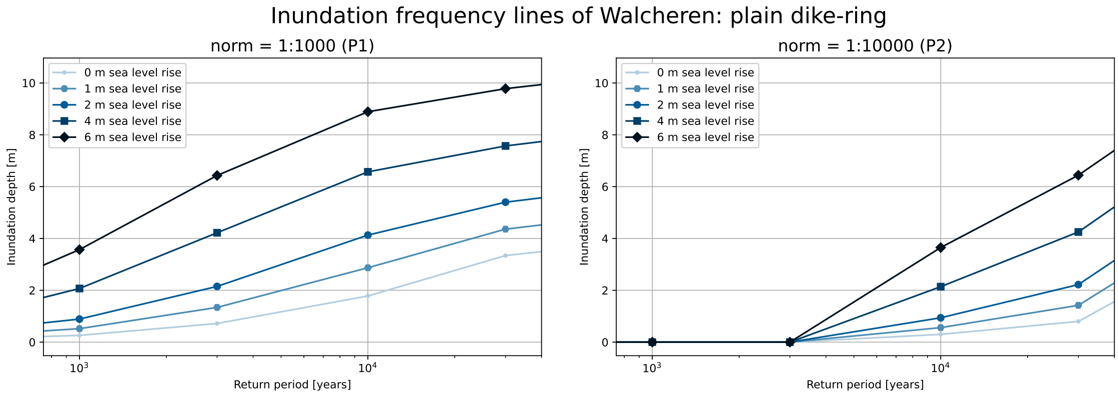


Figure D.3: Inundation frequency lines for Walcheren with a plain dike-ring

D.2.2. Secondary dike-ring

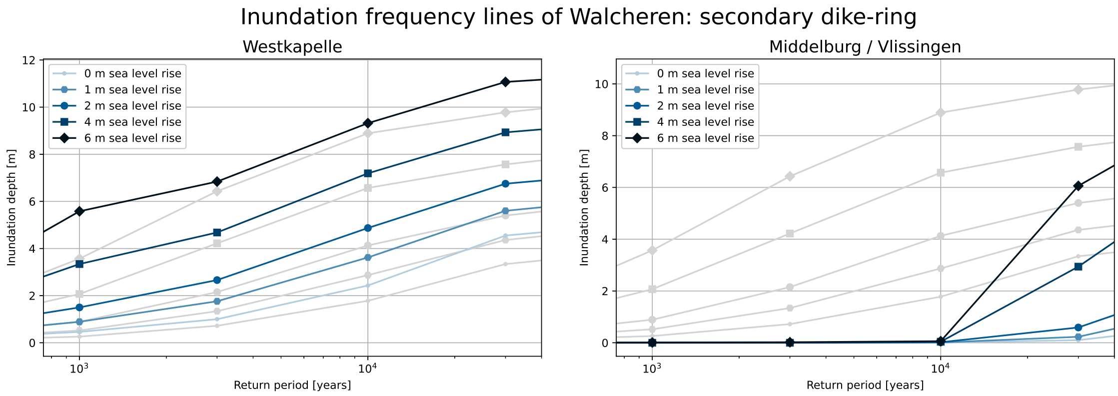


Figure D.4: Inundation frequency lines for Walcheren with a secondary dike-ring

D.2.3. Value protection dike-ring

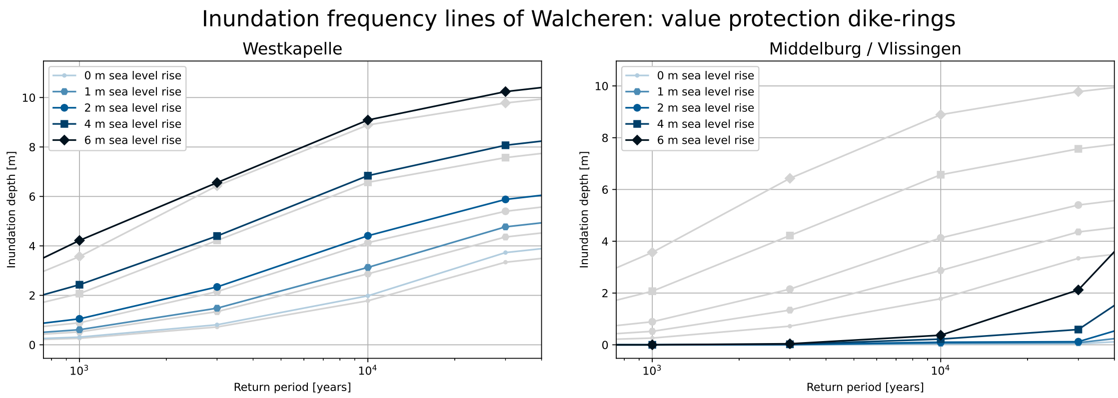


Figure D.5: Inundation frequency lines for Walcheren with value protection dike-rings

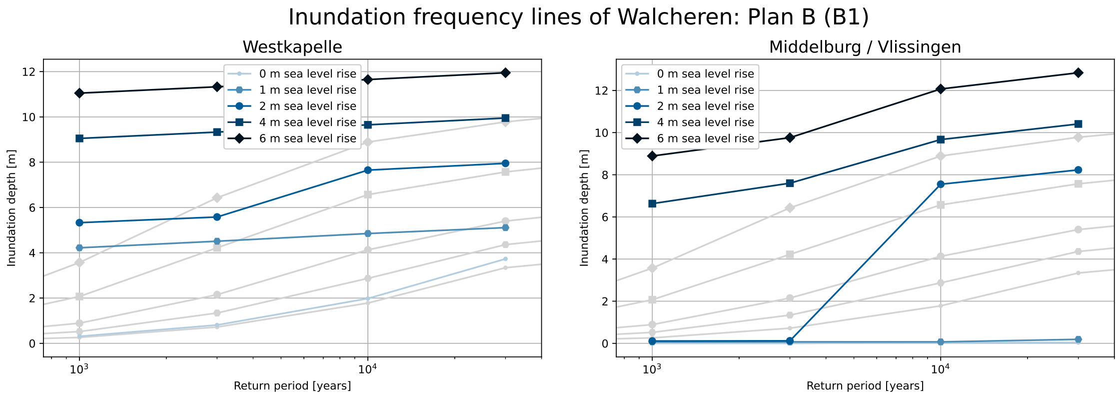


Figure D.6: Inundation frequency lines for Walcheren with Plan B (variant B1)

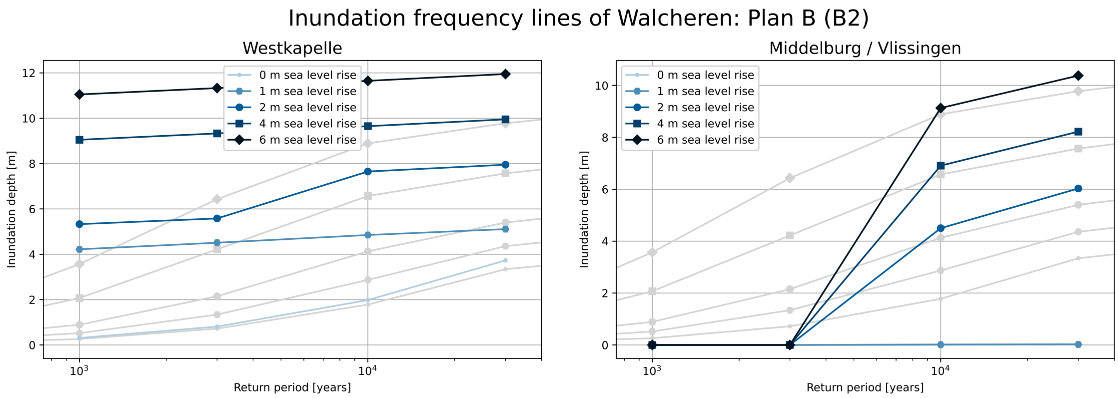


Figure D.7: Inundation frequency lines for Walcheren with Plan B (variant B2)

D.2.4. Compartmentalization

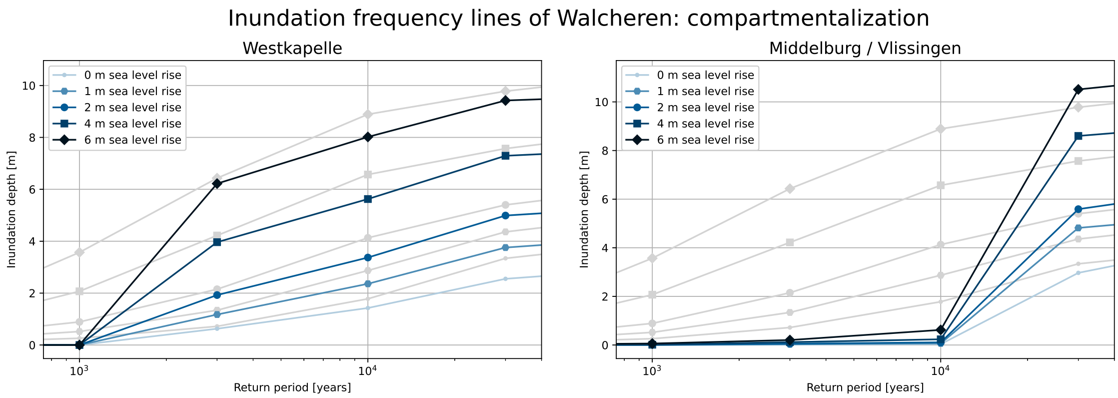


Figure D.8: Inundation frequency lines for Walcheren with compartmentalization

D.3. Flood maps

D.3.1. Plain dike-ring

Configuration P1

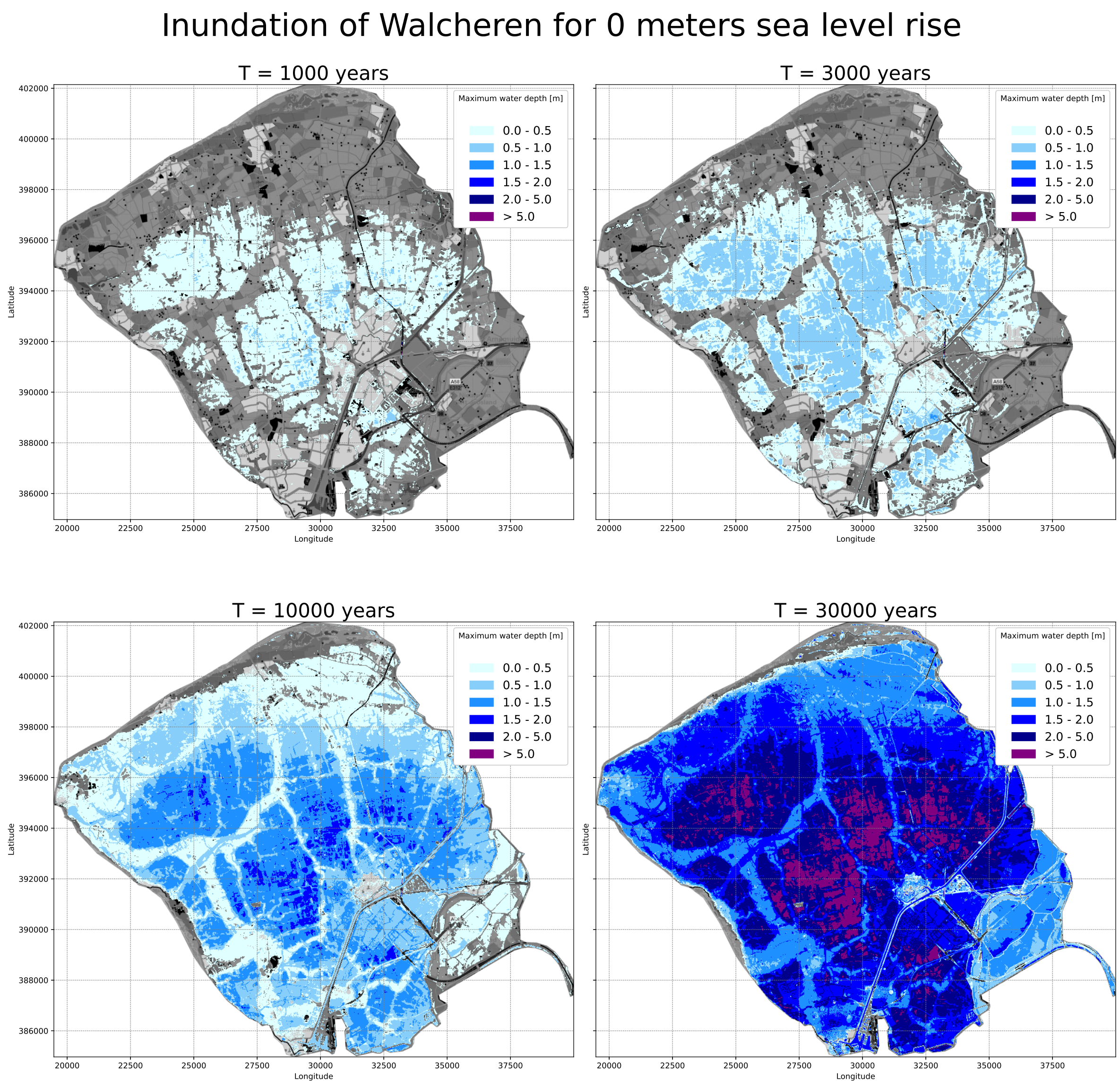


Figure D.9: Flood maps Walcheren for 0 meters sea level rise (plain dike-ring, P1)

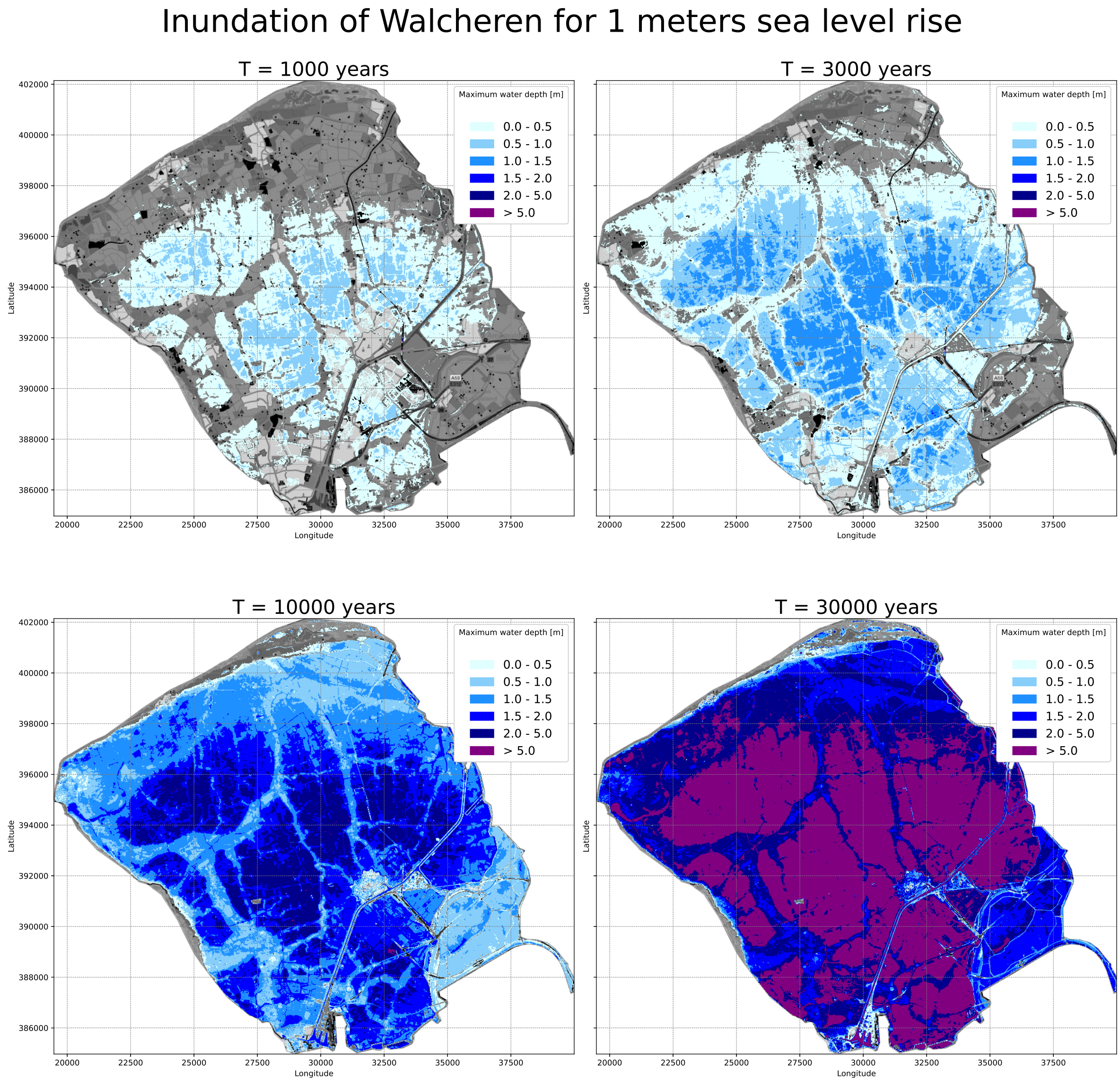


Figure D.10: Flood maps Walcheren for 1 meters sea level rise (plain dike-ring, P1)

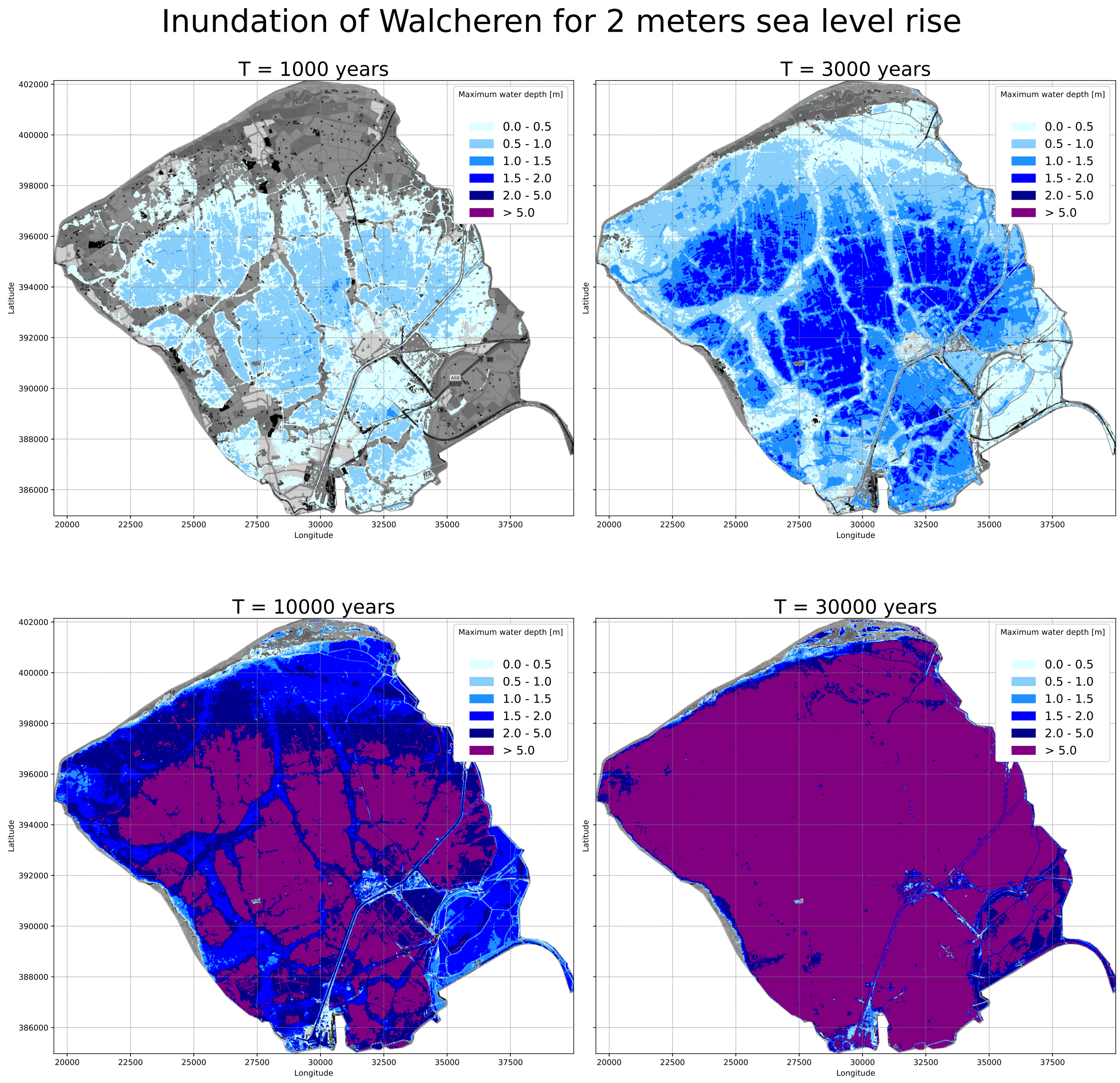


Figure D.11: Flood maps Walcheren for 2 meters sea level rise (plain dike-ring, P1)

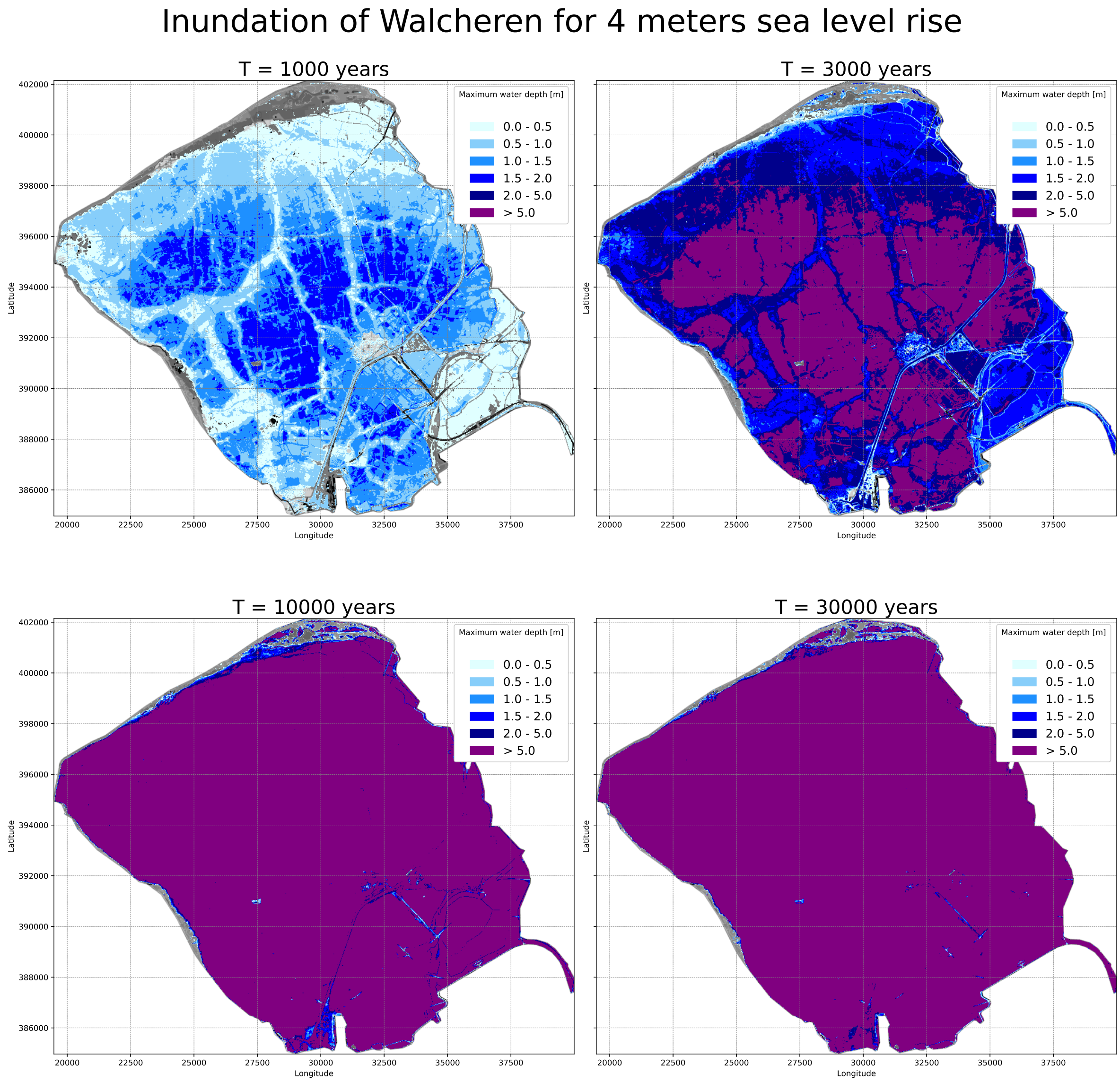


Figure D.12: Flood maps Walcheren for 4 meters sea level rise (plain dike-ring, P1)

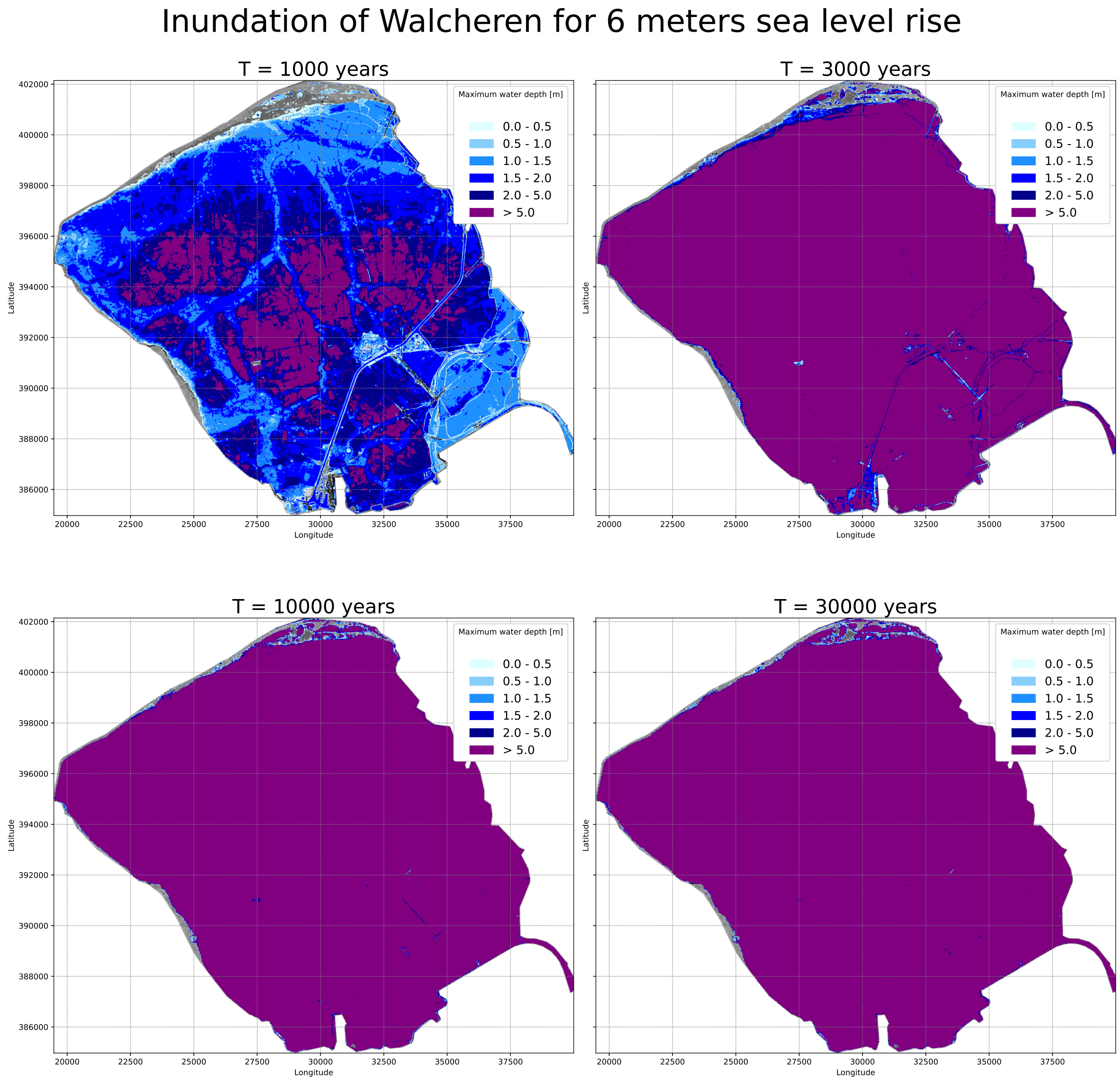


Figure D.13: Flood maps Walcheren for 6 meters sea level rise (plain dike-ring, P1)

Configuration P2

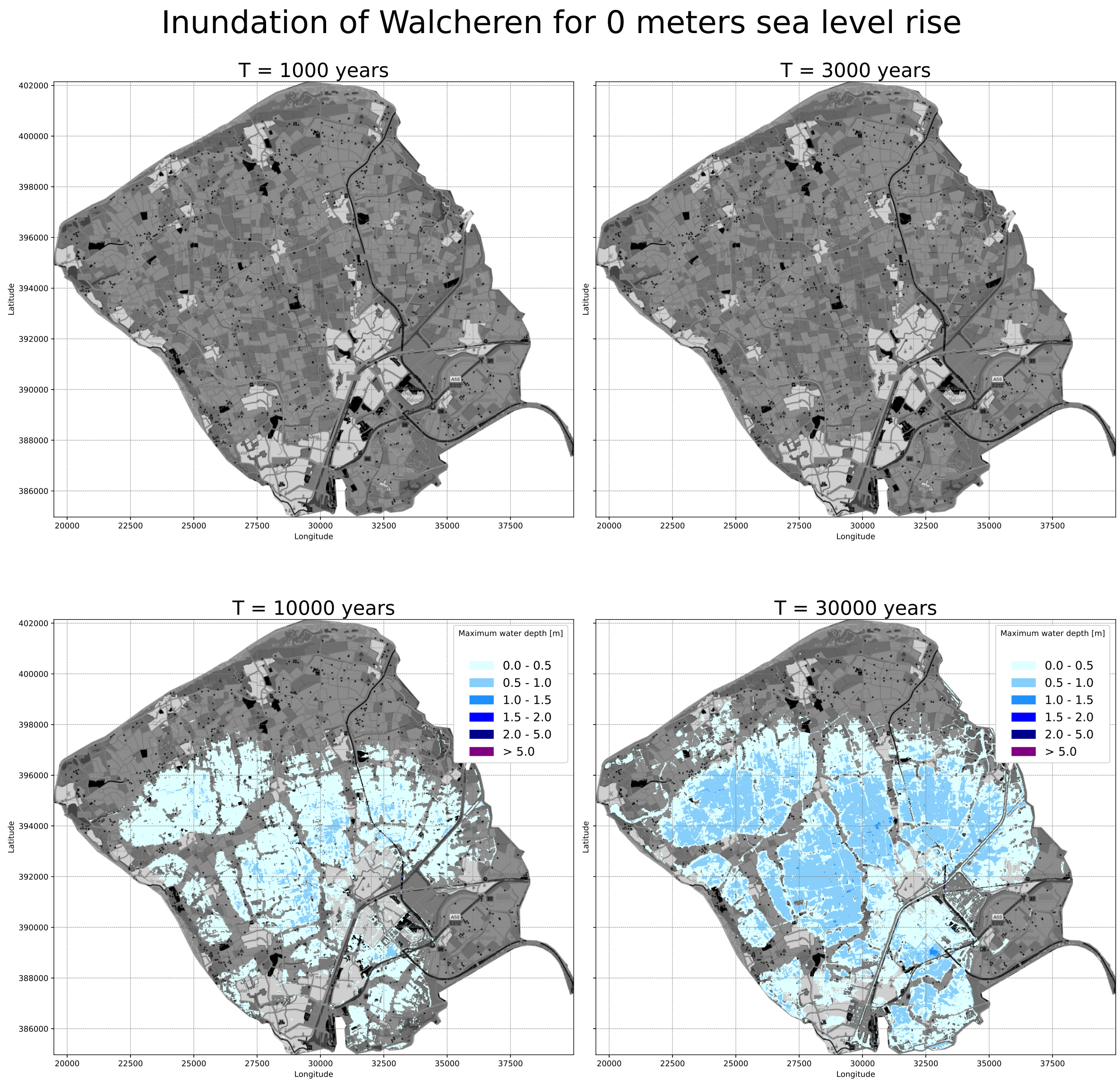


Figure D.14: Flood maps Walcheren for 0 meters sea level rise (plain dike-ring, P2)

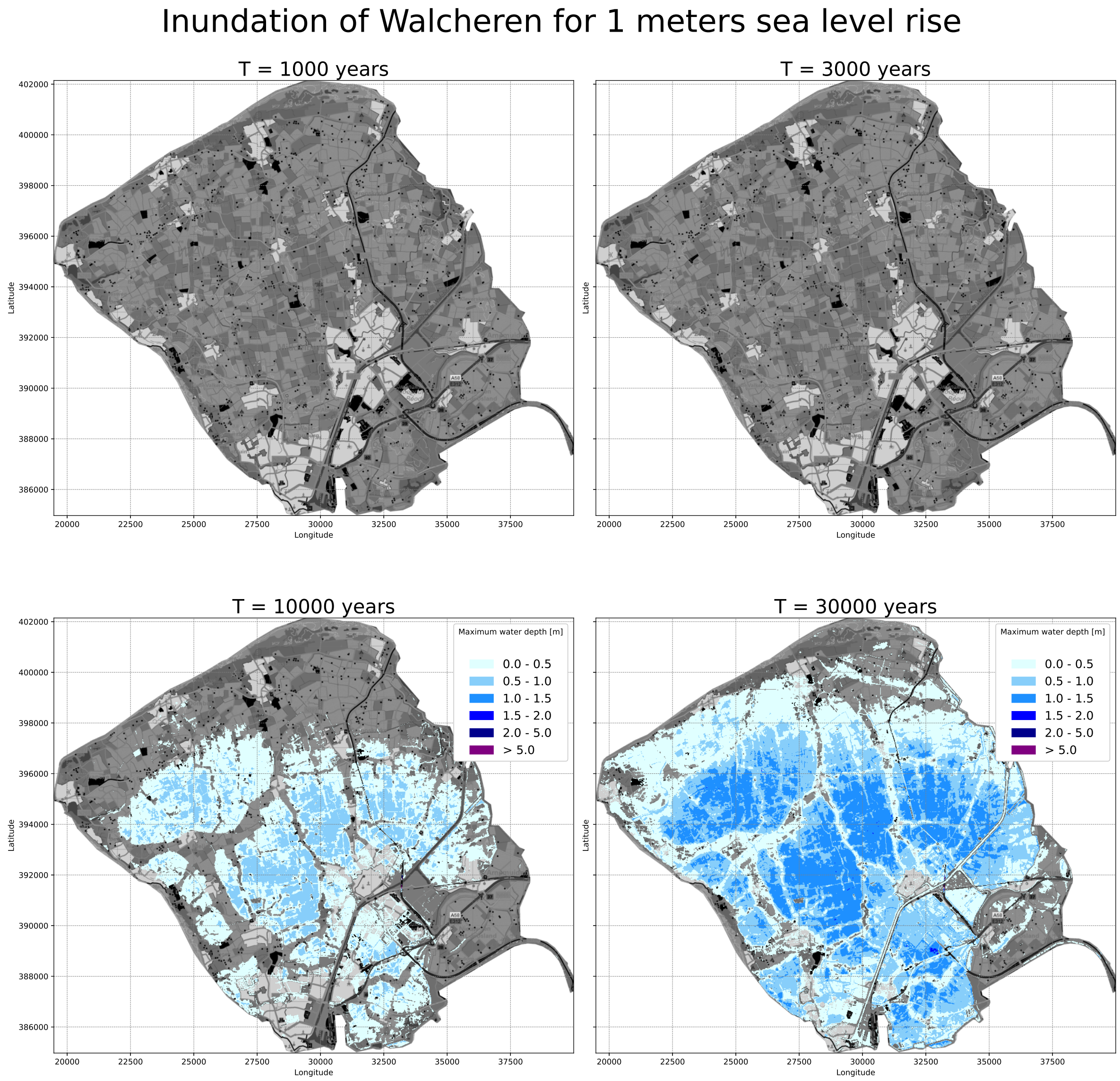


Figure D.15: Flood maps Walcheren for 1 meters sea level rise (plain dike-ring, P2)

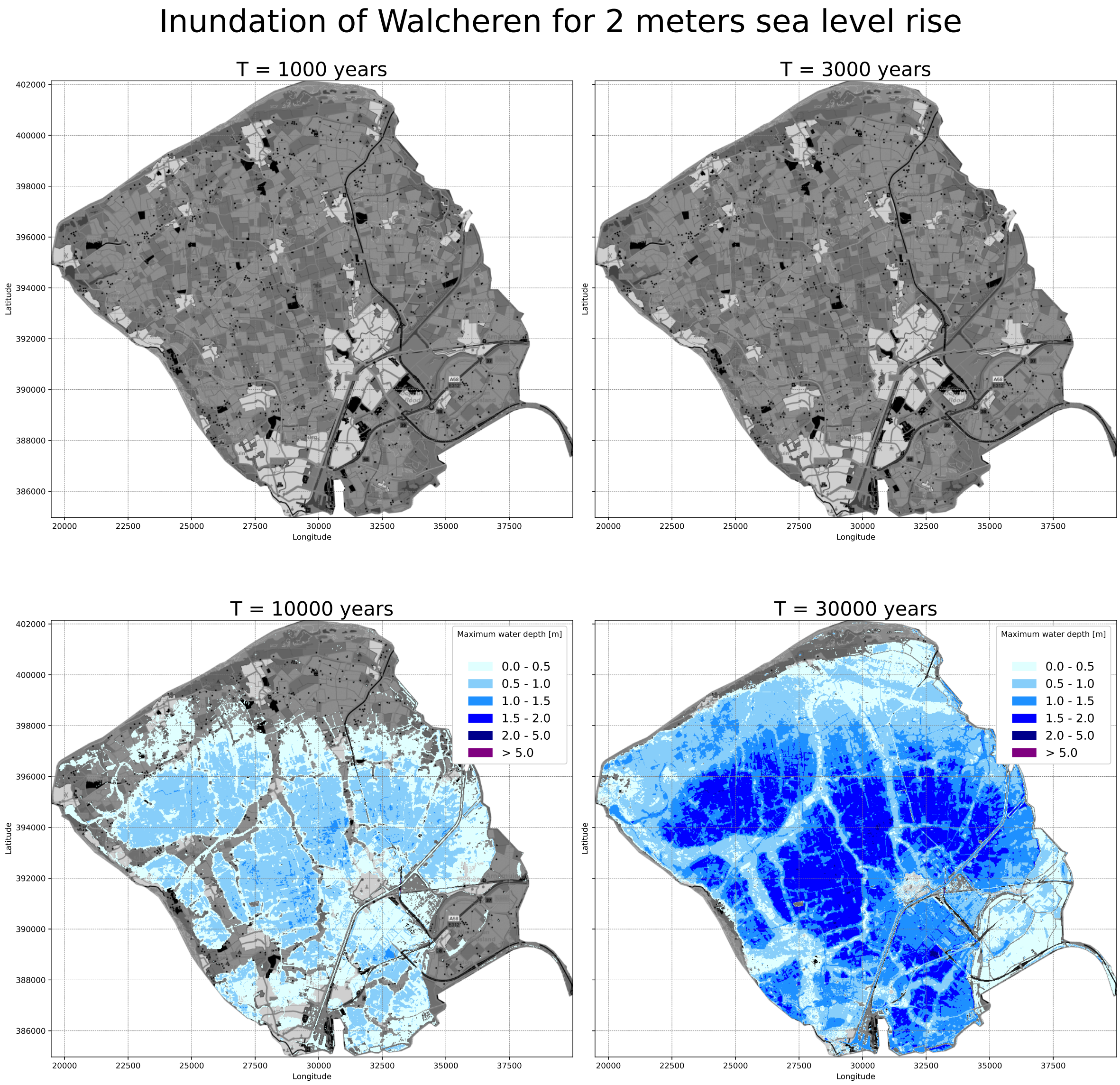


Figure D.16: Flood maps Walcheren for 2 meters sea level rise (plain dike-ring, P2)

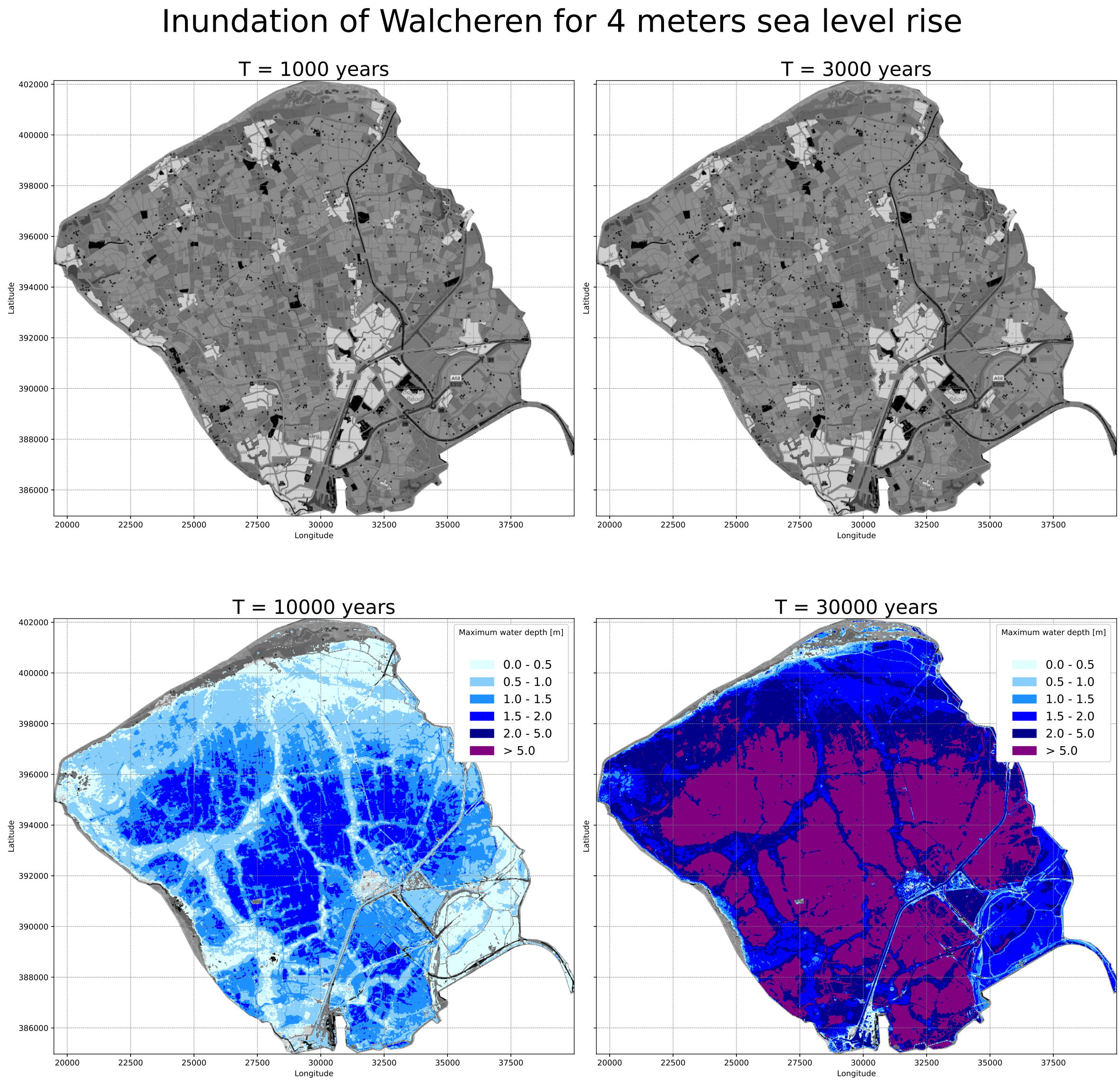


Figure D.17: Flood maps Walcheren for 4 meters sea level rise (plain dike-ring, P2)

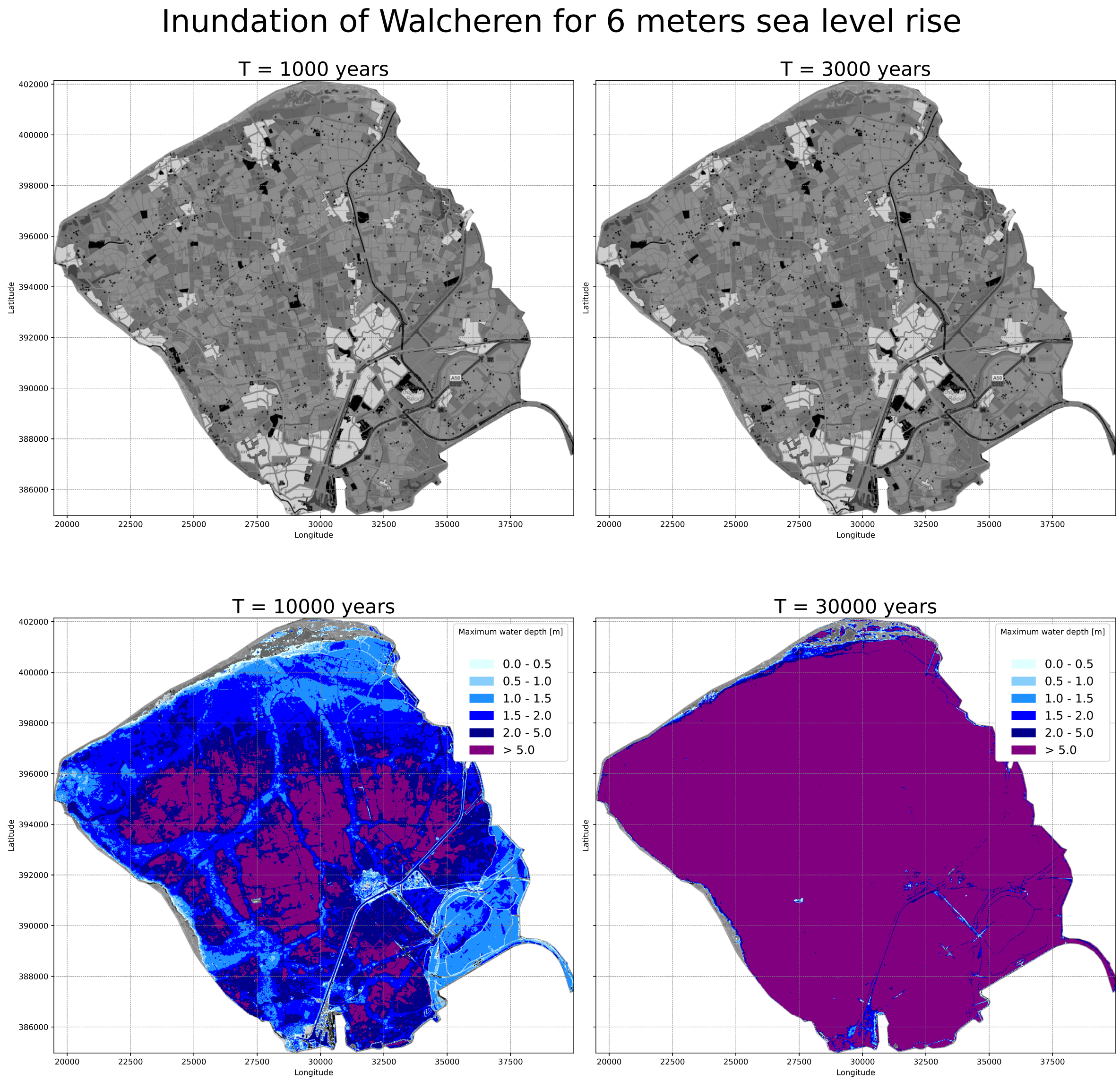


Figure D.18: Flood maps Walcheren for 6 meters sea level rise (plain dike-ring, P2)

D.3.2. Secondary dike-ring

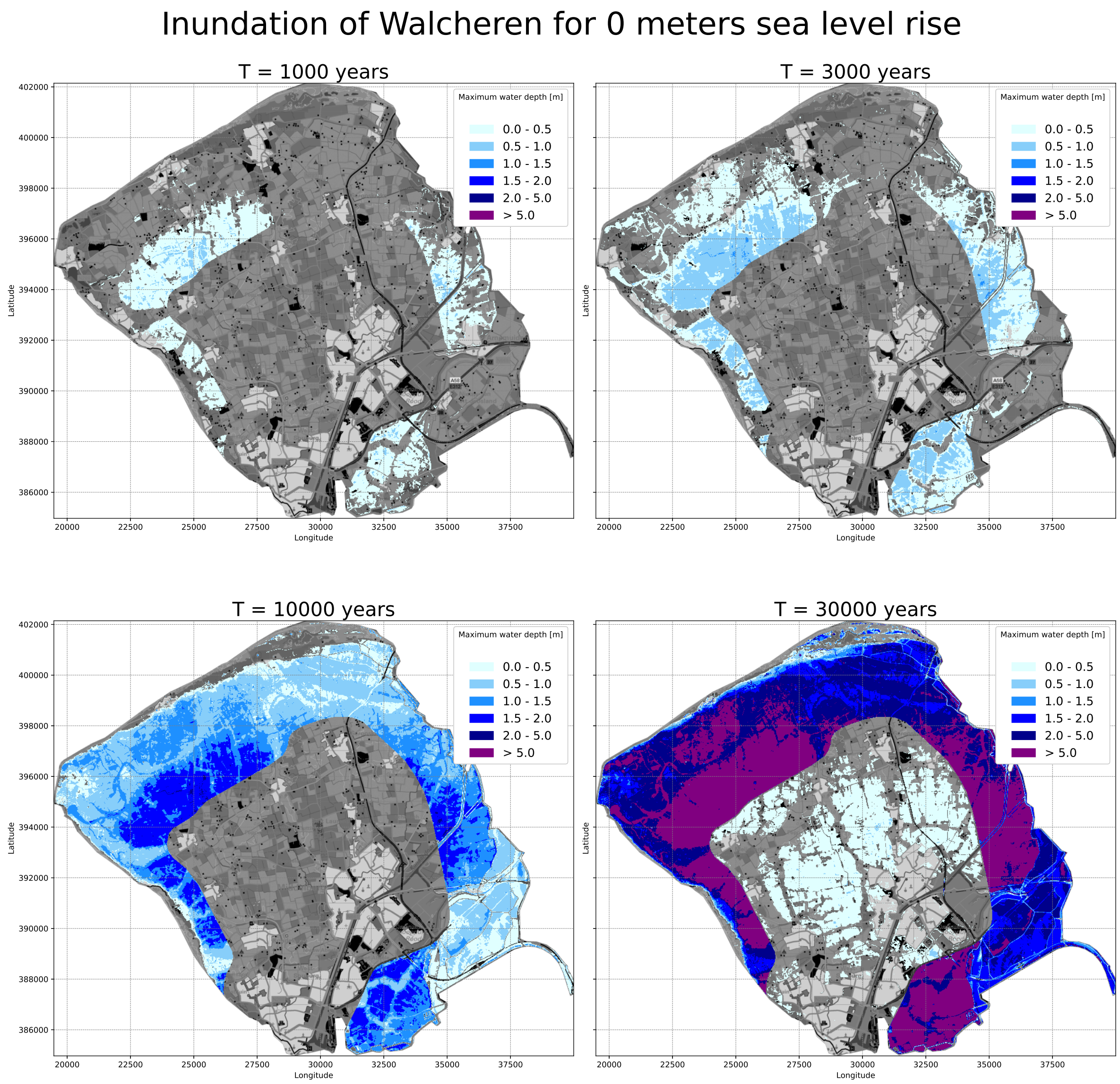


Figure D.19: Flood maps Walcheren for 0 meters sea level rise (secondary dike-ring)

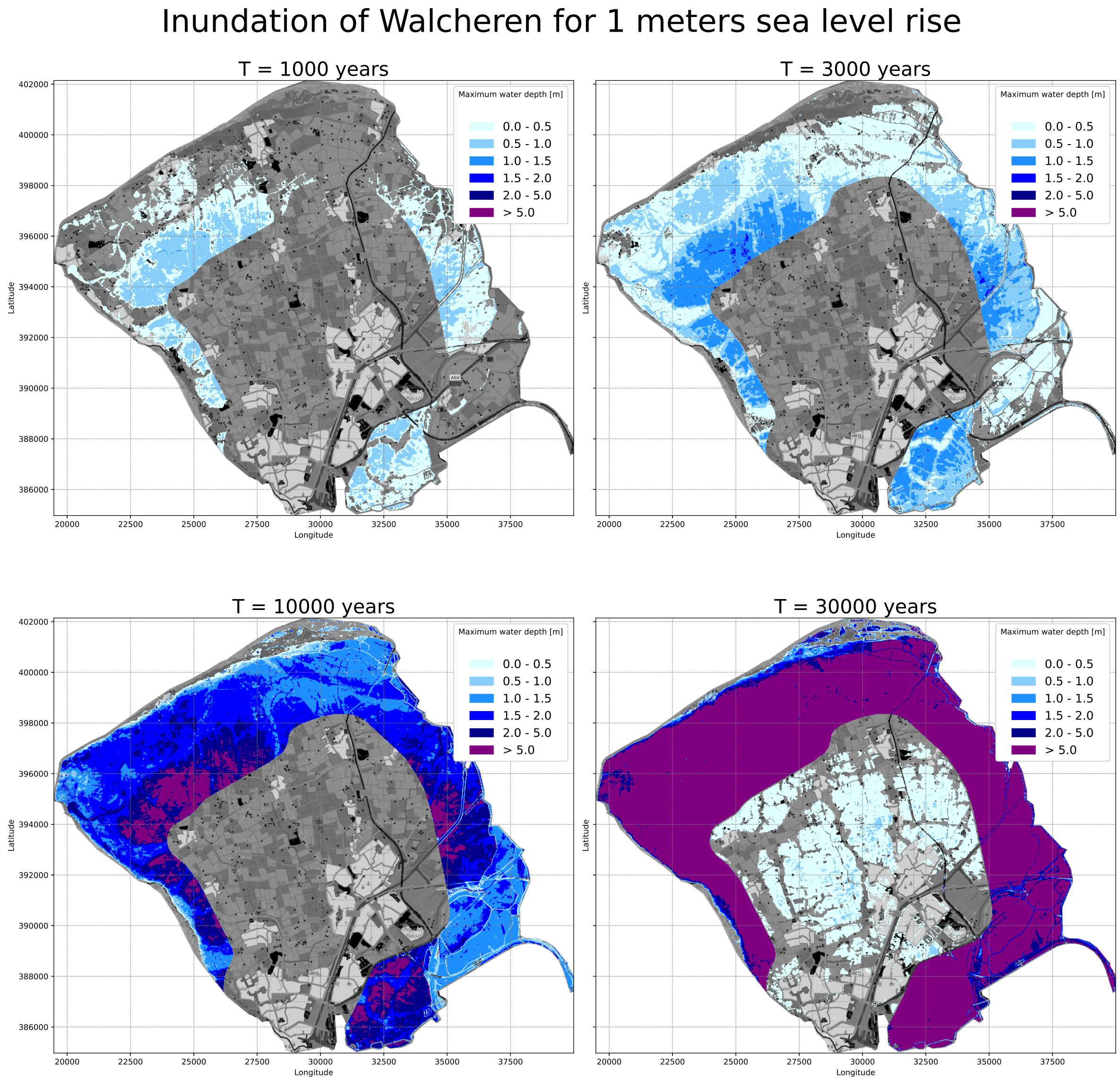


Figure D.20: Flood maps Walcheren for 1 meters sea level rise (secondary dike-ring)

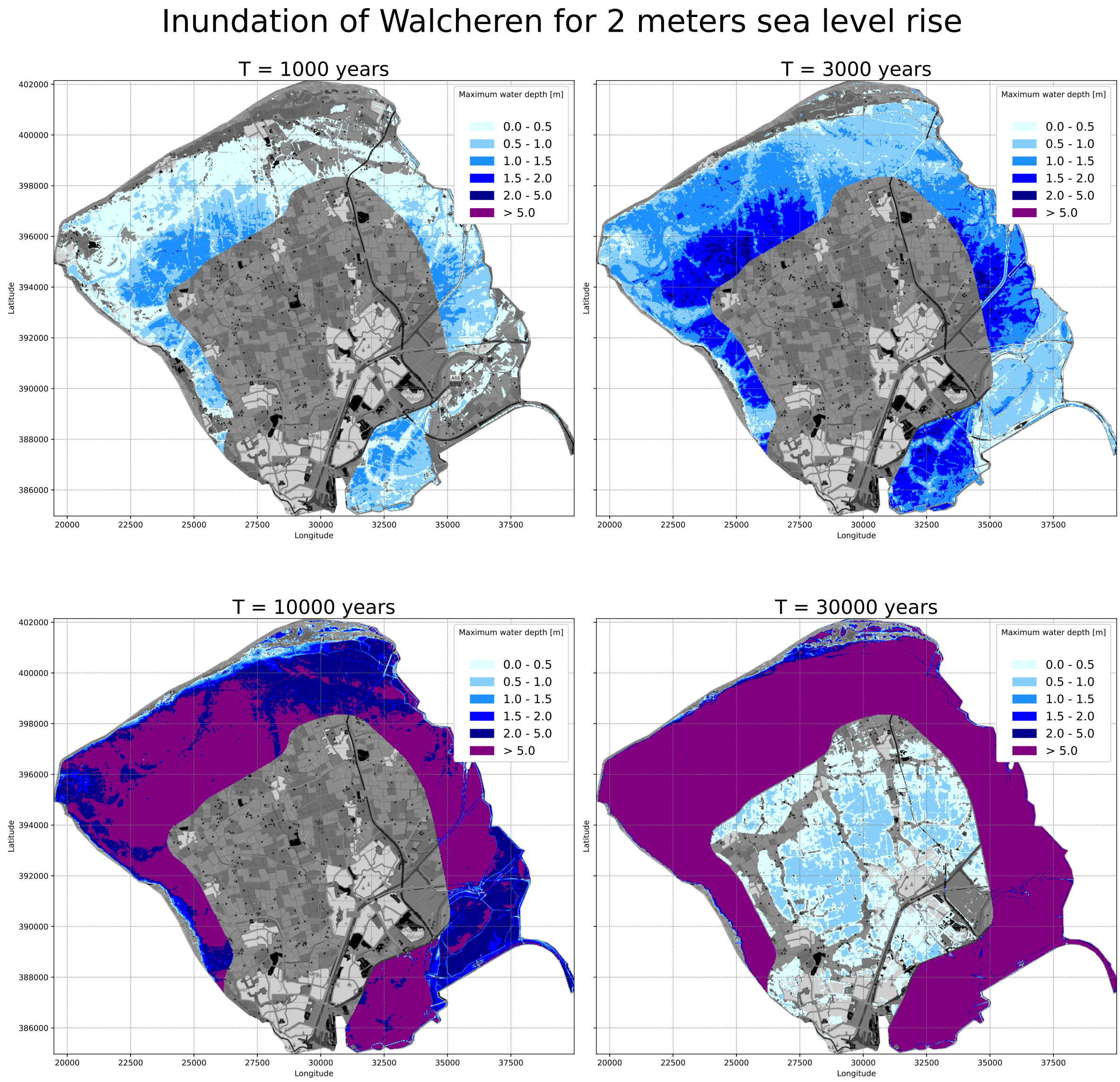


Figure D.21: Flood maps Walcheren for 2 meters sea level rise (secondary dike-ring)

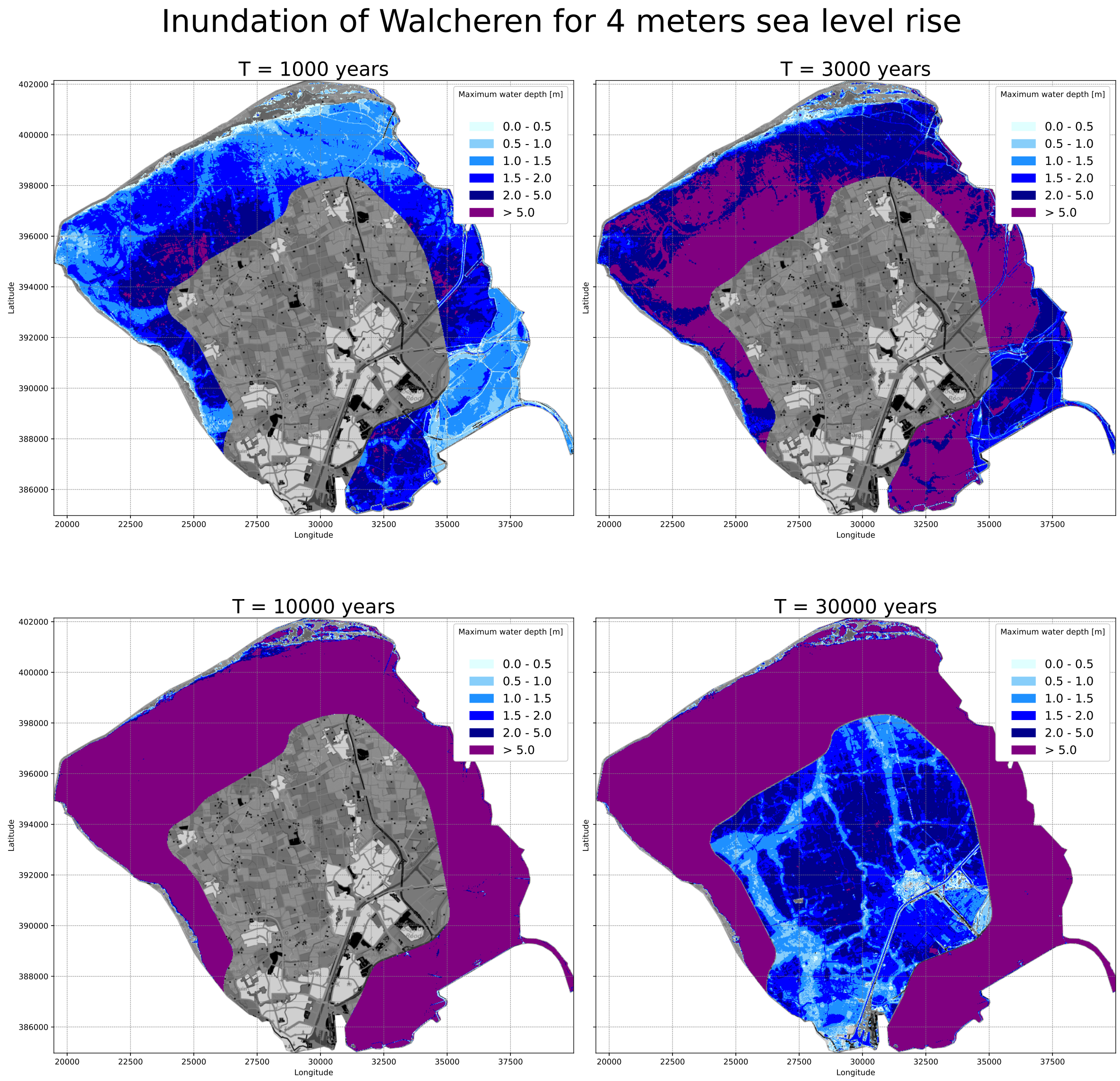


Figure D.22: Flood maps Walcheren for 4 meters sea level rise (secondary dike-ring)

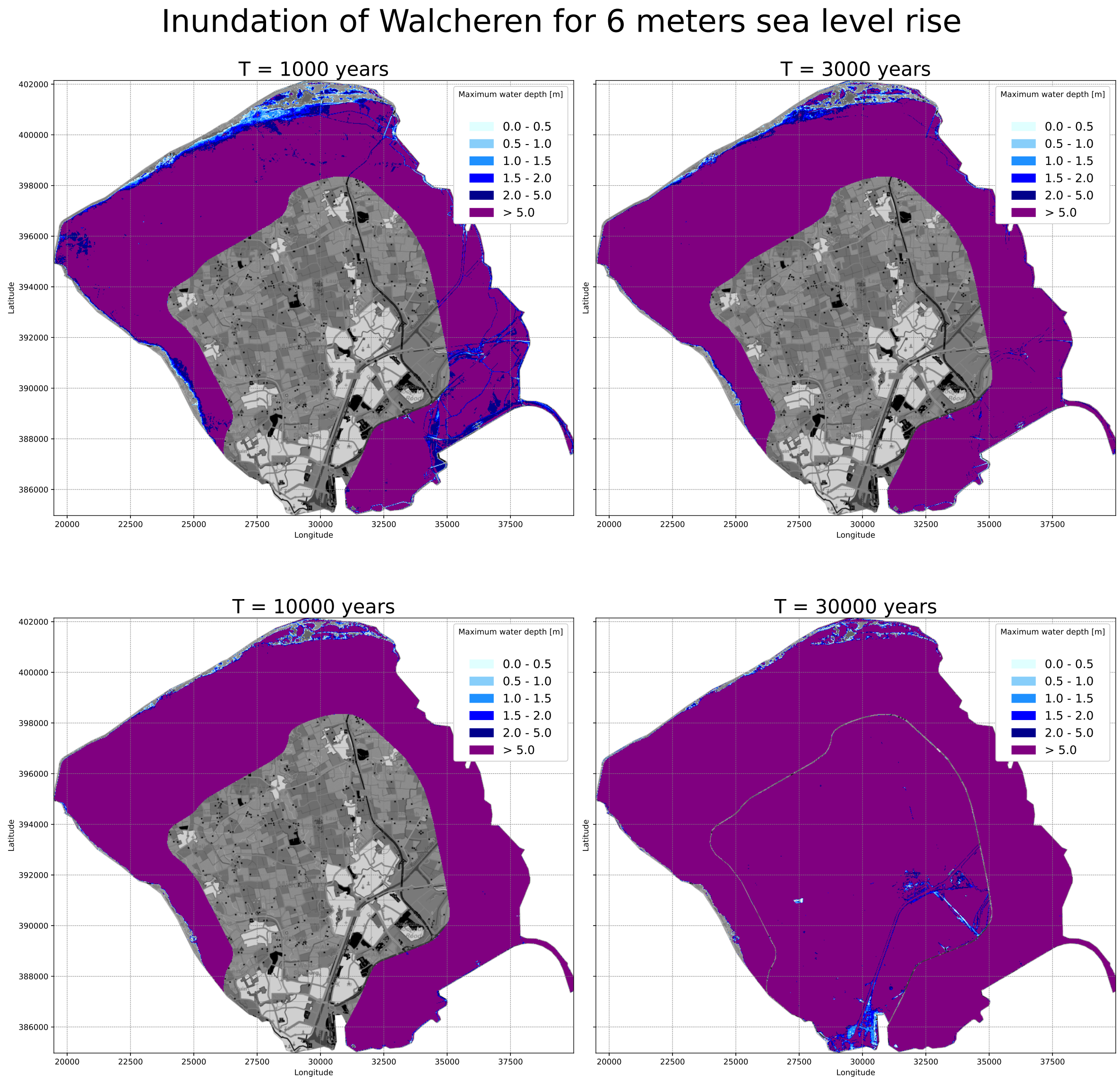


Figure D.23: Flood maps Walcheren for 6 meters sea level rise (secondary dike-ring)

D.3.3. Value protection dike-ring

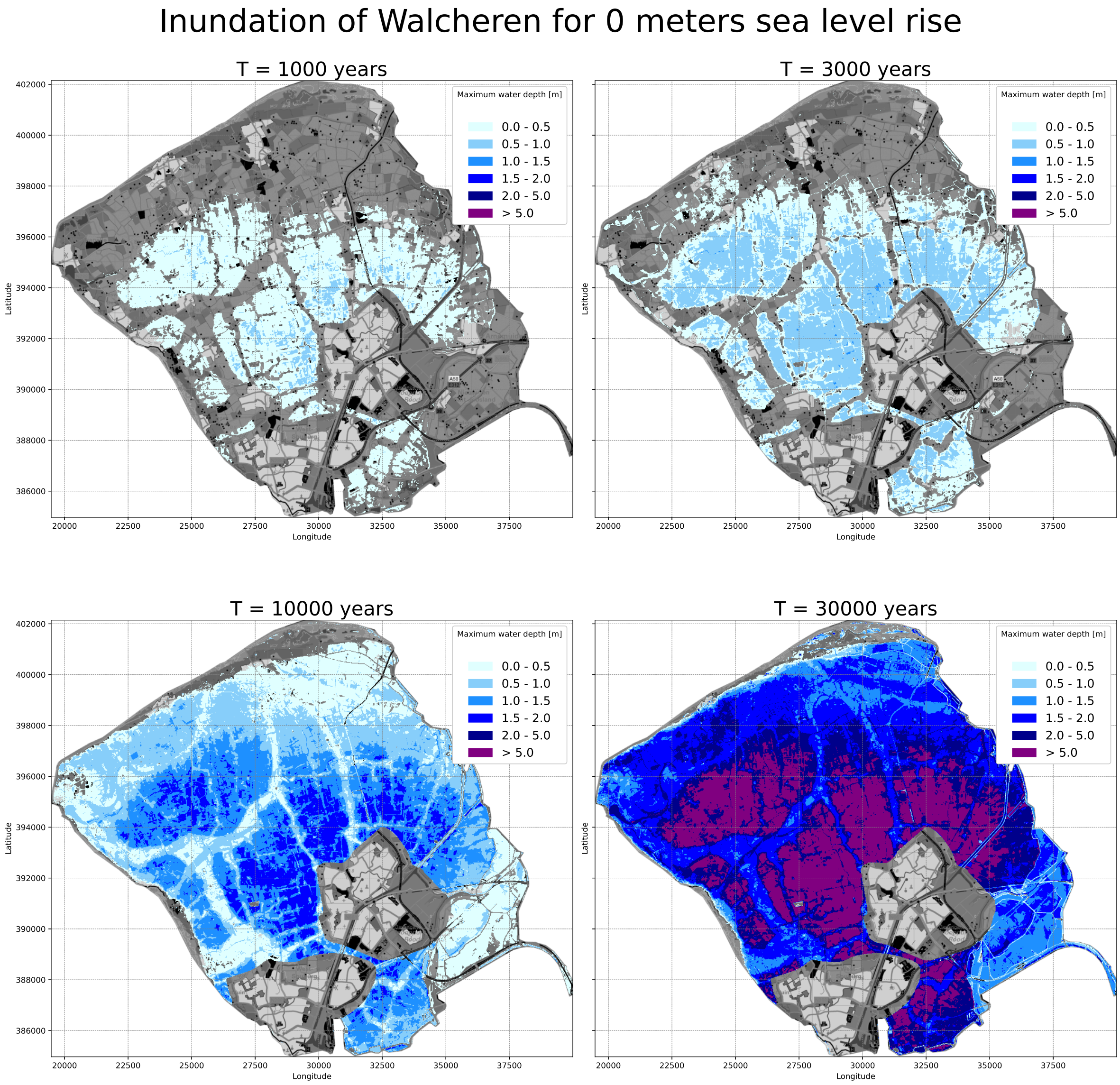


Figure D.24: Flood maps Walcheren for 0 meters sea level rise (value protection dike-ring)

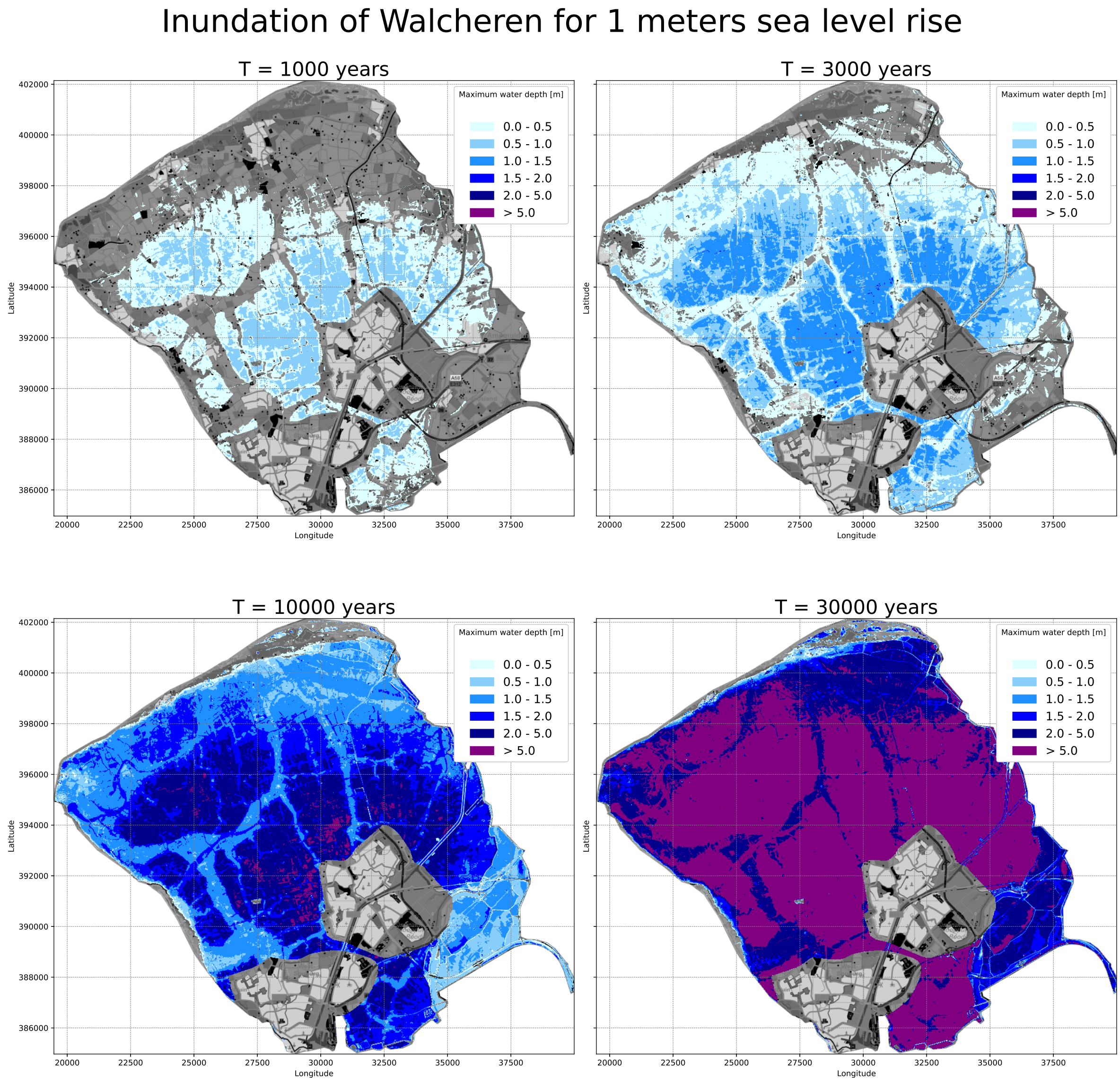


Figure D.25: Flood maps Walcheren for 1 meters sea level rise (value protection dike-ring)

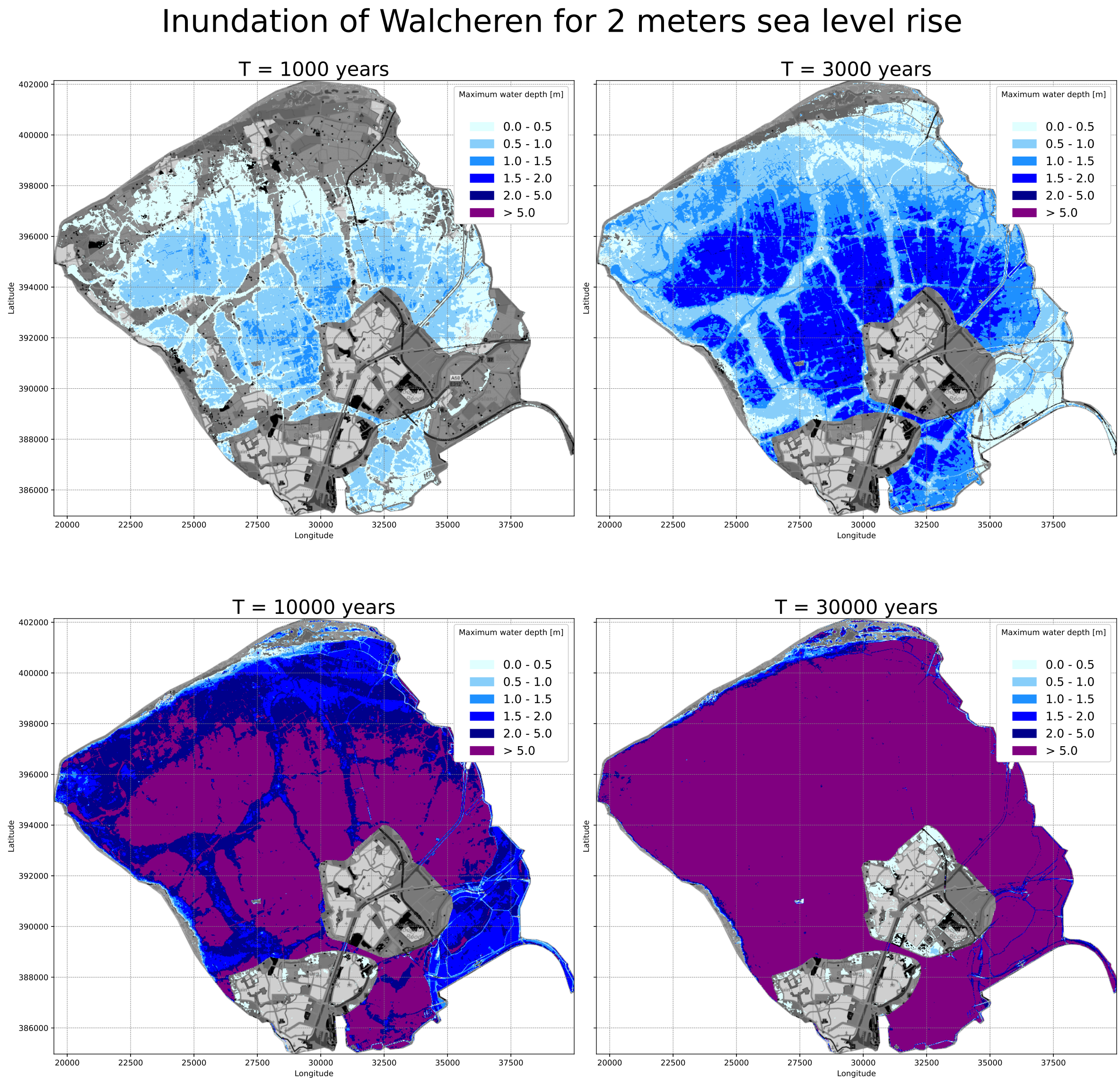


Figure D.26: Flood maps Walcheren for 2 meters sea level rise (value protection dike-ring)

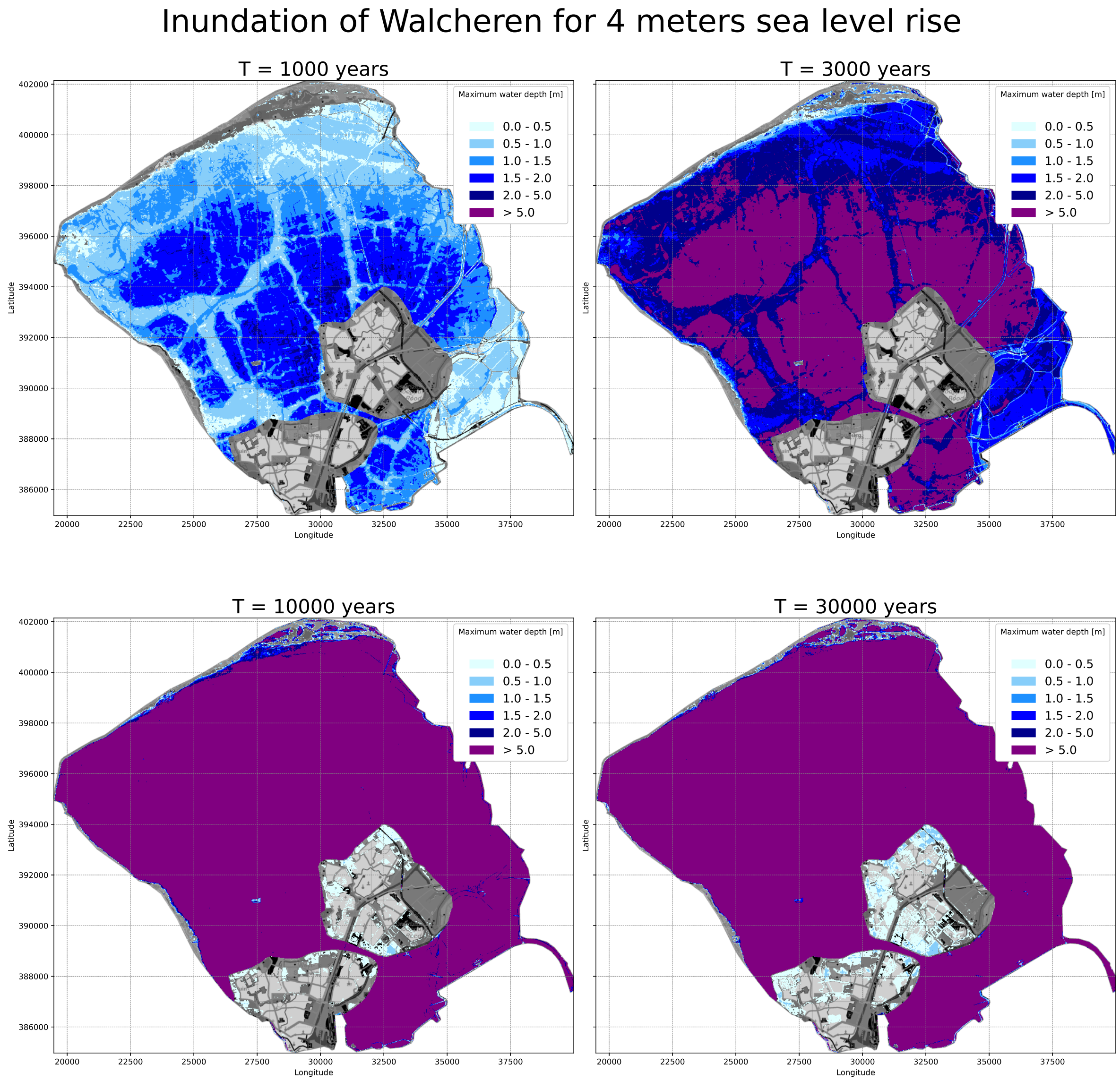


Figure D.27: Flood maps Walcheren for 4 meters sea level rise (value protection dike-ring)

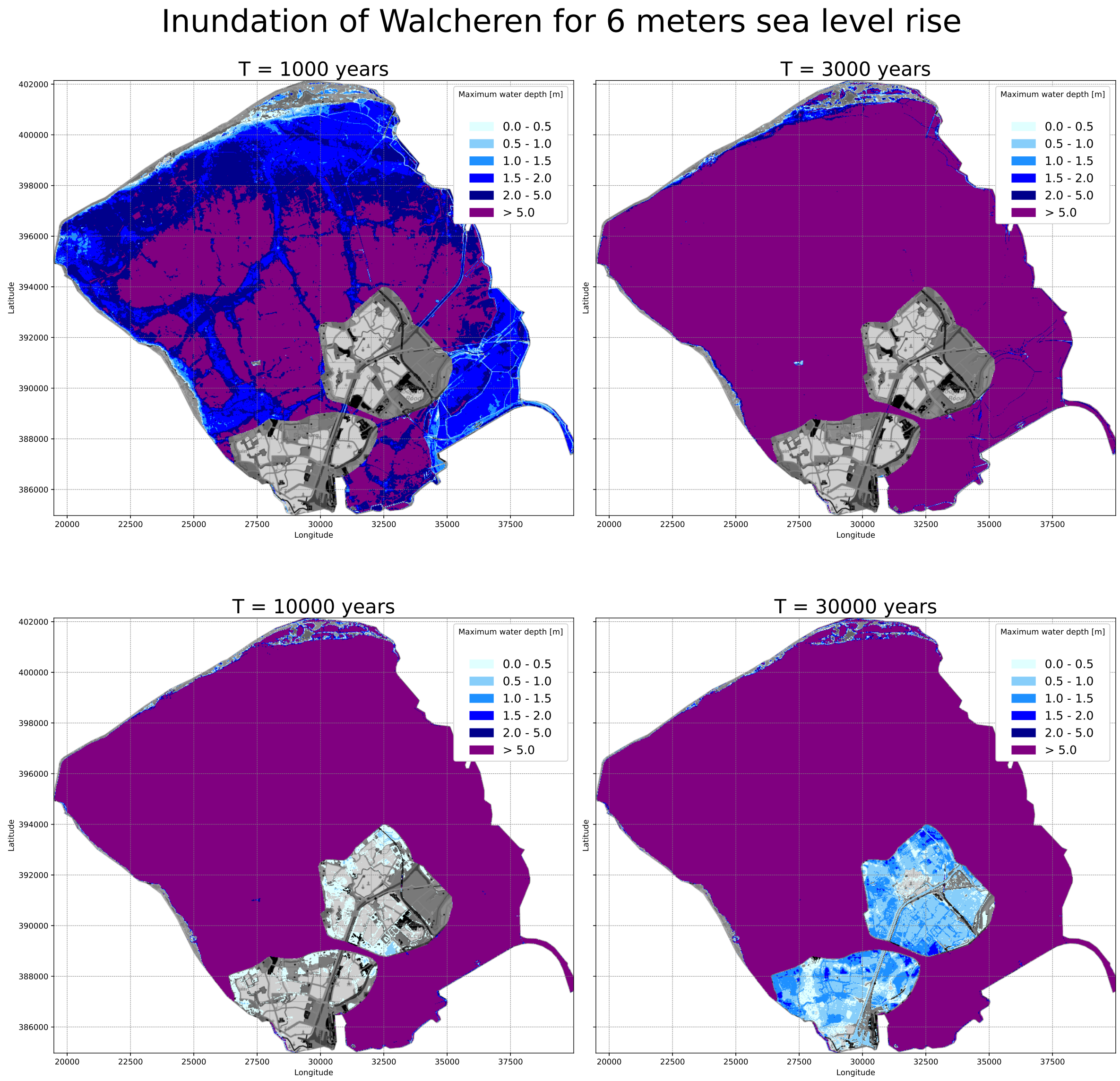


Figure D.28: Flood maps Walcheren for 6 meters sea level rise (value protection dike-ring)

D.3.4. Plan B (B1)

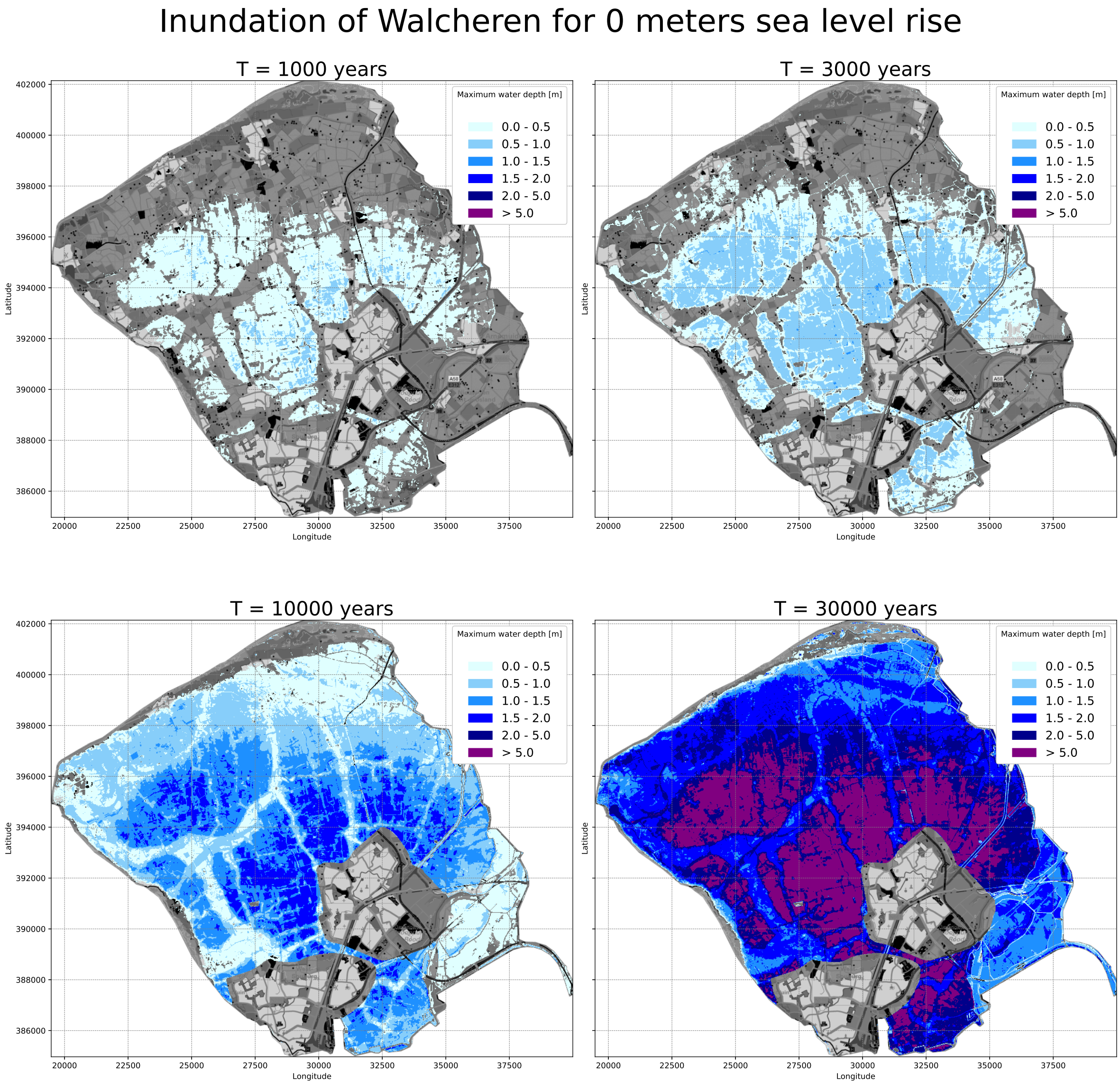


Figure D.29: Flood maps Walcheren for 0 meters sea level rise (Plan B (B1))

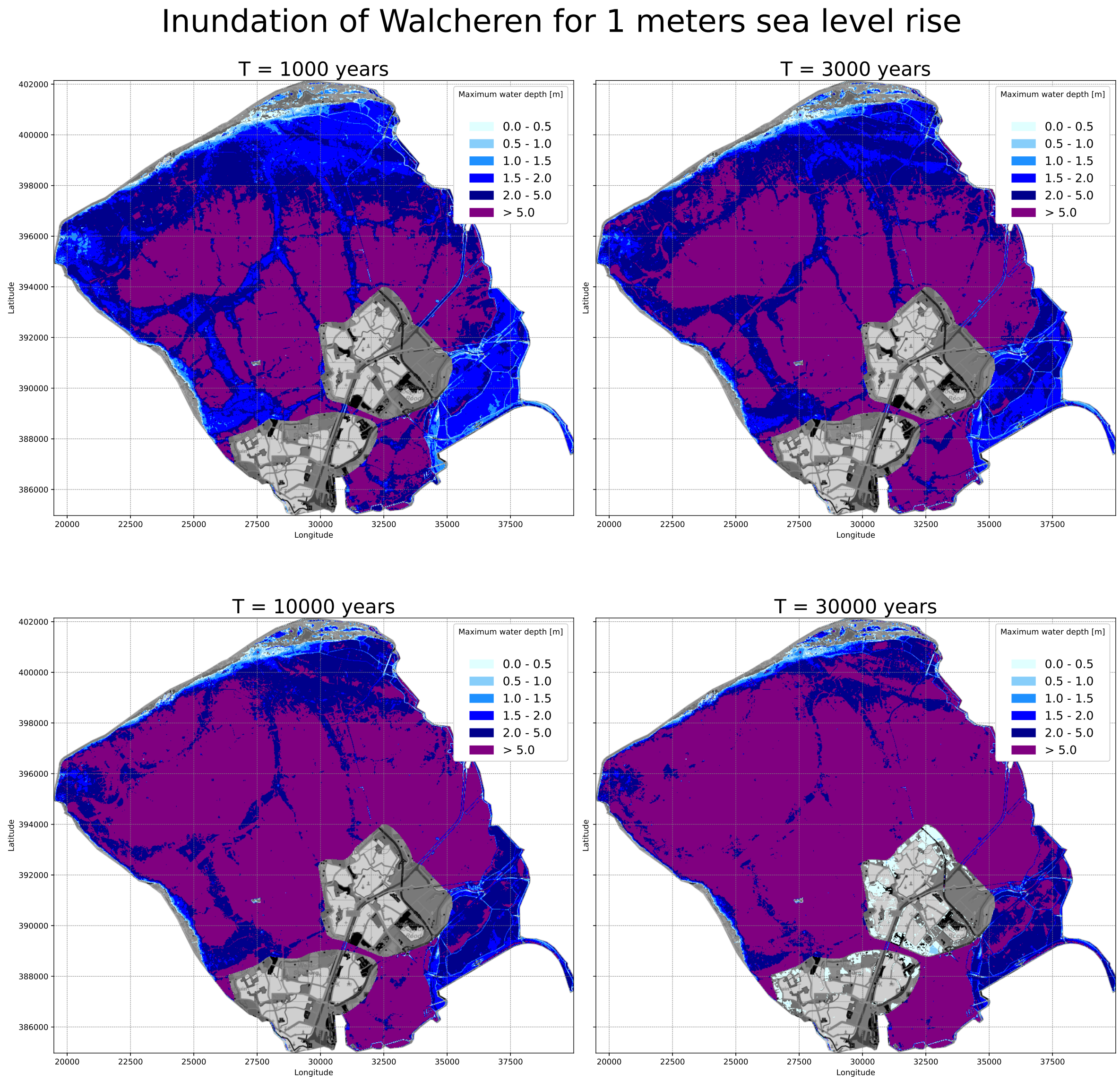


Figure D.30: Flood maps Walcheren for 1 meters sea level rise (Plan B (B1))

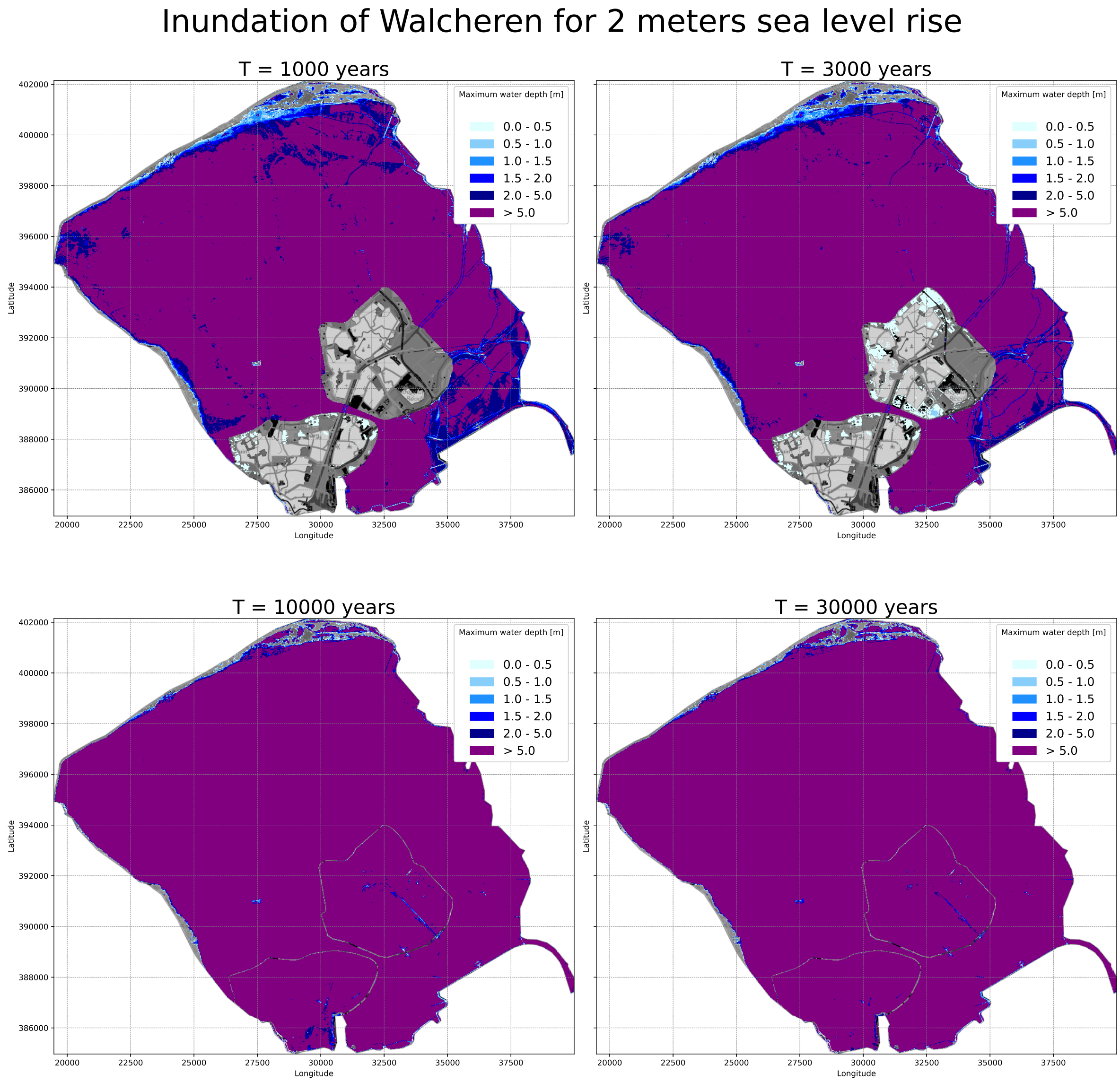


Figure D.31: Flood maps Walcheren for 2 meters sea level rise (Plan B (B1))

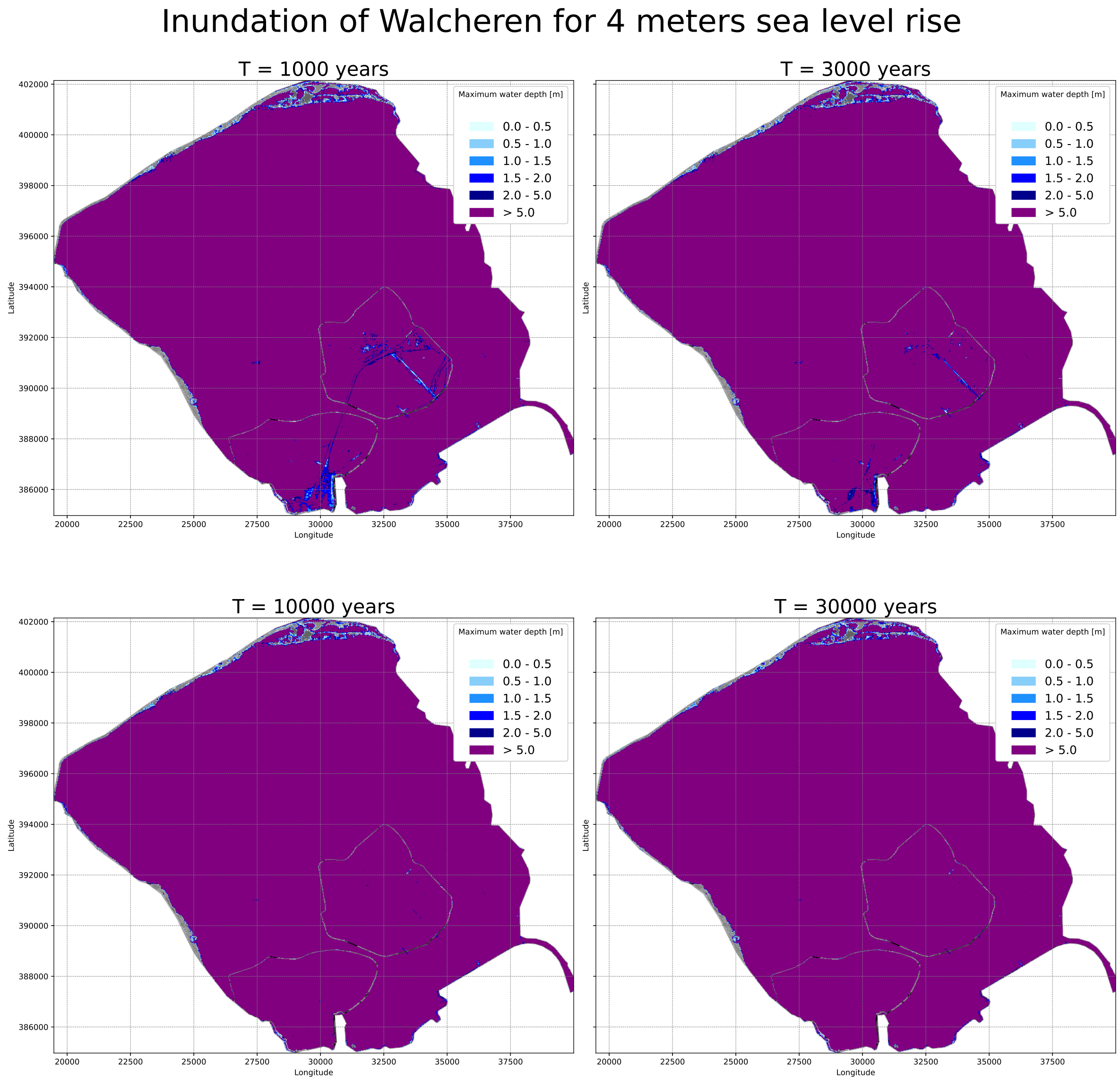


Figure D.32: Flood maps Walcheren for 4 meters sea level rise (Plan B (B1))

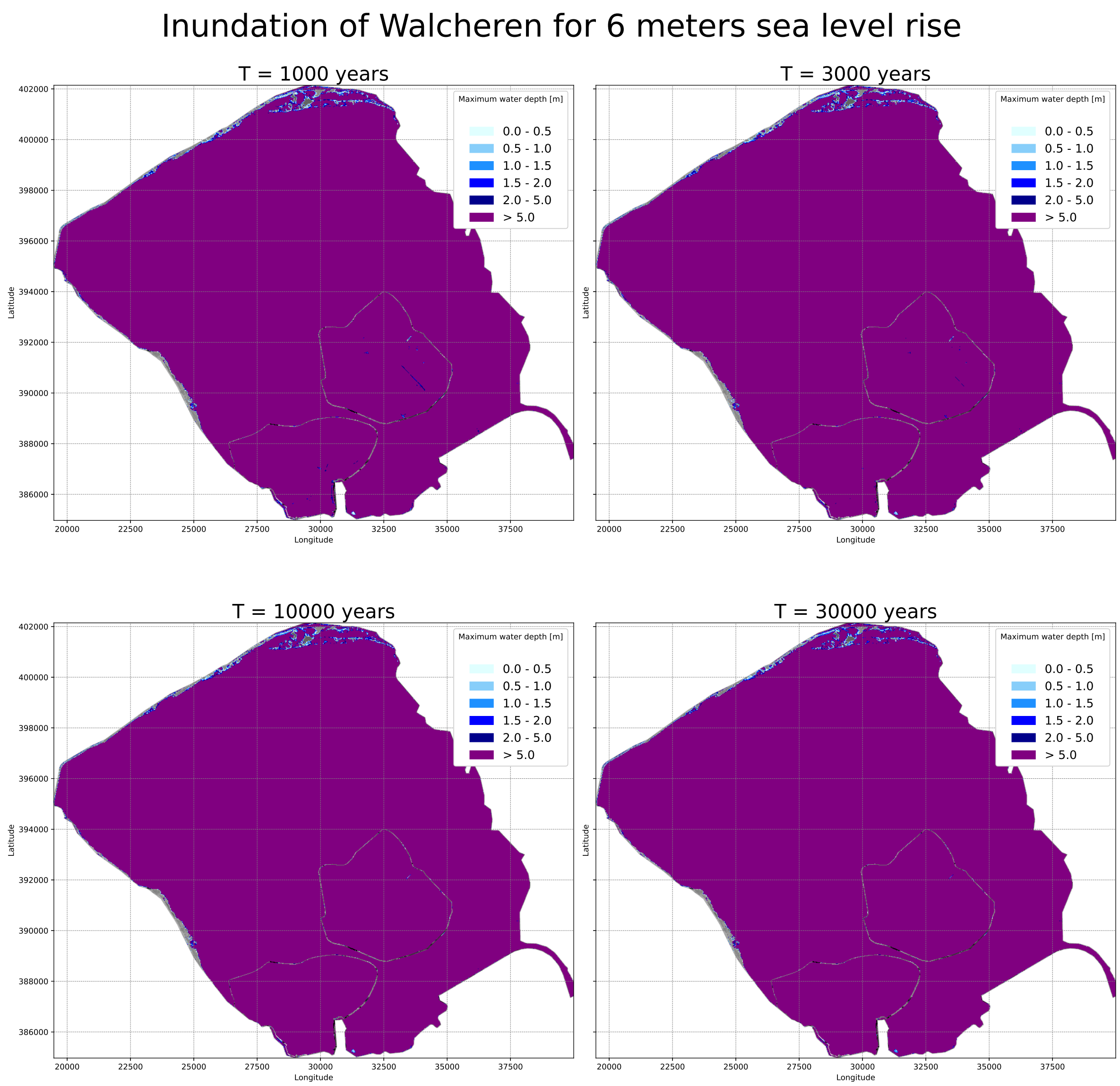


Figure D.33: Flood maps Walcheren for 6 meters sea level rise (Plan B (B1))

D.3.5. Plan B (B2)

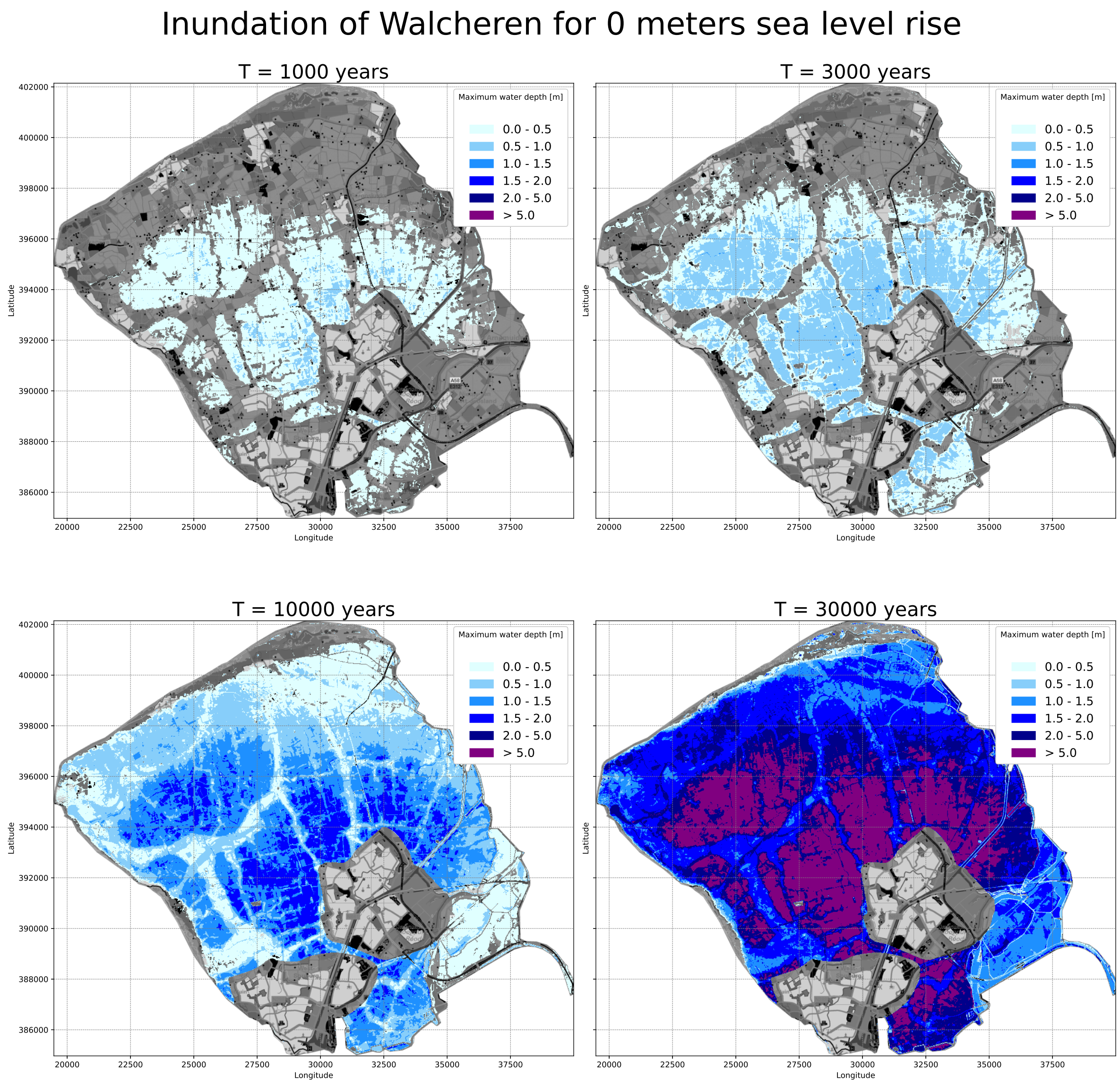


Figure D.34: Flood maps Walcheren for 0 meters sea level rise (Plan B (B2))

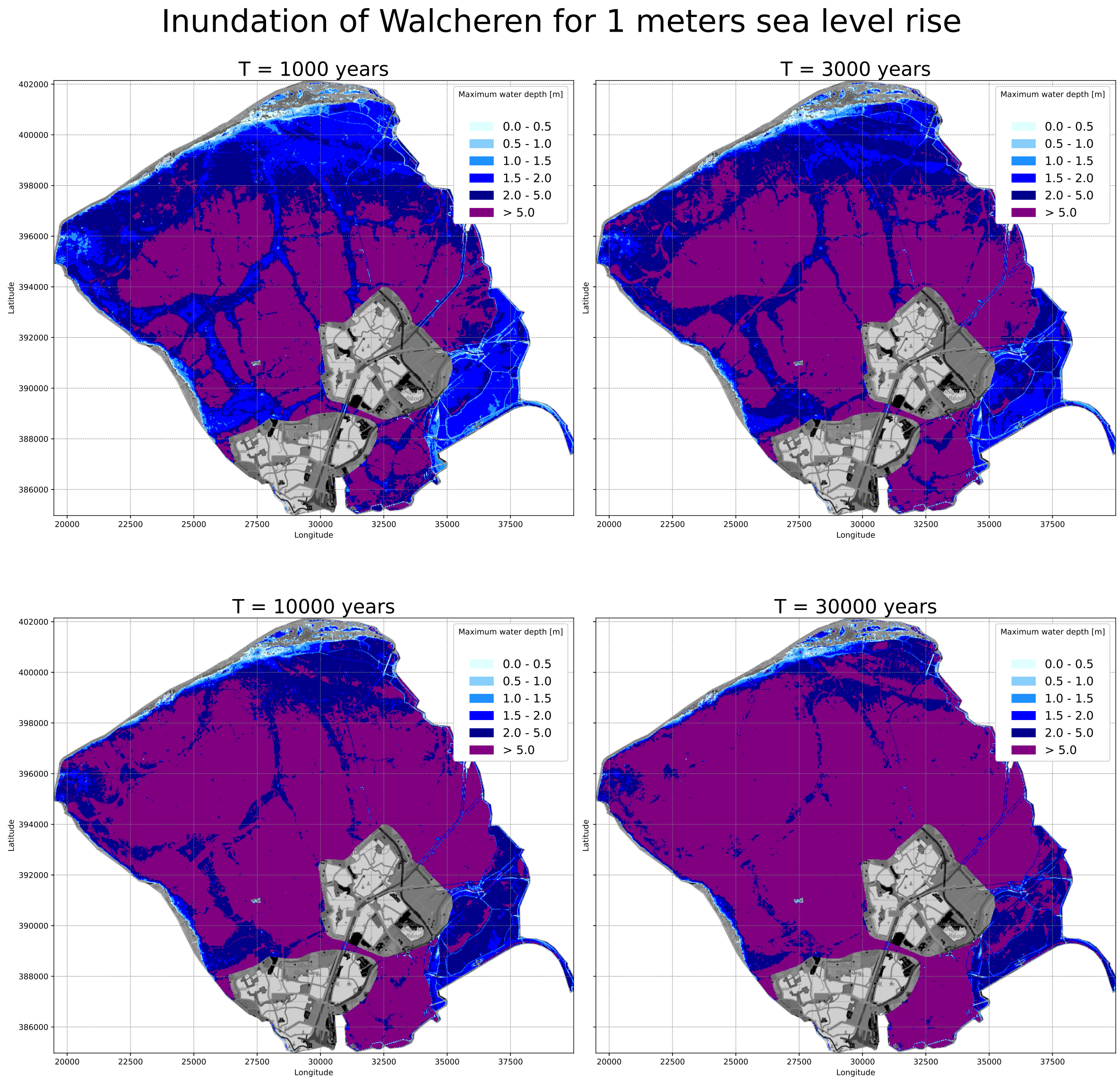


Figure D.35: Flood maps Walcheren for 1 meters sea level rise (Plan B (B2))

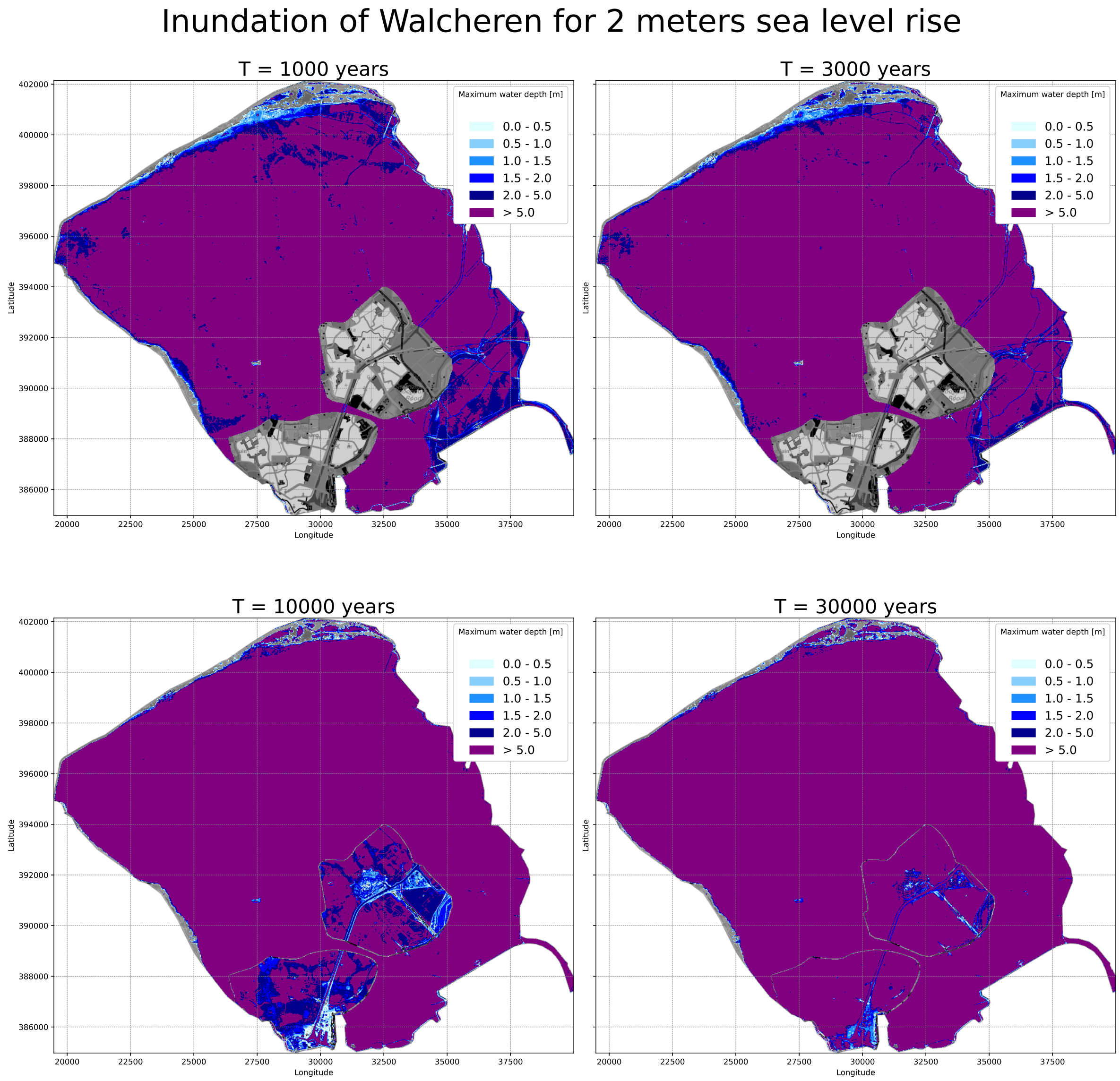


Figure D.36: Flood maps Walcheren for 2 meters sea level rise (Plan B (B2))

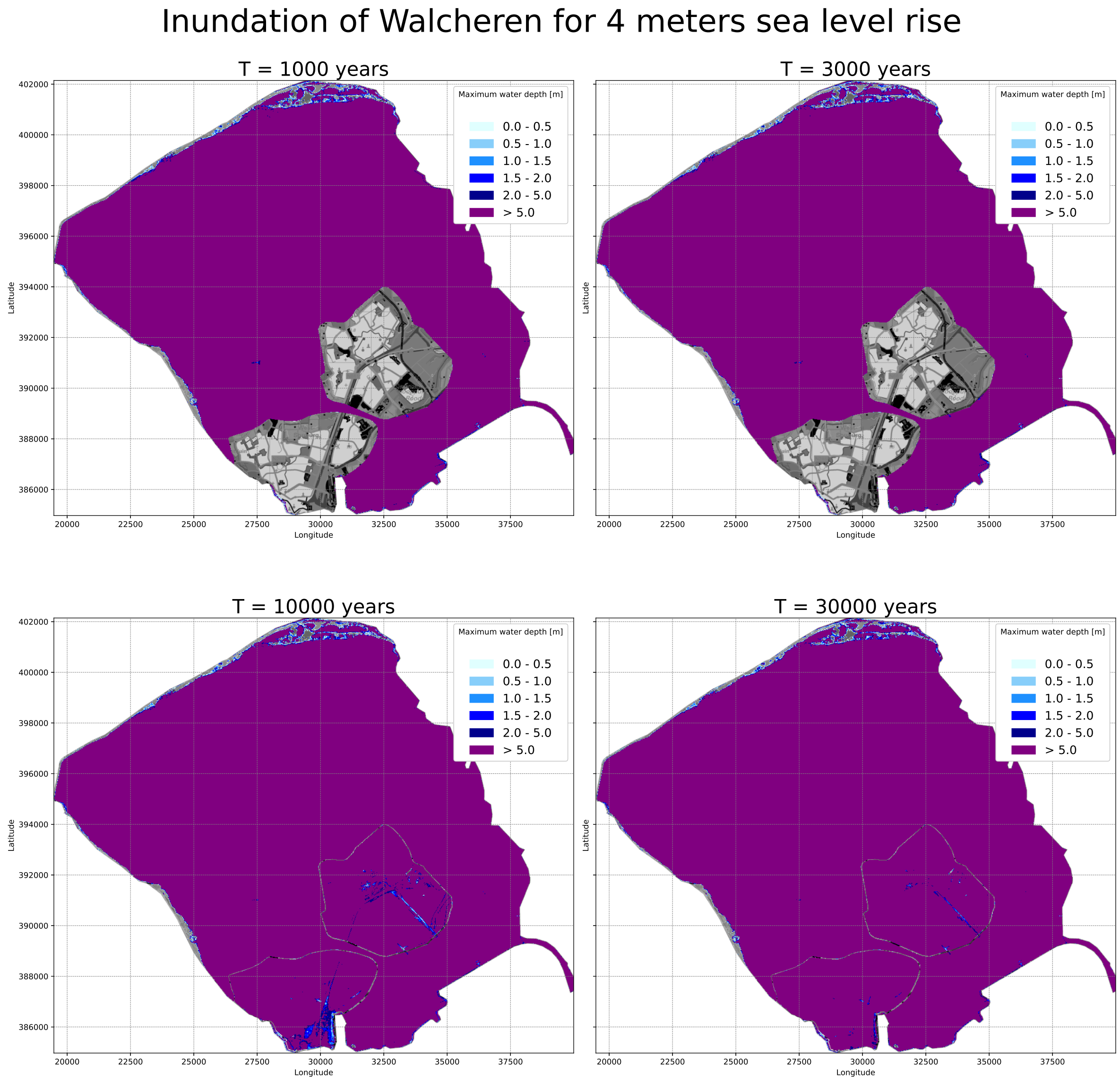


Figure D.37: Flood maps Walcheren for 4 meters sea level rise (Plan B (B2))

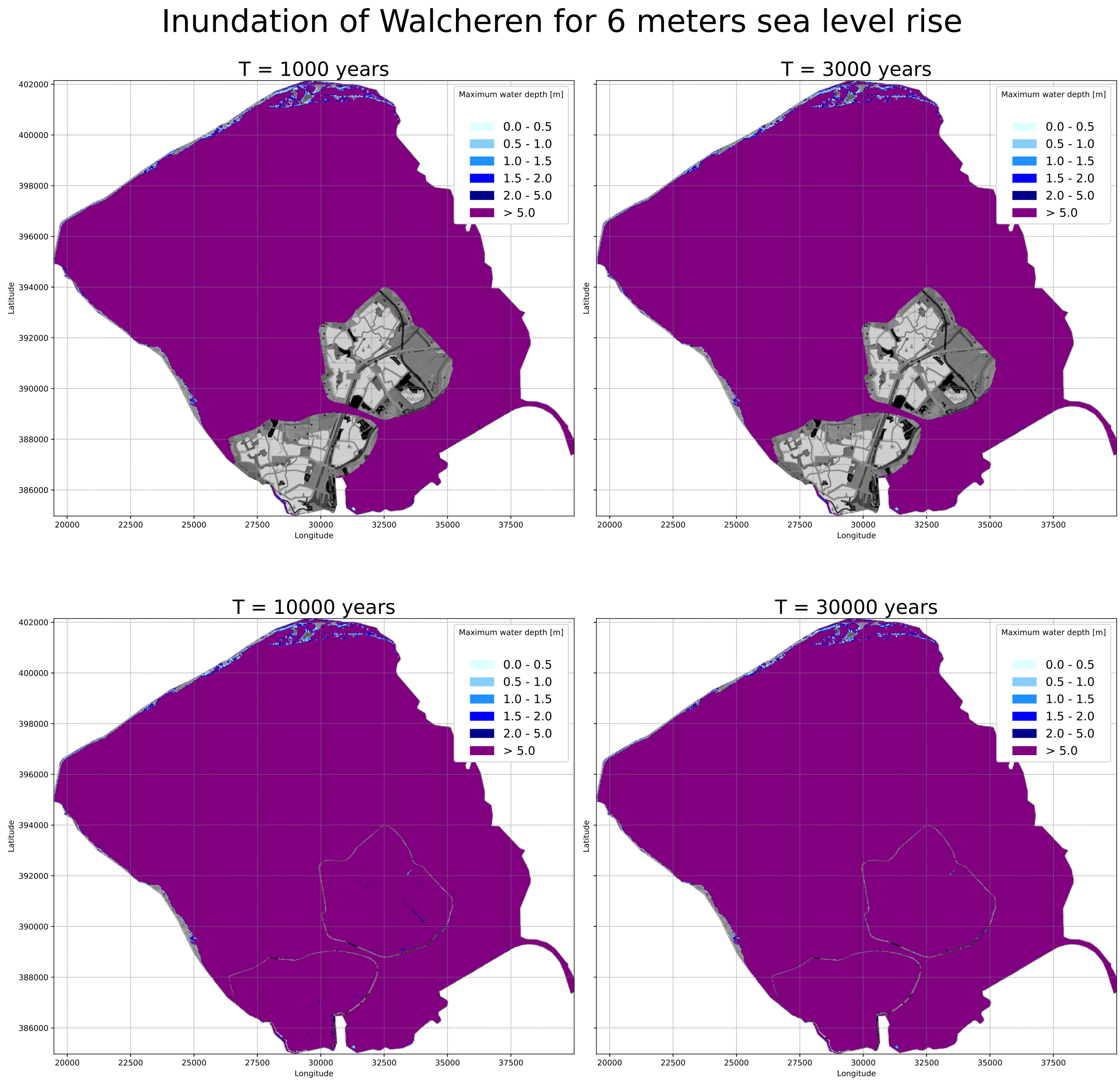


Figure D.38: Flood maps Walcheren for 6 meters sea level rise (Plan B (B2))

D.3.6. Compartmentalization

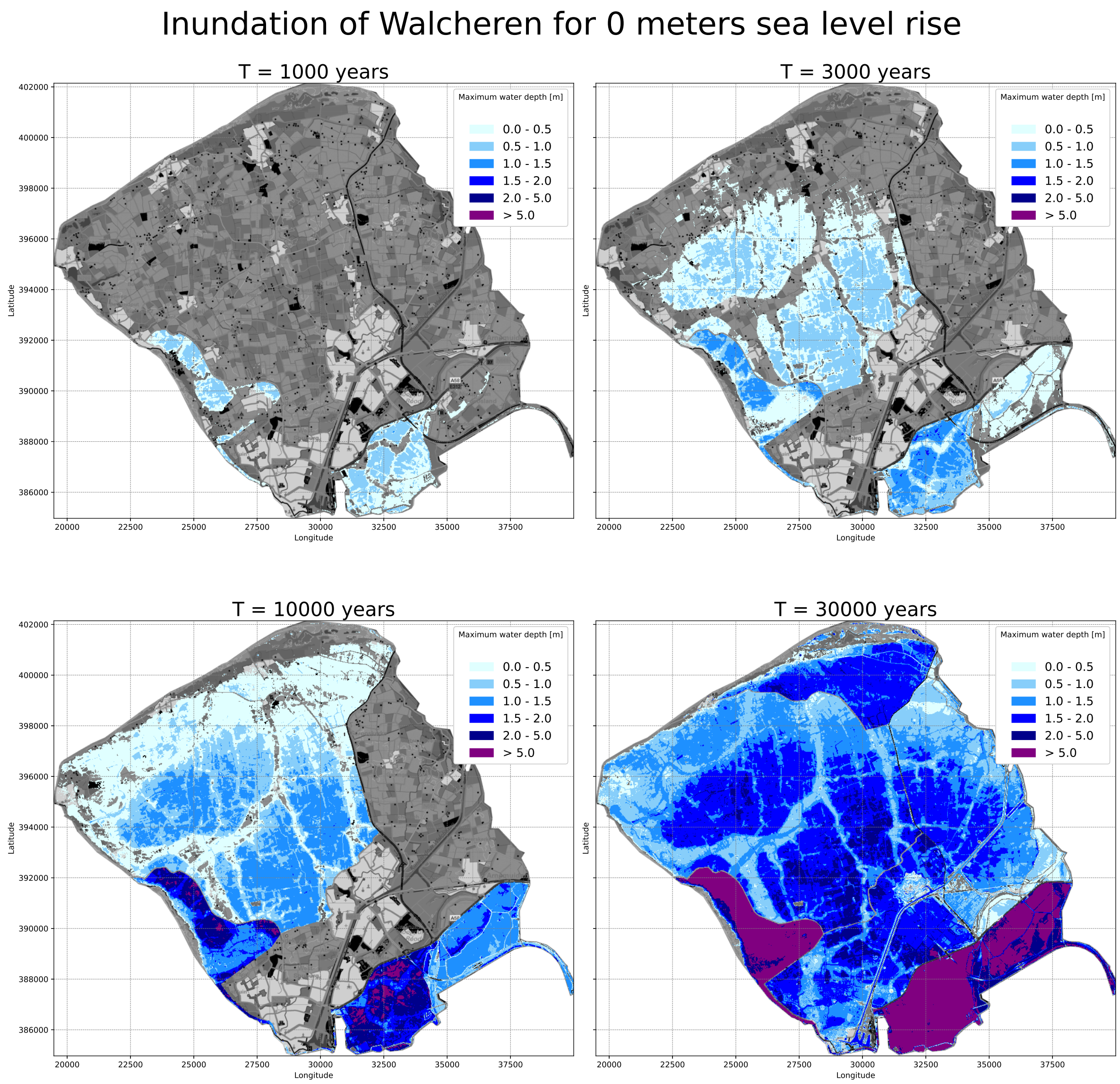


Figure D.39: Flood maps Walcheren for 0 meters sea level rise (compartmentalization)

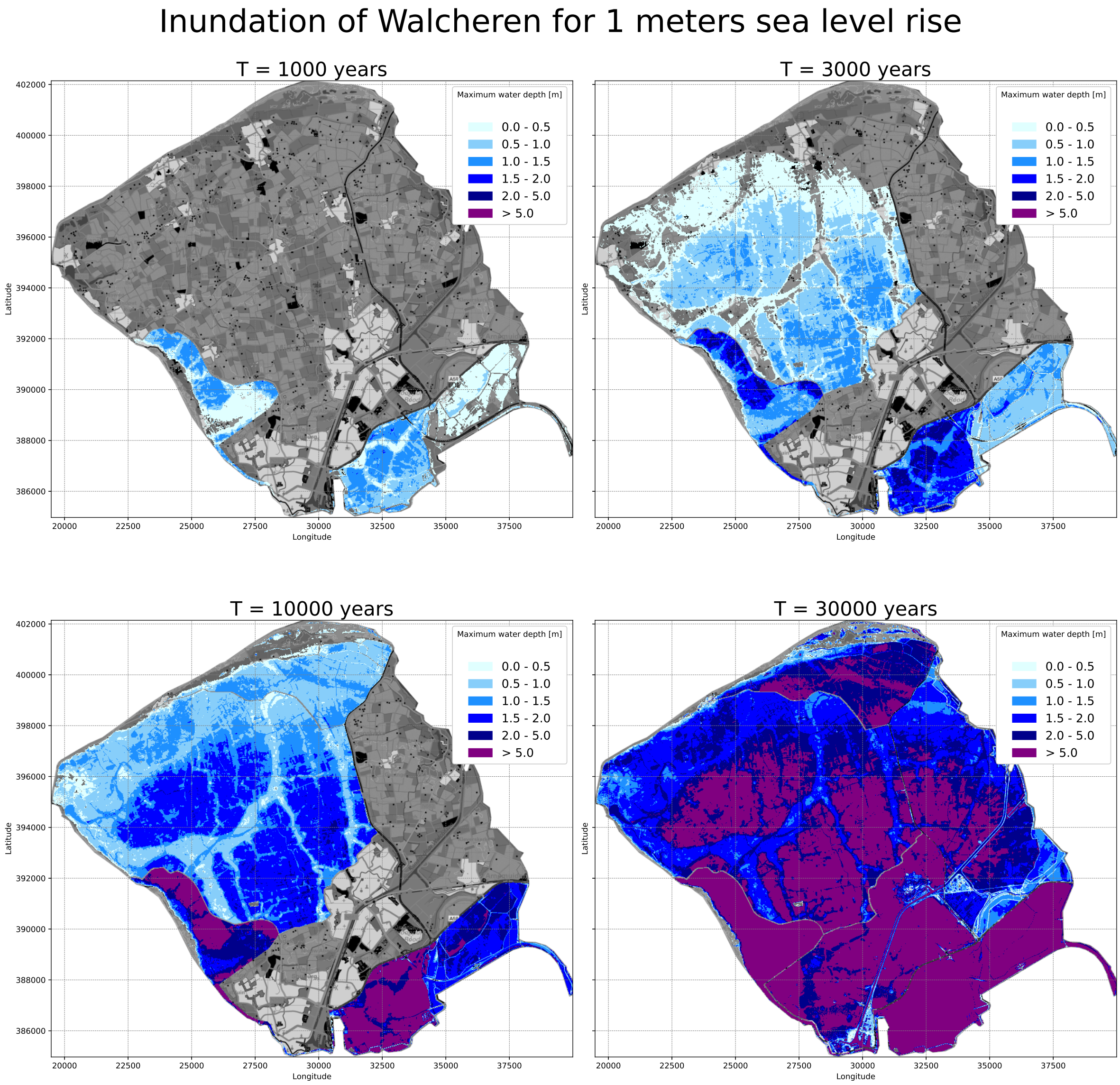


Figure D.40: Flood maps Walcheren for 1 meters sea level rise (compartmentalization)

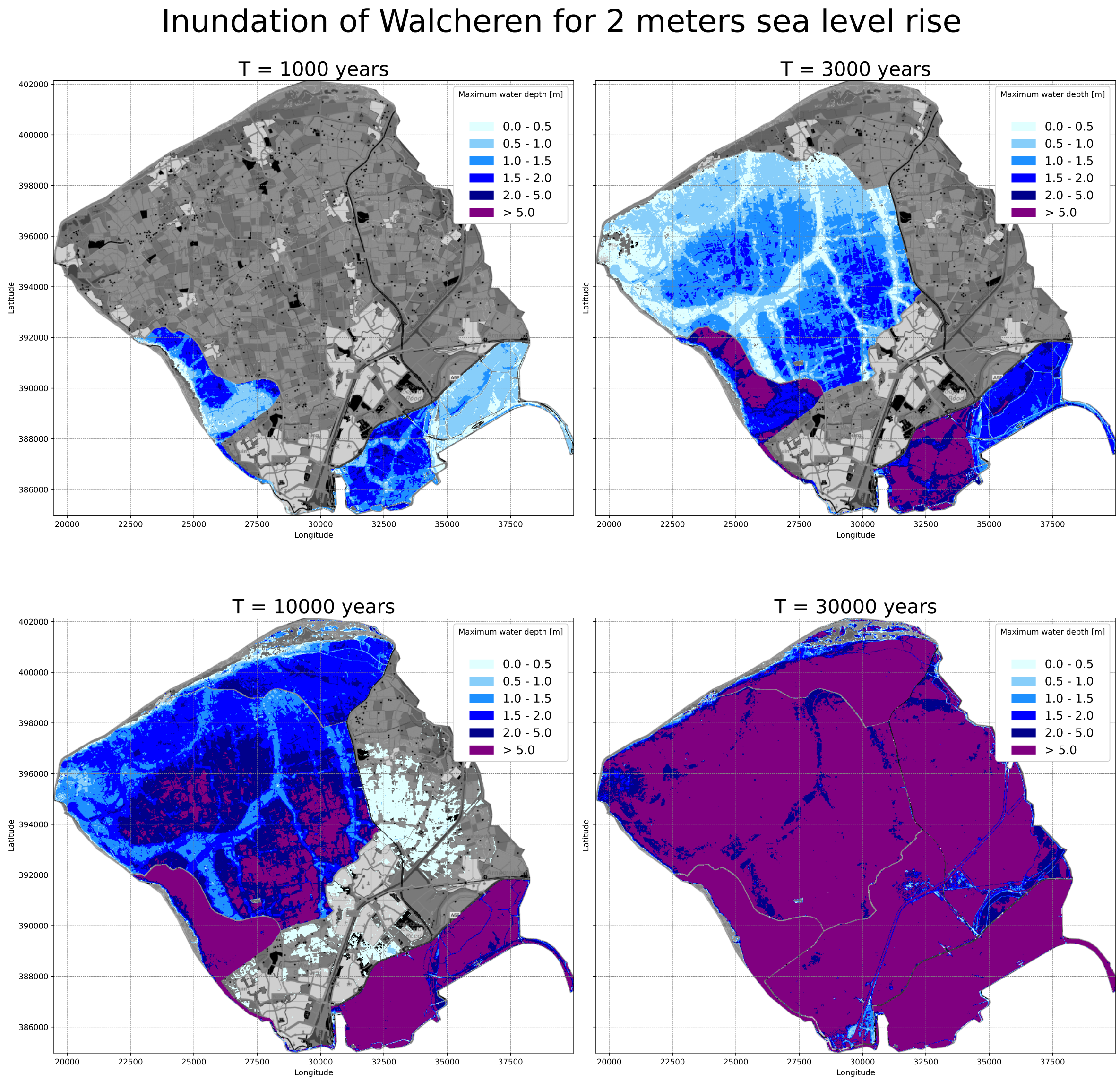


Figure D.41: Flood maps Walcheren for 2 meters sea level rise (compartmentalization)

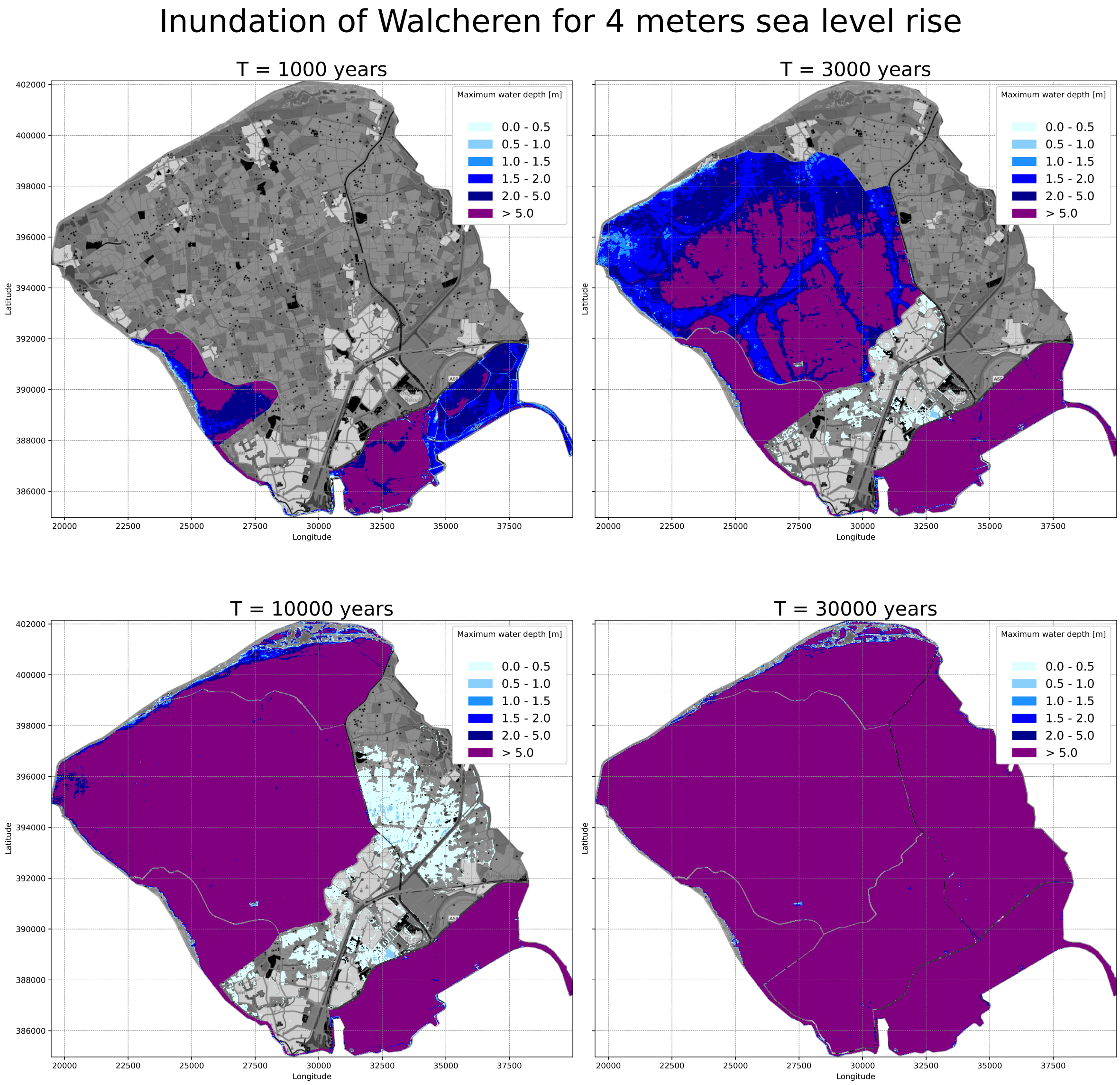


Figure D.42: Flood maps Walcheren for 4 meters sea level rise (compartmentalization)

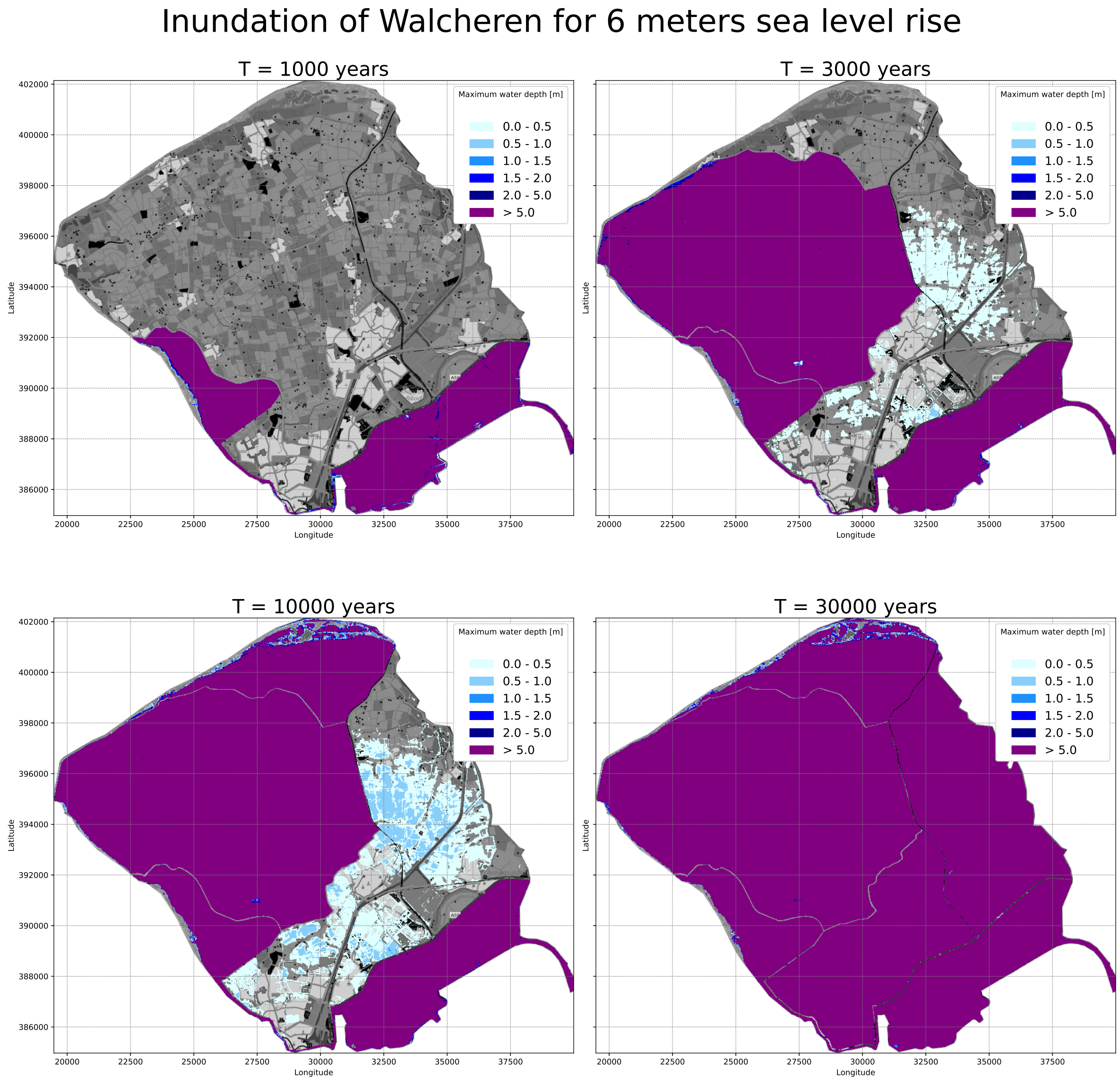


Figure D.43: Flood maps Walcheren for 6 meters sea level rise (compartmentalization)