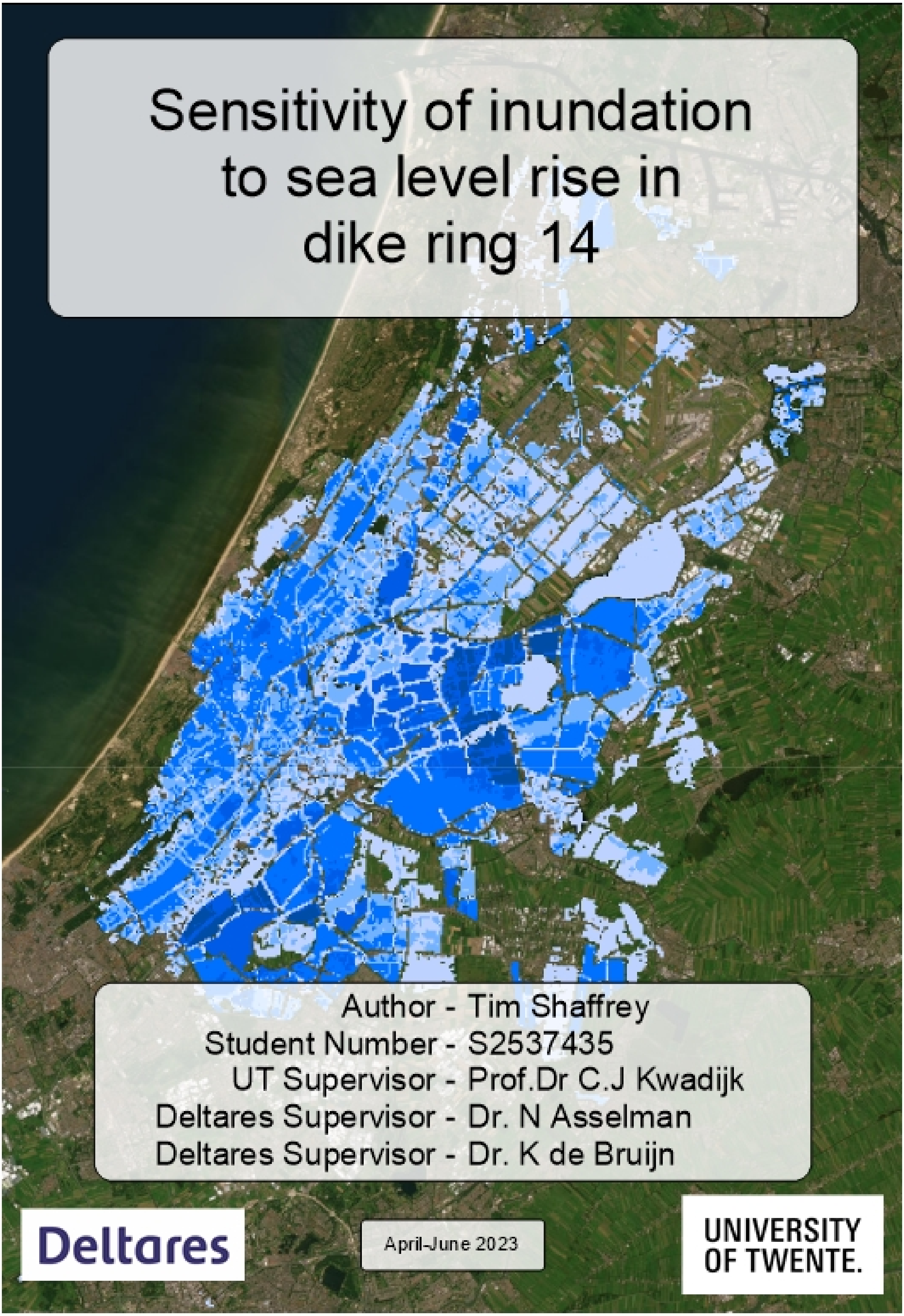

Sensitivity of inundation to sea level rise in dike ring 14

Author - Tim Shaffrey
Student Number - S2537435
UT Supervisor - Prof.Dr C.J Kwadijk
Deltares Supervisor - Dr. N Asselman
Deltares Supervisor - Dr. K de Bruijn

Deltares

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UNIVERSITY OF TWENTE.

Executive summary

Flood defence in the Netherlands has a long history of disasters, near misses and innovative solutions. The drive to create more arable land and space for its population, all while dealing with low laying elevation has formed an interconnected system of dikes, polders, pumping stations, and storm barriers. After disastrous flooding in 1953 and near misses in the 1990s, much of the modern practice of flood defence was adopted. These measures have led to some of the highest standards for safety in the world, particularly along the coastal areas. Dike ring 14 is one such coastal area and is the focus of this report. Dike ring 14 contains all of the provinces of South Holland, and parts of North Holland and Utrecht. The levels of protection here along the coast are so high, that this has had the effect of reducing the risk of inundation from the sea, at current sea levels, to such low levels that now it is more likely that dike ring 14 would be inundated by the inland river systems. Indeed, it is now assumed that the largest consequences of inundation in dike ring 14 will come from river dike breaches further inland, such as at Nieuwegein.

However, with an increasingly unpredictable and unstable climate, the impact of an inundation event from the sea might become worse and worse depending on the extent of sea level rise. This study focuses on the effects of flooding resulting from sea level rise along one of these such coastal areas, dike ring 14 which encompasses large parts of the most densely populated and economically valuable areas of the Netherlands. Meaning what will future sea level rise mean for the Netherlands, and specifically, dike ring 14?

To investigate this, the inundation (hazard) and damage (exposure) that increasing sea level rise will have on dike ring 14 will be examined. This will be done with the use of numerical modelling, which combines the one-dimensional (1D) flow of water along rivers, canals, etc., and the two-dimensional (2D) flow of water across the terrain. This 1D2D modelling allows for very accurate simulations to be created that most closely resemble a real-world flood, that would flow across the land, along rivers, and roads. The main aim is to conclude if there is any sea level rise point at which the resulting consequences begin to increase rapidly. To do this these consequences have been split into separate categories, the inundation pattern, such as the area inundated or volume, and the resulting damage in terms of monetary and fatalities estimations.

The extent of sea level rise was taken to show more reasonable sea level rise scenarios and also the most extreme cases, these being sea level rise scenarios of 1-5 meters. Four breach locations were investigated under various conditions, such as a breach during normal conditions and another during a storm surge, for increasing amounts of sea level rise. These breach locations were: Katwijk, the Hague, Hook of Holland, and Ijmuiden. These locations were selected to give the most comprehensive result possible within the short time allotted for this research (10 weeks), as while having huge numbers of breach locations would allow for more insight, they would also require significant amounts of time to simulate. All of this was carried out at Delatres, with their SOBEK modelling software which has been used for many years and projects to predict the consequences of flooding.

A combination of maps and graphs where used to build up an insight into the scenarios. The inundation pattern, the time at which it reaches certain areas, and the areas with high value that would be affected were mapped. The characteristics of the inundation, the total area inundated, the total volume, the average depth, the estimated damage, and the estimated fatalities were all graphed to see the level of sensitivity of each to sea level rise. The results of all of these show that there is a clear sensitivity to sea level rise, in terms of both hazard and exposure in the event of a dike breach. However, it is also clear that the location of the breach is more significant than the extent of sea level rise as different breach locations change substantially at different sea level rise scenarios. The largest consequences are seen with breaches at Katwijk and the Hague, with the hazard (the total area inundated) being the most substantial from the Katwijk breach, but the highest exposure (damage and fatalities) being from the Hague breach.

There are limitations to these findings, as the past simulations focused on lower levels of sea level rise, and thus validation proved difficult. Additionally, the past simulations that could be compared resulted in differences,

which could be the result of differences in modelling, changes in digital elevation maps, changes in population distribution, or property valuation. For a more robust result, more testing of different models with similar input conditions should be carried out.

This is particularly true of areas around Amsterdam and breaches simulated at IJmuiden, which contains a significant number of assumptions and simplifications that would have impacted the results here significantly.

This study found that for dike ring 14, almost all locations are highly sensitive to sea level rise, be it at different rates depending on their location. Further, with 2m-3m of sea level rise a breach from the seaward dikes of dike ring 14 would pose an equal or greater threat than that of past simulated breaches of river dikes.

Preface

Here I present my Bachelor's thesis, which I carried out during an internship in Deltares from April to June 2023. This thesis is the final requirement of my Bachelor of Civil Engineering studies, and the culmination of everything I have learnt during my years of study. It focuses on the sensitivity of inundation in dike ring 14 of the Netherlands to sea level rise.

During my internship, I got first-hand experience and advice from a dedicated flood risk management department, and I would like to take this opportunity to thank all those who have helped and guided me, such as Karin de Bruijn, Kymo Slager, Peter de Grave, and everyone within the FRM department.

Jaap Kwadijk, who was my university supervisor and who helped me at all points of my proposal, internship and final presentation preparation, and Nathalie Asselman who helped me with the day-to-day challenges of carrying out the modelling process and analysis. To both, I would like to not only express my thanks for sharing their expert knowledge on this topic, but for doing so in a manner that allowed me to exceed the goals I set for myself and achieve a final analysis of which I am proud.

Finally, I would like to thank Maria Hughes, without whom none of my work over the last few years would have been possible.

Tim Shaffrey
June 24th 2023

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) latest predictions indicate that sea level rise (SLR) will happen at a faster rate than was previously anticipated [Lee, 2023]. This will have consequences on all coastal areas, catastrophic consequences if not adequately addressed, and is of particular interest to the Dutch coastline. This report will be focused on the increase of inundation (hazard) and the resulting damage (exposure) in dike ring 14 caused by these rapid increases in SLR, and if the hazard and exposure increase proportionally or disproportionately to the SLR.

The Netherlands has a long history of flood protection and innovation. As early as the 14th-century large scale dikes were being created to deal with a low-lying topography, which in some cases was already equal to or below sea level [dutchdikes.net, 2023].

In the following centuries, land subsidence and sea level rise have only compounded the issues with balancing the current projection levels that existing dikes provide and the cost of improvements to meet the required standards. There have been multiple occasions where a large-scale flood or large-scale near miss has fostered innovation in the flood defence system of the Netherlands. In 1953 there was large-scale flooding of the southern Netherlands, resulting in the death of 1800 people. The conditions that led to this flooding were beyond the predicted possibilities and caused multiple breaches. As a result of this event the flood defence system of the Netherlands was re-examined, and this resulted in the 'Delta Works', which sought to reduce the length of coastline that required protection. Additionally, the South Holland area was examined to determine a cost-benefit calculation for the improvement of the existing dikes [Van Dantzig, 1956].

In the 1990s, a series of high-water events along the rivers of the Netherlands nearly caused another catastrophic flooding event. Like the events of 1953, this led to a re-formulating of the existing plans and resulted in the 'Room for the River' plan, which along with some of the traditional dike interventions, also proposed to allow a more natural hydraulic process, such as allowing the rivers room to flood with increased flood plains.

Finally, with the increasing capacity of simulation models for both the mapping of flood patterns and investigation of failure probabilities of dikes, a shift from using 'exceedance capacities' to define the flood risks (how often a certain event is predicted to happen), to a probabilistic model was made in the last decade. This defines 'Risk' as a combination of the probabilities of failure, inundation pattern (hazard), the predicted exposure or damage done, and how vulnerable the area is to flooding. This concept will feature at the core of this report, as not all flooding carries the same level of risk. This encapsulates the real risks related to flooding, as different areas have different notions of what the hazard and exposure are. For instance, if a large agricultural area, with no houses or livestock, was to be flooded by a river it may even be seen as a positive owing to the deposited nutrients. However, if a much smaller, urban area were to be flooded, the exposure and hence the risk could be huge [Slomp, 2016]. The results of the assignment will thus be used to investigate the hazard and exposure aspects of the overall 'Risk' in SLR scenarios.

The study area for this report will be focused on dike ring 14 of the Netherlands, with contains the key cities of Amsterdam, The Hague, and Rotterdam. Given the importance of these cities, and the high population of the area, dike 14 has been the focus of many studies over the past decades. From the beginning of the Delta Works, the impacts flooding of this area from a seaward dike failure was imagined to be a complete catastrophe as it assumed the whole area would be flooded. Thus, the dike ring received the highest safety standard in the Netherlands and dictated much of the standards of other dike rings [Kind, 2014]. In the years since, the more complex models showed that complete flooding was unlikely, due to the many sub-compartments in the area, and the real risk to dike ring 14 is from failures of the river dikes further inland. This is due to a cascading effect, that while these river dikes breach the resulting water will flow into dike ring 14. Hence, as long as the seaward dikes were strong enough to withstand predicted sea levels there was less concern given to simulating the real flood pattern that would result from a potential sea dike failure [ter Horst, 2012].

Yet, with the increasing predictions of the IPCC of sea level rise, storm events, uncertainties, and the changes in future population demographics, there is a renewed focus on the impacts of flooding from the sea for dike ring

14 and how can policy keep up with the demands.

All of this provides insight into the capacity for self-reflection and change that is inherent in the Dutch approach to flood safety. These are now being used to investigate the standards and paradigms used to define the risk that sea level rise poses to the Netherlands. This report, which has been commissioned by Deltares, will present a methodology for approaching the complex question of how to adequately encapsulate sea level rise scenarios while allowing for a realistic implementation of a test simulation, that neither over-complicates nor over-simplifies the scenario. The results of this report could have impacts on the policy implications for South Holland and thus should be able to give a realistic insight into the effects of sea level rise, from modest to extreme scenarios, and the impacts on the flood inundation pattern and depth that results from these scenarios.

2 Context

The Netherlands exists in a precarious position with potential flooding from the sea on one side, and flooding from major rivers such as the Rhine on the other. To combat this, they constructed an intricate system of flood defences. The dike rings are one of the most iconic images of the Netherlands, and protect much of its population.

This protection is defined by a balance of risk, costs, and benefits. From the beginning of the 'Delta Works' in the 1950s, dike ring 14 has been seen as a key strategic location, and has defined the flood protection standard in much of the rest of the Netherlands [Kind, 2014]. But these safety standards have been based on work carried out at different times and environments. Computer models now allow for new simulation models to accurately predict the results of a breach in the seaward dike, and a changing climate means many of the assumptions of sea levels made when creating the safety standards may be no longer valid. All of this casts doubt upon the safety standards and risks for the future, concepts that are at the heart of this assignment.

Using the results of the project to determine the relative cost-benefit relation of climate resilience and adaptation projects, based on population and land usage would potentially affect the overall risk calculation for the inhabitants of South Holland. Thus, it was imperative to report these choices in a transparent manner, particularly if there is a certain decision made that could be seen as a contradiction to the public intuition, such as deeming certain population centres as having lesser risk than others.

2.1 'Risk' definition

Previous methods of designing flood defences and quantifying the risk posed to areas were based on exceedance probabilities, such as the probability that a certain sea level will occur, and lead to failure much like the original method employed by the Delta Works in the 1960s [Van Dantzig, 1956]. However, with the advent of more complex simulation models, the possibilities to produce more complex, and more certain models and safety standards increased.

The move from using purely exceedance probabilities to one that encapsulates 'Risk' in the Netherlands happened in 2017 [Slomp, 2016]. This allows for a more complete assessment to be done on the safety, which takes into account multiple failure types (in terms of dike failure), the resulting inundation pattern, and vulnerability to flooding in the area [Plate, 2002]. This pattern additionally considers the land use and population in the inundation area. This definition of Flood risk can be seen in Figure 1 below.

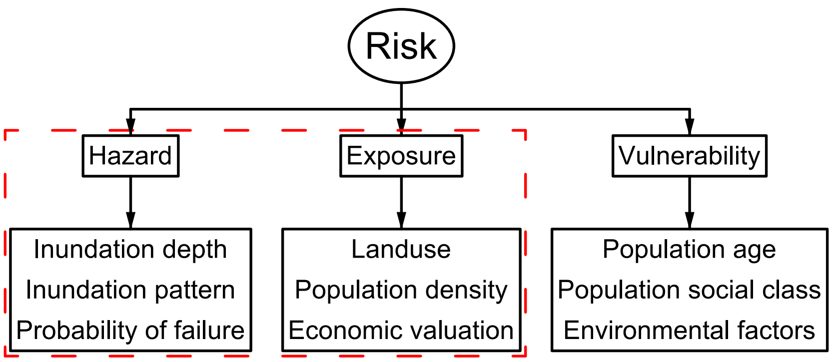


Figure 1: Defining risk, image based on the information given by Dewan [Dewan, 2013]

From Figure 1, the aspects of hazard, exposure, and vulnerability can be identified. Hazard can be seen as the actual flood inundation pattern and resulting flood depths, and exposure is based on the land use that is flooded or the number of people living in the flooded area and the economic value attached to this. For example, a large, agricultural area could be flooded which could result in relatively low damages, and thus the overall risk is low. In another case, an urban centre may experience a much smaller flooded area, but given that the land value is higher, and the population density is higher the resulting damages are extensive, thus the risk is large.

The last aspect, vulnerability, is difficult to define, as it can encompass a wide range of aspects, some of which contain large degrees of subjectivity, uncertainty, and bias [Dewan, 2013]. For this reason, and due to the time limit (10 weeks) of the assignment it was not included in the definition of risk given by Figure 1.

Finally, for the definition of risk given, there must be some form of probability of occurrence. In this case, the probability would be that the SLR causes the dike to fail. While vitally important, dike failure probability is outside the purview of this assignment and extensive literature (in much greater depth than this report will be capable to achieve) has been done on this topic. So for these reasons, it does not form part of this study. Meaning that the aim of this report is only to investigate the effects of SLR on the hazard (inundation pattern and depth) and exposure (damage to property and potential fatalities), leaving out those aspects of 'Risk' relating to the probability of failure of the flood defences and the vulnerability to flooding.

2.2 Study area - Dike ring 14

The existing dike ring 14 encompasses an area of 223'000 ha [Ministerie van Verkeer en Waterstaat Den Haag., 2005], a population of 3.8 million people as of December 2022 [Statline, 2023] and a density of 1'704 people per kilometre squared. It is responsible for 163'805 million (21%) of the Netherlands' Gross Domestic Product (GDP) [Eurostat, 2020], and the contains major cities of Amsterdam, The Hague, and Rotterdam, along with key pieces of infrastructure such as Schiphol airport and Rotterdam port. Its highly strategic value in terms of economics and human life is threatened by its elevation, some polder areas being 6.5m below mean sea level [De Moel et al., 2012], and its placement between the North Sea, the Amsterdam-Rhine Canal, the Hollandsche IJssel and the Nieuwe Waterweg. Given these factors, it is no coincidence that the dike ring 14 is one of the most studied areas in the Netherlands from the perspective of flood risk [De Moel et al., 2012][Jonkman et al., 2008] and these studies have been used to define flood risk in other parts of the Netherlands [Kind, 2014].

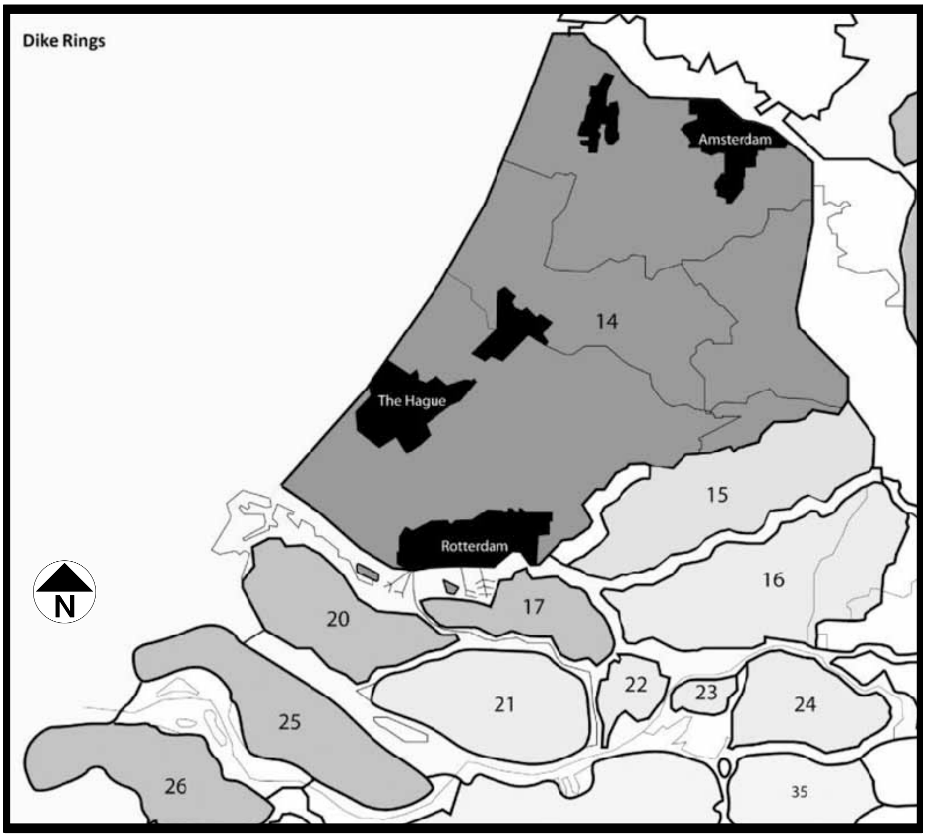


Figure 2: Dike ring 14 [Meyer et al., 2012]

The studies carried out on the dike ring however mostly focus on the perceived safety and overall flood risk of the area by analysing the uncertainties inherent in the inundation modelling process [De Moel et al., 2012]

[Brussee et al., 2021] or uncertain probability of failure mechanisms of flood defences and breach widths that lead to inundation [De Bruijn et al., 2018]. There are additional considerations to be made over the effects of sea level rise (SLR) and its effects on the damage, and therefore the risk pertaining to the dike ring area.

The low-lying elevation of the Randstad means that with climate change increasing the possibility of a dike failure there is considerable concern over the viability of the existing flood protection system.

2.3 Extreme sea level rise

The global sea level rise (SLR) will have a significant impact on the risk calculation of the South Holland dike ring, particularly in terms of the uncertainly [De Moel et al., 2012] [Jonkman et al., 2008]. This is due to the overall uncertainty of the amount of SLR and to the difficulty in accurately predicting the various effects that will cause it such as Antarctic ice sheet loss [Le Bars et al., 2017] or levels of Green House Gas emissions (GHG), thus leading to a wide range of potential SLR [Haasnoot et al., 2020]. The Intergovernmental Panel on Climate Change (IPCC) therefore presents multiple scenarios for SLR based on the level of GHG emissions [Intergovernmental Panel on Climate Change, 2014], leading to difficulty in knowing what standard to design flood defences and inundation models to [Haasnoot et al., 2020][Boettle et al., 2016].

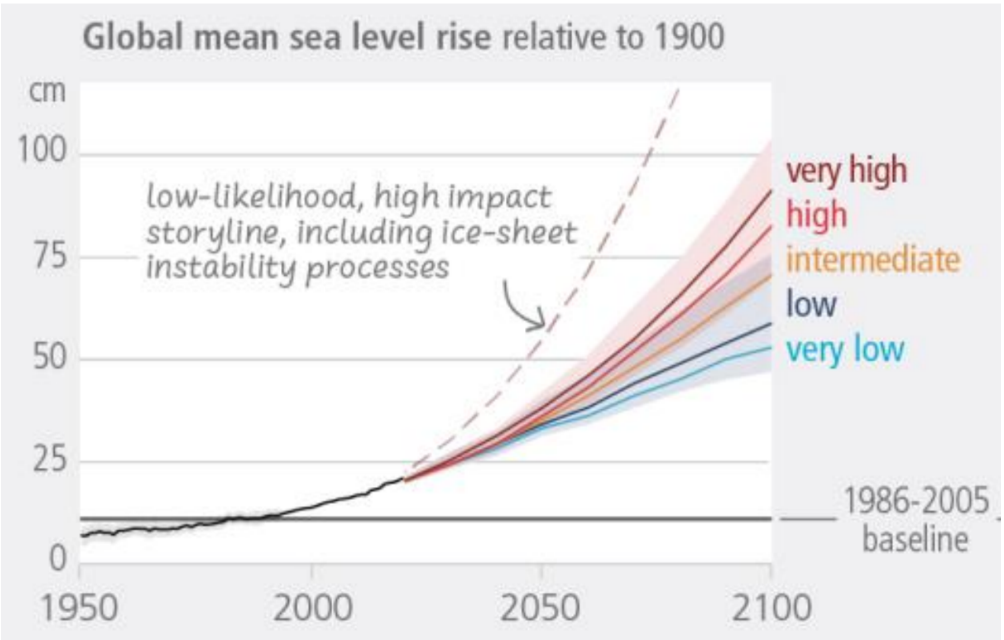


Figure 3: IPCC6 SLR predictions [Lee.H, 2023]

These uncertainties can be seen in varying predictions made by the IPCC since the early 1990s, which have ranged in forecasted SLR by 2100 by different amounts due to increasingly sophisticated modelling, for instance, the IPCC report of 2001 did not include the effects of SLR due to ice sheet loses [Watson, 2001]. Given the long-term investment of infrastructure, assuming leading times of more than 20 years for certain storm surge barriers, these changes and uncertainties of SLR would mean that upon the completion of a flood defence system that was designed for 50-100 years, it would already be insufficient and new adaptions would [Haasnoot et al., 2020]. This is all exasperated due to a low probability, high impact storm event that could happen in conjunction with these extreme SLR scenarios, which have also been predicted to increase in severity and frequency [Muis et al., 2020].

2.4 Flood modelling in coastal areas

There are multiple methods to model flooding, depending on the computational requirements of different resolutions. These have changed from simpler models, such as tray type using simple raster model based on Digital Elevation Model (DEM) [Bates and De Roo, 2000] to D-Hydro 1D2D models created by Deltares

[De Bruijn et al., 2018]. For inundation along the coast, the key input parameter will be the sea level, as this will define the failure probability and then the volume of water that will flood the given area. This moment of failure is important as if the failure happens at a point of a low tide that will increase over the course of a storm, the damage will be worse than if the flood defence fails at the maximum tide level. This is due to the effects of tidal shifts, which are also predicted to be affected by climate change [Pickering et al., 2012].

The area that was modelled will have certain characteristics of slope, area, and land use. These will affect the pattern of the inundation and the damage function used to predict the consequences of the flood. Additionally, the area will contain certain structures that could have water retaining functions which also need to be taken into account [De Bruijn et al., 2018].

2.5 Flood modelling in South Holland - dike 14 areas

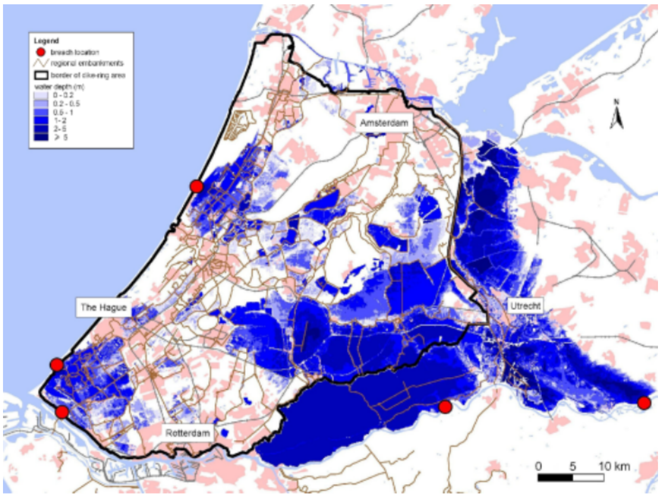
As mentioned previously, dike ring 14 has been a key part of defining the overall flood protection in the Netherlands after the floods of 1953 [Kind, 2014]. However, the initial standards applied to the area in the 1960s did not come from a complex inundation model, but rather from a cost-benefit model that considers the probability that a critical sea level event will happen [van Dantzig, 1954] & [Van Dantzig, 1956]. The model assumed that there would be a failure at this critical sea level height and that there would not be partial flooding, but complete losses of the entire area due to inundation, in this case, the entirety of dike ring 14 [Van Dantzig, 1956]. This can be seen in Equation 1 below.

$$S = \begin{cases} 0 \text{ if} & h \leq H \\ V \text{ if} & h > H \end{cases} \tag{1}$$

Where h denotes the sea level height at a particular time, H is the critical height above which flood will occur, and V is the total valuation of everything in the polder (including consequential losses, such as migration costs of the population and cattle) [Van Dantzig, 1956].

Thus the safety standard was created to allow for a realistic balance between the societal damage (monetary damage and fatalities) and the costs of prevention (dike raising, etc.).

However, the assumption used by the Delta Commission in the 1960s [Van Dantzig, 1956], of complete inundation does not hold in reality [Eijgenraam, 2006]. In the years since the introduction of simulation models for inundation means the actual inundation can be mapped with the use of 2D modelling, and it is expected that the entire area will not flood in the event of a dike breach [De Moel et al., 2012]. Examples of these can be seen in Figures 4a & 4b below. These figures show that large areas will not necessarily flood during a sea dike breach. Of note mainly is the effects on the key population centres of Amsterdam, Rotterdam, and the Hague all of which have not been extensively flooded in these examples. Thus, when considering risk based on hazard, as previously mentioned, the risk would be comparatively lower as large parts of the dike ring area have little or no flooding depending on the breach location. Additionally, in Figure 4b more seaward dike breaches have been included, which has led to more flooding on the western side of the dike ring. This shows the importance of the selection of breach locations, as different locations can give significant differences.



(a) Modelled inundation example 1 [Klijn et al., 2010]

(b) Modelled inundation example 2 [Oost and Hoekstra, 2009]

The project area was investigated with the SOBEK simulation software, which has already been used and validated for other dike rings in the Netherlands [HUTTEN et al., 2021]. The resulting inundation was used as input for damage models. These damage models use damage functions based on water depth, and a summation of the various categories based on land use [Slager and Wagenaar, 2017], seen in Equations 2 & 3. This can be seen as an updated method of the calculation made by Van Dantzig, as it takes into account only the areas that experienced flooding are considered.

$$S = \sum_{i=1}^{n} \alpha_i n_i S_i \tag{2}$$

Where:
α_i = damage factor category i
n_i = number of units in category i
S_i = maximum damage per unit in category i
n = total number of categories

$$S = \sum_{i=1}^{n} (\alpha_i n_i SN + (1 - \alpha_i) SB_i) \beta_i ID (1 - SF_i) M_i \tag{3}$$

Where:
β_i = damage factor business interruption in category i
SN_i = maximum net damage per unit in category i
SB_i = maximum gross damage per unit in category i
ID = 1 year; maximum operating outage duration of affected object
SF_i = category i substitution factor
M_i = indirect damage multiplier for category i

For dike ring 14, the usage of a SOBEK model allows for a better representation of reality, as there are certain secondary dike rings that will provide additional flood projection in the event of a failure of the sea dikes [STOWA,][De Moel et al., 2012]. As discussed previously, these secondary dikes/levees mean that the area may not flood completely. Hence the internal infrastructure will need to be modelled accurately (as a series of 1D elements), as these dikes and other major structures such as tunnels may have an effect on the inundation pattern. Careful consideration of the resolution will be required for these locations [HUTTEN et al., 2021] [Brussee et al., 2021]

2.6 Previous studies in literature

The predominate research relating to the South Holland dike ring focused on the probability and uncertainty of failure of the dikes [De Moel et al., 2012], the accuracy of the inundation model at predicting damage and risk [Kind, 2014], and the breach locations that have the greatest impact on the inundation pattern [ter Horst, 2012]. The latter of these is a point of note, as it is predicted that the greatest damage caused by flooding will not be as a result of a seaward dike breach (the focus of this study), but a breach along the primary river locations or a cascading effect from breaches in the adjacent dike rings (15 and 44). The comparison of these effects can be seen in Figure 5.

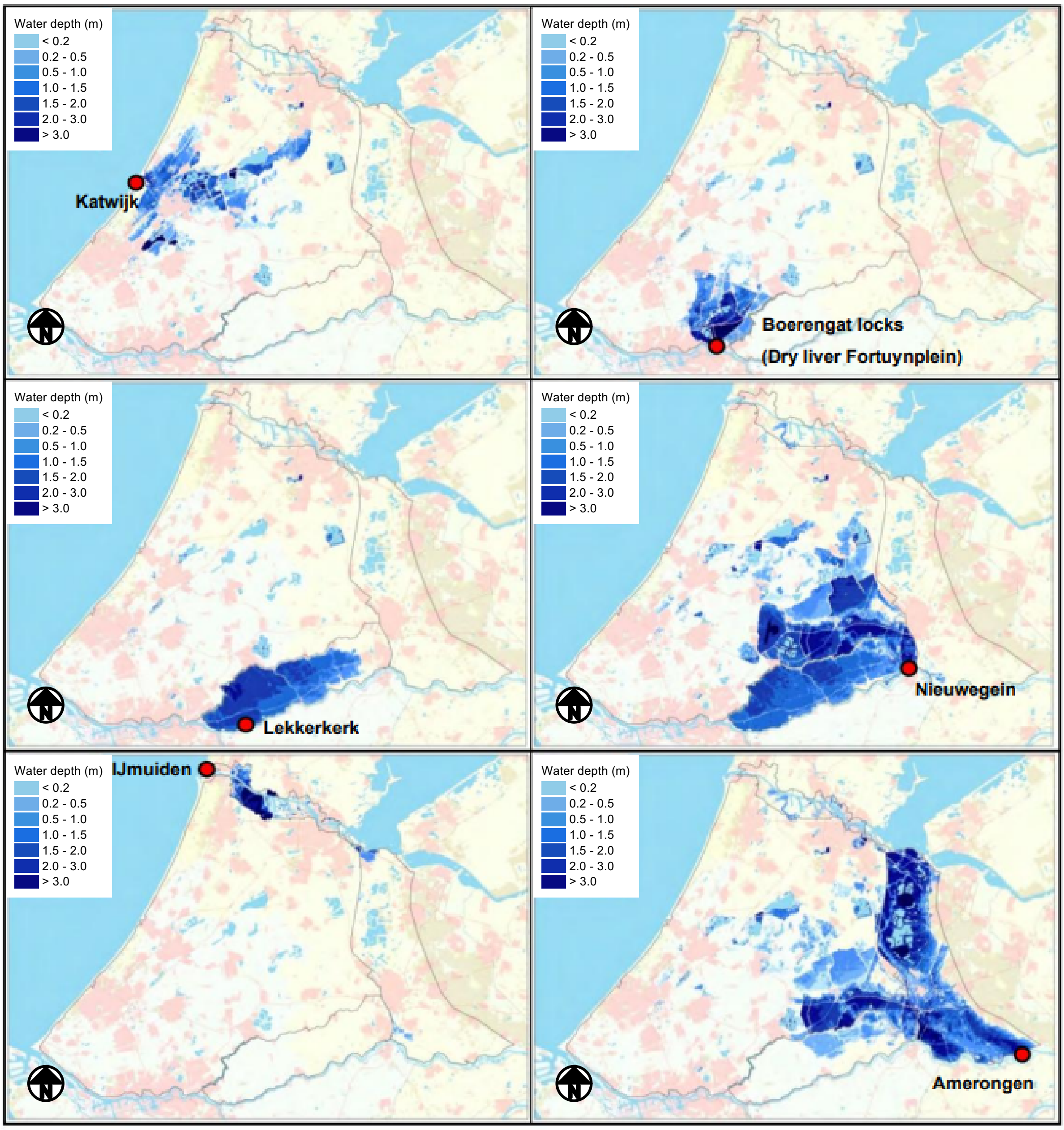


Figure 5: Flood patterns found at different locations [ter Horst, 2012]

Additionally, as previously discussed, there is significant work being done to accurately predicted future SLR. There is, however, a gap in the knowledge as to how sensitive the existing flood models are to SLR. This has huge implications for future flood defences, particularly *"when and how much to adapt"* [Haasnoot et al., 2020]. The impacts of this could have significant impacts on the perceived safety of the seaward dikes in dike ring

14, as the current assumptions based on existing simulation results that the impacts of seaward dike failure would be lesser than that of river dike failure. This assumption is predicated on the fact that flooding from the sea is dictated by the ebb and flow of tidal shifts and the coincidence of storm events with these 'high tide' periods [Asselman et al., 2010]. Much of the existing studies of SLR focus on the general effects on coastal regions around the world [Tiggeloven et al., 2020] or specific mitigation effects on a local level in the Netherlands [Kwadijk et al, 2010]. The general effects of SLR on the dike ring 14 can be seen in Figures 6 & 7, where an example of the general effects of SLR on inundation taking into account only the topography.

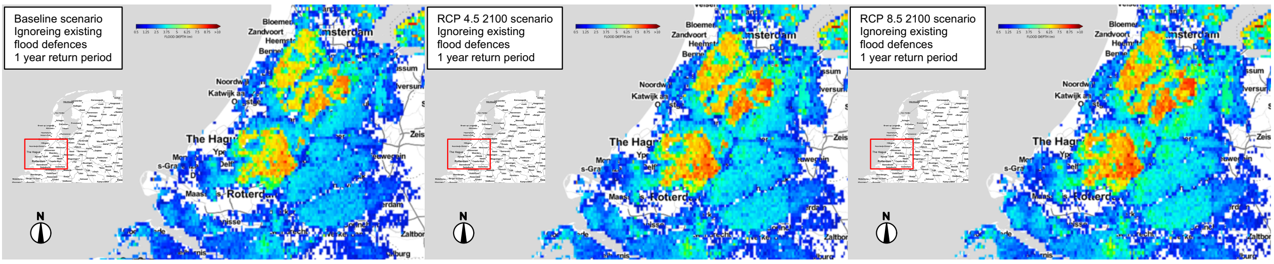


Figure 6: SLR effects on dike ring 14 with no flood defences (1 year return period) - Images made from http://coastal-futures.org/- Accessed 23/03/2023

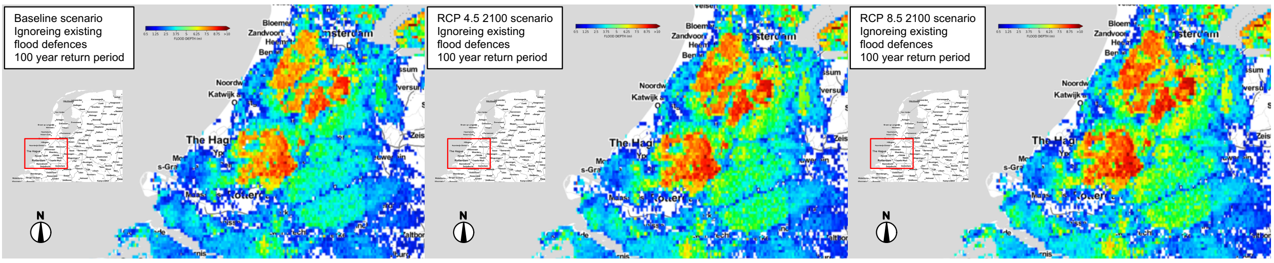


Figure 7: SLR effects on dike ring 14 with no flood defences (100 year return period) - Images made from http://coastal-futures.org/- Accessed 23/03/2023

This defines the key aspects of this assignment: What effects will SLR have on the flooding in dike ring 14? Will there be a 'tipping point' at which the hazard and exposure begin to increase rapidly? Do different breach locations greatly impact the hazard and exposure in future SLR scenarios?

3 Problem statement and research objective

3.1 The problem statement

As outlined in Chapter 2, there were issues in the previously defined safety standards as a result of previous assumptions of complete inundation in the event of a sea dike failure [Van Dantzig, 1956] [De Moel et al., 2012]. Additionally, there are concerns over the extent of sea level rise (SLR) and the effects that it will have on hazard and exposure in the dike 14 area during a flooding event from the sea [Haasnoot et al., 2020]. This is due to the difficulties in predicting SLR rise accurately, coupled with the limited studies using simulation models to accurately map the inundation for the most up-to-date SLR predictions [Lee, 2023], resulting in uncertainty regarding the level of hazard, and by extension the exposure. This uncertainty calls into question the existing safety standards, and if they are actually reflective of the real risk [Kind, 2014].

While this assignment did not deal with any forms of policy, it is worth noting that the work that was done can be seen in an overall approach to climate change and resilience. Rather than asking if the climate changes, then what will the implications and adaption measures be, the process can be seen as one to test how much climate change can we cope with, and where are there tipping points indicating that an adaptation measure is required [Kwadijk et al, 2010]? This process can be seen in Figure 8 below, and followings a bottom-up approach, which is counter to an approach that only tests if the current defences are sufficient. In this figure, the purpose of this report can be seen as providing insight into the pressures that come from changes in the climate, in this case, SLR. This will allow for more insights to be drawn as to how much climate change and SLR would cause an untenable situation, but this conclusion is outside the scope of this report.

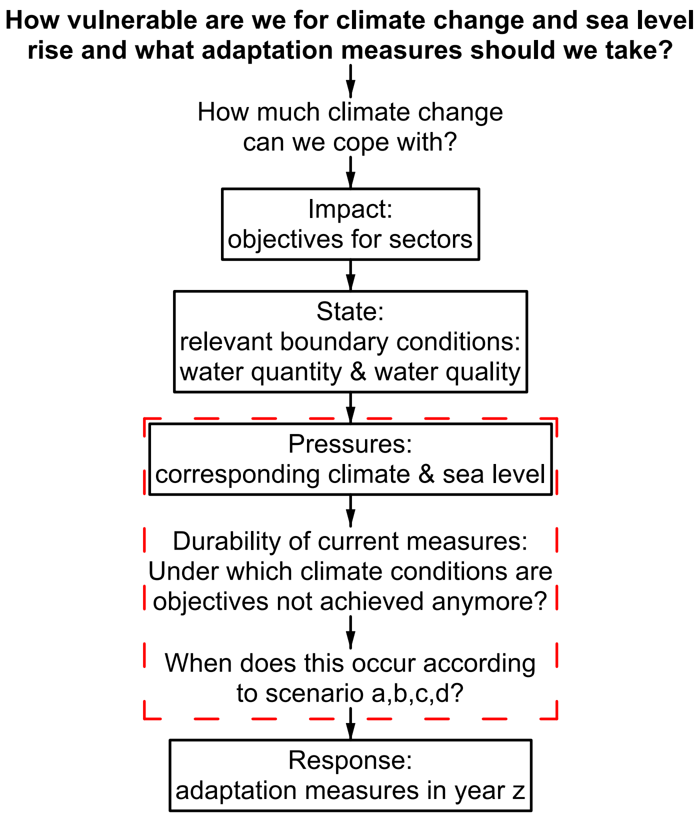


Figure 8: Environmental tipping points, adapted from Kwadijk [Kwadijk et al, 2010]

3.2 Research objective

The objective of this BSc research is to investigate the increase in flood hazard and exposure in Dijkring 14 (Zuid-holland) resulting from sea level rise.

4 Research questions

As outlined in previous Chapters, the inundation pattern will be defined by the location of the dike breach. Given the limitations of the software run times, and the short time of this assignment (10 weeks) it was not possible to stress test the entire length of the seaward dike of dike ring 14, so a targeted approach was needed to select the most appropriate locations. The same methodology was applied to the SLR scenario.

4.1 Research question 1 - How sensitive is the flood hazard in dike ring 14 to sea level rise?

4.1.1 Sub-question 1 - Based on certain SLR scenarios, what is the inundation pattern and depth that we can expect?

Running a simulation for each SLR scenario will give an overall inundation pattern and depth. These will then be compared to see what the trend is, be it linear or otherwise, and therefore the sensitivity.

4.2 Research question 2 - How sensitive is the flood exposure in dike ring 14 to sea level rise?

4.2.1 Sub-question 2 - Based on certain SLR scenarios, what is the exposure and damage that we can expect?

Using the data generated from research question 1, some damage functions can be applied to estimate the overall exposure.

4.3 Research question 3 - How will the hazard and exposure change when using different models?

The use of 1D2D SOBEK models gives an accurate representation of what will happen during a flood event when compared to a more simplistic model, such as a 'bathtub' or '2D' model. But is there an SLR scenario where both models give a similar result? This will be addressed in sub-question 3.

4.3.1 Sub-question 3 - At what SLR scenario will a 1D2D, 2D, and 'Bathtub model' give similar results?

Using the data generated from research question 1, a similar 'bathtub model' and '2D'model will be run for the same conditions. This will then be compared to the initial results of research question 1.

5 Research methods

This bachelor's assignment required a significant degree of assumption and streamlining due to the time demand of running each simulation. It was not possible to know the exact time demand before starting the study, as this was based on the resolution used, the period of the storm event and other factors that were only defined during the assignment. With this consideration, creating a robust analysis within 10 weeks required a specific methodology, particularly with the treatment of validation which was simplified given that it was not realistic to repeat a multitude of simulations for in-depth validation. This methodology is schematised in Figure 9 below. Included in this scheme is the theoretical framework, which was used to narrow and define the scope. This is discussed in detail in Chapter 5.

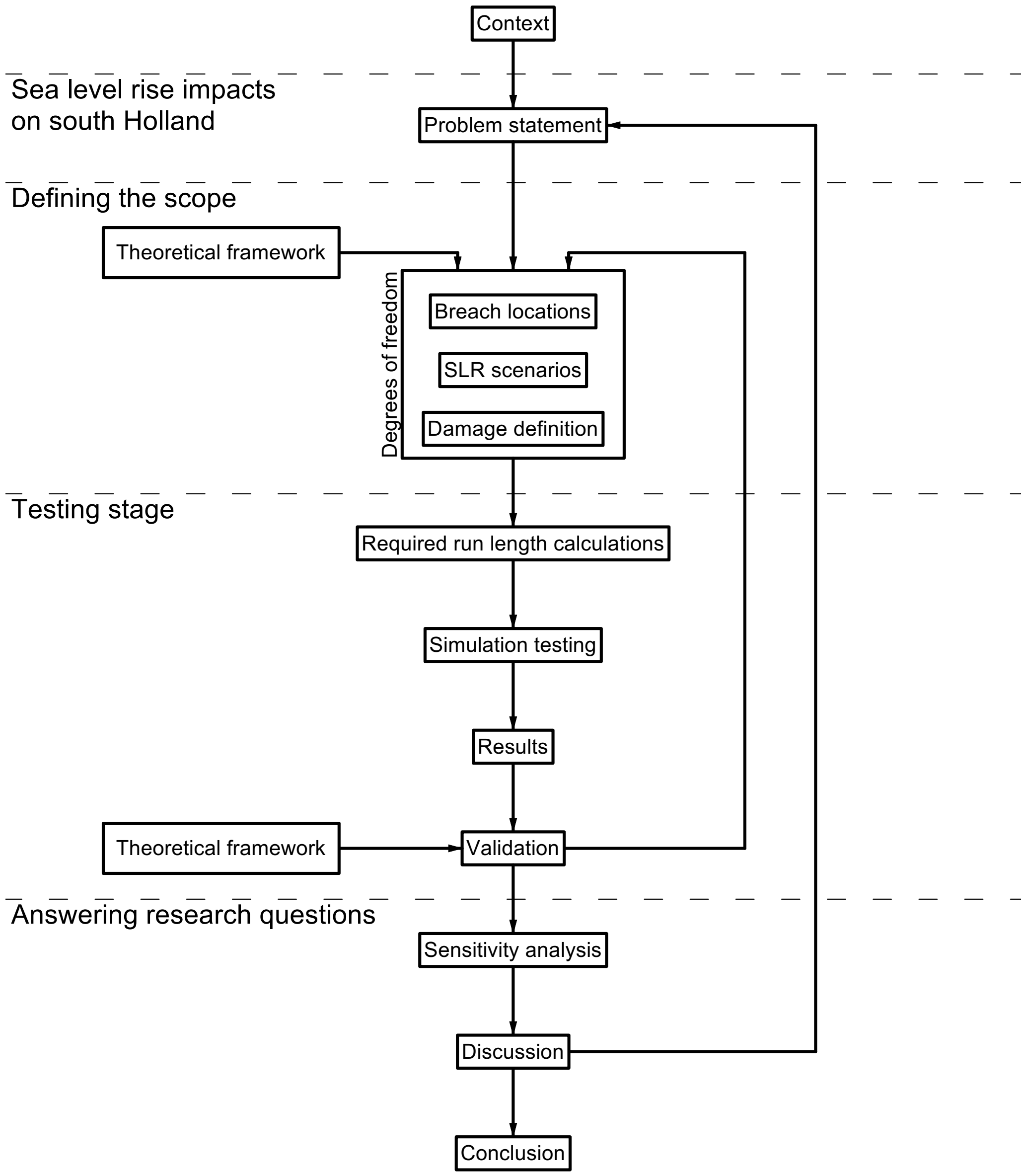


Figure 9: Research framework

5.1 Defining the scope

5.1.1 Theoretical framework

This bachelor assignment was contingent on three main aspects, breach locations, sea level rise scenarios, and damage definitions, all of which will be outlined in the coming section.

These three aspects contain multiple degrees of freedom in defining what was in, or out of scope. For instance, it was not practical to simulate the inundation that results from every possible breach location along the seaward dike of dike ring 14. However, using only one location would not be representative of the possible scenarios. Thus, a refined selection of locations was needed, but this begged the additional question of what the most appropriate method for these determinations is.

Introducing additional criteria for the selection process of the breach locations, and the other aspects would have increased the complexity of the project due to increasing the degrees of freedom. Using a framework to formalise the potential decisions allowed for the potential options to be identified. While, for simplicity, these choices could be refined to only the choices that were made, this would not adequately acknowledge the potential decisions (i.e. those decisions not taken) and reduce the legitimacy of the outcomes of this report [Haasnoot et al., 2020]. Thus, this framework allowed for clarification of the decisions made to create the simulated scenarios and provide transparency on the reasons for excluding other choices and scenarios. This theoretical framework can be seen in Figure 10, and includes many of the potential decisions that could lead to defining the scope. It should be noted that this is not a complete list, nor was every aspect included in defining the scope or exhaustively investigated.

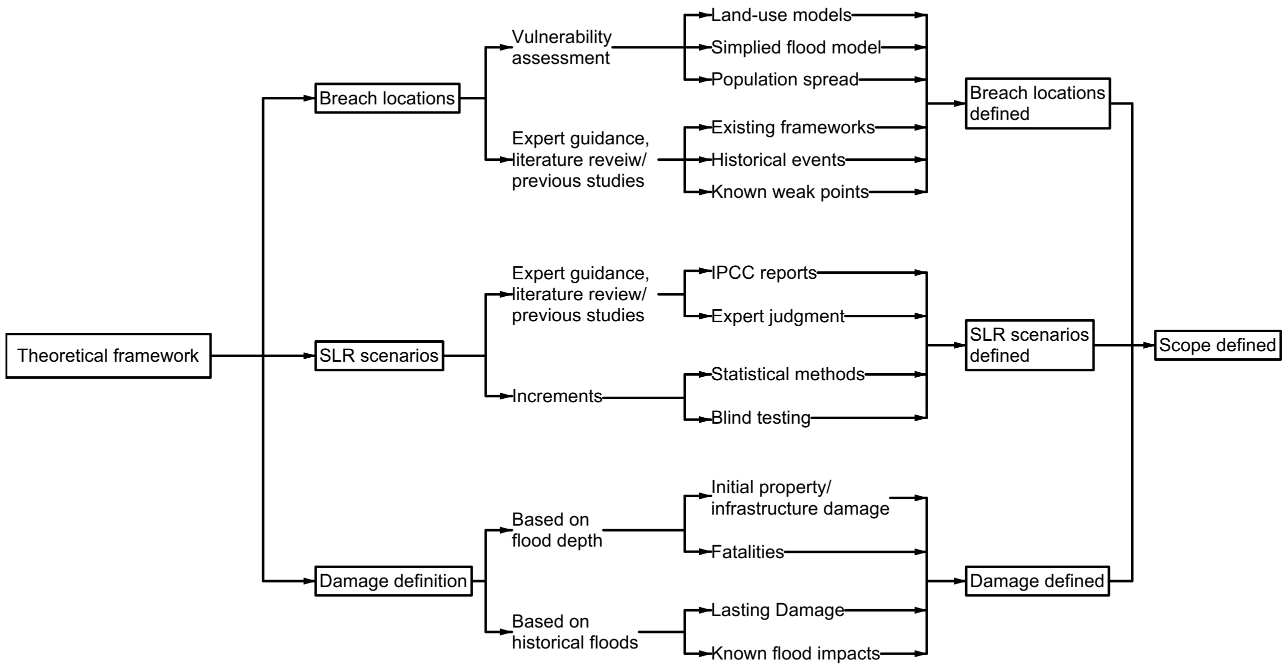


Figure 10: Theoretical framework

In Figure 10 above these potential choices have been laid out. However, it was not practical to choose multiple methods to define, for instance, the breach locations but it was necessary to state the possible options.

These choices will be the definition of the scope of this assignment. An example of how this might look can be seen in Figure 11 below. This example assumes breach locations based on literature, SLR scenarios based on various increasing increments, and the standard method of calculating damage.

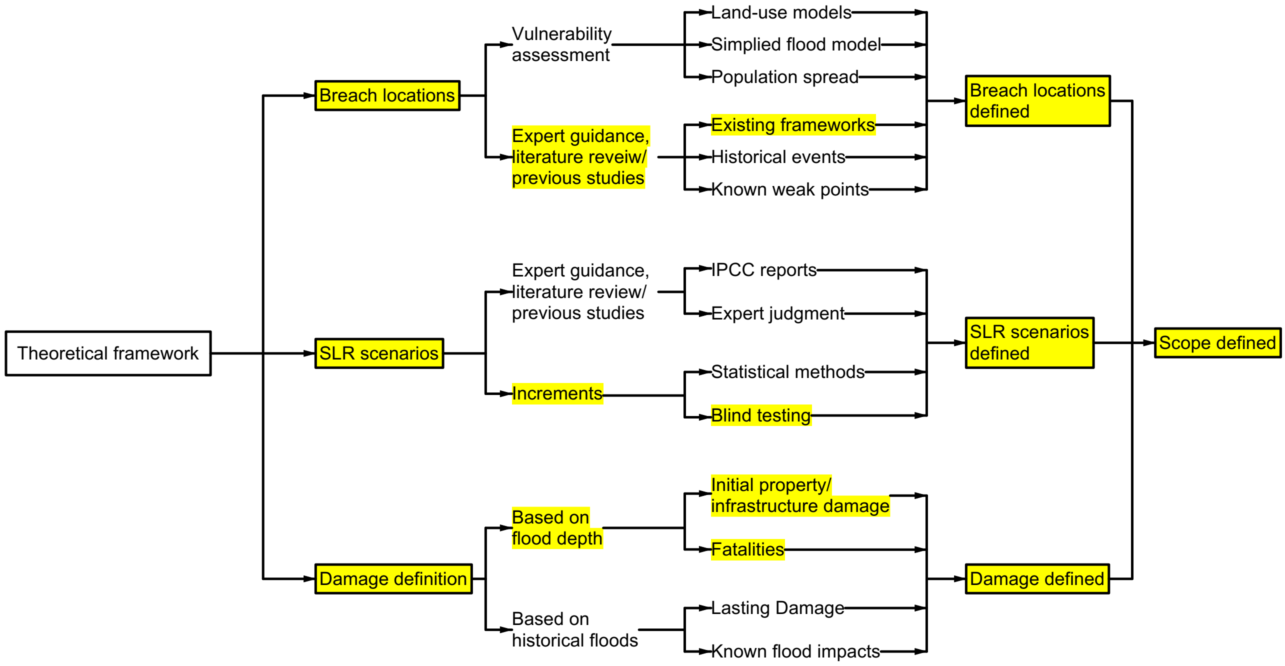


Figure 11: Defined scope

5.2 Demarcation

From the framework given in Figure 10 above, there were certain choices made about the conditions used in the model testing and these will be included in a section of demarcation. Additionally, those methods excluded will also be listed, and the reasons why. There are additional considerations that do not appear in the framework given, and these are those assumed to be completely out of the scope of this project. For instance, SLR that would cause wave propagation along the Nieuwe Maas or Hollandse Ijseel, assuming the failure of the Maeslant Barrier, that leads to failure from the river dikes of dike ring 14 will not be considered within the scope. This, and other examples, were included in a demarcation list in Chapter 7 (See Figure 2.

There are certain aspects that will be considered out of the scope during the testing but could have large effects on the outcomes of the model, such as the resolution or schemeazation of line elements (for roads, waterways, etc.), particularly if there are any issues. These facts will be included in the discussion section of this report. By doing this, it will allow for adequate acknowledgement of the potential effects on any issues here would have on the outcome of the model, without the need for an in-depth analysis of these elements.

6 Methodology

When breach locations are defined, initial SLR scenarios and damage methods chosen the next step was to propose a method of testing. This was done in a relatively straightforward manner by testing each of the breach locations under each SLR. This gave some initial data of both numerical (amount of inundation, depth, and consequential damage) and visual (actual pattern of inundation). The hazard and exposure will be presented in a graph such as the ones in Figures 12 & 13 below.

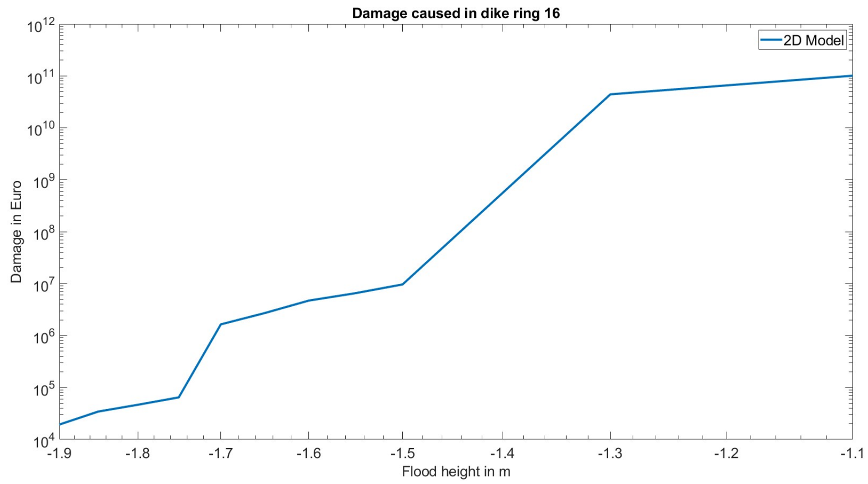


Figure 12: Example of damage by flood height, based on a rough 2D model (See Appendix B) used for dike ring 16

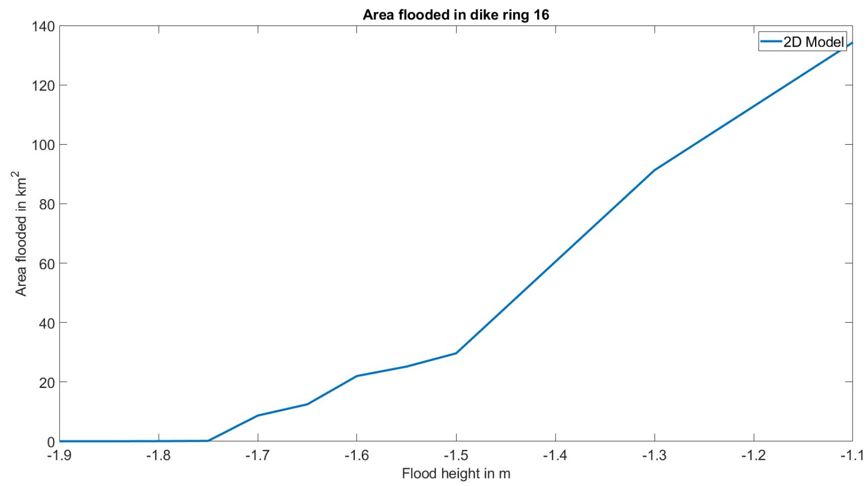


Figure 13: Example of the area flooded by flood height, based on a rough 2D model (See Appendix B) used for dike ring 16

6.0.1 Method for answering research questions 1 and 2

With the short time frame, it required a targeted approach, as discussed already. However, in the case of the breach locations, using two breach locations near each other, that give a similar inundation pattern would be inefficient. The ideal would be to have a minimal amount of breach locations that provide the most comprehensive insight into the general inundation, the probabilities of a particular, individual dike breach will not be the subject of this report. Hence minimal, but representative breaches were aimed for.

Some initial assumptions for SLR were needed, for instance, testing at certain increments from the intermediate SLR scenario given by the IPCC [Lee, 2023]. The main interest lies in the point at which the hazard and exposure change significantly (be it a non-linear change, like an exponential change). So the increments were tested until this change was seen (or until realistic levels have been passed, which would show that there is no great increase), When the large change is seen, the increments will then be decreased to see more definitely where this happens. For (an extreme) example, testing in 10m increments and finding that there are some major changes from 70-80m. Then reducing the increments to 5m, 2.5m,1m, etc. to find the exact point, if it exists.

Finally, when the breaches and SLR scenarios were defined, the effects of tidal and storm surges were investigated.

This was be done with the same method outlined by de Moel [De Moel et al., 2012], and can be seen in Figure 14 below. This gives the amplitude of the astrological tide (Amplitude), the elevation of the storm surge on top of the astrological tide (Max dH), the duration of the storm (DurationStorm), the duration of the peak of the storm (DurationPeak), and the timing of the peak of the storm surge with respect to the peak of the normal high tide (Offset) [De Moel et al., 2012] effects as probability distributions (uniform and normal) with mean and standard variations based on known literature and databases. The same process was used here.

The reason for defining the tidal and storm scenarios last is to be able to have a separation of scenarios. SLR is assumed to be a mean value that does not take into account tides and storms, and hence it will be useful to know the extent of inundation from a sea level in a 'normal situation' and then in a 'storm situation'. For example, an SLR of 1.5m with no storm might give the same inundation as a 1m SLR with an additional water height from a storm.

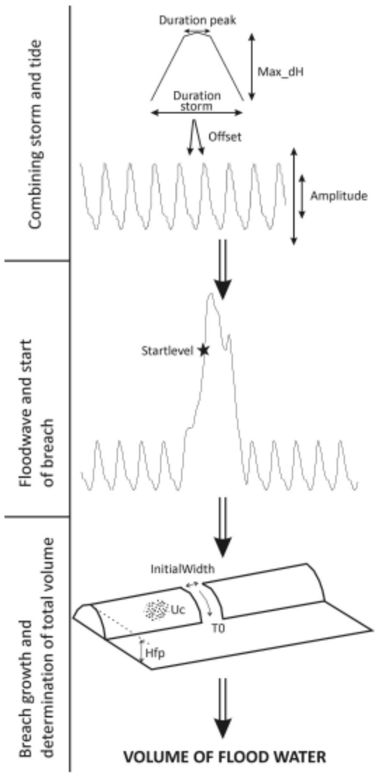


Figure 14: Tidal and storm surge, as given by de Moel [De Moel et al., 2012]

The process of all of this can be seen in Figure 15.

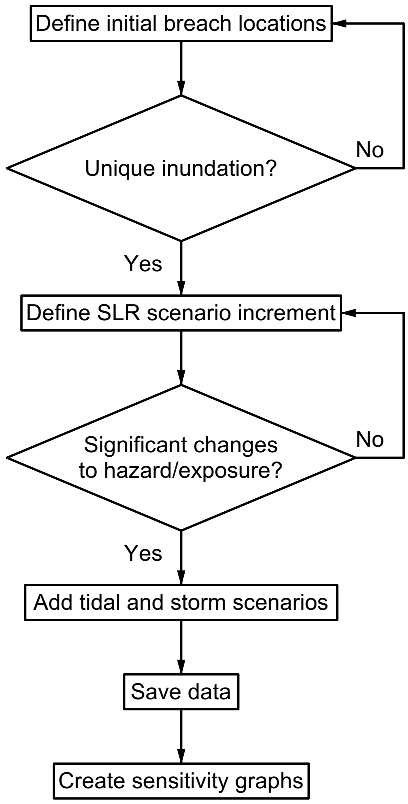


Figure 15: Testing process

The effects from all of these scenarios were recorded and graphed like the example of Figure 12. This allowed for the comparison between the scenarios, and insights into the overall effects of the inundation from SLR.

6.0.2 Method for answering research question 3

The data generated from the SOBEK model was compared to simplified models which were created for this project. The first of these was a 'bathtub' model, where a flood height was created, and initiated at the global minimum of the dike ring 14 elevations, i.e. the lowest point. This was then increased by an arbitrarily small amount until the total volume of water was equal to that of the SOBEK model. This was only tested for the SOBEK volumes that resulted from a breach at Katwijk with a storm surge, for no SLR to 5m of SLR. A description of this model can be seen in Appendix B and the code used for this can be seen in Appendix E.

The second of these models was a 2D model that takes into account only the terrain and is not a numerical model (not solving momentum or continuity equations). Additionally, there are no 1D elements modelled, such as rivers or canals. Thus, this would also give an indication of the importance of these elements in modelling inundation in dike ring 14. A description of this model can be seen in Appendix B and the code used for this can be seen in Appendix E.

6.0.3 Uncertainty

The model contains various sources of uncertainty, from the schematization to the conditions used, a listing can be seen in Appendix A. Given the time restraints, a robust validation would be unlikely. Rather, the insight gained from the literature was used to compare the model to others, as much as possible, to see if the results make sense within the greater context, although it is assumed that finding other studies with the exact conditions used here will not be possible, as discussed in Chapter 2 where previous literature was discussed.

7 Research carried out

7.1 SOBEK

SOBEK is a numerical simulation software used to simulate various flooding events, from rivers, the sea, or from precipitation events. The model consists of 1D elements and a grid cell with elevation data representing the 2D landscape. Additionally, there are 'nodes' that represent the connections of the rivers, roads and other important aspects of the area. The base model represents the South Holland dike ring 14 and has been used extensively in the past. Hence, much of the model is assumed to have been adequately verified and will be assumed to be a good representative of the area.

For this assignment, the 1D2D capabilities of the software were utilised. The theoretical background to these are discussed below.

7.1.1 1D Flow

SOBEK allows for the modelling of 1D elements that can be used to represent rivers, roads, tunnels, etc. These elements form a vital part of the model, as it can be seen that a significant amount of the initial flooding is caused by the water flowing along these rivers where there is little resistance to flood propagation when compared to the flow across the land. Particularly in dike ring 14 where there are significant amounts of secondary dike rings, as discussed in Chapter 3, the flow along these river and road elements has a great impact.

These elements are physically modeled in the software and the continuity and momentum equations are used to solve the flow of water along the elements.

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{4}$$

Where:
A_T = Total area (sum of flow area and storage area) $[m2]$
Q = Discharge $[m^3/s]$
q_{lat} = Lateral discharge per unit length $[m2/s]$. Positive value refers to inflow. A negative value refers to outflow.

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_F}\right) + gA_F\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_F} - \omega_f\frac{\tau_{wind}}{\rho_\omega} + gA_F\frac{\xi Q|Q|}{L_x} = 0 \tag{5}$$

Where:
A_F = Flow area $[m^2]$
C = Chézy value $[m^{1/2}/s]$
g = Acceleration due to gravity $[m/s^2]$
ζ = Water level $[m]$
L_x = Length of branch segment, accommodating an Extra Resistance Node $[m]$
Q = Discharge $[m^3/s]$
R = Hydraulic radius $[m]$
t = Time $[s]$
ω_f = Water surface width $[m]$
x = Distance along the channel axis $[m]$
ρ_ω = Density of fresh water $[kg/m^3]$
τ_{wind} = Wind shear stress $[N/m^2]$
ξ = Extra Resistance coefficient $[s^2/m^5]$

7.1.2 2D Overland hydrodynamic flow

In addition to the 1D line elements that represent the rivers, roads, etc. the flow of water across the land is modelled with the 2D capabilities. Again the continuity and momentum equations are solved, with the momentum being split into two separate components, reflecting the multi-directional paths that the flow of water can take over the land. These equations can be seen below.

While the 2D flow is simpler to model, only requiring an elevation map and an initiation point, the computational effort of the solution is greater than that of the 1D flow, as the number of flooded cells is greater.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{6}$$

where:
u velocity in x-direction $[m/s]$
v velocity in y-direction $[m/s]$
ζ water level above plane of reference $[m]$
h total water depth $[m]$
d depth below plane of reference $[m]$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{u|\vec{u}|}{C^2 h} + au|u| = 0 \tag{7}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial x} + g\frac{v|\vec{u}|}{C^2 h} + av|v| = 0 \tag{8}$$

where:
u velocity in x-direction $[m/s]$
v velocity in y-direction $[m/s]$
$|\vec{u}|$ velocity magnitude $(=\sqrt{u^2 + v^2})$ $[m/s]$
ζ water level above plane of reference $[m]$
C Chézy coefficient $[\sqrt{m}/s]$
h total water depth $(=d + \zeta)$ $[m]$
d depth below plane of reference $[m]$
a wall friction coefficient $[1/m]$

7.1.3 SOBEK vs the D-Hydro

It is important to mention that while the SOBEK model used has been used previously, the software itself is no longer state of the art being replaced by newer models such as D-Hydro. However, given the short time frame, it was decided to use the more stable SOBEK model to avoid issues with the newer models that are still being verified and tested for robustness.

7.2 Standard damage and casualty model HIS-SSM

To attain data on the exposure (damage and fatalities) resulting from the flood the standard damage and casualty model (HIS-SSM) was used. This creates a damage and fatalities estimation based on the maximum depth resulting from the flood. It uses land use, damage fragility curves and population data to create these.

7.3 Scope

As outlined previously, the scope consists of the definition of the breach locations, SLR scenarios, and damage estimation methods. For the latter, the HIS-SSM method was assumed, and for the others, they have been defined with the method outlined below.

7.3.1 Breach locations

A review of the literature was carried out to find the most appropriate breach locations. The results of this can be seen in Table 1 below. In this table, it is clear that Katwijk is an often simulated breach location. this is due to the canal that joins the sea here, and the relatively short and low dunes (compared to the northern section of the dike ring). Given its central point along the coast of dike ring 14, it will be used as the 'Base Case', as in all other breach locations and the resulting inundation will be compared to it.

Using this comparison location, some initial runs were done for the following locations: The Hague - Scheveningen, Ter Heijde, Hook of Holland, the Hague dune, and IJmuiden. The other locations seen in Table 1 are located behind the Maeslantkering storm barrier, and it is assumed that this would be able to deal with storm surges in future scenarios. Thus, these locations were not considered.

The locations at Ter Heijde and the Hague dune were excluded due to the former having a very similar inundation pattern to that of Hook of Holland and The Hague - Scheveningen, and the latter having a similar inundation pattern to that of The Hague - Scheveningen. Additionally, the likelihood of flooding from The Hague - Scheveningen was deemed higher than elsewhere in the Hague, given the harbour and canal access. Haarlem was excluded as it lies behind the widest point of the coastal dune and was thus deemed to be a highly unlikely location for dike failure.

Thus four testing locations were defined as: **Katwijk, The Hague - Scheveningen (The Hague), Hook of Holland, and IJmuiden**.

Table 1: Literature review of dike breaches

Breach Locations	Studies								Reason for rejection
	Maaskant et al	Jonkman et al	Klijn et al	Osst et al	de Moel et al	Asselman	ter Horst		
Katwijk	*	*	*		*	*	*	6	
The Hague - Scheveningen	*	*		*				3	
Ter Heijde	*	*		*	*	*		4	Similar pattern
Hoek van Holland	*	*	*					3	
Den Haag dune	*	*						3	Similar pattern
Rotterdam West		*						1	Behind storm barrier
Rotterdam East		*						1	Behind storm barrier
Kralingen		*		*				2	Behind storm barrier
Oude Massdijk			*					1	Behind storm barrier
Hollandsche Ijssel			*					1	Behind storm barrier
Prinsendijk and Oude Rijndijk			*					1	Behind storm barrier
Haarlem				*				1	Widest point of costal dune
Maassluis					*	*		2	Behind storm barrier
Ijmuiden							*	1	

7.3.2 SLR Scenarios

Given that the aim of this research was to find the sensitivity of the flooding in dike ring 14 due to SLR, and the short time frame, spending exhaustive amounts of time on defining the realistic probabilities or amounts of SLR was deemed to be of lesser importance than that of recording the resulting flooding. Thus, a simple increasing increment method was used, given SLR scenarios of 1 to 5 meters of sea level.

The tidal variation and potential storm surge scenarios must be completed to create an accurate picture. The tidal variation open source data was taken from Rijkswaterstaat [Rijkswaterstaat, 2023]. Figure 16 shows an example of this for the Hook of Holland.

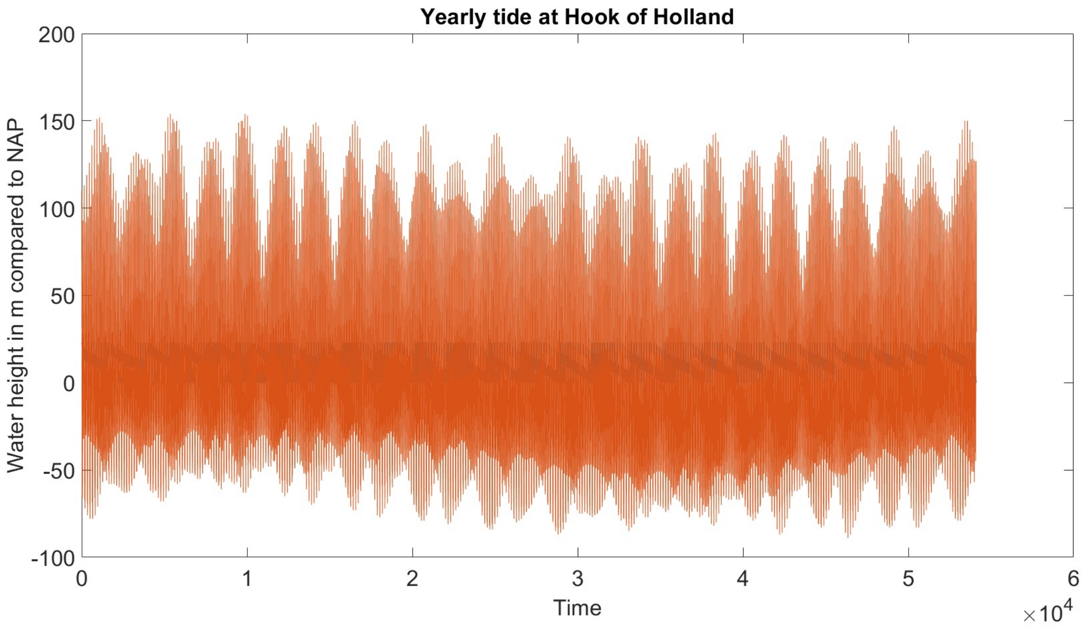
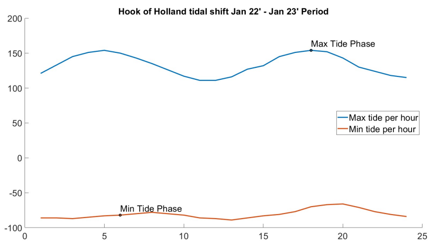
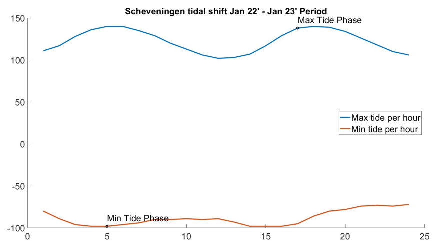


Figure 16: Yearly tide variation from Jan 22 - Jan 23 [Rijkswaterstaat, 2023]

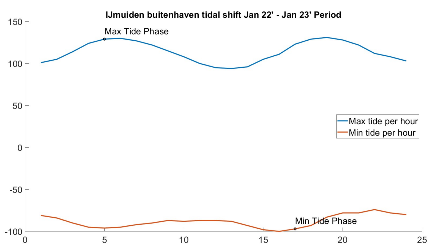
Figure 16 was grouped to create a more usable form. The method to carry this out was as follows: The maximum and minimum water level was taken for each hour, and then a 12-hour tidal shift was assumed. The water height at each hour was compared to 12 hours later, and the biggest tidal shift was used as input into the model. This can be seen in Figures 17a to 18b below.



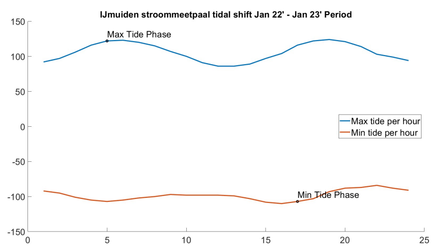
(a) Tides for Hook of Holland [Rijkswaterstaat, 2023] - Accessed 1/5/23



(b) Tidal shift for Scheveningen [Rijkswaterstaat, 2023] - Accessed 1/5/23



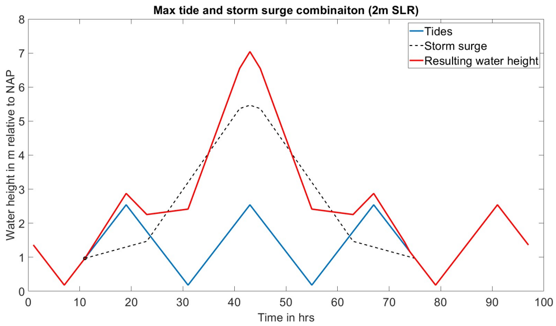
(a) IJmuiden buitenhaven tidal shift [Rijkswaterstaat, 2023] - Accessed 1/5/23



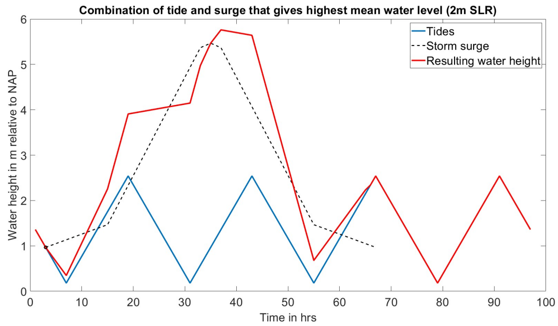
(b) IJmuiden stroommeetpaal tidal shift [Rijkswaterstaat, 2023] - Accessed 1/5/23

The storm surge was created, using a standard procedure, by adding an additional water level on top of the constant tidal variation [De Bruijn et al., 2018]. A storm surge of 4.5m was used for all scenarios. Here it was assumed that potential changes to the storm surge with SLR were minimal, and the standard procedure was still applicable to all SLR scenarios.

The timing of this surge was also considered. The maximum water level would happen when the maximum of the surge coincides with high tide, but then it is expected that the receding tide would mean that the average effect of the storm surge would be lower. Hence, there is a situation where the storm surge would not lead to such a maximal water level but have a higher average water level. Both of these were found (see Figures 19a & 19b) and simulated.



(a) Surge Highest Max Lvl 2m SLR



(b) Surge Highest Mean Lvl 2m SLR

7.3.3 Outliers

For completeness, a check for outliers was carried out. This was done with a combination of methods, checking the frequency of occurrence of large water depths, 3D graphing all the observations, and checking the SOBEK model itself. The generated data were grouped by water depths, and how many times that depth was observed was found. It was expected that the shallower water depths would be more prevalent, and those deeper observations would be less frequent.

Given that there is expected to be a degree of outliers in terms of the elevation (such as deep polders), any water depth outside the 99th percentile was identified, as seen in Figure 20. From this figure, it can be seen that any value above a depth of 8m will be treated as an outlier.

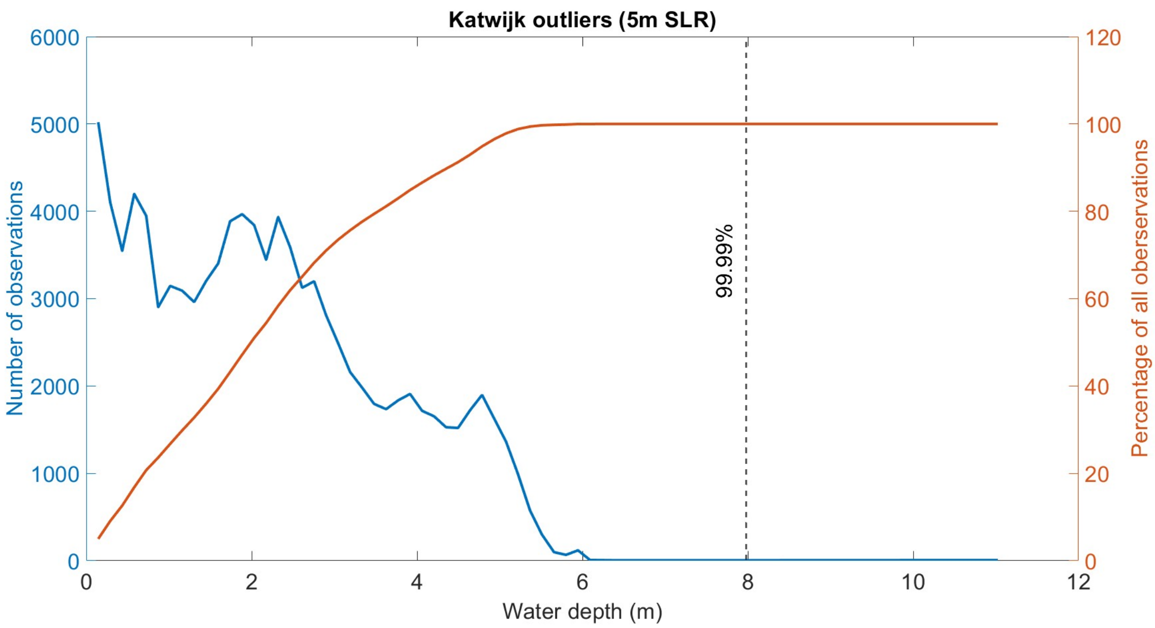


Figure 20: Water depths in the 0.1 percentile - Katwijk breach for 5m SLR

To confirm the approximate location of the outliers and their actual depth, a 3D plot of the same scenario was made, which can be seen in Figure 21. This figure plots the inundation depth for each observation in the area. In this figure, quite a few outliers of significant scale were identified (the max depth being ≺40m) which could skew the results of the analysis.

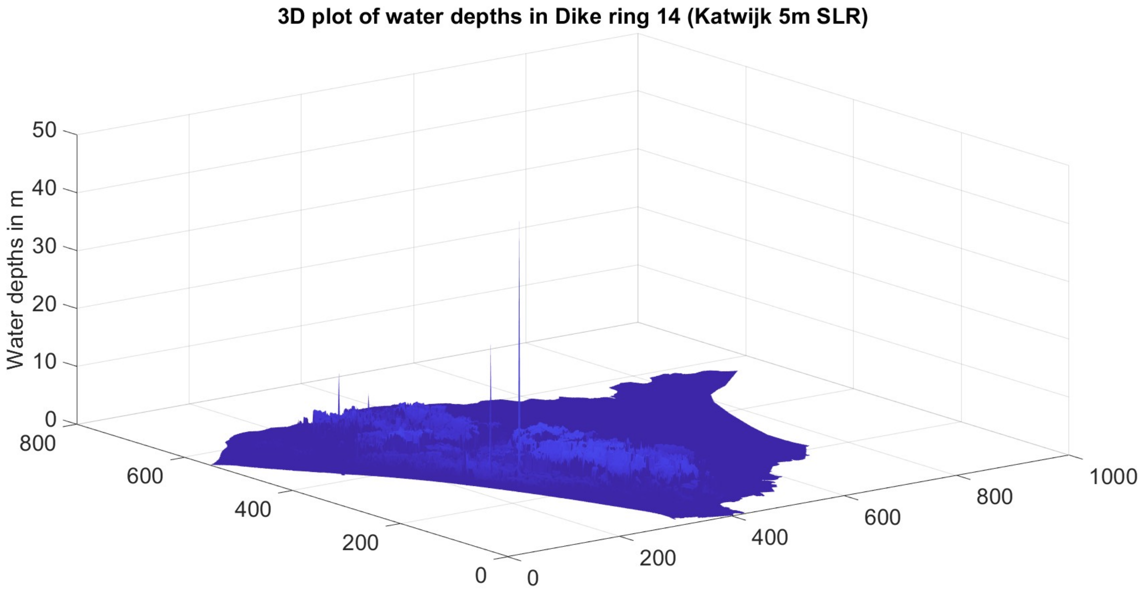


Figure 21: 3D plot of outliers for Katwijk 5m SLR

With the information, the locations of these outliers were identified and inspected in the SOBEK model. There were various reasons leading to these outliers, some being initialisation errors with the breach locations, and some being storage nodes within SOBEK both of which result in outliers. Another cause of outliers is being caused by extremely deep locations within the AHN elevation data. For the latter of these, if there was a value suddenly deeper than the nearest neighbours (more than several meters difference) it was assumed to be an error, but a very deep area, such as the polder area around Hoofddorp would not be counted as an outlier as despite resulting in significant inundation depths it is a naturally occurring feature of the terrain in dike ring 14. Thus, these outliers were identified through the above methods and removed from the data set. The results can be seen in Figures 22 & 23 below.

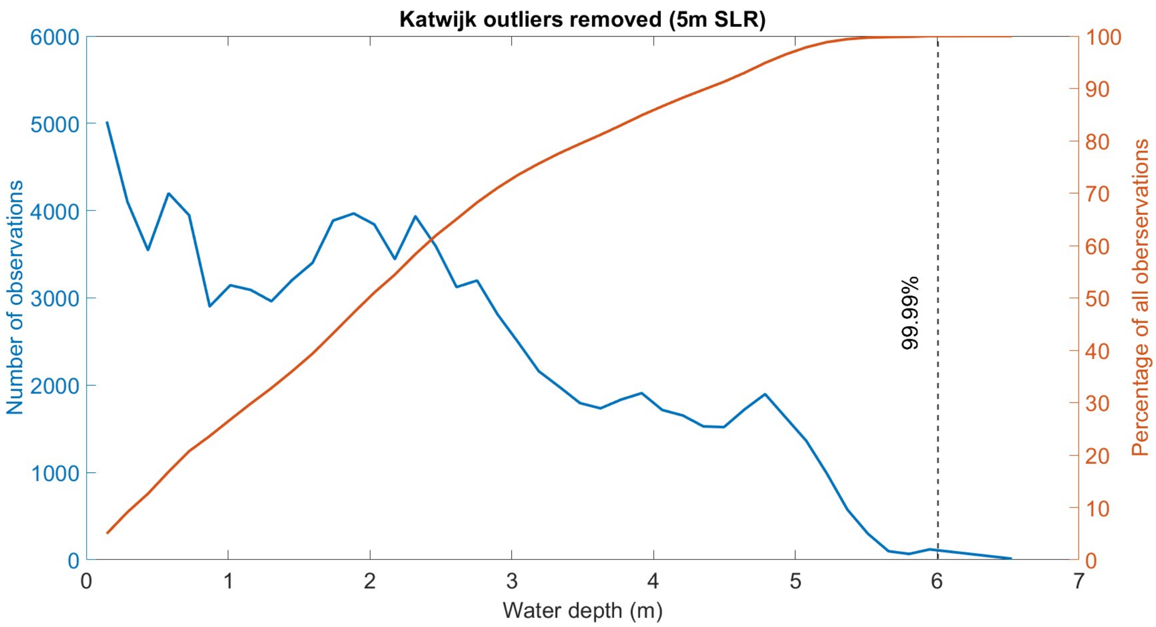


Figure 22: Water depths in the 0.1 percentile with outliers removed- Katwijk breach for 5m SLR

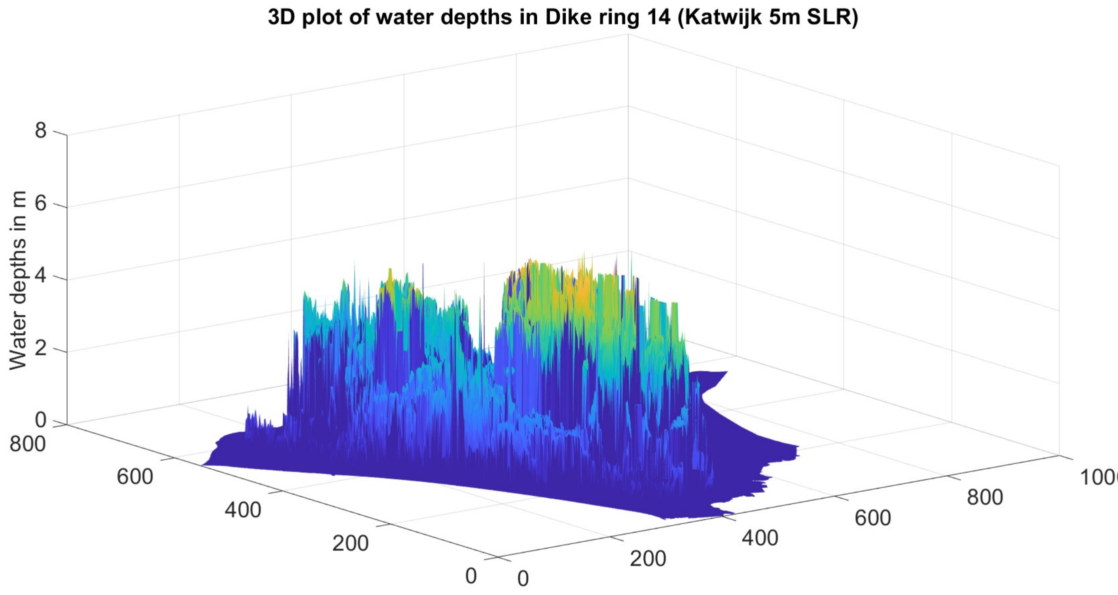
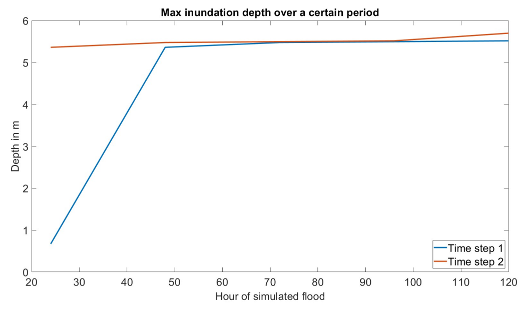


Figure 23: 3D plot of outliers removed for Katwijk 5m SLR

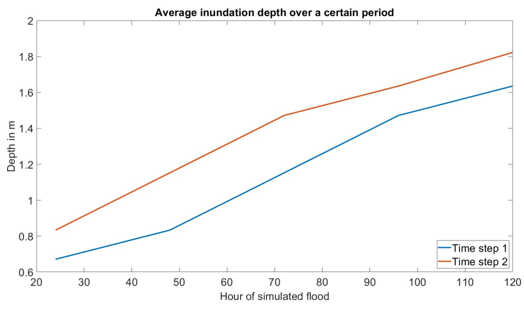
7.3.4 Run length

The final input component is the required run length. It is assumed that there is no intervention to close the breached dike, so the water discharge will only be influenced by the water level in the sea. Using the standard flooding practice [De Bruijn et al., 2018], the flood simulation should be allowed to run until an equilibrium (volume and/or area inundated) is reached (as in there is no more propagation of the flood across the terrain. It was assumed that this equilibrium would be reached at different points, for different breach scenarios. It is expected that less water will get in during a breach with no SLR when compared to that of 5m of SLR. Rather than having different run lengths for different cases, it was decided to test the worst-case scenario, that of 5m of SLR, to find this equilibrium and assume that the less severe cases would result in less inundation and thus would reach an equilibrium at the same point or earlier.

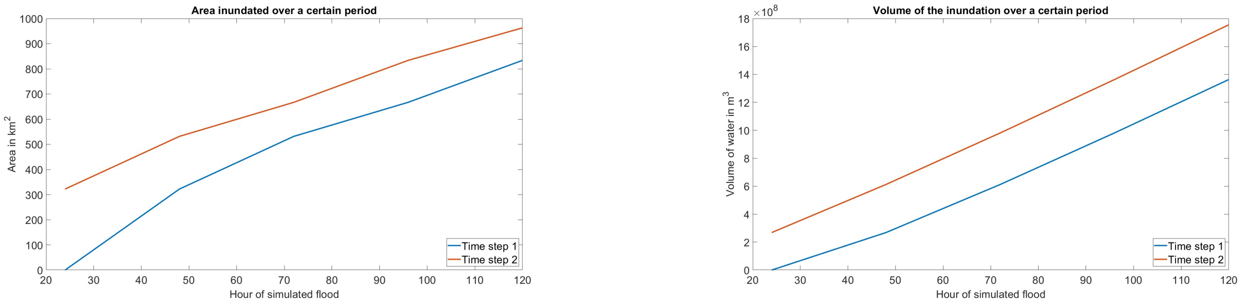
Thus, a 5m SLR breach at Katwijk was simulated for 2,3,4, and 5 days. The maximum water depth, average water depth, area inundated, and total volume of the inundation were all tested. A time step of 24 hours was used to compare the scenarios, the inundation at time zero was compared to the inundation at 24 hours, the inundation at 24 hours was compared to the inundation at 48 hours, etc. These results can be seen in Figures 24a to 25b.



(a) Max depth at each time step



(b) Average depth at each time step



(a) Area inundated at each time step

(b) Volume of inundation at each time step

For this scenario, it was found that there was no equilibrium reached within any of the tested time frames. However, as each of the tested parameters where increasing linearly, except for the max depth which did not increase linearly, it was decided to use a linear (Pearson) correlation test to compare the inundation in the same manner (0 hours with 24 hours, etc.). The correlation test was checking the actual depth of each cell, which gave an indication of both the volume and area inundated, if one cell had the same depth between two-time steps it was strongly correlated, and if one cell was not inundated at one-time step but inundated at another this would result in a low correlation score.

From this, it was seen that there is little overall difference between the two flood events after four days, with the correlation score of 3 to 4 days being 0.93 and that of 4 to 5 days being 0.94 seen in Figure 26. Given the long times required for more than 4 days of simulation, it was decided to take 4 days as the simulation time for all scenarios, despite the possible error in the final results.

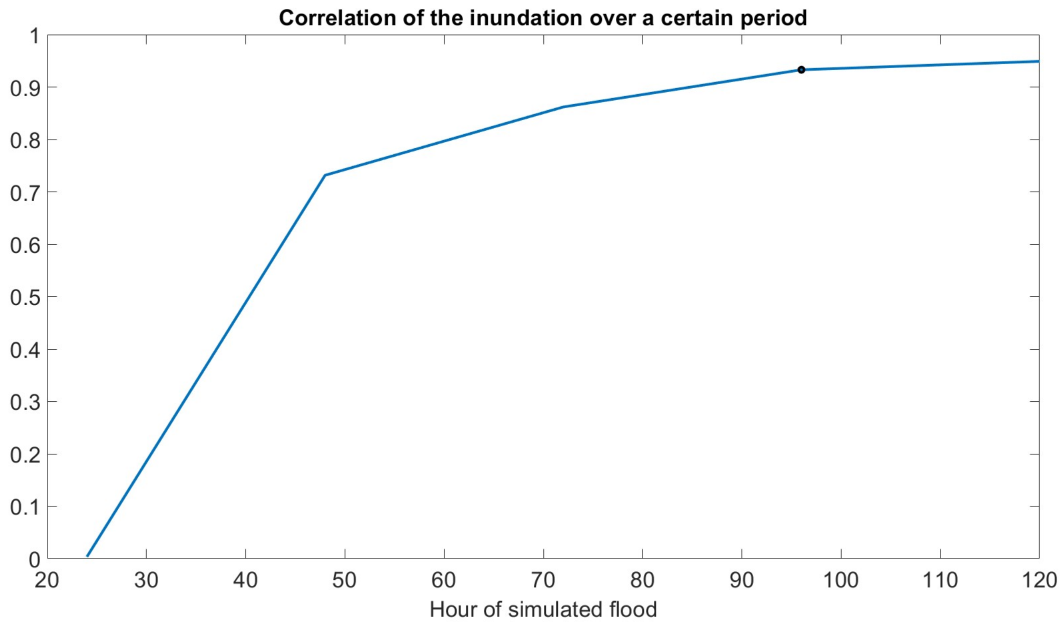


Figure 26: Correlation between the scenarios

7.4 Land-use data set

The land-use data set was generated from available open-source data [Centrall Bureau voor de Statistiek, 2017]. This file contained shapefiles representing the land-use for the whole Netherlands. A grid cell was aligned with the 100x100 Digital Elevation Map (DEM) and used to create a workable file, this process can be seen in Figure 27 below. The resulting data set contained a detailed description of the land-use, that was somewhat simplified for ease of use.

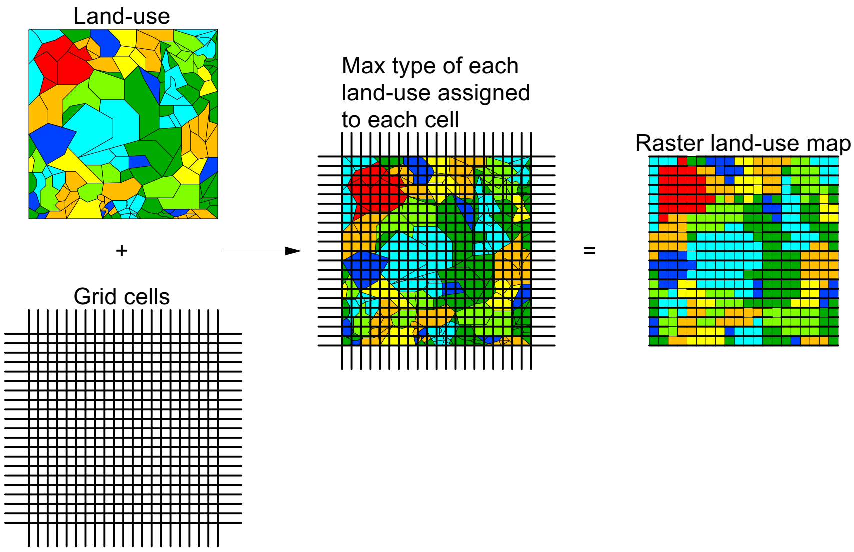


Figure 27: Land-use data set generation

The creation of this data set was validated briefly by comparing it to the SSM input data. The SSM uses many individual different maps of different land-uses. The map containing details of the industry was taken and compared to the created data set. It was found that there was an 87% similarity between the created land-use data set and the file existing in the SSM software. This is likely due to the simplifications made and potentially some changes in land-use since the creation of the SSM model. This could be greatly improved, but for the purposes of this study, this was deemed to be sufficiently accurate to give insight into the general impact of flooding in terms of land-use which will be discussed in the Results Chapter (See Chapter 8).

7.5 Validation

To validate the results of the simulation past simulations, available as open-source data, will be used [Jongejan, 2010]. The following characteristics will be investigated: the inundation pattern of the past simulations, the resulting depths, and the exposure in terms of the estimated damage and fatalities. For the majority of the past simulations, the scenarios are limited to those of more realistic SLR scenarios [Jongejan, 2010], thus only it will only be possible to compare the first few meters of SLR, as for 5m of SLR there is unlikely to be any worthwhile comparisons possible.

7.6 Model set up and assumptions

The model is an existing SOBEK model that has been used by Deltares and other municipal bodies to carry out studies into the inundation of dike ring 14 (and parts of dike ring 15 and 43). For the purposes of this study, some key assumptions have been made as to the model set-up. These can be seen in Table 2 below.

Table 2: Assumptions/demarcation

Assumption	Description
No secondary dike failures	Simplification due to time constraints, assuming that all secondary dikes are stable, even with increases of SLR.
96 hrs run length	There will be sufficient information given by this time, even if the 'equilibrium' of the inundation is not met.
Levels of Markemeer and Ijmeer kept constant	Future increases to the levels in the lakes not taken into account.
Pumping capacity increased in line with SLR	It is assumed that the pumping capacity at Ijmuiden will stay at its current levels, and increase in line with the relevant SLR.
Standard method for storm surges	The standard method of calculating the storm surges used by Deltares (and the rest of the Netherlands) will be used.
Wind effects neglected	Strong winds that are associated with storm surges will not be considered.
Rainfall neglected	Rainfall during storms are not considered.
Tidal changes with SLR neglected	Any changes to the pattern of tides due to SLR is not considered.
Vulnerability neglected	To define 'Risk' only 'Hazard' and 'Exposure' are used.
Land-use changes neglected	The future changes of land-use are not considered.
Changes in population density neglected	The future changes of population are not considered.
Any changes to elevations.	Any future subsidence is not considered.
Flooding from major rivers negected	Changes in river flows due to climate change are not considered.
0.5m of water depth highly important for fatalities	After 0.5m of water depth evacuation becomes incredibly difficult and would result in significant numbers of fatalities.
0.3m of water depth would have a huge impact on key land-uses	For residential, commercial, and key infrastructure (Schiphol, etc.) would be significantly damaged with 0.3m of water.

8 Results

To process the results the following aspects have been mapped and graphed. The extent of the inundation, the time it takes for a cell (a 100x100m square) to be inundated above 0.5m at certain time steps, the highly impacted areas in terms of land use, and the general characteristics of the inundation (max depth, the area flooded, average depth, and total volume) have been recorded.

8.1 Katwijk

8.1.1 Katwijk Inundation extent

Below can be seen the mapped flood from the Katwijk breach location. These represent the maximum depth reached for each cell, as given from the SOBEK results. These results were then mapped with GIS software. Included in the images is the boundary of the study area (the extent of the SOBEK model) indicated in red.

The results presented here are for the maximum storm scenario (where the storm surge peak coincides with the tidal peak, as discussed in Section 7). For the other scenarios see Appendix C & D.

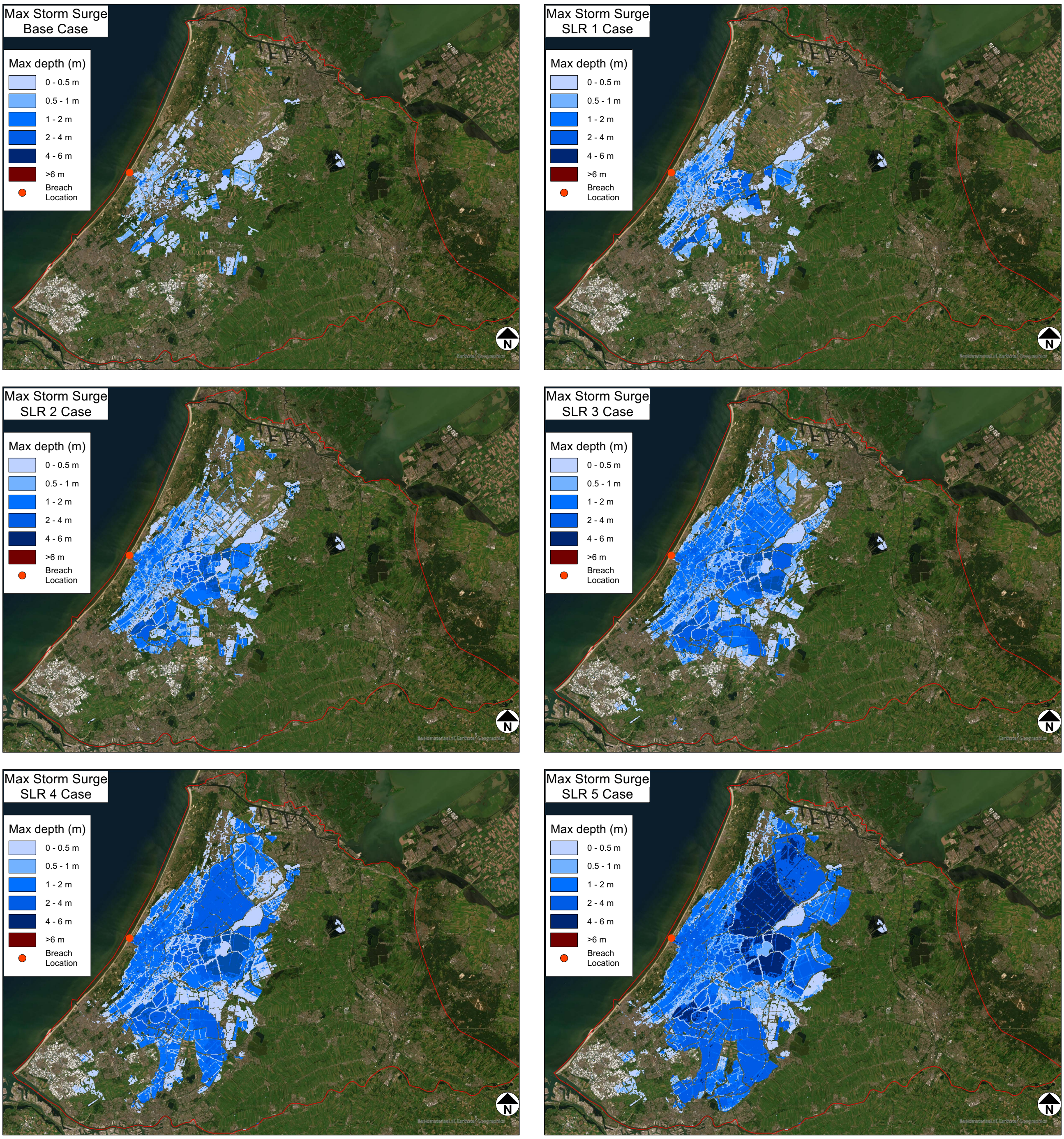


Figure 28: Breach at Katwijk with a maximum storm surge

From these maps, a significant area of the dike ring is inundated even without any SLR, and this continues to grow with each increase in SLR.

8.1.2 Katwijk Arrival times

The time in which an area reaches a depth over 0.5 m can be seen below. This 0.5 m was assumed to represent a scenario where evacuation or other emergency responses would become very restricted.

The scenario mapped here is again the maximum storm scenario, for the other scenario results see Appendix C & D.

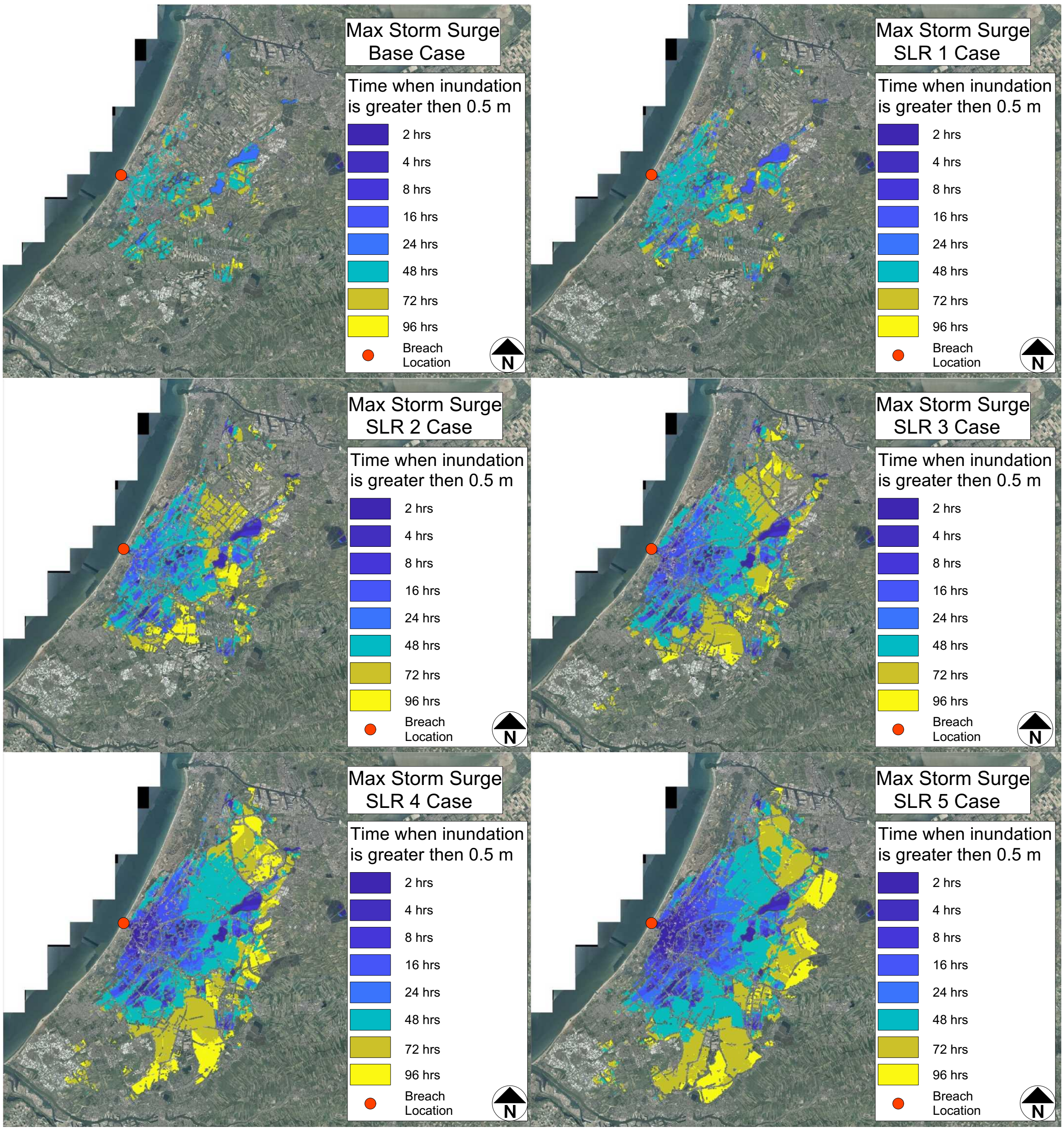


Figure 29: Time till areas are inundated to a depth of 0.5m from a breach at Katwijk with a maximum storm surge

8.1.3 Katwijk Land-use impact

Using the created land-use data set, as described in Section 7, the highly valuable areas that are flooded above 0.3m are mapped. These areas are Residential areas, commercial areas, and infrastructure such as major roads or Schiphol airport. It was assumed that 0.3m of water would render these areas non-operational in terms of the infrastructure, and result in huge damages in the case of residential and commercial areas.

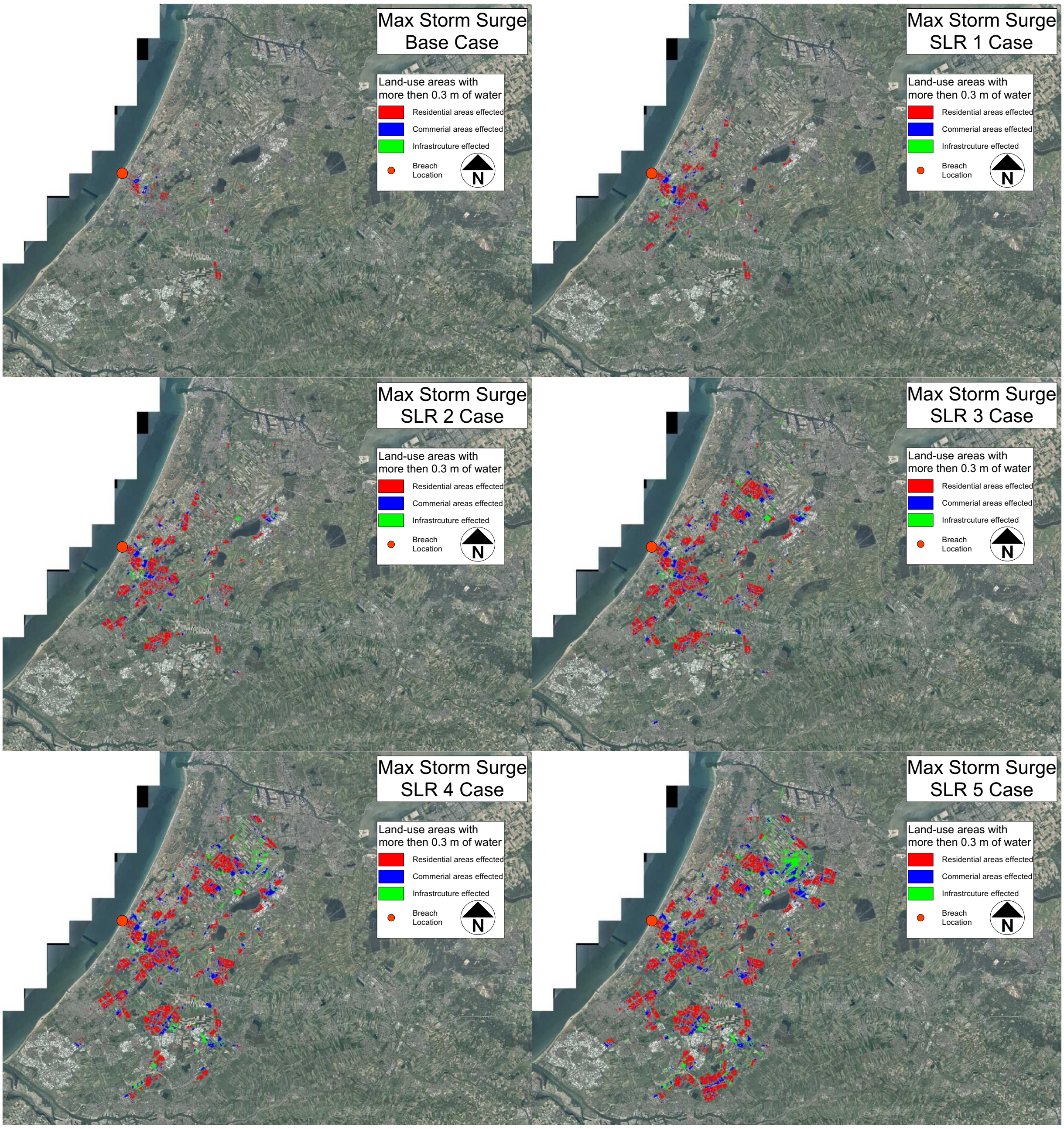


Figure 30: Effect on land-use areas from a breach at Katwijk with a maximum storm surge

8.1.4 Katwijk Inundation characteristics

In Figure 31 below, the inundation characteristics can be seen. Indicated in each graph is the actual measured trait in blue, and in red the relative change of the trait. For example, the max depth resulting from a breach at Katwijk with an SLR of 1m is 4.9m, and with no SLR it is 3.7m. Hence, the absolute increase of the maximum depth is 1.25m, which is what is shown in red.

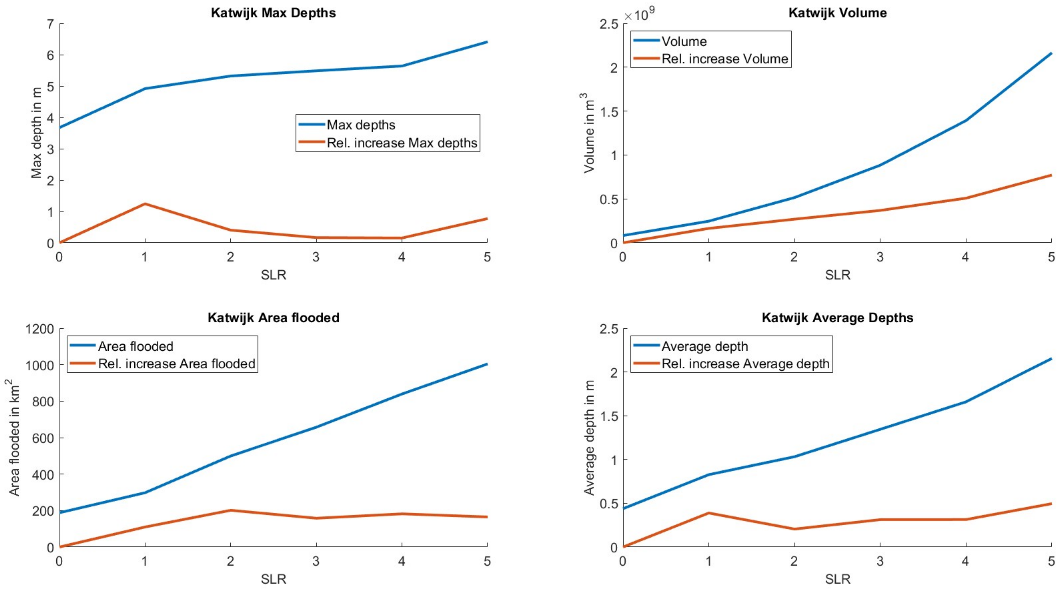


Figure 31: Inundation characteristics from a breach at Katwijk with SLR of 0-5m

8.1.5 Katwijk Damage

Using the SSM model the damage was calculated by using the max depth file from SOBEK. The resulting damage can be seen in Figure 32 below. In the top plot, the total damage from each SLR scenario can be seen in blue, and the relative damage from the different SLR scenarios can be seen indicated in red. For example, the total damage at the base case (no sea level rise) is approximately €3.6 billion, and at 1m SLR, the damage is approximately €12 billion hence the actual increase is €8.4 billion, which is what is plotted in red.

In the second plot, the rate of change can be seen. Again using the example of the base scenario to the 1m SLR scenario, it can be seen that with a SLR of 1m the damage increases by a factor of approximately 2.3. Thus, the largest relative difference in damage can be seen at lower SLR scenarios, despite the increase in damage for subsequent SLR scenarios.

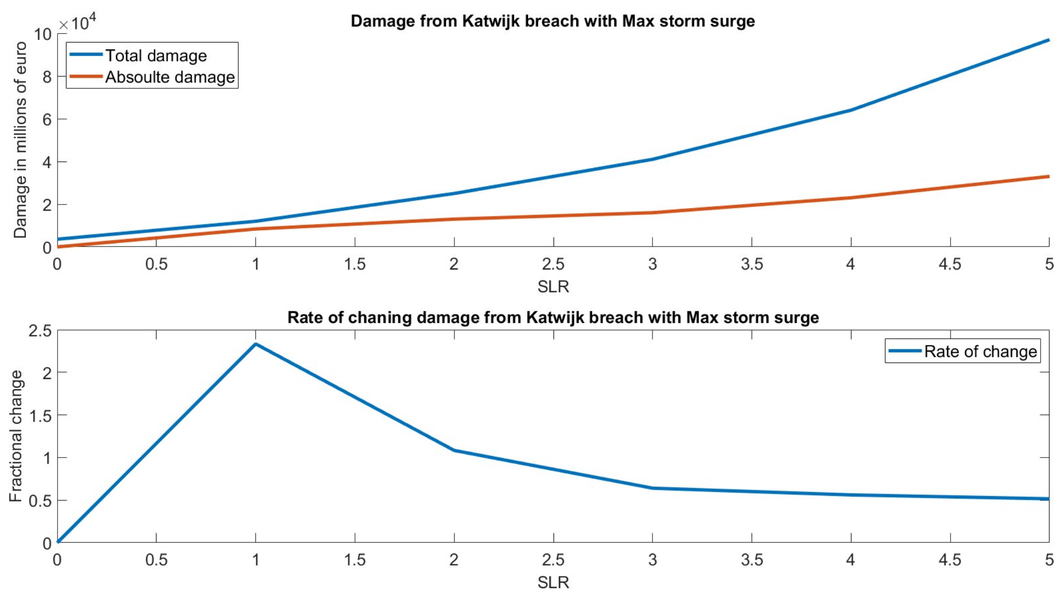


Figure 32: Katwijk Damage from maximum storm surge with SLR of 0-5m

8.1.6 Katwijk fatalities

Using the SSM model the fatalities for this flood scenario were estimated. This can be seen in Figure 33 below, where the same method as graphing the damage has been used, with the actual fatalities in blue, the change from each scenario in red, and the rate that it changes in the lower plot.

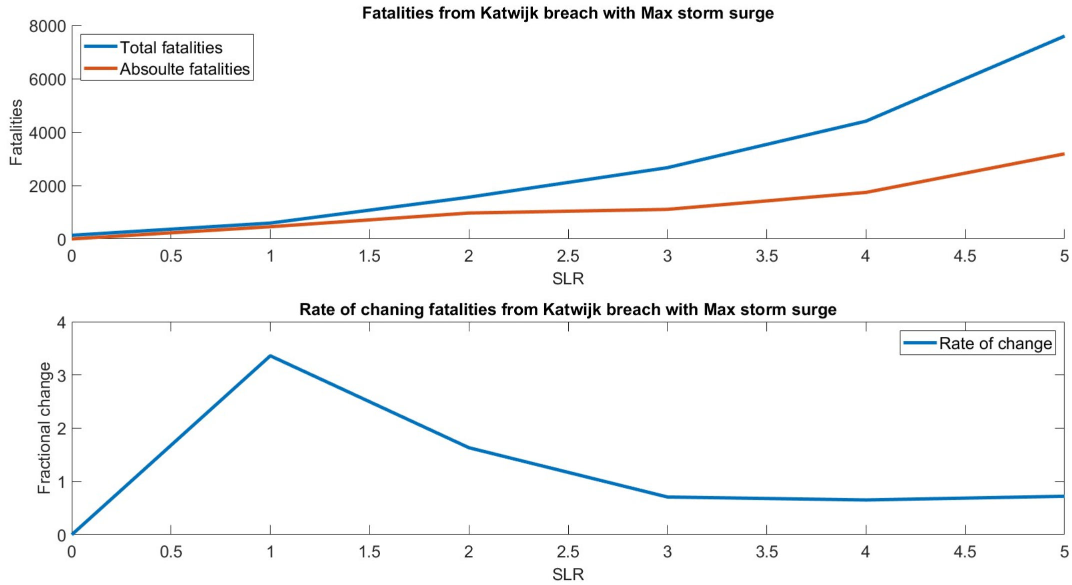


Figure 33: Katwijk fatalities from maximum storm surge with SLR of 0-5m

The graphs show a very similar pattern as with the damage, with the initial 1m of SLR resulting in a sudden increase in fatalities.

8.2 The Hague

8.2.1 The Hague Inundation extent

Following the procedure stated for Katwijk, the inundation maps for a breach at The Hague can be seen in Figure 34. This Figure shows the maximum storm surge.

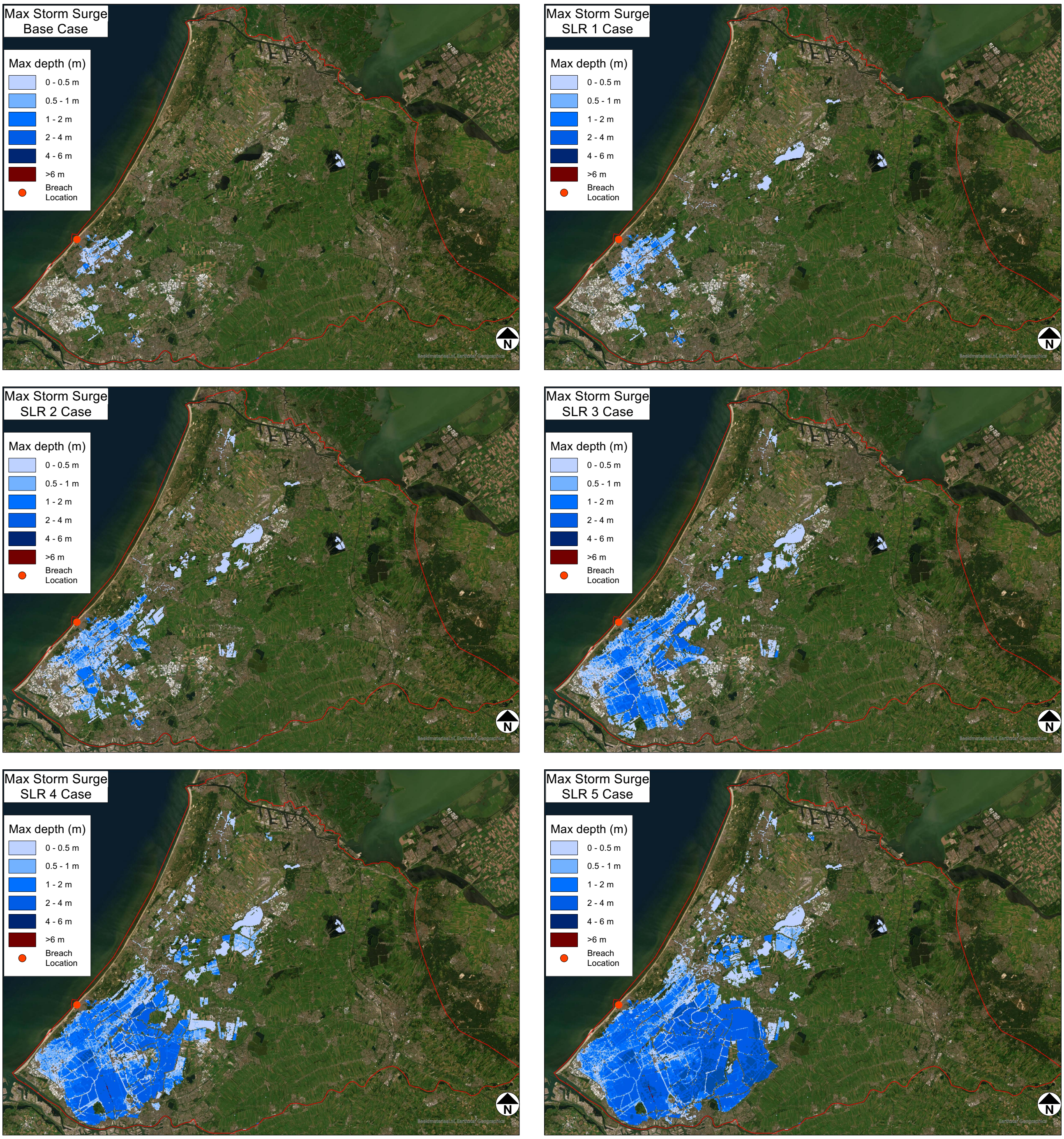


Figure 34: Breach at The Hague with a maximum storm surge

The results of these simulations show that there is a clear increase in the depths and areas affected for each meter of SLR, starting from very little inundation at present levels, to the vast majority of the southern dike ring being inundated with 5m of SLR. Additionally, it is clear that the central section of The Hague will be significantly affected by even 1m of SLR, given changes in elevation which is relevantly high close to the dunes and breach location, compared to the central sections of The Hague which is lower.

8.2.2 The Hague Arrival times

Assuming that a 0.5m water depth proves problematic for evacuation, and other emergency responses (as with Katwijk) the time in which this occurs for each SLR scenario is mapped in Figure 35. The maximum storm surge is used here.

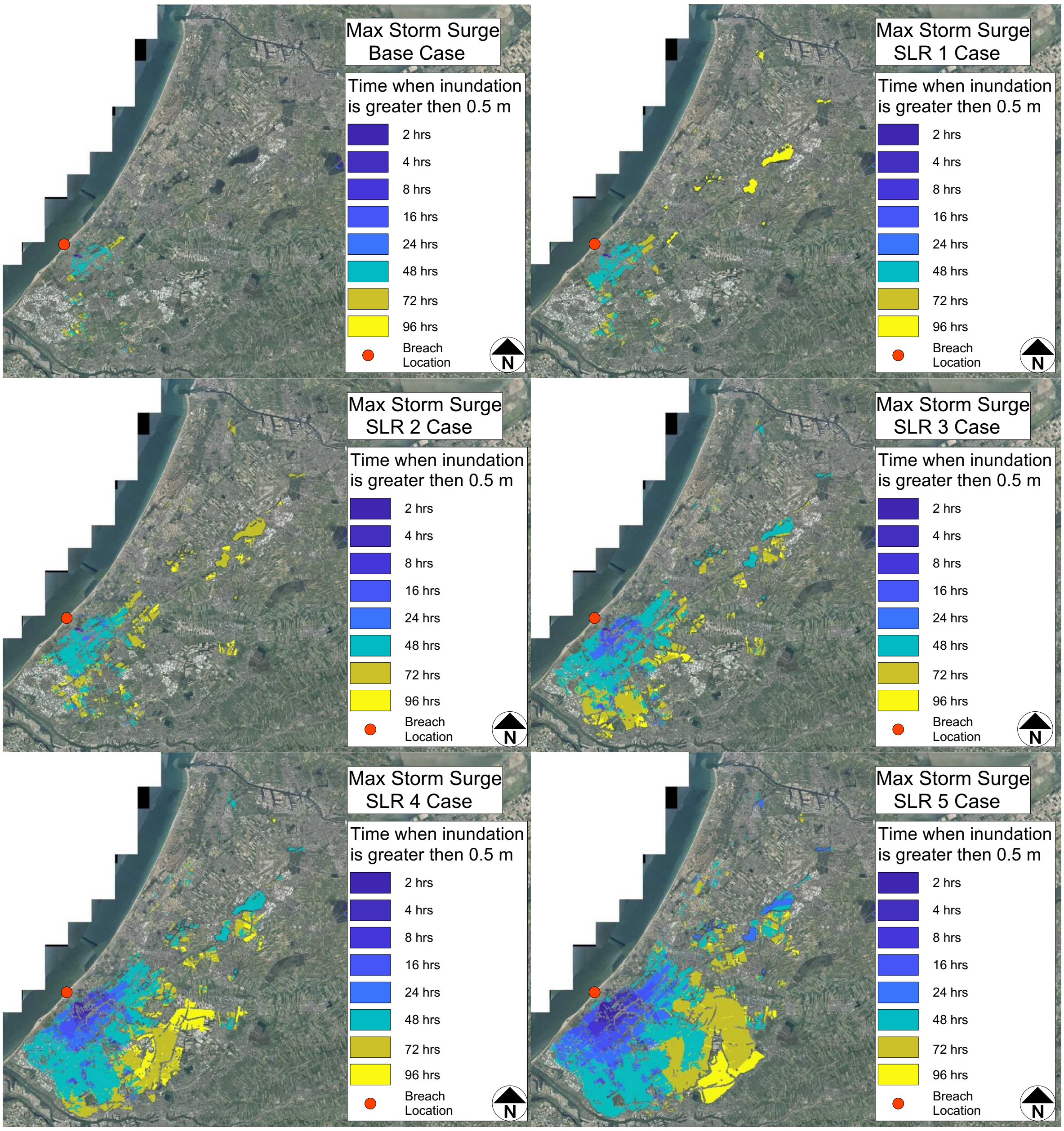


Figure 35: Time till areas are inundated to a depth of 0.5m from a breach at The Hague with a maximum storm surge

As stated above the elevation changes from the dunes to The Hague means that very quickly the centre of the city is inundated. However, the water does not rest here and continues into the dike ring. This can be seen as despite the centre being inundated with 1m of SLR (See Figure 34 it is not until 4m of SLR that significant amounts of the centre (where the highest population is assumed to be) are inundated by more than 0.5m within 8 hours.

8.2.3 The Hague Land-use impact

Using the created land-use data set, the effects of a breach at The Hague can be seen in Figure 36 below. The maximum storm surge is presented here.

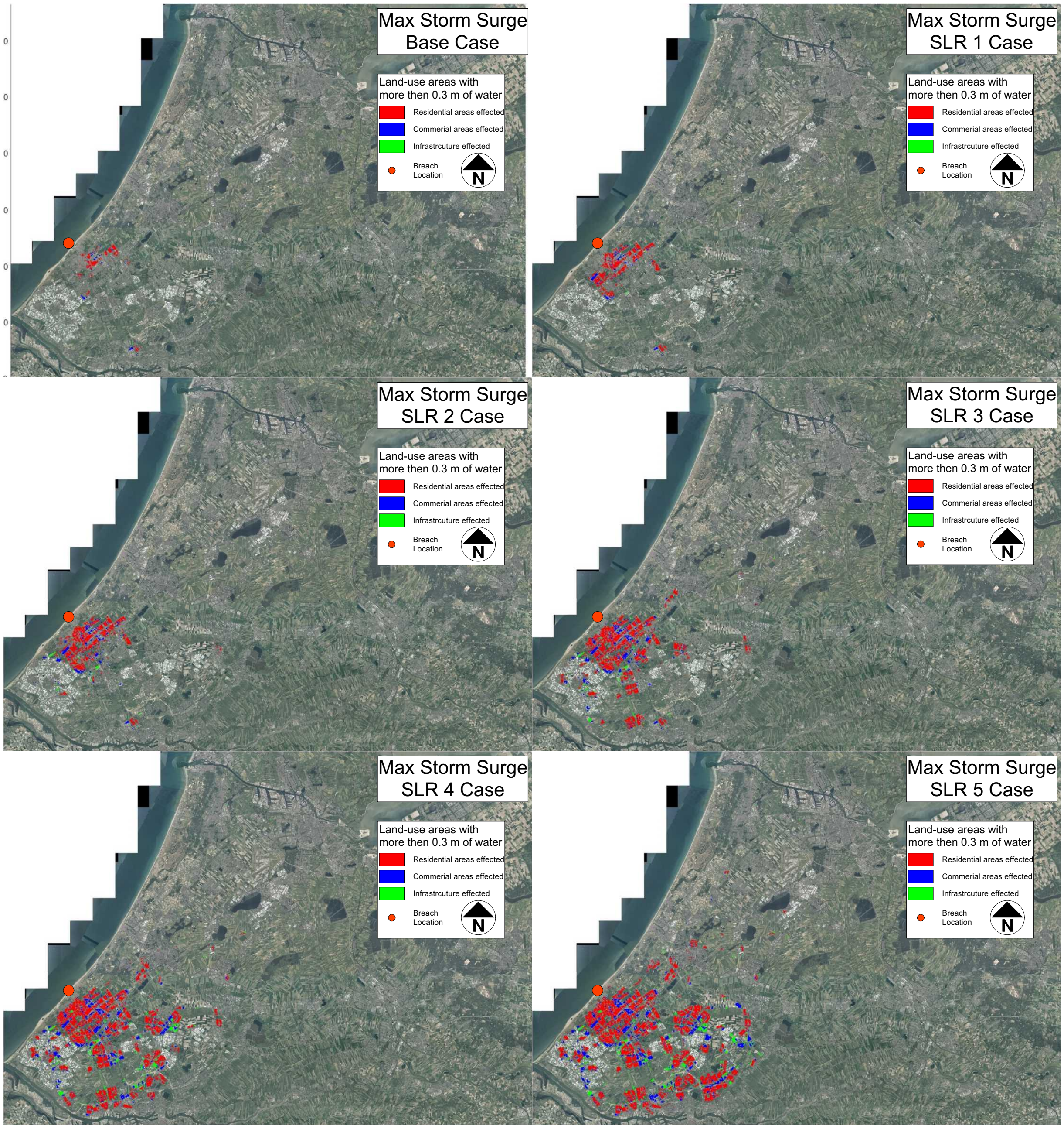


Figure 36: Breach at The Hague with a maximum storm surge

From these maps, it can be seen that there is significant damage done to residential areas in The Hague from 1m of SLR, and this increases significantly with each meter of SLR. This can be seen by the dense red areas indicated in the maps, which show the residential areas with inundation of more than 0.3m.

This damage will begin to impact Rotterdam after 3m of SLR, with 5m of SLR causing large damages to the suburban area around Rotterdam, with only the centre of Rotterdam being largely unaffected.

8.2.4 The Hague Inundation characteristics

The pattern seen in the flood maps (See Figure 34) can be seen with the graphs in Figure 37 below. Like the graphs of Katwijk, these graphs show the characteristics of the flood in blue and their relative increase in red.

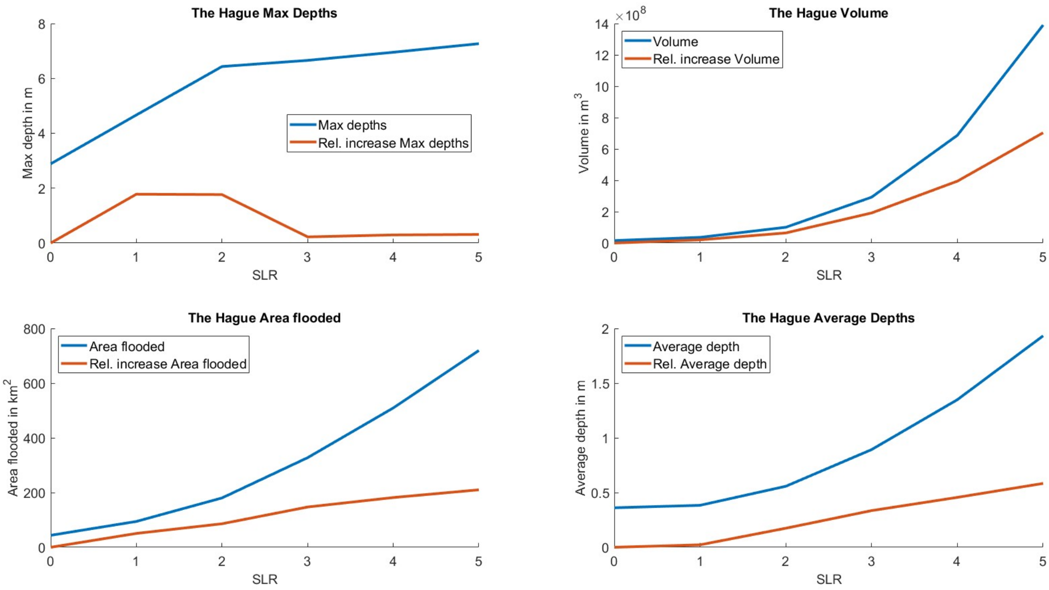


Figure 37: Inundation characteristics from a breach at the Hague with SLR of 0-5m

The increasing trend of the inundation is seen in the exponential increase of volume, and relatively more linear increase of the area flooded and the average depth.

8.2.5 The Hague Damage

The damage calculated with the maximum depths of each cell in the SSM model can be seen in Figure 38 below. This shows a linear increase of damage, with blue showing the damage and red the absolute increase of damage from each SLR scenario.

In the second plot, the rate increase of the damage is shown. This is however skewed due to the low amounts of damage that occur with no SLR, €55’000, followed by €1.2 billion for SLR of 1m, and €20 billion for SLR of 2m. Hence, it is difficult to see the rate that the damage increase for the increasing SLR scenarios.

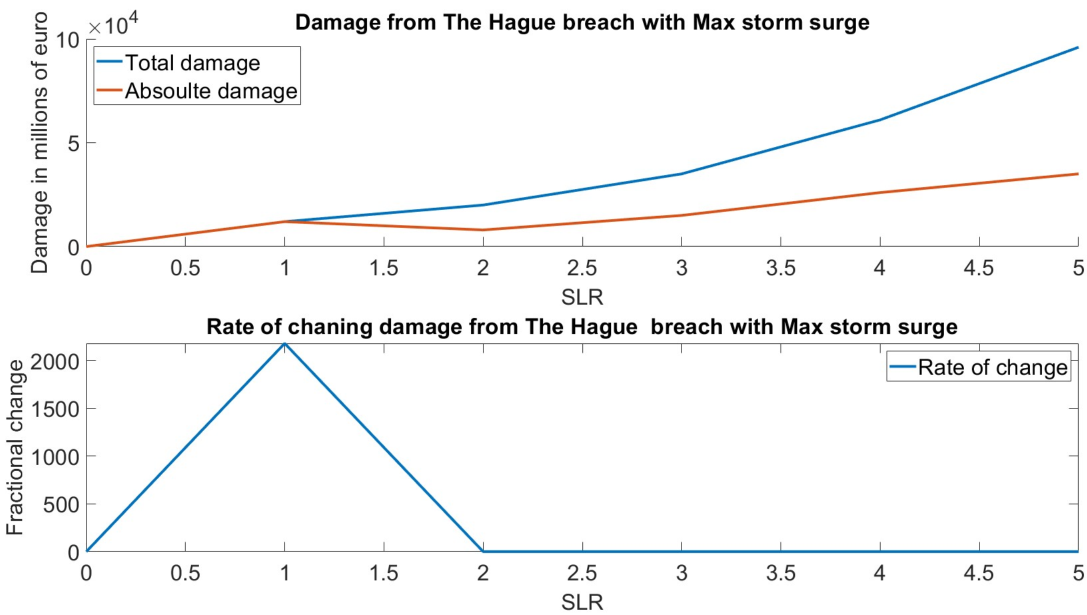


Figure 38: The Hague Damage from maximum storm surge with SLR of 0-5m

8.2.6 The Hague fatalities

The fatalities resulting from a breach at the Hague with a maximum storm surge can be seen in Figure 39 below. The top plot shows the total fatalities and the absolute increase of fatalities for each increase in SLR.

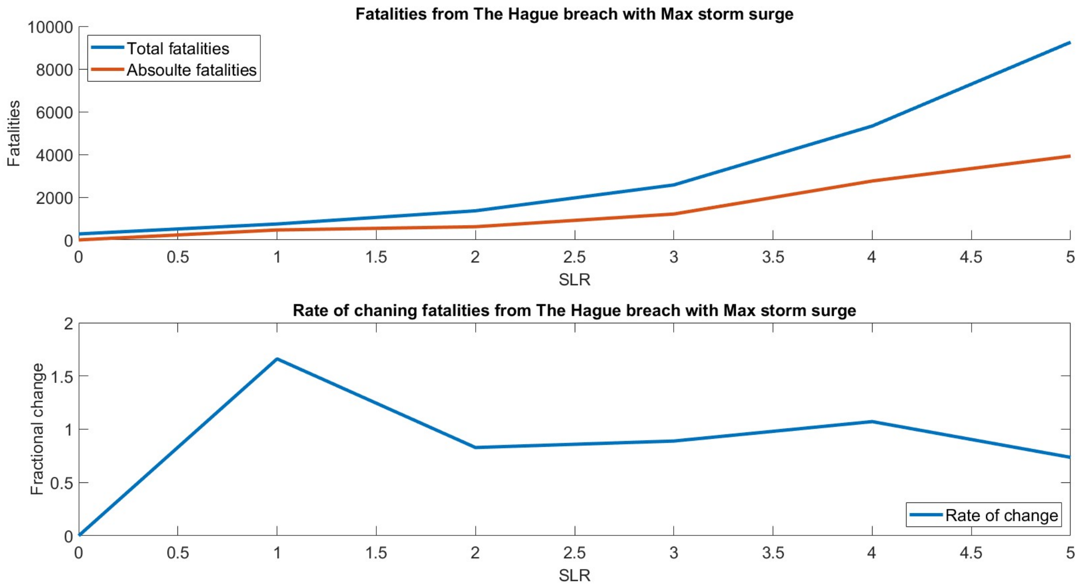


Figure 39: The Hague fatalities from maximum storm surge with SLR of 0-5m

From this figure, the increase in fatalities can be seen to be very dependent on the level of SLR with a large increase from 1 to 2m of SLR, and an increase but at a lesser rate until 4m of SLR.

8.3 IJmuiden

8.3.1 IJmuiden Inundation extent

The flood that results from a breach at the locks of IJmuiden is seen in Figure 40 below. As discussed in Chapter 7 the pumping system located at IJmuiden was assumed to still retain the same capabilities in the increasing SLR scenarios. This was assumed to allow for a realistic scenario, rather than assuming that the pumps would become completely obsolete with a higher sea level. Additionally, as also stated in Chapter 7 there are no secondary dike breaches along the Noordzeekanaal and the levels of the Markemeer and IJmeer remain the same. The maximum storm surge scenario is presented here.

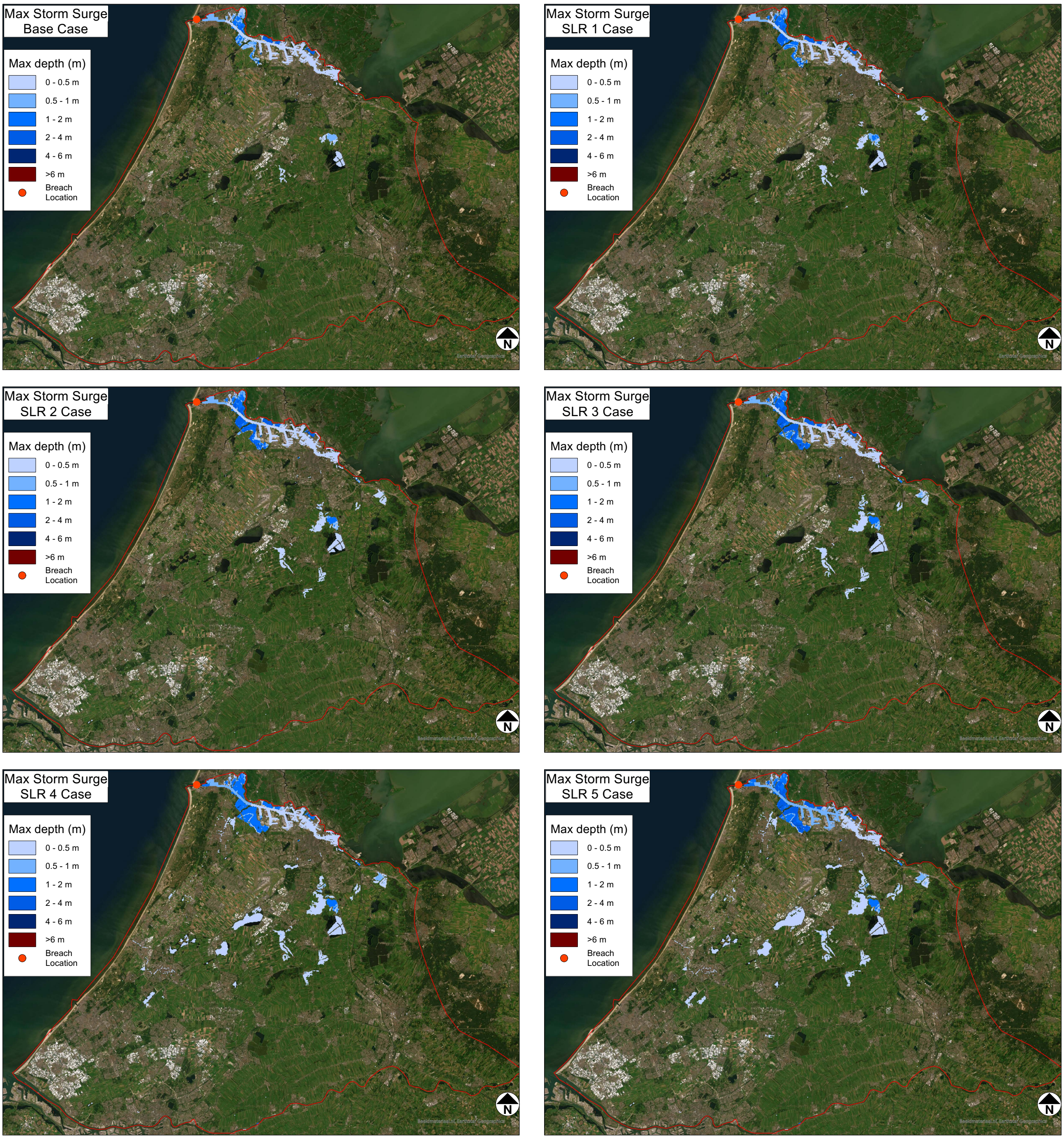


Figure 40: Flood resulting from a breach at IJmuiden with a maximum storm surge

These maps show that the flooding as a result of the breach at IJmuiden is largely contained along the Noordzeelanaal and the increases are minimal, as the largest extent of the inundation in the extreme SLR scenarios is contained within the water bodies in dike ring 14.

8.3.2 IJmuiden Arrival times

With the same procedure as for Katwijk, and the Hague the time until 0.5m of inundation has been mapped. This can be seen in Figure 40 below.

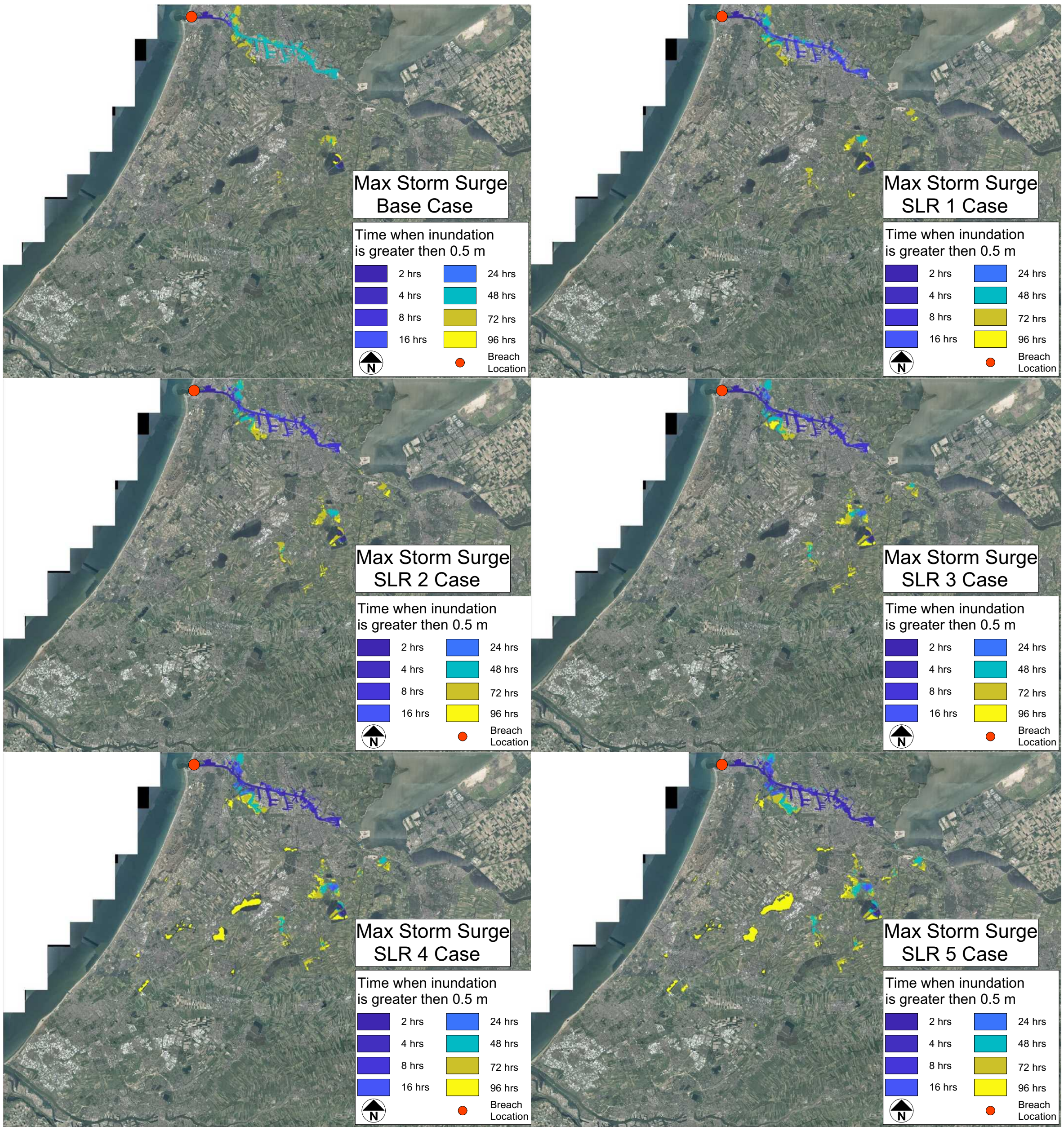


Figure 41: Time till areas are inundated to a depth of 0.5m from a breach at IJmuiden with a maximum storm surge

From the figure, it can be seen that the deepest inundation is mostly contained in the Noordzeekanaal.

8.3.3 IJmuiden Land-use impact

With the land-use data set, the high-impact locations from the resulting breach can be seen in Figure 42.

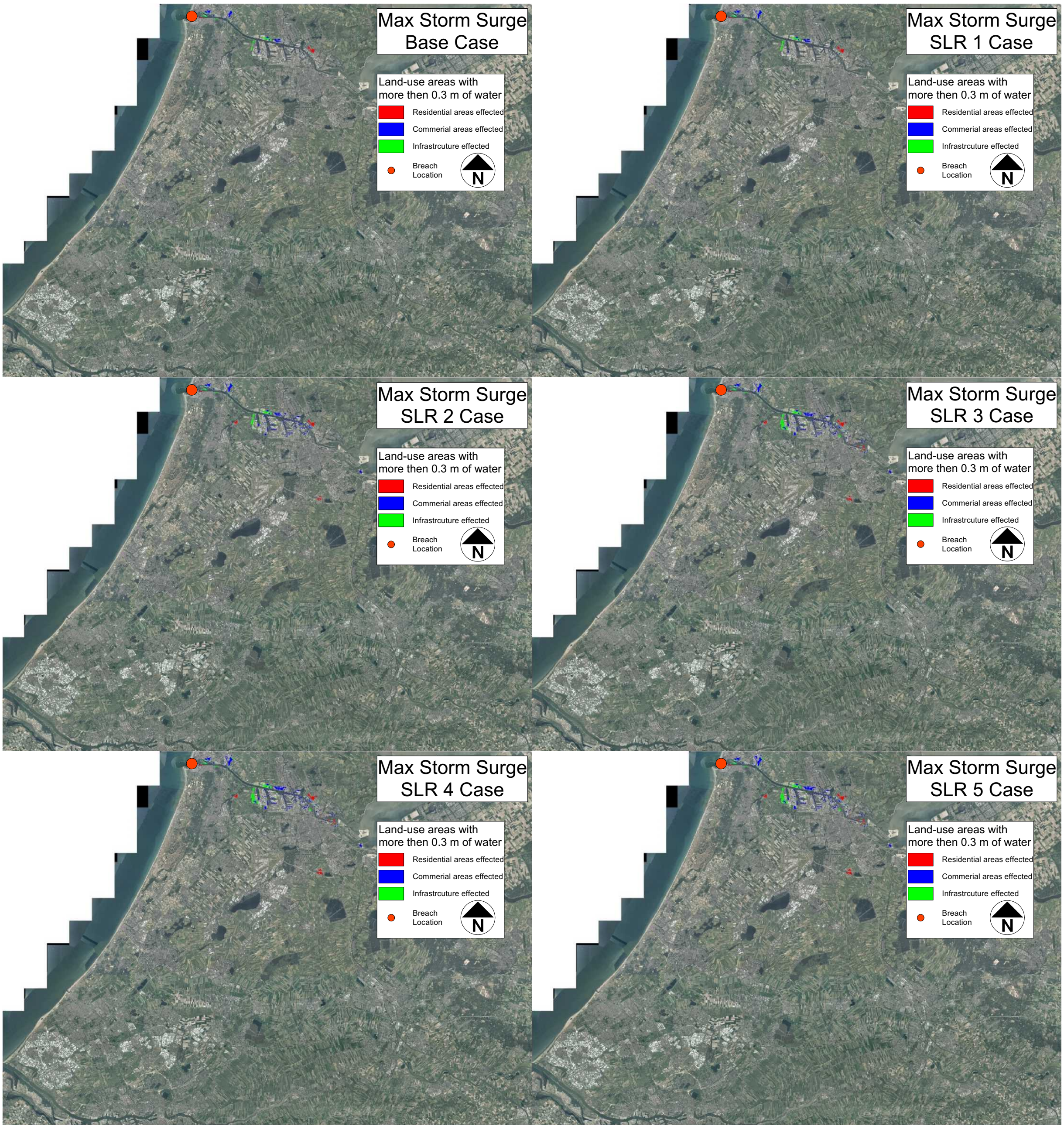


Figure 42: Key land-use areas inundation depth of 0.3m or more from a breach at The Hague with a maximum storm surge

There is not a significant impact on the area, relative to the damage done from Katwijk and the Hague. However, there is a significant area in Westpoort that has been affected.

8.3.4 IJmuiden Inundation characteristics

The inundation characteristics of the IJmuiden breach can be seen in Figure 43. The measured characteristic is given in blue and the absolute increase between scenarios is given in blue.

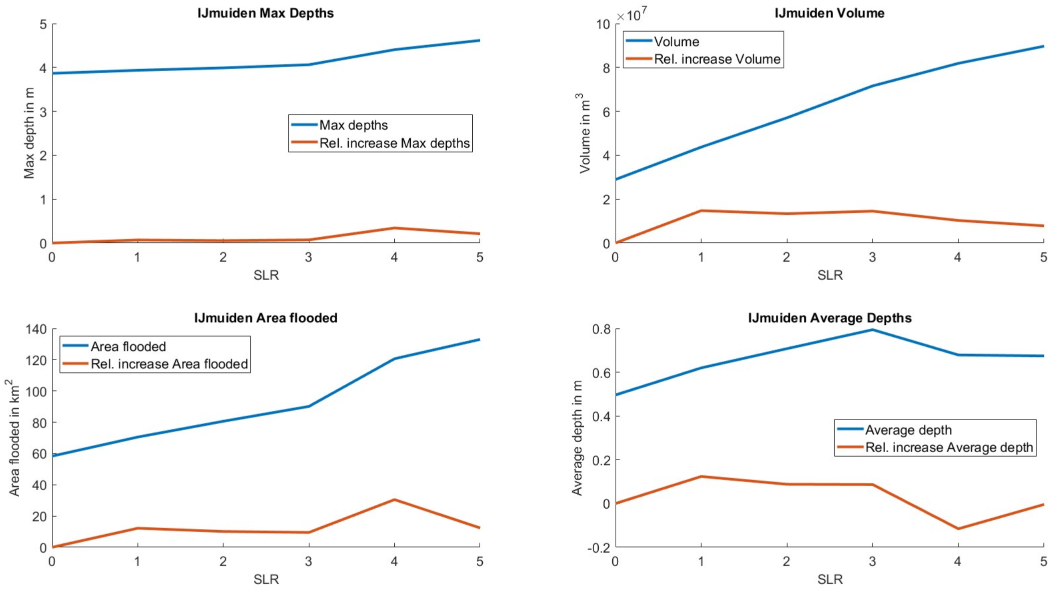


Figure 43: IJmuiden Inundation characteristics from a breach at IJmuiden with SLR of 0-5m

As the changes to the area flooded, volume and depths are minimal, the inundation can be said to be relativity contained, as also seen in the flood maps (See Figure 40). The lack of changes to the max depths is caused by a low-lying polder south of Zaandam which is completely flooded even with no sea level rise.

8.3.5 IJmuiden Damage

The resulting damage is still significant, being €1.3 billion for no SLR and €3.4 billion for 5m of SLR.

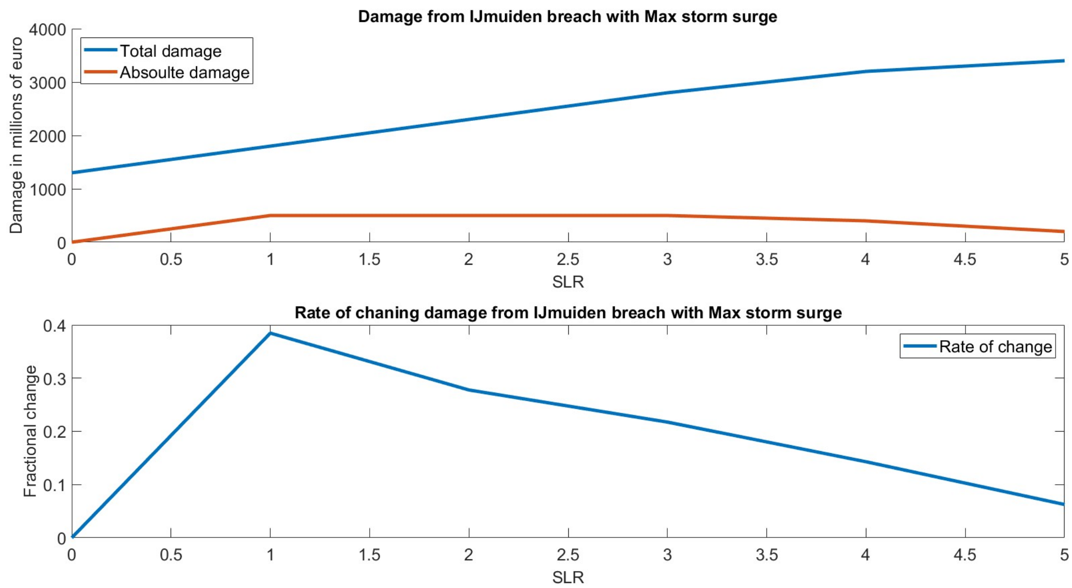


Figure 44: IJmuiden Damage from maximum storm surge with SLR of 0-5m

The assumptions made for IJmuiden, the pumps being as efficient for 5m of SLR as for the current case, and the Markemeer and Ijmeer remaining at the same levels have a significant impact on the scale of the inundation. Particularly given that Amsterdam remains largely unaffected in all scenarios. It is likely that changes to the Markemeer and Ijmeer that would be expected in future SLR scenarios such as rising their levels would mean there would be less discharge going from the Noordzeekanaal to the lakes. This could result in a larger area of effect and greatly impact Amsterdam.

Additionally, it was discovered that many of the tunnels under the Noordzeekanaal were not included as 1D elements in the model. However, they were identified with the elevation data, as being low points that correspond to the mouth of these tunnels. This resulted in many localised areas of deep inundation at the mouth of these tunnels (which were treated as outliers, and hence removed as stated in Chapter 7). In reality, if modelled as 1D elements, it is possible that they would flood and result in flooding that bypasses the secondary dikes into dike ring 14.

8.3.6 IJmuiden fatalities

The fatalities that result from a breach at IJmuiden can be seen in Figure 45 below where the total fatalities are shown in blue and the absolute increase of fatalities from each SLR scenario is given in red. The bottom plot shows the rate at which these change. The rate shows that for IJmuiden there is little rapid increase in the fatalities due to SLR.

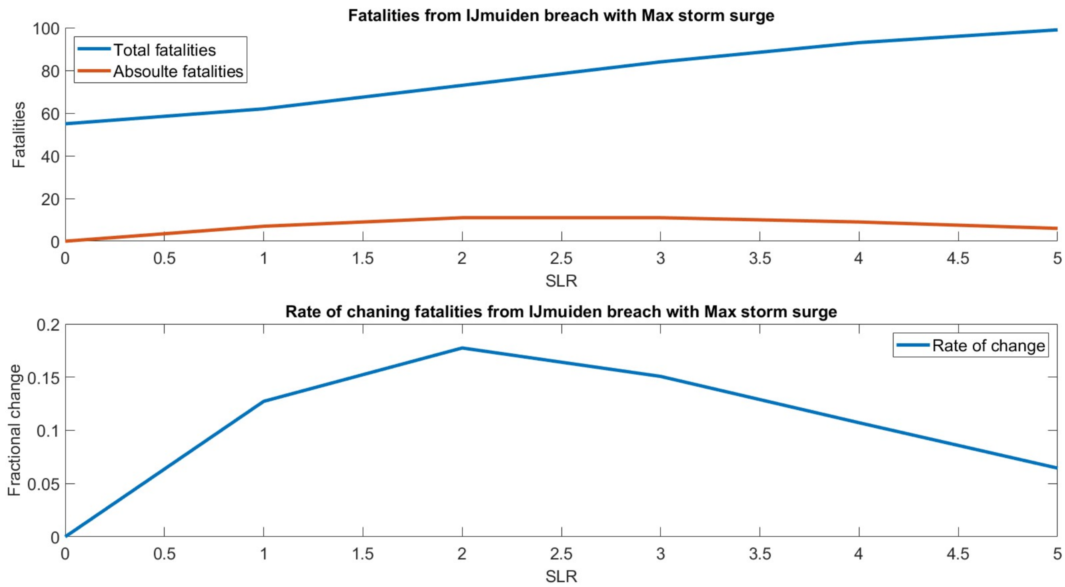


Figure 45: IJmuiden fatalities from maximum storm surge with SLR of 0-5m

8.4 Hook of Holland

The results of the simulation of a breach at Hook of Holland are presented here. The scenario is a maximum storm event. Of note for the breach at Hook of Holland is that it is more sensitive to the timing of the storm surge, unlike the other breach locations. For the other locations in all cases the maximum storm surge results in worse consequences for all SLR scenarios. However, for Hook of Holland, a SLR scenario of 3m is worse for an average storm event (See Section 7) but for 5m of SLR the maximum storm surge is again worse. The scenarios of no storm surge and the average storm surge can be seen in Appexdix C & Appexdix D.

8.5 Hook of Holland Inundation extent

Figure 46 below shows the extent of the inundation.

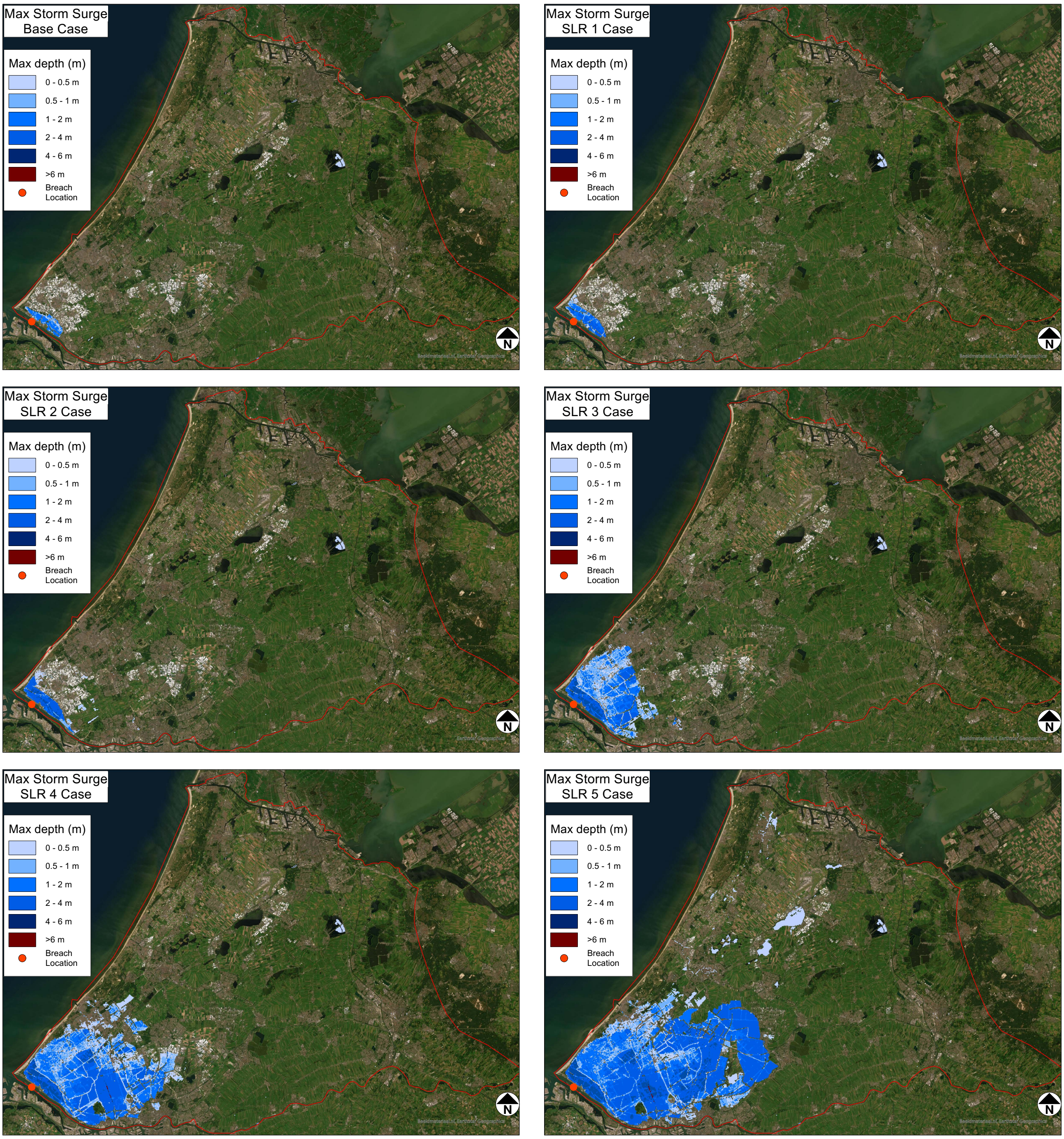


Figure 46: Breach at Hook of Holland with a maximum storm surge

8.6 Hook of Holland Arrival times

Figure 47 below shows the time at which areas are inundated above 0.5m.

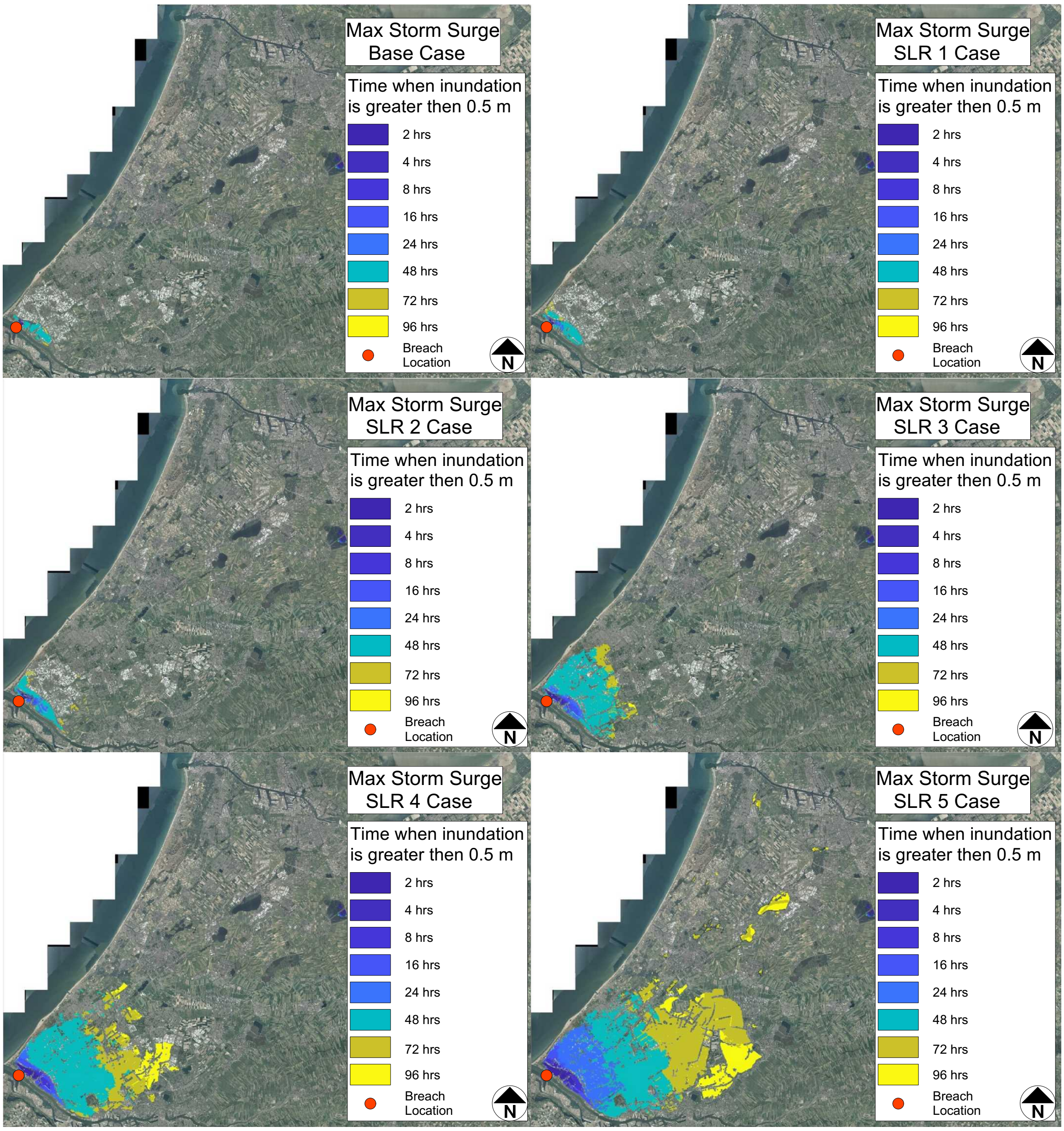


Figure 47: Time till areas are inundated to a depth of 0.5m from a breach at Hook of Holland with a maximum storm surge

8.7 Hook of Holland Land-use impact

Figure 48 below shows the areas most affected by the inundation.

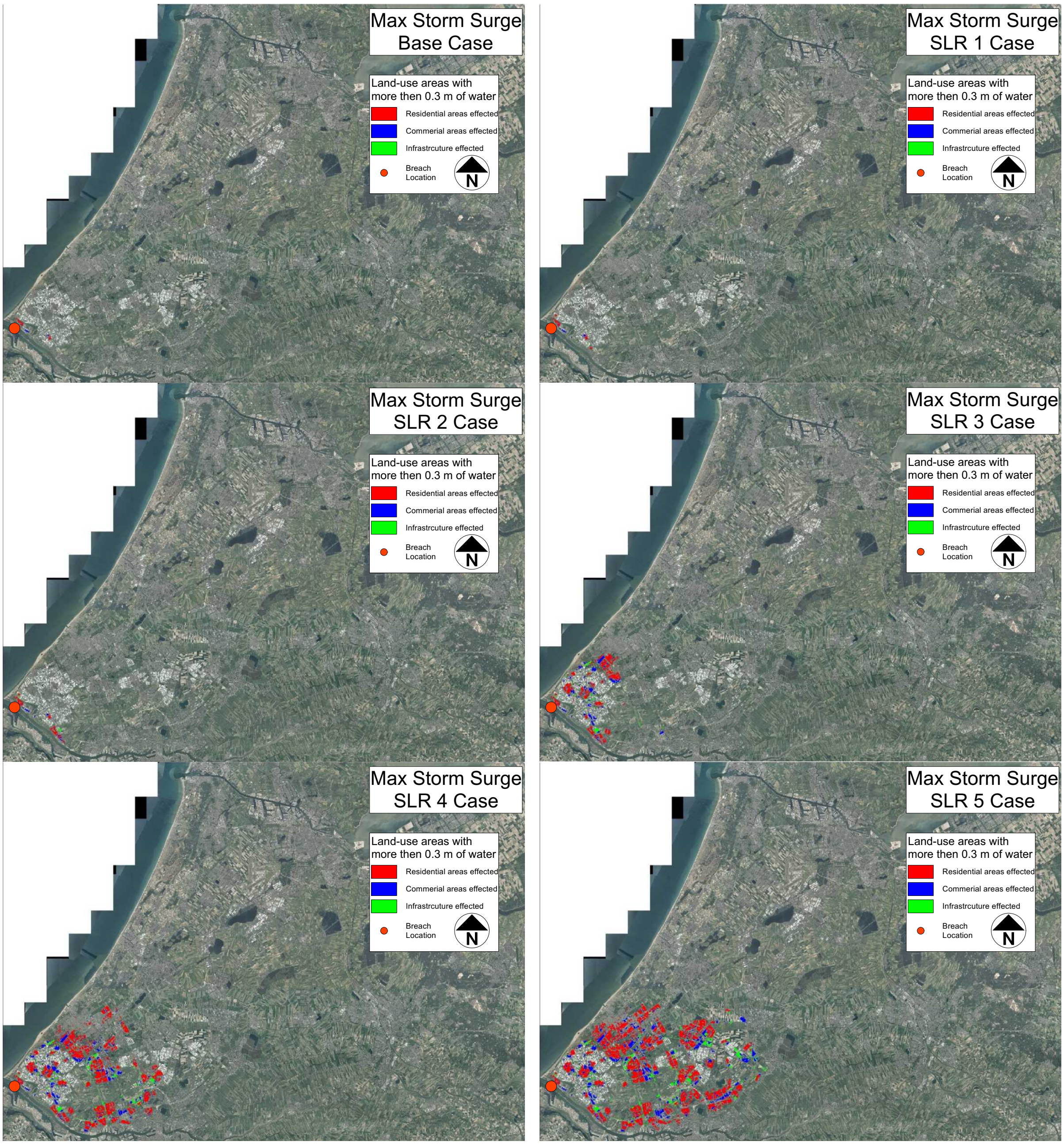


Figure 48: Effect on land-use areas from a breach at Hook of Holland with a maximum storm surge

8.8 Hook of Holland Inundation characteristics

Figure 49 below shows the foundation characteristics. The breach at Hook of Holland has a unique situation where a large secondary dike (Maasdijk) lies in very close proximity to the breach location. This secondary dike stops the inundation from spreading like for Katwijk and the Hague and is only overtopped after 3m of SLR. The result of this is a sudden increase in the area inundated and a sudden decrease in the average inundation depth after this point. This can be seen in Figure 49.

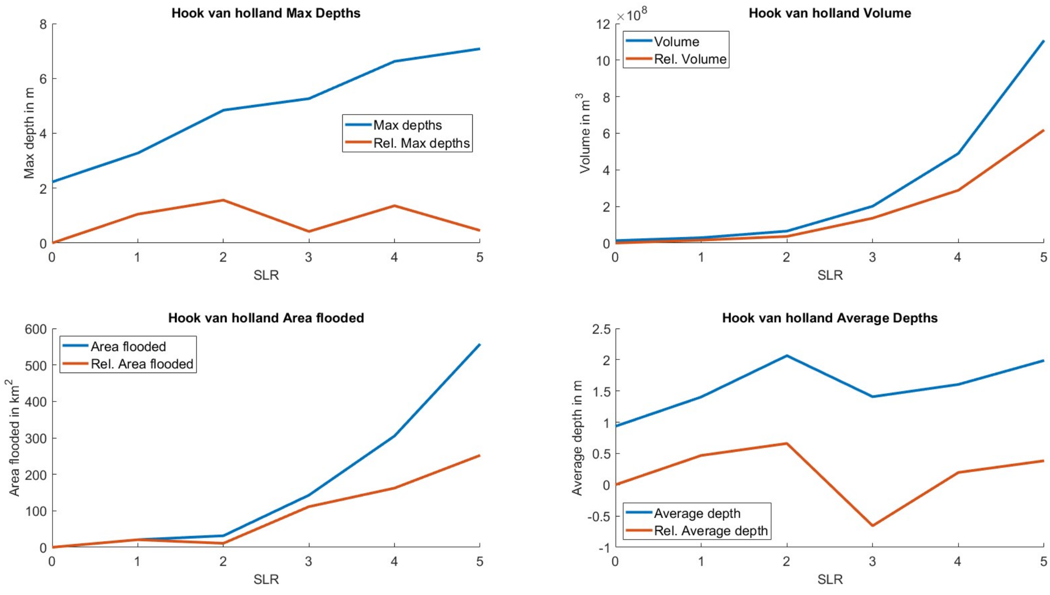


Figure 49: Inundation characteristics from a breach at Hook of Holland with SLR of 0-5m

8.8.1 Hook of Holland Damage

As with the inundation characteristics suddenly increasing after 3m of SLR, the damage follows from the same consequence (the secondary dike being overtopped). The resulting damages can be seen in Figure 50 below.

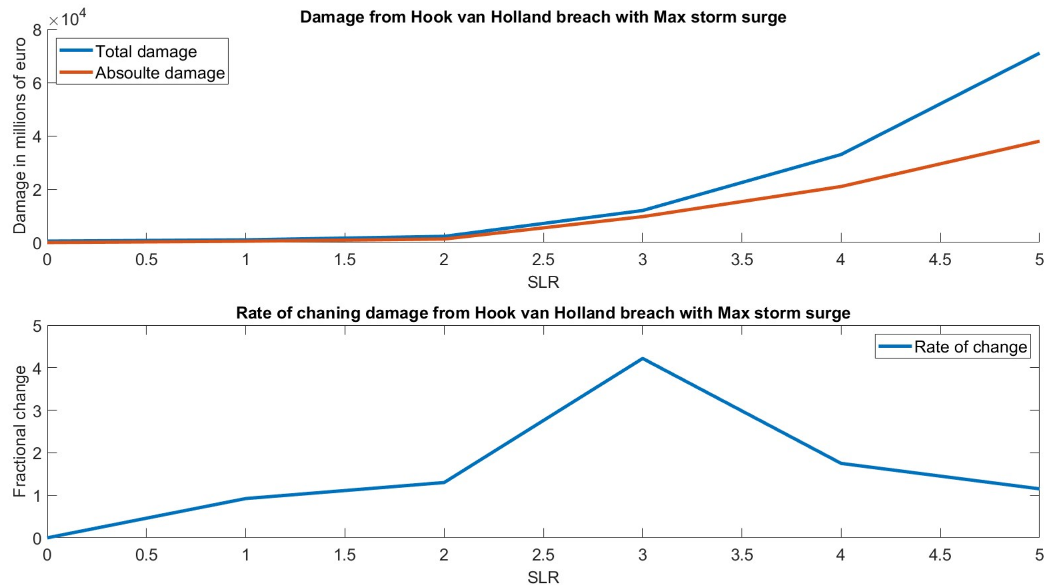


Figure 50: Hook of Holland Damage from maximum storm surge with SLR of 0-5m

8.8.2 Hook of Holland fatalities

The resulting fatalities can be seen in Figure 51 below.

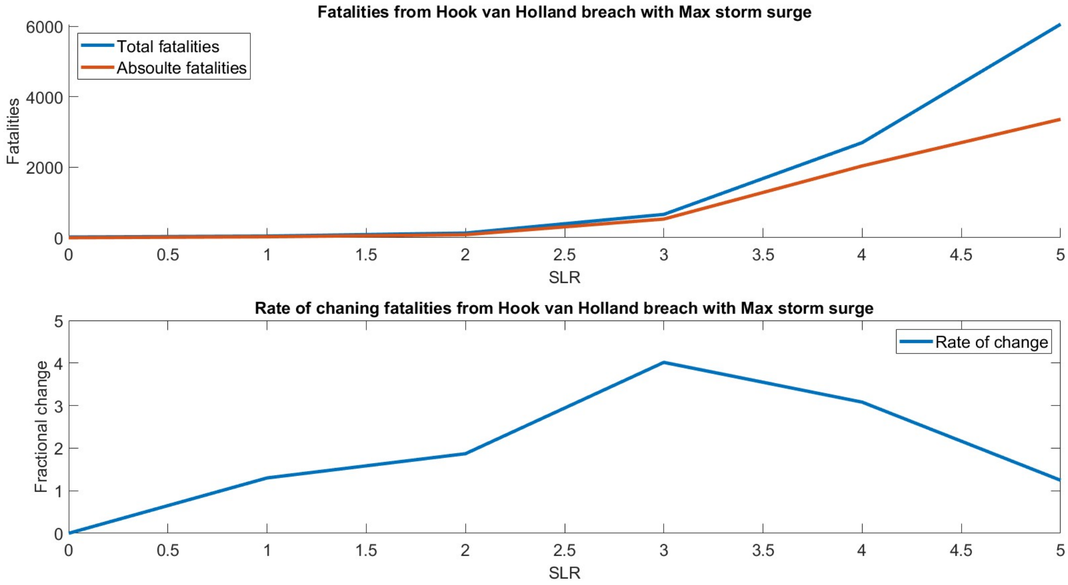


Figure 51: Hook of Holland fatalities from maximum storm surge with SLR of 0-5m

8.9 Key areas in dike ring 14

8.9.1 Schiphol

Schiphol Airport is the main airport in the Netherlands, and one of the busiest in Europe [CBS Data, 2023]. As seen in the previous Figures 29 & 30 the impact on the area of Schiphol is minimal from breaches at Katwijk for SLR scenarios of 1-2m. Only from 3m onwards is there an impact on Schiphol. To show this, measurements have been taken in-situ around Schiphol for all scenarios run. These locations can be seen in Figure 52 below.

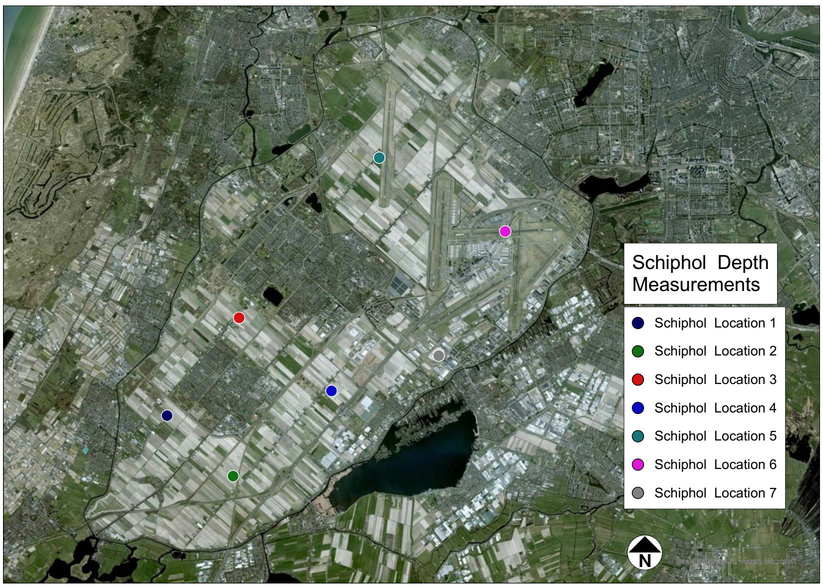


Figure 52: Locations of measurement points around Schiphol

Using these locations the depths were measured, as shown in Figure 53. These graphs show the scenario of a breach at Katwijk with a maximum storm surge.

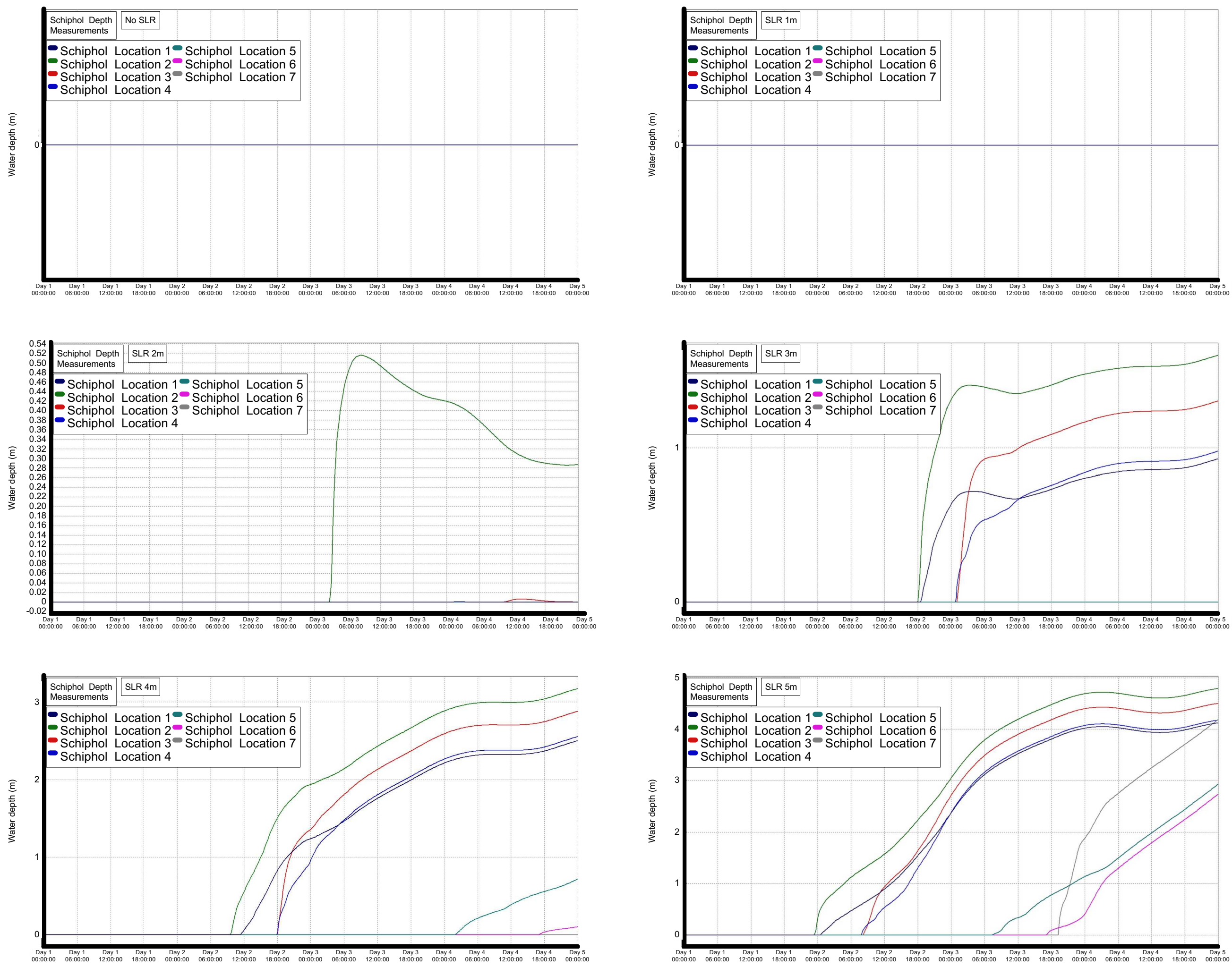


Figure 53: Inundation around Schiphol during maximum storm surge

It can be seen from the figure above that there is no measured inundation in the Haarlemmermeer, near Schiphol, until 2m of SLR, and there is a significant delay in the time for this inundation to occur. In the SLR of 2m case, this depth occurs towards the end of the storm surge, at 00:00 of day three, and the return to the normal ebb and flow of the tide at the breach location accounts for the decrease of water depth.

In the following scenario, (SLR of 3m) a similar initial pattern is seen, where a water depth peak is observed and is followed by a slight decrease. However, with this extra meter of SLR, the inundation occurs earlier (at 18:00 of the second day) and thus does not decrease with the receding tide, but increases. This pattern occurs with greater magnitudes for 4&5 m of SLR (parts of Haarlemmermeer being inundated by more than 4m by 5m of SLR) and occurs earlier and earlier (by 00:00 of the second day with 5m of SLR). However, the measurement stations at Schiphol only recorded significant inundation depths with 5m of SLR, and this only after several days.

8.9.2 The Hague

The Hague is the city that potentially experiences the greatest impact from the breach, given its location in relation to the simulated breaches (Amsterdam and Rotterdam are not directly located at a breach location). A selection of measurements is presented here, and their locations can be seen in Figure 54 below. The scenario presented is for the maximum storm surge.

Figure 54: Locations of measurement points around The Hague

The water depth pattern can be seen to be consistent with the storm surge, with the deepest depths occurring at the peak of the storm surge (around day three). Initially, there is little impact for these locations from a breach at the Hague, as there is no recorded water depth until the storm peak (day three). From SLR of 3m the inundation depth and the time it occurs increases, and by 5m of SLR the water depth closely resembles the pattern of the tides at the breach, showing the sensitivity of these areas to the changes of tides from 3m+ of SLR.

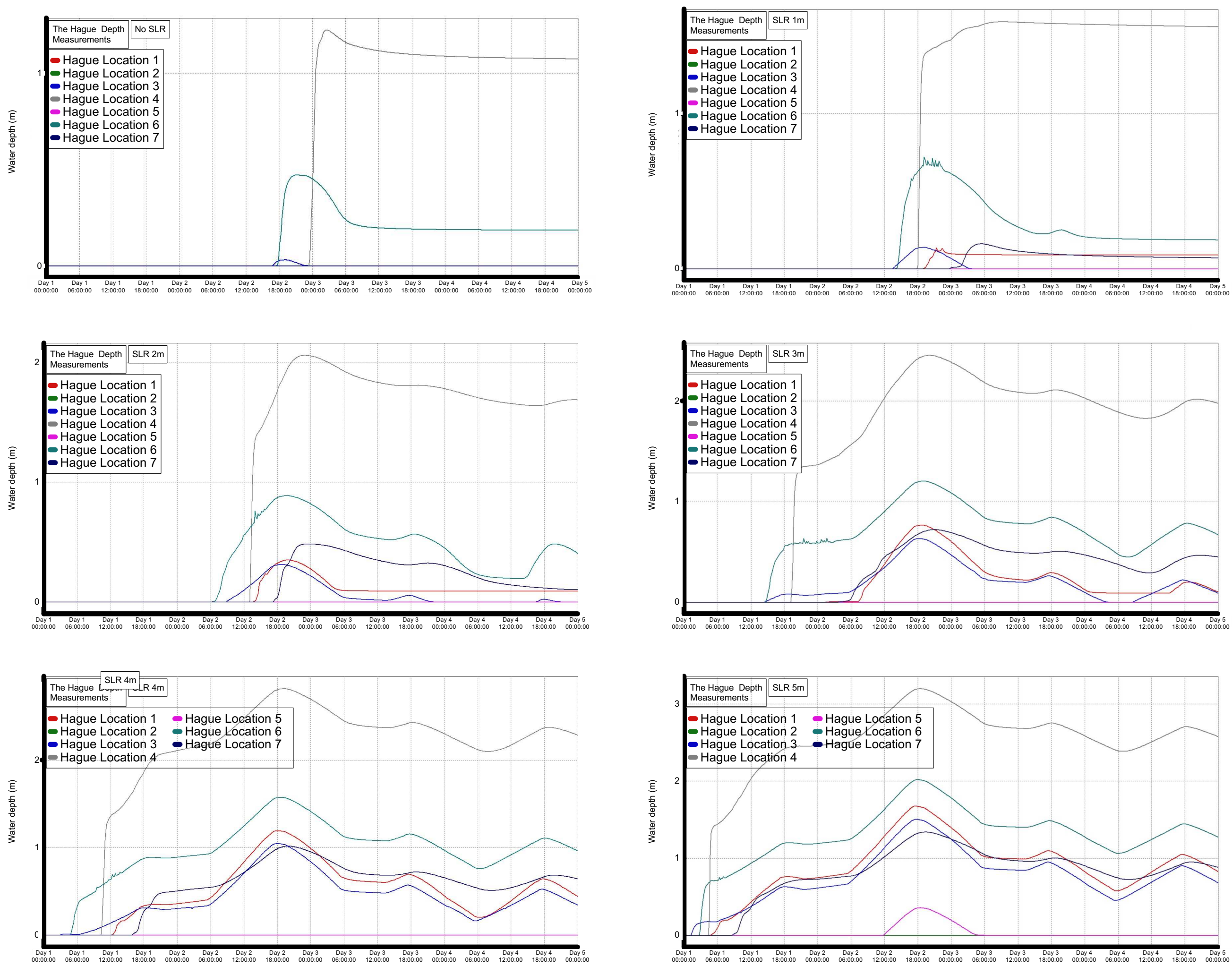


Figure 55: Inundation around The Hague during maximum storm surge

There are areas that remain unaffected at 5m of SLR however. The measurements that were taken at location 2 (See Figure 54) experience no inundation, even at 5m of SLR. Other locations increase at different rates depending on the SLR amount.

8.10 Comparison to simple 'bathtub' model

The results of using the other models can be seen in Figure 56 below. This figure shows the resulting area inundated from the different models, SOBEK, a simplistic 2D model, and a simple bathtub model. Each was run until the volume of inundation was similar to the volume measured for the SOBEK model during a breach at Katwijk with a maximum storm surge. Thus, for the same volume of water, there can be significantly different areas inundated.

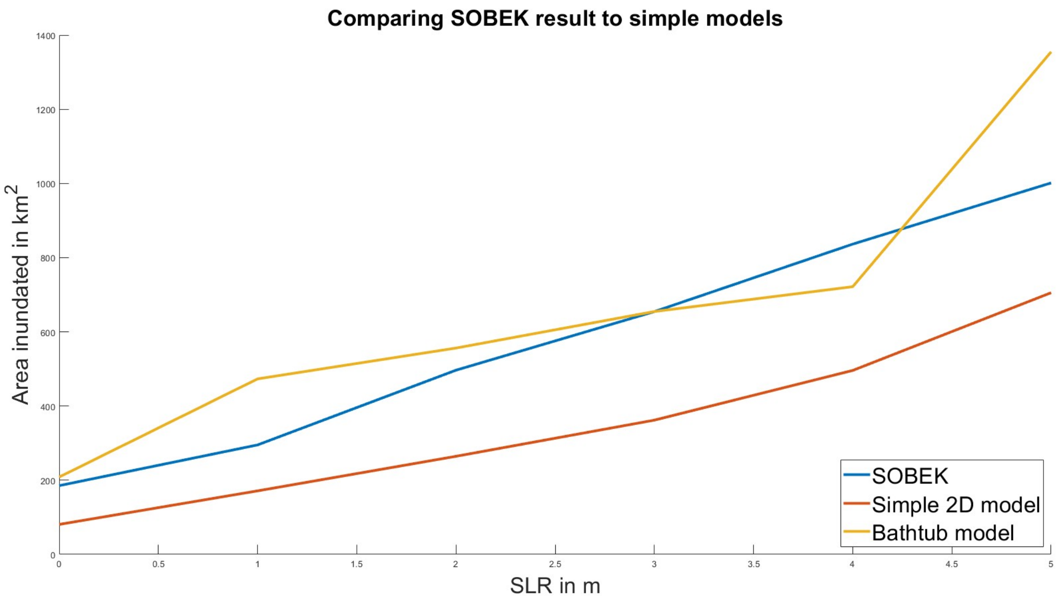


Figure 56: Comparing the area inundated from different types of models

The use of a bathtub model in dike ring 14 is greatly impacted by the polder and resulting compartmentalisation, as these areas would fill quite quickly initially, given the similarity of the elevation. But the spread of the inundation would be limited by the surrounding secondary dikes of those polders, meaning it can not spread. Thus, while initially resulting in a much greater area for 1m of SLR compared to the SOBEK model the increase in area after this point is lesser. This continues until the water height can overtop those secondary dikes, which can be seen after 4m of SLR.

The comparison of the SOBEK model to that of just a 2D model shows a consistent underestimation of the 2D model. This shows the importance of the 1D elements, particularly at Katwijk, as there is a significant concentration of canals and waterways that result in a much larger spread of the inundation when compared to the 2D model.

9 Discussion

This section will focus on the interpretation of the results in terms of addressing the research questions that relate to the sensitivity of the inundation (hazard) and the damage (exposure) to increasing SLR.

9.1 Katwijk sensitivity

From the investigation of the inundation maps and characteristics in Chapter 8 it can be seen that a breach from Katwijk does result in a highly sensitive result for both the hazard or exposure in dike ring 14. The inundation pattern continues to grow for each subsequent SLR scenario, which results in an increase in volume and average depths. The rate that this increases is predominately linear.

Given this, and taking into account that the run time of 96 hours did not result in an equilibrium being reached, it is highly probable that the actual result from a breach at Katwijk would be even more significant if the run times were increased significantly.

The time in which the inundation reaches a significant depth, in this case, 0.5m, also shows how highly sensitive the inundation is at Katwijk. However, unlike the general flood characteristics like the area flooded and volume that increases at a similar rate, there is a significant difference when the inundation reaches these significant depths. This was further emphasised in Figure 53, which shows the flood depths around Schiphol. That figure shows that there is a large difference between the measured water depths at each of the SLR scenarios and the time at which these water depths occur during the simulation. The measured locations here experienced no flooding for the scenarios of no SLR and 1m of SLR. This was then followed by only one out of the seven measured locations being flooded with 2m of SLR (Location 2, see Figure 53). The subsequent scenarios of 4 and 5m of SLR had more of the locations inundated (all locations were inundated by 5m of SLR), at much deeper levels (more than 4m for some locations by 5m of SLR). These depths also occur earlier in each scenario after 2m of SLR.

The areas that have been affected in terms of monetary damage, meaning those land-use areas with more than 0.3m of water, are also highly sensitive to the various SLR scenarios. However, much of the areas inundated are not 'high value' areas such as residential, commercial or vital infrastructure. Thus, the resulting damage, and the definition of hazard for this case, increases constantly with a rate of 0.5-1 times with each 1m increase of SLR. For example, going from €25 billion for SLR of 2m to €41 billion for SLR of 3m. The exception to this is the change from no SLR to 1m of SLR which gives a sudden increase of damage as calculated with the SSM method. However, as discussed previously Schiphol remains largely unaffected until SLR of 4 and 5m. This is seen in the effect on land-use maps (See Figure 30) where Schiphol is not significantly flooded until 4m of SLR. Again, the simulation time is too short and may have skewed this result, and it is possible that with a longer run time that there would be a larger effect on Schiphol.

These differences in the timings and effects on land use are not reflected in the calculation of the exposure, damage and fatalities using the SSM model, due to the large area that is inundated, which is more than 1000 km^2 with 5m of SLR. Thus, despite isolated areas such as Schiphol, which has huge economic value, not being inundated when taken in the wider context of the dike ring the resulting hazard has considerable influence on the exposure.

Additionally, there is an overestimation made by using the SOBEK maximum depth files, which only reflect the deepest inundation that a cell has experienced during the simulation. For example, when considering the maximum surge at Katwijk, when calculating the exposure using the depths at the end of the simulation (96 hours) results in a considerable difference when compared to that of the maximum depths, the former having €90 billion worth of damage with 6'563 fatalities, and the later having €97 billion worth of damage with 7'594 fatalities.

It can be thus said that the hazard and exposure that result from a breach at Katwijk are highly sensitive to SLR, but not equally as sensitive. Using the indicators of the area flooded and volume to represent the hazard it is clear that both differ, with there being a more rapid increase in the area flooded until 2m of SLR after which it increases in a more linear fashion, and the volume increases more rapidly with the greatest increase happening for 5m of SLR. The volume is particularly influenced by the polder areas in the dike ring, like the Haarlemmermeer which experiences significant differences from 4m of SLR to 5m of SLR (See Figure 28, in Section 8). The indicators used for the exposure are the damage and fatalities, which both experience a steady increase with each SLR scenario (with the exception of the change of no SLR to 1m of SLR). However, as stated previously, the effects of the overestimation made by using the maximum depths for the exposure calculation could impact this significantly.

When taken in a larger context these results can be compared to the past simulation of river locations in the Netherlands. As stated in Section 2, it is known that the largest threat to the dike ring area is not actually from the sea, but from the rivers and the resulting cascading effect that a breach would have [Asselman et al., 2010]. When these river flooding scenarios are compared to the results of this study, it can be seen that both the hazard and exposure are much greater from a sea breach with SLR than from the rivers. Looking at previous simulations of breaches at Lopik and Nieuwegein both for an exceedance of 1/2000 years, the resulting damages and fatalities estimated are €25 billion and 1'740 fatalities for Lopik, and €25 billion and 1'894 fatalities for Nieuwegein. For a breach at Katwijk with 2m of SLR, the damage and fatalities already reach these levels with a storm surge and greatly exceed them for further SLR.

9.1.1 Katwijk Validation

There are significant differences between the simulated floods here and of those past simulations [Jongejan, 2010]. The closest match between the LIWO simulation of a breach at Katwijk for a frequency of 1/1000 years, and this study's maximum storm surge with 1m of SLR. Comparing these two scenarios sees a 60% match between the inundation pattern and a 45% match with the inundation depth. However, for the depth, there are significant additional factors to discuss. The past simulation can be seen in Figure 57 below. In this figure, the large water bodies that have been inundated are shown. Some of these have a depth of over 1.8m. In comparison, the simulations run with SOBEK in this study correct for these water bodies so they do not skew the results, and the same water body that has 1.8m in the past simulation, only has a depth of 0.2m. This represents an additional 0.2m of water ontop of the existing water surface. Given the large areas of some of these lakes, such as Westeinderplassen, this could lead to a large difference in water depths.

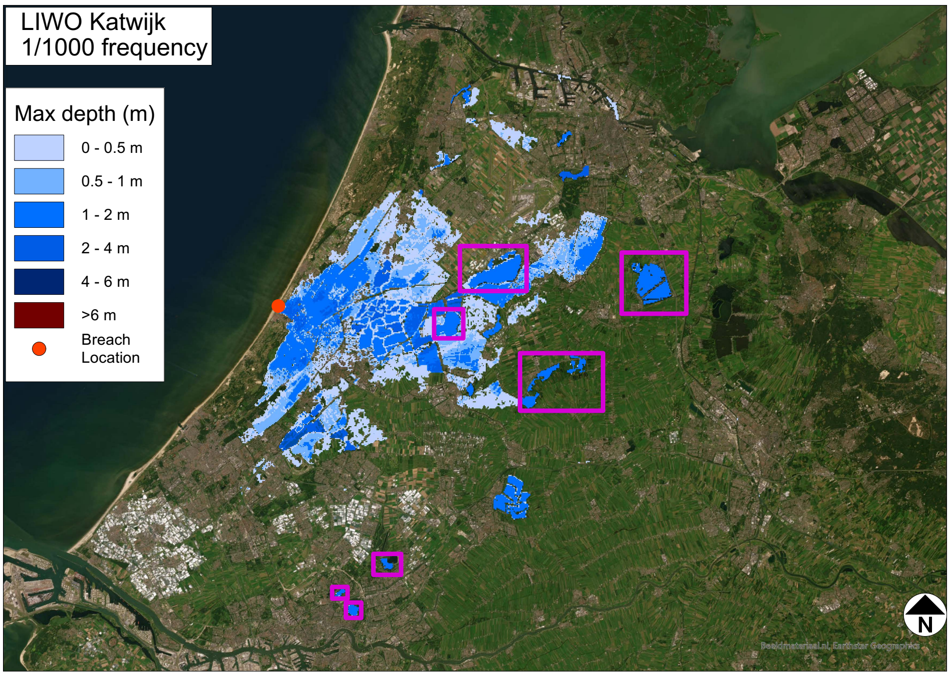


Figure 57: Results of past simulation available on LIWO

The resulting exposure also differs substantially, with the past simulation estimating €6 billion in damages and 263 fatalities and the simulation of this study resulting in nearly double this with €12 billion in damages and 593 fatalities. But as the exact simulation conditions of this past scenario, such as SLR, simulation length or storm surge events are not known, a definite answer as to the validity of the comparison can not be made. Further testing at different increments of SLR and longer simulation runs would be required to gain clarity on this.

However, the initial breach scenario damages and fatalities with no SLR and 1m of SLR are in line with the expected for dike ring 14 [Jongejan, 2010] and are deemed to be acceptable for a general comment to be made for the sensitivity of the hazard and exposure to the various SLR scenarios.

It was possible to take the digital elevation map (DEM) used in a previous SOBEK model, which was used to create the past simulation. This DEM was inputted into the current model, and run for the same simulations. This gave a substantially closer result to the past simulations on LIWO, a 60-70% match. Although there are substantial differences in the 1D elements, the current SOBEK model has a much more extensive 1D network, this result shows that the DEM map has a very significant impact on the results. In Figure 58 the results of LIWO scenario (1/1000 year), the current model results calculated for 1m of SLR and a maximum storm surge, and the current model using the previous DEM map for 1m of SLR and a maximum storm surge.

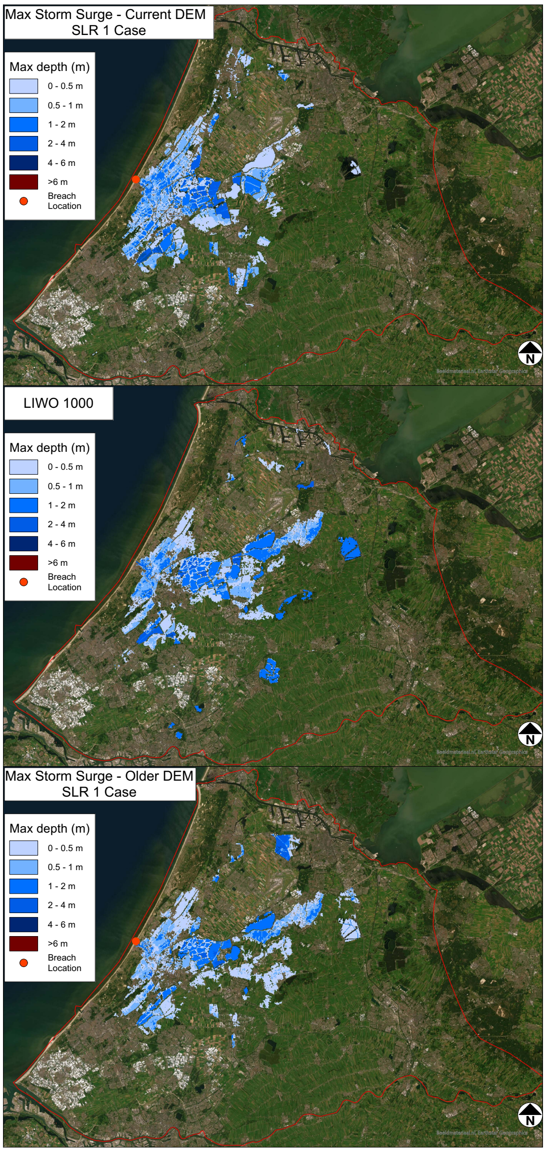


Figure 58: Comparing LIWO, current model results, and current model with older DEM input

9.2 The Hague sensitivity

The results from the Hague breach show a rapid increase in inundation from each SLR scenario. This was seen in the flooding maps seen in Section 8 (See Figure 34 where each subsequent increase in SLR resulted in a much more severe inundation pattern. When considering the inundation characteristics, such as the area flooded, volume and average depth that was presented in Section 8 (See Figure 37) all three indicators increase significantly with each SLR increase. Of particular note is the increase in volume, which increases rapidly despite no SLR having a relatively small amount of inundation volume ($121250m^3$) to a huge volume ($1453700000m^3$) by 5m of SLR. Given the highly compartmental nature of the area in the dike ring 14 this is consistent with other studies [Oost and Hoekstra, 2009] as those areas are likely to experience significant inundation depths.

It is also important to note that in all cases the trend continues to increase. Hence, the simulation time (96 hours) is likely insufficient to capture the full inundation pattern. Given this, it is again assumed that the total hazard would increase if the simulation time was increased. With the area and average depth also experiencing significant increases the overall hazard can be seen to be highly sensitive to changes of SLR.

The damage done, while increasing at each stage, did not increase as rapidly as the hazard. This is predominately due to the land use affected by the inundation. While the majority of the Hague was affected, there were large areas of agriculture, nature, etc. which were included in the inundation pattern. Given the relatively lower valuation of this land, this resulted in a slower increase of the exposure damage than that of the hazard. Additionally, there were areas in the Hague that were not inundated (See Figure 55). This further reduced the monetary impact of a breach at the Hague, and thus, the overall exposure.

The fatalities that resulted from the Hague breach overall followed the same pattern as that of the damage, with a large initial change of fatalities from no SLR, where there were no fatalities, to 745 with 1m of SLR. This continued to increase, with the largest increase occurring from 3 to 4m of SLR.

The time of inundation above 0.5m also shows an interesting aspect that is not reflected in the SSM calculation of the exposure. Large parts of the central part of the Hague remain below 0.5m until 24 hours into the dike breach for 1-3m of SLR, with the timing reducing significantly after this point. The centre of the Hague would be inundated above 0.5m with 4-8 hours of a dike breach with 5m of SLR. This means that any particular evacuation procedure would be fraught with difficulty. This is not encapsulated by the exposure calculation.

The highly urban population around the Hague results in very significant levels of fatalities when compared to the breach simulated at Katwijk. When comparing the Katwijk breach to that of the Hague, the Katwijk covers approximately $200km^2$ more than that of the Hague for 5m of SLR. However, due to the difference in land use, with more density-packed residential areas being affected by the Hague breach (See Figure 36) the resulting damage is comparable between the breach at Katwijk and that at the Hague. Comparing the fatalities, however, results in a much more significant impact for a breach at the Hague than that at Katwijk, with the Hague breach resulting in 9'252 fatalities and the Katwijk breach resulting in 7'594 for 5m of SLR.

Both the hazard and exposure resulting from a breach at the Hague are highly sensitive to SLR. The hazard is seen to increase more rapidly than that of Katwijk. Much like a breach at Katwijk, the breach at the Hague with 2m of SLR will reach the levels of exposure predicted by simulations at Lopik and Nieuwegein [Asselman et al., 2010], and greatly increase thereafter.

9.2.1 The Hague Validation

As with Katwijk, there are differences in the comparison to past simulations at the Hague and the simulations of this study, but for the Hague, some of the large water bodies that skew the data of the Katwijk breach do not have as large an impact. The same issues over unclear conditions of SLR. simulation times and storm conditions persist.

The past simulation, with a frequency of 1/1000 years, and the simulation of this study with a maximum storm surge and 1m of SLR result in a very similar damage and fatality estimation. The past simulation frequency of

1/10000 years and the simulation of this study with a maximum storm surge and 2m of SLR differ substantially, however. This further suggests that the past stimulations may have a different increase in SLR increment.

9.3 Hook of Holland sensitivity

The secondary dike (Maasdijk) located close to the breach location serves to stop the most significant inundation that would result from 1 and 2m of SLR. This means that there is little sensitivity to SLR increases to 2m. However, after 3m of SLR, the Maasdijk is overtopped and the inundation spreads rapidly in many directions, quickly reaching areas of the Hague and Rotterdam. The consequences for the hazard and exposure thus grow substantially after this point.

As mentioned, there is a large dependence on the characteristics of the storm on the resulting hazard and exposure. The average storm surge, the storm simulated which would result in more water flowing through the breach, has a larger impact on the area initially than the maximum storm surge, the surge that coincides with the high tide point. This is due to the Maasdijk, as the larger impact is seen when there is more water overtopping, coming from the larger volume of water coming through the breach. With 5m of SLR, this reverses, with the maximum storm surge becoming more impact full. This is of note, as, unlike the other locations, the most extreme storm surge does not necessarily result in the highest hazard and exposure.

With 5m of SLR, the time in which the inundation around Rotterdam and the Hague reaches a depth of more than 0.5m is approximately 48 hours, which is similar to that of the breach at the Hague. Again, due to the Maasdijk, the largest indicator of this is the timing at which the Maasdijk is overtopped. The overall impact on the commercial, residential, and infrastructure areas is substantial after 3m of SLR. It can be seen that the resulting hazard and exposure after 3m is similar as the breach at the Hague, which is to be expected given their close proximity and the surrounding terrain. However, when addressing the question as to if there is a tipping point at which both the hazard and the exposure begin to increase rapidly due to SLR it is clear that there exists one. Prior to 3m of SLR, the Maasdijk will effectively deal with the resulting inundation, but the chosen SLR increment (from 2 to 3 meters) is not sufficient to show the point at which this occurs. Thus, further simulation would be needed in smaller increments to identify this point.

9.4 Hook of Holland validation

For the breach at Hook of Holland the resulting damage, fatalities, and average depths were compared to past simulations at a similar location [Jongejan, 2010]. The past simulations resulted in €0.6-1 billion, 15-115 estimated fatalities, and an average depth of 1-2m. The simulations of this study resulted in similar results, €0.5-2 billion, 20-132 estimated fatalities, and an average depth of 1-2m. The damage for the last compared simulation being considerably more, potentially due to changes in land-use which are not taken into account in the past simulations [Jongejan, 2010].

All of the past simulations investigated did not overtop the Maasdijk, so it is not possible to compare the later SLR of 3-5m.

The existing Maasdijk contains a series of road connections, mostly on top of the dike. However, to confirm the retaining structure of the Maasdijk, more up-to-date DEM maps would be needed to confirm if these connections have created any weak points.

9.5 IJmuiden sensitivity

The results of IJmuiden show that neither the hazard nor exposure is heavily influenced by SLR when compared to the extent that Katwijk and the Hague breaches. This can be seen in the maps in Section 8 (See Figure 40), and the graphs of the inundation characteristics in the same section (See Figure 43). Neither these maps or the graphs show the same level of increase as for Katwijk or the Hague.

For the case of the time taken for areas to be inundated by more than 0.5m, even for 5m of SLR the limited areas near Amsterdam that would be inundated by this much would not occur till well after 48 hours. The impact on land use is also limited to areas around Westpoort and limited parts of North Amsterdam, however, these areas are affected even from no SLR. This does lead to an initially high damage estimate, €2 billion for no SLR, which is much higher than either Katwijk and the Hague for no SLR.

The same pattern is seen for fatalities, with 55 estimated for no SLR during a maximum storm surge which is again higher than the same scenario at the Hague.

However, as discussed in Section 8 there were significant assumptions made in the model set up for this breach location. The amount of water allowed to discharge into the Markermeer and IJmeer meant that the water levels in the Noordzeekanaal never reached levels that would have resulted in catastrophic flooding in areas such as Amsterdam. The reality is that these lake water levels would also need to be increased in line with the SLR scenario, meaning that the potential flooding along the Noordzeekanaal would be many times greater. Given the close proximity to Amsterdam, and the highly dense, urban population there a resulting flood would be severe. Not only could Amsterdam be devastated, but the Haarlemmermeer (including Schiphol) would certainly be affected more than by the other scenarios.

Thus, neither the hazard nor exposure for this location has been found to be highly sensitive to SLR, but further studies on this area are required.

9.5.1 IJmuiden Validation

The comparison of a previously simulated breach at IJmuiden and the simulations run for this study can be seen in Figure 59 below. Here the inundation of each cell, at each location is compared. The previously simulated flood from LIWO, with an exceedance of 1/3000 years can be seen in red and the simulated flood of this study, for a maximum storm surge and 2m of SLR, can be seen in blue.

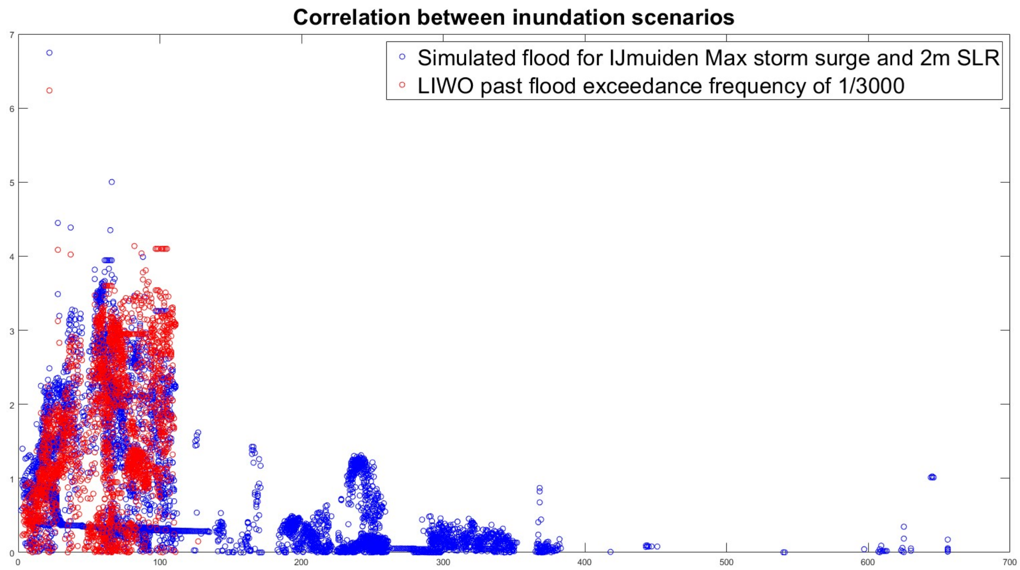


Figure 59: Comparision of IJmuiden breach to LIWO simulations

Despite there being a much large area inundated for this study, there is a significant similarity between both floods for locations along the Noordzeekanaal, which are those measurements on the left side of Figure 59 above.

9.6 Schiphol sensitivity

Only looking at the dike ring as a whole could miss some of the key locations, such as Schiphol or the highly urbanised area in the Hague. These areas are highly sensitive to high levels of SLR. For Schiphol, there is a clear increase of inundation depth between 3m to 5m of SLR. This is mainly due to the lower elevation of the

Haarlemmermeerm where once inundated any increase in SLR will cause a rapid increase in water depths. For the Hague, this pattern of rapid increases can be seen from 2m plus of SLR. However, for both locations only limited observations have been taken into account here, and a more robust study in isolated locations in the dike ring could lead to greater insights, but this is beyond the scope of this report.

With the results of this study, the held assumptions over the largest impacts of hazard and exposure to dike ring 14 coming from river breaches [Asselman et al., 2010] & [ter Horst, 2012] may not hold for SLR of 2m and above, particularly for breaches at Katwijk or the Hague.

9.7 SOBEK vs other models comparison

It is clear that SOBEK gives a much more accurate picture, even for large volumes of inundation, such as those resulting from 5m of SLR. Given the terrain in dike ring 14, and the large degree of secondary dike systems, roads, and other structures that could form a barrier to the spread of inundation a bathtub model is clearly not an acceptable model to use (when there are better alternatives) as it would both under and overestimate the inundation depending on the amount of volume that would actually enter into the area.

A 2D model lacks the specific detail required to make accurate predictions in the event of a dike failure, as it consistently gives an underestimation. Although it is more applicable for usage in dike ring 14 as it will be able to take into account the systems of secondary rings.

Both of these models where only created to give a sense of the effects of different models on the results, and would require much more extensive work, discussion, and validation for any real in-depth comparison to be made.

10 Conclusion

From the results seen in Section 8 the initial research questions relating to the sensitivity of the hazard (inundation) and exposure (damage and fatalities) to various SLR increases have been investigated. For all the breach locations it can be seen that there is sensitivity to SLR, however, there is not a consistent increase in the hazard and exposure indicators between the breach locations.

10.1 Research question 1 - How sensitive is the hazard to SLR?

Using the area flooded, the volume of inundation, and the average depth to define the hazard gives varying results depending on the breach location. Figures 60 to 62 below show the results of these characteristics for a maximum storm surge for each location.

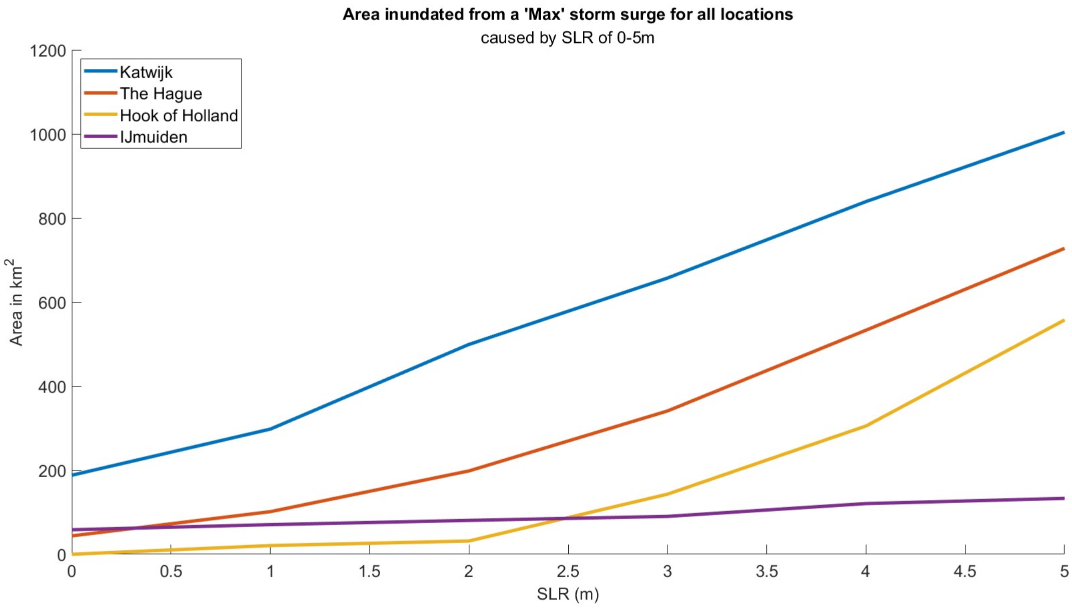


Figure 60: The area inundated resulting from a maximum storm surge for each breach location with SLR of 0-5m

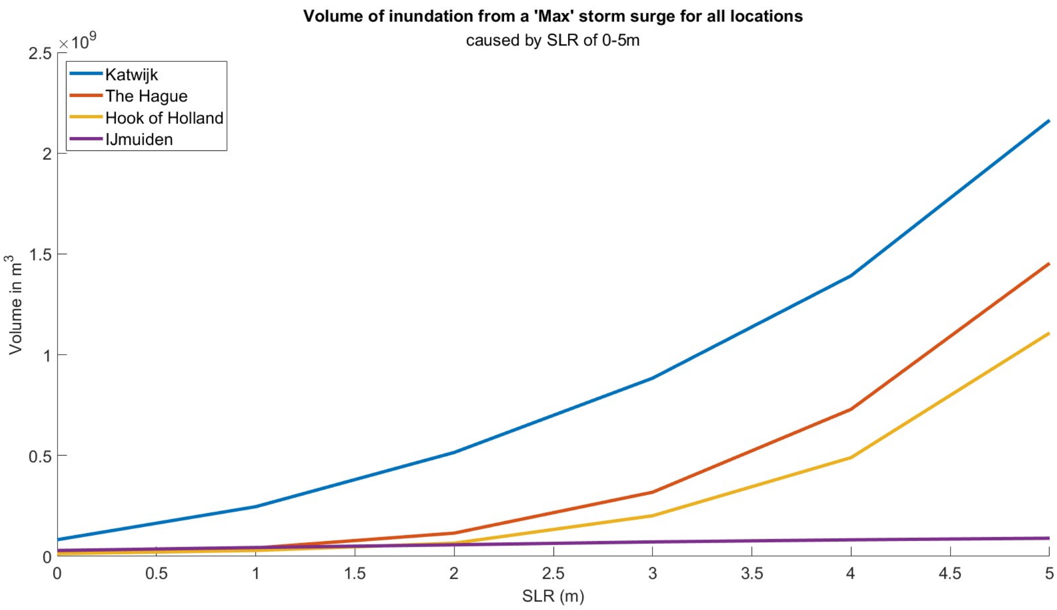


Figure 61: The volume inundated resulting from a maximum storm surge for each breach location with SLR of 0-5m

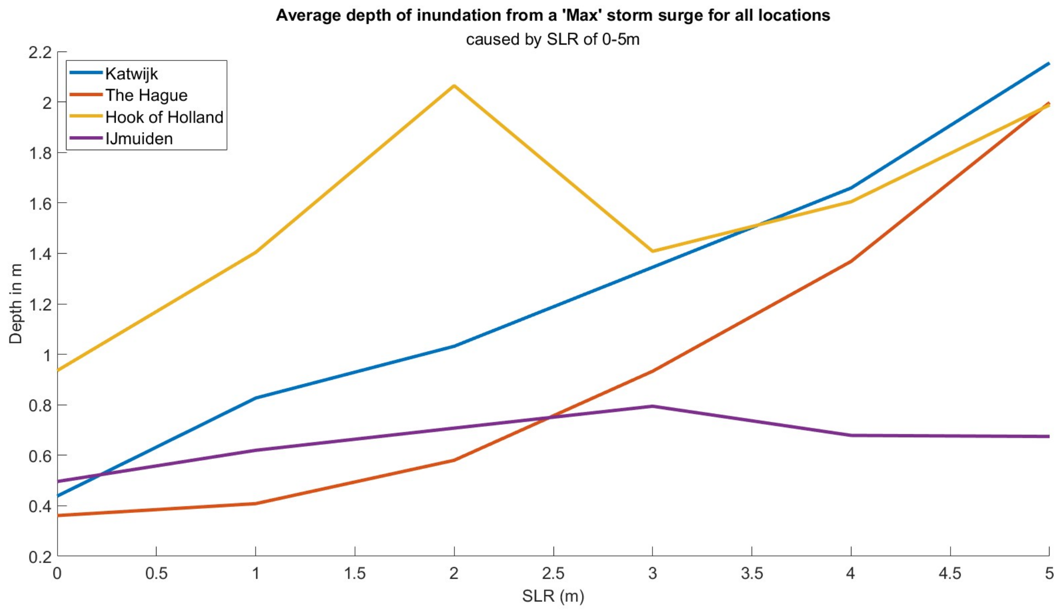


Figure 62: The average depth inundated resulting from a maximum storm surge for each breach location with SLR of 0-5m

The latter of these figures shows the average depths at each location. Of note here is the average depth from the breach at Hook of Holland, as it increases substantially until 2m of SLR, after which it decreases. This is due to the Maasdijk, which is located close to the breach location at Hook of Holland. Between the seaward dikes (where the breach is located) and the Maasdijk fills up like a bathtub, resulting in very deep inundation at places, and when this water finally overtops the Maasdijk it spreads rapidly across the land (See Section 8), Figure 46. This results in a much greater inundated area with shallower depths, reducing the overall inundation depths.

From these figures, it is clear that the location where a breach occurs has a stronger influence than the level of SLR. A breach at Katwijk will result in the most severe hazard regardless of the SLR. A breach at IJmuiden is clearly the least sensitive to SLR, as the characteristics of the hazard remain relatively stable, compared to the other breaches. The close proximity of the Hague to the Hook of Holland explains the similarities in their hazard characteristics, particularly for higher levels of SLR. This is to be expected, as once the initial Maasdijk compartment is overtopped at Hook of Holland, there is little to stop the inundation from following the same pattern as from the Hague.

When comparing Katwijk to the Hague breaches for both area inundated and volume of inundation it can be seen Katwijk is by far the most impactful. The area and volume inundated reached with 1m of SLR at Katwijk would require approximately 3m of SLR to be reached from a breach at the Hague.

10.2 Research question 2 - How sensitive is the exposure to SLR?

Like the hazard, the sensitivity of the exposure to SLR is more strongly influenced by the location of the breach. This is seen in Figures 63 & 64 below. These show the damage and fatalities for a maximum storm surge at each location.

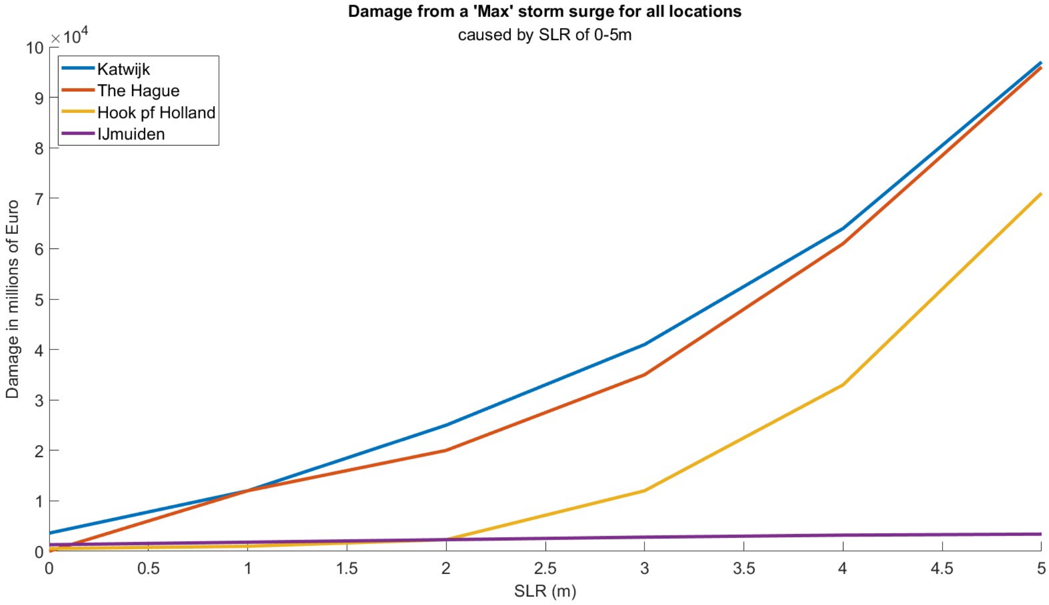


Figure 63: The damage resulting from a maximum storm surge for each breach location with SLR of 0-5m

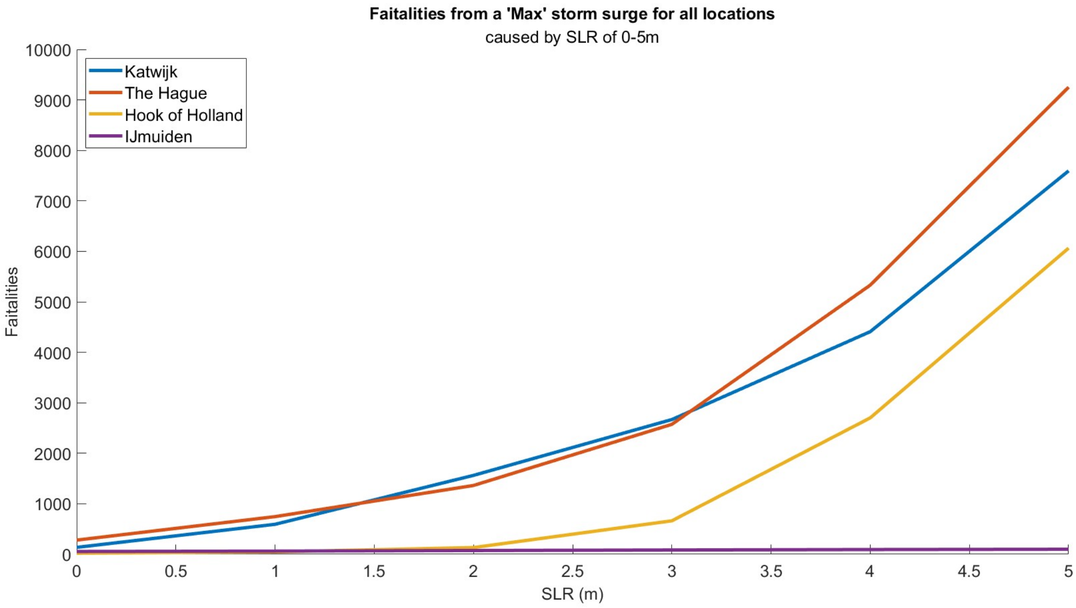


Figure 64: The fatalities resulting from a maximum storm surge for each breach location with SLR of 0-5m

From these figures, a similar trend as to the area and the volume increases can be seen. However, given the differences in land use, particularly with a much higher concentration of residential areas in the Hague, a breach at the Hague and the resulting exposure has a higher sensitivity to SLR, than that of the hazard. This means that for a much smaller volume and area of inundation, the exposure can be higher at the Hague than Katwijk. This is seen particularly in the levels of estimated fatalities in Figure 64, whereby 4m of SLR results in more fatalities from a breach at the Hague, than that at Katwijk. This is due to the inundation resulting from a breach at the Hague that would reach Rotterdam after 4m, causing significant fatalities.

Comparing the volume to the damages and fatalities, it is clear that for the smaller volumes of water, the consequences of a breach a the Hague or Hook of Holland would be greater than that at Katwijk. This can be seen in Figures 65 & 66 below.

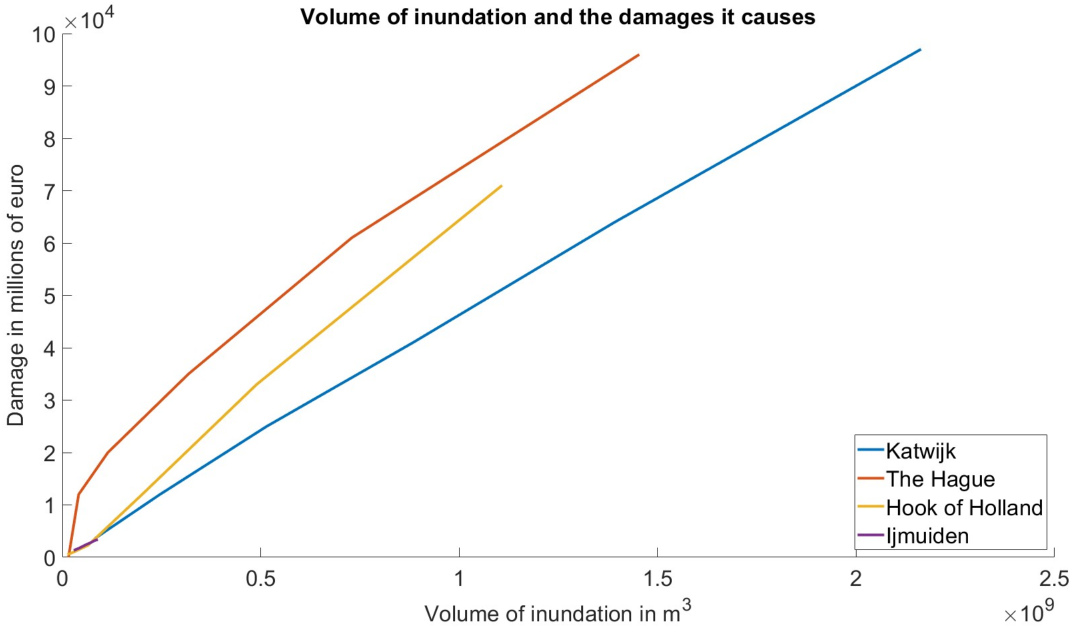


Figure 65: Comparing the resulting volume from SLR to the resulting damage for each location with SLR of 0-5m

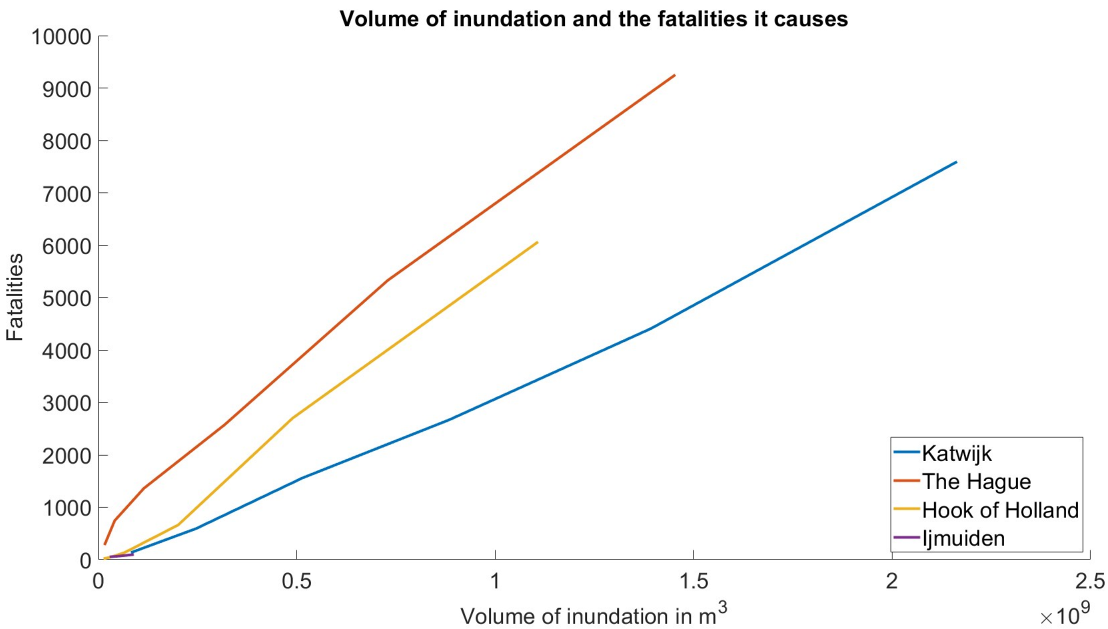


Figure 66: Comparing the resulting volume from SLR to the resulting fatalities for each location with SLR of 0-5m

What is seen is that for both Katwijk and the Hague breaches the overall exposure sensitivity to SLR is not the same. This is due to despite the inundation (in terms of area and volume) being greater from a breach at Katwijk, the consequences of damages and fatalities from a breach at the Hague are greater. IJmuiden remains largely unaffected by the increases in SLR in terms of exposure.

Overall, the sensitivity for both hazard and exposure continues to increase for all locations (Ijmuiden to a lesser extent) for each SLR scenario. The rate of this increase is defined more so by the location, rather than the SLR. From this, a conclusion can be taken that there is no significant tipping point that causes significantly higher levels of hazard or exposure from increasing SLR. However, given the fatalities results of the Hague breach, it can be seen that breaches in close proximity to urban centres result in a more sensitive exposure to SLR. As discussed, there were significant assumptions affecting the IJmuiden simulations, and it is likely that the real impact would be greater. This would result in a much greater exposure for areas around Amsterdam, and would likely show a greater level of sensitivity.

When comparing these results of the previous simulations, where the largest impact to the hazard and exposure in dike ring 14 is from breaches at dike ring 15 and 44, it can be seen that initially, the assumption holds that the largest impact will be from these river breaches [Asselman et al., 2010]. This does not hold for more extreme levels of SLR. All of the breaches, with the exception of IJmuiden, would eventually result in greater hazard and exposure impacts. The SLR scenario in which this happens can be seen in Figure 67 below, where the compared river breaches are also indicated. This shows that after 2m of SLR, the threat posed by a sea breach will outstrip that of the breach of the river dikes (if no changes to river discharges are assumed).

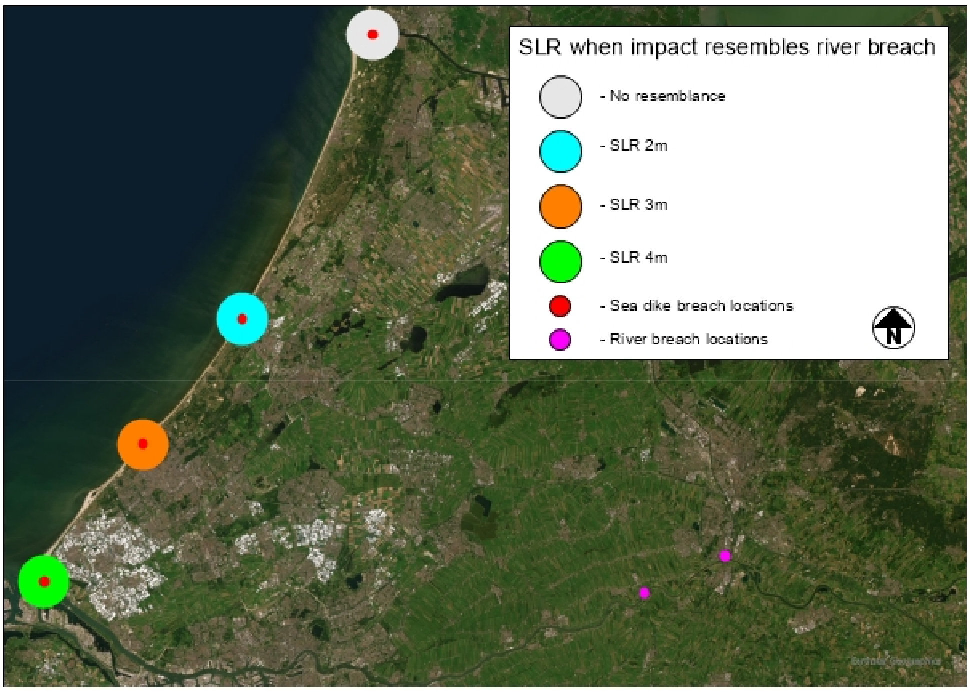


Figure 67: Map of the sensitivity

10.3 Research question 3 - How will the hazard and exposure change when using different models?

Using other models, such as a bathtub or 2D model, would lead to various levels of under and over-estimating of the hazard and exposure. Particularly in such a densely populated area, with many polders, rivers, canals, roadways, etc. neither model would give an adequate result. However, it was seen that a 2D model would follow the same trend as the SOBEK model, but much underestimated. The bathtub model would be much more sensitive to changes in total inundation volume as soon as it extends beyond the polders the area increases significantly.

11 Recommendations

As discussed in Section 7, there were significant assumptions made during the simulation process. Of particular note are the simulation length and the treatment of the in and outflow along the Noordzeekanaal. In the case of the simulation time, a more robust would be to increase the simulation time until an equilibrium, in terms of the inundation characteristics such as volume or area inundated, were to be reached. Given the large differences in inundation volume that were recorded for 96 hours, it is assumed that using the same simulation length is not sufficient to completely capture the resulting inundation. Hence, for each SLR the simulation time should be increased until this equilibrium is found, which would result in much longer run times for 5m of SLR than that for 1m of SLR. This would give a more accurate picture of the inundation but would mean comparing the scenarios would be problematic as each would present different simulation times, with different tidal phase effects.

The breach location at IJmuiden should be revisited. Given the system of pumps at the sea locks here, the lack of properly modelled tunnels under the Noordzeekanaal, and the discharge to the Markermeer and IJmeer, this location is fraught with modelling difficulties. With Amsterdam's close proximity any errors made here that result in an underestimation of the potential hazard or exposure could have drastic consequences and a heavy degree of caution should be applied to simulations run in this area.

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Appendices

A Appendix 1 - Uncertainties

Uncertainty in model schematization	Definition Model settings
Model settings	Settings such as duration of simulation, calculation step size, etc. that are used in flood modelling
Water system • Watercourses • Works of art • Lakes	Schematization of one dimensional water system. Divided into: the way in which watercourses, structures and lakes are included in the schematization and whether these are included in the schematization at all
Terrain height • Topography • Line elements in the terrain (e.g roads, railways, barriers and noise barriers) • Viaducts, tunnels and other passages	Schematization of terrain elevation: How are elevation elements in terrain characterized. E.g. can all relevant line elements be found in the height? And do they have a representative height? The schematization of passages (tunnels, etc.) in higher-lying line elements is extremely important
Hydraulic roughness of the land	Schematization of terrain roughness. How is this one modelled, How does it change with land use change and/or landscape management?
Grid cell size	How big are the height grid cells?

Figure 68: Uncertainty in model schematization,, translation of uncertainties in report of N. Asselman [Asselman et al., 2010]

Uncertainty in scenario choice	Description What
Conditions • Water level at breach location • Storm duration • Flow rate at breach location • Waveform (discharge gradient)	kind of water level and discharge development has been assumed?
Wind	Has the effect of wing been taken into account in the simulation itself?
Breach growth • Time of day • Breach width • Breach depth (depth of scour pit) • Breach location • Number of breaches	Does the breach occur before or after reaching the maximum outdoor water level? Is the breach location located upstream or downstream, does the breach location border on a deep polder, or is the area behind it relatively high up? Is there 1 breach or multiple breaches?
Stability internal line elements	Has it been assumed that all regional flood defences, railway embankments and other line elements will remain intact? Or can breaches occur?
Control measures	How have control measures such as placing sandbags and closing off passages been taken into account?

Figure 69: Uncertainty in model conditions, translation of uncertainties in report of N. Asselman [Asselman et al., 2010]

B Appendix 2 - 2D and Bathtub models

B.1 Bathtub model

From the global minimum of dike ring 14 a plane that represented the flooding was created, and filled with an arbitrary amount (was taken as a very small amount to try to simulate an actual flood event) every time step. This was stopped at either a total volume that had flooded the area or a water height. An example of the inundation can be seen in Figure 70 below.

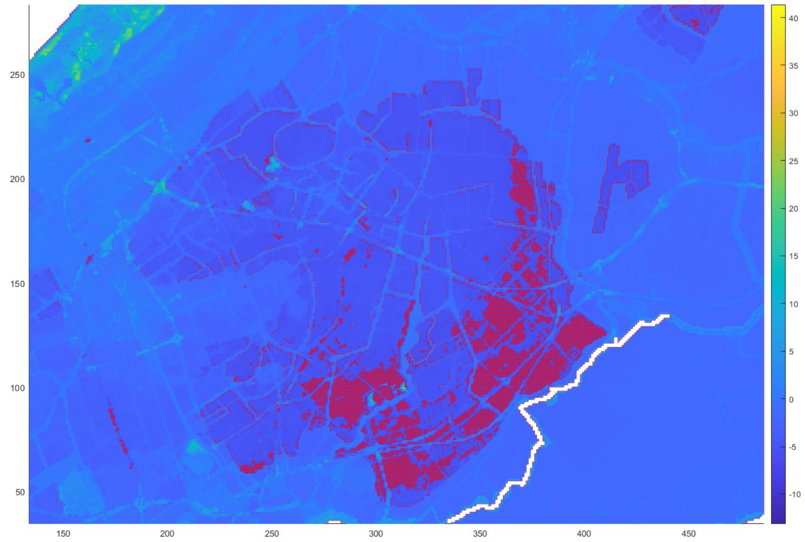

Figure 70: Bathtub model inundation pattern for $10000000m^3$ volume, where red is a flooded cell

B.2 2D model

In the case of the more complex 2D model, each available path of the water was considered. Taken from the breach location, a path to a local minimum was found by modeling the first step of the inundation as a river (with a 100x100m resolution this was deemed acceptable). From this minimum, a constant volume was added to the flood height (a constant volume increase was considered for the whole simulation), based on Equation 9 [Visser, 1998].

$$Q_{br} = m(\frac{2}{3})^{\frac{3}{2}}\sqrt{g}B(H_w - Z_{br})^{\frac{3}{2}} \quad (9)$$

With:
Q_{br} = the discharge at the breach location (m^3/s)
m= $\pi/2$ (-)
g = the gravitational constant, 9.81 (m/s^2)
B = the width of the dike breach (m)
H_w = the height of the water (m +NAP)
Z_{br} = is the constant level of the fore land (m +NAP)

Which this increase of volume at each time step, the initial flooded cell was checked against all of the neighboring cells and checked if the flood height was higher than the surrounding elevation. If not, then the flood increased by the constant volume, if there was a cell that was at a lower elevation than the flood height, then the water flooded into that cell (it was simply assumed that the cell was now flooded to the same height as the previously flooded cell. The process of checking check cell 'i,j', where i and j are the real-world coordinates of the cell.

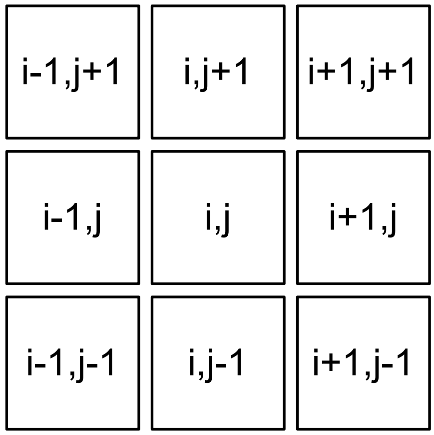

Figure 71: Propagation pattern of inundation

Once any of the surrounding cells is flooded it is added to a data set of all the flooded cells in the area, then the propagation pattern seen in Figure 71 above is applied to each cell. This process is repeated until a stopping condition is reached (either the total volume of the inundation or the water height).An example of the inundation can be seen in Figure 72 below.

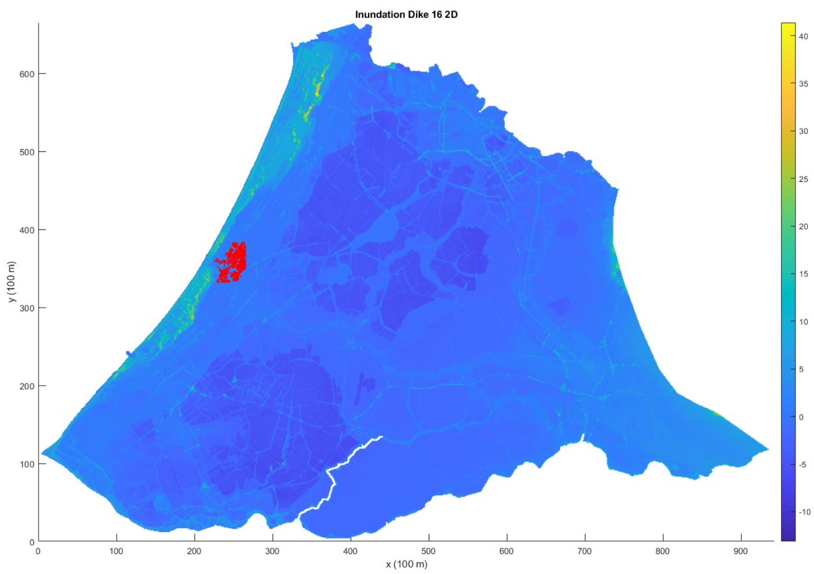

Figure 72: 2D model inundation pattern for a 10000000m^3 volume, where red is a flooded cell

The depth for both models was calculated by taking the height of the water from the actual elevation.

C Results for no storm surge

The following section presents the results of the breaches with no storm surge. This reflects the situation where the dikes would fail under normal conditions with varying SLR.

C.1 Katwijk breach

C.1.1 Katwijk Inundation extent

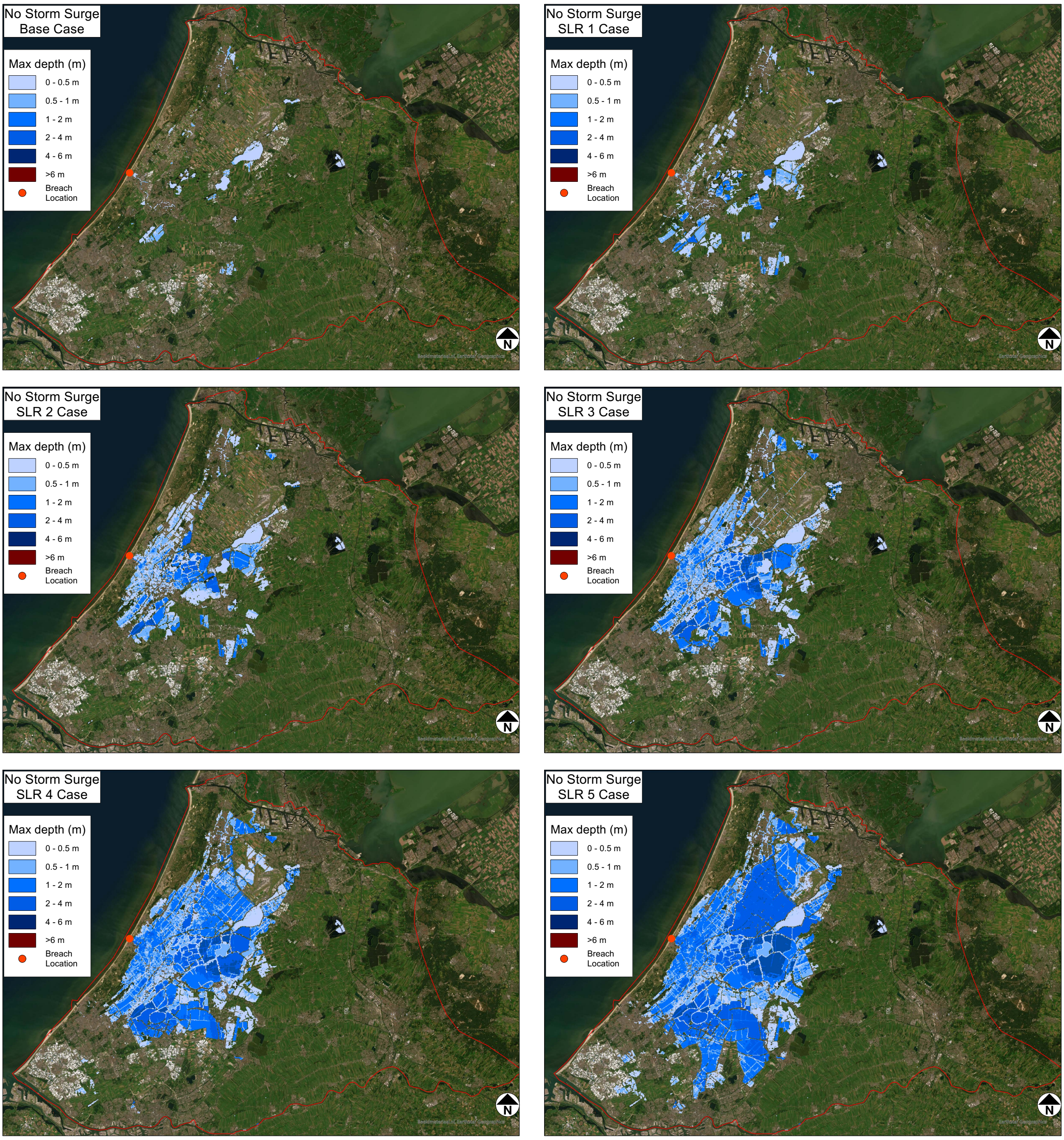

Figure 73: Breach at Katwijk with a no storm surge

C.1.2 Katwijk Arrival times

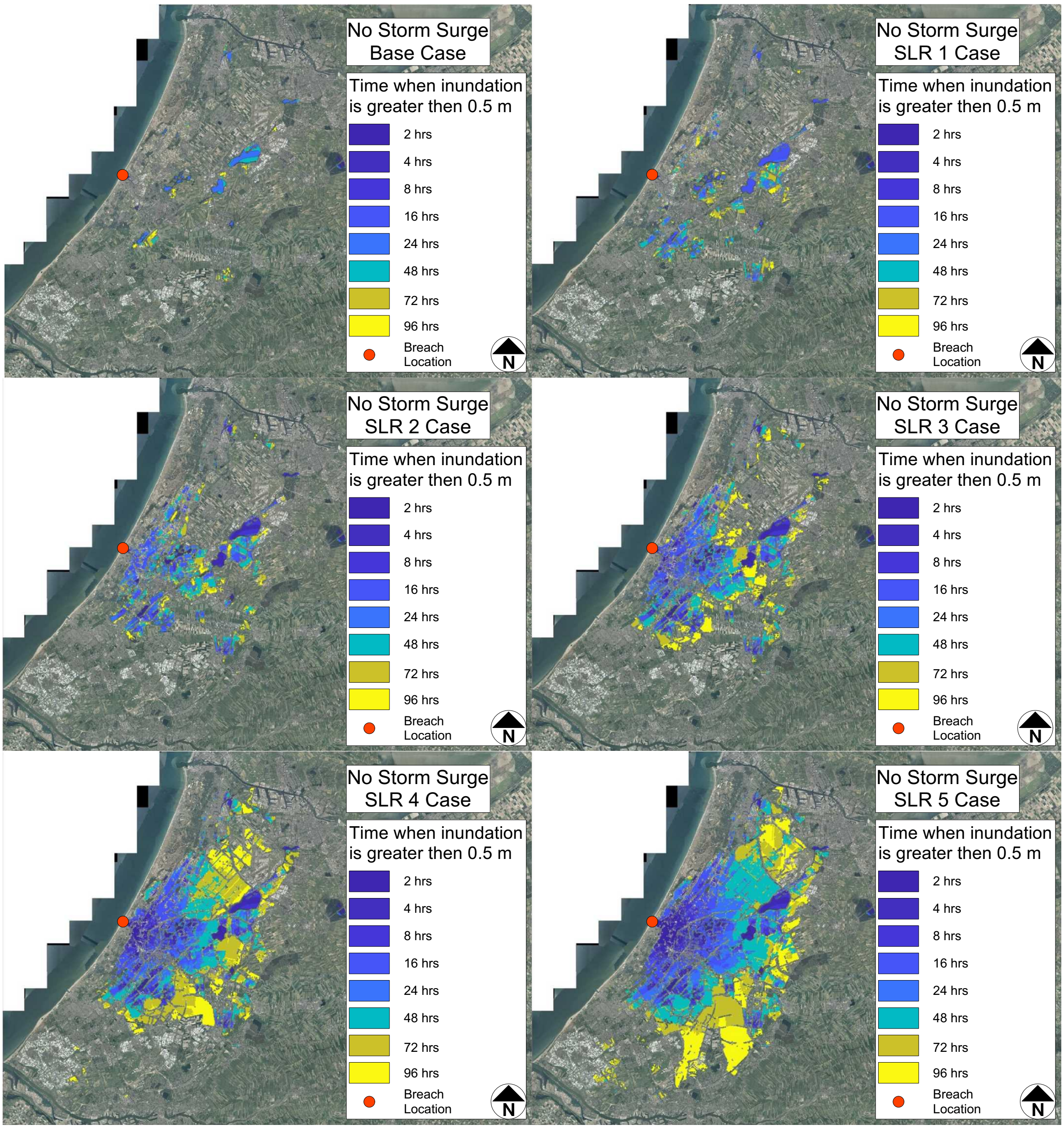

Figure 74: Time till areas are inundated to a depth of 0.5m from a breach at Katwijk with a no storm surge

C.1.3 Katwijk Land-use impact

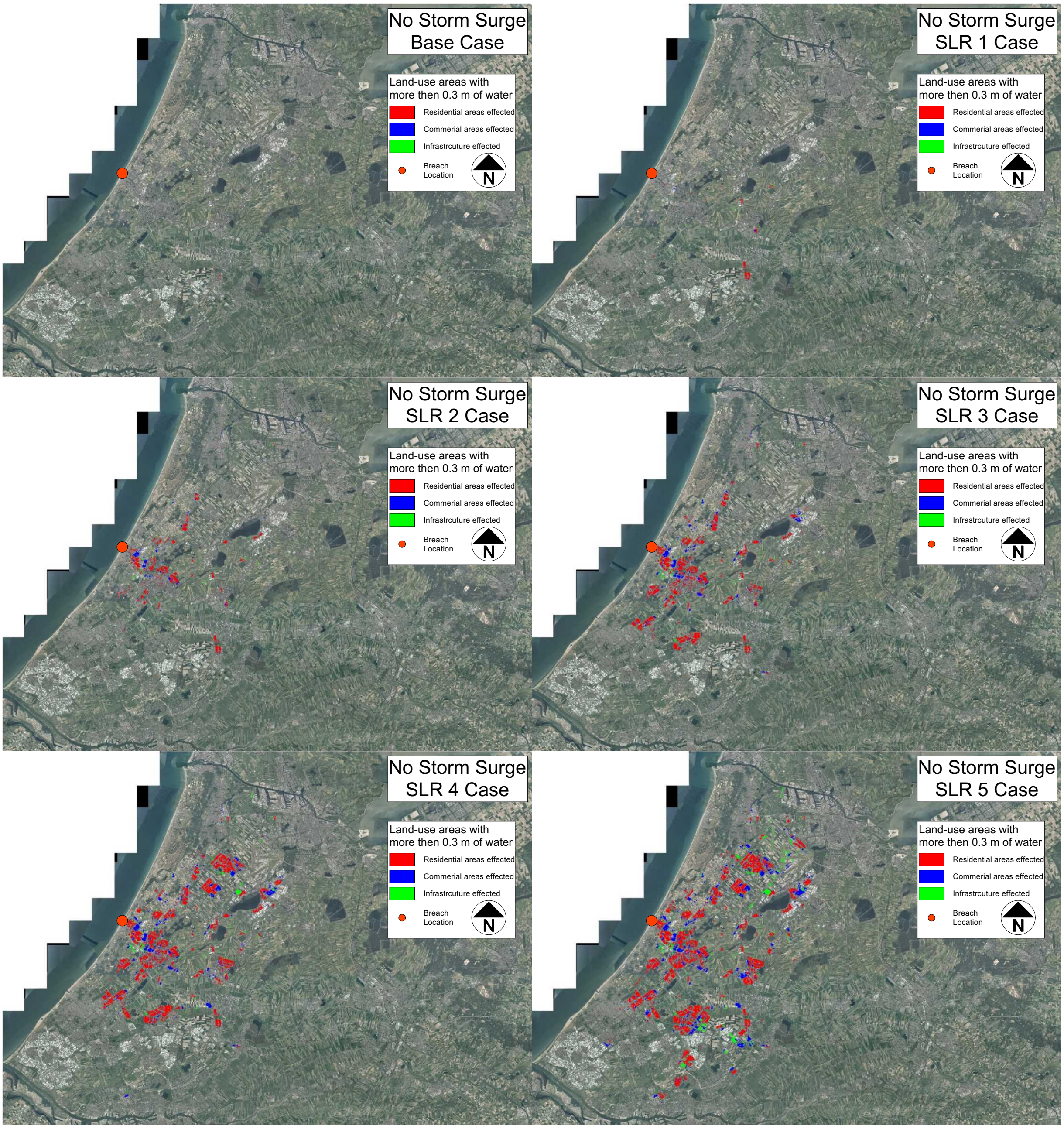

Figure 75: Effect on land-use areas from a breach at Katwijk with a no storm surge

C.1.4 Katwijk Inundation characteristics

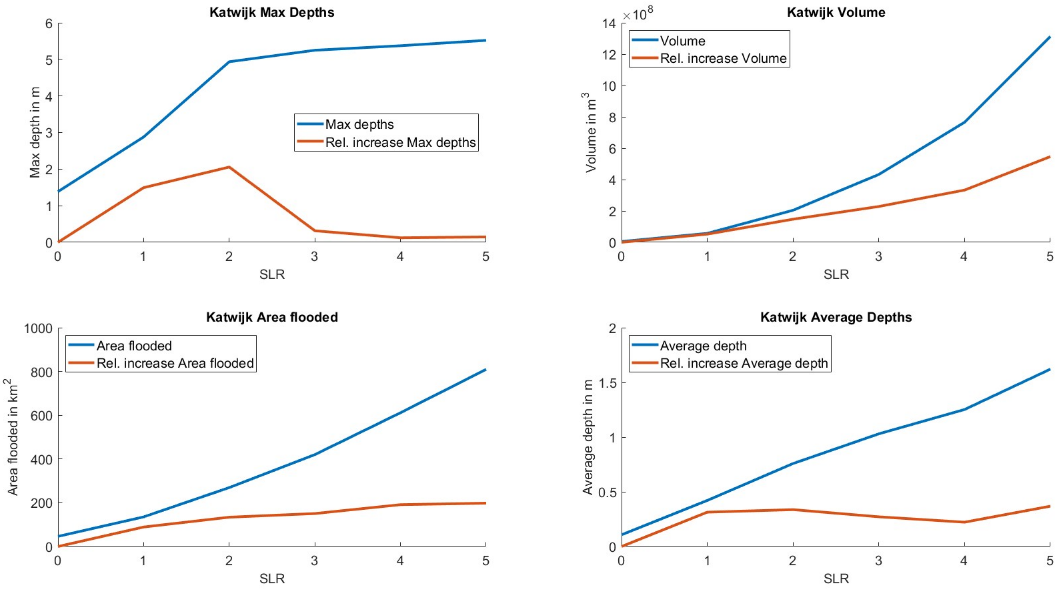

Figure 76: Inundation characteristics from a breach at Katwijk with SLR of 0-5m

C.1.5 Katwijk Damage

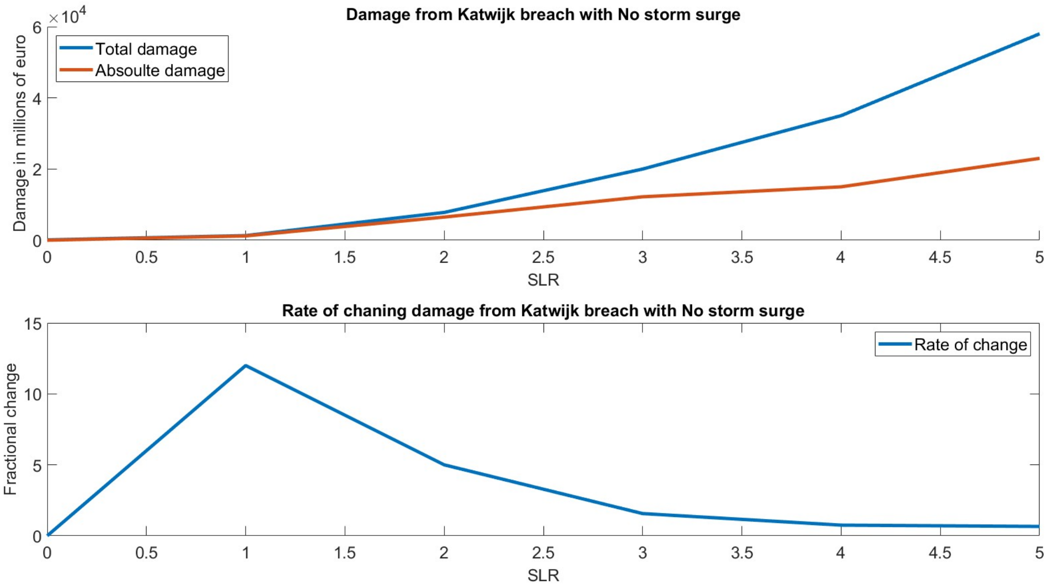

Figure 77: Katwijk Damage from no storm surge with SLR of 0-5m

C.1.6 Katwijk fatalities

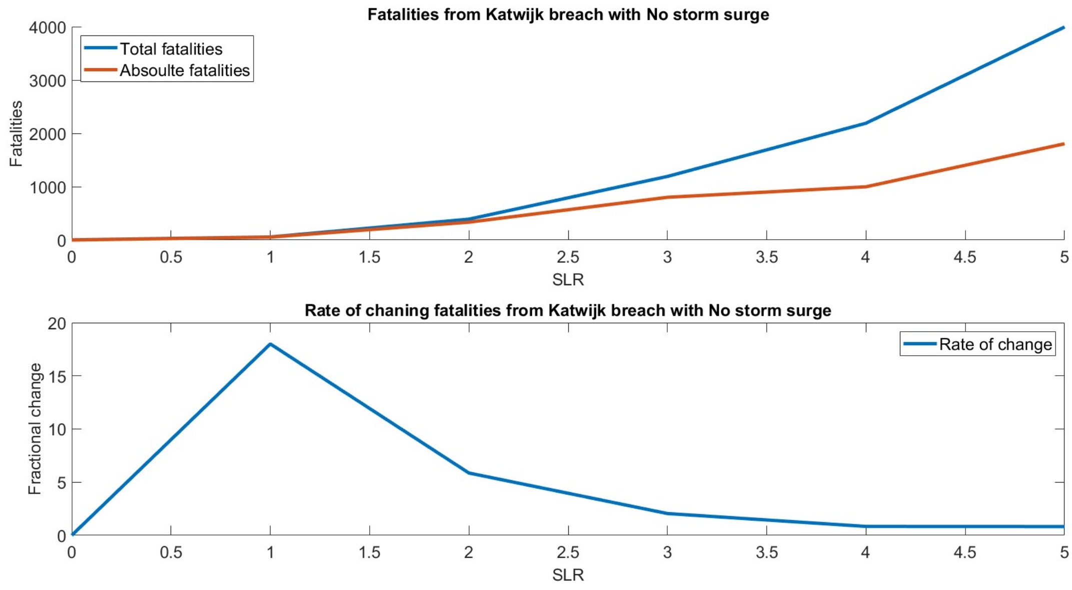

Figure 78: Katwijk fatalities from no storm surge with SLR of 0-5m

C.2 The Hague breach

C.2.1 The Hague Inundation extent

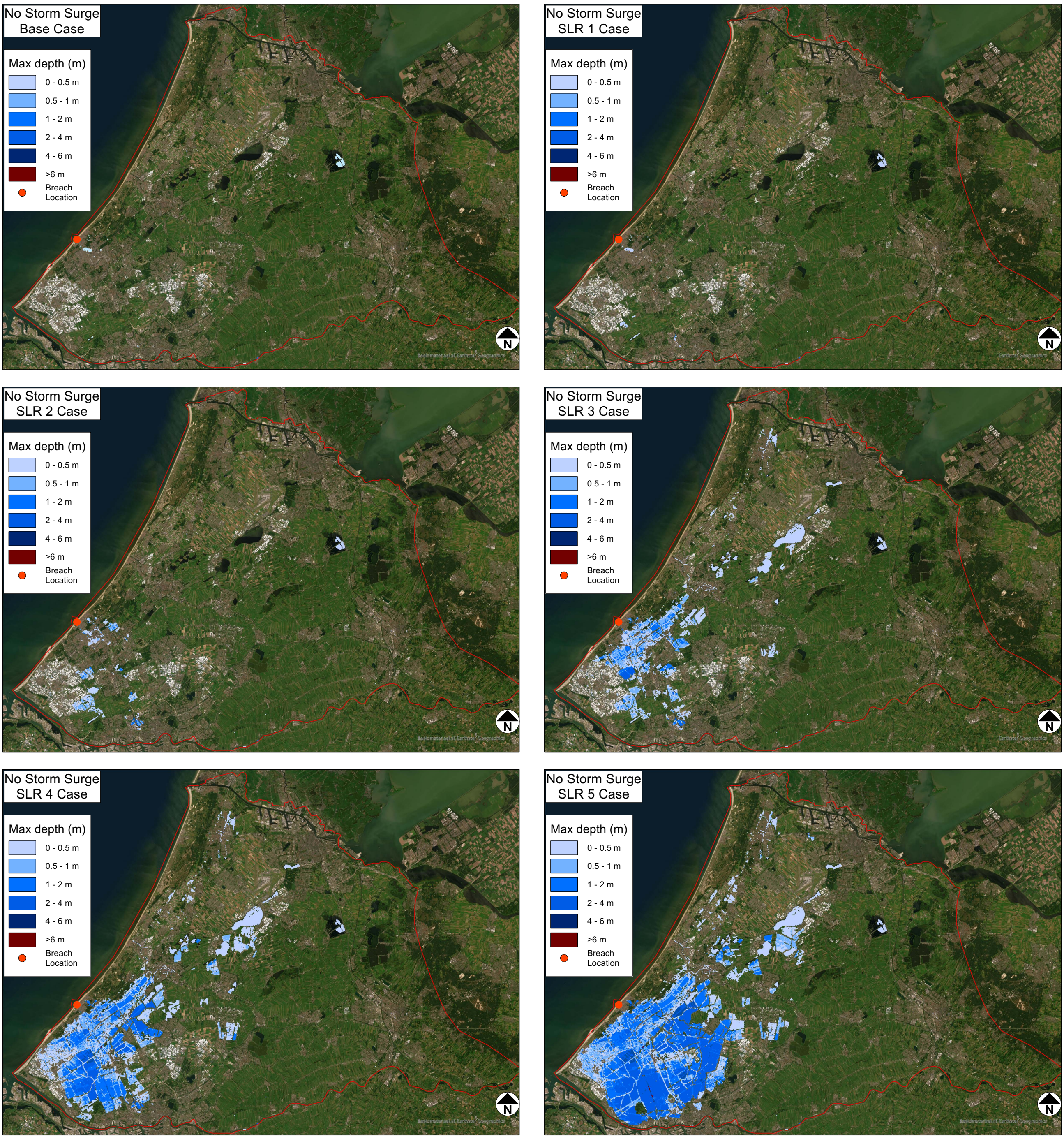

Figure 79: Breach at The Hague with a no storm surge

The Hague

C.2.2 The Hague Arrival times

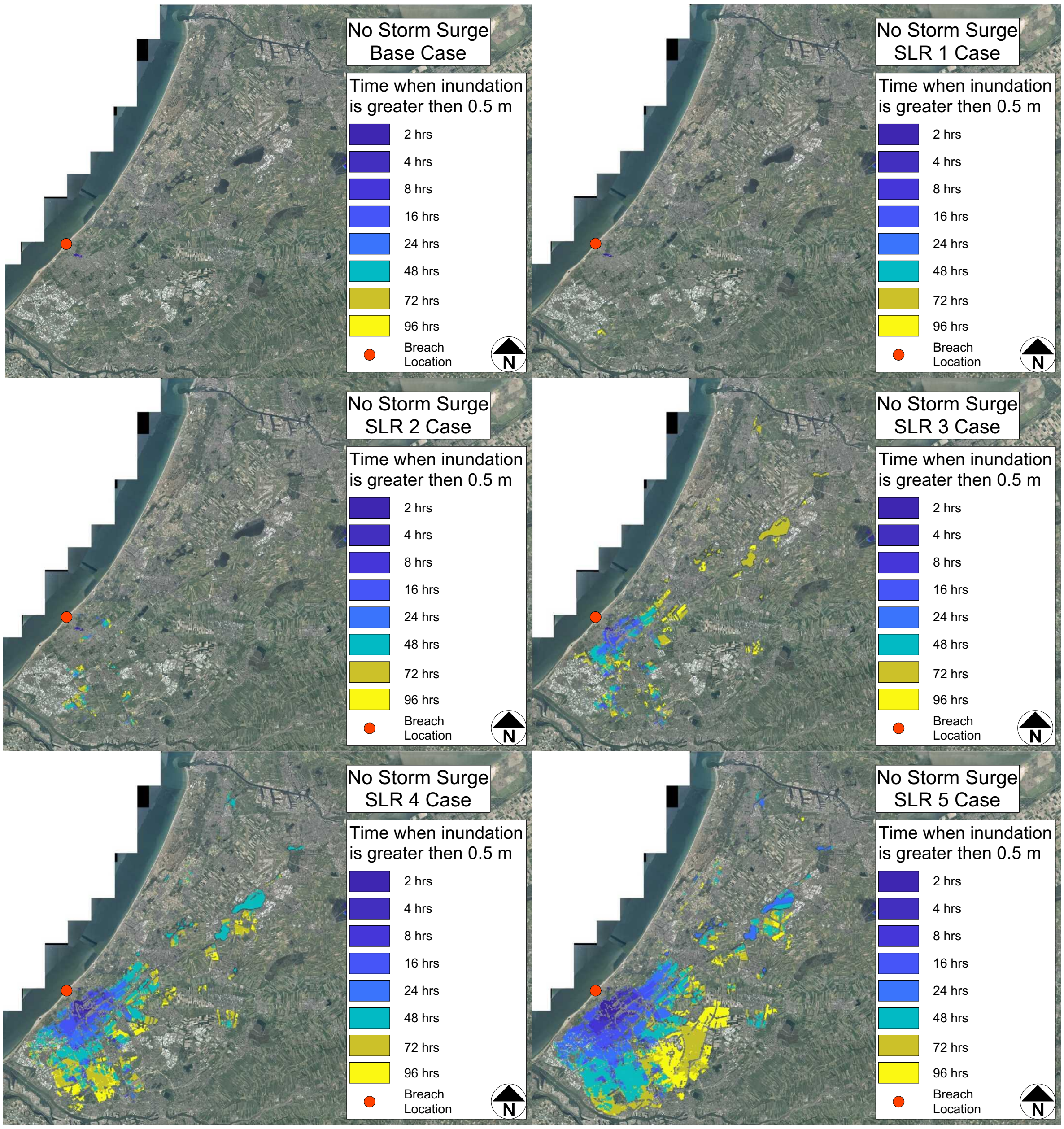

Figure 80: Time till areas are inundated to a depth of 0.5m from a breach at The Hague with a no storm surge

C.2.3 The Hague Land-use impact

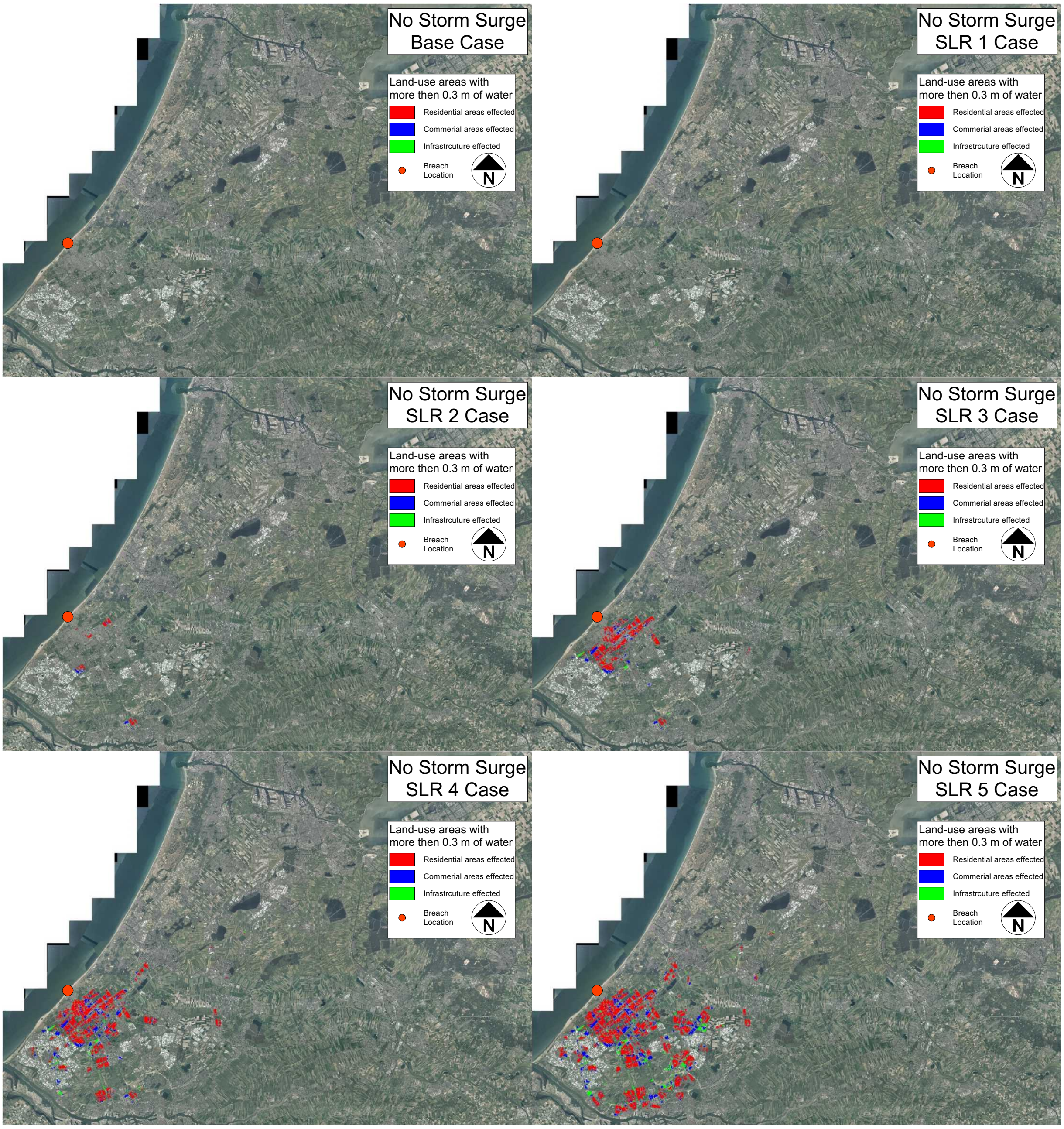

Figure 81: Effect on land-use areas from a breach at The Hague with a no storm surge

C.2.4 The Hague Inundation characteristics

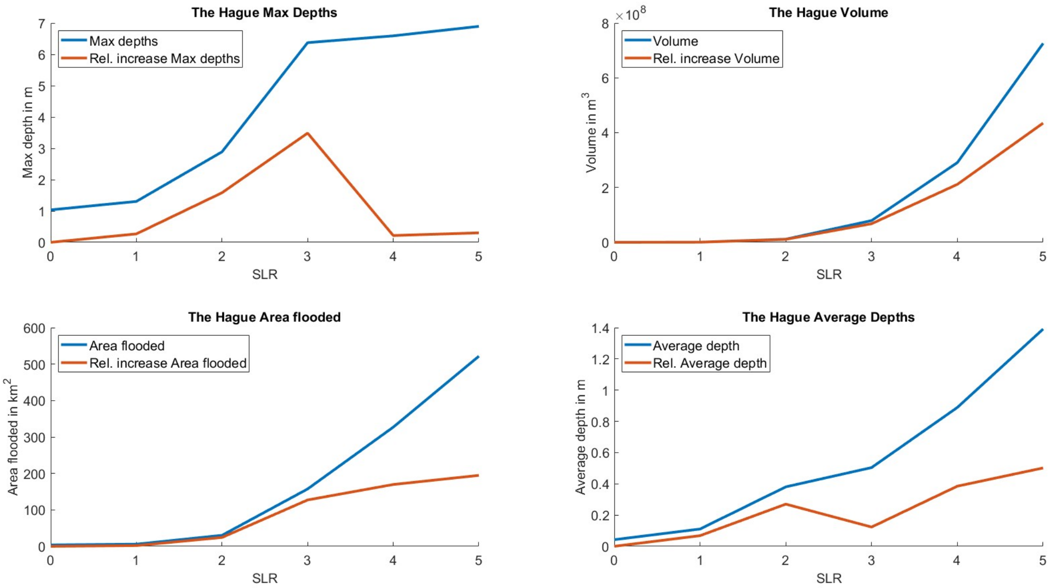

Figure 82: Inundation characteristics

C.2.5 The Hague Damage

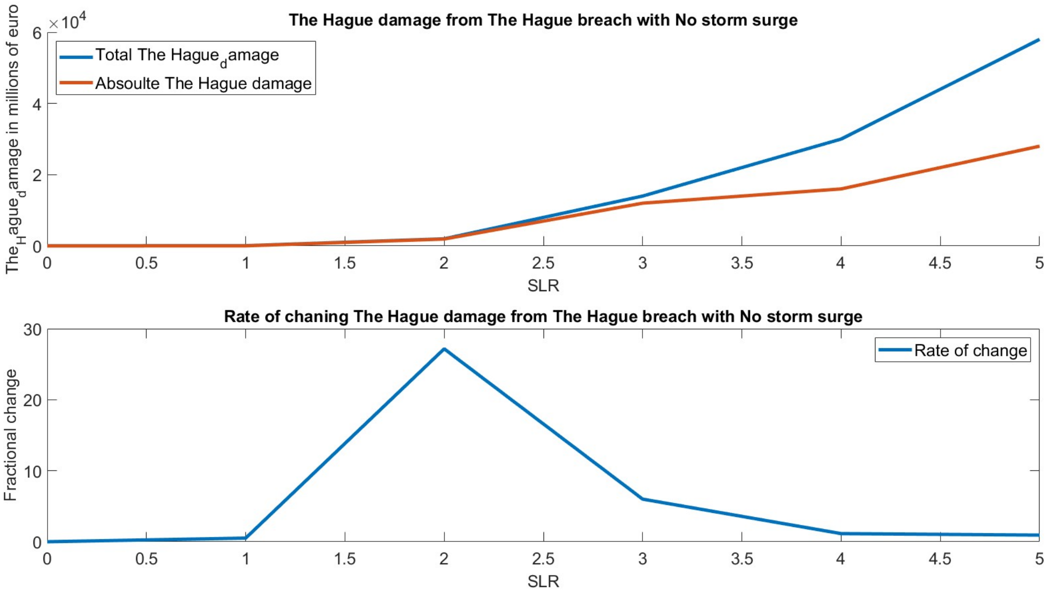

Figure 83: The Hague Damage from no storm surge with SLR of 0-5m

C.2.6 The Hague fatalities

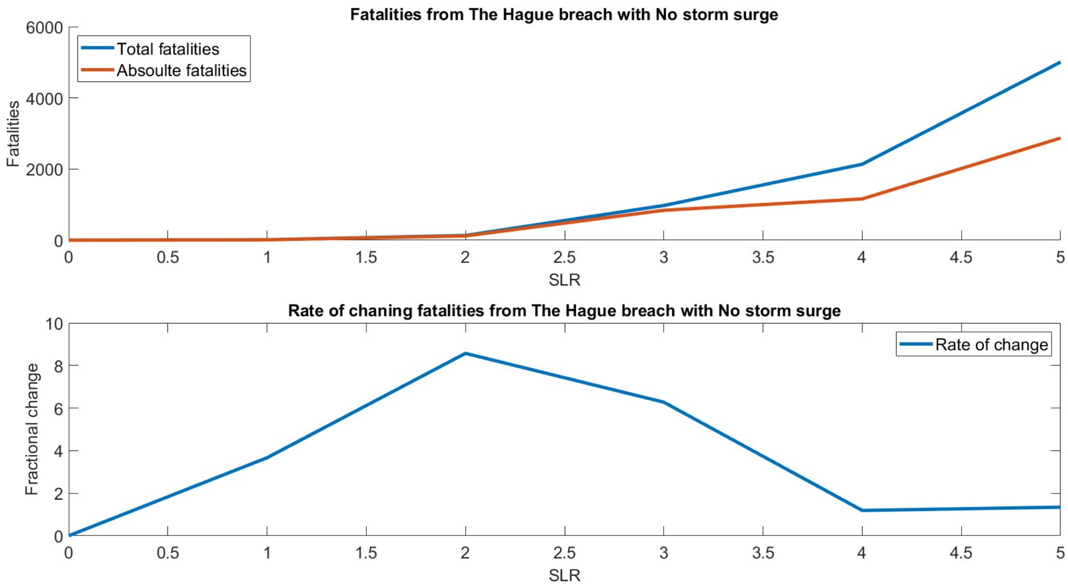

Figure 84: The Hague fatalities from no storm surge with SLR of 0-5m

C.3 IJmuiden breach

C.3.1 IJmuiden Inundation extent

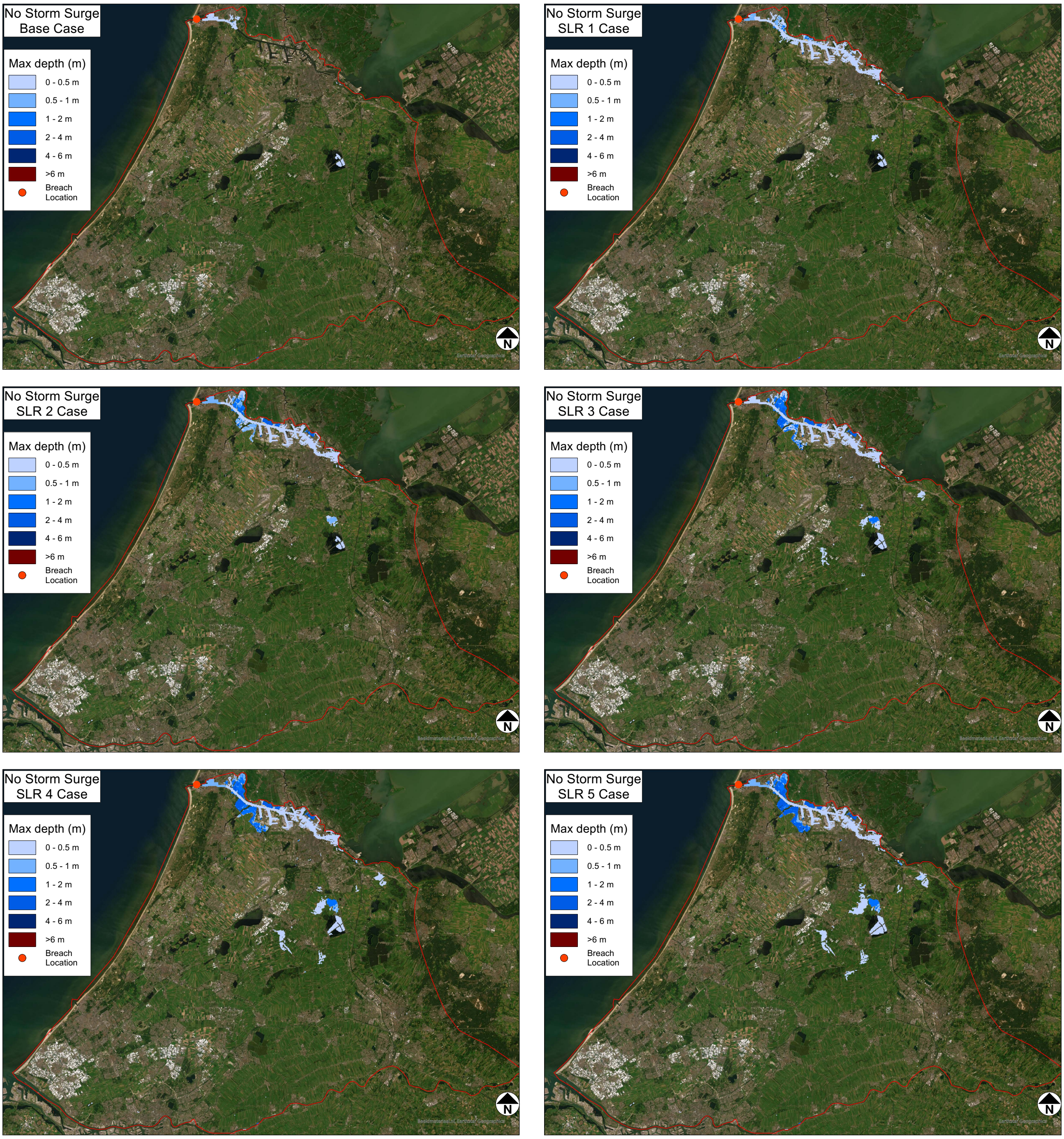

Figure 85: Breach at IJmuiden with a no storm surge

C.3.2 IJmuiden Arrival times

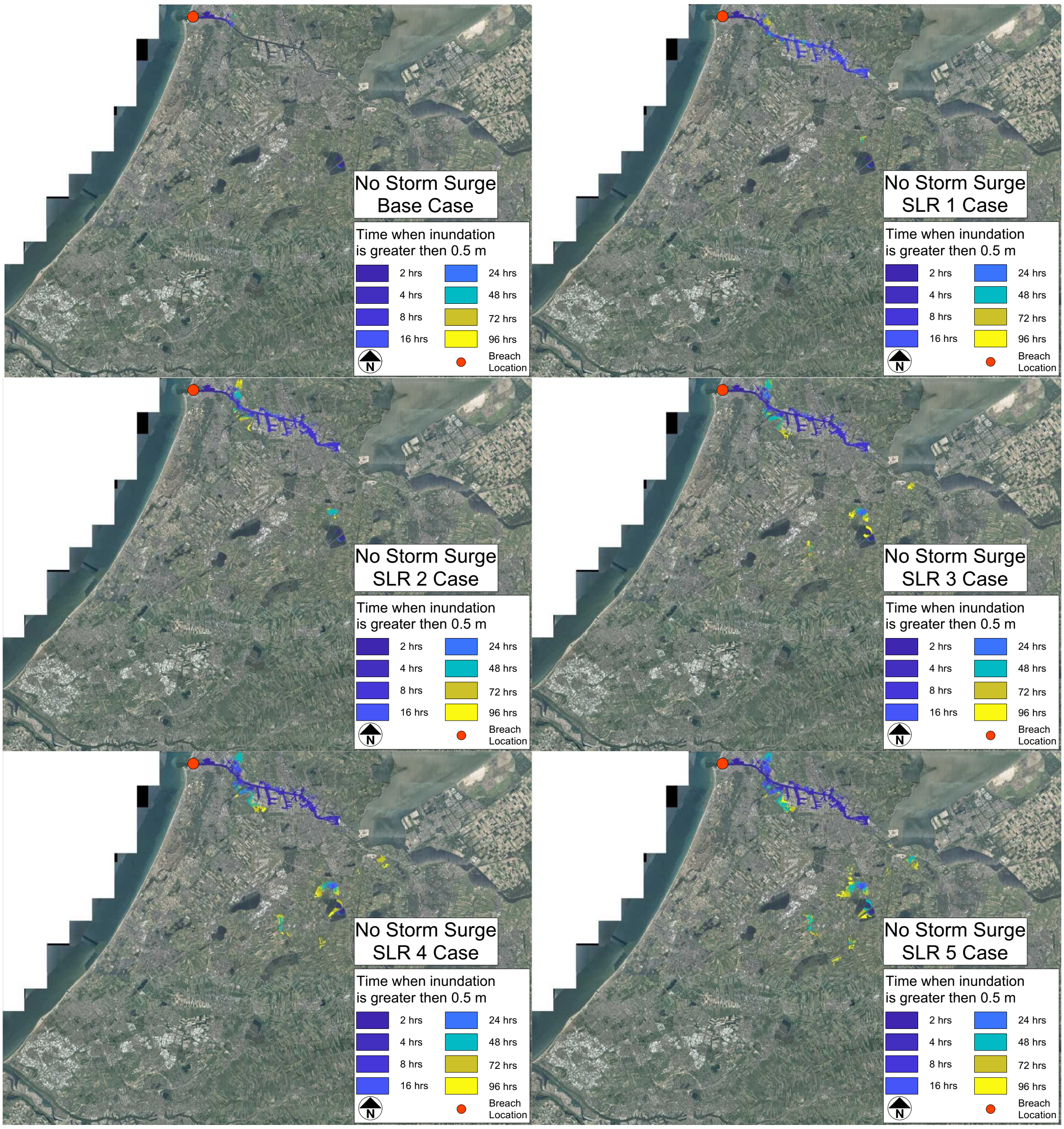

Figure 86: Time till areas are inundated to a depth of 0.5m from a breach at IJmuiden with a no storm surge

C.3.3 IJmuiden Land-use impact

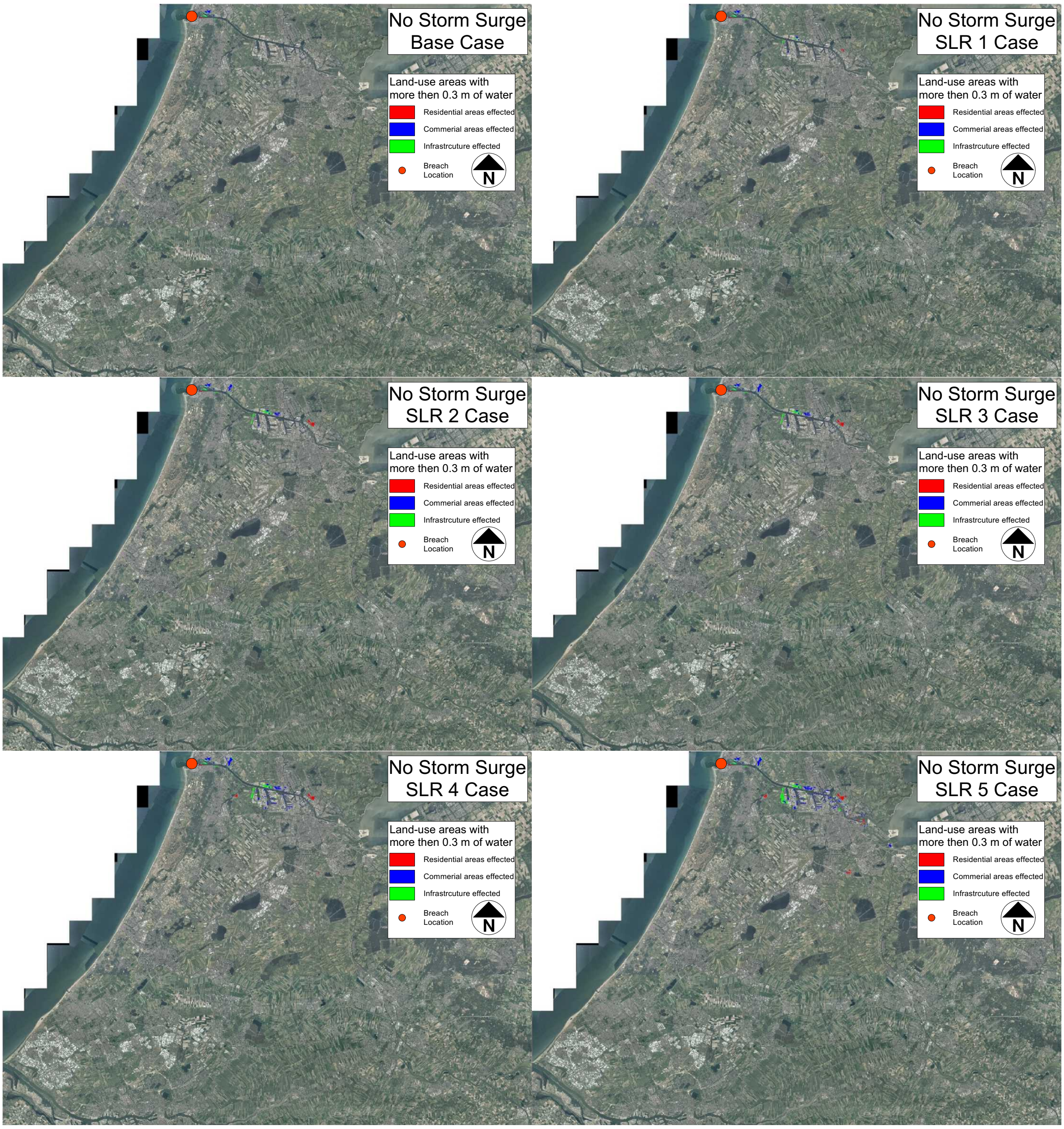

Figure 87: Effect on land-use areas from a breach at IJmuiden with a no storm surge

C.3.4 IJmuiden Inundation characteristics

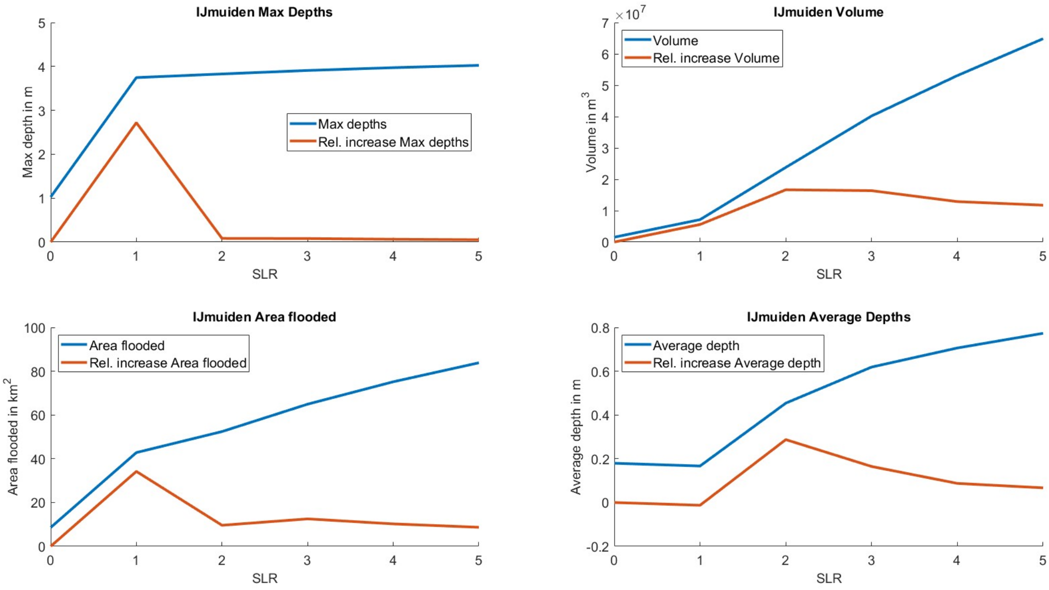

Figure 88: Inundation characteristics from a breach at IJmuiden with SLR of 0-5m

C.3.5 IJmuiden Damage

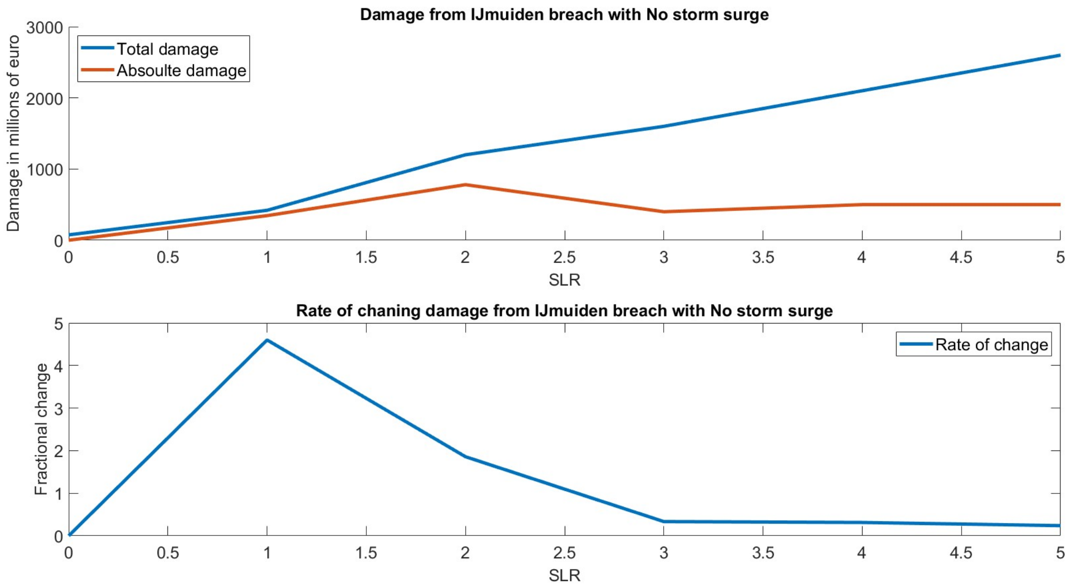

Figure 89: IJmuiden Damage from no storm surge with SLR of 0-5m

C.3.6 IJmuiden fatalities

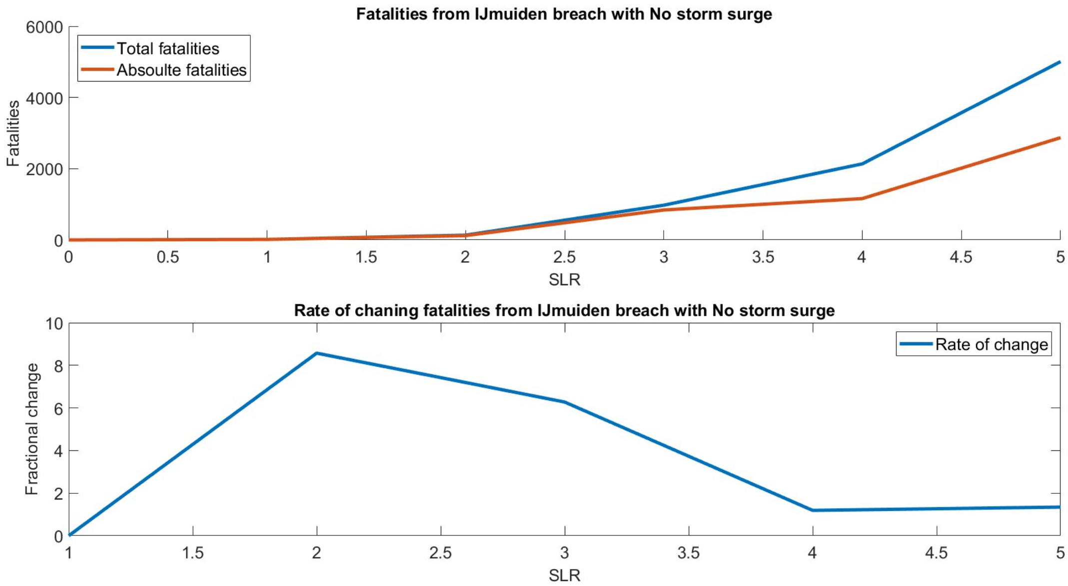

Figure 90: IJmuiden fatalities from no storm surge with SLR of 0-5m

D Results for average storm surge

The following section presents the results of the breaches with average storm surge. This reflects the situation where the dikes would fail under a storm surge with varying SLR.

D.1 Katwijk breach

D.1.1 Katwijk Inundation extent

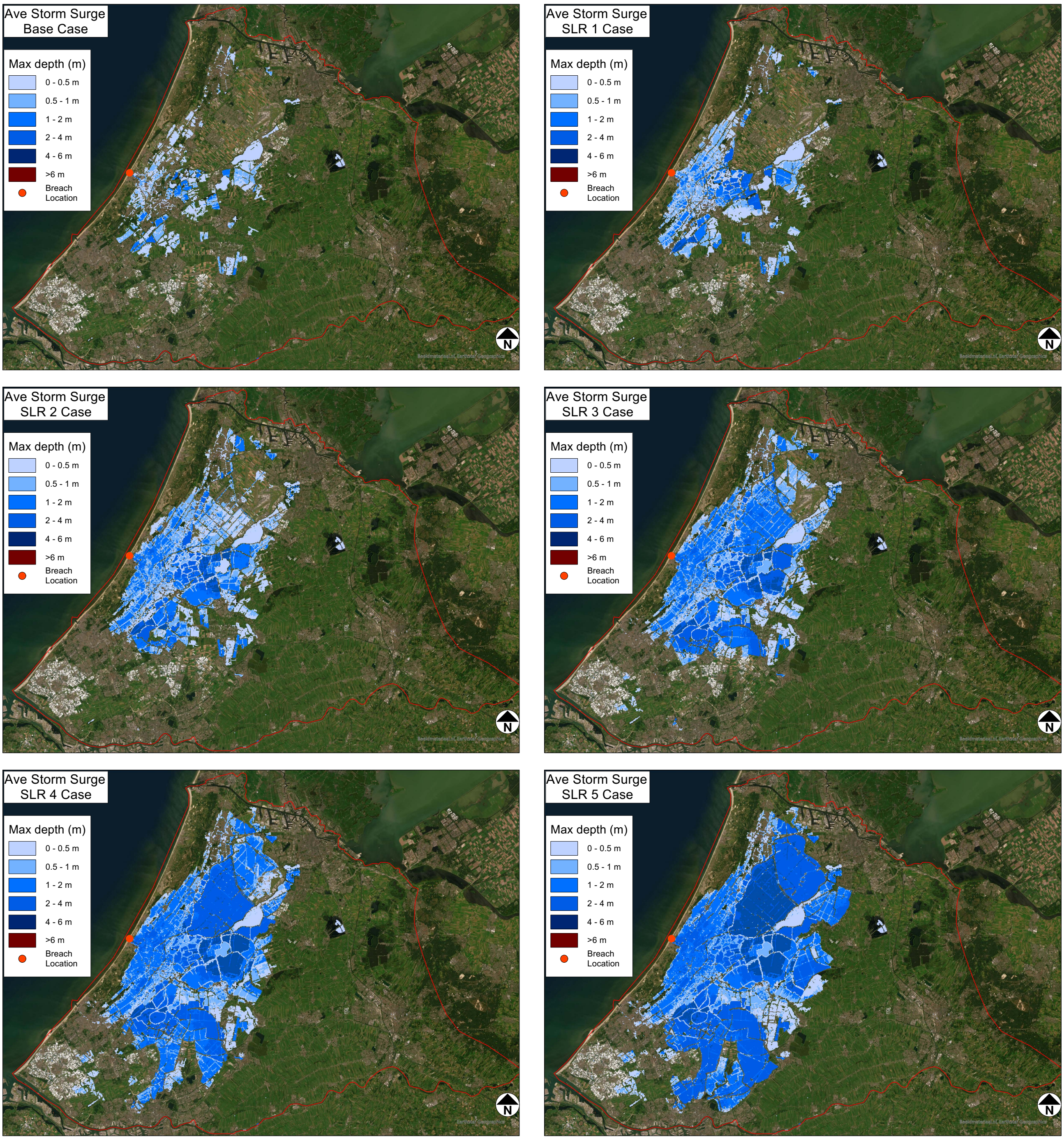

Figure 91: Breach at Katwijk with an average storm surge

D.1.2 Katwijk Arrival times

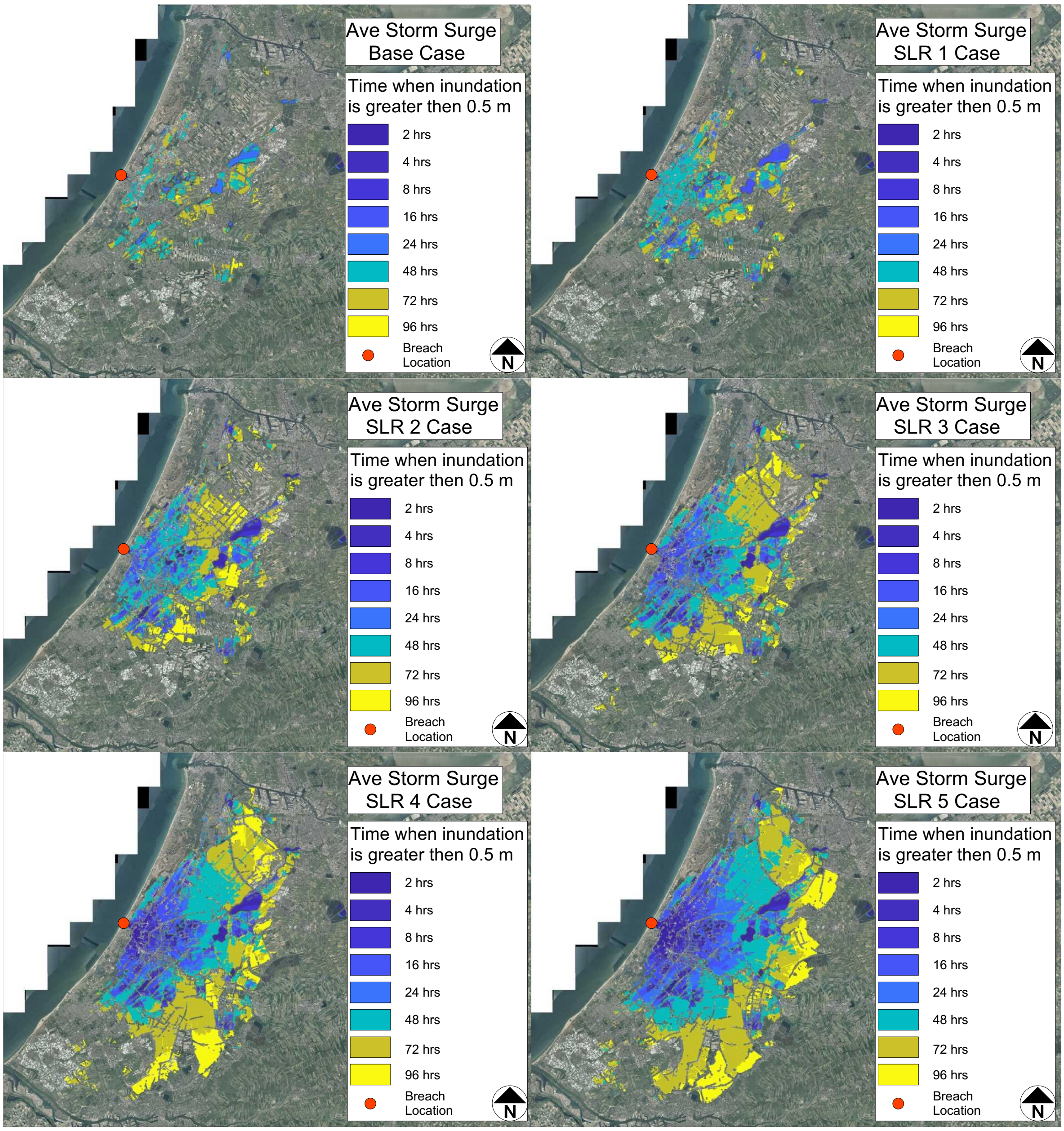

Figure 92: Time till areas are inundated to a depth of 0.5m from a breach at Katwijk with an average storm surge

D.1.3 Katwijk Land-use impact

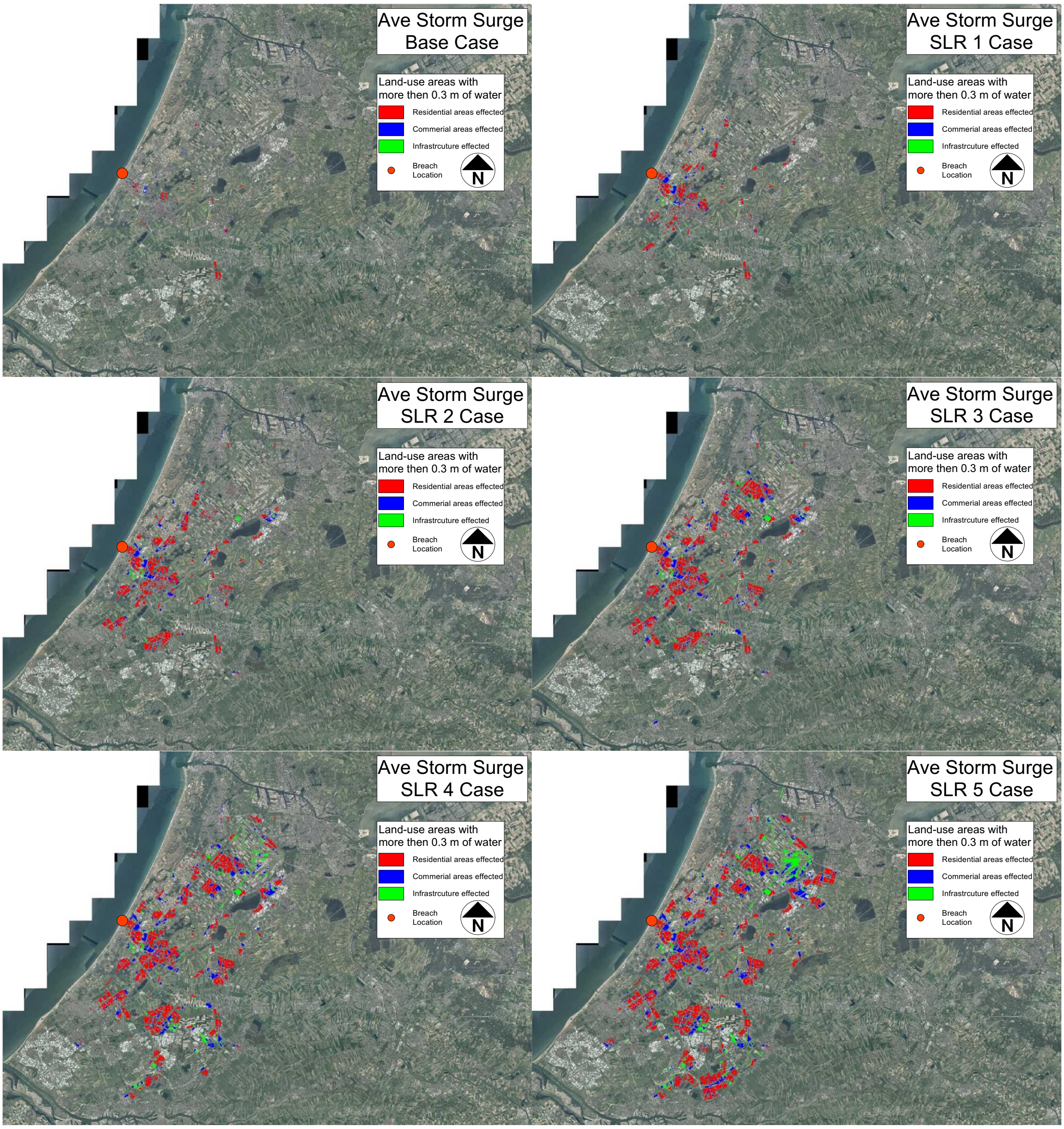

Figure 93: Effect on land-use areas from a breach at Katwijk with an average storm surge

D.1.4 Katwijk Inundation characteristics

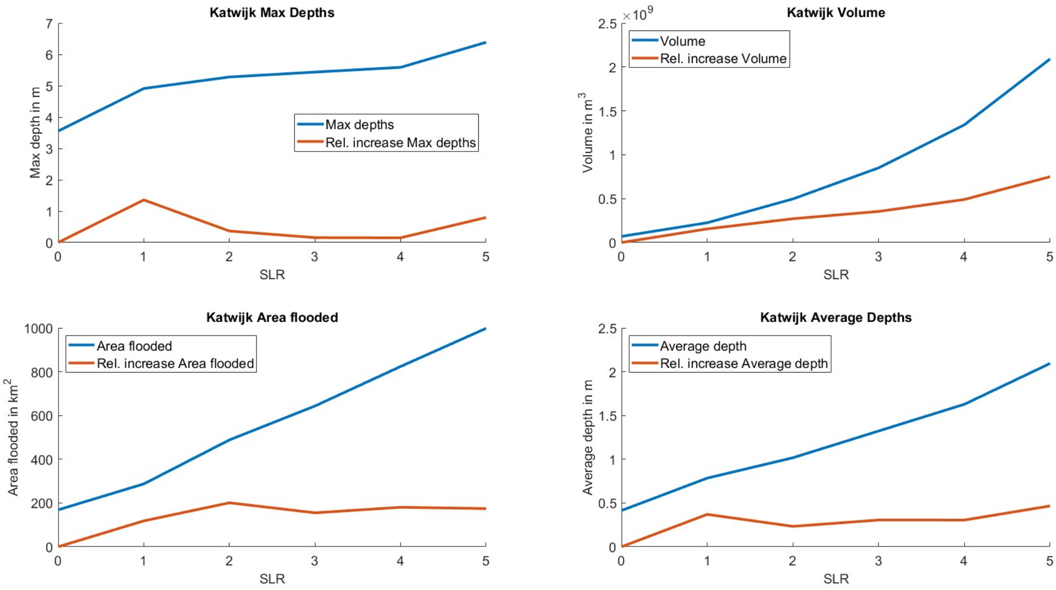

Figure 94: Inundation characteristics from a breach at Katwijk with SLR of 0-5m

D.1.5 Katwijk Damage

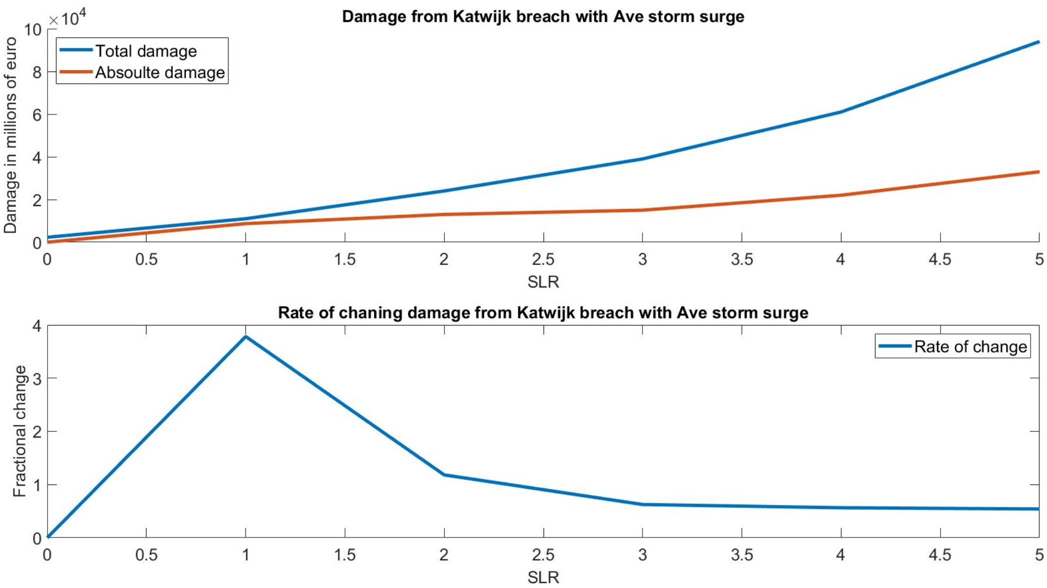

Figure 95: Katwijk Damage from average storm surge with SLR of 0-5m

D.1.6 Katwijk fatalities

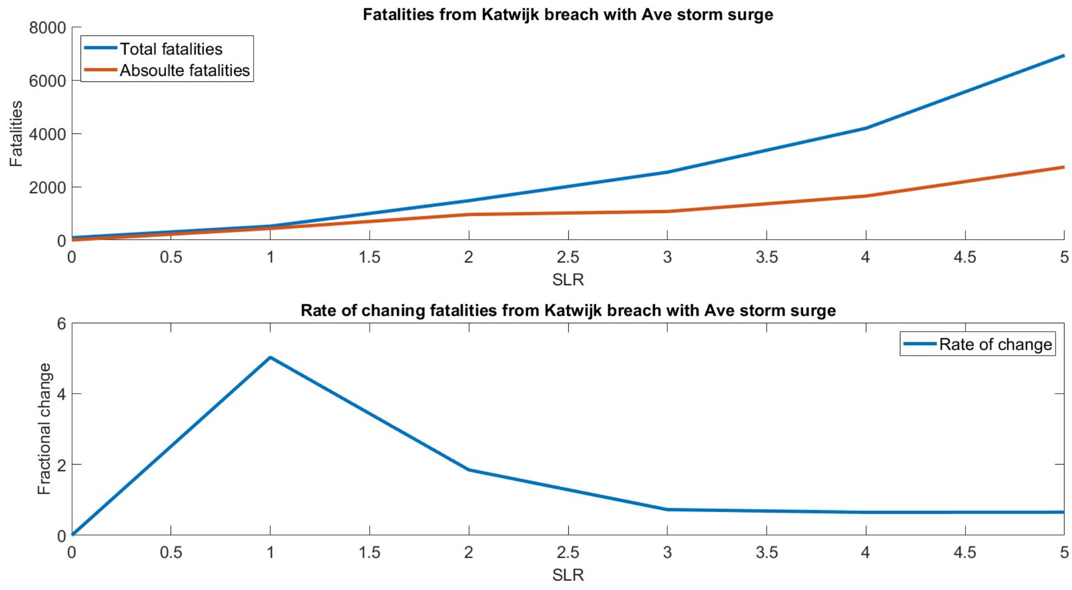

Figure 96: Katwijk fatalities from average storm surge with SLR of 0-5m

D.2 The Hague breach

D.2.1 The Hague Inundation extent

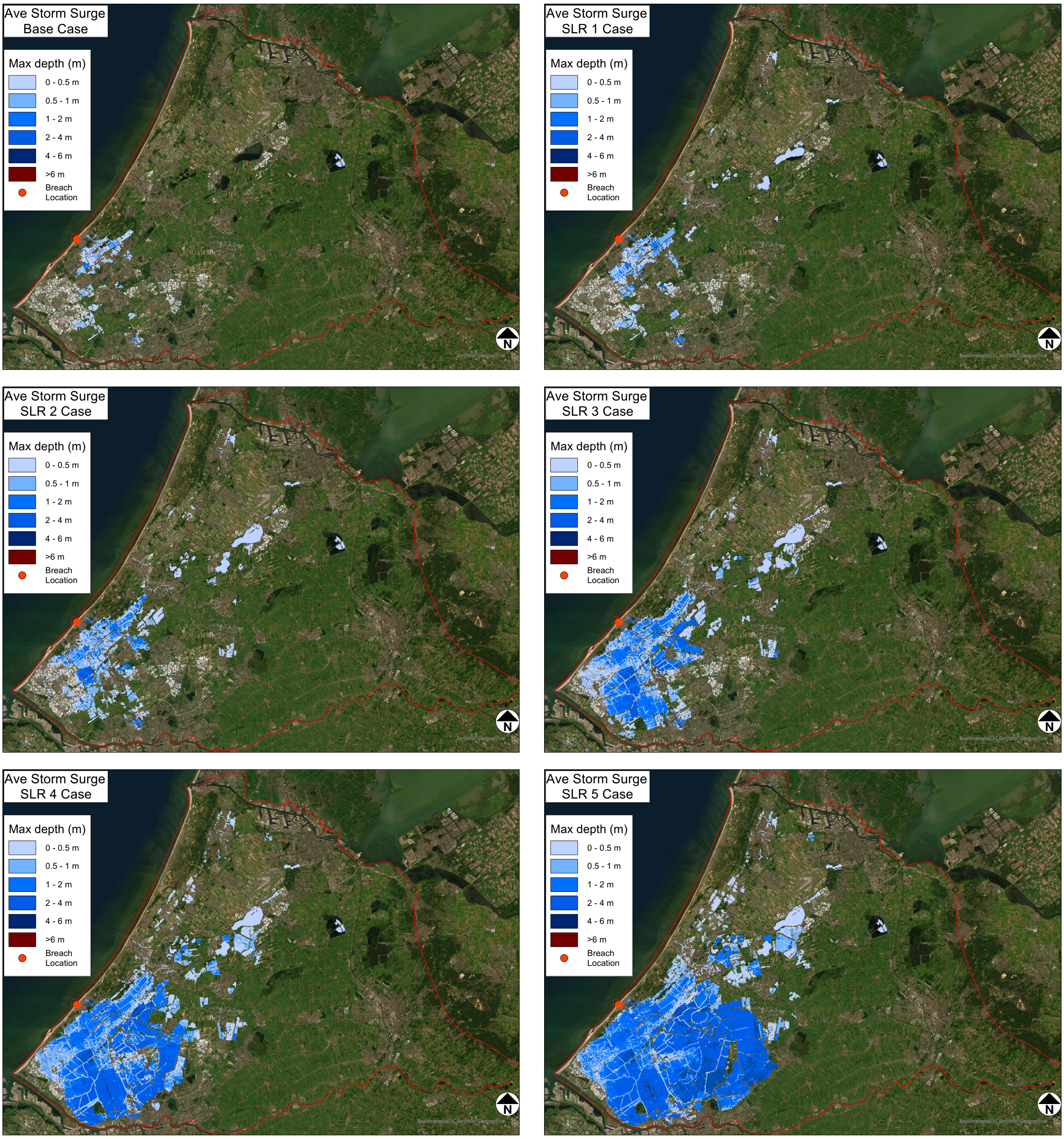

Figure 97: Breach at The Hague with an average storm surge

The Hague

D.2.2 The Hague Arrival times

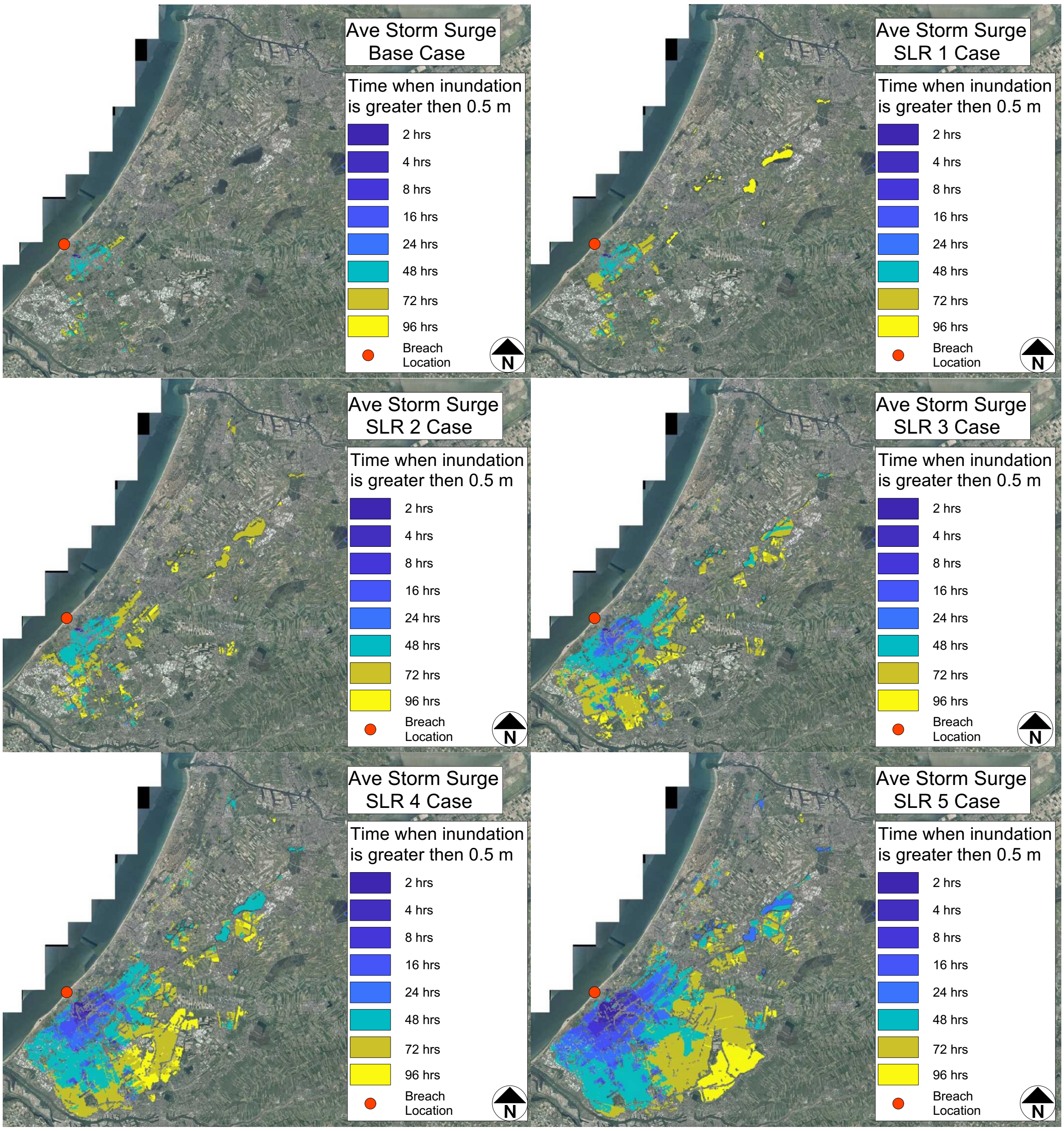

Figure 98: Time till areas are inundated to a depth of 0.5m from a breach at The Hague with an average storm surge

D.2.3 The Hague Land-use impact

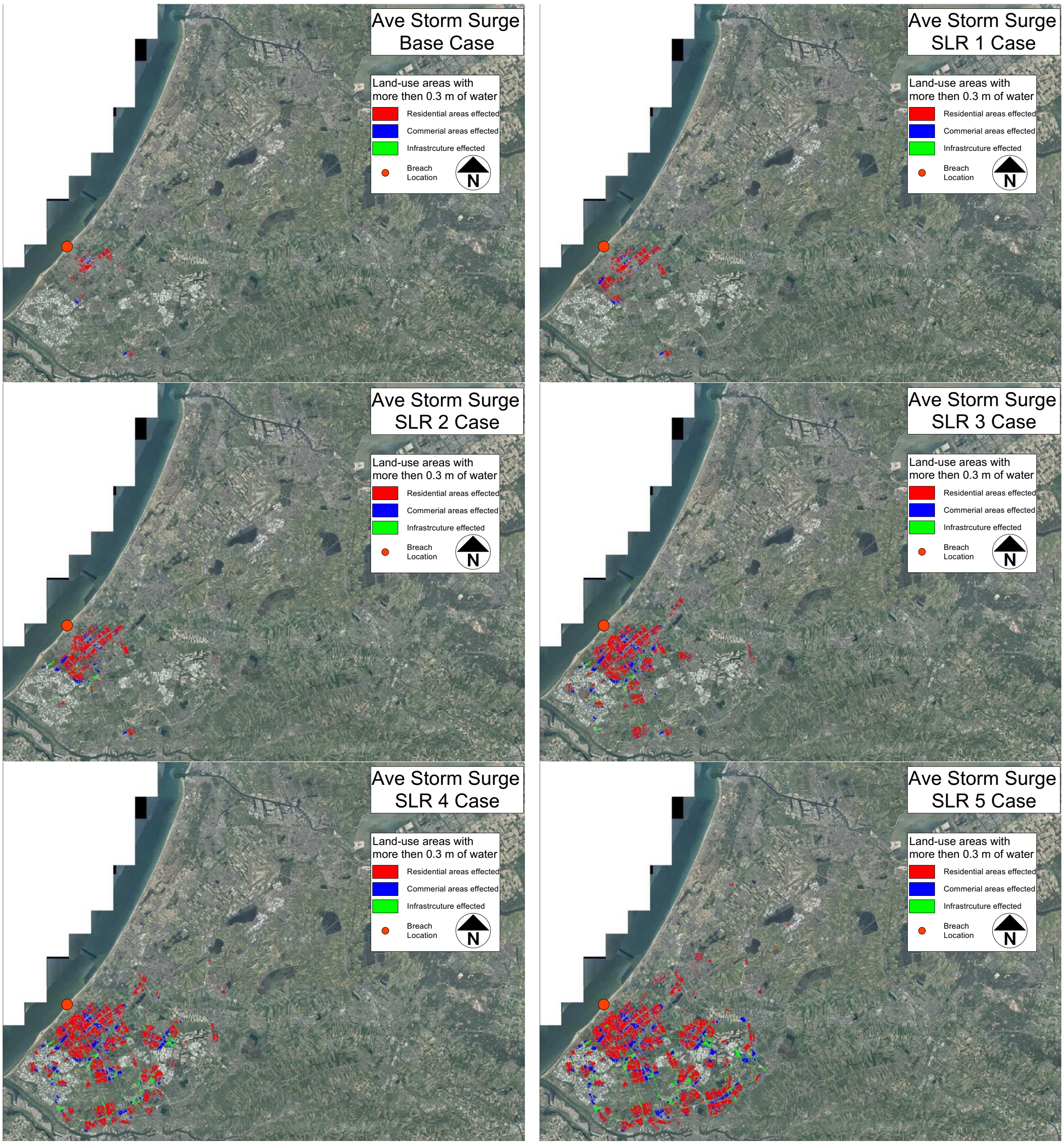

Figure 99: Effect on land-use areas from a breach at The Hague with an average storm surge

D.2.4 The Hague Inundation characteristics

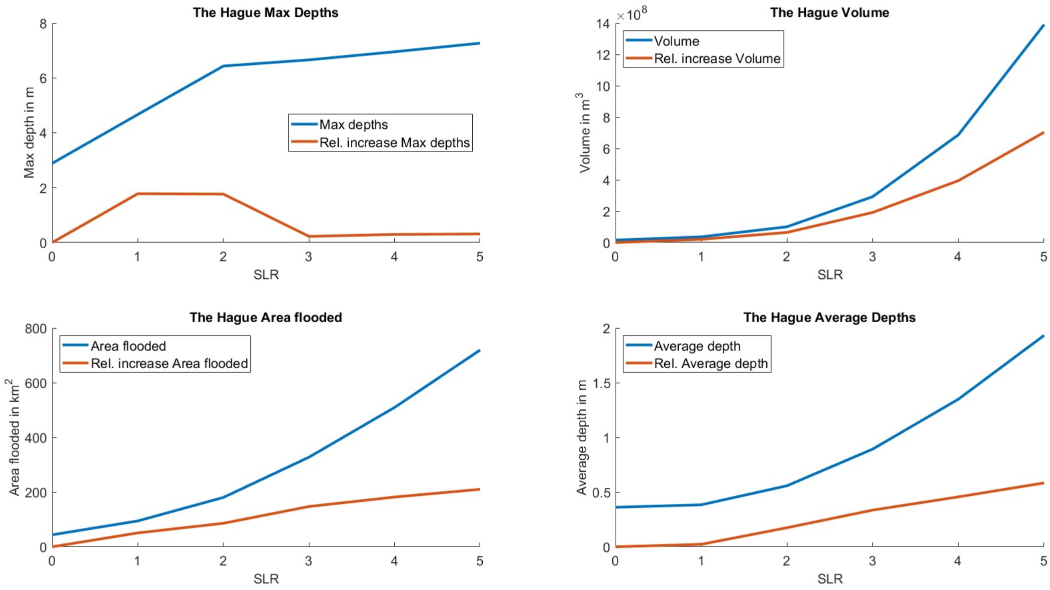

Figure 100: Inundation characteristics

D.2.5 The Hague Damage

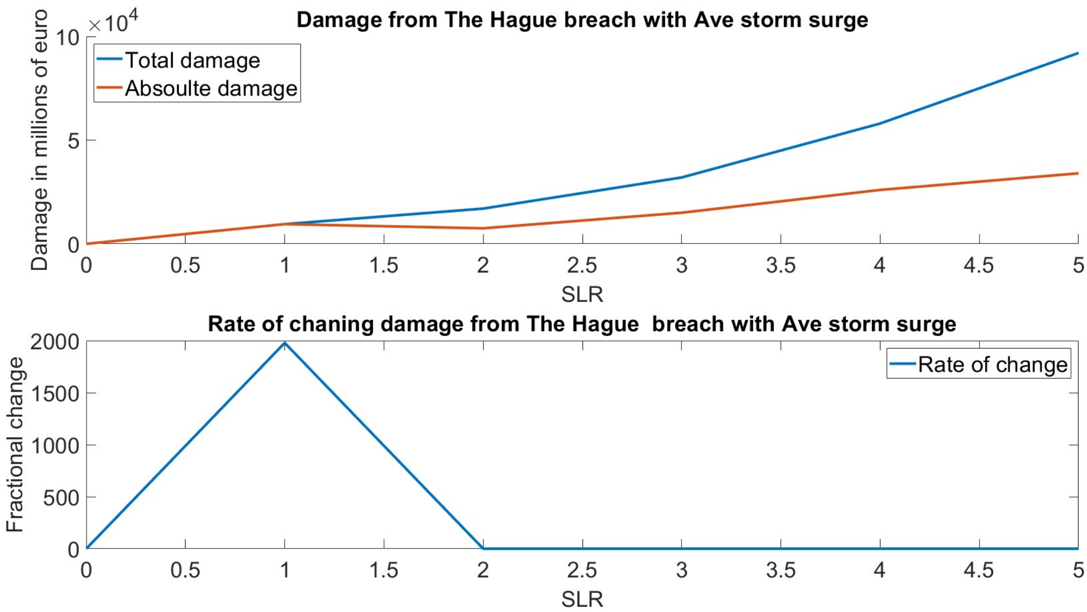

Figure 101: The Hague Damage from an average storm surge with SLR of 0-5m

D.2.6 The Hague fatalities

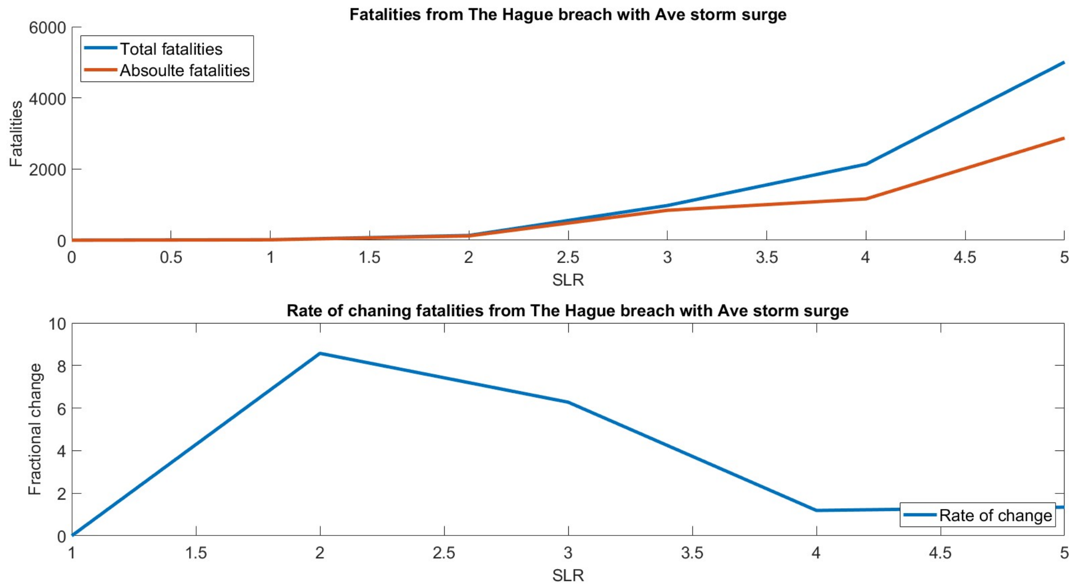

Figure 102: Katwijk fatalities from average storm surge with SLR of 0-5m

D.3 Hook of Holland breach

D.3.1 Hook of Holland Inundation extent

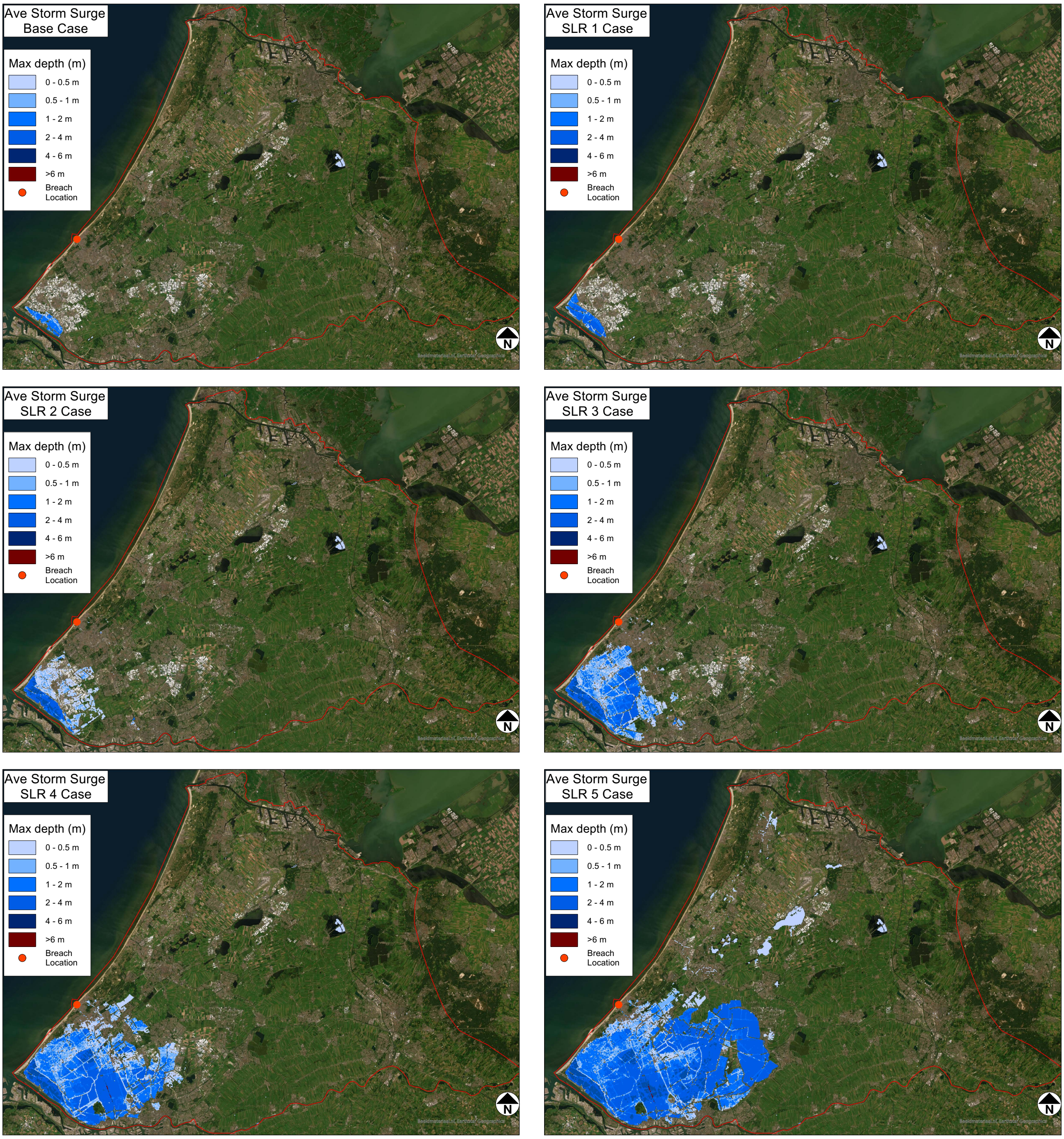

Figure 103: Breach at Hook of Holland with an average storm surge

The Hague

D.3.2 Hook of Holland Arrival times

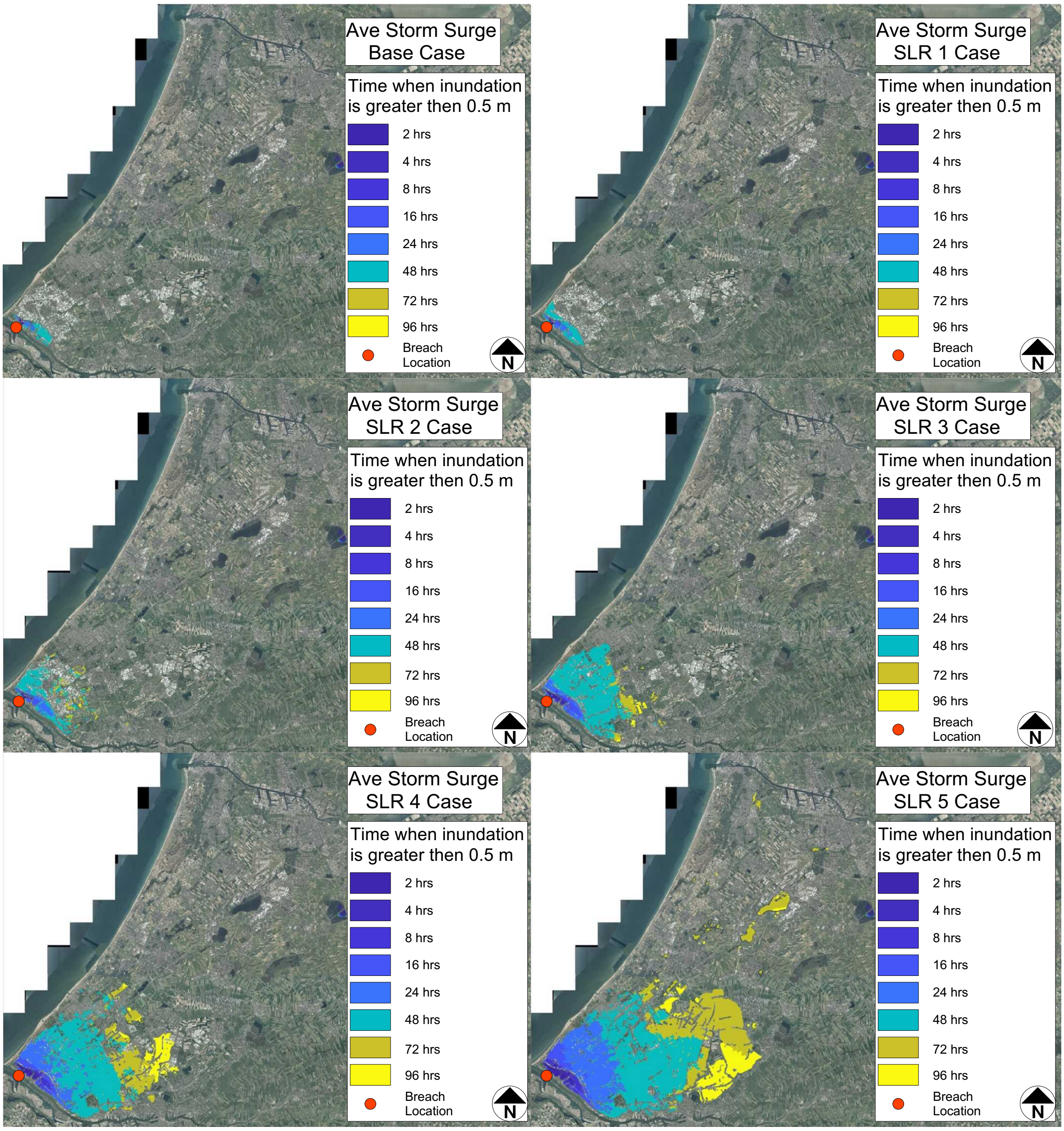

Figure 104: Time till areas are inundated to a depth of 0.5m from a breach at Hook of Holland with an average storm surge

D.3.3 Hook of Holland Land-use impact

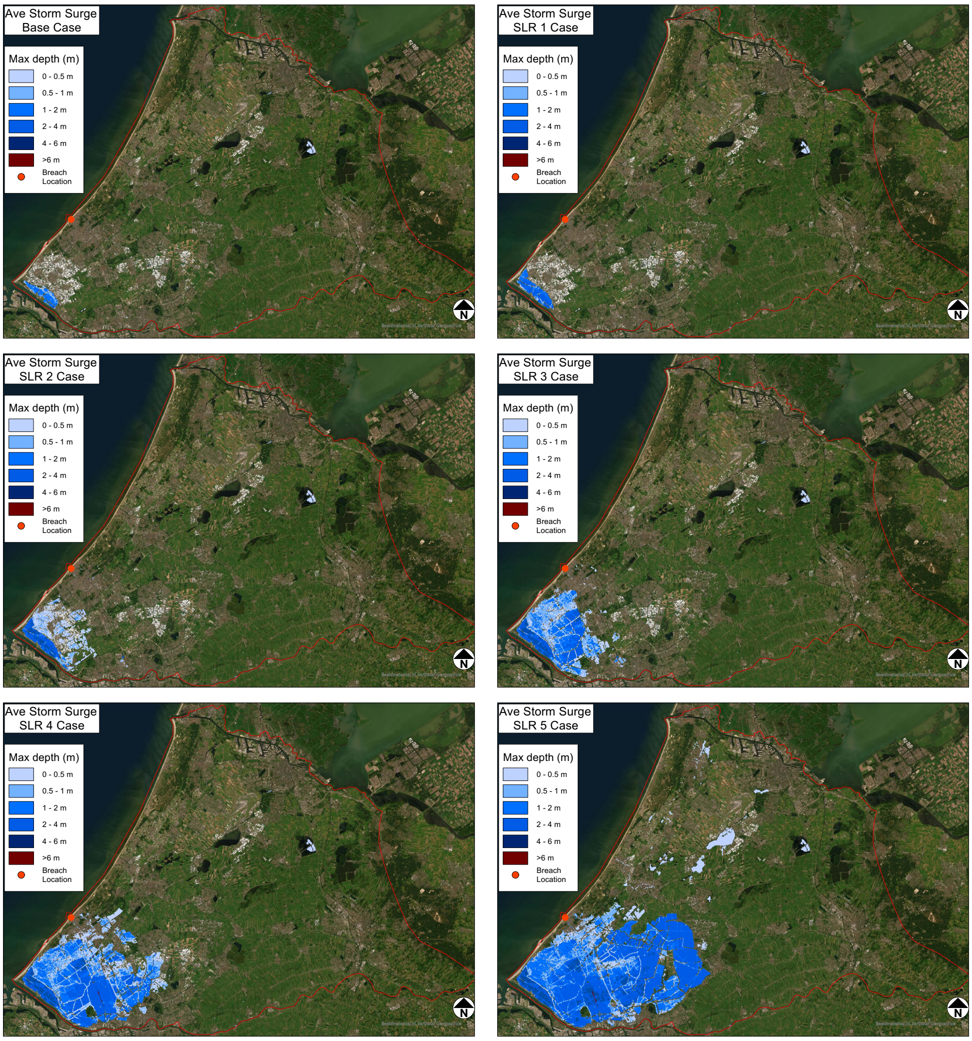

Figure 105: Effect on land-use areas from a breach at Hook of Holland with an average storm surge

D.3.4 Hook of Holland Inundation characteristics

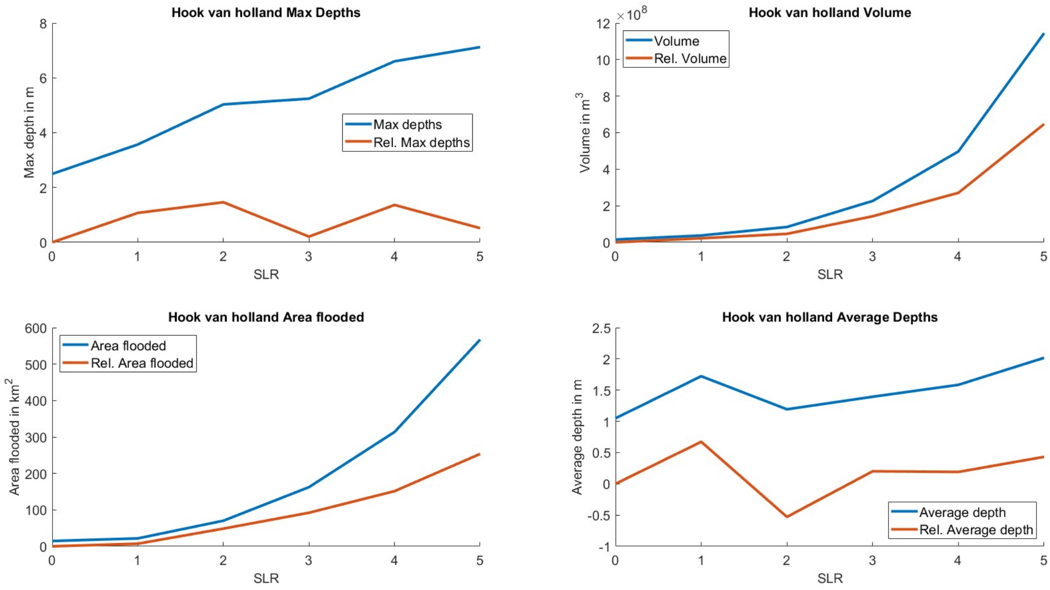

Figure 106: Inundation characteristics from a breach at Hook of Holland with SLR of 0-5m

D.3.5 Hook of Holland Damage

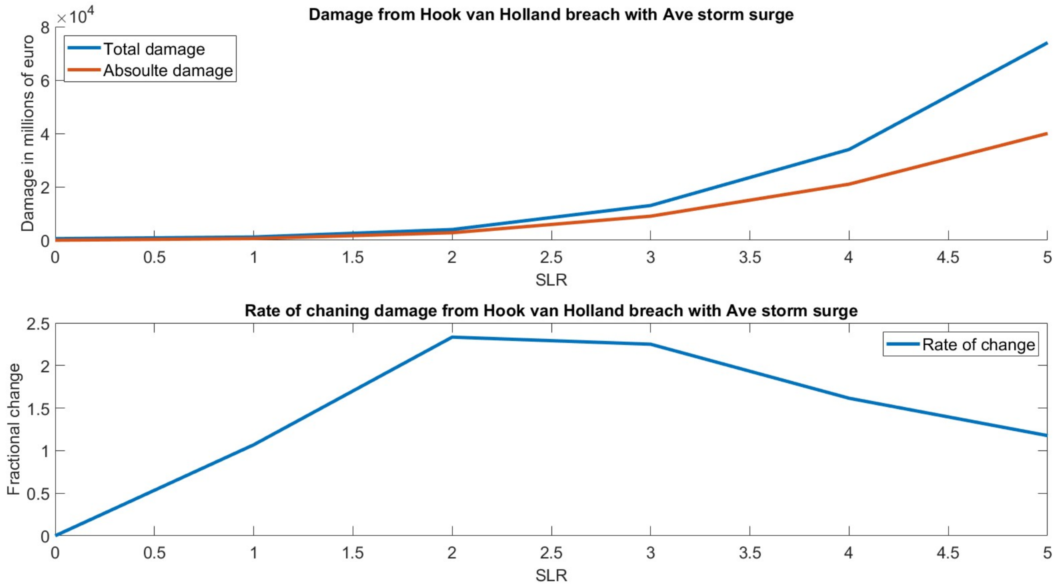

Figure 107: Hook of Holland Damage from an average storm surge with SLR of 0-5m

D.3.6 Hook of Holland fatalities

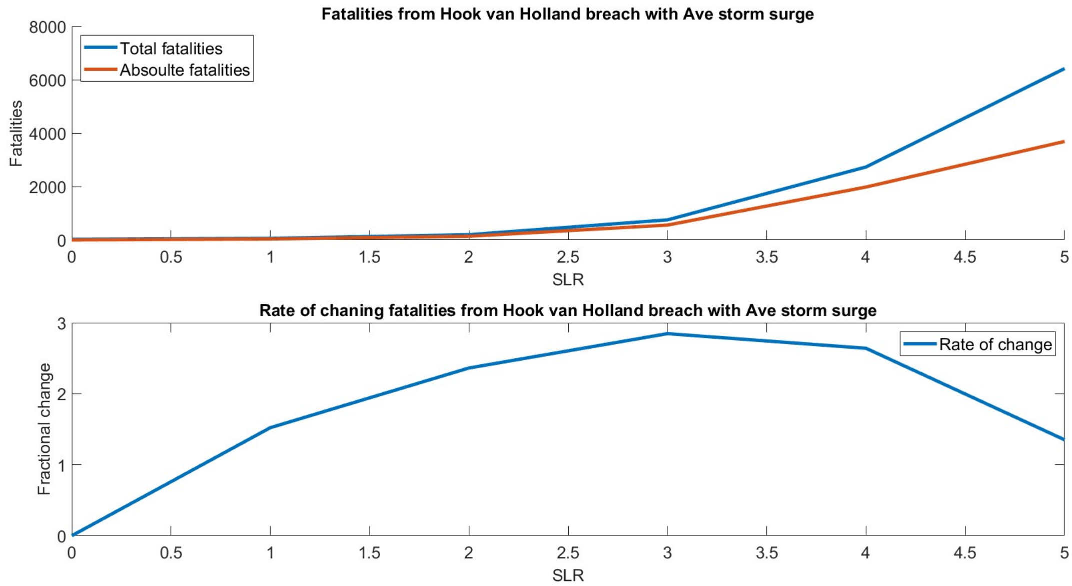

Figure 108: Hook of Holland fatalities from an average storm surge with SLR of 0-5m

D.4 Ijmuiden breach

D.4.1 Ijmuiden Inundation extent

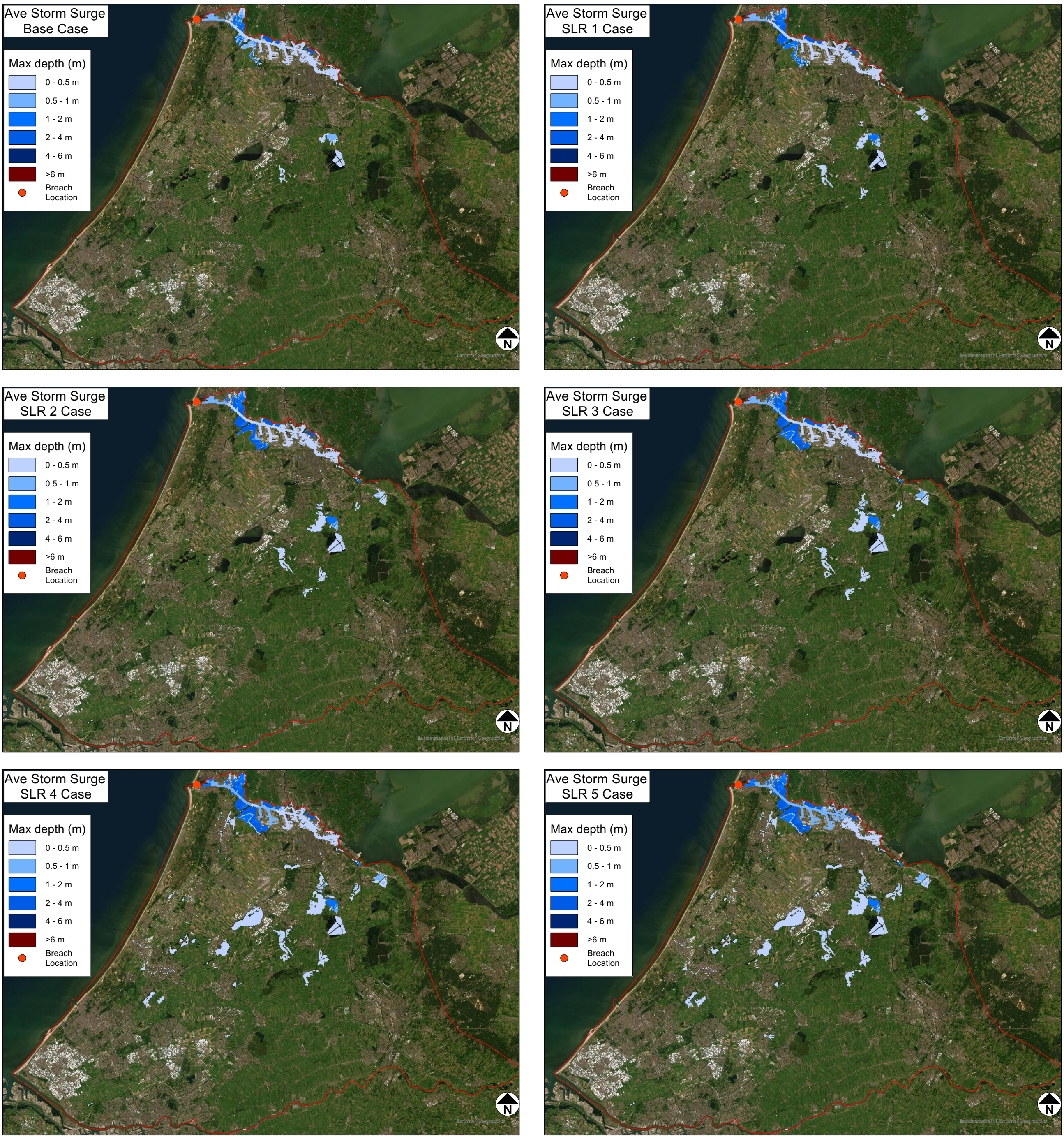

Figure 109: Breach at Ijmuiden with an average storm surge

D.4.2 Ijmuiden Arrival times

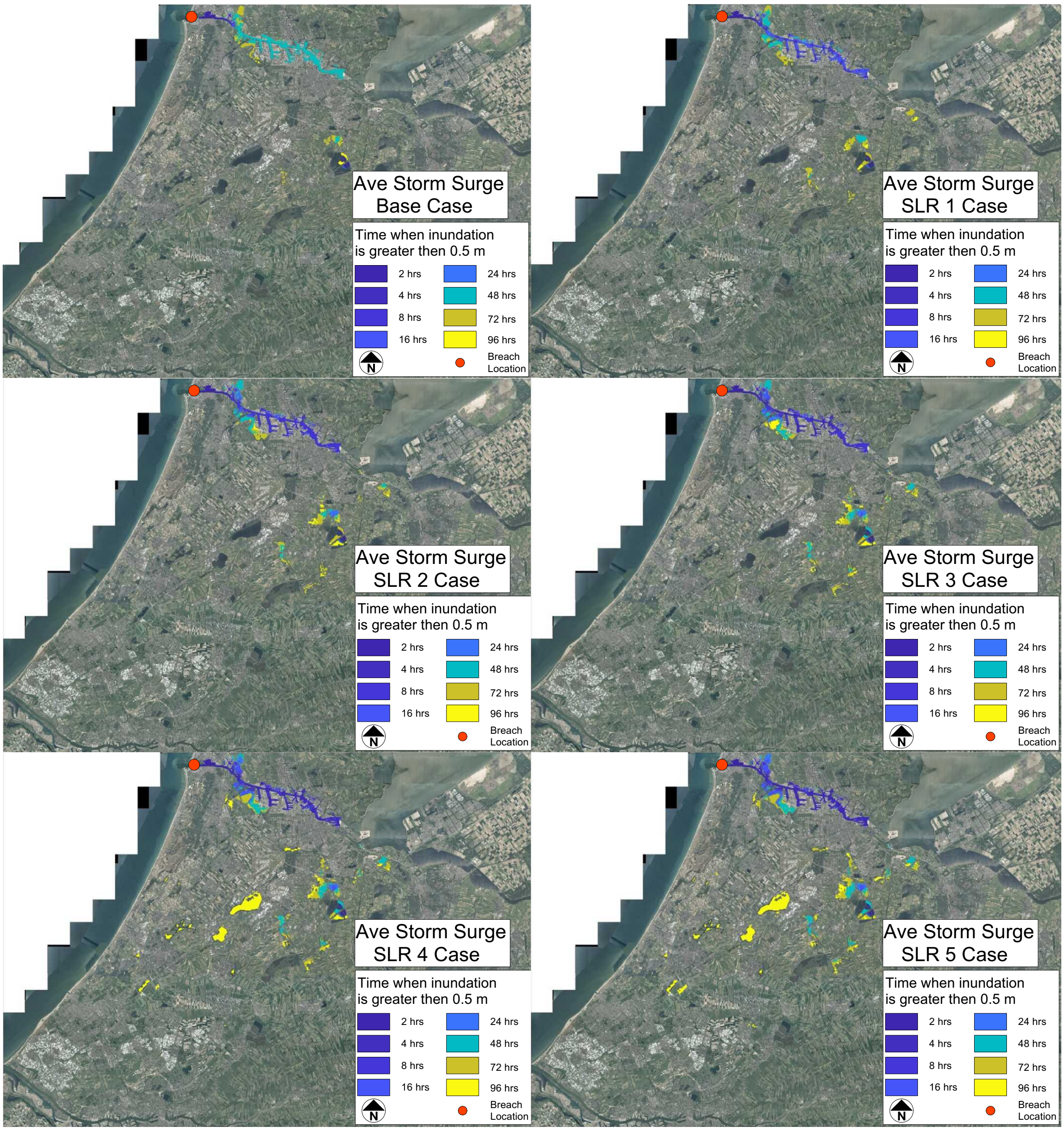

Figure 110: Time till areas are inundated to a depth of 0.5m from a breach at Ijmuiden with an average storm surge

D.4.3 Ijmuiden Land-use impact

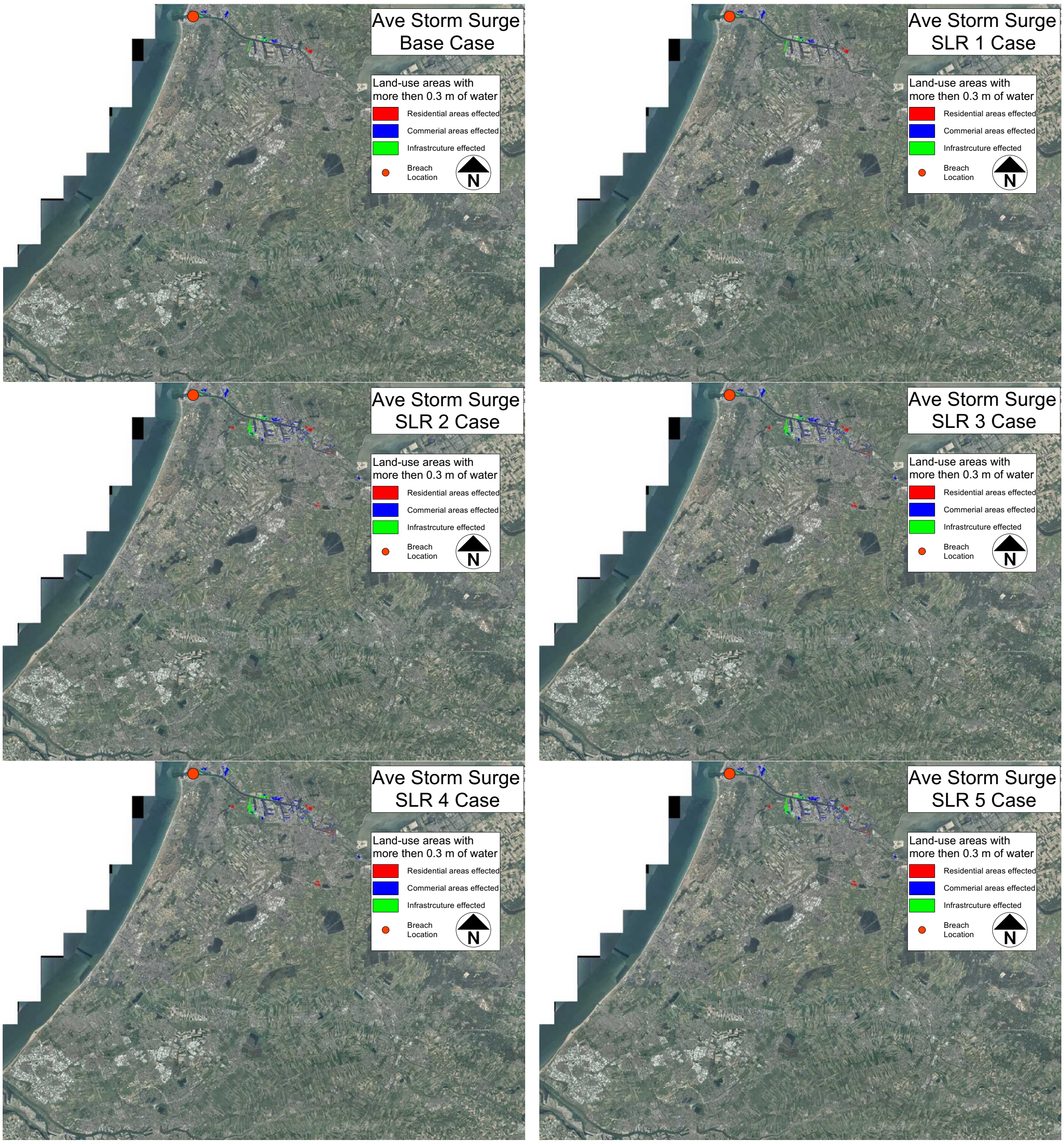

Figure 111: Effect on land-use areas from a breach at Ijmuiden with an average storm surge

D.4.4 Ijmuiden Inundation characteristics

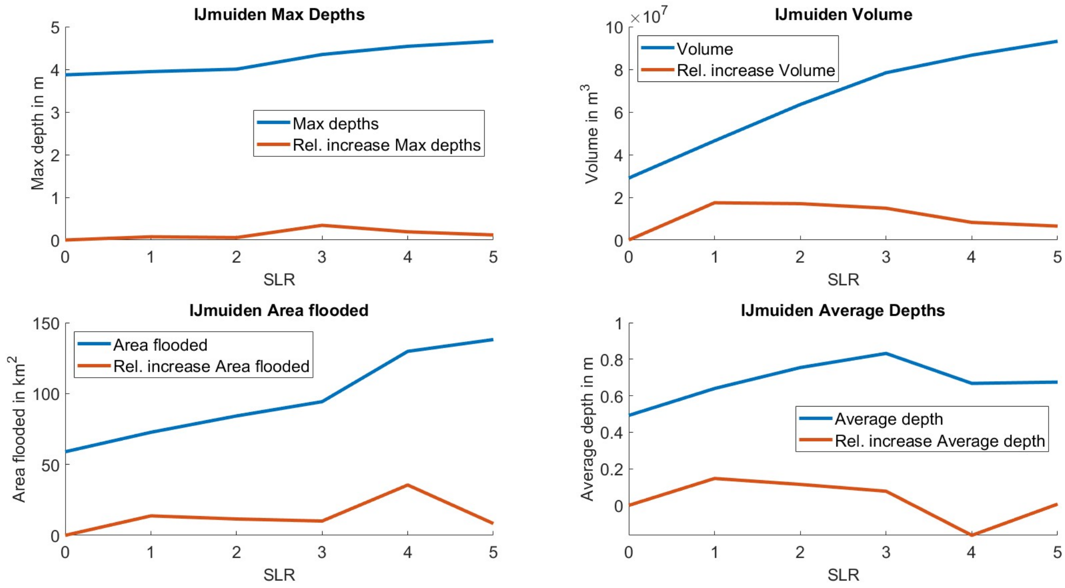

Figure 112: Inundation characteristics from a breach at IJmuiden with SLR of 0-5m

D.4.5 Ijmuiden Damage

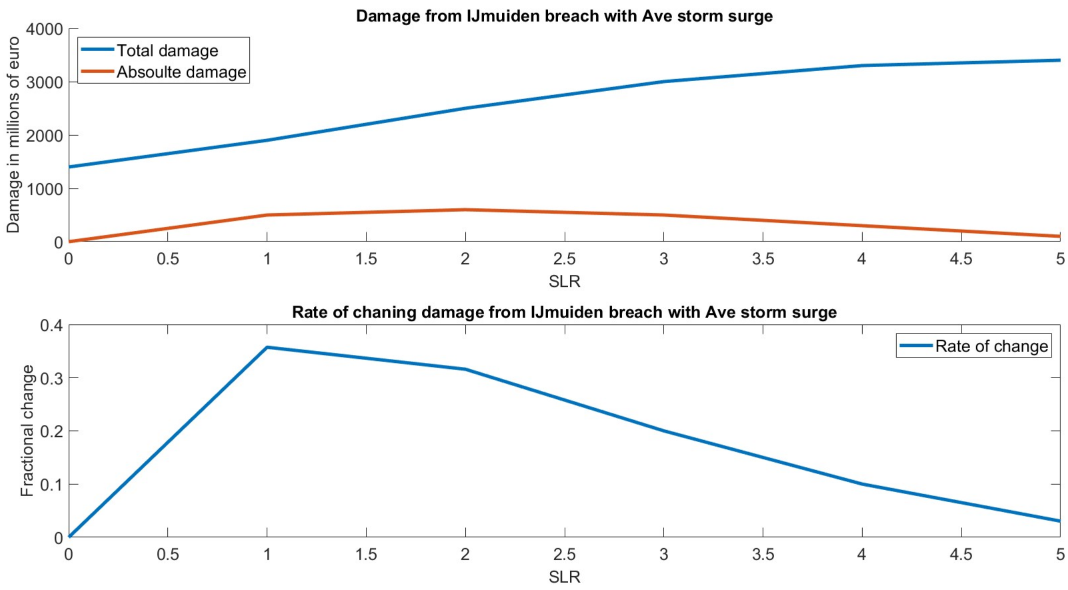

Figure 113: Ijmuiden Damage from an average storm surge with SLR of 0-5m

D.4.6 Ijmuiden fatalities

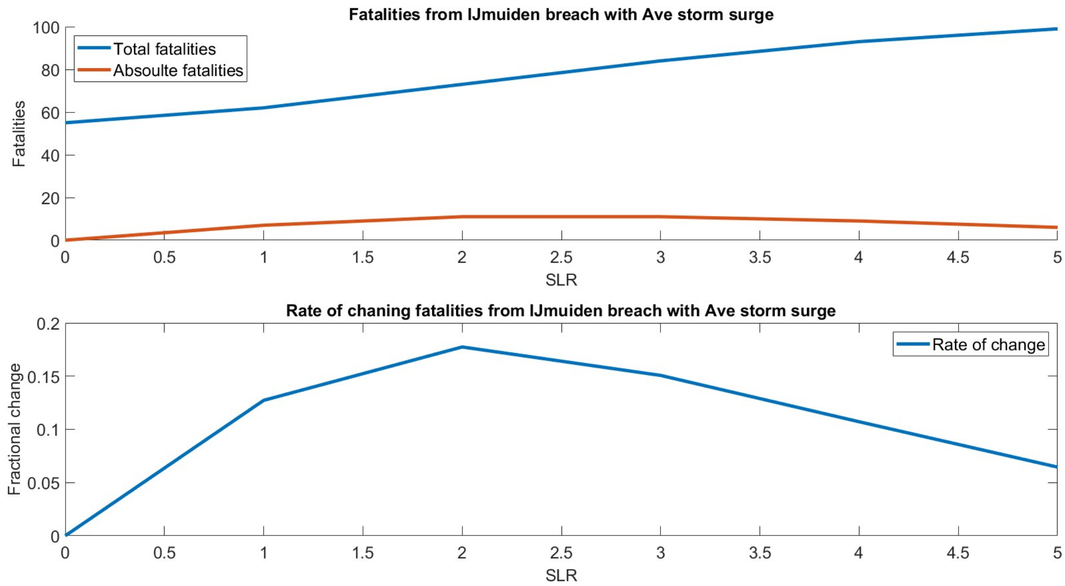

Figure 114: Ijmuiden fatalities from an average storm surge with SLR of 0-5m

E Matlab code

E.1 2D model

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clear,clc

Katwijk_Max_Surge_Volumes = [0.0824e+09 0.2462e+09 0.5152e+09 0.8838e+09
    1.3921e+09 2.1634e+09]; % Volumes found from SOBEK rungs

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opts = spreadsheetImportOptions("NumVariables", 942);

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opts.Sheet = "Sheet1";
opts.DataRange = "A1:AJF665";

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% Import the data
ahn100gem = readtable("C:\Users\t_sha\OneDrive\Desktop\Elevations.xlsx",
    opts, "UseExcel", false);

%% Convert to output type
ahn100gem = table2array(ahn100gem);

%% Clear temporary variables
clear opts


[x, y]= size(ahn100gem);
C = NaN(x,y);                                    % Creating a matrix of the
    same size as ahn100gem, but with all NaN values
n_X = 665;
```

```
n_Y = 942;
Elevations = ahn100gem;

Save_cords = [];                                   %Empty file to keep track of
    all points in elevation map already investigated or flooded
Test_elevations = Elevations;
Test_elevations(:) = 1000;

Depth = NaN(665,942);                              % Creating depth matrix
Min_elevation = min(min(Elevations));

for k=1:665
    for j = 1:942
        if Elevations(k,j) == Min_elevation
            Global_min = [k,j]
            globMinX = k;                                   % These are the
               points that the flood starts to fill from
            globMinY = j;
            break
        end
    end
end

globMinX = 665-359;                                          % These are the
   points that the flood starts to fill from
globMinY = 227;


Flood_height = Elevations(globMinX ,globMinY);               % The flood
   height is equal to the starting elevation point


% To simulate the filling, each tile in an ever increasing sqaure is
% investigated
topLayer = [];                % Top layer of the surounding tiles
botLayer = [];                % Bottom layer of the surounding tiles
leftLayer = [];               % Left layer of the surounding tiles
rightLayer = [];              % Right layer of the surounding tiles



Flooded_cells = NaN(665,942);   % Matrix of flooded cells

Flooded_cells(globMinX,globMinY) = Flood_height;

Q= [Flooded_cells(globMinX,globMinY)] + 1;       % Tracking flooded cells
Save_cords = [globMinX,globMinY];                % First cell that is flooded
    , inization point
prev_Save_cords_length = length(Save_cords(:,1));   %size of saved cords
```

```
hm = 11;

Dike_Vol = 0;
t = 0.001;          % The increase of water height, aribtary value




Vol = 0;

while Dike_Vol < Katwijk_Max_Surge_Volumes(1)


[Q,Flooded_cells,Save_cords] = testing_sqaure(Q,Save_cords,Elevations,
    Flooded_cells,Flood_height,prev_Save_cords_length);

% Flooded cells
     if length(Save_cords(:,1))>prev_Save_cords_length
         for k = 1:length(Save_cords(:,1))
             Flooded_cells(Save_cords(k,1),Save_cords(k,2)) = Flood_height;
                % If the elevations have been found to be lower then the
                flood height, then that cell is then flooded
             Q = [Flooded_cells(Save_cords(k,1),Save_cords(k,2))];
         end
     end



if prev_Save_cords_length == length(Save_cords(:,1))
             Flood_height = Flood_height + t                   % if there are
                no cells that are below the height of the flooded cell, then
                the entire flood height increases
end

prev_Save_cords_length = length(Save_cords(:,1));            % updateing the
    length of the flooded cells

         for k = 1:665
             for j = 1:942
                 if Flood_height < 0 && ~isnan(Flooded_cells(k,j)) && ~isnan(
                     Elevations(k,j))
                      C(k,j) = Flood_height;

                          % generating a matrix to create maps
                 elseif Flood_height >= 0 && ~isnan(Flooded_cells(k,j)) && ~
                     isnan(Elevations(k,j))
                      C(k,j) = Flood_height;
                 elseif isnan(Flooded_cells(k,j))
                      Flooded_cells(k,j) = NaN;
                      C(k,j) = NaN;
                 end
```

```
        end
    end


    figure(1),clf(1)            % Inundation Pattern
    hold on
    surf(flipud(Elevations),'EdgeColor','none'); view(2); colorbar; axis
        equal;
    axis([0 942 0 665])
    xlabel('x (100 m)')
    ylabel('y (100 m)')
    title('Inundation Dike 16 2D')
    surf(flipud(C),'EdgeColor','r')
    hold off

    % calculating the depths
    for kk = 1:665
        for jj=1:942
            if Elevations(kk,jj) < 0
                Depth(kk,jj) = 0-Elevations(kk,jj) + C(kk,jj);
            elseif Elevations(kk,jj) >= 0
                Depth(kk,jj) = C(kk,jj);
            elseif isnan(Depth(kk,jj))
                Depth(kk,jj) = NaN;
            end
        end
    end

    figure(2),clf(2)            % Inundation Pattern
    hold on
    xlabel('x (100 m)')
    ylabel('y (100 m)')
    title('Inundation depth Dike 16 2D')
    surf(flipud(Depth),'EdgeColor','none'); view(2); colorbar; axis equal;
    axis([0 942 0 665])
    hold off

    Dike_Vol = (sum(nansum(Depth))).*(100.*100)


end

    if Save_cords([1,1]) == 0
        Save_cords(1,:) = [];
    end


function [Q,Flooded_cells,Save_cords] = testing_sqaure(Q,Save_cords,
    Elevations,Flooded_cells,Flood_height,prev_Save_cords_length)
```

```
%% This function creates an expanding square, where each new cell is checked
    to see if it is below the flood height. If it is below the flood height
   its coordinates are saved, and will be flooded.
% if it is above the flood height then it will be removed from the sqaure.
% It is possible that many points can be reached from mulible directions,
% leading to duplicates in the saved coordinates. These must be removed to
% save combutational time

i = 1;


for k = 1:length(Save_cords(:,1))

    testing_x = Save_cords(k,1);
    testing_y = Save_cords(k,2);
    topLayer = [];                  % Top layer of the surounding tiles
    botLayer = [];                  % Bottom layer of the surounding tiles
    leftLayer = [];                 % Left layer of the surounding tiles
    rightLayer = [];                % Right layer of the surounding tiles
    New_Cord_x = [];
    New_Cord_y = [];


        topLayerX = testing_x - i;          % Top layer of the 'sqaure'
        topLayerY = testing_y - i;

            for  m = 0:(2.*i)
                topLayer = [topLayer; topLayerX,topLayerY+m;];
                    for kk = 1:length(topLayer(:,1))
                        if [topLayer(kk,1)] <= 0 || [topLayer(kk,2)] <= 0 ||
                            [topLayer(kk,1)] > 665 || [topLayer(kk,2)] > 942
                            [topLayer(kk,:)] = [];
                            break
                        end
                        if Elevations(topLayer(kk,1),topLayer(kk,2))>
                           Flood_height || ~isnan(Flooded_cells(topLayer(kk
                           ,1),topLayer(kk,2)))
                            [topLayer(kk,:)] = [];
                        end
                    end
            end

        botLayerX = testing_x + i;          % Bottom layer of the 'sqaure'
        botLayerY = testing_y - i;

            for  mm = 0:(2.*i)
                botLayer = [botLayer; botLayerX,botLayerY+mm; ];
                    for kk = 1:length(botLayer(:,1))
                        if [botLayer(kk,1)] <= 0 || [botLayer(kk,2)] <= 0 ||
                            [botLayer(kk,1)] > 665 || [botLayer(kk,2)] > 942
                            [botLayer(kk,:)] = [];
```

```
                    break
                end
                if Elevations(botLayer(kk,1),botLayer(kk,2))>
                   Flood_height || ~isnan(Flooded_cells(botLayer(kk
                   ,1),botLayer(kk,2)))
                    [botLayer(kk,:)] = [];
                end
            end
    end


leftLayerX = testing_x - i+1;       % Left layer of the 'sqaure'
leftLayerY = testing_y - i;

    for  r = 0:(2.*i-2)
        leftLayer = [leftLayer; leftLayerX + r,leftLayerY;];
            for kk = 1:length(leftLayer(:,1))
                if [leftLayer(kk,1)] <= 0 || [leftLayer(kk,2)] <= 0
                   || [leftLayer(kk,1)] > 665 || [leftLayer(kk,2)] >
                    942
                    [leftLayer(kk,:)] = [];
                    break
                end
                if Elevations(leftLayer(kk,1),leftLayer(kk,2))>
                   Flood_height || ~isnan(Flooded_cells(leftLayer(kk
                   ,1),leftLayer(kk,2)))
                    [leftLayer(kk,:)] = [];
                end
            end
    end


rightLayerX = testing_x + i-1;     % Right layer of the 'sqaure'
rightLayerY = testing_y + i;

    for  rr = 0:(2.*i-2)
        rightLayer = [rightLayer; rightLayerX-rr,rightLayerY; ];
            for kk = 1:length(rightLayer(:,1))
                if [rightLayer(kk,1)] <= 0 || [rightLayer(kk,2)] <=
                   0 || [rightLayer(kk,1)] > 665 || [rightLayer(kk
                   ,2)] > 942
                    [rightLayer(kk,:)] = [];
                    break
                end
                if Elevations(rightLayer(kk,1),rightLayer(kk,2))>
                   Flood_height || ~isnan(Flooded_cells(rightLayer(
                   kk,1),rightLayer(kk,2)))
                    [rightLayer(kk,:)] = [];
                end
            end
    end
```

```
x = []; y = [];       % All the x values
%      if length(topLayer)>0
        x = [ topLayer(:,1); botLayer(:,1); leftLayer(:,1); rightLayer(:,1)
            ;];
            for dd = 1:length(x)

                if x(dd) <= 0    % To stop the x values going outside the
                   grid - i.e x can't be zero or 224
                    x(dd) = 1;
                elseif x(dd)>665
                x(dd) = 665;
                end
            end
%      end
%      if length(topLayer)>0
        y = [ topLayer(:,2); botLayer(:,2); leftLayer(:,2); rightLayer(:,2)
            ;];
            for dd = 1:length(y)         % To stop the y values going outside
                the grid - i.e y can't be zero or 983
                if y(dd) <= 0
                    y(dd) = 1;
                elseif y(dd)>942
                    y(dd) = 942;
                end
            end
%      end

    New_Cord = [x,y];
    Save_cords = [Save_cords' New_Cord']';


end

Save_cords = unique(Save_cords,'rows');
```

E.2 Bathtub model

```
clear, clc
% close all


Katwijk_Max_Surge_Volumes = [0.0824e+09 0.2462e+09 0.5152e+09 0.8838e+09
   1.3921e+09 2.1634e+09];

%% Set up the Import Options and import the data
opts = spreadsheetImportOptions("NumVariables", 942);

% Specify sheet and range
opts.Sheet = "Sheet1";
```

```
opts.DataRange = "A1:AJF665";

% Specify column names and types
opts.VariableNames = ["VarName1", "VarName2", "VarName3", "VarName4", "
    VarName5", "VarName6", "VarName7", "VarName8", "VarName9", "VarName10", "
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% Import the data
ahn100gem = readtable("C:\Users\t_sha\OneDrive\Desktop\Elevations.xlsx",
    opts, "UseExcel", false);

%% Convert to output type
ahn100gem = table2array(ahn100gem);

%% Clear temporary variables
clear opts


elevation = ahn100gem;       % Loading the elevation data
flood_plane = ahn100gem;     % Initialising the flood plane
Finding_min = ahn100gem;
Depth = nan(665,942);        % Creating a depth matrix with empty values
kk = 1;

t = 0;
Volume = [];
Total_Volume = 0;

format long

Min_elevation = min(min(elevation));
Max_elevation = max(max(elevation));

format short
% Finding the inital point to start filling from
for k=1:665
```

```
    for j = 1:942
        if elevation(k,j) == Min_elevation
            Global_min = [k,j]
            break
        end
    end
end

for k=1:665
    for j = 1:942
        if ~isnan(flood_plane(k,j))
            flood_plane(k,j) = Min_elevation;
        end
    end
end


% while t <= Max_elevation
while Total_Volume < 10000000
 %while mean(mean(flood_plane,'omitnan'),'omitnan') < -1.5


for k=1:665
    for j = 1:942
        if ~isnan(flood_plane(k,j))
            flood_plane(k,j) = flood_plane(k,j)+t;
            if flood_plane(k,j) > Max_elevation
                "Model error"
            end
        end
    end
end

for k = 1:665
    for j = 1:942
        if flood_plane(k,j)>elevation(k,j)
        Volume(k,j) = (flood_plane(k,j)-elevation(k,j))*(100*100);
        end
    end
end
Total_Volume = sum(Volume(:));

for k = 1:665
    for j = 1:942
        if elevation(k,j) < flood_plane(k,j)
            Depth(k,j) = flood_plane(k,j) - elevation(k,j);
            Save_cords_x(kk) = k;
            Save_cords_y(kk) = j;
            Save_cords = [Save_cords_x' Save_cords_y'];
            kk = kk+1;
        end
```

```
    end
end

Dike_Vol = (sum(nansum(Depth))).*(100.*100);


figure(3),clf(3)
hold on
surf(flipud(elevation),'EdgeColor','none'); view(2); colorbar; axis equal;
surf(flipud(flood_plane),'EdgeColor','r'); view(2); colorbar; axis equal;
axis([0 942 0 665])

figure(4),clf(4)
hold on
surf(flipud(Depth),'EdgeColor','none'); view(2); colorbar; axis equal;
axis([0 942 0 665])


t = t+0.01; % Increase the flood by abitary amount
end
```