Impact of Extreme Sea Levels and Waves in the Bay of Lundåkra

- Present Situation and Future Scenarios

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Preface

This Master Thesis represents the final step of our engineering education programs. The report has been produced during the period 2013-01-07 - 2013-06-11 at the request of the municipality of Landskrona. The project has been accomplished at the division of Water Resources Engineering at the Faculty of Engineering of Lund University.

We would like to thank Professor Hans Hanson who has been our supervisor for the project, and also Professor Magnus Larson. Both of them have taken the time to answer all our questions and to guide us through the different steps of the project. Many questions have been answered and we have learnt a lot during the consultations.

We would also like to thank Olle Nordell, ecologist at the environmental department at the municipality of Landskrona, who has been our contact person at the municipality. He has provided ideas and inspiration in the start-up phase and during the continuous work with the project. He has also helped us with materials and useful information.

Special thanks go to Charlotta Borell Lövstedt at DHI who has supported us with external supervising for the project. She has provided us with answers to questions and many valuable comments to improve our work and bring in new perspectives. We are further very thankful for letting us use data provided by DHI as well as additional useful materials.

Very special thanks finally to Peter Jonsson at Engineering Geology at the Faculty of Engineering of Lund University who has been very helpful with the treatment of the raw data from the laser scan provided by Landskrona and Kävlinge. Without his contribution this processing would have taken a much bigger portion of time from the project. During the process he has also provided many answers and explanations concerning the treatment of elevation data.

Karin Vendt and Sandra Ottosson
Lund, June 2013

Abstract

This report is a study of the impacts of extreme sea levels and waves on the coastal area of the bay of Lundåkra. The bay is characterized by shallow sea bottoms and a flat topography, particularly in the north. Analyses have been based on historical data. To expand the analyses to apply for a future scenario a change in mean sea level has been considered. Based on general recommendations from the Swedish Meteorological and Hydrological Institute (SMHI) and recent research from the Arctic Monitoring and Assessment Program (AMAP) two future scenarios have been chosen, a sea level rise of 1 m and 1.6 m respectively, for the year of 2100.

The bay of Lundåkra is a Natura 2000 area and also contains smaller areas of nature reserves. The bay area holds many conservation values. Some of the most important ones are found in an area of coastal meadows in the northernmost part close to the Saxån estuary. This site is important to many red listed birds. This area is particularly threatened since the highway E6 runs very close to the coast here. The bay area is also of great importance for fish and other animals.

Bathymetry and topography data collected by a laser scan method have been obtained from the municipality of Landskrona and Kävlinge and combined with the New National Height Model (NNH) from Lantmäteriet. Modeled wave data (1994-2011) have been extracted for the bay from the company Denmark's Hydrological Institute, DHI. Sea levels (1992-2012) have been obtained from SMHI and combined with a longer series extracted from a previous study by Karlsson Green and Martinsson (2010).

Return periods have been estimated for sea levels and waves by fitting the data to Weibull and Gringorten distribution functions. For the extreme event of the November storm in 2011-11-27 the waves reached 2.2 m, which has the estimated return period of 32.5 years. The sea level reached at the same time 1.47m, with the estimated return period of 27.5 years.

Applying the Bruun rule to the future scenarios a risk has been estimated of a coastline retreat of several hundreds of meters along the entire bay area. The northernmost part with the important coastal meadows will likely be flooded already at a sea level rise of 0.75 m. An analysis for calculating the wave runup levels indicate that the highway may be exposed to wave runup at extreme events in the future scenario of a 1 m sea level rise. The wave runup analysis further shows some indications that some sections of the coastline will be more exposed to wave erosion than others.

Keywords: The bay of Lundåkra, Natura 2000, wave runup, erosion, flooding, sea levels, climate change, bottom profiles

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1 Introduction

1.1 Background

The climate change has been one of the biggest and most important phenomena on Earth during the last decades. The global change in the mean temperature is predicted to provoke a rise of the global sea level. This will have a negative impact on a big amount of coastal areas all over the world. Land areas will be flooded and big amounts of sediments will be eroded.

Winds, waves and sea levels are connected to each other and therefore the studies of these phenomena will be the key to the understanding of the impacts that climate change will have on coastal areas. In many places these coastal areas have become urban while still holding important nature values. These values are threatened to be squeezed between the sea and urban areas or farm land when the coastline retreats towards land. Sweden with its many coastal urban areas will be one of the affected countries. Even if the risks concerns a relatively distant future it is important for the coastal municipalities to start make investigations and try to gain an overview of the potential risks connected to a rising sea level.

The municipality of Landskrona is located on the southwestern coast of the province of Skåne in Sweden. Previous studies have analyzed the risks of erosion along the coast. However, focus has been on sections where infrastructure is threatened. The bay area of Lundåkra south of the city of Landskrona is a protected area by Natura 2000 as well as the Ramsar convention. The values of the area include shallow sea bottoms and coastal meadows, providing unique environments important to e.g. the fish and bird life. The nature values give the area the status of national interest, hence the need of an investigation of the possible consequences of a sea level rise in this particular area.

1.1.1 Recent extreme event

On the 27 November in 2011 the western coast of Skåne was hit by a big storm. This event brought the extreme sea level of 147 cm (RH 2000), the highest value measured in Barsebäck since the measuring station was started up in 1937. In Landskrona the storm caused some erosion of the beach at some sections along the coast, but no damage was done to the urban infrastructure. In the city of Helsingborg, however, that was hardest hit by the storm, more serious damage was done to both infrastructure and property (NSVA, 2012).

In the north part of the bay of Lundåkra a floating dock was stranded during the storm, more details concerning this incident are described in section 2.2.

1.2 Objectives - Question at issue

The objectives of this study are to investigate how the area of the bay of Lundåkra will be affected by a sea level rise as a result of the climate change. The procedure has been to analyze the frequencies and the impacts of extreme sea levels and waves today and extend the analyses to apply for two different future scenarios.

Based on these analyses the aim is to provide some guidance when estimating the risks for the studied area with a sea level rise. The hopes are also to provide some guidance when it comes

to planning of future land use of adjacent areas to the protected area. More specifically the objectives of the report are to try to answer the following questions:

- What changes in the characteristics of the bay are there to expect at a future scenario with a sea level rise, in particular concerning the protected coastal meadows and the shallow sea bottoms?
- Are there indications that any special sections of the bay coastal area are more exposed to erosion than others?
- What actions may be planned for the future to maintain the values of the protected areas? Are there other adjacent areas that may take over the characteristics of the protected areas that will potentially be lost?

1.3 Delimitations

The future scenarios of this study have only taken into account the predictions of a raised sea level. Other parameters, such as wind and precipitation are considered to be too uncertain in a future perspective. No calculations have been done on the currents. The isostatic rebound is not included in the calculations either since its effects are also regarded to be insignificant when considering the uncertainties of the studied future scenarios.

The time perspective considered in this report extend to the year of 2100 since this is the year stated for the used future predictions. It should be remembered, however, that the impacts of climate change are predicted to continue in a future beyond this time. Further, for some of the analyses of the report the time perspectives are unspecified.

1.4 Methods

The work for this master thesis started in January 2013. Earlier reports on the subject have been studied at an introductory phase to the work of this project. During a literature study theory and examples have been gathered from books and internet sources concerning climate change and the coastal processes.

Considering the analysis part, the report is based on calculations and estimations according to theoretical methods such as the Bruun rule and Hunt's method. Results have been compared to real observations when possible. Professors and other professionals have been consulted during the project. Computer softwares such as Excel, MATLAB, ArcMap 10.1 and Fledermaus have been used for processing data supplied by different sources. Data series of waves, runup and sea levels have been extracted or calculated and then analyzed in terms of e.g. return periods. A flooding analysis has been performed in order to see the extent of the area that may be flooded at different sea levels and the risk of a future coastline displacement has been estimated.

1.5 Disposition

This report contains nine chapters. The report starts with an introduction (chapter 1) followed by a description of the area (chapter 2). The next chapter describes the theory of the costal processes that affects the coastal area (chapter 3). After that follows chapter (4) that contains relevant information about the climate change.

Chapter 5 is the analyses part containing the calculations and investigations that have been carried out, followed by a discussion chapter (6). Chapter 7 contains the conclusions and recommendations for the future, followed by acknowledgements (chapter 8) and a reference list (chapter 9).

Also found in the end of the report are the appendices 1-3 that will be helpful for the understanding of this report.

2 Area description

The bay of Lundåkra is located in the west part of Skåne, Sweden, south of the city of Landskrona and north of Barsebäck in the municipality of Kävlinge (Figure 1, left). The municipality border is situated halfway down along the bay. The bay area is 52 km^2. The stretch of the coastline along the bay is 17 km, while the linear distance from the north end to the south is 12 km according to eniro.se (2013). In the north part of the bay the highway E6 runs very close to the coast and is, thus, providing a geographical limit of the nature area, farther south the adjacent areas are mostly containing farmlands.

Figure 1. Left: A map over Landskrona and the bay Lundåkra (eniro.se 2013). Right: Orthophoto of the bay© Lantmäteriet i2012/901

The bay is characterized by its extensive shallow areas, 40% of the bay has a depth less than 3 m (Coastal Resources Delegation n.d.). As can be seen in Figure 1(right) the shallow areas are concentrated to the north. The biggest part of the bay area consists of bottoms with uncovered sand. In the south parts there is an area of unstable sandbars changing their shape according to the wave direction (The county board of Skåne 2005). Moreover, historical sand suction pits are still to be found in the south part of the bay.

The beach landscape of the area consists of coastal meadows that get flooded frequently due to the flat topography of the landscape. This gives a beach landscape with areas occasionally covered with water, in particular in the northern parts where there are shallow pits along the beach, made from extraction of peat and by grazing animals. When filled with water these beach basins serve as a favorable environment for animals in the area such as frogs and birds (The county board of Skåne 2005). There are also wetlands found in the northern part, associated to the outlet of the river Saxån.

Five rivers are connected to the bay, the biggest one is the Saxån River and it empties in the north part of the bay. The river can be seen in the top of the orthophoto of Figure 1(right) and is further marked in Figure 2. Other outlets close to the area are the dyke Örjadiket north of the Saxån River, on the other side of the area boundary. Further south there are the brooks

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Sandåkerbäcken and Välåran, a brook on the municipality border between Kävlinge and Landskrona (The county board of Skåne 2005). Potential pollutants into the bay come from the river basin to the rivers Saxån-Braån. This basin cover 36000 ha where79% is agricultural land (The county board of Skåne 2005). The Saxån River is also a recipient for municipal storm water of several municipalities as well as treated waste water from the municipality of Svalöv. North of the bay area is an industrial site. Other threats to the water quality of the bay are posed by a waste water treatment plant, a waste dump and an artificial island made out of plaster, called Gipsön (The county board of Skåne 2005).

2.1 Hydrography and hydrology

The waves in Öresund are induced by winds and therefore their directions will be the same. The wind directions that induce the highest waves are the ones that represent the biggest distance of open sea surface. For the bay that means that winds blowing from northwest as well as from south southwest. Further a certain correlation between sea levels and wind directions exist in the region. In general winds from the northwest coincide with high water levels and winds blowing from south southwest give lower sea levels, the most extreme sea levels coincide with western wind directions. This is explained by the phenomenon of the threshold area in Öresund that is located approximately at the position of the bridge between Denmark and Sweden. When winds are pushing the water towards this area the sea level of the Öresund will be raised, when the winds are blowing from this area the water will instead be pushed towards Kattegat to where the passage is free (DHI 2013; Karlsson Green and Martinsson 2010).

Öresund has an excess of freshwater since the flow from the rivers in combination with the precipitation volumes are bigger than the evaporation (Hörnsten *et al.* 1977). According to the Swedish Meteorological and Hydrological Institute, SMHI, the yearly average potential evaporation in Landskrona is 600 to 700 mm (between the years 1961and 1990) (SMHI 2009d) and the yearly precipitation is 500 to 600 mm (2012) (SMHI 2012b).

The freshwater from the rivers are mixing with the brackish Baltic water and more saline Kattegatt water which give rise to complicated current conditions. The direction and speed of the currents at the surface are affected by factors different from the ones at deep conditions farther out in the sea. A division in current behavior is represented by the salt thermocline, the position of this varies between a depth of 8-20 meters but is normally found at the approximate depth of 10 meters (Hörnsten *et al.* 1977). The surface water in Öresund is brackish water with a salinity of 8-10‰. At deeper levels more saline water from the Kattegatt is found in two layers of different salinity. One is of Kattegatt surface water with a salinity of 18-24‰ and the other is Kattegatt deep water with the salinity of 30-40‰ (Hörnsten*et al.* 1977).

2.2 Sand suction pits and an underwater channel

During the 1950's and 1960's sand was extracted from the bottom in the bay of Lundåkra. This sand was used for building material and it was believed that the pits would get refilled through natural processes. Today several holes in the sand bottoms can still be found, these can be seen in the bathymetry representation in Figure 7. In these pits salinity will accumulate, due to its higher density. Hörnsten *et al.* (1977) brings up the unsuitability of sand suction in areas such as the bay of Lundåkra, a shallow area located north of the threshold area in Öresund with a slow turnover of water. According to the authors trapped

water of high salinity in the pits will eventually lead to anaerobic conditions in the depression. A more recent update states that the bottoms in the pits are dead due to the lack of oxygen (Havsresan 2013).

During the big November storm in 2011a floating dock with a length of 135 m, width of 35 m and weighing 6000 tons was stranded on the beach in the northern bay area after having broken free from Varvsudden south of Landskrona. The county board of Skåne came up with the solution of digging a 2.4 km underwater channel that was big enough to transport the dock out from the bay. This channel was planned to be refilled afterwards but this work has still not been started. This has influenced the values of the nature in the bay negatively and as for the sand suction pits salinity has started to accumulate on the bottom of the channel (Strömkvist 2012).

2.3 Geology

The geology around the bay has been analyzed using maps from the Geological Survey of Sweden, SGU. Both the land and marine geology have been studied.

2.3.1 Land Geology

For the analysis of the bedrock and sediments in the bay coastal area, maps from SGU have been used from the year of 1976. The scale is 1:50 000.

The bedrock map shows that the entire coastline mainly consists of the youngest type of bedrock (850-34 million years) which is rich in carbonate. This includes rocks like limestone, dolomite and marble.

The soil map indicates that along the coastline there is plenty of postglacial sand with small amounts of fine sand. In the coastal area about one kilometer south of the river Saxån boulder clay can be found. Farther south, outside Barsebäck, some gyttja is located. The northern part of the bay, namely the harbour, is covered with artificial filling material.

2.3.2 Marine geology

Marine geology maps from SGU (1979) have been used to analyze the sediments of the sea bottom. There is sand along the entire bay several meters out from the coastline. In the north part of the bay there are traces of fine sands as well as farther out in the sea. In the north part there is also an area filled with gyttja bearing clay and clayey gyttja. In the south part of the bay (around Barsebäck) till can be found below a thin layer of sand.

The content of calcium carbonate in the sediments is 0-1% except for a small area in the central parts where the number is a bit higher, specifically 1-2%. The content of organic carbon is 0-1% and the content of clay is 0-10%. The contour map from SGU shows that the depth of post-glacial sediments is approximately 5 meters in the bay (SGU 1979).

2.4 Flora and Fauna

The algae situation in the bay of Lundåkra has not been investigated at any extensive level, only a few studies have been made. However, they all state a "normal" amount of algae in the

bay. At the Saxån estuary a big amount of phytoplankton has been measured, probably due to high levels of nutrients in the river (Coastal Resources Delegation n.d.).

As already mentioned most of the bay consists of uncovered sand bottoms. However, at calm conditions the bottoms between the sandbanks, as well as at the river outlet, may be covered with a thin biofilm (The county board of Skåne 2005).

By using maps that show the plant species in Öresund from the Sound Water Cooperation (n.d) two species are particularly abundant. The first one is widgeon grass that can be found in the bay close to the coastline. Widgeon grass is a perennial plant that grows up to a length of 90 cm. The plant can live in fresh and brackish water of up to 10‰ salinity or higher (Texas A&M agrilife extension 2013). Further out the widgeon grass will be replaced by eelgrass. Since the shallow bottoms cover a big area of the bay, big populations of these two species of vegetation can develop and form shelter and food for several species of marine animals. Eelgrass is also preventing sediment erosion through wave energy dissipation at shallow waters. Therefore it is important to preserve the eelgrass in the area (Olsson 2010 and Seagrass recovery 2012).

Eelgrass has the ability to handle big amounts of salt, and therefore the salinity of the water can be 5-35‰ and still represent a good environment for the plant. The eelgrass plant consists of two parts. One is the underground rhizome part with a belonging root system that grows horizontally in the sediments and the other part is the sprouts with green leaf. In deep water the plant is struggling to come closer to the sun light, therefore the sprouts will grow longer and the leafs will be wider (Olsson 2010).

The amount of documented species in the bay increases with the depth. Many investigations have been made indicating that this relation seems to depend on the increasing salinity at deep waters. The total amount of registered species in the bay is around 150. More samples would need to be analyzed to confirm the amount (Coastal Resources Delegation n.d.).

2.5 Nature protection

The bay of Lundåkra is a very important area for fishes and birds, particularly in the northern part with its coastal meadows in the area around the Saxån River. Here a nature reserve has been established. Moreover the coastal area of the bay is protected according to the Natura 2000 as well as the Ramsar convention. These are presented farther down in this chapter.

2.5.1 Values of the area

The northern part of the bay coastal area, with its occasionally water covered meadows, is of great importance to the birds living in and passing by the area. The shallow pits made from extraction of peat and by grazing animals offer a unique environment for birds and other animals such as frogs (Swedish environmental protection agency 2012a).

Further, the bottom ecosystem with its vegetation and small animals provides food for the birds in the area. Swans for instance feed on the eelgrass on the bottom. The combination of the shallow sea bottoms and the coastal meadows makes the area very important for birds as a resting place and a site for wintering (The county board of Skåne 2005).

Concerning the marine life, the specific characteristics of the area make it an important site for fishes. The shallow bay offers a protective environment for juvenile fish, for species such as eel and plaice. The area also provides a feeding source and species such as cod and mackerel use it as a breeding location. At winter time the bay produces food (small fishes and crustaceans) that feed fish populations in the sea outside of the bay. These features give the bay the status of national interest for the fishing industry (The county board of Skåne 2005).

2.5.2 Natura 2000

Natura 2000 by the European Union is an ecological cooperation established to prevent extinction of flora and fauna. All kind of activities within or in connection to a Natura 2000 area that may affect the environment requires permission of the county board. All Natura 2000 areas are considered to be of national interest (The county board of Skåne n.d).

The goals concerning the establishment of the bay area as a Natura 2000 site are described by the County Administrative Board of Skåne in an area preservation plan (The county board of Skåne 2005). A general goal of the European project is to preserve nature types and species of specific value. The preservation plan should describe the specific nature values for the concerned area and state what actions or precautions are needed to guarantee the continued existence of these values (The county board of Skåne 2005).

For the coastal area of the bay of Lundåkra, the species concerned by the Natura 2000 protection are some red listed bird species using the area for breeding, resting and wintering. The specific goal for the area states that the number of individuals and populations of the listed species should be "maintained or increased". A following goal is to maintain or increase the inhabited area of each of the listed species and to maintain or enhance the biodiversity as well as the abundance of species other than the listed ones, including the full spectrum of the naturally occurring flora and fauna of the area (The county board of Skåne 2005). The area concerned by the Natura 2000 protection is the shallow area in the bay, its beaches as well as the outlet of the river Saxån (Figure 2).
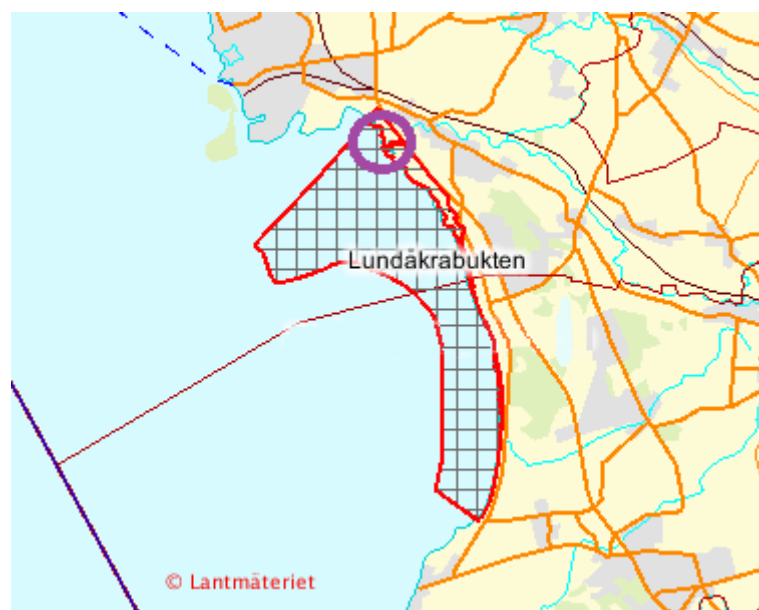

Figure 2. A picture showing the Natura 2000 and Ramsar site in the bay of Lundåkra. The purple circle shows Saxåns estuary. © Lantmäteriet (Lantmäteriet 2013).

2.5.2.1 Protection and preservation of the area

To maintain a favorable conservation status the needs of the area are defined by the county administrative board of Skåne. They mention, among others, the importance of a continuous mowing of specific areas to maintain the meadow landscape. Low disturbance from recreational activities is another important aspect for the preservation. Any activities or exploitation that may affect the protected area needs to be approved upon by the county administrative board of Skåne.

A nature protection plan is to be developed for the total area of the Natura 2000 protection, giving the area a status of a nature reserve. The idea is to give the main part of the area visiting restrictions for the part of the year when birds are nesting, as are applied for the reserve around the Saxån River outlet. The visiting restrictions would cover the area above water as well as below water. Restrictions are also suggested to keep recreational activities to certain areas, such as paths and bird watching towers. Methods, apart from grazing or mowing, to maintain the open landscape might be needed. Actions such as burning or clearing of reed and other high-growing vegetation may also be implemented (The county board of Skåne 2005).

2.5.3 Ramsar site

There are about 2000 Ramsar sites all over the world, and one of them is the bay of Lundåkra. The Ramsar denomination is given to a site that is important to preserve due to its global nature values and it states that the biodiversity of the area should be protected against deterioration. Ramsar sites are usually wetlands, marches, fences, swamps and mosses, but can also be lakes, streams and marine shallow areas. The Ramsar convention was signed 1971 and came into effect in 1975, and it is the first convention about biodiversity. The Ramsar convention is an independent organization and does not belong to the UN system (Swedish environmental protection agency 2012c).

There are 51 Ramsar sites in Sweden covering in total a land area of 5147 km^2, all over the country. However, most of them are located in the south of Sweden. The bay of Lundåkra became a Ramsar site in 2001. The bay Ramsar site is 1980 ha big and covers approximately the same area as the Natura 2000, see Figure 2 (Swedish environmental protection agency 2012b).

"The bay of Lundåkra have become a Ramsar site because of four criterias, they are:
- The area represents an example of a partly affected type of wetland (shallow marine environment) within the EU continental region.
- The area is hosting 10 red listed bird species
- The area is hosting species that are typical for the EU:s continental region
- The area is important for spawning, nursery and foraging for fish, especially flatfish. The area is of national importance for commercial fishing."
(Swedish environmental protection agency 2012a)

2.5.4 Nature reserves

Apart from the protection defined by Natura 2000 and the Ramsar convention, there are two subareas in the area that are appointed nature reserves. One is the area around the outlet of the

Saxån River where the 27 ha big area consisting of coastal meadows was turned into a nature reserve in the year of 1972, mostly because of the ornithological values (Coastal Resources Delegation n.d.). This area, stretching north along the coastline, provides shelter for several red listed species. Another reserve further down south was founded already in 1950, in the municipality of Kävlinge, at Järavallen. Here the beach gets exposed to washed up eelgrass that is left to decompose in a natural way (The county board of Skåne 2005).

2.6 Previous studies

In a former study by Karlsson Green and Martinsson (2010) the northern part of the coastal area of the bay was represented in different analyses. Historical aerial photographs from the early 1940's were digitalized and analyzed. The difference in location of the vegetation line was defined and the retreat of the shoreline over the years thus estimated. Their results can be seen in Figure 3 where a negative value represents a retreat of the vegetation line which indicates that erosion has occurred in that location over the years. The analysis results for the bay area were considered more uncertain than for the analysis in general by the authors, as the vegetation line was difficult to distinguish in the photos. The authors present the results for two separate time periods, one for 1940-1984 (left photo, Figure 3) and one for 1984-2008 (central photo, Figure 3). Comparing the two results a change in the erosion situation seems to have occurred from earlier to later years. The area just south of the Saxån delta shows no signs of erosion up until 1984. However, for the period after that year a yearly retreat of the vegetation line is indicated by the analysis results. Looking at the longer time perspective though, the bay proves to be stable in terms of erosion, apart from one area in the in the southern end of the northern part of the bay. The coastline here seems to be more exposed to erosion (right photo, Figure 3).
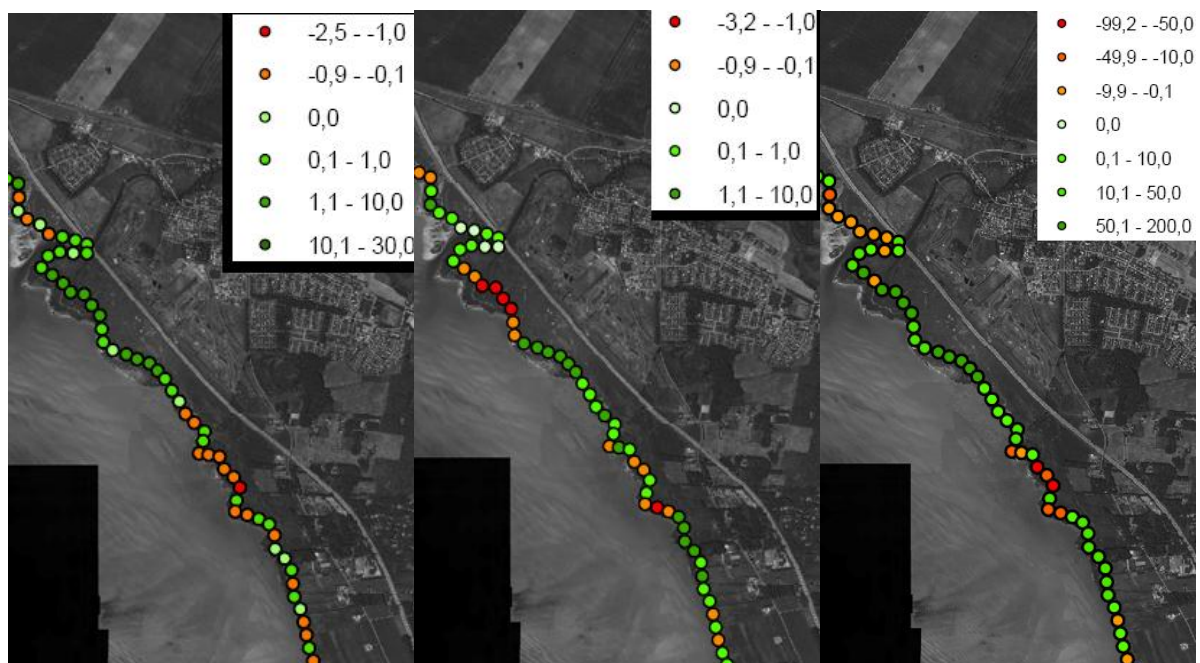

Figure 3. An analysis of aerial photographs over the northern part of the bay by Karlsson Green and Martinsson (2010) shows the retreat of the shoreline in the period 1940-1984 (left photo), 1984-2004 (central photo) and for the total period 1940-2008 (right photo).

3 Coastal processes

3.1 Winds

When there is a temperature difference between two locations as well as a difference in the atmospheric air pressure, the air starts to move. This movement is the beginning of the creation of wind (Andersson 2001). When the pressure difference is big, the wind becomes stronger than if there is a low pressure difference. The wind is able to move in all directions i.e. vertical, horizontal and in vortices. The wind is measured by its speed and direction with the unit meter per second, m/s. In the process where waves are built up by winds the wind speed is critical for the wave height (SMHI 2012a).

The strength of the wind can be measured by the Beauforts scale. The scale is between 0-12, were zero means calm and still wind while 12 means hurricane wind speed (Hörnsten *et al.* 1977).

Another phenomenon that is affecting the winds is the Coriolis effect, which is the impact from the rotation of the earth. The Coriolis effect was discovered in the 1830's by a French physicist and mathematician called Gaspard Gustave Coriolis. The force of Coriolis is proportional to the speed of the object and is equal to zero at the equator and strongest at the poles (SMHI 2009a).

3.2 Waves

Waves are created by winds blowing over the sea surface. The wave heights are depending on the speed and the duration of the wind as well as the fetch length, i.e. the distance of open water in the direction of the wind (SMHI 2009c).

Out in deep water where waves are created there is no interaction between the sea bottom and the wave. As the wave approaches land it will slow down due to friction from the sea bottom, also different processes will change its characteristics. Waves at an angle to the coastline will change their direction to hit the coast close to perpendicularly. This is induced by a process called refraction. Other interactions with the sea bottom or coastal structures may cause wave reflection as well as diffraction which will also change the directions of the wave (SPM 1984).

As the wave gets even closer to the coast it will break, this happens more specifically when the water depth is less than 1.3 times the wave height. After the breaking the wave will continue forward. Soon the wave height is small enough to stop breaking and just continue to the beach where it will again have contact with the bottom and then break again against the beach (SMHI 2009c).

3.3 Sea levels

The sea level depends on several factors, such as the local climate and the tide. Along the Swedish coasts the sea level depends mostly on the air pressure and winds (SMHI 2013a). Also the periodic oscillation in the oceans is affecting the sea level.

SMHI operates 23 stations along the Swedish coastlines that measure the water level every hour. The station located closest to the bay of Lundåkra is in Barsebäck where the sea level observations started in 1937. However, the station was not in service between 1970 and 1991. The water level varies slowly and depends on the winds speed and direction as well as the atmospheric pressure in the area (Nerheim 2007).

3.4 Wave runup

Wave runup is a process where the waves are washing up onto the beach after they have broken on their way into land. How far up the runup will reach depends on the energy that is left in the wave after it breaks as well as the sea level and the characteristics of the beach profile. Runup may increase the erosion of the beach when there is an extreme event like a big storm. The best way of decreasing the runup is to force the waves to break further out in the ocean, in that way the wave energy will be less when the wave hits the beach. This can be done by building different structures out in the sea (Dahlerus and Egermayer 2005).

3.5 Sediment transport

When the depth becomes less than half the wavelength of the most frequently occurring waves, a wave motion is created that will move bottom sediments to other locations and sediment transport will occur (SMHI 2009c).Sediment transport forms the coastline and can be divided in two groups, cross-shore and longshore sediment transport. Cross-shore sediment transport is the process that determines the shape of the beach profile while longshore sediment transports affect the coastline plan shape (DHI 2013).

3.5.1 Cross-shore sediment transport

The wave component in the cross-shore direction contributes to transversal sediment transport and is often biggest during storms. The shape of the beach is determined by the characteristics of the waves as well as the sediment properties of the area. More fine grained sediments are more mobile than coarser sediments and can be carried a longer distance by the waves, i.e. the waves perform a sorting of the beach sediments. Further, waves of different height and energy in combination with different sea levels will reach different sections of the beach and thereby impact beach sediments of different size. The impacts of waves on the beach profile are thus varying with the local climate. However, if the natural processes are undisturbed, the beach profile will vary around a point of equilibrium and will in the long term maintain its shape. In different terms this means that the amounts of sediments that are transported from the coast are equal to the amounts of sediments that are transported back to the coast. Long term erosion will occur when a beach profile is not in equilibrium (SPM 1984).

3.5.2 Longshore sediment transport

Longshore drift is the movement of material along the coastline. Incoming waves may break at a certain angle relative to the coastline; the component of the waves that is not perpendicular to the coast will give rise to a coast parallel current. This current will generate a transport of sediments along the coastline. The transport will change in direction due to variations in the directions of the incoming waves but it may have a total net direction and amount of sediments that are transported in one specific direction. If, for a certain section of the coast, the total amount of sediments transported away from the area is bigger than the total

amounts being brought to the section, the section will not be in balance in terms of sediment transport and erosion will occur. When erosion occurs due to longshore sediment transport at one section, accumulation will occur at another section (SPM 1984).

4 Climate change

The research concerning the global climate and climate change has been extensive over the last years. Understanding the complexities of the climate is still a big challenge. However, predictions for the future have been attempted on request of policy makers and are continuously updated.

Political action programs and recommendations in Sweden are based on reports from the United Nations Environment Program (UNEP) in collaboration with the World Meteorological Organization (WMO). In 1988 they together started the Intergovernmental Panel on Climate Change (IPCC). In the year of 2007 their fourth Assessment Report, AR4 was published, concluding results from publications on climate research up until 2006. A following fifth report will be released in 2013-2014 (IPCC 2013). In 2009 the Swedish government released a report by Rummukainen and Källén (2009) giving an analysis of the AR4 and the development of the climate as well as new climate research from the years after the release of the assessment. The overall conclusion by the authors was that the results by the AR4 could be confirmed by the past years climate development and supported by further evidence by more recent research, many reports have also shown indications of bigger impacts to expect (Rummukainen and Källén2009).

4.1 Sea level rise - predictions for the future

The expected temperature increase according to the AR4 is 1.1-6.4°C from 1990 to 2095 (IPCC 2007). The sea level rise followed by the temperature increase is due to mainly two different factors. One is the thermal expansion of the water in the oceans and the other is the additional water volumes as ice on land starts to melt (Rummukainen and Källén 2009). When it comes to predictions for the future the changes in the ice cover are difficult to foresee. In particular the future of the ice cover in Antarctica is highly uncertain. A warmer climate may cause extended melting of the ice cover but there is also a possibility that it will grow thicker as precipitation increases (Rummukainen and Källén 2009). However, many studies, since the release of the AR4, give arguments for fearing a greater change of the global sea level than what has been expected earlier. The eventual acceleration of ice melting was not taken into consideration in the AR4 and its resulting sea level rise prediction is now considered an optimistic scenario according to the report by Rummukainen and Källén (2009). The authors refer to newer studies that count on a possible sea level rise that go beyond the prediction by the AR4 of a sea level rise interval of 18-59 cm.

In 2012 a report was released by NSVA with general recommendations for planning and constructing in the city of Landskrona. The report was based on the SMHI general recommendations as well as a report by Arctic Monitoring and Assessment Program (AMAP 2011). The AMAP report is the most extended assessment of the situation in the Arctic that has been released in the last years. The report will be included in the AR5 coming up and it predicts a sea level rise between 0.9 and 1.6 m until 2100 (AMAP 2011). This latest AMAP report sets the new prediction based on the last year's development in the Arctic.

The latest recommendation by SMHI, also considered by NSVA, is stated in a report by Nerheim & Hammarklint (2010). Based on the AR4 and the various researches since then, the recommendation is now to consider a sea level rise of 1 m by 2100.

For this report the two alternative future scenarios of a sea level rise have been chosen as one standard prediction of +1m as well as the one more extreme prediction of +1.6 m.

4.1.1 Mean sea level in south of Sweden

During the last decades the sea level has increased and is still doing so. In the south part of Sweden the sea level has increased with approximately 20 cm since the end of the 19th century. The latest years have had an increasing mean sea level rate of 3 mm/year (SMHI 2013a).In the Scandinavian area there is an isostatic rebound that is counteracting the rate of the sea level rise. The effects of the rebound are largest in the north part and it only has a minor impact in the south.

Considering the future scenarios of a sea level rise of 1 – 1.6 m the impact of the isostatic rebound will not be taken into account in the analyses of this report. The uncertainties of the predictions are considered to contribute to the error margin to a far bigger extent than the land elevation.

4.1.2 Extreme sea levels

Extreme sea levels depend mostly on the local wind climate and on the gravity from the moon, also known as the tidal water. The moon period is 12 hours and 25 min, so there can be up to two high water level periods per day (SMHI 2013a). However, at the location of the bay there are no significant tidal variations to consider.

While future predictions of the global sea level rise concern the mean sea level, a climate change may also bring effects of more extreme and frequent high sea levels. Since the extreme sea levels depend on the wind climate as well as other factors the understanding of how a global temperature change would affect the winds is crucial to be able to make any predictions for the future.

4.2 Change in wind climate

Some estimations of a possible change in the regional wind climate have been made and presented by various reports. A general result is a certain increase in wind speeds during winter months as well as an increase in winds of the direction from the west.

One of the studies indicating an increasing winter wind speed was ordered by the Swedish government (SOU 2007). Based on a regional atmospheric model, RCA3-E and one of the scenarios from AR4 by IPCC (2007) a resulting increase in wind speed of 7-13% during the winter months was given.

A report by Rummukainen *et al.* (2004) also states an indication of an increase of wind speed in Scandinavia of 5-10% at a future climate scenario. This scenario applies in particular during the winter months and for the winds blowing from a western direction.

As mentioned in section 2.1 there is a correlation between winds from this direction and extreme wave heights. A future scenario with an increase in frequency of westerly winds in the Öresund would hence potentially bring more waves of extreme wave height to the bay area.

5 Analyses

To estimate the impact of extreme sea levels and waves of the bay area a number of different analyses have been carried out. The wave runup has been estimated with the help of the Hunt's rule. Frequencies and return periods of sea levels, waves and wave runup have further been estimated. Future flooding scenarios have been analyzed by visualization in ArcMap. Finally erosion of the bay coast has been considered and an estimation of the position of the future coastline has been performed, using the Bruun rule.

Although there are indications of a future change in wind climate this has not been taken into account for the analysis. The earlier mentioned previous study by Karlsson Green and Martinsson (2010) involved a winter month wind speed increase of 13% in the wave runup analysis; the results indicated that the system was relatively insensitive to these wind changes.

Calculations of a longshore sediment transport have not been performed. Instead the indications of stability of the bay coastline, discussed in section 2.6, have been considered.

5.1 Available data

For this report, several sources of data have been used for the different analyses. Data has been collected for waves and sea levels as well as the bathymetry and topography. They are all described further in this chapter.

5.1.1 Height systems

When it comes to data of elevation there are different systems of referencing. Sea levels for instance are typically measured in relation to a local reference specific for each measuring station. The data thus needs to be transferred into a more general system. The Swedish national height system, RH 2000 is the official system of reference since the year of 2005 (Lantmäteriet, n.d.). Some data used in this report have been of the former system, RH 70, and has needed to be transformed into RH 2000, the conversion is a matter of simply adding the difference between the systems. The same vertical datum, point of reference, is used for RH 70 and RH 2000, it is a point in Amsterdam called the Normaal Amsterdams Peil (NAP), that is a common point of reference in most of Western Europe (Lantmäteriet n.d.).

5.1.2 Waves

Hindcasted waves have been supplied by the company DHI. The waves were extracted from the model MIKE 21 SW. The model calculates waves based on the local winds, taking into account a number of different processes that determine the development of the waves. More details about the model can be found in the report by DHI (2012). The information from the model includes the significant wave height, peak wave period and the mean wave direction in three different locations in the bay (Figure 4). The hindcasted waves have been obtained for the period 1994 - 2011 with one hour between two readings. The wave heights are referred to the water surface.
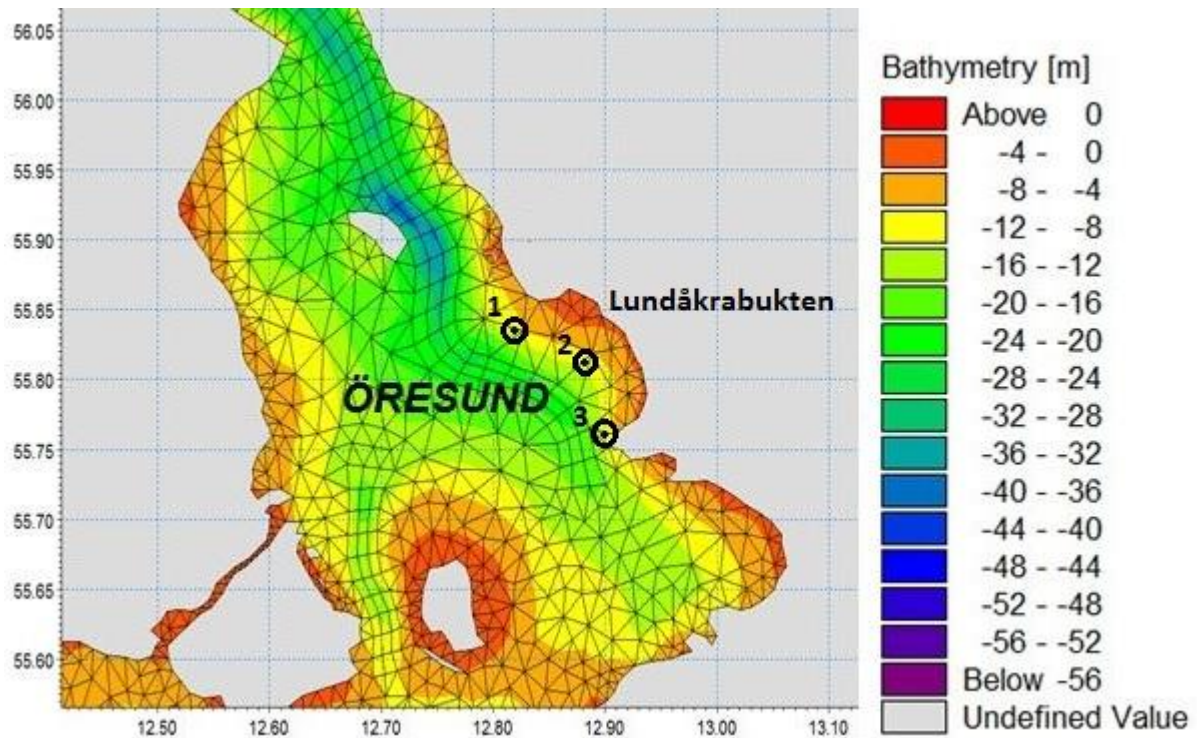
Figure 4. A modified picture from DHI (2013) shows the locations of the three extracted series of hindcasted waves.

5.1.3 Sea levels

Sea level data obtained from SMHI for Barsebäck has been used. The data covers the period 1992 - 2012. Values for the sea levels are in the RH 2000 system.

For the frequency analysis a longer detrended (see following section) time series of sea level data from Barsebäck has been extracted from Karlsson Green and Martinsson (2010), the authors used raw data from SMHI for the period 1938-1969, 1982, 1992-2008, this data is by the older reference system RH 70.

5.1.3.1 Pretreatment of data series

To be able to perform wave runup analysis hourly values were needed to obtain a series of sea levels simultaneous to the wave heights. The series to be used, contained data of irregular measuring intervals for the period of 2004 (June) -2012, which needed to be adjusted. By using MATLAB it was possible to extract one value every full hour and create a homogenous series from 1992 to 2012 of hourly values. (Except for 27/11-28/11 2012 where there was a lack of full hour values, for this small section of the series values are measured 5 min past or before the hour).

Since an extreme event happened at the November storm in 2011 there is an interest to update the frequency analysis performed by Karlsson Green and Martinsson (2010). The new data collected from SMHI for this report contains values from 2009-2012, these years were not included in the study by Karlsson Green and Martinsson (2010). However, these new data points could not simply be added to the older data series. The data extracted from Karlsson Green and Martinsson (2010) are represented in the RH70 reference system while the newly

extracted data is by the newer RH 2000 system. The conversion could be made using information from Karlsson Green and Martinsson (2010) of the local measuring reference system in Barsebäck compared to RH70, combined with information from SMHI (2013c) of the difference in elevation between the local system and RH 2000. Further, a new max value trend needed to be estimated to give a result that is adapted to the present situation, while a new mean water trend is considered to have an insignificant impact (a change on the mm scale). The max value trend, calculated by Karlsson Green and Martinsson (2010), 0.48 cm/year (Figure 5) was thus re-added to the former data series and the RH70 representation was replaced with RH 2000. Yearly maximum values for the years 2009-2012 were added to this series and a new max value trend could be calculated as 0.46 cm/year and removed from the series (Figure 6).
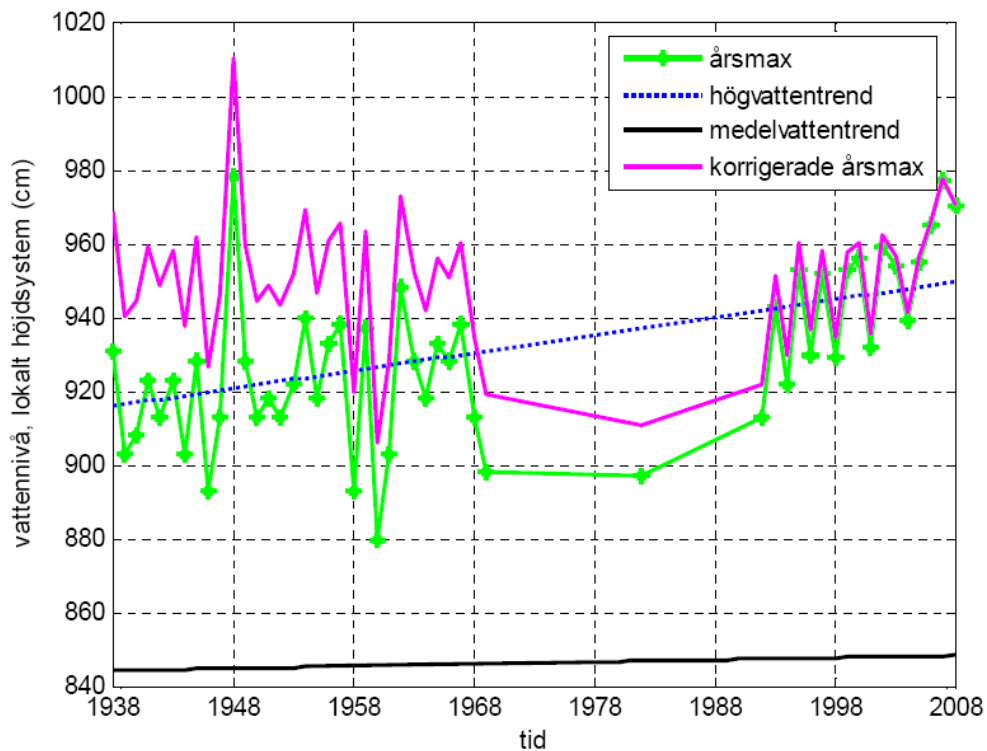
Figure 5. Sea level data from Barsebäck by SMHI, corrected for a mean sea level trend as well as a max sea level trend, by Karlsson Green and Martinsson (2010).

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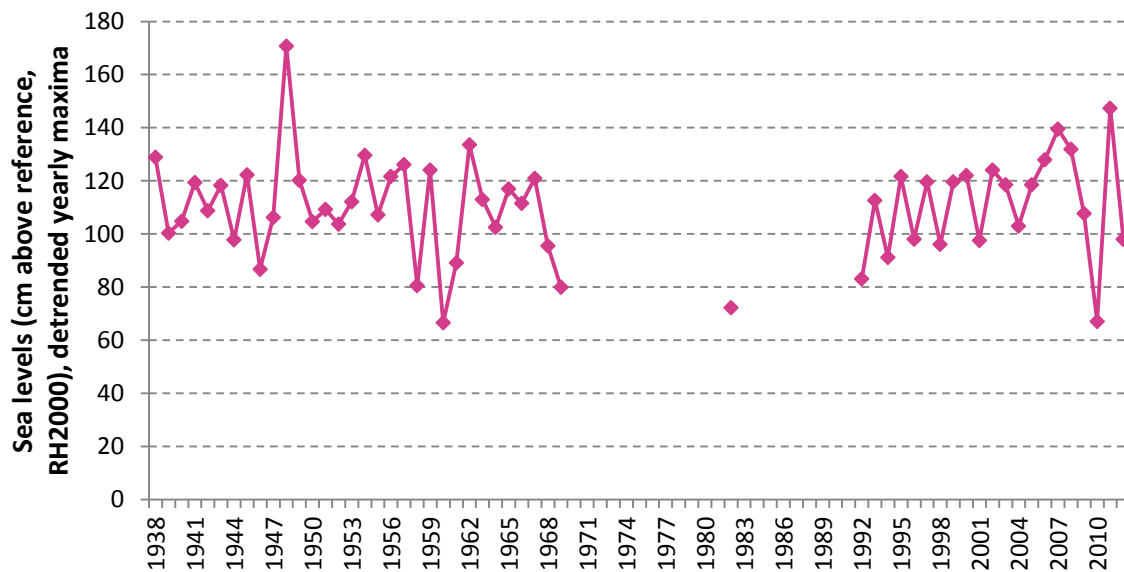
Figure 6. Sea levels at Barsebäck. Newly extracted data from SMHI for the period 2009-2012 have been added to the series extracted from Karlsson Green and Martinsson (2010). The series have been detrended using the newly calculated trend 0.46 cm/year.

5.1.4 Bathymetry and topography

Three different sets of data have been used for the different analyses. Data supplied by the municipality of Landskrona from a laser scan cover the northern part of the bay, the sea bottom as well as an area of land. The laser scan was performed in the end of 2012. Data from the municipality of Kävlinge, covering the sea bottom of the southern part of the bay is combined with the data set from Landskrona. The Kävlinge data is from a laser scan in 2008 and is geographically limited by the coastline, not covering any land surface. Land surface data has been obtained from Lantmäteriet, from their New National Topography Model, NNH (Ny nationell höjdmodell). The model consists of a 2 m grid and it has been processed to only contain the ground surface, buildings and trees have been removed. Figure 7 shows an overview of the three datasets combined. The three different models have been used together or separately during the different analyses of this report. The three datasets combined will be called the Bathymetry and Topography Model while the New National Topography Model as used alone will be referred to as the NNH.
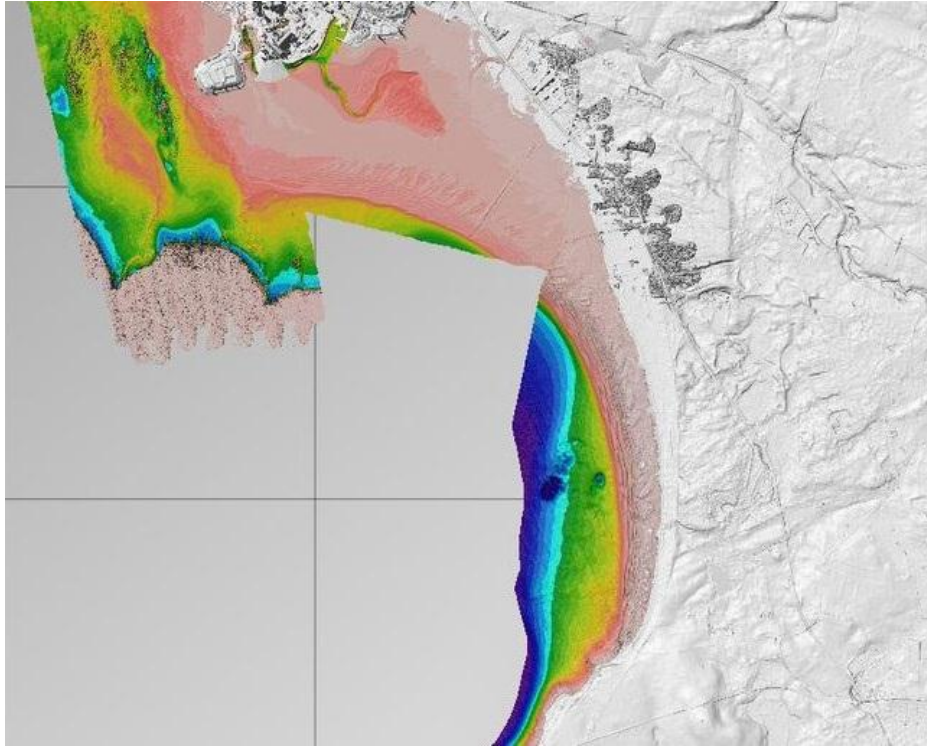
Figure 7. An overview over the laser scanned data from the municipality of Landskrona and Kävlinge together with land data from Lantmäteriet. The different colors indicate different sea depths, the line along the change from pink to yellow represents an approximate depth of 3-4 m and the line along the change from green to blue represents a depth of approximately 6 m. Historical sand suction pits are seen as dark traces in the southern section of the bay.

5.1.4.1 Laser scan

A laser scan of the coast was performed for the municipality of Landskrona in December 2012. The method uses an airplane and a GPS System. Sensors on the airplane are used to send out signals in different directions and together with GPS and inertial navigation it is possible to detect from where and when the signal is reflecting the surface ground. A certain filtering of the data is needed and data can then finally be processed further into an elevation model (Lantmäteriet 2009).

The accuracy of the collected laser data is 0.5 meters in the water, vertically, with a horizontal accuracy of 5 meters. For surfaces on land, the accuracy is 0.2 meter in xyz directions. This means that the accuracy is better on land than at sea. The dataset from Kävlinge was also collected using the laser scan method, in 2008, the same accuracy of the data is assumed as for the Landskrona data.

5.1.4.2 Data processing

Bathymetry and topography data have been read and combined into one model using the software Fledermaus, this proved to be an appropriate tool for treating the laser scan data obtained in the formats Lidar files and xyz-files.

Combining the three datasets, some complications and dilemmas were encountered. The bathymetry data provided by the municipality of Kävlinge has the border along the coastline. The coastline will thus be the border between the topography model NNH and the bathymetry

data for the southern part of the bay. Differences of the two models cause some irregularities along this border. At some of the extracted profiles a sudden change in elevation can be seen along the coastline, at others there are gaps in data, representing a difference in the definition of the coastline by the two different datasets.

To get a smooth transition from one dataset to another the data could be re-gridded as one data set (Jonsson 2013). In this case though, a regular border line is not of significant importance. Since the irregularities are due to measurement errors in the data the border data representation is only visualizing a global error margin of the model. To perform the analysis requiring the combined model values have been interpolated where data is missing. For the analyses only requiring land data the NNH model has been used.

Topography data of the NNH has been modified by Lantmäteriet. Trees and buildings have been removed so that the model represents the ground surface position. In this way the model is not consistent with the reality. The laser scan data obtained from the municipalities have not gone through the same treatment. The surface represented by the data may thus not strictly represent the bottom or ground surface.

ArcGIS (ArcMap) has been used when working with the NNH alone for the flooding analyses.

5.2 Methodology

In the following sections the methods used for the different analyses are described. To analyze the impacts of waves and sea levels along the coastline of the bay 12 different profiles have been drawn and extracted from the Bathymetry and Topography Model and the NNH. The 12 profiles represent different sections of the coast area from the south to the north where profile 1-10 represent the southern and the central areas and profile 11 and 12 represent the northern part. The positions of the profiles can be seen in Figure 8, where the dots in the middle show the estimated position of the coastline. An orthorectified photo of the area, by Lantmäteriet shows the coastline of the bay as it was when the photo was taken in the year of 2010. The position of the coastline has been defined according to that photo for each of the extracted profiles along the bay.

When extreme scenarios have been studied based on the historical data it is the November storm in 2011(section1.1.1) that represents the most extreme event observed during the time represented by the series. Hence, whenever a historical extreme case is discussed, it is from the November storm.

Figure 8. Modified orthophoto © Lantmäteriet, i2012/901. The profiles extracted from the Bathymetry and Topography Modelare marked, stretching from a depth of 6 m up to the highway (except for profile 1 that stretches up to another road). The dot in the middle of each profile marks the estimated location of the coastline.

5.2.1 Wave runup analysis

An investigation of the wave runup in the area is interesting considering some different aspects. One is to give some indications of the sensitivity to wave impact of the different sections along the coastline. Another is to estimate if the highway will be exposed to over-wash at a future scenario with a raised sea level and with the highway positioned where it is today.

To estimate the extension of the waves as they wash up onto the beach the Hunt rule may be applied. The rule calculates the level up to which a wave will reach relative to the sea level. Combining these values with simultaneous values of the sea level an actual value of the vertical reach of the waves will be obtained. Hunt calculates a runup level from the deep water wave parameters as well as the beach characteristics. The analysis is thus based on the wave data extracted at the location for point 2 (Figure 4) and sea level data from Barsebäck. The two series contain simultaneous hourly values for the period 1994-2011.

5.2.1.1 Hunt's method

The level to which waves are washed up onto a beach can be estimated by the Hunt formula (Mayer *et al.* 1994). The formula is usually presented as Equation (1) (Hanson and Larson, 2008).

$$\frac{R}{H_0} = \frac{\tan \beta}{\sqrt{\frac{H_0}{L_0}}}$$
(1)

Where:

R = Runup height, meters above still water level (m)
H_0 = Wave height at deep water (approximate depth of 10 m) (m)
L_0 = Wave length at deep water (m)
β = Slope of swash zone (-)

5.2.1.1.1 Calculating the wavelength

The wave length can be calculated using equation 2 (SPM 1984). It is assumed that all the waves are at deep water.

$$L = C \cdot T$$
(2)

Where
L = wave length (m)
T = wave period (s)
C = wave velocity (m/s) (which can be calculated by using equation 3 for the different wave periods).

$$C = \frac{g \cdot T}{2 \cdot \Pi}$$
(3)

Where
C = wave velocity (m/s)
G = gravitational constant (m/s^2)
T = wave period (s)

5.2.1.1.2 Calculating the slope

To determine the slope of the swash zone (the section of the beach affected by wave action) a topography model is needed that represents the topography of the zone closest to the coastline. For this analysis the NNH model has been used. The 12 profiles were extracted from the model, starting at the position of the defined coastline (Figure 8). In a further step the horizontal limitation of the swash zone needed to be defined, starting at the coastline and ending at the highest point ever reached by the waves. Photos of the coastal zone of the bay taken right after the November storm in 2011 provided by the municipality of Landskrona, show the dark traces of washed up seaweed. These photos have been obtained for sections of the beach covering profiles 4-12 (Appendix 2). The position of the seaweed has been used as an indicator of the extent of the swash zone. In the northern part (profile 11 and 12), however, these seaweed traces are less visible but instead the full area between the sea and the highway appears to be flooded. This gives reasons to assume a swash zone stretching all the way up to the foot of the highway bank. A slope has then been estimated for each profile, simplifying its actual topography with a straight line.

Where there have been gaps (July 1998 for example) in the data series of the water level, the value of 0 has been set, thus assuming a water level of 11 cm below the mean.

5.2.2 Frequency analysis and estimation of return periods

The November storm was an extreme event that caused some damage to coastal societies; to analyze the importance of preparation for such events in the future it is of interest to estimate the return periods of the event and to estimate the risk of worse scenarios. This applies for sea levels as well as wave heights and wave runup.

Moreover, to evaluate the consequences or suitability of different future scenarios and solutions, e.g. flooding of certain areas it may be useful to consider the occurrence and frequency of different sea levels, not only the most extreme cases.

For the recent sea levels (1992-2012) and wave heights (1994-2011) as well as for the calculated wave runup (1994-2011) frequencies of different intervals have been investigated. Return periods have further been estimated for a longer series of sea levels as well as for the wave heights and wave runup levels. The method used is further described in the following section.

5.2.2.1 Return periods

The return period of a specific event is a statistically determined estimation of how often the event occurs within a specific time interval. An event with a 10-year return period for instance, will happen in average once in a 10-year interval, not specifically every 10th year (Dahlerus and Egermayer 2005). Climatic variations such as the variations in yearly se level maxima can be described and predicted with the help of different statistical distributions. By expressing the data points of a series of yearly maxima as an empirical distribution function a theoretical distribution function can further be estimated and fitted to the data series.

Return periods have been estimated for sea levels, wave heights and wave runup levels by using Weibull and Gringorten distributions. A plotting position formula, specific for each distribution method is applied to the data to express the data points according to an empirical distribution function. By this the plotting position formula determines the return period for each value of the series. A Weibull distribution is more suitable to use for longer series (more than 25 years), while the method by Gringorten makes a weighting which is suitable for shorter series, 10-25 years (Hamill 2002).

The data plotted according to the empirical distribution function can further be fitted to an estimated theoretical distribution function. One way to estimate this function is to plot the obtained data according to a Gumbel linear derivation. A fitted theoretical distribution function can then be obtained as a linear regression of the plot (Hamill 2002). Comparing the plotted data points of the empirical distribution to the obtained theoretical distribution is a way to evaluate how well the studied variations can be explained statistically by the chosen distribution. The R^2 value describing the correlation between the plotted data points and the linear regression gives a number for that evaluation.

5.2.2.2 Sea levels - long series

The sea level data is from 1938-2012 with a gap between 1970-1981 and 1983-1991. This will for the analysis be treated as one complete series even though it may be more correct to treat it as two separate ones. However, regarding it as one, the series is considered to be sufficiently long, thus an empirical Weibull distribution function has been used for estimating the return periods.

The procedure is to first sort the series of yearly maxima with the greatest value first, then give the values a rank number, the highest is put to 1 and the lowest to N. The following Weibull plotting position formula (4) is then used for determining the return periods according to the empirical distribution function.

$$T_r = \frac{N+1}{r} \qquad\qquad (4)$$

Where
T_r = return period (year)
r = rank number (-)
N = total amount of values (-)

An analysis of the return periods of the studied sea level extremes was already performed by Karlsson Green and Martinsson (2010). After comparing their data points to different fitted theoretical distributions (Figure 9) the authors decided to use a normal distribution for their analysis. However, as can be seen from Figure 9, the fitted Weibull distribution follows the same curve as the fitted normal distribution and should thus give an equally good fit. Similar results are thus to be expected from corresponding analyses based on the two different distributions. The series of sea levels used in the former study has now been modified and prolonged (section 5.1.3.1). To establish that the longer series gives the expected better fit to a theoretical distribution function the analysis has been performed for both series to obtain R^2 values to compare. The resulting return periods have also been compared to the ones estimated by Karlsson Green and Martinsson (2010) and are presented in Table 1.

Table 1. Extreme sea levels in Barsebäck (today) with different return period assuming a normal distrubution (RH 70) according to Karlsson Green and Martinsson (2010).

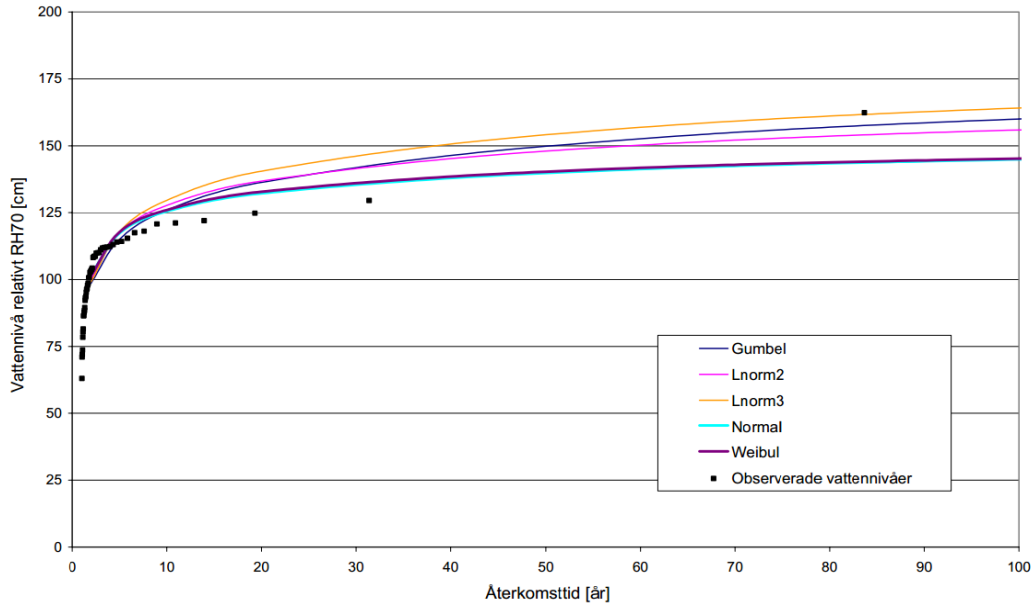| Return period (year)	Frequency (%)	Sea level (cm RH70)
2	50	102.2
5	20	117.8
10	10	126.0
20	5	132.7
50	2	140.3
100	1	145.4

Figure 9. Empirically distributed yearly maxima of sea levels at barsebäck (RH70) for the period 1938-1969, 1982, 1992-2008 plotted together with different fitted theoretical distributions (Karlsson Green and Martinsson, 2010).

Observing the theoretical Weibull distribution and the theoretical normal distribution in Figure 9 it seems like the series of sea level maxima would be better fitted to the distribution functions if the one extreme value (1948) was removed. This possibility has been considered and the two versions of the series have been further analyzed after removing the maxima of the years 1948 and 2011. The analysis has thus been performed for the full series as well as for a shortened series.

5.2.2.3 Wave heights and wave runup - short series

The wave height data is of the period 1994-2011. This is considered to be a short series and therefore a Gringorten distribution (Hamill 2002) has been used for estimating the return periods.

The procedure is the same as for the Weibull distribution. The series is sorted with the greatest value first, then each value is given a rank number, the highest is put to 1 and the lowest to N. The following plotting position formula (5) is then used for calculating the return periods according to the obtained empirical Gringorten distribution function.

$$T_r = \frac{N+0,12}{r-0,44} \qquad\qquad (5)$$

where
T_r = return period (year)
r = rank number (-)
N= total amount of values (-)

5.2.2.4 Estimating a theoretical distribution function

After plotting the data series according to the plotting position formula a further step is to plot the series according to a Gumbel linear derivation. The data points will then be positioned on a straight line and a theoretical distribution function can be estimated as a regression line of the plot.The data series can be expressed according to a Gumbel linear derivation (Hamill 2002) by using the formula below (6).

$$y = -\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right) \qquad (6)$$

Where
y = linear derivation (-)
T = return period (year)

As explained above the correlation between the estimated theoretical function and the empirically distributed data points can be used to evaluate how well the distribution function explains the variations of the data series. The coefficient of determination, R^2 ranges between 0 and 1 where a full correlation gives the value 1.

5.2.3 Bruun rule - estimating the coastline retreat

A rising sea level will alter the beach equilibrium as the waves will reach farther up on the beach, erosion of the coast will thus occur until a new equilibrium has been reached. The resulting coastline retreat can be roughly estimated by the Bruun rule. To get an idea of the land area that will have been lost due to erosion in a future scenario, the Bruun rule has been applied for the 12 profiles along the bay coastline. In this way an estimated future coastline retreat following a 1 m sea level rise has been obtained. For profiles 2, 6 and 10 the more extreme future scenario of a sea level rise of 1.6 m has further been investigated. These profiles are in this case regarded to together represent the southern and central parts of the bay. The time it takes for the new equilibrium to be reached is not estimated using the Bruun method. At what point in the future the estimated result may be expected is therefore unknown.

The Bruun rule (Silenzi *et al.* 2002) is based on the assumptions that the beach profile that will be affected contains easily erodible sediments (sand) and no hard constructions or rocks. It is also based on the principle that the beach profile will keep its shape, slope and dimensions i.e. the only change taken into account is the sea level (Silenzi *et al.* 2002). A general rule of thumb is that one centimeter of elevation of the mean sea level affects the coastline one meter in towards land. The Bruun rule is expressed by equation (7) and the principle is illustrated in Figure 10.
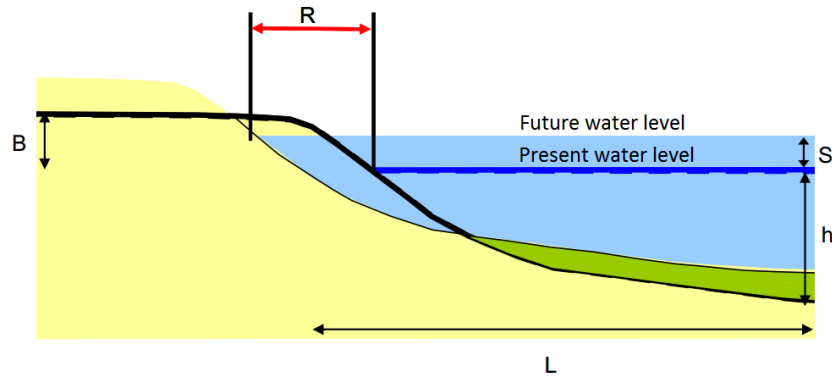
Figure 10. Modified figure from Hansson *et al.* (2006) illustrating the Bruun rule. The letters are explained further in equation 7.

$$R = \frac{L \cdot S}{B+h} \quad (7)$$

Where
R = the horizontal extension of the coastal erosion (m)
h = the maximal depth where exchange of sediment happens (m)
B = the elevation of the sand dune (m)
L = the horizontal distance between B and h (m)
S = increase in mean sea level (m)

The maximal depth where exchange of sediments happens, h, has been chosen as 6 m (Larson, 2013). Since the highway has been chosen as the point up to which erosion may occur, the remaining parameters of the equation, i.e. the horizontal distance and the elevation of the sand dune will be determined for each profile according to that.

The Bruun rule is contentious among different authors. According to Andrew and Pilkey (2004) numbers of attempts, for example in Australia, the Caspian Sea and in Louisiana, have been made to compare the Bruun rule with real erosion rates without any results. The problem with the rule is that the assumptions behind it are limiting and far from reality as the law neglects several important variables, it is also argued that it is based on old relationships. However, the Bruun rule is used all over the world and is widely spread over the continents (Andrew *et al*. 2004).

In this report the Bruun rule has been used since there is no better method to use and the rule has been approved by many other authors despite the flaws. Moreover the application of the Bruun rule in this report is taking the topography along the entire profile into account where normally the profile is simplified into a straight line. It may thus be argued that the rule in this case gives a more realistic result. Nevertheless, considering its weaknesses, the results should be regarded as a rough estimation that may, however, give some guidance when a future perspective needs to be considered.

To perform the analyses using the Bruun rule the 12 profiles along the coastline have been extracted from the Bathymetry and Topography Model. The profiles have the approximate angle of 90 degrees to the coast and stretch from a starting point in the sea at the depth of 6 m and up on land to where the highway starts, defining this as the limit of how far the beach will be allowed to erode. For profile 1 this limit is instead defined by a smaller road (Figure 8).

5.2.4 Flooding analysis

Different flooding analyses in the bay have been made with the help of GIS (ArcMap). Topography data of the NNH has been used. An orthophoto from Lantmäteriet has been combined with the NNH and map images have been created. The topography has then been classified by different intervals of elevation. Maps have been produced that show the different flooding scenarios at different steps towards a sea level rise of 1m. The different scenarios chosen are the future mean sea levels of + 0.25m, +0.50m+ 0.75m, +1.0m as well as +1.6 m together with a corresponding maximum sea level of a 2 year return period.

Adjacent areas to the bay coastal area have been investigated as well to look for alternatives to replace the protected nature areas and their specific characteristics. Even areas on the other side of the highway for the north part of the bay have been considered.

5.3 Results

5.3.1 Waves and runup

5.3.1.1 Wave climate

The maximum wave height during 1994-2011, was according to the wave model results by DHI (DHI 2013c), occurring during the big November storm 2011-11-27 at 21.00.This is the same time as the highest sea level was measured in Barsebäck for the period 1992-2012. The significant wave height at this event measured 2.2 m with a peak wave period of 5.23 sec and a wave direction of 281.5 degrees. This wave direction that also represents the wind direction coincides as expected with extremely high sea levels (discussed in section2.1).

The frequency distribution of the wave heights can be seen in Figure 11. For the period of investigation the most frequently occurring wave heights are represented by an interval of 0.15-0.24 m, waves within this interval occur 23 % of the time (Figure 11) while the mean wave height reaches 0.40 m.
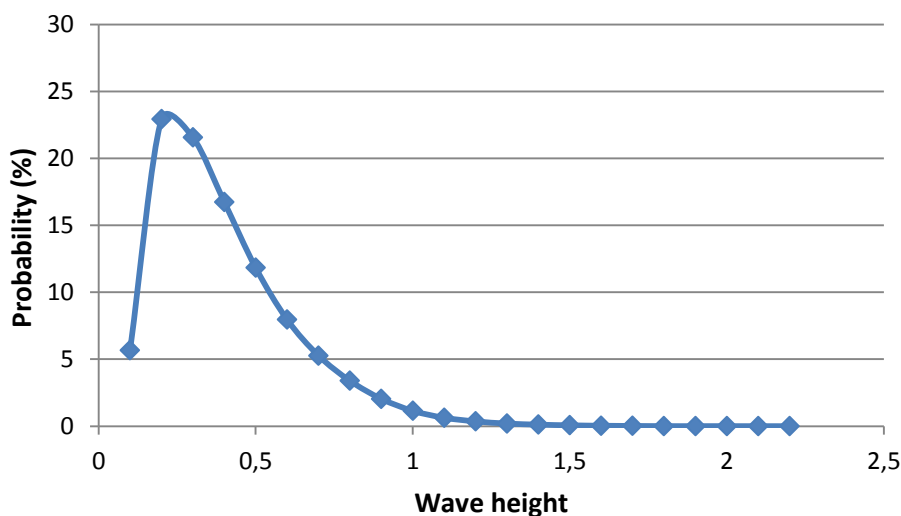
Figure 11. A diagram showing the frequency of different wave heights (intervals of 0.1 m) occurring in the bay during 1994-2011.

A further analysis considering an empirical Gringorten distributionfunction gave an estimation of the return periods for the different wave heights of the data series. The theoretical distribution function fitted to the empirically distributed data points is shown in Figure 12.The R^2 value 0.93 describes a good fitof the data series to the distribution function. In the next plot (Figure 13) the wave heights have been plotted against their return periods. From this figure the return period of the highest wave height (2.2 m) can be estimated as 32.5 years. For more return periods see Table 2.

Table 2. Return periods of different wave heights according to a Gringorten distribution, based on modeled wave heights of 1994-2011.

Return period (year)	Waveheight(m)
2	1.53
5	2.03
10	2.09
30	2.19
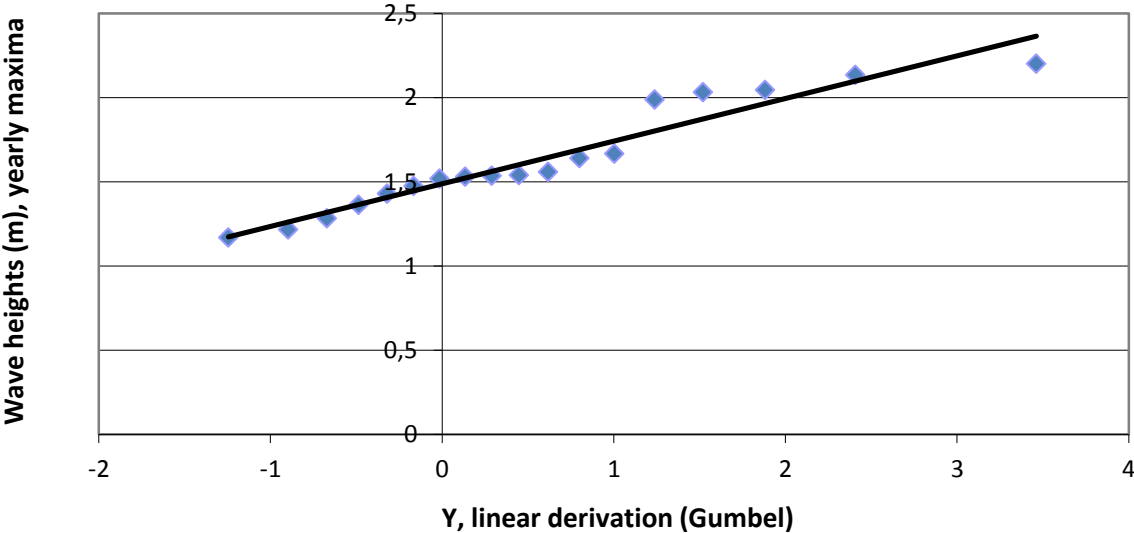
Figure 12. The empirical Gringorten distribution of yearly wave height maxima (1994-2011) plotted according to a Gumbel linear derivation, together with the theoretical distribution function obtained as a linear regression of the plot. R^2 =0.93.
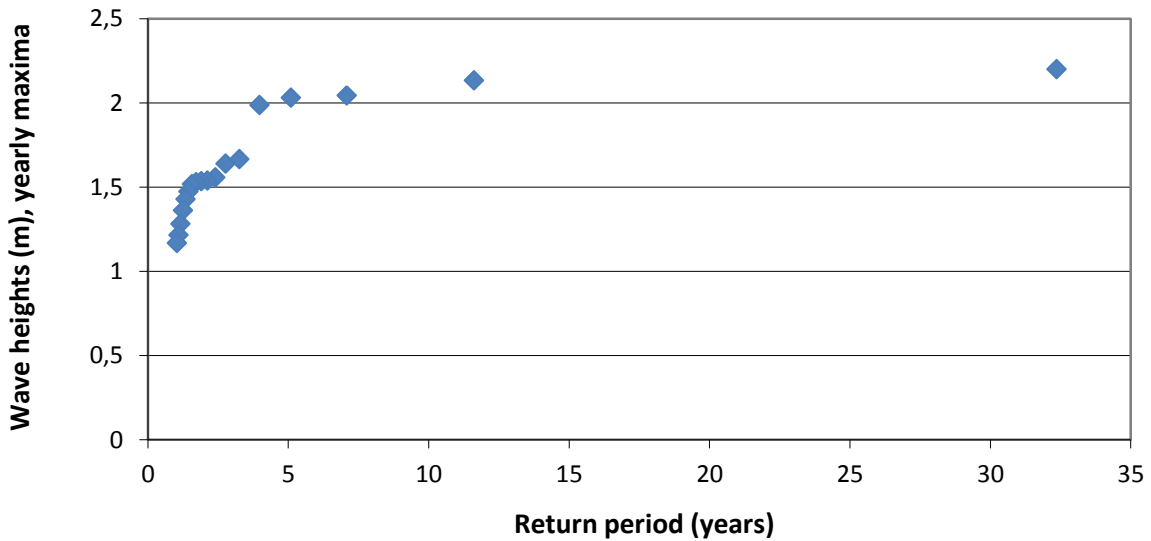
Figure 13. Return periods for each yearly wave height maximum (1994-2011) by an empirical Gringorten distribution.

5.3.1.2 Wave runup analysis

Hunt's method has been applied to all of the 12 profiles to get an idea of the wave runup for different sections along the bay coastline. The maximum runup level that was calculated occurred during the November storm at 2011-11-27 at 21:00. Both the sea levels and the wave heights reached their maxima of the analyzed period at this time. The sea level measured 1.47 m and the wave height 2.2 m.

The extreme sea level of 1.47 m caused at the time a temporary displacement of the coastline, this horizontal displacement has been estimated by studying the topography of each profile (appendix 1). The displacement of the coastline gives a new swash zone to consider for this specific extreme case and thus a slope that may differ from the normal case. Studying the results it has been observed that the sea level at this extreme event reached a peak in the topography for many of the profiles. The slope of the profile on the other side of this peak sometimes becomes very flat or even negative. For these profiles the resulting extreme case wave runup has reached farther than seems realistic and has thus been considered an overestimation. Some results were, however, considered to be realistic; they are marked in Table 3.

By the photos of the coast after the November storm obtained from the municipality of Landskrona (example shown in Figure 15, all photos in Appendix 2) the distance of the washed-up seaweed was measured for each profile (Table 3). This distance was then compared to the horizontal reach of the wave runup as well as the horizontal temporary displacement of the coastline due to the extreme sea level. To determine if the seaweed had been washed up by the force of the waves or if it had just been lifted up onto the beach by the raised sea level the position of the seaweed has been compared to the two distances. As can be seen from Table 3 the measured distance of the washed-up seaweed correspond well to distance of the displaced coastline. For the two profiles where the wave runup result is considered, profile 5 and 6 the comparison gives that the horizontal reach of the waves was much longer than the seaweed wash-up. These results show that the position of the seaweed

indicates only the extreme sea level and not the wave runup. The estimation of the horizontal reach of the waves in this analysis is complicated by the error in the topography model used. A measurement error of at least 0.1 m is considered and in some cases this uncertainty gives some very different options for how far the coastline will have been displaced in over land. Here the photos have given guidance and the results that are in accordance with them have been chosen. However, in most cases the horizontal displacements according to the analysis were well in agreement with the photos, which proofs a good reliability in the data used.

Table 3. Using Hunt's method the wave runup level has been calculated for the extreme case of 2011-11-27 at 21:00. The sea level for the specific hour is 1.47 m and the wave height is 2.2 m. The table shows the observed distance the sea weed has been washed up onto the beach during the storm; the temporary coastline displacement caused by the extreme sea level; the vertical wave runup level calculated by Hunt's rule and the estimated total horizontal reach of the waves. The results of profiles 1, 5 and 6 are considered relatively realistic while for the rest of the profiles the results should be interpreted with caution.

Profile	Sea weed wash-up distance (m from mean coastline)	Horizontal coastline displacement (m from mean coastline)	Vertical wave runup (m)	Horizontal reach of waves (m from mean coastline)
1		**15**	**2.46**	**20**
2		97	2.05	120
3		27	2.04	60
4	15	9	2.73	140
5	**70**	**77**	**1.64**	**128**
6	**90**	**102**	**1.61**	**153**
7	90	91	1.64	218
8	40	46	1.61	200
9	15	15	1.60	332
10	25	32	1.76	452
11		> 400	2.30	> 400
12		> 300	1.80	> 300

Profile 6 represented the biggest impact of the extreme sea level and the greatest distance of wave runup onto the beach among the results, and is considered to be most reliable. The result for this profile is considered to represent a worst case scenario among the profiles representing different sections of the bay area. As its topography is fairly homogenous the results are also considered the most reliable. The topography for profile 6 and the used slope for the analysis are presented in Figure 14. A photo showing the section of the coast represented by this profile is shown in Figure 15. All profiles can be seen in Appendix 1 together with the corresponding slope to each profile.
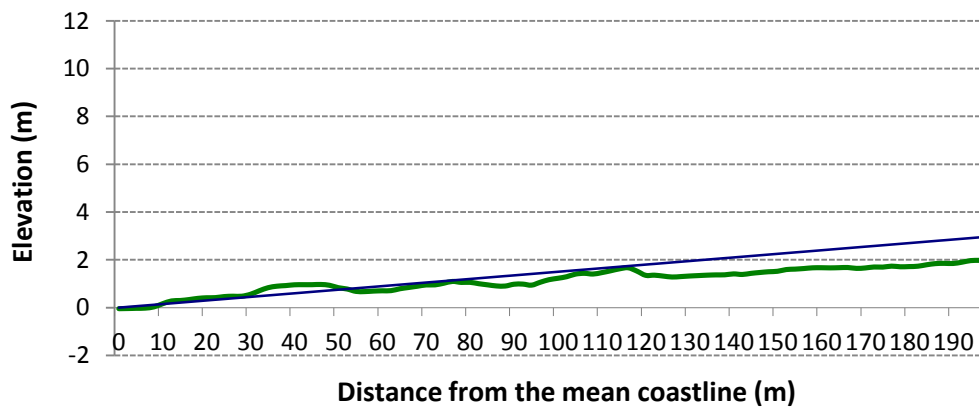
Figure 14. Profile 6 extracted from the topography model NNH (Lantmäteriet 2013). The blue line represents the estimated average slope of 0.015.

Figure 15. Photograph of the bay (Gustavsson, 2011) after the storm in November 2011, at the section of the coast where profile 6 is located. Washed up seaweed from the storm can be seen as dark traces.

The runup situation for profile 6 was further analyzed. The results in Figure 16 show the exceedance of the different runup levels, where each point represents an interval of ± 0.05 m around the marked value. The mean runup has been calculated as 0.14 m while the maximum reached was 1.61 m (as can be read from Table 3). The horizontal distances the waves reach at the most commonly occurring runup levels (of a positive value) have been marked in Figure 19.

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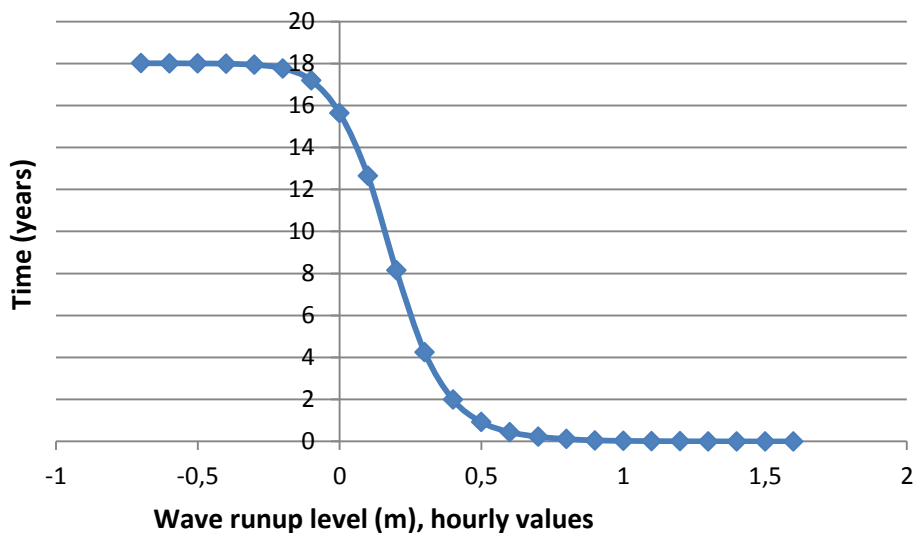
Figure 16. A diagram showing the exceedance in years of the different wave runup levels for profile 6 during the period 1994-2011. The data points represent intervals of ±0.05 m around their values.

An analysis using a Gringorten distribution has given the return periods for the maximum runup levels (Figure 17 and Figure 18). The first figure shows the data points plotted as a Gumbel linear derivation together with the theoretical distribution function fitted to the data as a regression line of the plot. The R^2 value is 0.93 which indicates a good fit. The second figure shows the maximum runup levels plotted against the return periods. The return period given for the highest level of runup, 1.6 m is 32.4 years. For more return periods see Table 4. The horizontal distances the waves reach at a runup situation of a return period of 2 years and 30 years respectively are marked in Figure 19.
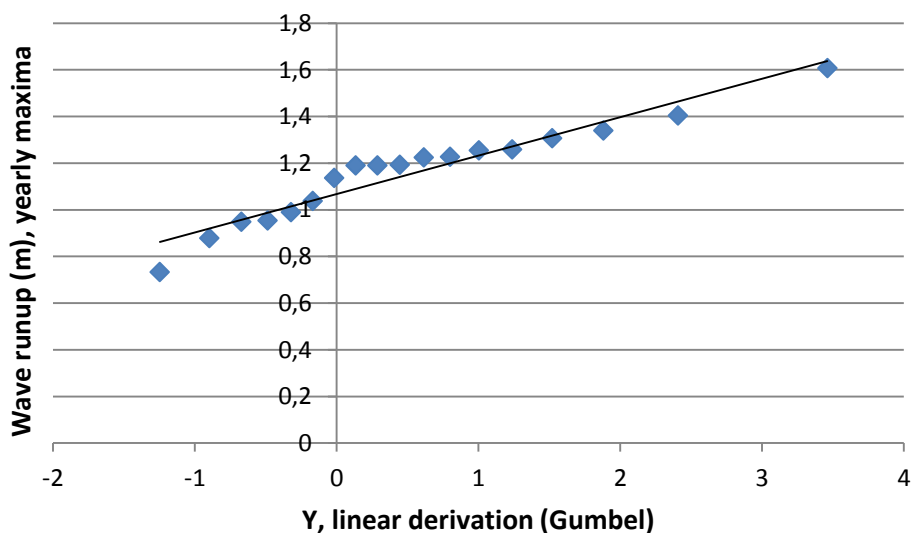
Figure 17. The empirical Gringorten distribution of yearly maximum levels of wave runup (1994-2011) for profile 6 plotted according to a Gumbel linear derivation, together with the theoretical distribution function obtained as a linear regression of the plot. $R^2 = 0.93$.
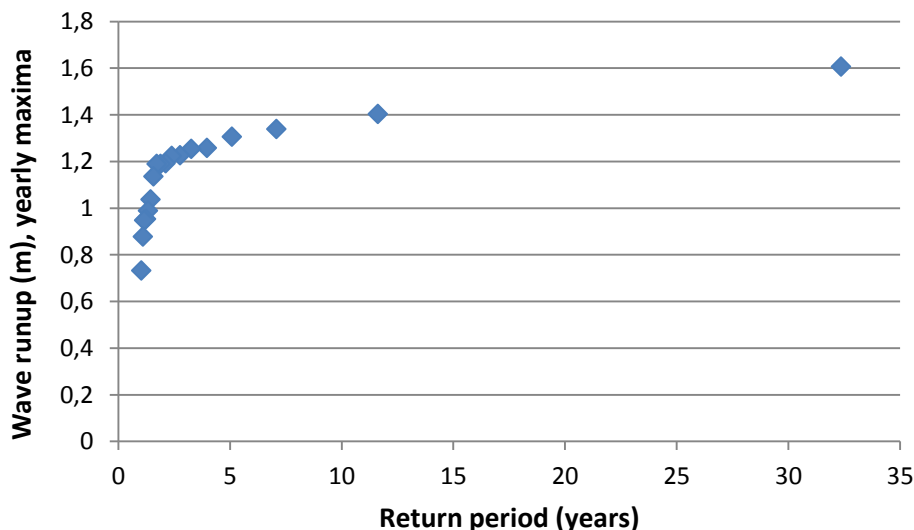
Figure 18. Return periods, by a Gringorten distribution, for each yearly maximum level of wave runup (1994-2011) for profile 6.

Table 4. Return periods of different runup levels at profile 6, according to the empirical Gringorten distribution. The analysis is based on calculated wave runup levels for the period 1994-2011, using Hunt's rule.

Return period (year)	Runup (m) Profile 6
2	1,19
5	1,31
10	1,38
30	1,59
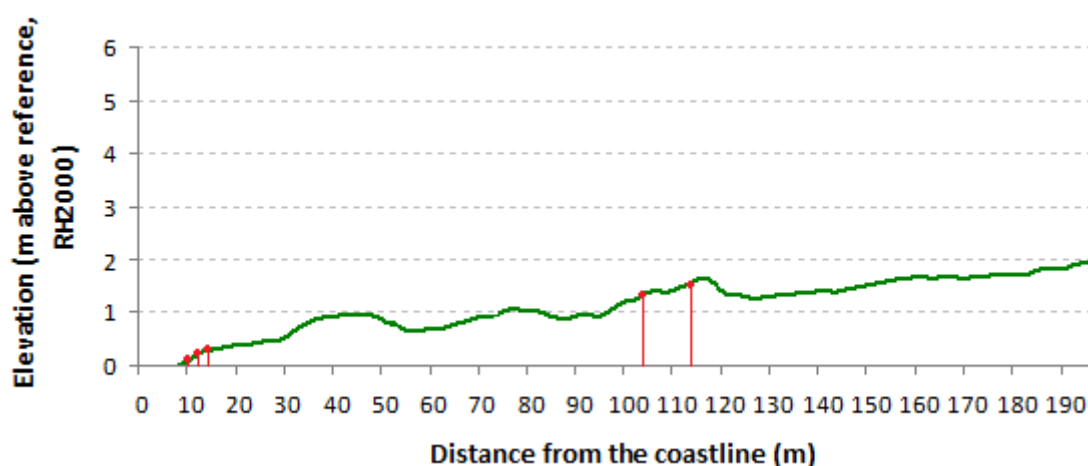
Figure 19. The levels up to which the waves will reach according to Hunt's rule for the period 1994-2011.The first three levels represent the three most commonly occurring runup levels that are bigger than 0 (Figure 16). The two higher levels represent the wave runup levels with the return periods of 2 years and 30 years respectively (Table 4).

There are weaknesses of the method chosen for this wave runup analysis. As already pointed out, when there is no positive slope, i.e that the elevation is always growing with the distance from the shoreline, the method does not strictly apply. For this reason the profiles 11 and 12 are difficult to investigate in terms of wave runup, as their topography is very flat. However, for the two chosen future scenarios the sea level will reach up to the foot of the highway at an extreme sea level situation. The method has thus been used to calculate the wave runup up on the highway bank. The resulting maximum wave runup for the profile 11 and 12 is presented in Table 5 (future scenario with a sea level rise of 1 m) and Table 6 (future scenario with a sea level rise of 1.6 m). The tables also include the elevation of the highway to give an indication of the risk of waves washing up over the highway. This is a simplified future scenario only considering the mean sea level rise. Taking into account the maximum sea level trend presented in section5.1.3.1 (see also following chapter), these maximum values would have been raised with 40 cm.

Table 5. Using Hunt's rule the wave runup has been calculated for a future scenario with an increase of the mean sea level of 1 m for profile 11 and 12 representing the northernmost area of the bay. The slope of the high way bank was estimated as 0.10. The runup was calculated for the period 1994-2011. The wave height of the extreme event of 2011-11-27 at 21:00was 2.2 m. The sea level for the same event but modified for a future scenario reaches 2.87 m. The table shows the calculated wave runup. The elevation of the highway is also presented here.

Profile	Wave runup(m)	Elevation of highway (m)
11	3.43	3.00
12	3.43	3.28

Table 6. Using Hunt's rule the wave runup has been calculated for a future scenario with an increase of the mean sea level of 1.6 m for profile 11 and 12 representing the northernmost area of the bay. The slope of the high way bank was estimated as 0.10. The runup was calculated for the period 1994-2011. The wave height of the extreme event of 2011-11-27 at 21:00was 2.2 m. The sea level for the same event but modified for a future scenario reaches 3.47 m. The table shows the calculated wave runup. The elevation of the highway is also presented here.

Profile	Wave runup(m)	Elevation of highway (m)
11	4,.03	3.00
12	4.03	3.28

The topography of profile 11 and 12 are showed in Figure 20 and Figure 21. The extracted profiles stretch from the coastline up to the opposite side of the highway. For profile 12 the topography of the section is so low that a sea level increase of 1 m would bring the mean

coastline up to the foot of the highway. For all the situations with the sea level close to the mean or above it the swash zone would be represented by the highway bank. The slope of the bank, 0.10, can thus be used to calculate the runup for this future scenario.
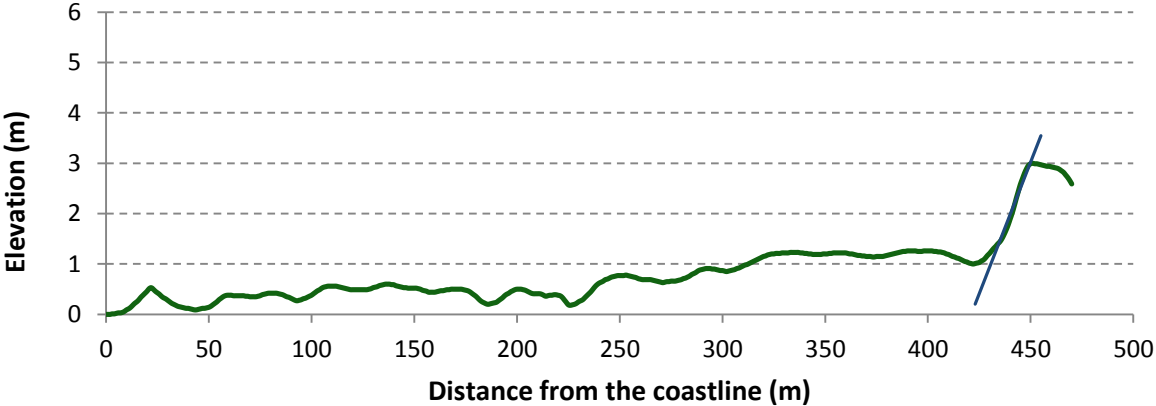

Figure 20. Profile 11 extracted from the Bathymetry and Topography Model. The estimated slope of the highway bank 0.10 is presented as the blue line.
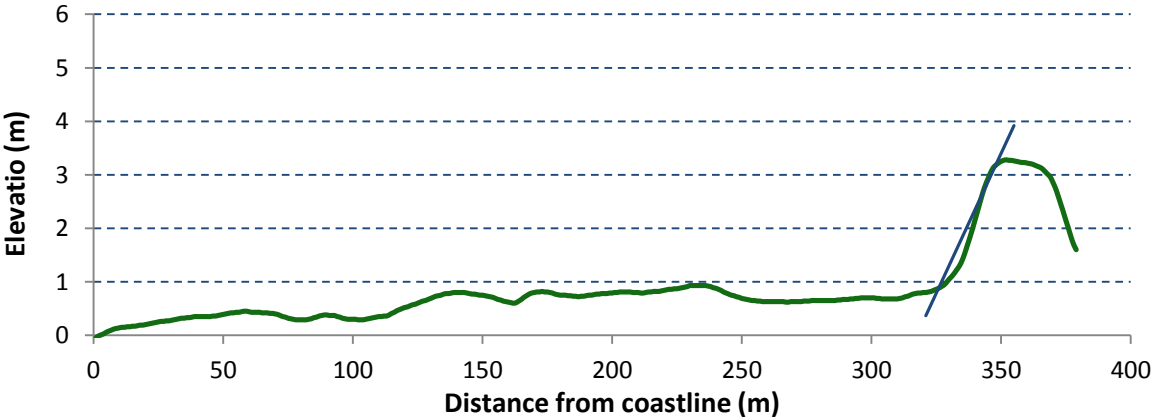

Figure 21. Profile 12 extracted from the Bathymetry and topography model. The same slope of the highway bank as estimated for profile 11; 0.10 is presented as the blue line.

The exceedance of different runup levels representing both profile 11 and profile 12 at a 1 m mean sea level rise are represented in Figure 22.For this future scenario (only considering the mean sea level rise) the highway at the location for both profiles would only be washed over for the extreme case equivalent to the November storm at 2011-11-27. For 3 hours the runup levels would exceed 3.28 m (highway elevation at the location of profile 12) and for 5 hours the level of 3.0 m (highway elevation at the location of profile 12) would be exceeded.

For the future scenario of a 1.6 m sea level increase the highway would have been washed over for a total of 240 hours, at 35 different occasions at profile 11 and 45 hours at 10 different occasions at profile 12, over a time period corresponding to the investigated period of 1994-2012.
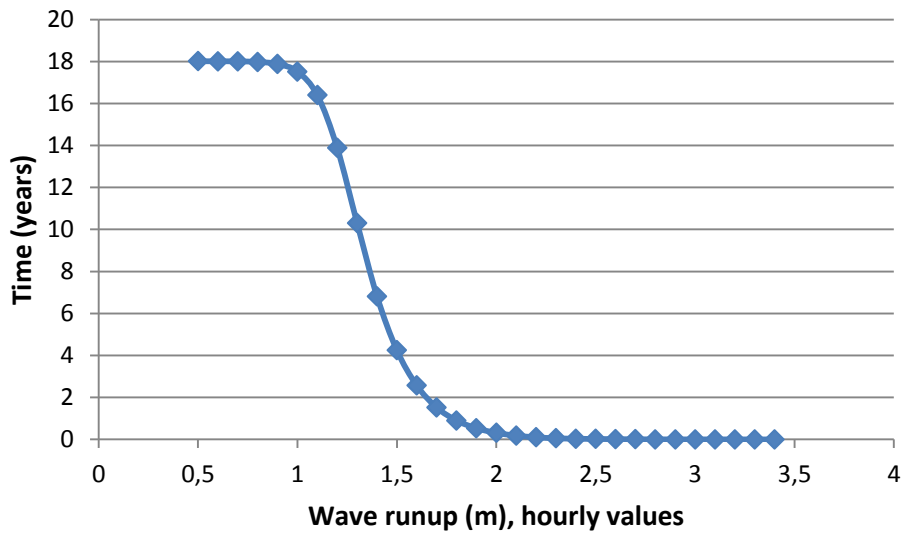
Figure 22. A diagram showing the exceedance (in years) of different wave runup levels (1994-2011) for profile 12 in a future scenario with a mean sea level increase of 1 m.

Return periods for the different runup situations have been estimated by an analysis plotting the data according to an empirical Gringorten distribution function. The future scenario of a 1 m sea level rise has been used for the analysis, the results apply for both profile 11 and profile 12. Figure 23 shows the data plotted as a Gumbel linear derivation together with the regression line representing the fitted theoretical distribution function. The R^2-value is 0.93 for the plot. In Figure 24 the runup levels are plotted against their return periods according to the Gringorten distribution, the highest level 3.43 m has been given the estimated return period of 32.4 years. For more return periods see Table 7.
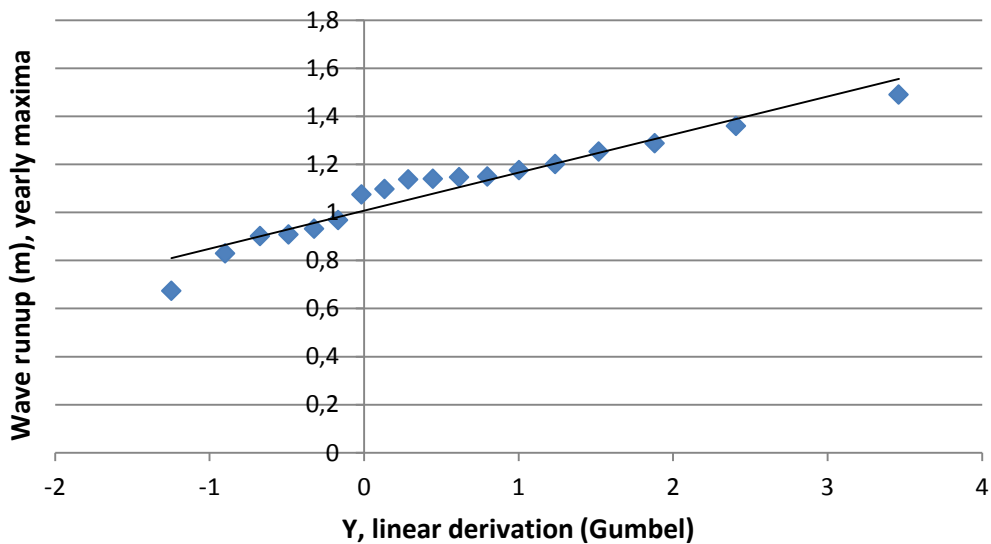
Figure 23. The empirical Gringorten distribution of yearly maximum levels of wave runup (1994-2011) for profile 12 plotted according to a Gumbel linear derivation, together with the theoretical distribution function obtained as a linear regression of the plot. R^2 =0.93.

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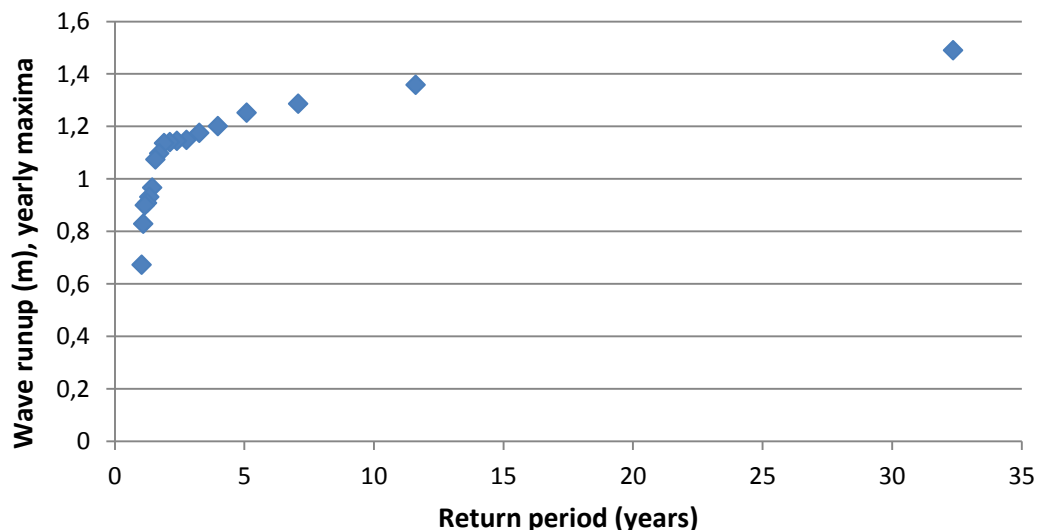
Figure 24. Return periods, by a Gringorten distribution, for each yearly maximum level of wave runup (1994-2011) for the future scenario with a mean sea level rise of 1 m, for profile 12.

Table 7. Return periods for different runup levels for profile 12, according to a Gringorten distribution. The analysis is based on calculated wave runup levels for the period 1994-2011, using Hunt's formula, the runup levels have been modified for a sea level increase of 1 m to apply for a future scenario.

Return period (year)	Runup level Profile 12 (m)
2	2.67
5	2.84
10	2.96
30	3.38
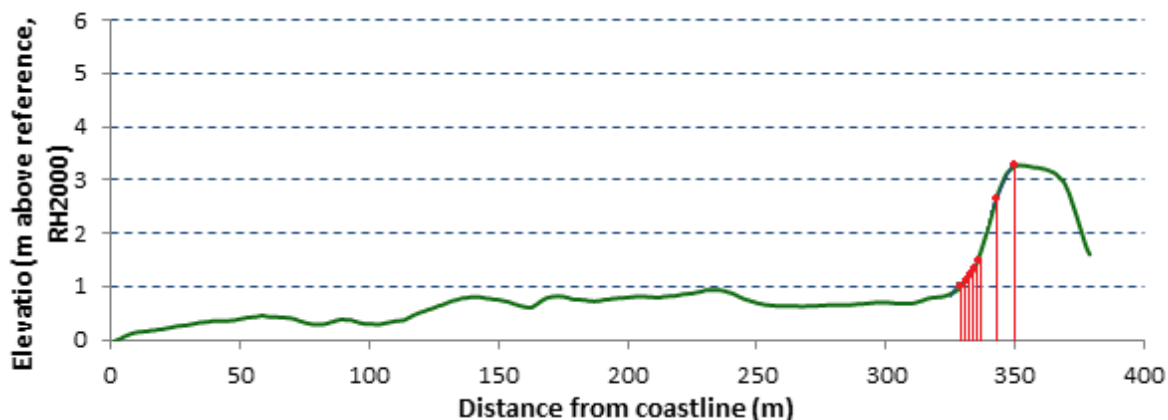
Figure 25. The wave runup onto the highway bank at profile 12 considering a future scenario of a 1 m sea level rise. The first three levels represent the six most commonly occurring runup levels (Figure 22) The two higher levels represent the wave runup levels with the return periods of 2 years and 30 years respectively (Table 4).

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5.3.2 Sea levels

To analyze the probability of different sea levels to arise in the bay a frequency analysis of hourly values measured in Barsebäck for the period 1992-2012 has been performed. The results are shown in Figure 26 where the sea levels are represented in intervals of ±5 cm around the marked value. The mean sea level during 1992-2012 is 11 cm above the reference level in RH 2000. This is also the most commonly occurring level. The median of the series is, however, 10 cm above the reference. As can be seen from the diagram in the figure, approximately 25% of the time the sea level stays within an interval of ± 5 cm around the median of 10 cm. Approximately 85 % of all sea levels of the measured period are within the interval of ±20 cm around the median 10 cm. The highest level measured for this period was 147 cm, at the November storm 2011-11-27 at 21.00.
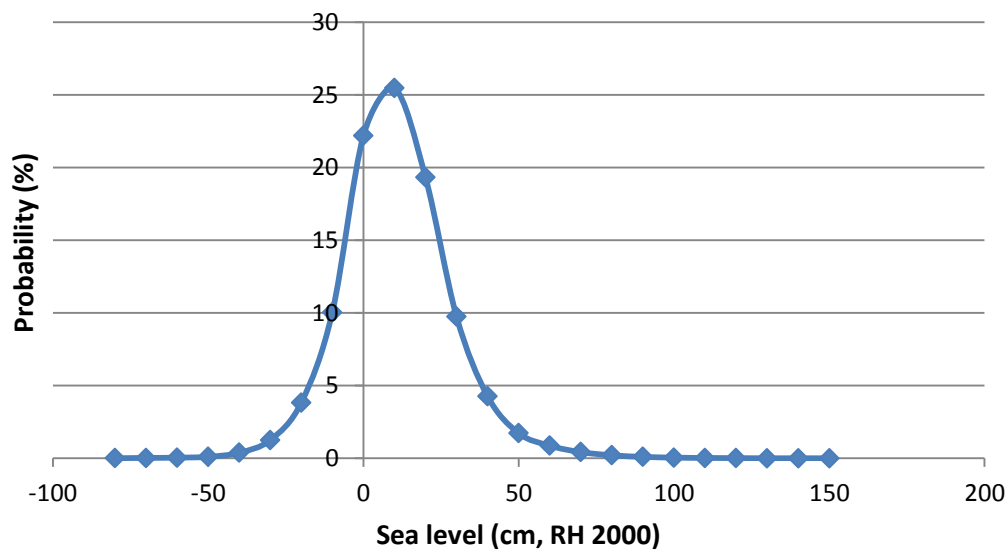
Figure 26. A diagram showing the probability of different sea levels in intervals of ±5 cm, based on hourly values from Barsebäck 1992-2012.

In the further analysis, a longer series has been used (for the periods 1938-1969, 1982, 1992-2012). The data plotted according to a Weibull distribution and the resulting return periods are presented in Figure 27 and Figure 28. In the first figure the suitability of the chosen distribution method can be estimated by considering the R^2 value of the data represented by a Gumbel linear derivation and the fitted theoretical distribution function, obtained as the linear regression. The R^2 value of 0.93 indicates a good fit. In the second figure the yearly maximum sea levels have been plotted against the return periods according to the empirical Weibull distribution, giving a return period of 55 years for the highest value of the series, 171 cm, occurring in 1948. The second highest sea level in the analyzed period, 147 cm, occurred during the November storm in 2011. The method gives the estimated return period for this extreme sea level of 27.5 years.
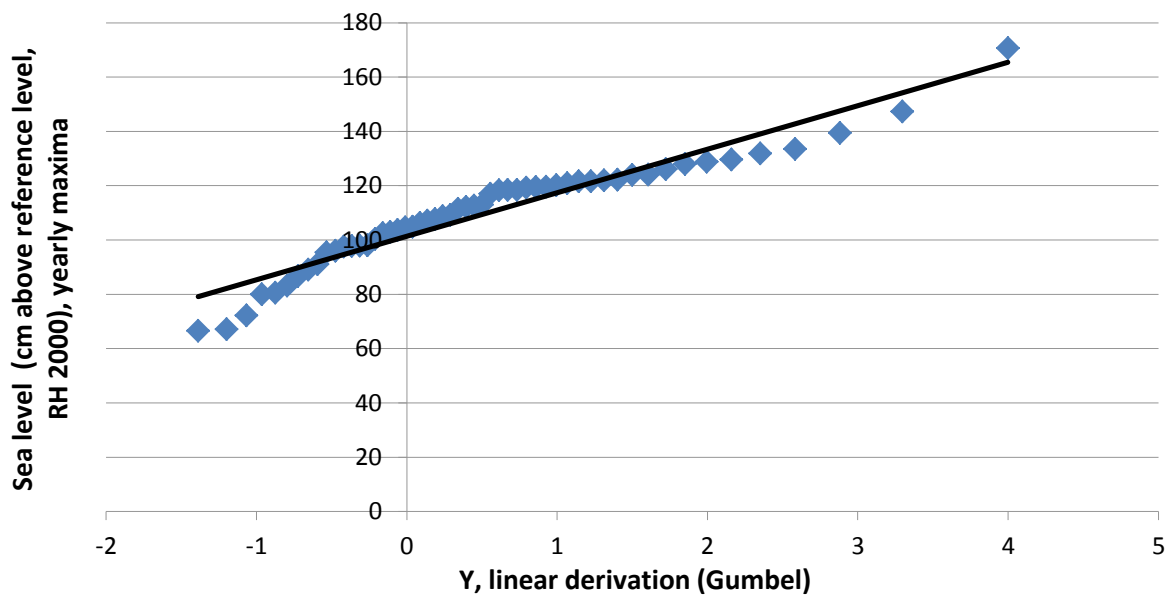
Figure 27. The empirical Weibull distribution of yearly maximum sea levels (Barsebäck 1938-1969, 1982, 1992-2012), plotted according to a Gumbel linear derivation, together with the theoretical distribution function obtained as a linear regression of the plot. $R^2 = 0.93$.
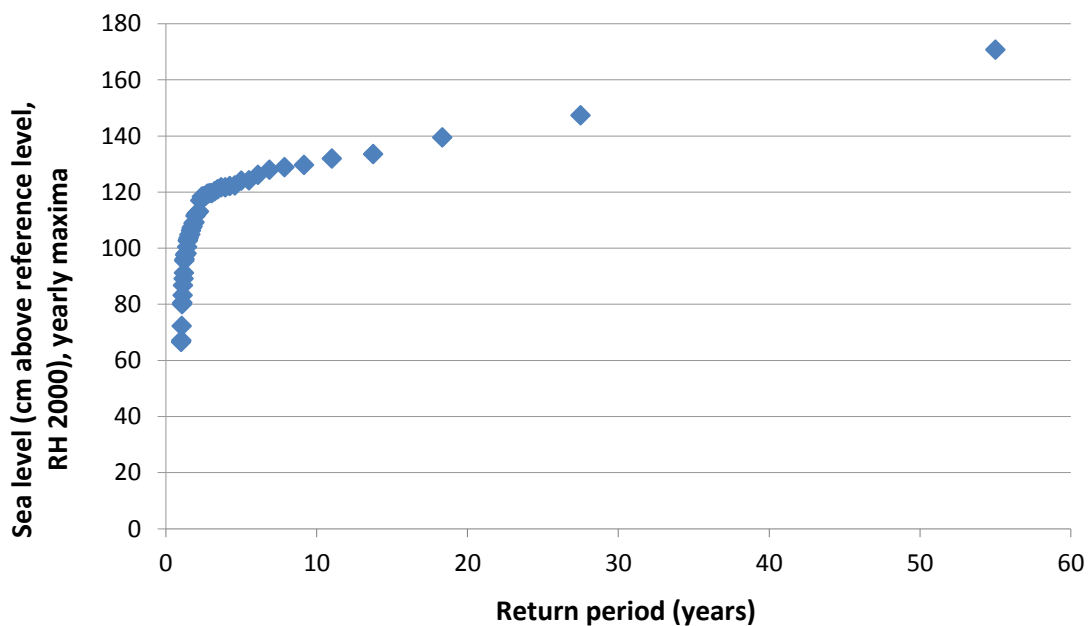

Figure 28. Yearly maximum sea levels (Barsebäck 1938-1969, 1982, 1992-2012) plotted against their return periods, as estimated by an empirical Weibull distribution function.

Table 8. Return periods for sea levels at Barsebäck obtained from a former study of Karlsson Green and Martinsson (2010) have been converted from the reference system RH70 to RH 2000 and compared to the corresponding return periods from the results of the present study.

Return period (years)	Sea level, former study (cm, RH70)	Sea level, former study (cm, RH 2000)	Sea level, present study (cm, RH 2000)
2	102	113	112
5	118	129	124
10	126	137	131
20	133	144	141
30	-	-	150
50	140	151	166
100	145	156	-

The obtained results for the return periods of different sea levels have been compared (Table 8) to the results obtained by Karlsson Green and Martinsson (2010). For the sea levels of return periods 2 to 20 years the results are similar although a bit higher by the former analysis. However, concerning the longer return periods the new results indicate higher sea levels. A sea level of a 50 year return period was 151 cm according to the previous study while the new results instead indicate a level of 166 cm. The level of 150 cm had an estimated return period of 50 years in the previous study while the new results gave an estimated return period of 30 years for the same sea level. The main differences between the two analyses is the change in distribution from normal to Weibull as well as the addition of four more values from the years 2009-2012.

According to the analysis by Karlsson Green and Martinsson (2010) the fit of the sea level series to a normal distribution would be very similar to the corresponding fit to a Weibull distribution (Figure 9). By that result the change of method would not be the explanation to the difference in the results.

To evaluate if the longer series give a more trustworthy result the Weibull analysis was performed for the former data series as used by Karlsson Green and Martinsson (2010), the result has been plotted in Figure 29. The obtained R^2 value was here 0.91. When using the longer series the higher value of $R^2 = 0.93$ is instead obtained, indicating a better fit for the longer series.
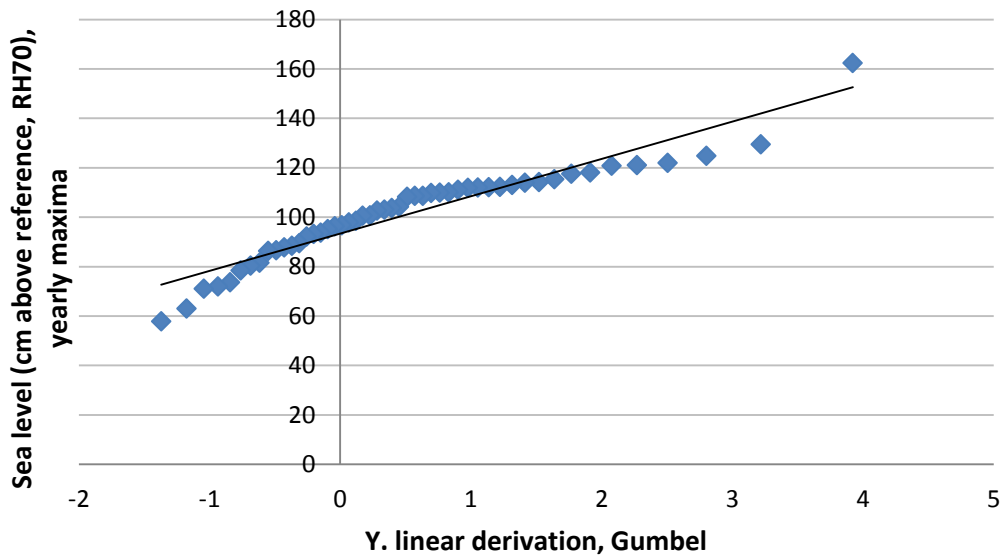
Figure 29. The empirical Weibull distribution of yearly maximum sea levels for the shorter time series (Barsebäck 1938-1969, 1982, 1992-2008) plotted according to a Gumbel linear derivation, together with the theoretical distribution function obtained as a linear regression of the plot. $R^2 = 0.91$.

The two series have been analyzed after removing the maxima of the years 1948 and 2011. For both series the same R^2 value of 0.86 was now obtained. It can thus be concluded that the Weibull distribution offers a good fit to the series of sea level maxima and that the fit became even better when the series was prolonged to contain a second extreme level (2011).

5.3.3 Flooding analysis

Future extreme sea levels have been calculated for the two chosen mean sea level rise scenarios and by considering the max sea level trend that was calculated in section 5.1.3.1. Imagining first a smooth continuous rising sea level of 1 m up until the year 2100, three intermediate levels on the way have been considered for the years 2035, 2057, 2079. The mean sea level rise is presented in Table 9 for each of these years together with the calculated elevation to be added to the maximum sea levels, following the maximum sea level trend 0.46 cm/year. This is again a further simplified scenario since there are no indications that the sea level rise will follow a linear development.

Table 9. The extreme sea level trend that was calculated in section 5.1.3.1, 0.46 cm/year, will be added to each extreme sea level for the different stepwise future scenarios. The additions to be made for each specific year are marked in the table.

Year	Sea level rise (m)	Trend addition(cm)	Trend addition (m)
2035	0.25	10	0.10
2057	0.5	20	0.20
2079	0.75	30	0.30
2100	1	40	0.40

The mean sea levels and the extreme sea levels with the return periods 2, 5, 10, 20, 30 and 50 years have been calculated for each considered future sea level rise, this can be read from Table 10. The different sea levels are all calculated for their specified year given in Table 9, with the sea level of +1.6 m as an alternative scenario for the year 2100. While the difference in mean sea level between the present situation and the most extreme future scenario is 1.6 m the corresponding difference in extreme sea levels is estimated as 2 m. The uncertainty here is very big since the factors determining the behavior of extreme sea level situations are even harder to predict than the factors deciding the mean sea level rise.

Table 10. Calculated sea levels (RH 2000) for the mean situation as well as for different return periods for 5 considered future scenarios. The time perspective for the four first sea levels is indicated in Table 9, the last considered sea level is an alternative scenario for the year 2100.

		Sea level (m)	Sea level +0.25m	Sea level +0.50m	Sea level +0.75m	Sea level +1.0m	Sea level + 1.6m
Mean sea level		0.11	0.36	0.61	0.86	1.11	1.71
Return	2	1.12	1.47	1.82	2.17	2.52	3.12
Period	5	1.24	1.59	1.94	2.29	2.64	3.24
(year)	10	1.31	1.66	2.01	2.36	2.71	3.31
	20	1.41	1.76	2.11	2.46	2.81	3.41
	30	1.50	1.85	2.20	2.55	2.90	3.50
	50	1.66	2.01	2.36	2.71	3.06	3.66

Considering the different future scenarios the impacts of the bay could finally also be investigated in terms of flooding. Figure 30 to Figure 38show the northern part of the bay at different mean sea levels and extreme levels with a two year return period. From analyzing the images, the sea level of +0.75 m seems to be the crucial one for the existence of the area on the west side of the highway in the northern bay area, hosting the coastal meadows. This can be observed in Figure 32 that shows the area of the north part of the bay as it looks today and the parts of it that would potentially be water filled at a sea level of +0.75 m. Observing this map image there are reasons to believe that the area of coastal meadows between the coastline and the highway will be lost at the studied future scenario. It can further be observed that an area on the other side of the highway has a potential of providing a water filled basin at this sea level.

To analyze the dimensions of this water basin at an interval of commonly occurring sea levels an additional +0.25 m sea level is considered. It has earlier been stated (section5.3.2) that the sea levels stay within an interval of approximately ± 20 cm around the mean 85 % of the time. Hence, the considered level will represent a slightly extended interval of the commonly occurring sea levels at the future scenario of a 0.75 m sea level rise. The dimensions of the potential water basin in that situation can thus be analyzed by considering the scenario of a +1 m sea level (Figure 33).
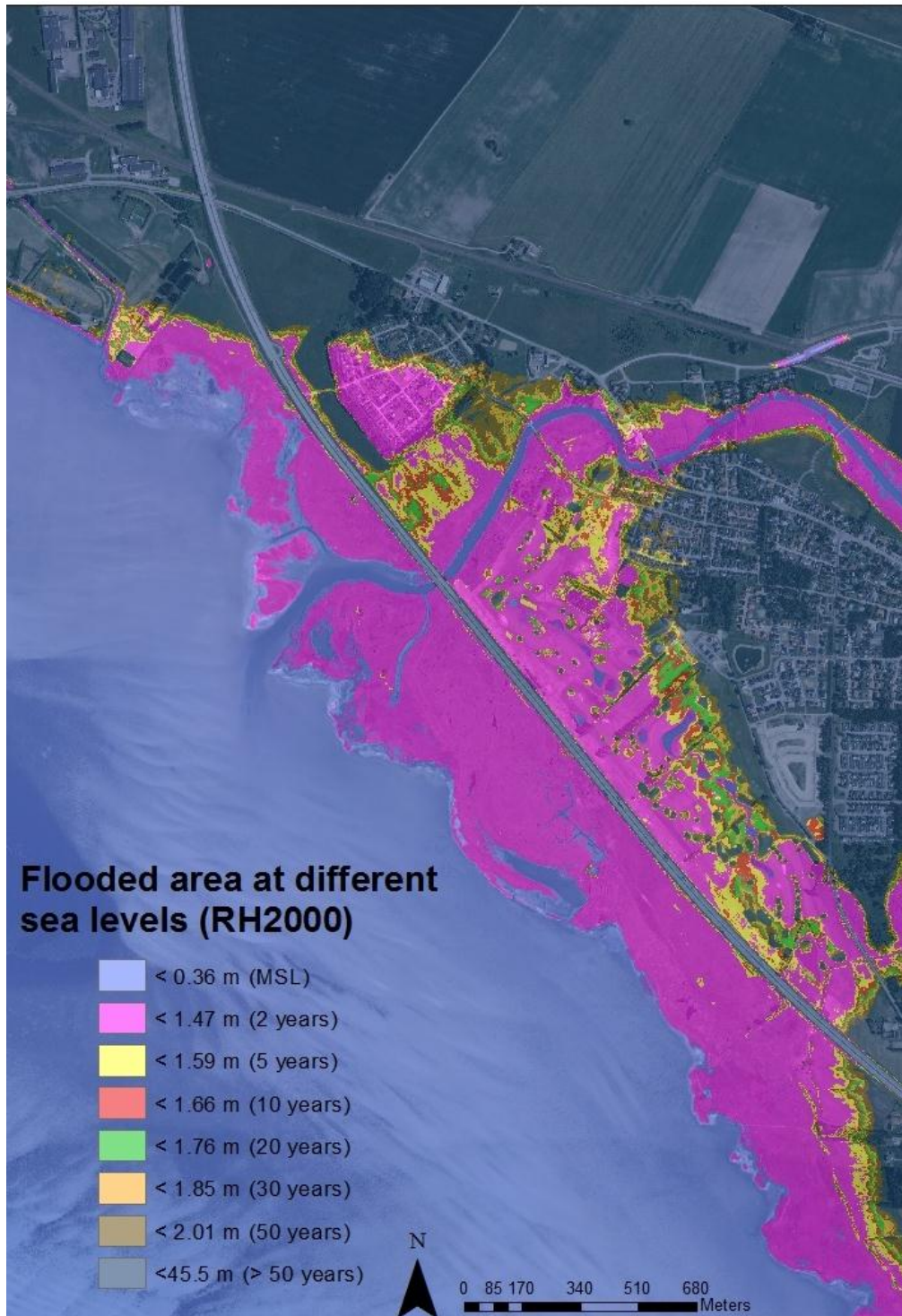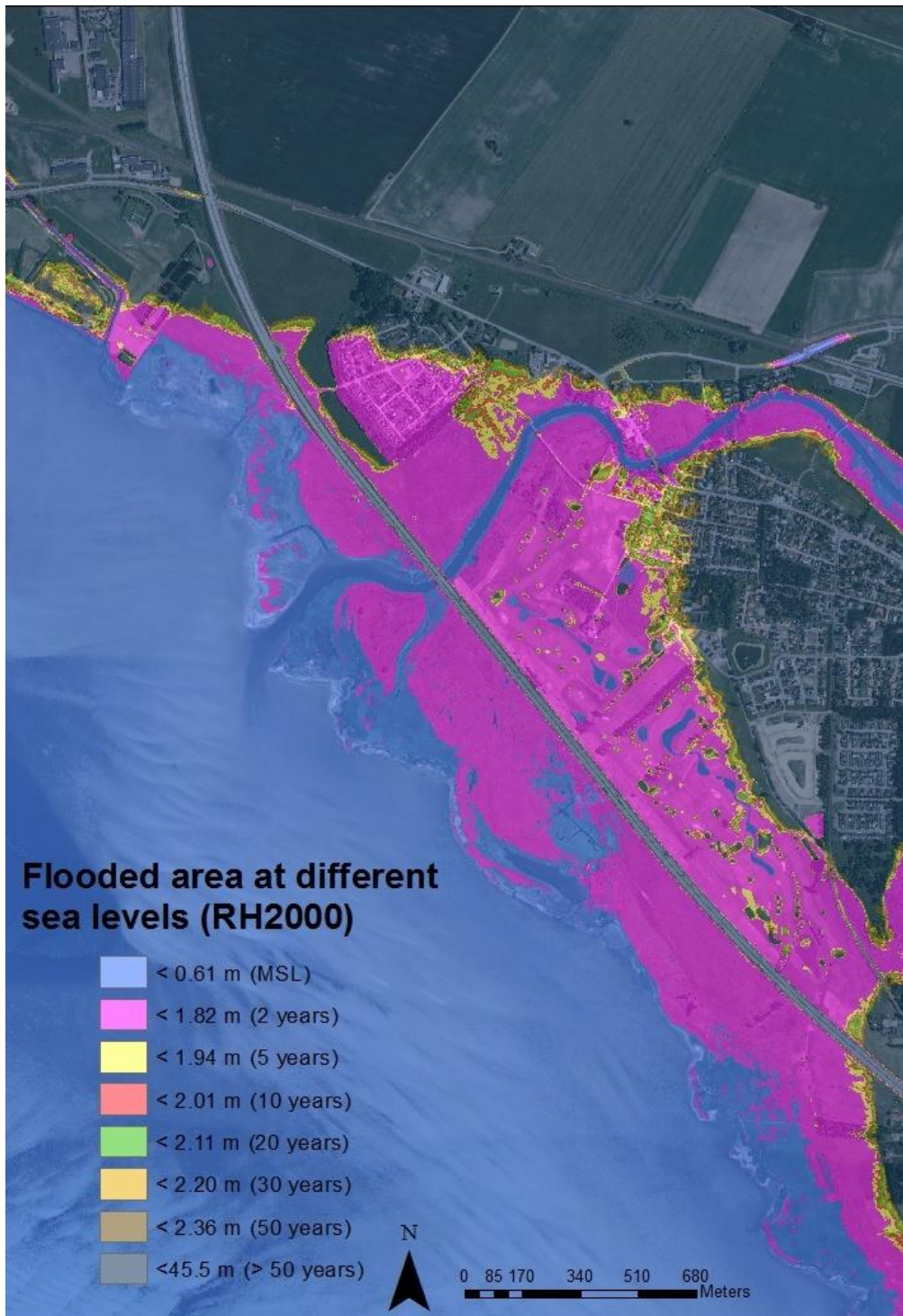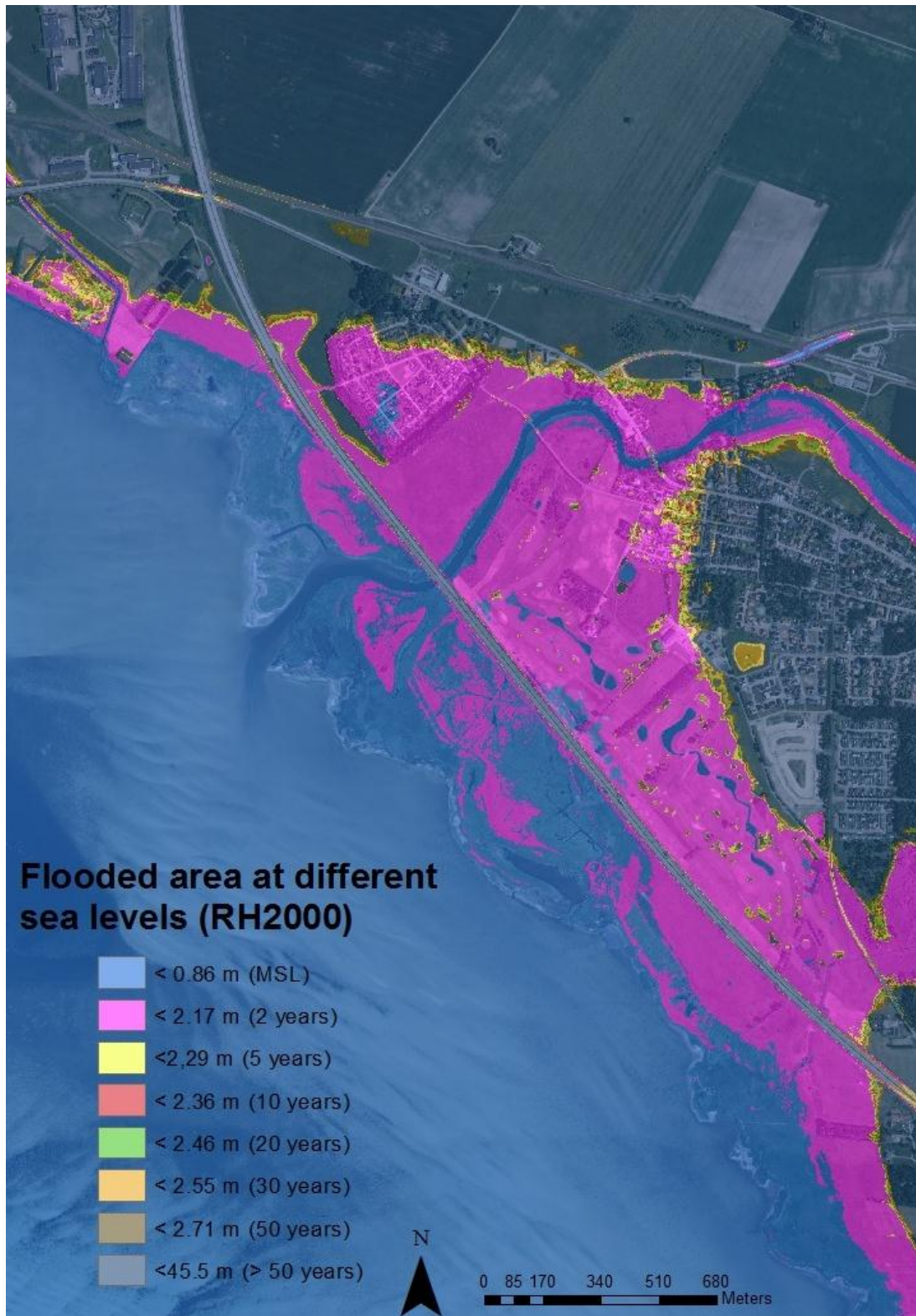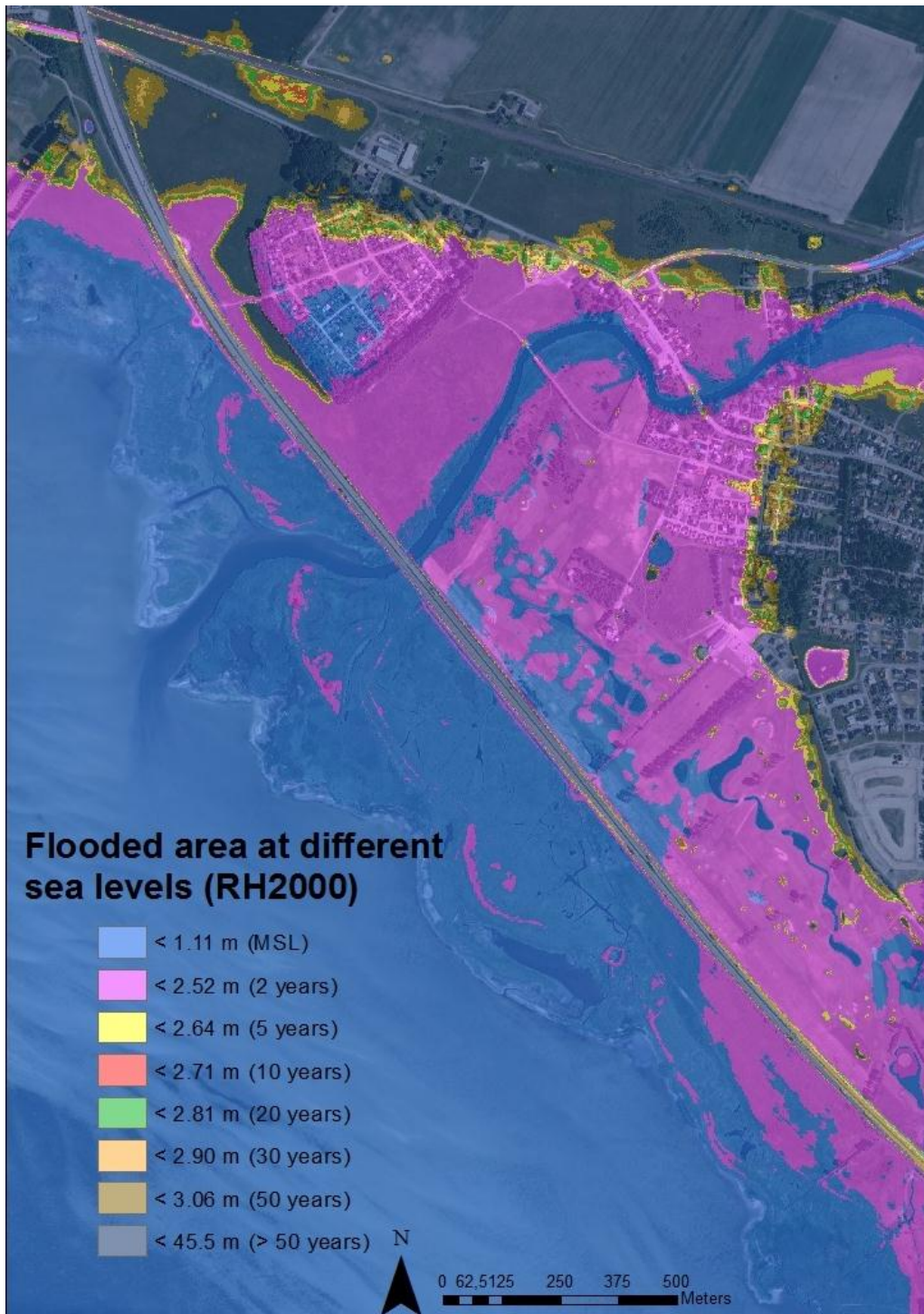
Figure 30. Return periods for different water levels and corresponding flooded areas, considering a future scenario 2035 with a 0.25 m mean sea level rise. Blue color represents areas under mean sea level 0.36 m (RH2000). Pink color represents areas flooded at a sea level from the mean sea level up to the level of a 2-year return period, 1.47 m. Other colors represent flooded areas with longer return periods. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
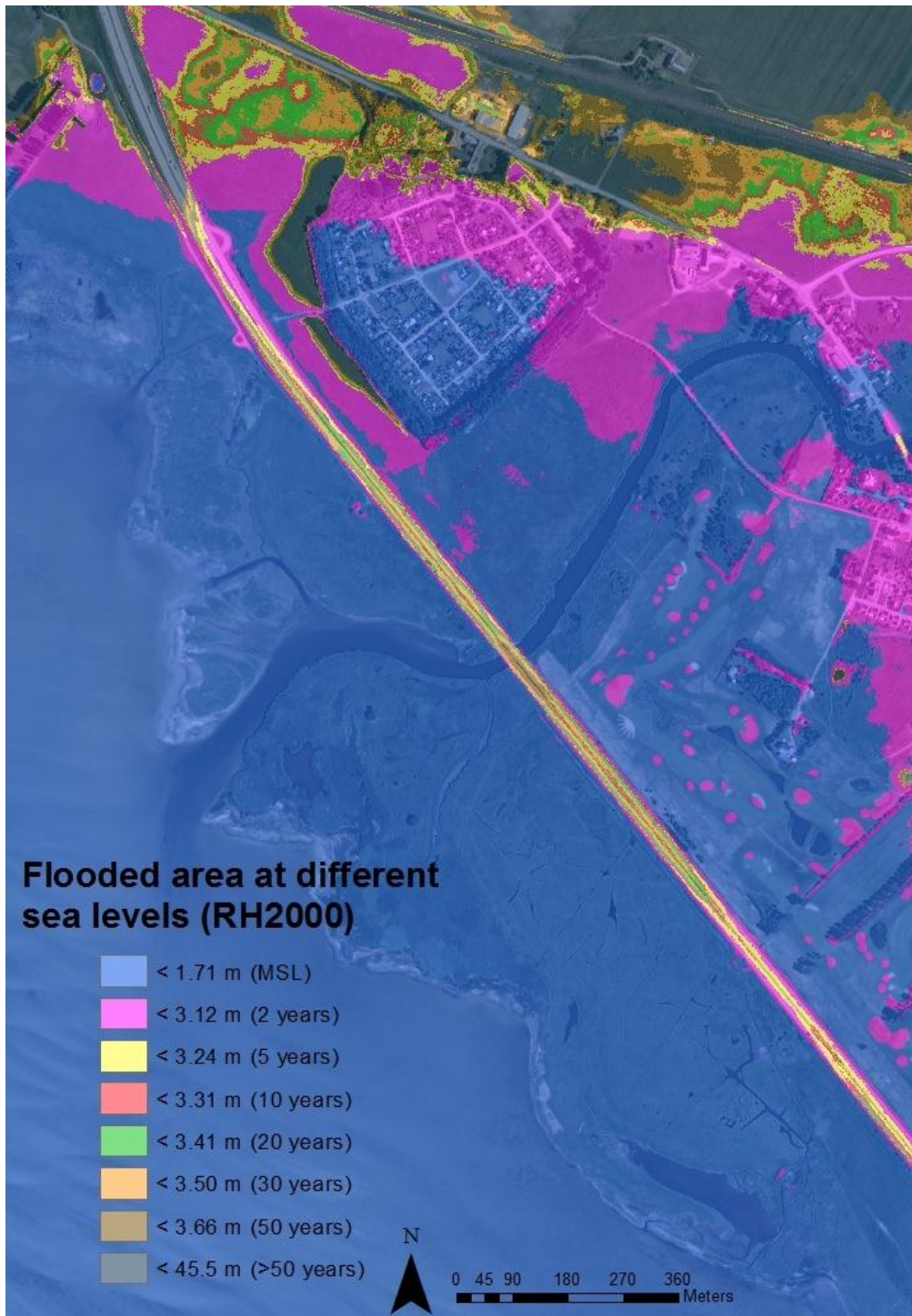
Figure 31. Return periods for different water levels and corresponding flooded areas, considering a future scenario 2057 with a 0.5 m mean sea level rise. Blue color represents areas under mean sea level 0.61 m (RH2000). Pink color represents areas flooded at a sea level from the mean sea level up to the level of a 2-year return period, 1.82 m. Other colors represent flooded areas with longer return periods. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

Figure 32. Return periods for different water levels and corresponding flooded areas, considering a future scenario 2079 with a 0.75 m mean sea level rise. Blue color represents areas under mean sea level 0.86 m (RH2000). Pink color represents areas flooded at a sea level from the mean sea level up to the level of a 2-year return period, 2.17 m. Other colors represent flooded areas with longer return periods. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

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Figure 33. Return periods for different water levels and corresponding flooded areas, considering a future scenario 2100 with a 1.0 m mean sea level rise. Blue color represents areas under mean sea level 1.11 m (RH2000). Pink color represents areas flooded at a sea level from the mean sea level up to the level of a 2-year return period, 2.52 m. Other colors represent flooded areas with longer return periods. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

Figure 34. Return periods for different water levels and corresponding flooded areas, considering a future scenario 2100 with a 1.6 m mean sea level rise. Blue color represents areas under mean sea level 1.71 m (RH2000). Pink color represents areas flooded at a sea level from the mean sea level up to the level of a 2-year return period, 3.12 m. Other colors represent flooded areas with longer return periods. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

Figure 35 and Figure 36 compares the flooding situation today with the situation at the future scenarios of a 1 m mean sea level rise and a 1,6 m mean sea level rise in the central and the southern part respectively. These images are cut out from the full scale map images that are found in Appendix 3. The results of these figures show that a 1 m sea level rise would not

have any considerable impact on the central and southern parts of the bay. However, the additional 0.6 m to a +1.6 m sea level would have a big impact on the central part of the bay and also shows a geographically varied impact in the southern part.
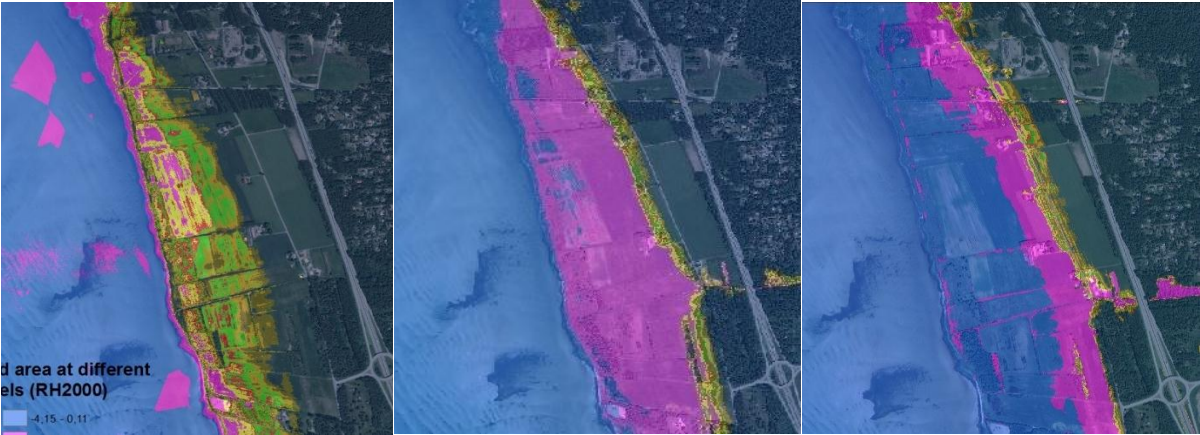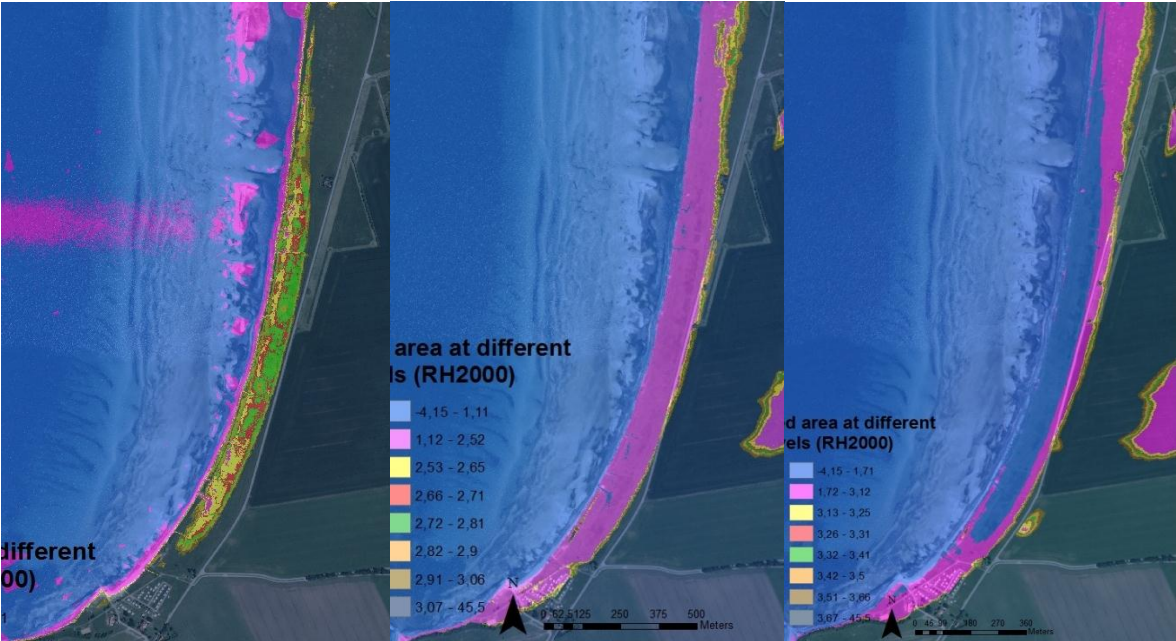

Figure 35. The central part of the bay considering the situation today (left), a future scenario at 2100 with +1.0m mean sea level (center) and a future scenario at 2100 with a +1.6 m mean sea level (right). Blue color represents areas under water at a mean sea level (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period. For the full version of the images, see Appendix 3. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013)."

Figure 36. The south part of the bay considering the situation today (left), a future scenario at 2100 with +1.0m mean sea level (center) and a future scenario at 2100 with a +1.6 m mean sea level (right). Blue color represents areas under water at a mean sea level (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period. For the full versions of the images, see Appendix 3. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

5.3.4 Coastline retreat

The Bruun rule has been applied to the 12 bottom profiles (Figure 8). When the sea level rises, the coastline will retreat until it has regained equilibrium in terms of the transversal sediment transport. The rule gives an estimation of the distance of this retreat. The results can be seen in Table 11 and in Figure 37. In the figure the green dots are showing were the coastline is today and the pink dots show the estimated position of a future coastline, at 1m sea level rise, if the coast will be allowed to erode freely without obstacles stopping the process. The orange dots are showing the further estimated displacement of the coastline for some chosen profiles if the sea continues to rise to +1.6 m, here the two end profiles and the one in between were chosen, not counting profile 1, 11 and 12. These distances are also marked in the table. For profile 11 and 12 the same method was used to analyze for what sea level rise the estimated future position of the coastline would reach the highway (Table 11).

Figure 37. Modified orthophoto © Lantmäteriet, i2012/901 showing an overview of the bay. The green dots show the coastline of today and the pink dots show the future coastline estimated by the Bruun rule if the coast is allowed to erode freely at a 1 m sea level rise. For profile 2, 6 and 10 an orange dots are indicating the same displacement following a 1.6 m sea level rise.

The results indicate that when the sea level rises with one meter the coastline is estimated to retreat approximately 250 m in average into land in the south and the middle part of the bay. In the north part of the bay, close to the city of Landskrona the theoretical coastline displacement would be much more, approximately 820 m. The highway is located 220 m (at

the closest point) inland from today's coastline. If the highway will be there also in the future the coastline will never reach as far as the 820 m. The further analysis give the resulting estimation that the coast would reach the highway at profile 11 at a sea level rise of 0.75 m and for profile 12 the highway will be reached already at a sea level rise of 0.5 m. This indicates a risk that the area of coastal meadows in the nature reserve (north part of the bay) will stepwise be lost with a sea level rise of 0.5-1 m. The highway is placed on a high enough level not to be flooded by the considered future mean water level. However, extreme sea levels and wave runup onto the highway would also need to be considered to estimate appropriate protective measures for the highway in accordance with the analyzed future scenarios. This has already been discussed in sections 5.2.1 and 5.3.1.2.

Table 11. The displacement of the coastline for each profile 1-12 at a sea level rise of 1 m. This displacements are estimated by the Bruun rule, together with the same displacement for some of the profiles at a sea level rise of 0.5 m, 0.75 m and 1.6 m.

Coastline retreat (m)

Profile	Sea level rise (m)		Profile	Sea level rise (m)	
	0.5	0.75		1	1.6
11		423	1	250	
12	318		2	370	600
			3	290	
			4	255	
			5	230	
			6	197	300
			7	180	
			8	205	
			9	210	
			10	280	550
			11	770	
			12	870	

5.3.5 Summary

Return periods for sea levels, wave heights and wave runup have been estimated along the coast of the bay of Lundåkra. For the sea levels a return period of 27.5 years has been estimated for the 147 cm sea level reached during the November storm in 2011. This may seem like an overestimated frequency considering that this level is the highest one ever observed in Barsebäck. However, this result is obtained by considering a max value trend of the series, assuming that maximum sea levels increase in amplitude over time due to a change of various climatic factors. Adapting the historical sea levels according to this trend a previous extreme sea level in 1948 obtained a new value that reaches even higher than the level of 2011.

The return periods for the waves in the bay were estimated as 32.5 years for the highest wave observed, with the wave height 2.2 m. The same return period was obtained for the highest runup level of 1.6 m at profile 6, in the central part of the bay. The runup at profile 12 of the northern part of the bay was analyzed for a future scenario of a 1 m sea level rise. According to this analysis the highway would, in a future scenario, be over-washed by waves only at an occasion as extreme as the November storm. Extending this analysis to a future scenario of a 1.6 m sea level rise the corresponding result estimated that the highway would be washed over by waves at 10 as well as 35 different occasions at profile 12 and profile 11 respectively, for a period of time equivalent to 1994-2011. These results are, however, considered to be an underestimation since only the mean sea level rise has been taken into account. Applying the calculated maximum value trend the extreme future runup levels would reach 40 cm higher, and the highway would accordingly be much more exposed to wave runup.

The runup results obtained for all the 12 profiles (Table 3) are of different quality due to how well the simplifications correspond to the reality. Hence, the results are interpreted with caution. Indications can, however, be observed that profile 2, 5, 6 and 7 seem to be more exposed to extreme sea levels as well as to high wave runup levels (out of these four profiles 5 and 6 are considered to represent the most reliable results). A careful estimation can thus be made that the sections of the coast represented by these profiles may be more sensitive to erosion.

The flooding analysis has given a first indication of what to expect at the studied future scenarios. Even without taking erosion into account the area of the northern part of the bay would likely be covered with water and the coastline would be positioned at the foot of the highway bank if the sea level increased by 1 m. For the southern parts the topography is less flat than in the north and the sea level rise would not have as big an impact here. The studied flooding scenario of the 1 m sea level rise shows only a very limited impact on the coastline position (Figure 35 and Figure 36).

According to the Bruun rule the coastline in the northernmost part of the bay of Lundåkra has been estimated to retreat to be positioned at the foot of the highway bank with a sea level rise of 0.5 – 0.75 m. Considering the chosen scenario of a sea level rise with 1 m up until 2100 the northern part of the bay will thus have lost the coastal area between the sea and the highway. For the central and the southern parts of the bay the coastline retreat according to the Bruun rule has been estimated as 180-370 m.

6 Discussion

The bay is, as already mentioned, considered as stable with respect to erosion. It may be speculated whether a future change of the bay may change this or not. The considered future scenario of a 1 m sea level rise until the year of 2100, will likely lead to a situation where the northern coastline in the bay will be defined as the highway. The way the Bruun r ule applies to this scenario is given by imagining the beach profile as it would develop according to the rule and then project the inflexible reality upon that image. Although since the beach profile displacement is depending on a sediment supply from farther inland, the section of the profile nearest to the sediment barrier, in this case the highway, will fail to reach equilibrium. Sediments will be taken from here to compensate farther offshore for the higher sea level, but no sediments will be supplied to compensate for the higher sea level at the actual section. The new profile may thus develop a deeper section at the foot of the highway; in addition the new profile will be characterized by the lack of a natural beach zone. The bottom profile that today gradually rises from sea to land will in the considered future scenario get a very different shape with a more abrupt rise from a certain depth up to the relatively steep slope represented by the highway bank. This change in characteristics of the beach profile gives a new situation in terms of sediment transport. The longshore transport that normally is biggest near the shore might be decreased by the loss of the shallowest section of the sea. There is hence a risk of a disturbed balance in the sediment transport along the bay coastline that may cause certain erosion at the coast south of where the highway will define the coastline. However, as the longshore sediment transport is estimated as low in the bay this may also not have a significant impact.

Concerning the shallow sea bottoms farther out in the bay, these should not have a problem to develop in agreement with the rising sea level and reach a reestablished equilibrium, i.e. the same depth as today. This requires, however, that the sediment supply proves to be sufficient and the section deepened by an uncompensated sediment loss will not cover a big enough area to include the big area of shallow sea bottoms.

Concerning the northernmost part of the bay (profile 11 and 12) the very flat topography would make it vulnerable to flooding and wave impact. However, the vast area of shallow bottoms off the coast may have a protective effect, this part of the coast would not be exposed to as powerful waves as the coast farther south. After the November storm in 2011 not as much washed-up seaweed was observed in this part of the bay (see photos in Appendix 2), this may be seen as an indication of the expected smaller exposure to wave forces.

7 Conclusions and recommendations

The results have shown some strong indications that the coastal area in the northern part of the bay is indeed threatened by a rising sea level. The flooding analysis has proved that the area will be covered with water at a sea level rise of 0.75 m. Even if the sea does not reach that level there is still a risk of a coastline retreat due to erosion that may also have some devastating effects on the area. A sea level rise of 0.5 m may already cause a coastline retreat all the way back to the position of the highway, according to the estimation using the Bruun rule.

At the future scenario of a 1 m sea level rise the needed actions for this part of the bay would be to take suitable measures to protect the highway bank from eroding. If the highway will still be positioned here by that time it may also be necessary to consider additional ways to protect the highway from wave runup during extreme weather situations. With a sea level rise of 1 m this is already a risk to consider. Regarding the more extreme future scenario of a 1.6 m se level rise the highway would likely be washed over frequently.

Concerning the important nature values connected to the coastal meadows that are very likely to gradually disappear with the rising sea, a reestablishment of this environment at a different location seems to be the only option. A possible direction for the migration of this area with its characteristics would either be to the south along the coast or to the east, on the other side of the highway. The flooding analysis shows one potential area on the east side of the highway that is at the moment occupied by a golf course. At this site there is a lower area just next to the highway that is low enough to be filled with water when the sea level has reached a level of +0.75 m (Figure 32). Thus, here is a potential for creating a sea water lagoon which might succeed in providing a similar environment to the occasionally water filled shallow depressions of the coastal meadows today. Further investigations to evaluate the area's suitability for such a lagoon are of course needed. The construction of a passage for the sea water underneath the highway would need to be considered if this solution is applied. This passage may need a barrier to use at extreme sea levels. As can be seen from Figure 32, a 2-year extreme sea level may already have the potential to flood a big area. A more sophisticated flooding analysis is needed to assess this risk. The barrier towards the sea may also be used to occasionally shut off the inflow to the lagoon to let it dry out after being filled up, in this way the characteristics of the coastal meadows' occasionally flooded depressions would be better restored.

For the central and the southern sections of the bay coastal area the future development is not as strongly indicated by the results as for the northern part. The direct impact of a rising sea level would not be as dramatic here since the topography is not as flat as in the north. For some sections in the south of the bay a mean sea level +1 m would not flood any land areas according to the results obtained. However, results from the analysis using the Bruun rule have given indications of a risk of an erosion of the entire bay area with an estimated coastline retreat of 180-370 m. Even if the results obtained by the Bruun rule are considered uncertain this risk of extensive coastal erosion should be considered. A geographical expansion of the protection by Natura 2000 and the Ramsar convention may be needed in the future to be able to keep protecting the nature values of the area.

An expansion of the bay area may create potential land usage conflicts. In the north the suggested area on the other side of the highway is today used as a golf course. In the south a big part of the protected area neighbors farmland. However, the future scenarios discussed here are not likely to become reality within the next 50 years at the earliest. Regarding the

analysis of the coastline retreat the time perspective is not even taken into account. The uncertainty of the study that comes with this long and not strictly defined time perspective does not only concern the assumptions and the estimations but also the relevancy of the investigations. Values protected today may change due to various unknown reasons. Potential conflicts today may not exist in the future. The preparations recommended at this point for an eventual expansion of the protected area would hence be restricted to keep the concerned areas from being further exploited. In the meantime, however, further studies are recommended to analyze the suitability of a nature protection expansion to the appointed area east of the highway in the northern bay area. A more profound assessment would be needed, studying ecological as well as hydrological parameters.

The most important recommendation is to follow up the continuous research regarding the climate change and to monitor the local development in the area. The indications of higher sensitivity to erosion and flooding of some specific sections of the bay coastline may be taken into account when planning the monitoring procedure.

8 Acknowledgements

9 References

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Appendix 1 – Beach profiles

The 12 different beach profiles can be seen in Figure 38 - Figure 49 together with the corresponding estimating slope for the swash zone for each profile. The positions of the profiles are marked in Figure 8.
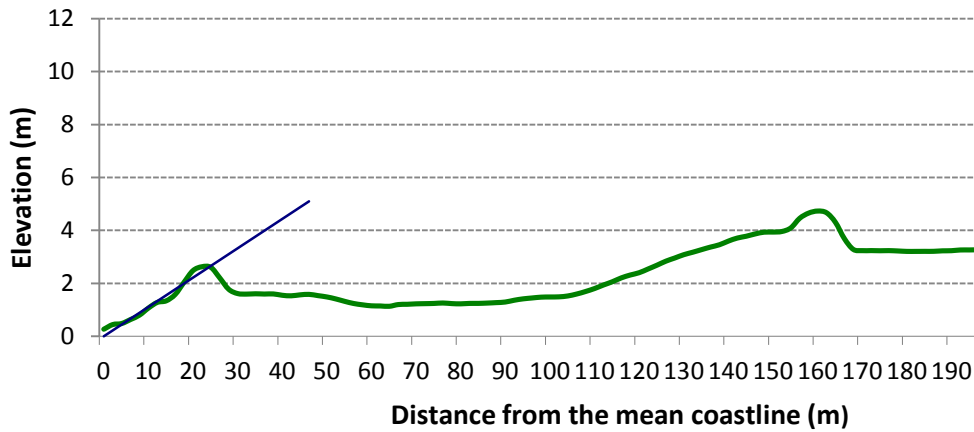
Figure 38. The figure shows the beach profile for profile 1 with an estimated slope of 0.111.
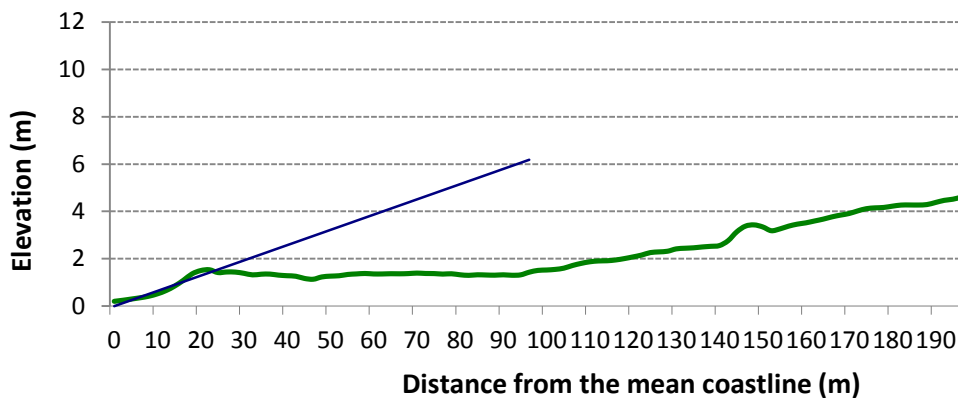
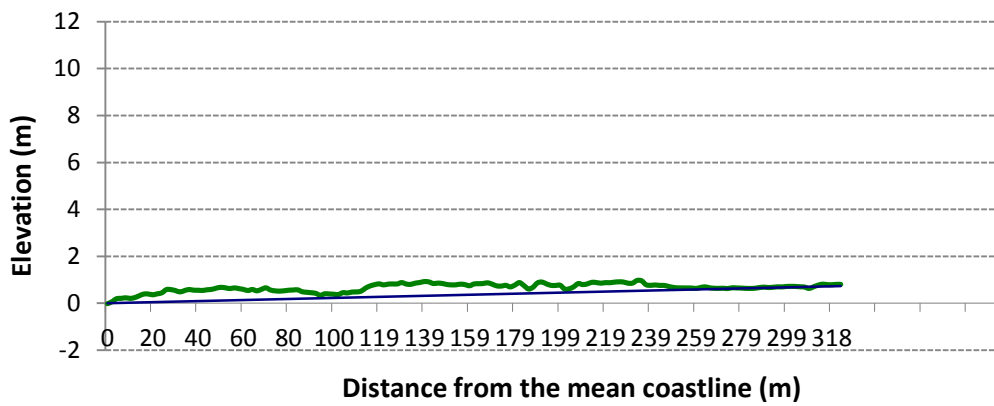**Figure 39. The figure shows the beach profile for profile 2 with an estimated slope of 0.064.**
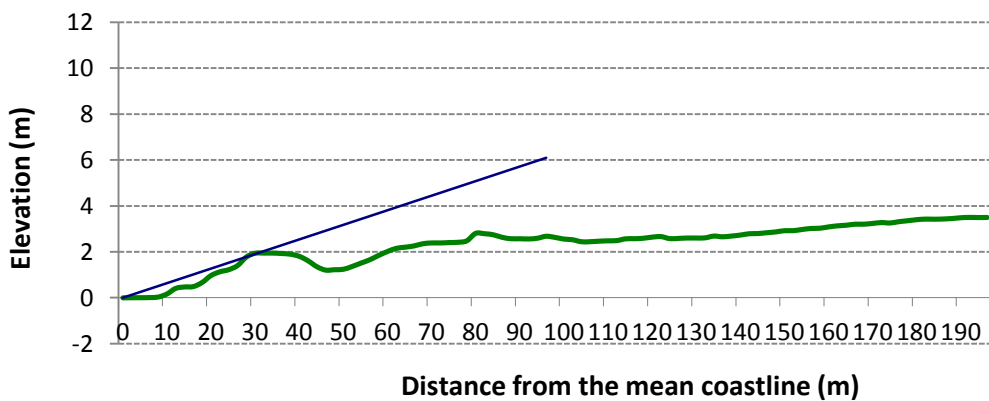
Figure 40. The figure shows the beach profile for profile 3 with an estimated slope of 0.064.
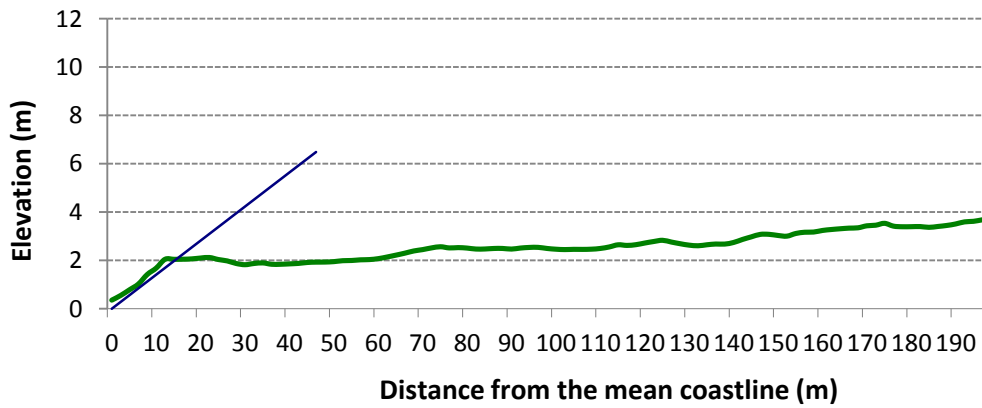
Figure 41. The figure shows the beach profile for profile 4 with an estimated slope of 0.141.
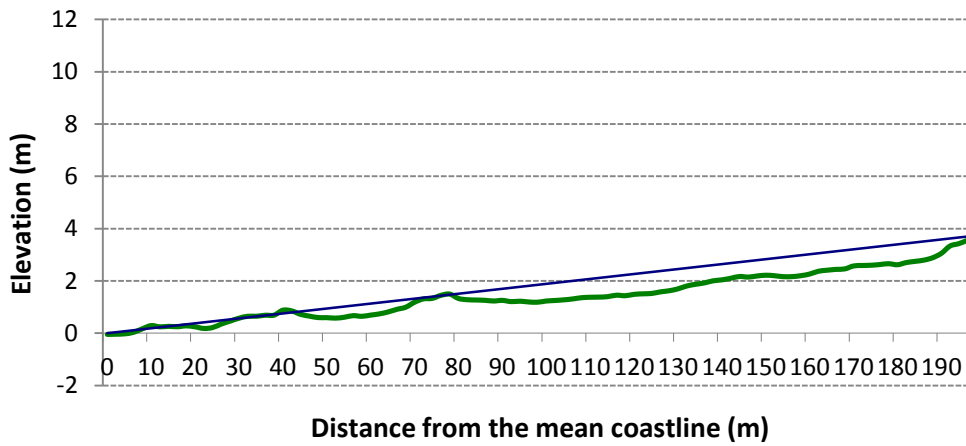
Figure 42. The figure shows the beach profile for profile 5 with an estimated slope of 0.019.
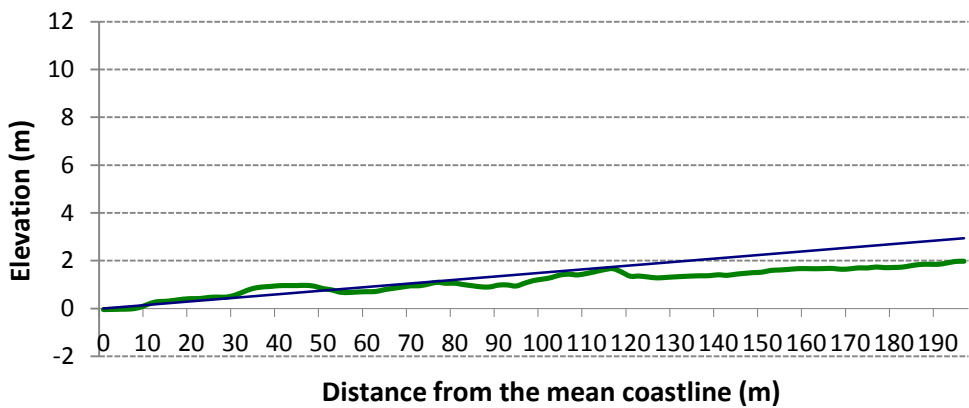
Figure 43. The figure shows the beach profile for profile 6 with an estimated slope of 0.015.

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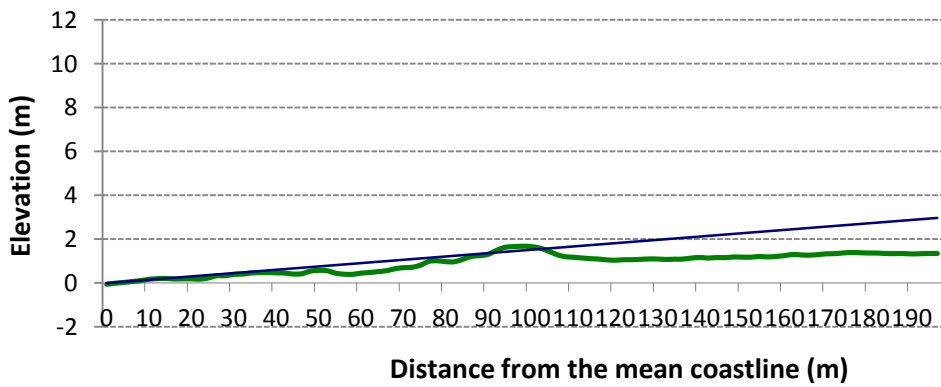
Figure 44. The figure shows the beach profile for profile 7 with an estimated slope of 0.015.
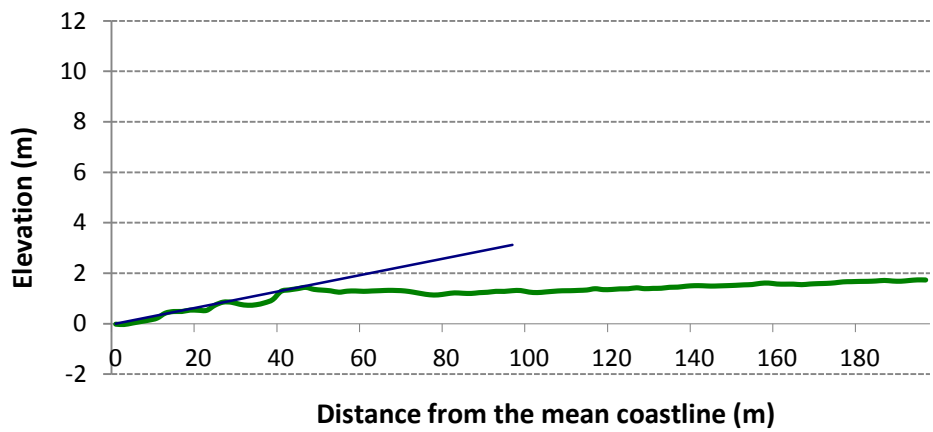
Figure 45. The figure shows the beach profile for profile 8 with an estimated slope of 0.033.
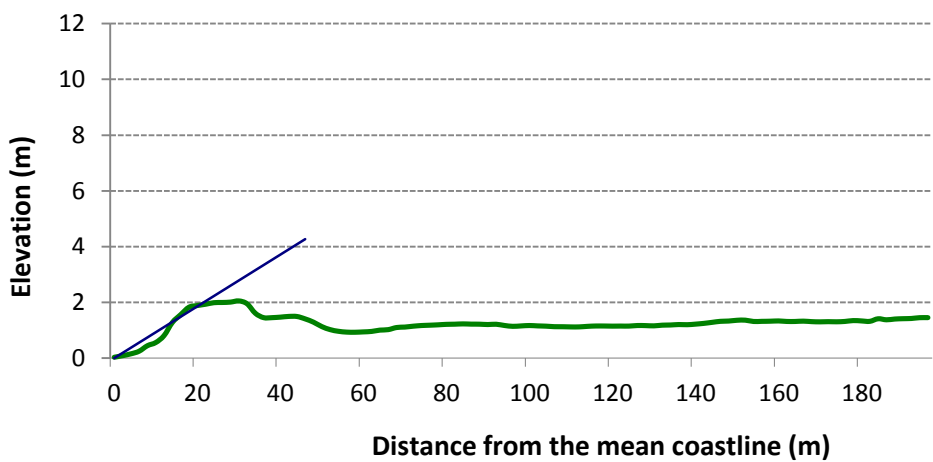
Figure 46. The figure shows the beach profile for profile 9 with an estimated slope of 0.093.
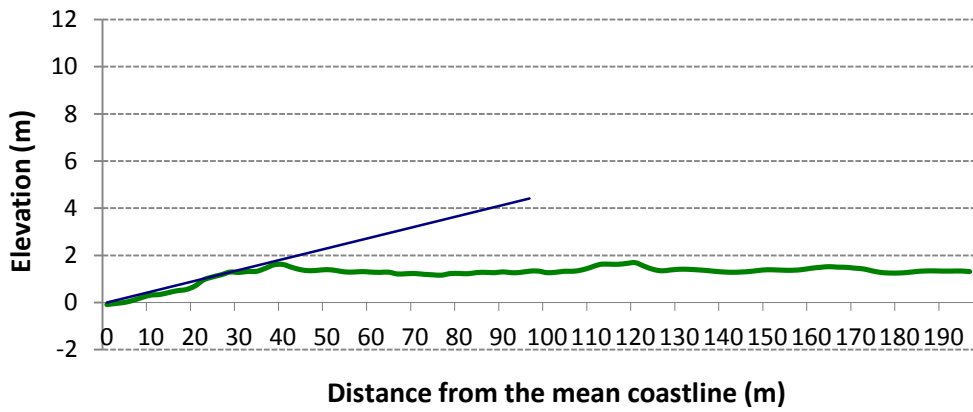
Figure 47. The figure shows the beach profile for profile 10 with an estimated slope of 0.046.
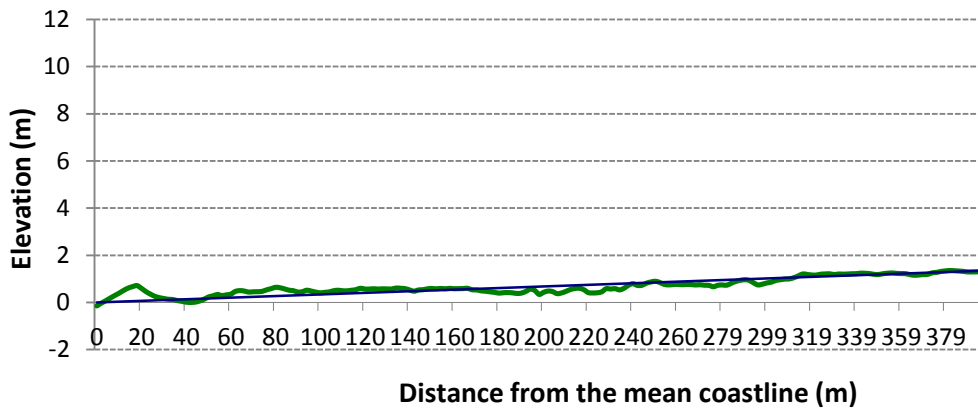
Figure 48. The figure shows the beach profile for profile 11 with an estimated slope of 0.003.

Figure 49. The figure shows the beach profile for profile 12 with an estimated slope of 0.002.

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Appendix 2 – Photos of the coastline after the November storm

Photos taken from a helicopter of different sections of the bay coast of Lundåkra. Each section is represented by one of the profiles 4-12. These can be compared with the beach profiles in Appendix 1.

Figure 50. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 4. Seaweed has washed up 10-15m from the mean coastline.

Figure 51. Photo (Gustavsson 2011) taken after the storm 2011-11-27,section including profile 5. Seaweed has washed up 70 m.

Figure 52. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 6. Seaweed has washed up 90 m.

Figure 53. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 7. Seaweed has washed up 90 m.

Figure 54. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 8. Seaweed have washed up 40 m.

Figure 55. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 9. Seaweed has washed up 15 m.

Figure 56. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 10. Seaweed has washed up 25 m.

Figure 57. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile 11.

Figure 58. Photo (Gustavsson 2011) taken after the storm 2011-11-27, section including profile12.

Appendix 3 – Flooding analysis

This appendix includes additional map images showing the potentially flooded areas at different sea level scenarios. Four cases have been studied, case 1 shows the situation of today and case 2 the situation of the northern part of the bay at different stepwise sea level rises. Case 3 shows the situation of the bay at a sea level of 1m and case 4 shows the situation at a sea level rise of 1.6 m.

Case 1: The situation in the bay today.
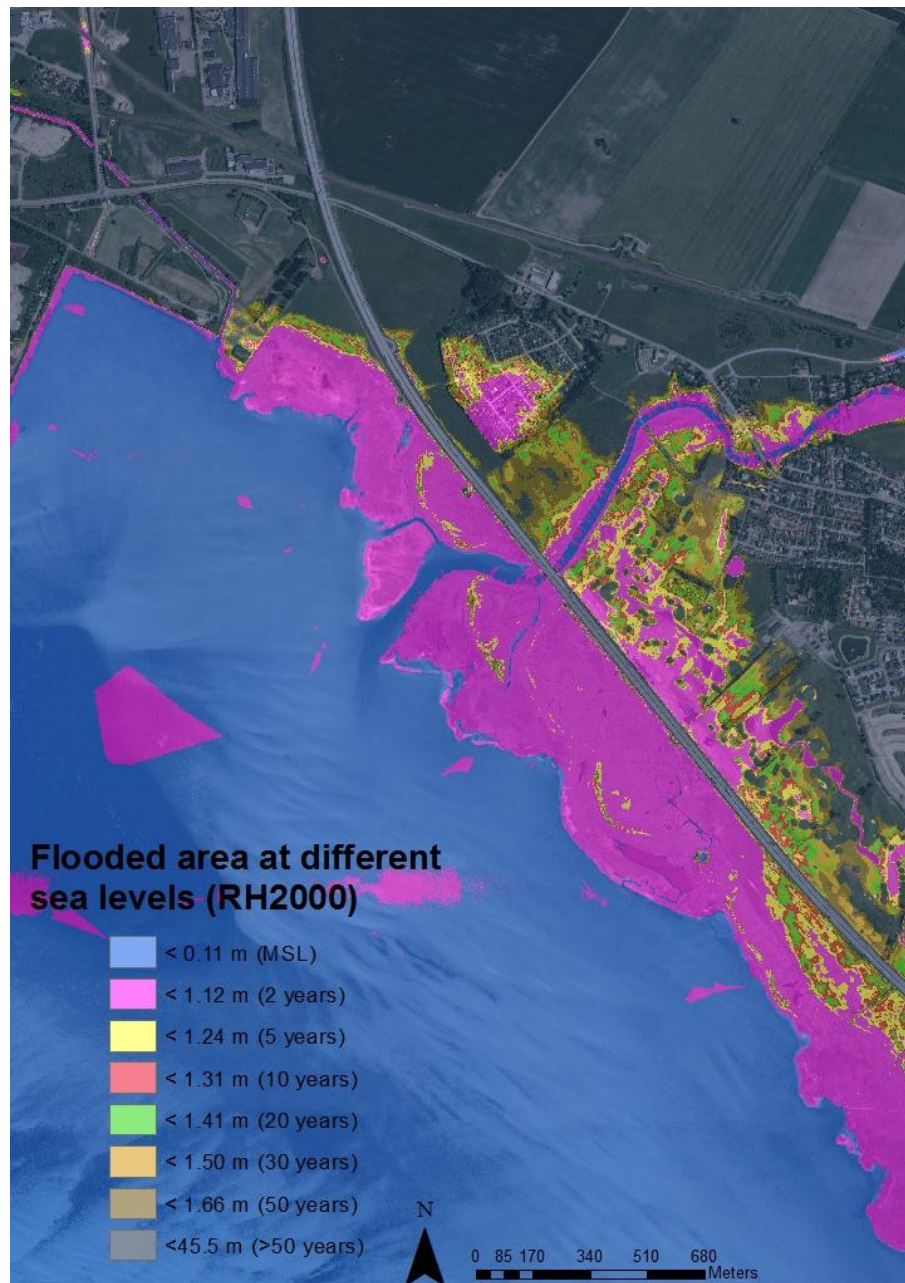
Figure 59. The situation of the north part of the bay today. Blue color represents areas under water at a mean sea level 0.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 1.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

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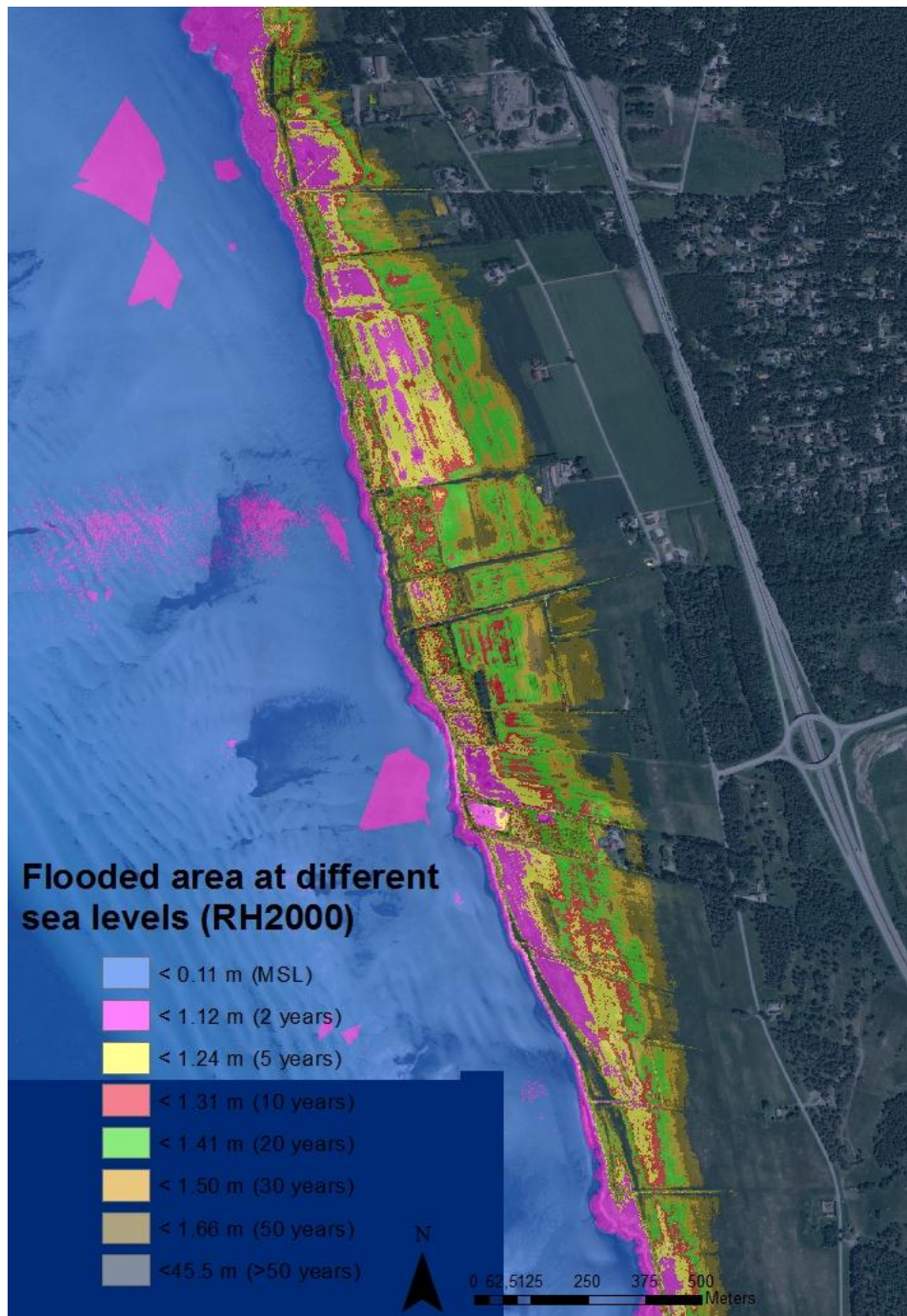
Figure 60. The situation of the central part of the bay today. Blue color represents areas under water at a mean sea level 0.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 1.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
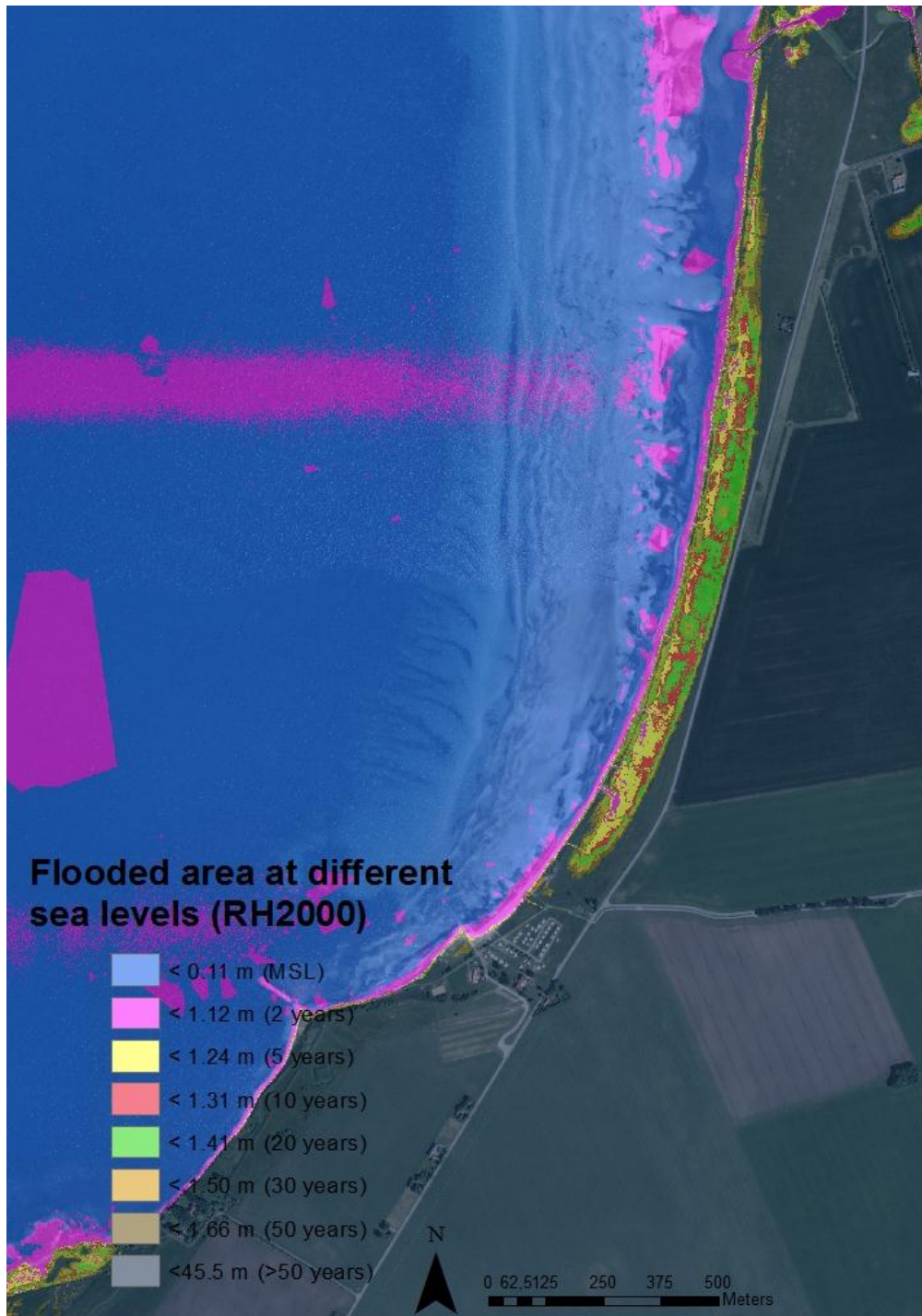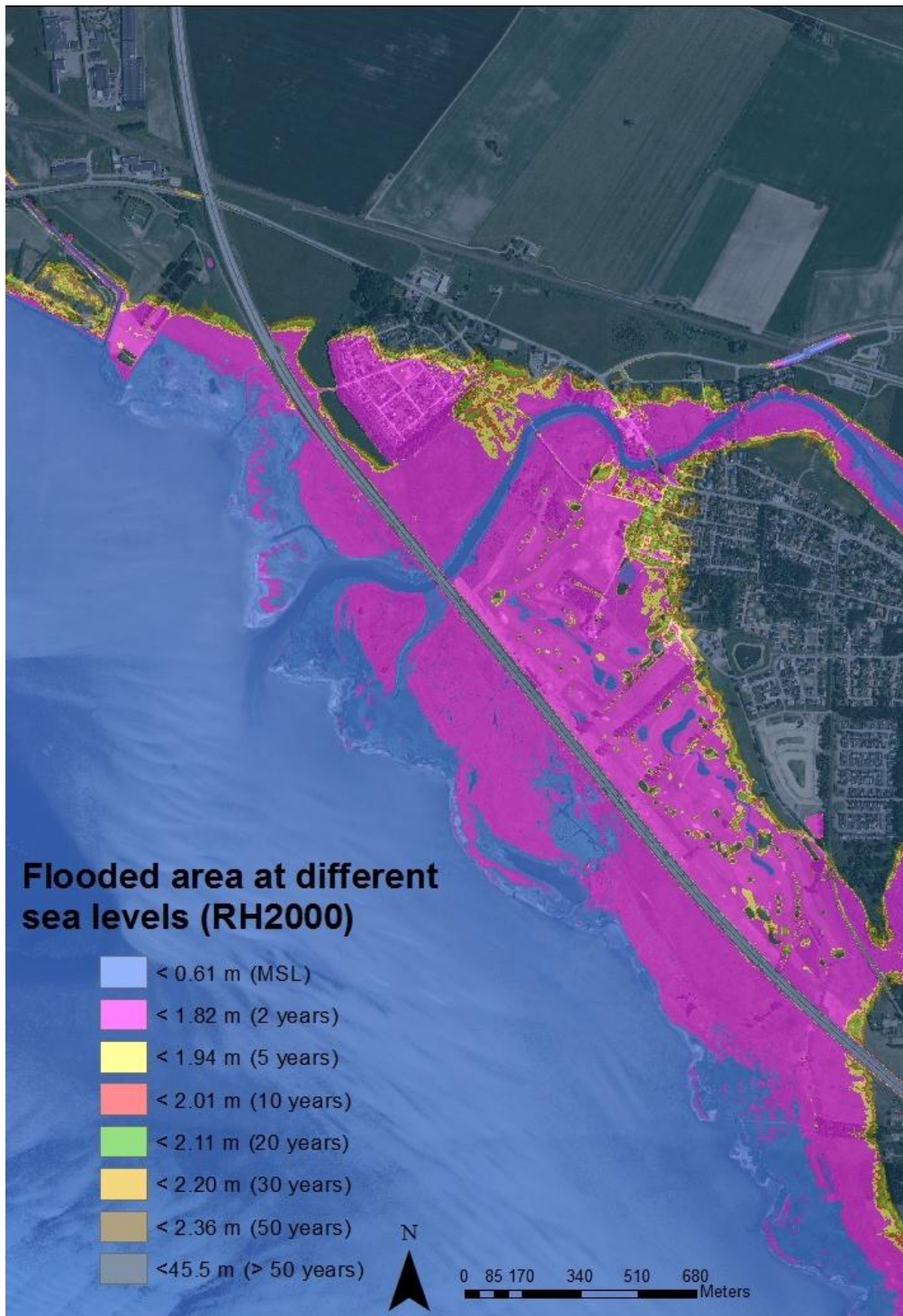
Figure 61. The situation of the southern part of the bay today. Blue color represents areas under water at a mean sea level 0.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 1.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
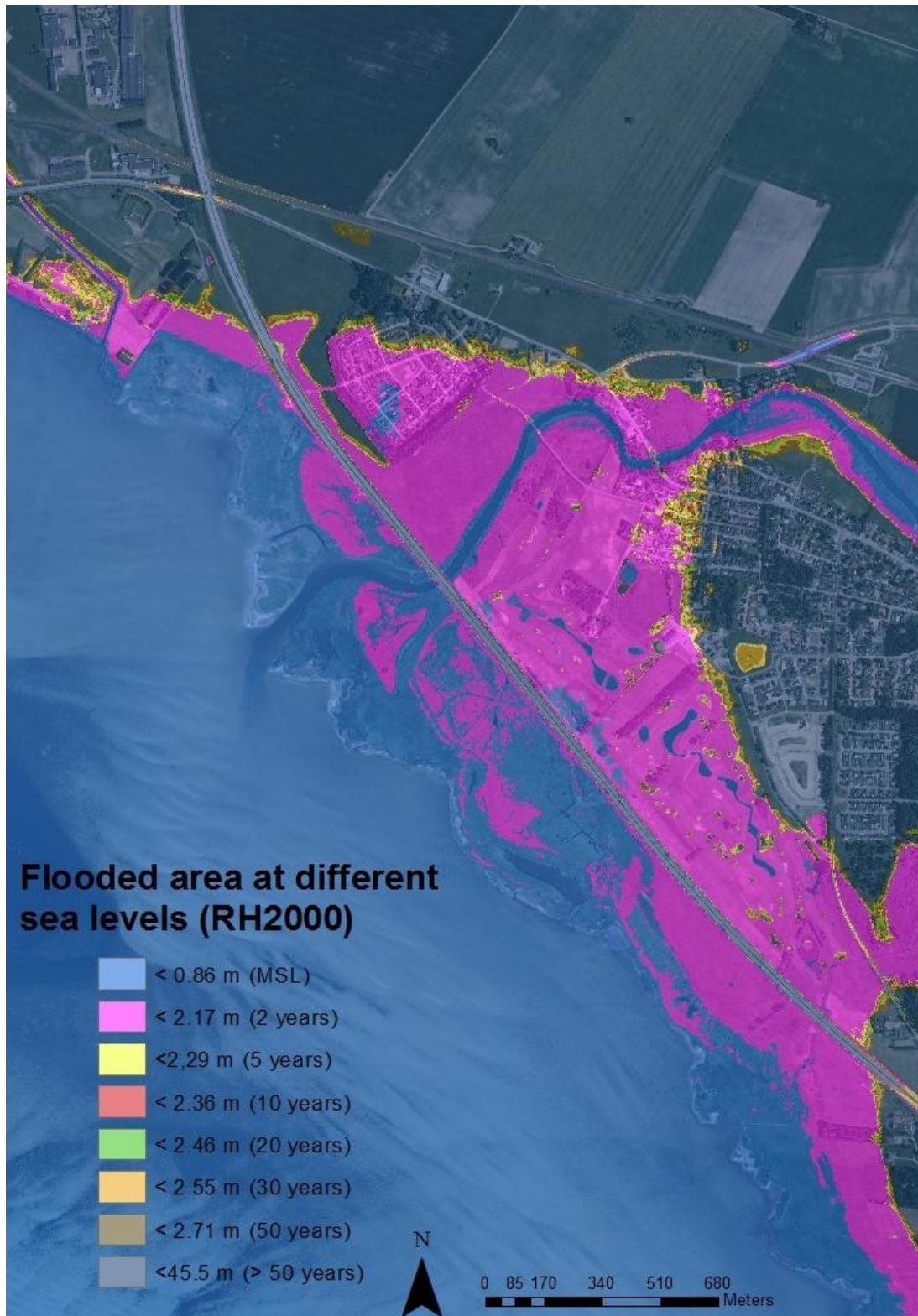
Case 2: The situation in the northern part of the bay at a stepwise sea level rise of 0.25m, 0.5m and 0.75m.
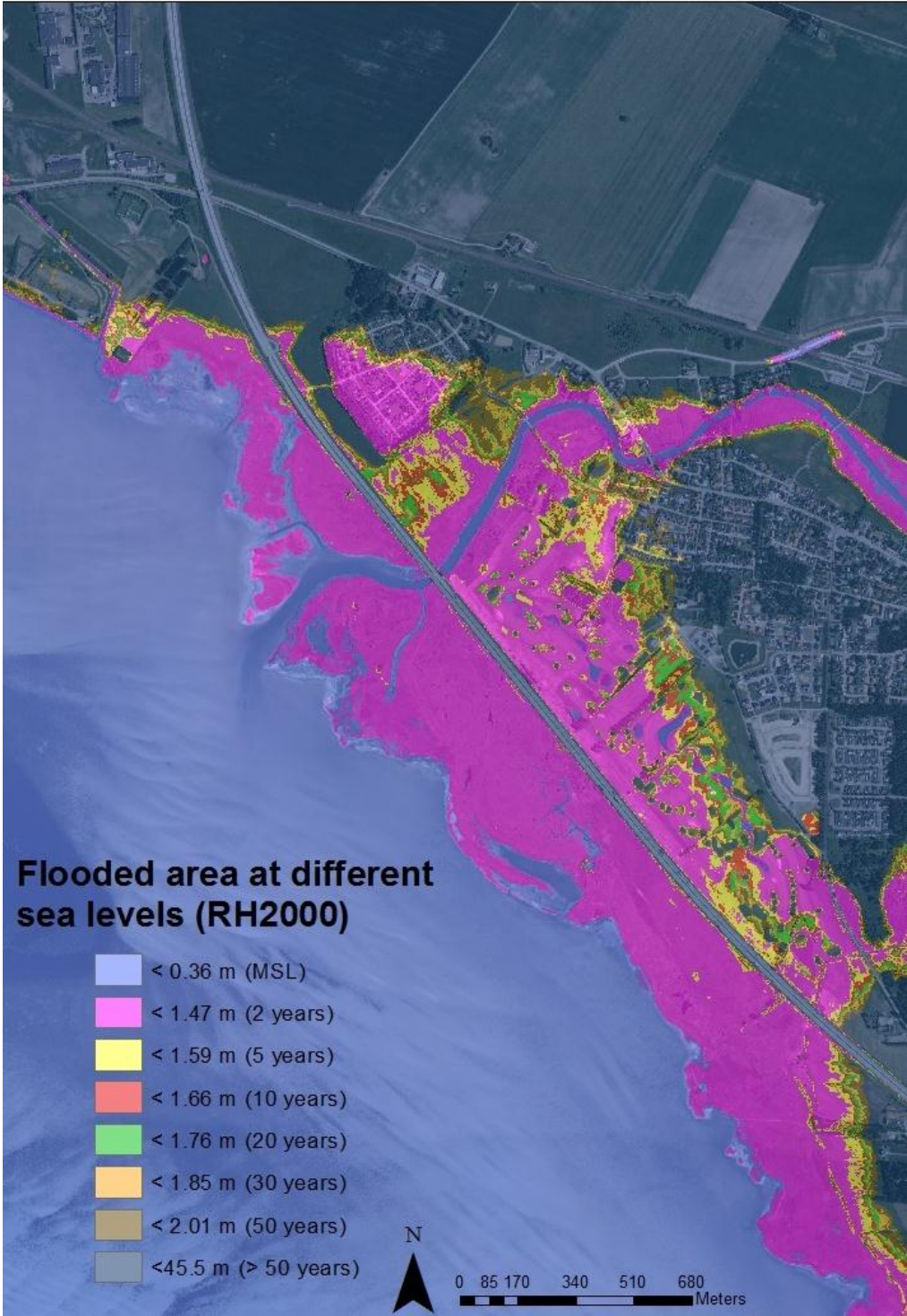
Figure 62. The situation of the northern part of the bay at a future scenario with a sea level rise of 0,25 m. Blue color represents areas under water at a mean sea level 0.36 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 1.47 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
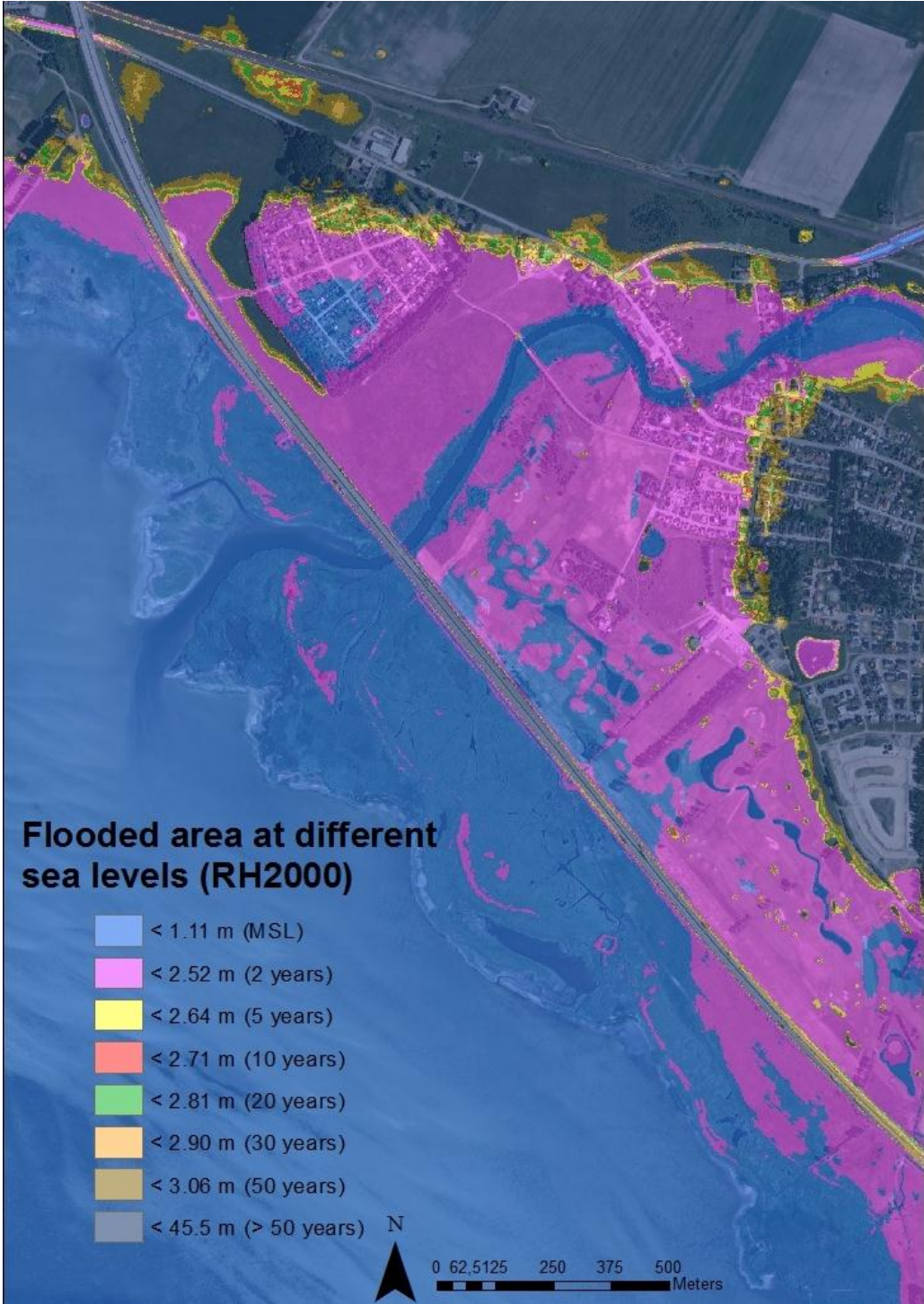
Figure 63. The situation of the northern part of the bay at a future scenario with a sea level rise of 0,50m. Blue color represents areas under water at a mean sea level 0.61 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 1.82 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

Figure 64. The situation of the northern part of the bay at a future scenario with a sea level rise of 0,75 m. Blue color represents areas under water at a mean sea level 0.86 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 2.17 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
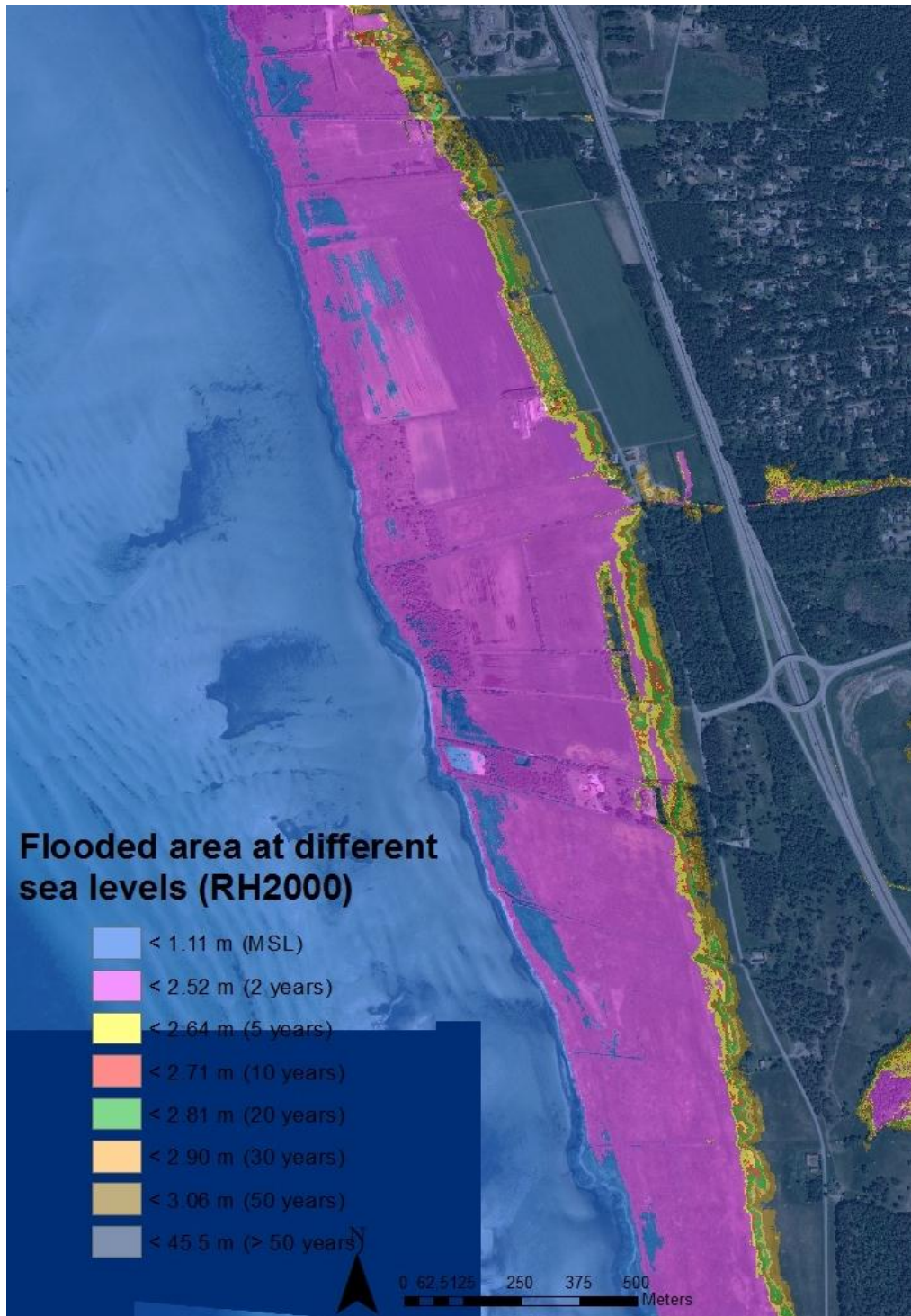
Case 3: The situation in the bay at a 1 m sea level rise.

Figure 65. The situation of the northern part of the bay at a future scenario with a sea level rise of 1 m. Blue color represents areas under water at a mean sea level 1.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 2.52 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
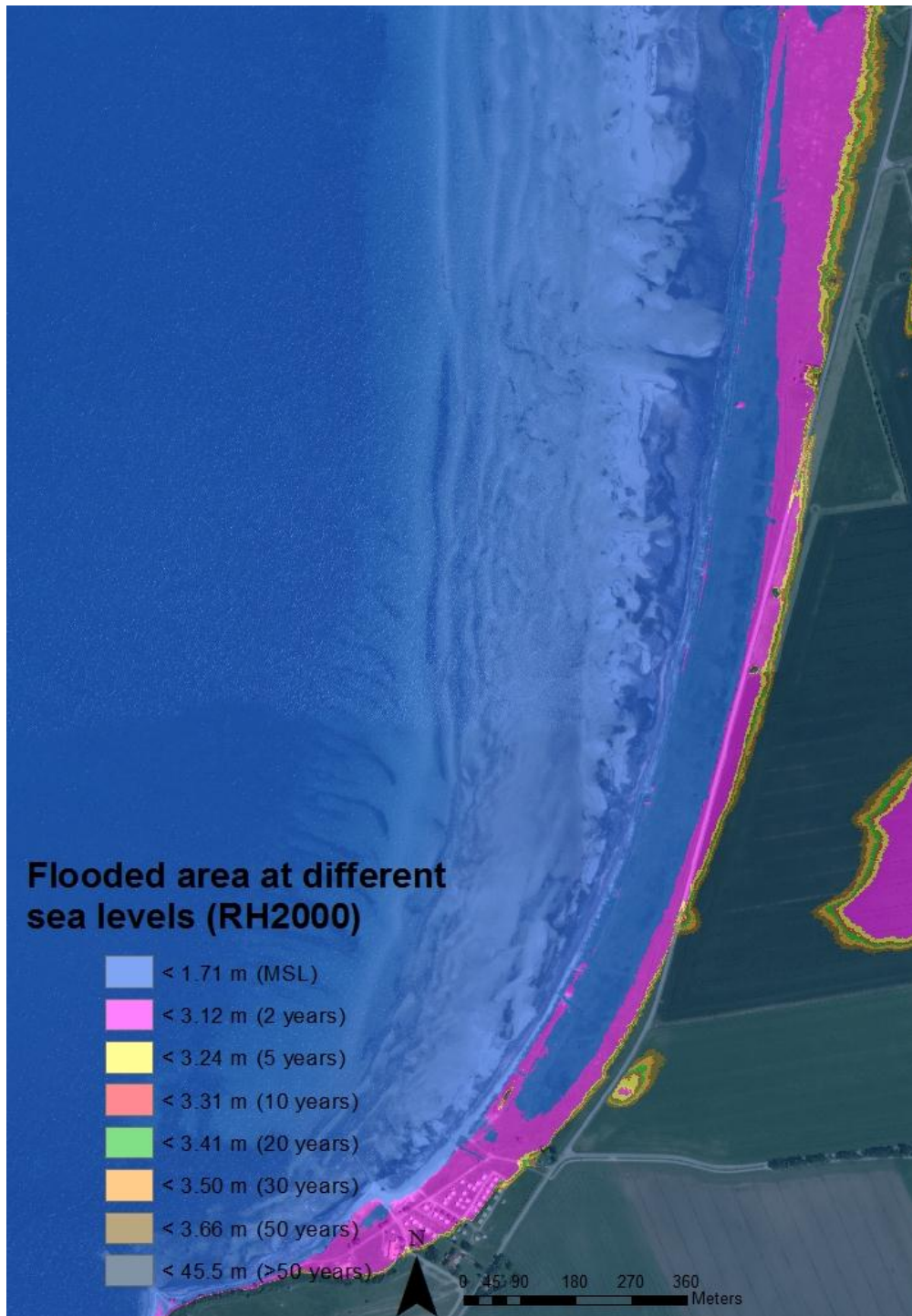
Figure 66. The situation of the central part of the bay at a future scenario with a sea level rise of 1 m. Blue color represents areas under water at a mean sea level 1.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 2.52 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
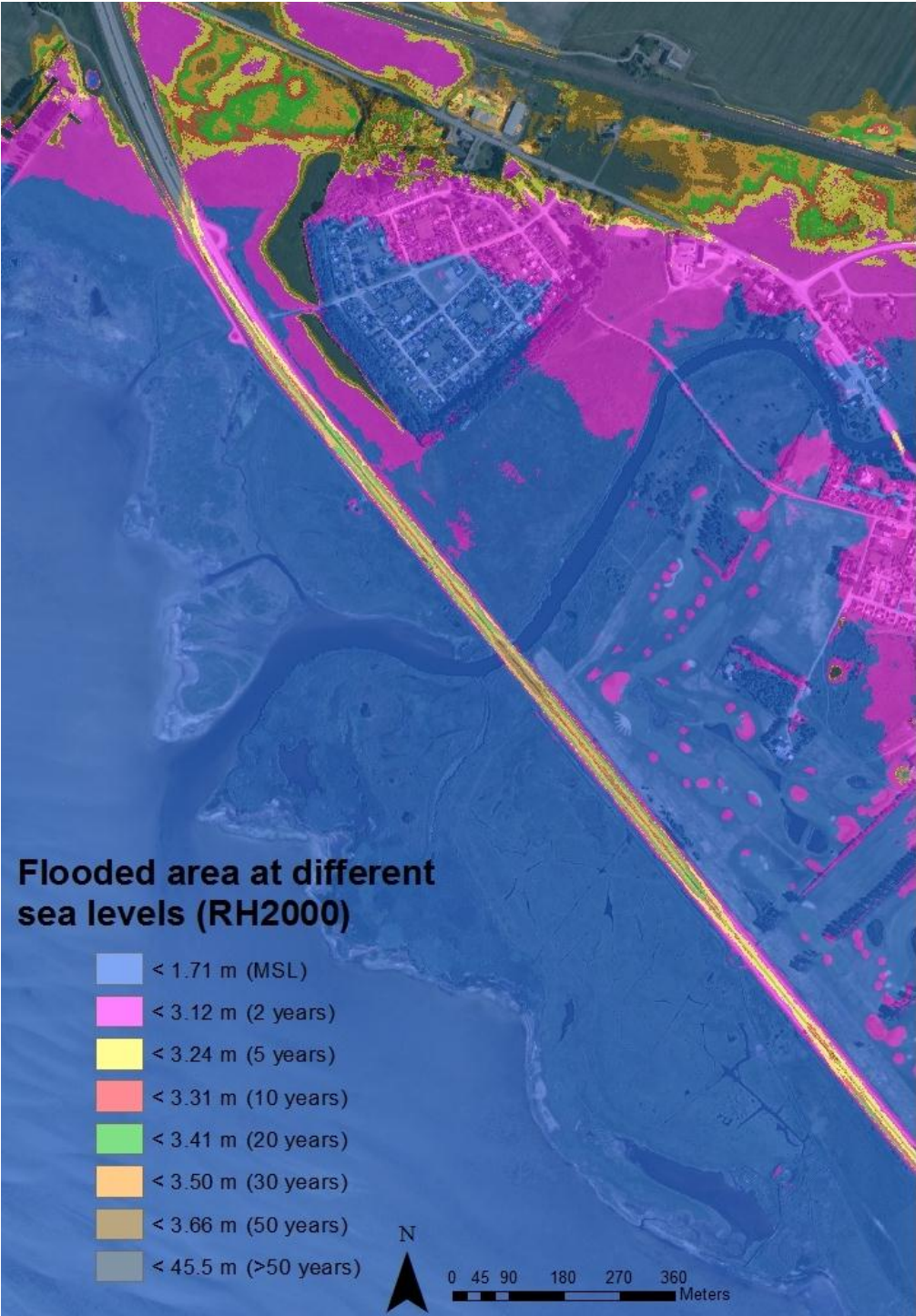
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Figure 67. The situation of the southern part of the bay at a future scenario with a sea level rise of 1 m. Blue color represents areas under water at a mean sea level 1.11 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 2.52 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).

Case 4: The situation in the bay today at 1.6 m sea level rise.

Figure 68. The situation of the northern part of the bay at a future scenario with a sea level rise of 1.6 m. Blue color represents areas under water at a mean sea level 1.71 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 3.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
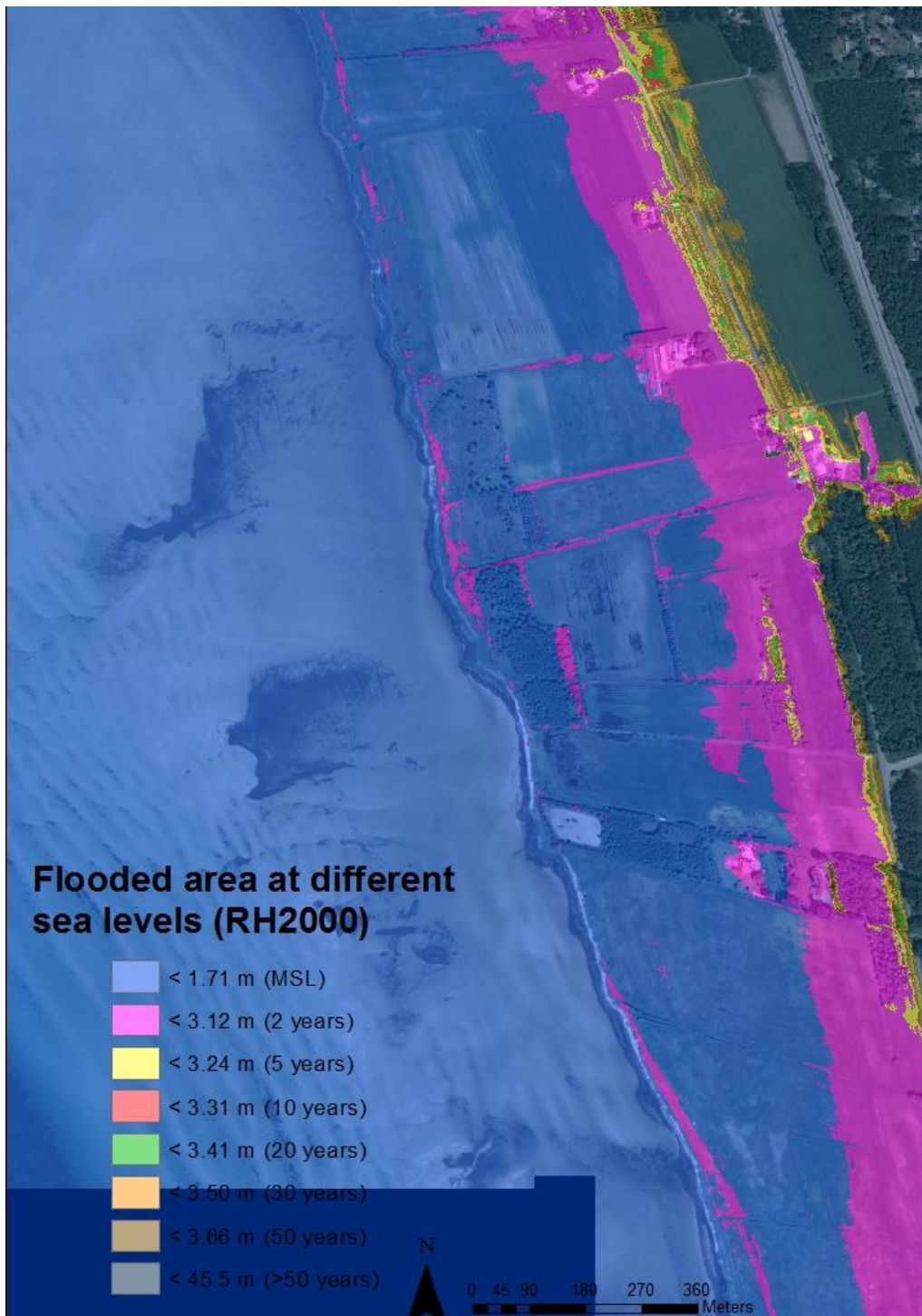
Figure 69. The situation of the central part of the bay at a future scenario with a sea level rise of 1.6 m. Blue color represents areas under water at a mean sea level 1.71 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 3.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).
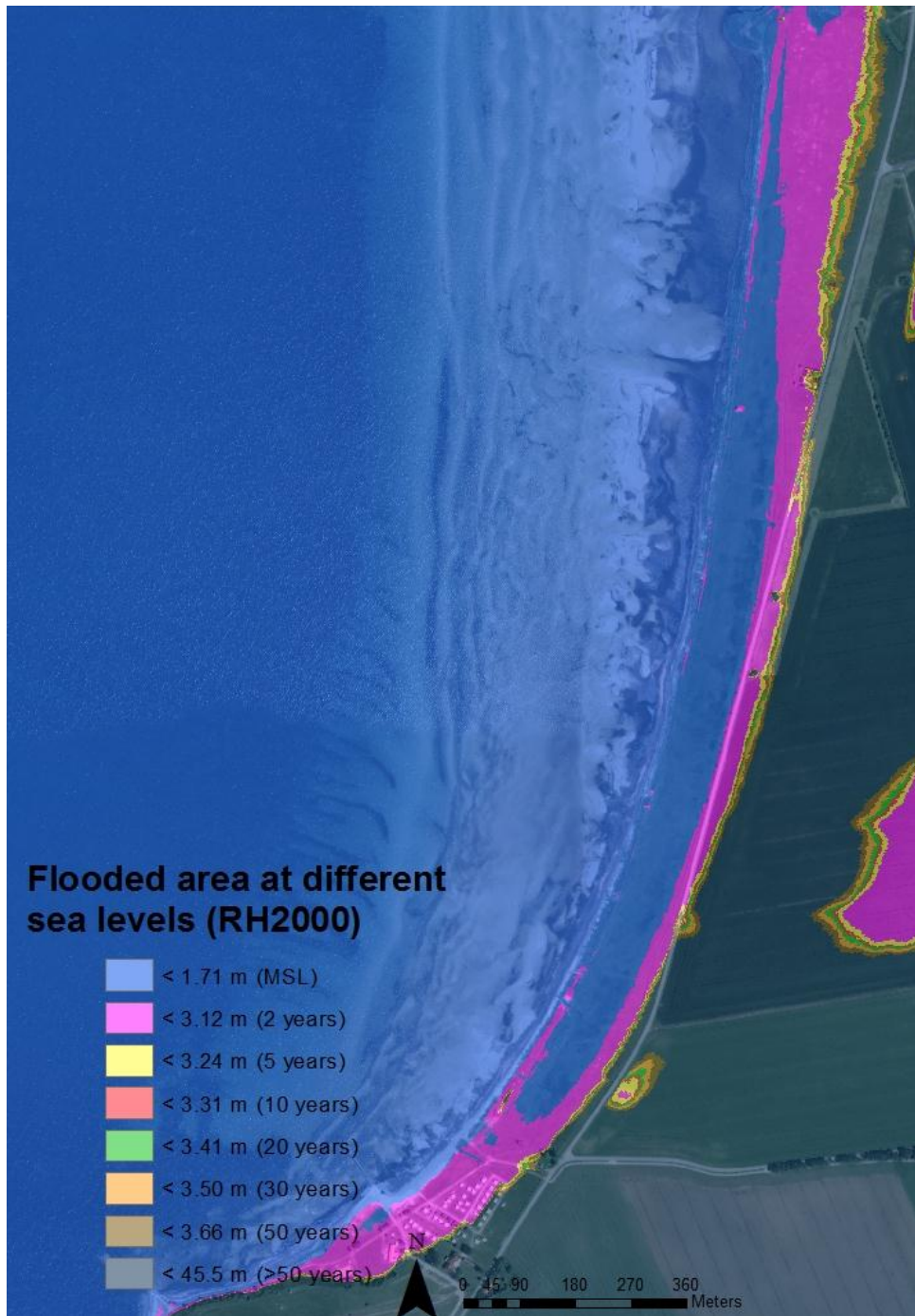
Figure 70. The situation of the southern part of the bay at a future scenario with a sea level rise of 1.6 m. Blue color represents areas under water at a mean sea level 1.71 m (RH 2000). Pink color represents areas flooded at a sea level interval from the mean sea level up to the level of a 2-year return period, 3.12 m. Modified orthophoto © Lantmäteriet, i2012/901 together with the topography model NNH (Lantmäteriet 2013).