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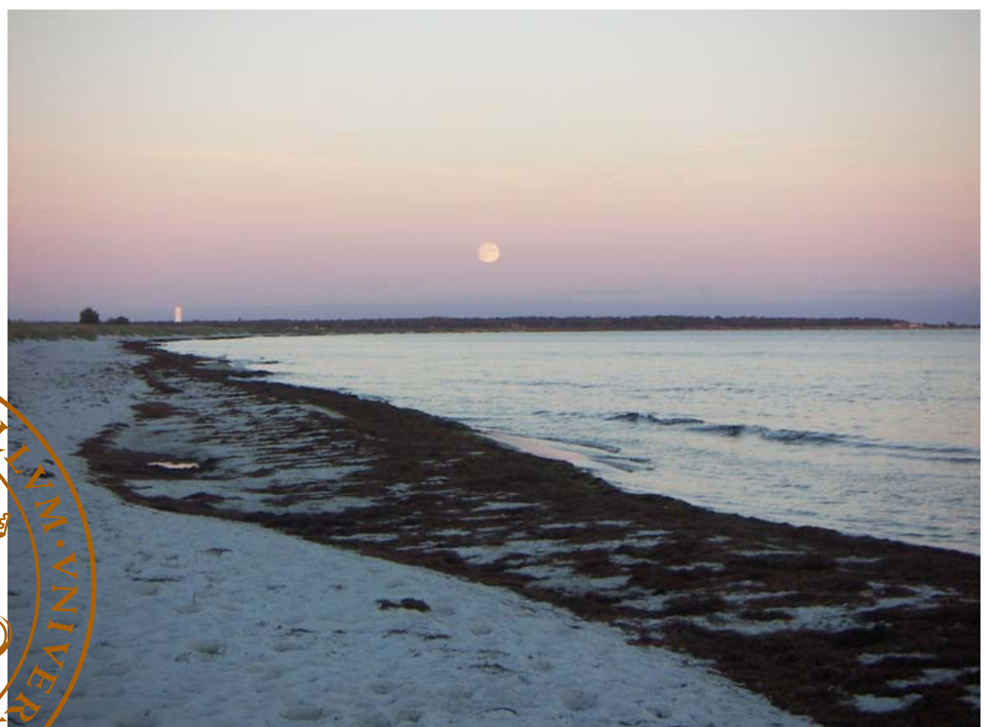
Extreme water levels and wave run-up in Falsterbo peninsula, Sweden

- Future scenarios by extreme value analyses

Meriç Pakkan



Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

Preface

I would like to thank to;

My father and my mother for being ‘there’ for me whenever I needed, making everything I need possible, their continuous support and belief in me, sharing my success, my sadness, in short for being my parents.

My supervisor, Prof. Dr. Hans Hanson for his guidance through my way to coastal engineering field and to this thesis subject. This study would not have been possible without his invaluable support, help and patience.

Prof. Dr. Magnus Larson for being a real problem-solver. Never once has Magnus been too busy to help me and he always came up with a word of encouragement.

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Last, but definitely not the least, my girlfriend Lina for standing me through this tough time, not complaining even once and being ‘the one’.

Meriç Pakkan

Lund, Sweden, January 2006

Abstract

Title: Extreme water levels and wave action in Falsterbo peninsula, Sweden
Future scenarios by extreme value analyses

Author: Meriç Pakkan

Supervisor: Prof. Hans Hanson, Department of Water Resources Engineering, Lund University, Lund, Sweden

Presentation of problem: Located in the Baltic Sea coast, the study area, Falsterbo peninsula is in the south-west corner of Sweden and a very low-lying area, which makes it very vulnerable to a future sea-level rise phenomenon and wave action. High water levels and large waves and run-up heights in connection with the global warming can cause serious damages within the area, which is a very prestigious place regarding its location and all the facilities it holds. This means that the area is in danger of land loss due to flood-based inundation and erosion, flooding of residential areas, and saltwater intrusion to fresh water aquifers.

Objectives: The main aim of this study is to analyze water levels, waves and run-up heights with the using existing water level and wind data to determine future water levels in Falsterbo peninsula. The future water levels will be obtained by means of different analyses, taking into account water levels only and water levels and run-ups together so that a ground for assessing the possible consequences can be prepared.

Procedure:

In the first phase of the study, the water level data was compiled and monthly extremes were extracted out of it. Then, an extreme value analysis on water levels only was conducted and future projections were made. In the second part of the study, available wind data was utilized to obtain corresponding wave characteristics and run-up heights in two different points of the peninsula. Wind and wave climates off the southern and western parts of the area were analyzed prior to extreme value analyses on the combination of water levels and run-up heights. These extreme value analyses led to having the most realistic and probable water level values in the 20 and 100-yr time intervals. Trend analyses were also included within these extreme value analyses to see the temporal variation in the water level and run-ups. Finally, the report was concluded with discussions about results and some critical points and conclusive remarks.

Conclusions:

The analyses performed indicate that water level rise by itself and water level rise combined with wave action can have drastic effects on Falsterbo peninsula. It was found out that 84 and 160 cm of rise in sea level can be expected for the years 2020 and 2100. On the other hand this rise goes up to 229 and 333 cm for the same time intervals in the southern part of the peninsula if run-up phenomenon is considered together with the water level rise. These future sea level heights are, no wonder, seriously threatening the peninsula, which is below 3-meter water level with 90% of its area. In other words, in 2100, for instance, more than 90% of the southern part may be under water. It was also concluded that southern coasts are much more vulnerable to sea level rise and wave action in this respect, and coastal impact analyses in Falsterbo peninsula should be made in a point-wise manner.

The future sea levels obtained can cause

flooding on the coast and no wonder these levels will be the cause of diminishing of attractive and important sandy beaches. Nonetheless, the flooding may even proceed to the residential areas and disrupt life routines in this prestigious area. Thus this study together with its analyses and results is a good indicator of the future scenarios in sea water levels. It is thought that in the light of findings of this study, grounds for further research and planning of appropriate protection measures and design of necessary sea defense structures against indicated potential dangers are laid.

Keywords: Falsterbo, water level, waves, run-up, future sea levels, global warming.

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1 Introduction

1.1 Background

In the coastal areas, the main masses of the planet, air, water and land, meet and interact. Each of these masses has its own specific and dynamic nature, thus creating a complicated and challenging environment for all kinds of engineering activities. The physical system existing in this environment is composed of the action of the wind and the waves as energy supplier and the absorbing nature of the shore. The motions of the sea which shape and affect the physical beach system include waves, currents, tides, storms, and tsunamis. The coincidence of these motions, such as, high sea level occurrences and waves, has already caused serious floods in many coastal areas all over the world, claiming major economic and material damages, even human lives. [1]

Sea-level rise is one of the most crucial problems to tackle for the safety of coastal regions. Although the triggering mechanisms of sea-level rise, global seal level rise (GSLR) in a worldwide manner, are still controversial, global warming (greenhouse effect) is seen as the main factor. Increasing greenhouse gas emissions is expected to make climate warming even more intensive during the next century. Greenhouse effect would have a strong influence on natural processes of Earth. It is already observed and predicted that sea level rise is and will more likely continue being one of the more prominent results of climate change in this way. According to the Intergovernmental Panel on Climate Change (IPCC) 2001, it is foreseen that global warming will contribute significantly to future sea level rise, because of thermal expansion of sea water and widespread loss of land ice. Human habitat could very well be affected seriously, since almost 20 percent of the world's population lives within 30km of the sea, and approximately 40 percent live within 100km. of the coast. It is estimated that by 2100, 600 million people will inhabit the coastal floodplain below the 1000-year flood level. [2]

Any low-lying coastal area, island or country which has a relatively long coastline is in the most vulnerable position to rising sea level. The major effects of sea-level rise, as will be discussed in the latter parts of this study, are the land loss due to flood-based inundation and erosion, worse storm flooding and damage, thus flooding of residential areas, and saltwater intrusion to fresh water aquifers and estuaries. [3] Located in the Baltic Sea coast, the study area, Falsterbo peninsula of Sweden, shown in Figure 1, is a very low-lying area, which is very sensitive to a future sea-level rise phenomenon. Apart from it being in a danger zone, it is a very prestigious place regarding its location and all the facilities it holds. High water levels combined with the large waves can cause serious damages, as mentioned above, within this area. It is therefore of great importance to assess the risk of flooding because of high water levels in combination with wave action to develop proper precaution against the threats.

Figure 1. The study site in a larger perspective
(http://www.skof.se/fbo/index_e.html, retrieved 05/08/2005) [4]

1.2 Objectives

The main objective of this study is to assess the flooding risk and to observe the extent of flooding due to extreme water level occurrences and waves. The mean sea level measurements available are projected into the future by means of an extreme value analysis and the waves are determined depending on the wind data. Knowledge of future sea levels and the associated flooded portion of land due to the waves in near future, in 20 years or in 100 years, are important for the understanding of the degree of possible impacts. Also, other potential impacts of these phenomena as will be included in Chapter 2 should be outlined. In that way, protective measures, *e.g.* warning systems, can be decided upon by policy makers in the area. The results may also be of help to some extent in the planning, design and construction infrastructure in the coastal zone.

1.3 Limitations

In the study, although some restrictions were induced because of time and content concerns, the majority of the limitations can be attributed to data availability and type.

Data analysis, where big data sets are dealt with, is always a complicated problem. Data sets of many years are usually fragmented and include trends that disturb the nature of the analysis. Furthermore, the statistical independence between the selected events is another issue to tackle. For this purpose a dynamic cluster interval concept was applied to provide the independency of consecutive events as explained in detail in the later parts of the report. Since the sea level measurements are in focus here, following requirements can be listed for the records to be the most useful in the analyses: (i) be at least 60 years in length, (ii) not be from sites at collision tectonic plate boundaries, (iii) 80% complete or better, (iv) in a reasonable agreement with the records taken from a nearby gauge, (v) not from areas deeply covered by ice. [5]

The data set existing includes daily mean sea water level measurements of 56 years. However, values are missing in some days. The requirements listed above were applied to the data set to see whether it fulfils them or not. It was observed that except the condition (i), the data set in question conforms to the established standards. The data set, covering 56 years only, can be regarded as a limiting factor for obtaining more reliable results in this way. Besides, the daily sea water level measurements, taken from the gauge installed in the south of Falsterbo, were used for the purpose of monthly extreme value analysis since only annual maximum values were available from the gauge installed in the north. It is thought that the results would be more representative for the area if the daily data from both gauges would be at hand. The sensitivity of the data set to the addition or the subtraction of couple of years is also worth to mention.

While determining wave parameters from the wind climate, a numerical model written for this aim in FORTRAN was utilized. The version used does not have the wave growth/decay model. However, this fact is considered to affect the results only marginally.

1.4 Procedure

The water level and wind measurements were available from a previous study, *Blomgren S.* (1999), Doctoral Dissertation Thesis at Lund University. The data sets were investigated and selected according to the usefulness and suitability for the purposes in the study.

In the study, the work is divided into two parts. In the first part, the daily mean sea water level measurements available between the years 1942-1998 are used for data analysis. First of all, monthly extreme values from this data set are extracted and the trends in mean sea levels and extremes themselves are subtracted so that projection of the results into the future would become much easier and time restriction would be removed. Then by using these adjusted extreme values, an extreme value analysis is conducted to estimate the possible sea levels corresponding to some particular return periods. Gumbel distribution is utilized in this extreme value analysis since it is expected to fit the data set the best.

In the second part of the study, the coupled effect of extreme sea water levels and waves are investigated as this scenario is important for dune erosion. Out of available wind observations for the duration 1961-1996, corresponding wave properties are determined by making use of a FORTRAN (a computer programming language) code, which is taking all wind-wave relations and wave kinematics into account. Next step is to estimate run-up heights by the help of a common run-up formula in coastal hydraulics. It will be seen in the latter parts of the thesis that the most critical condition takes place when the sea level rise is combined with the wave action. Therefore, this situation allows us to be able to make an analysis on the combined effect of extreme water levels and waves.

1.5 Disposition

This thesis was tried to be carried out in a systematic manner. In the first chapter, the background information, the main objectives of the study, which factors limited the study and the accuracy of the results and the procedure which was followed throughout the report are given. In the next chapter, sea level rise and wave action are defined. The reasons for the sea level increase are mentioned while global warming takes the most attention. In connection to these, the possible consequences of these coastal processes are explained with the attributions to the study area, specifically. Chapter 3 introduces the study site, Falsterbo peninsula of Sweden, from different points of view. In Chapter 4, extreme value analysis technique is outlined together with its background and procedure. The same chapter also includes an extreme value analysis on water levels. Next chapter's headline is 'wave prediction from wind data and run-up height analysis'. As the headline reveals, in this chapter how wind data is converted to wave data and the comparison of run-up heights for two different points are mentioned. Besides, extreme value analyses on 'water level + run-up', (WL + RU), can also be found in this chapter with all the results. The report was finalized with some discussions and conclusive remarks in Chapter 6.

2 Sea-Level Rise and Waves as Coastal Processes

In this chapter, a general overview is given about the causes and the outcomes of sea-level rise and wave action as coastal processes. The possible effects of these phenomena on the coastal areas are also included. Sea-level rise and wave action can be quite harmful both individually and collectively. Figure 2 is a good schematic representation of what will be discussed through this chapter.

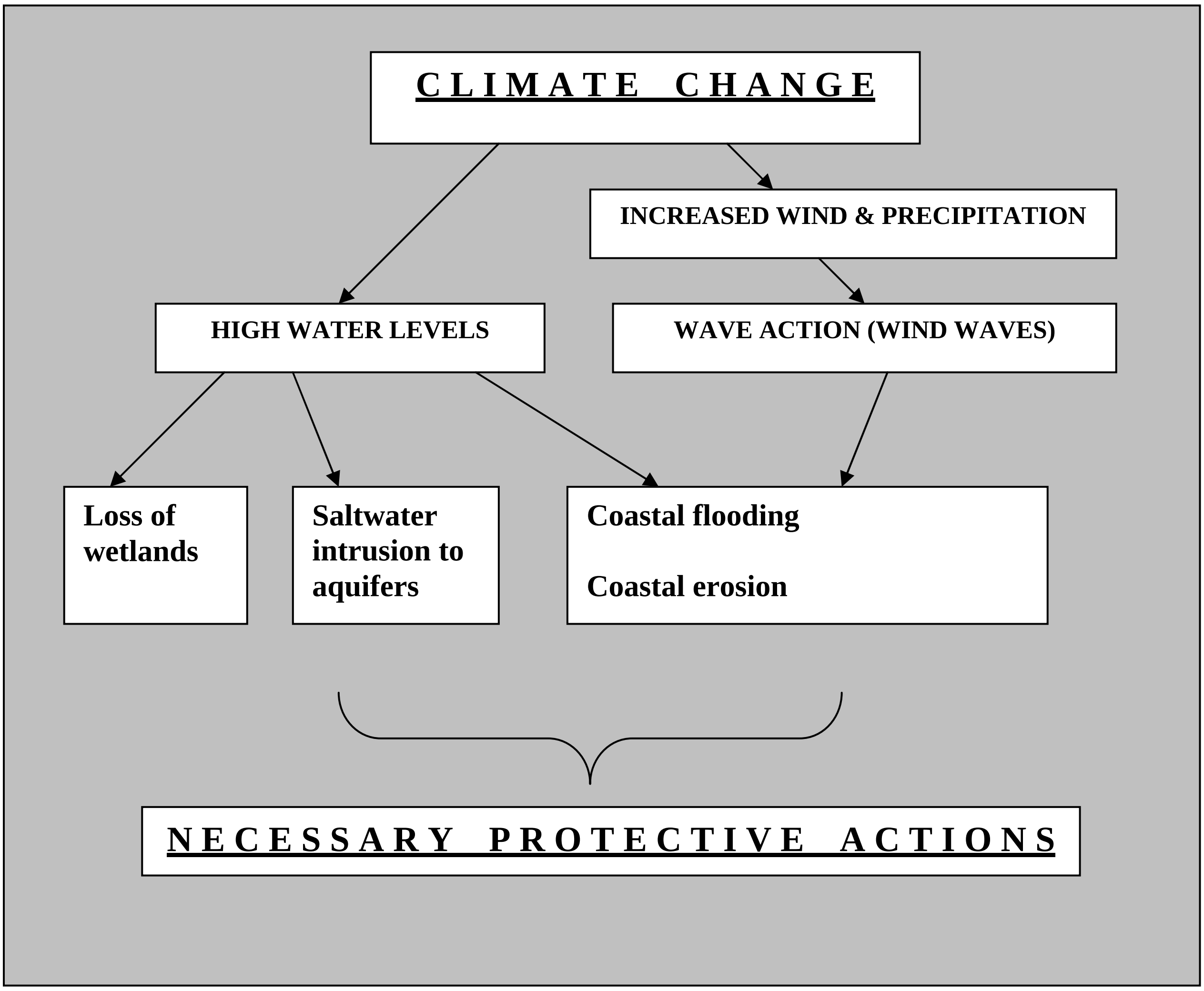

Figure 2. Schematic illustration of sea-level rise, waves and their effects

2.1 Sea-Level rise, climate change and the coast

Throughout the twentieth century, studies indicate that global sea-level rise (GSLR) lies between 1 mm/yr and 2 mm/yr, being much closer to 2 mm/yr in the most of the studies. It has captured much interest because it is important from two points of view. Firstly, it has the capability of having major impacts on coastal regions. This side of sea-level rise is in the focus of the study. On the other hand sea-level rise can be used as a scientific proof of climate change in a global manner. [5] For these reasons, understanding the reasons of sea-level rise is a necessity. Similar to the rates, the factors leading to sea-level rise have been the main subject of many studies, but still remained controversial. However, there is almost a consensus on the point that greenhouse effect (global warming) is the main triggering cause for the global sea-level rise. During the twentieth century, CO_2 and other greenhouse gases (e.g.CH_4, N_2O etc.) concentrations and, thus, the atmospheric loads due to them, have been increasing due to the burning of fossil fuels. According to this scenario, these gases form something like a blanket in the atmosphere and trap the infrared radiation (heat) emitted by Earth's surface, giving rise in world's global temperature. [6] Climate change as global warming has a great number of important implications, in addition to sea-level rise. It makes significant impacts on the hydrological cycle, altering both the quality and quantity of components, causing variations in time of the occurrences of these components and frequency of them. [7]

One of the potential causes of increase in global sea levels, in connection with the greenhouse effect, is the melting of land-based ice sheets and glaciers. The studies estimate the effect of melting of polar ice-caps as changing between 0.5-1.0 mm/yr. As the other main potential cause for sea-level rise, thermal expansion of the oceans can be mentioned. Not more than approximately 25% of the total increase, less than 0.5 mm/yr may be attributed to the thermal expansion effect of oceans. [8] In addition to the discussions above, it should be emphasized that the share of mankind activity in this increase is totally uncertain.

After the recognition of the climate change and global warming problem in all over the world, World Meteorological Organization (WMO) and United Nations Environment Program (UNEP) have established a yearly panel, called Intergovernmental Panel on Climate Change (IPCC) in 1988. (http://www.ipcc.ch/about/about.htm, retrieved 05/10/2005) This panel estimates a sea-level rise of 49 cm by 2100 as can be seen in the best estimate line in Figure 3 below. [9]

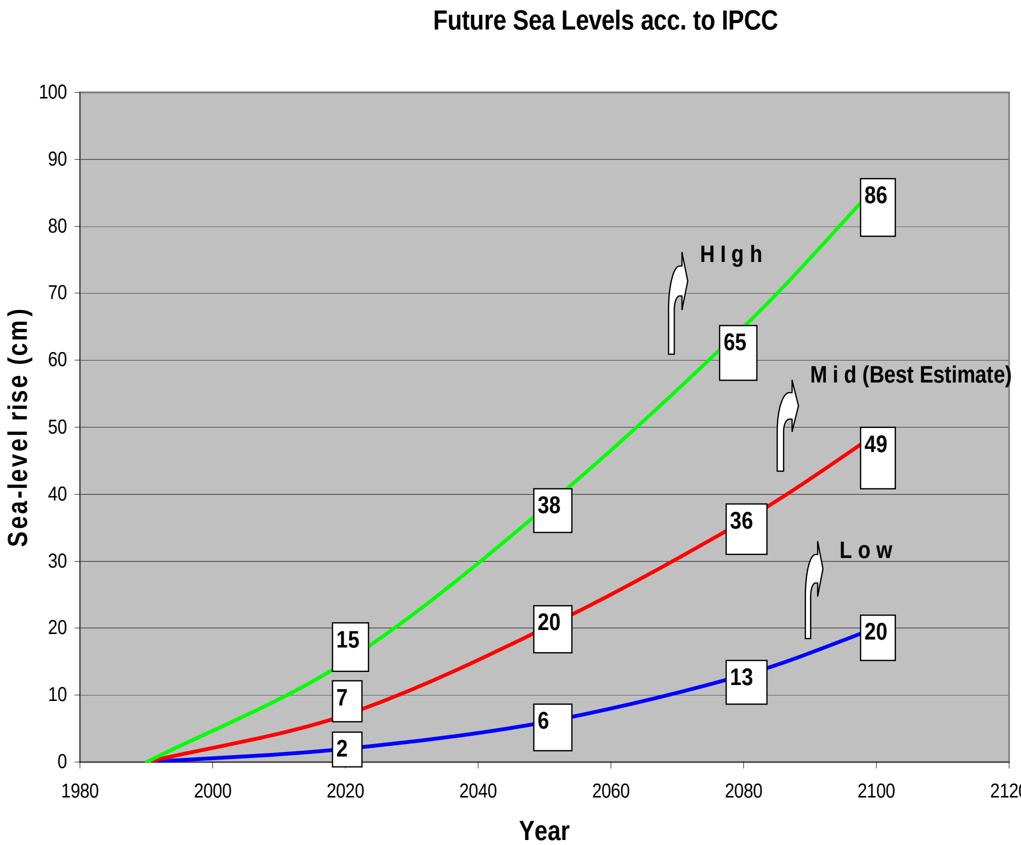

Figure 3. The future sea-level rise estimation graph stated by IPCC in 1996 (modified after Blomgren, 1999) [9]

Regarding the hazards caused by sea-level rise on a costal region, coastal flooding, inundation and erosion the beaches, loss of wetlands and disturbance of ecosystem, and saltwater intrusion to the coastal freshwater aquifers should be considered. Below is given a brief review of these hazards.

2.1.1 Coastal flooding

Coastal flooding can be described as the phenomena resulted by extreme sea water levels. As stated before, more than 50 % of the world's population lives on the coast or very close to the sea, in other worlds in the coastal floodplain. For these people, even a small increase in sea level can mean a lot. In this respect, coastal flooding in the coastal floodplain has an enormous potential to cause serious damages in fields, residential areas, destructions of harbour structures and coastal installations. Figure 4 illustrates the zones classified according to the different risk levels in case of extreme sea levels of different return periods. [10]

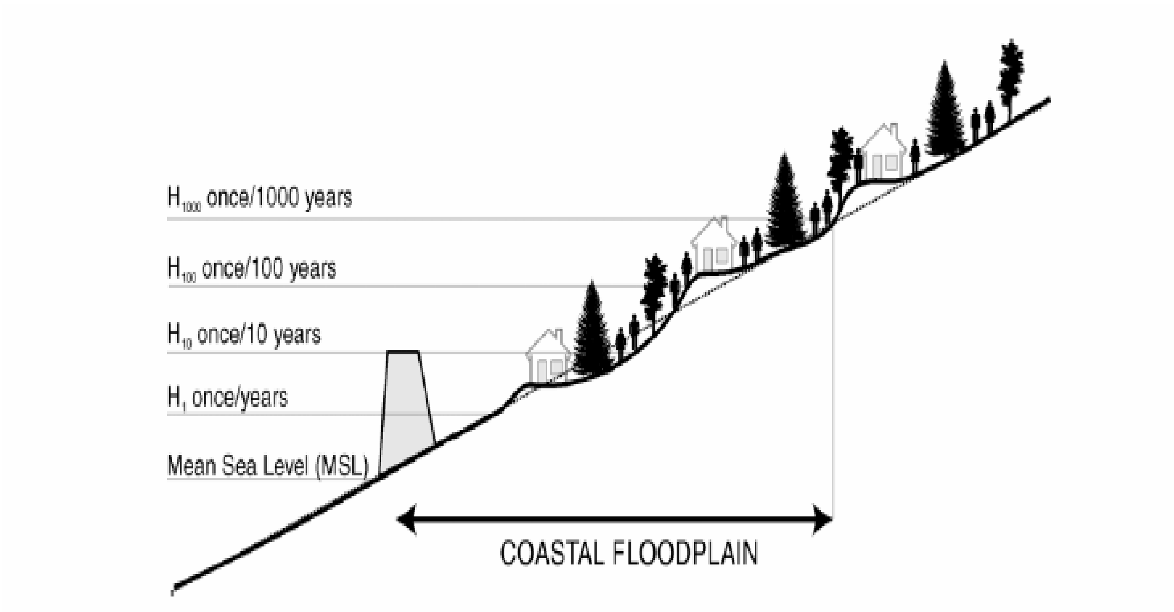

Figure 4. Illustration showing the coastal floodplain and different zone levels [10]

Figure 4 is important from the point of view that it reveals the vulnerability of social infrastructure and population under the consideration of the extreme sea water levels together with the increase in the mean sea level.

2.1.2 Coastal erosion of sandy beaches

Coastal erosion is a problem for almost 70% of beaches all over the world. Studies indicate that this often-encountered problem can be caused by three different events, namely sea-level rise, change in storm climate, meaning larger waves, and mankind activity, which is difficult to assess. [11] In this part, sea-level rise is outlined as a driving force for costal erosion.

Erosion of sandy beaches is the process of a redistribution of sand formation from the beach to offshore. Sea-level rise induces coastal erosion, and more interestingly, the coastal erosion occurs in much more higher rates than sea-level rise. However, it should not be interpreted as sea-level rise causing long-term erosion, which is demanding much more energy. An increase in sea level makes it possible for the waves to reach the further points in the beach profile and create conditions for the sand to slide towards the sea. [11] This is resulted by that offshore bottom responses in the same way and amount to rise in sea-level, i.e. if sea-level raises 1 cm. , so does the offshore bottom. The restricting condition for coastal erosion is revealed by the famous Bruun rule (see Figure 5), stating that ´the coastal erosion, because of the rise in sea level, is dependent upon the average slope of the entire beach profile extending from the dunes out to the point where the water is too deep for waves to have a significant impact at the bottom.` [12]

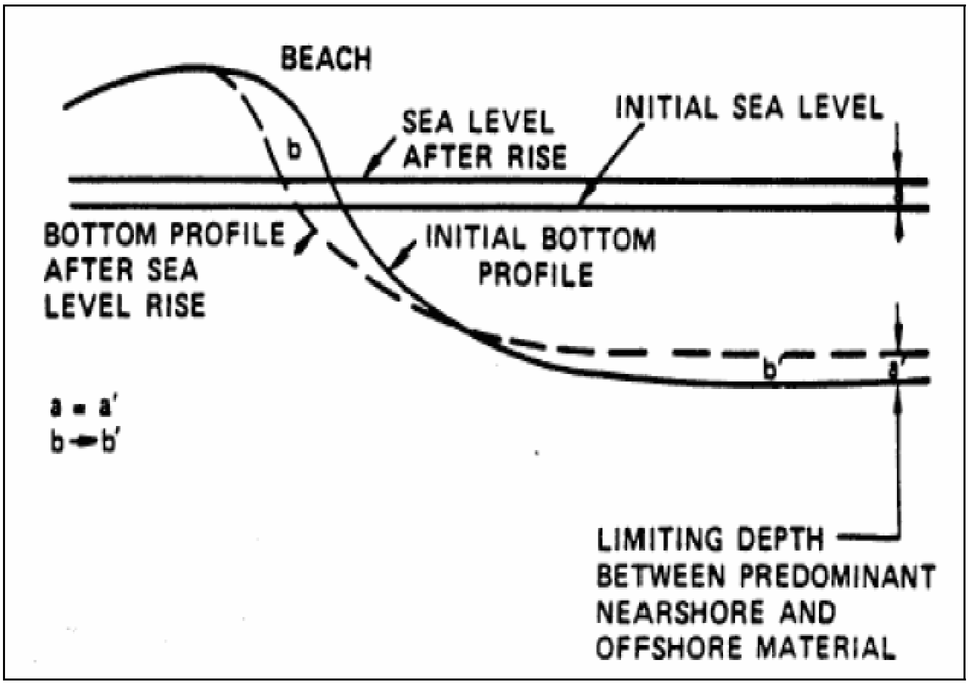

Figure 5. The Bruun rule: sea level rise as a cause of coastal beach erosion (http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BVJSU/$File/ocean_city.pdf, retrieved 20/10/005) [13]

As the beach is lost in the way explained above, the structures or constructions in the neighbourhood are getting much more exposed to the storm waves, and damaged seriously in the absence of costly beach protecting measures. This is very critical if one remembers that some of the most economically developed real estate exists nearby sandy beaches, as in case of Falsterbo peninsula, Sweden. Already going-on coastal erosion of sandy beaches of Falsterbo can be observed in Figure 6.

Figure 6. Coastal erosion in southern Falsterbo.

2.1.3 Loss of wetlands and disturbance of ecosystem

Highly populated areas or sandy beaches are not the only places threatened by sea-level rise. Coastal wetlands are also very sensitive to the changes in sea-level due to their location of being next to the sea. In the study site, Falsterbo, there exist many wetlands in the junction of sea and land. (See Figure 7) These areas are quite fertile and highly turbid areas forming very suitable bases for food protection, waste assimilation, nature conservation, etc thanks to their high biodiversity. [10] It can easily be stated that their productivity is much more than that of any natural system. Besides, they offer excellent environment for animal and fish life, e.g. fish spawning and bird nursery grounds, so they are vital for the continuation of ecosystem chain. [6]

Figure 7. Coastal wetlands in southern part of Falsterbo.

Wetland loss is an already ongoing process. Approximately 1% of world's wetlands disappear every year, mainly because of human effects. [10] However, it is obvious that this process will progress in a faster manner due to sea-level rise since coastal wetlands do not have the ability of adapting themselves to the rapidly changing sea-level. [6] Figure 8 below illustrates the evolution of coastal wetlands loss process associated with the sea-level rise

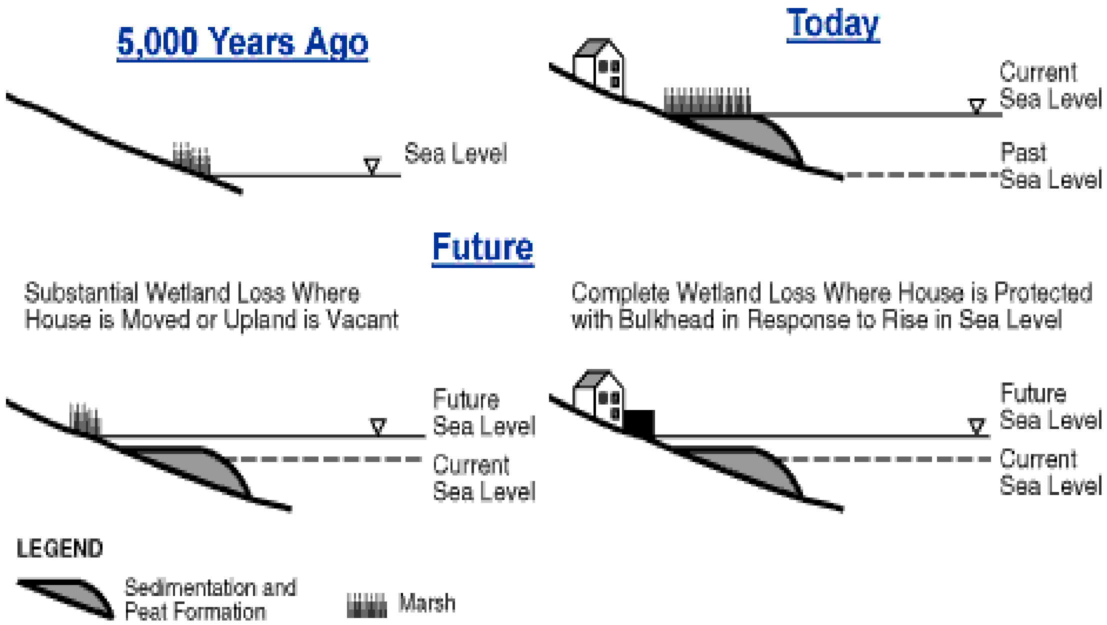

Figure 8. Evolution of a coastal wetland area under the effect of sea level rise [13]

2.1.4 Saltwater intrusion to coastal aquifers

Groundwater makes up 0.76% of Earth's water, and almost 30% of fresh water exists as stored in groundwater. It is the second biggest fresh water source after polar ice caps, which constitutes 69% of total fresh water. Thus groundwater storage is the largest available source of fresh water. [15] It is worth to mention that groundwater is relatively free from contamination. The most common geological formations that store groundwater are aquifers. 'They contain high amount of water and also have the ability to transmit the water in large quantities under ordinary hydraulic gradients.' [15] Well and spring formations occur in aquifers. There are different types of aquifers, classified according to the place, to the extent of confinement, and to the content, etc. Coastal aquifers are one of those types.

Saltwater intrusion to freshwater aquifers not nearby coast generally occur because of extensive pumping from the aquifer. In the coastal aquifers, however, it occurs due to fluctuations in the sea-level. In the case of sea-level rise, the groundwater heads in the coastal side of the aquifer increases instead of staying constant. However, the groundwater table increase in the sea side will not be of the same amount. That will result in decrease in groundwater table and/or piezometric head there, letting more saltwater intrusion to the aquifer body happen. According to this scenario, saltwater intrusion to deep coastal aquifers because of sea-level rise is much easier. [7]

2.2 Waves, climate change and the coast

Apart from the effects outlined in the previous part, among the possible outcomes of global warming, observable changes in atmospheric conditions and in the nature of hydrologic cycle can be listed as well. The speed of wind, precipitation regime, thus storm occurrences, increases because of these. This idea is very well approved for the study area by the measurements taken at a wind gage in north of Falsterbo between the years of 1941-1996. [16] There is a clear increasing trend in these measurements, justifying the fact that global warming is also giving rise to storm events.

Considering the location of Falsterbo, and the closed-sea feature of Baltic Sea, it can be easily stated that there is no or ignorable threat for tsunamis, tides or tidal currents, and strong storm surges. The only significant wave action remaining to be taken into account is wind waves. The description and the nature, the factors playing crucial role in formation of the wind waves and their possible impacts on the coast are treated in the following sub-sections.

2.2.1 Description and generation of wind waves

Waves of period smaller than 30 seconds are called wind waves, which account for the major part of the waves. Wind waves are generated in the open sea by the effect of wind. [1] Despite many studies for clarifying the mechanism behind the wind wave generation, no single theory so far proposed is adequate to explain the whole process in a proper manner. The instability at the interface between two layers with different densities, in this case air and water was the milestone of these studies. After this theory, it has been taken further by including the importance of surface tension, K. It has been followed by the attempts trying to fill in gaps in between these two fundamental approaches. The resonance phenomenon and inclusion of shear flow model were suggested within the existing context. [17] Explanations of these theories revealing the wind wave generation mechanisms are out of scope of this study. For further details original papers or books should be referred.

The length of the fetch is the first important factor in determining the characteristics of the generated wind waves. Wave height is limited by the length of the fetch region. Fetch length can be constrained by land mass blocking and wind area. The shorter the fetch distance is, the smaller the heights and periods of the generated waves are. In other words, a longer fetch causes an increase in the height of the waves. Secondly, the duration of the wind can be classified as a major factor. For the same fetch and the same wind velocity, the heights and the periods of the waves increase as the duration of the wind gets longer. As the last and the most crucial factor controlling (or limiting) the size of the waves, wind speed should be added. Needless to say, the wave height increases with the increasing wind speed. The effects of these three factors mentioned above have an upper limit. As the fetch length, wind duration and wind speed increase to some extent, an equilibrium point is reached, as shown in Figure 9.

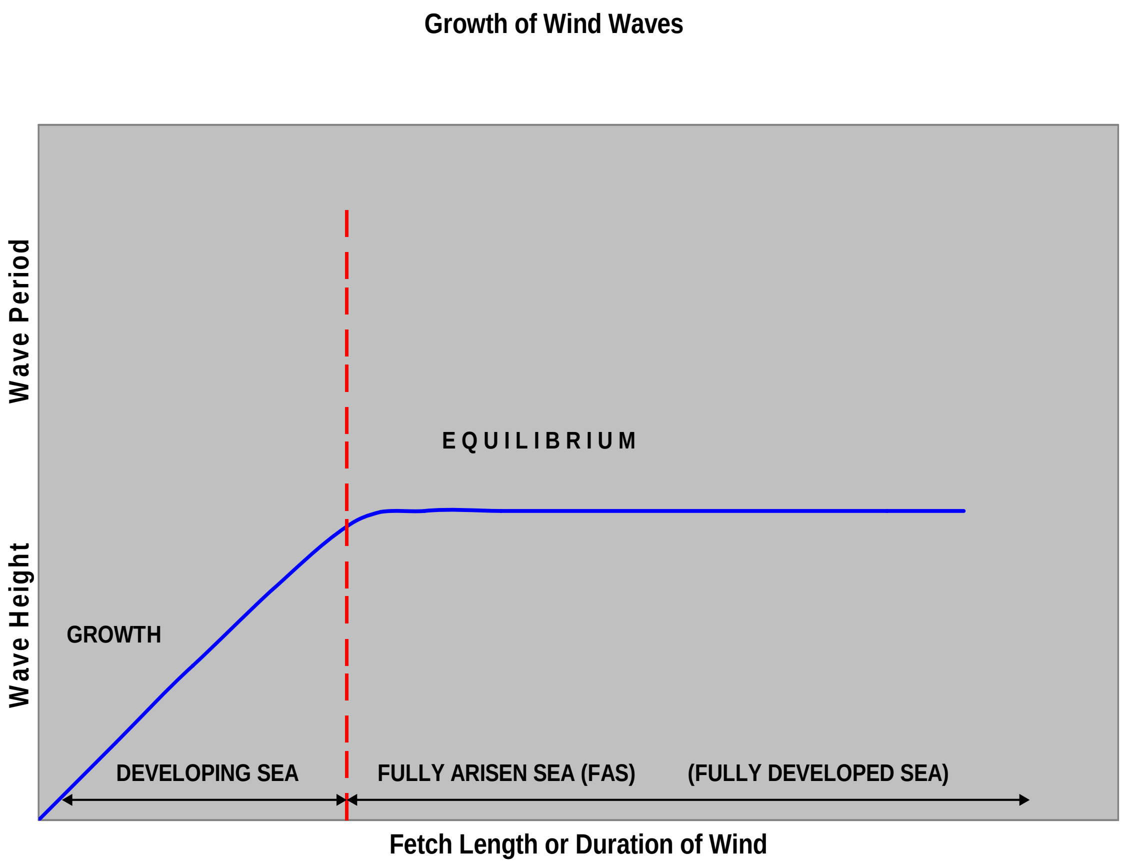

Figure 9. Growth of wind waves (modified after Ergin, 1998) [1]

At the equilibrium point seen in the Figure 9, the energy input to the waves being generated due to the wind is balanced by the energy output, caused by wave breaking and turbulence. This equilibrium state of the waves is known as a fully arisen sea (FAS) or fully developed sea. If the energy conditions necessary for forming the equilibrium state do not occur, then the waves can not grow till their maximum possible heights, therefore such a sea is named a developing sea. [1]

2.2.2 Wind wave prediction

Reliable wind wave information is necessary for any coastal design, planning or construction activity. It is even required for national defence plans, navigation routes, and tourism and recreation purposes. However, proper measurement of wind waves is a difficult and sometimes not economically feasible process depending on the purpose. It has been implemented in even rich countries not so long ago. That brings the issue of ‘estimating the wave characteristics, i.e. wave height and period, from available wind data’. [1]

Estimating the wave characteristics from wind data for the region of interest is called ‘wave hindcasting’. Whereas, to estimate the winds expected to occur in the future first and then to derive wave height and period out of that is classified as ‘wave forecasting’. Either for wave hindcasting or for wave forecasting there can be found three different methods in the literature, namely empirical relations, spectral models and numerical models. [1]

2.2.2.1 Empirical relations

Graphs or equations are utilized to compute the significant wave height and the period, $H_{1/3}$ and $T_{1/3}$, respectively. A widely-used one is called the SMB (Sverdrup-Munk-Bretschneider) method. It basically employs wave-energy growth concept to predict the desired parameters. [1]

2.2.2.2 Spectral models

These are three one dimensional spectral models for deep water, which are empirically fitted to measured waves. All of them have been proposed under the assumption of wave growth process being in the same direction with the wind. [18] ´The Bretschneider Spectrum (Bretschneider, 1959) shows a period spectrum as a function of wind speed, fetch and wind duration`. [18] A wave frequency spectrum based on analysis were compiled by Pierson and Moskowitz (PM, 1964), and this wave frequency spectrum is named as PM Spectrum. [18] The JONSWAP (Joint North Sea Wave Project) spectrum (Hasselmann *et al*., 1973) facilitates a fetch-limited spectrum. This enables one to relate wave frequency to wind speed and to fetch distance. This spectrum model has been taken as a base for deep water wave prediction for *The Shore Protection Manual (SPM)* by U.S. Army Coastal Engineering Research Center, 1984. [18]

2.2.2.3 Numerical models

The numerical models compute the wave growth/decay and give directional distribution of wave field. In most of the numerical models energy conservation principle is referred. Wave generation, propagation, interaction with the environment, and dissipation processes are simulated to some extent of accuracy depending on the model used. [1]

2.2.3 Wave impacts in the coast

As stated in the former parts of this study, climate change in the way of global warming causes not only sea-level rise but also changes in storminess and storm patterns by altering the elements of the hydrological cycle. The more the storminess is, the more the wind speed is. This increase in wind speed will cause bigger waves to propagate towards the coast.

Among the impacts of waves on the coasts and coastal structures, flooding or inundation of inertial areas, overtopping, and destruction on the coastal structures by breaking waves, coastal erosion, sediment transport and loss of nearshore sand banks can be listed. These impacts are important from two perspectives. They demolish or damage the coastal structures or residents within the coastal floodplain, claiming both economical and human life losses. At the same time, they dictate the coastal managers to make decisions about construction of preventive installations, which brings economical burdens to the country and changes the nature of the coast.

3 Study Area

3.1 Location

The study site in this report is a peninsula located in the south-west corner of Sweden, called Falsterbo peninsula, belonging to the province of Scania. The Falsterbo peninsula is the name of the south-westernmost tip of the Scandinavian Peninsula, about 25 kilometres south of the city of Malmö (Figure 10). As can be observed in the Figure 9, its shape resembles a trumpet, extending 7.5 km both in the east-west and north-south direction. The Falsterbo peninsula covers an area of approximately 23 km^2. It marks the border between the Baltic Sea and the Öresund straight between Sweden and Denmark. [19]

Figure 10. The general view of Falsterbo Peninsula

(http://www.nationmaster.com/encyclopedia/Falsterbo, retrieved 01/08/2005) [19]

Falsterbo peninsula, owing to its waterway, Falsterbokanalen, shortens the route between The Sound area and most Baltic destinations. It lies on a very important point in Baltic Sea, also when the currents and the wind effects are taken into account.

3.2 Socio-economic aspects of the study site

3.2.1 Population

Falsterbo is a small community in Scania, Sweden. Falsterbo forms a conurbation with Skanör, with a joint population of almost 7,000 as of 2004. Falsterbo peninsula area, during the 20th century, has tended to become an affluent suburb for people working in the cities of Malmö and Lund. It is also a site popular among people who have retired from positions abroad or from the capital. [19]

3.2.2 Major Attractions

Falsterbo peninsula is an important attraction point from many points, which makes it a place to be given extra attention for possible threats. Falsterbo peninsula is known for its own unique scenery and view, white and fine sand beaches, which makes it possible for Falsterbo to offer some of the best sea bathing in Sweden in addition to wind-surfing and sailing activities. One of the most famous golf courses in Sweden is located in Falsterbo. [19] Not the least but probably the most important facility of Falsterbo is that it has one of Europe's most important bird migration points, known as Falsterbo Bird Observatory. Most migratory birds of prey fly over the Scandinavian Peninsula and leave there via the 5 km-long reef in the south of Falsterbo, especially in the time span between August and October. [20] (Figure 11 below) Furthermore, Falsterbo has an annual horse jumping show, Falsterbo Horse Show. Apart from all listed above; the exceptional natural environment is declared a marine nature reserve and is listed in the *Convention of Wetlands of International Importance*. [20] Accordingly, Falsterbo Peninsula with Måkläppen is recognized among Sweden's marine protected areas by scientists, working with the Baltic Sea Region. [21]

Figure 11. Migrating birds in Falsterbo
(http://www.travel-travel-travel.com/eco/SwedenBirds/article.htm, retrieved 14/08/2005) [22]

3.3 Geological and morphological features of the study site

'The Falsterbo peninsula came into existence after the ice age as a result of marine sand deposits around several moraine beds, among others at Måkläppen, Knösen and Skanörs heath.'[23] The peninsula can be described as a very low lying piece of land, being below the 3-meter level with 90% of its area, and it is built of unconsolidated sand. Basically, several and different sand formations exist as the dominating soil type through the peninsula. The constant and never-ending beach processes have formed the coastal morphology which can be characterised by long even beach lines with fine sandy beaches and a dune landscape along the Baltic and Sound coasts. [23] Concerning the coastal geography and geology around Falsterbo peninsula, it can be mentioned that bottom sediments are composed of mainly of sand and moraine, together with mud in deeper areas. [24]

The peninsula is believed not to have reached its equilibrium shape yet. It is foreseen that the island of Måkläppen will become totally connected to the peninsula due to sediment transportation from peninsula, and the two sand-tongues on the south coast will eventually join, giving rise to the formation of a new coastline. Then, the similar coastal and morphological processes, which were playing the crucial role in the formation of peninsula, will fill the lagoon. [25]

3.4 Vulnerability to sea level rise and wave action

For a low-lying part of land such as Falsterbo the most important threats come from sea in the form of sea-level rise and an increase in both the height and frequency of waves. As mentioned before, almost 90% of peninsula's area lies under the 3-metre level, indicating a high risk of flooding. It is surrounded by the unconsolidated sandy beaches with gentle slopes, which are very susceptible to erosion. What is even worse is that no protecting measure system exists in the coastal floodplain to secure the area. From the population in danger point of view, a study by Hanson ([25]) indicates that Falsterbo is in high risk with the population rate 200 persons/km^2, according to the risk chart given in Table 1. [25]

Table 1. Table of assessment of risk according to several criterions (modified after Eurosion [25])

CRITERIONS	**LEVEL OF RISK**
City or major part, or >150 person/km^2, or >150 km road/ km^2, or >10 m pipeline/ km^2	**High**
150 < persons/ km^2 > 75, and 150 < m road/ km^2 > 100, and 10 < m pipeline/ km^2 > 0	**Moderate**
Persons/ km^2 < 75, and m road/ km^2 < 100, and no pipelines	**Low**

Although the current effects in the area are not drastic at all, above picture of future vulnerability of Falsterbo peninsula of Sweden clearly underlines the criticality of the need for a proper assessment of the possible impacts of sea-level rise and wave action.

4 Sea Level Measurements

Sea level measurements at noon taken by a recording gauge attached to the ground in the south part of the Falsterbo Channel were available for the years between 1942 and 1998. This gauge represents the level in the Baltic Sea side of the area. There are missing values occurring in some days in the data but when this missing portion is compared to the data size, it has been concluded that they do not distort the character of the data, thus not posing any problem in principle. It is also worth mentioning that isostatic land uplift issue, the uplift phenomenon of land because of tectonic movements, is included in these measurements since the gauge was in attached position to the ground. Southern parts of Sweden are known to be stable from these points of view. [26] Furthermore, astronomical tides are negligible in the Baltic Sea.

These sea level measurements for 57 years have been used to detect the changes taking place in the state of the sea level and also to draw a future picture so that possible impacts in the Falsterbo coasts would be assessed and precautions would be planned. Looking at annual extremes is what has been commonly done in the literature. However, in this study monthly extremes have been chosen to investigate the pattern in data set so as to get more in-depth results, or not to neglect the marginal changes within the years themselves.

In this chapter, an extensive extreme value analysis on monthly extreme sea water level measurements starting from 1942 to 1998 has been conducted. By means of this extreme value analysis, a future projection of sea level in Falsterbo together with the risk and the probability concepts involved has been attempted. Different analyses have been made on the data to remove the time dependency and to reveal the trends existing in the data itself. These analyses are given in detail together with the explanations and the results obtained in the following sub-chapters.

4.1 An overview of the methodology

The starting point for the analyses was frequency analysis. Its principles were taken as a base. Then, extreme value analysis on monthly extremes was conducted. Below is given an overview of the methodology followed and the basics of the procedure applied.

4.1.1. Frequency analysis

"A full series of data is useful for interpolation, but cannot be used directly for extrapolation. Frequency analysis can be used for either interpolation or extrapolation. It evaluates the relationship between the return period (*T*) and the magnitude of a particular, e.g., hydrological event, such as a peak flood discharge, a high sea surface elevation, or wave height. Thus, if we want to design a bridge to withstand a 1 in 100 year flood, frequency analysis can provide an estimate of the design discharge. When '1 in 100 years' is said, it is being quoted an average return period (also commonly called the frequency of occurrence, frequency, or return interval). It doesn't mean that it will take 100 years before the event occurs." [27] Indeed it does mean that it can happen any time within this 100-year time interval.

"The water level (i.e. an event) with a return period of *T* years is denoted by Z_T and is called the 1 in *T* year water level, or often just the *T*-year water level. The relationship between *T* and the probability (*P*) that an event of magnitude Z_T will be exceeded in any one year is given as" [27]:

$$P = 1 / T \qquad (1)$$

The probability can be seen as the measure how likely the event in question is, and expressed in different ways, such as fractions, percents (%), or decimals, depending on the purpose of usage. It can be taken further from here that the probability that the event will not be experienced in any one year, that is non-occurrence, is equal to (1 - *P*). The risk, on the other hand, can be viewed as the product of related probability and possible consequences within this context.

In the case of sea level observations data set in Falsterbo, the concept of frequency analysis was the starting point. However only monthly extremes are extracted and used for an extreme value analysis to get future estimates of sea levels together with the associated probabilities.

4.1.2 Extreme-value technique

The objective of the extreme value analysis is to determine the estimates of desired return values, e.g. 20 years or 100 years in Falsterbo case. The procedure includes deciding on a probability distribution function to represent the joint extreme behaviour of the variables included. The elements of the procedure can be seen below in Figure 12.

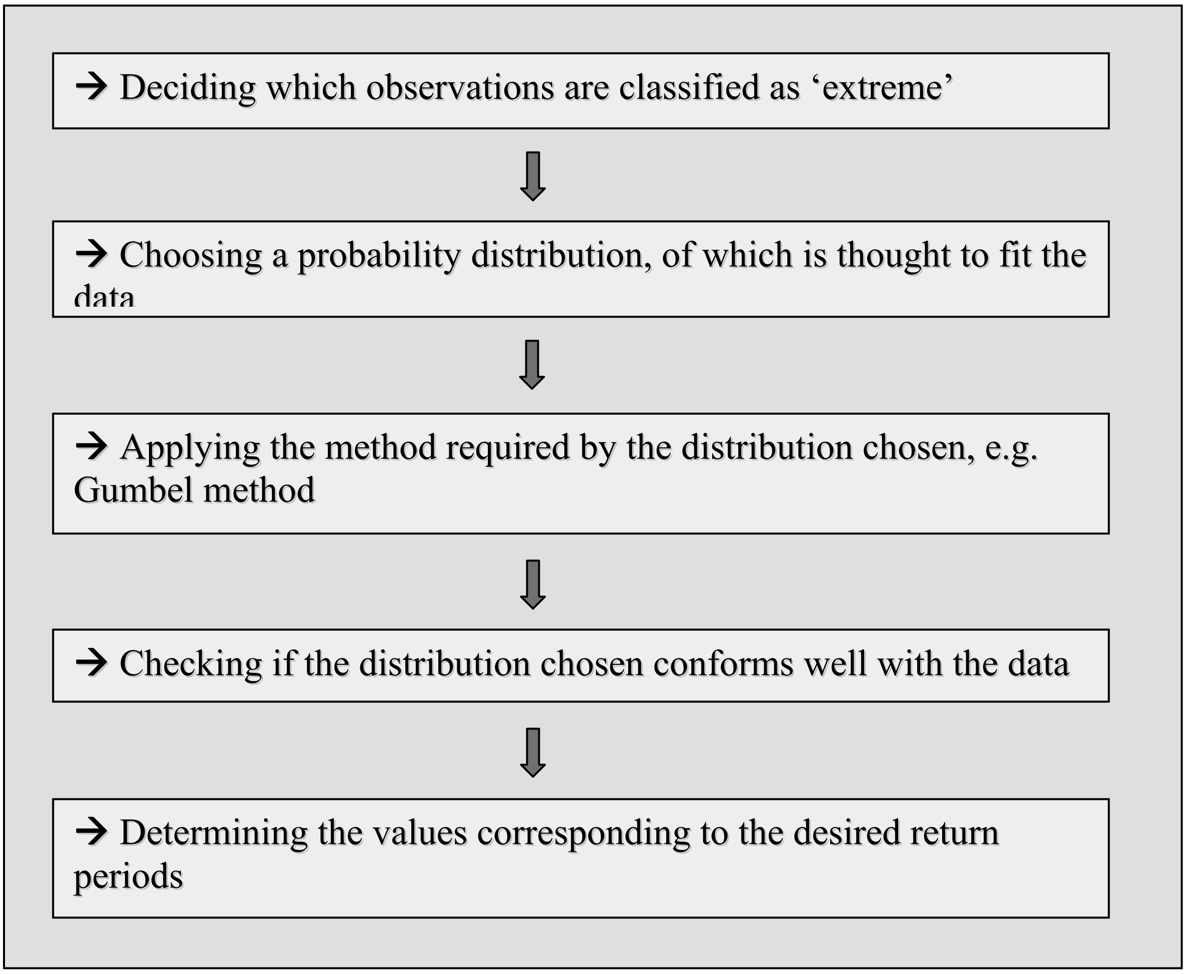

Figure 12. The elements of extreme value analysis

While this methodology is still being developed and applied in different ways for application to several fields, such as meteorology, hydrology, wind engineering, material engineering etc., the standard procedure as demonstrated in Figure 12 has been set up. In more detail, the first step is to answer the question, what is an extreme in this study? It is accomplished by declustering time series of the data to distinguish peak events which are sufficiently separated from each other in time so that they can be accepted as independent events. Generally a cluster interval is chosen and it is stated that two peak events should not be taking place within this interval. [28] Defining the cluster interval is not an easy and straightforward task. It is very dependent upon the study field, and the methodology followed. In the present study, maximums of months are extracted from the data. This process is explained in more detail the upcoming parts of the report.

Having determined the extreme events, now the probability distribution to represent the data behaviour should be decided. While dealing with extremes, the statistical methods which make use of normal distribution are not suitable to model the behaviour of the data set. For this purpose, one of the extreme value distributions and techniques available in the literature must be selected according to some criterion, such as data size, field of study, time available to test several distributions, easiness, etc. In the extreme value distribution, the density function curve is skewed to one of the sides, and the peak of the curve does not coincide with the mean. (See Figure 13) The main characteristic of these distributions is that the larger values have tendency of occurring than smaller values. This is also proven by the practice, as well as by the data set of maximums in this study, i.e. while very low maximum values rarely occur, very high maximum values can be said to be happening infrequently. This consideration gave rise to the formation of the curve seen in Figure 13. [29]

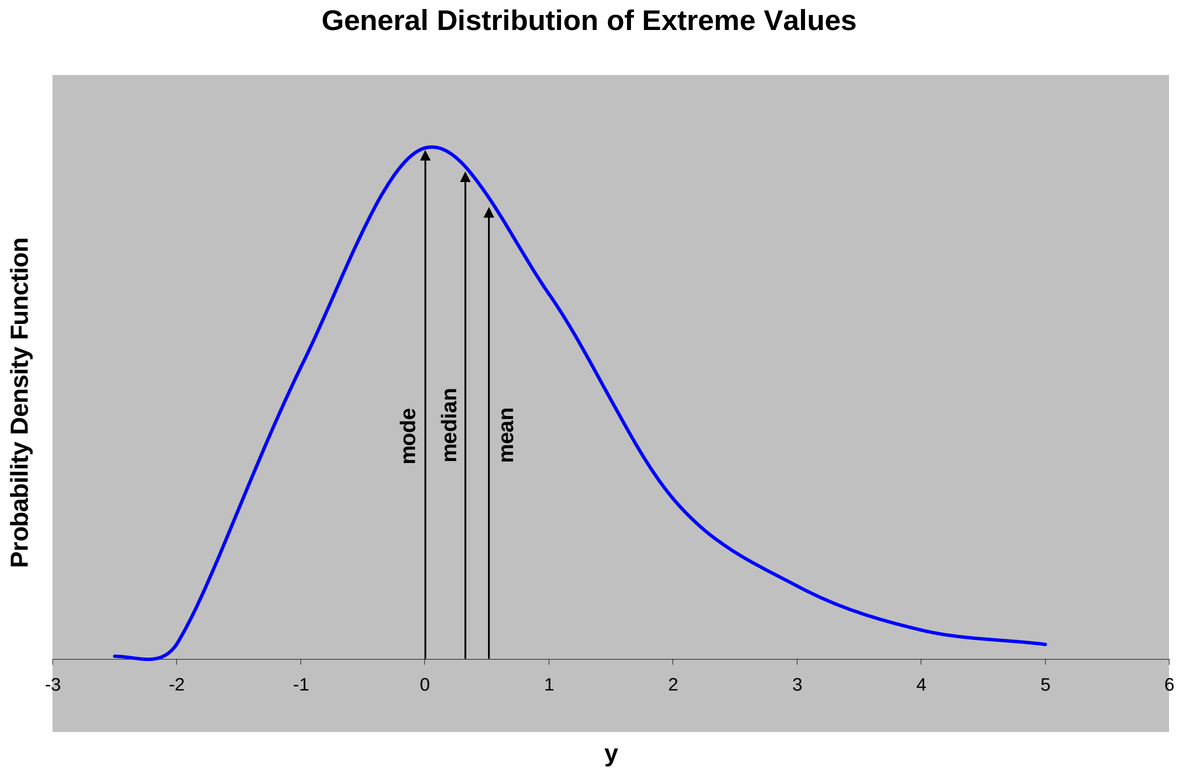

Figure 13. Theoretical plot of extreme-value probability density function (modified after Gumbel and Lieblein, 1954) [29]

Once the distribution is decided upon, the method dictated by this probability distribution can be applied. The data of extreme values are plotted against the associated probabilities by following the rules, and the probability plot is obtained. Next step is to check whether the distribution chosen appropriately fits to the data or not. This check also differs depending on the method followed, and the sensitivity level of the analysis. For instance, it can be in the form of constructing confidence intervals (bands), the tendency in data scattering, the value of the likelihood function, or method of moments estimation etc. In this study, to model the monthly extreme sea level values observed in Falsterbo, a special case of Generalized Extreme Value (GEV) distribution, which is called the Gumbel distribution, has been used. Therefore, a very brief background of the Gumbel method is given in the following subsection.

4.1.3 The Gumbel method

As already stated before, Gumbel distribution is a special case of the Generalized Extreme Value (GEV) distribution. Its name comes from Emil J. Gumbel, who pioneered the application of the statistics science to the extremes. The extreme values are often accepted to follow the Gumbel distribution, which is also called extreme-value distribution or Fisher-Tippett type I distribution. The distribution function and parameter descriptions are out of scope of this text since a graphical solution is preferred. One of the most common application ways of the Gumbel method to the extreme events, which was also utilized in the present study, can be described as follows. In the presence of a set of N extreme data values, first the values are ranked in descending order so that the smallest value takes r=N and the largest one is numbered as r=1. Then, these ranked extreme values of the event of concern are plotted against the reduced Gumbel variate, y, which is formulated by $y=\ln(-\ln(r / (N+1)))$. From the scattered data, a straight line is fitted and used for extrapolation to read a value of the event for a desired probability of occurrence (or non-occurrence). [30]

The method outlined above is arithmetically simple and straightforward. It does not take any additional knowledge about the data set in question into account. It is not a necessity that one should be aware of the fact that the data set fits well to the Gumbel distribution. However, if the solution is done in the graphical manner, the suitability of the distribution for the data set being analyses will be revealed by that the plot does not result in a straight line. In the case of availability of further information about the data set, several improvements in the accuracy of the results are possible by, for example, taking the effects of correlation concept into account, changing the plotting axes, different techniques of fitting a straight line to the plot, etc. [30] Nevertheless, while investigating the extreme sea levels in Falsterbo in this report, the simple algorithm was followed, and the improvements suggested were not tried, having thought that these improvements would not cause such a drastic difference, maybe just in the order of couple of centimetres, on the results obtained.

4.2 Extreme value analysis of sea level measurements

After reviewing the meaning of some concepts and the background of the method that will be utilized; now the procedure applied on the data set of sea level measurements in Falsterbo, Sweden can be initiated. In this context, the first step was to select the data set to be analysed. Annual maximum series is the most general alternative and it is suggested to be used in the cases of having data sets for more than 14 years. [27] In this report, it is more suitable to use monthly extreme observations. Annual extreme observations can be suspected to have more of an erratic resolution over the recording period of 46 years, since they are selected potentially from any month throughout the year. As mentioned before, daily mean sea level measurements made in southern Falsterbo Peninsula, Sweden for 57 years between 1942 and 1998 were available. For the sake of easiness, the reason explained above and better demonstration, the monthly maximum (or extreme water levels) values were extracted from the data set.

One of the challenging parts in this method was the phase of specifying the extreme events. In any of the alternatives existing in the literature, it is of utmost importance that the events are independent of each other. In order to be classified as an independent extreme, an event should satisfy some criteria, such as, cluster interval and threshold. In this report, only cluster interval criterion is explored. As explained in the overview of methodology section, the time span between two extreme events should be long enough to guarantee the independency of these events between each other, i.e. no two events should be drawn from the same storm. In this manner, to obtain independency between extreme water levels, while choosing the monthly maximum values, extra attention was paid so that the consecutive extremes do not belong to the same event. For this purpose, if the extreme of any month was observed to be the continuation of the previous extreme, then the second largest value of this month was taken as the monthly extreme value, the larger value, in this case, was discarded. The criterion of a dynamic cluster interval between extreme events was provided, since the duration between the extremes changes all the time. By that way, it is thought that a declustering mechanism was induced.

Furthermore, the year was sometimes considered to be starting in June, so that all winter months, thus all the storms and peak sea levels could be encountered in the same year. This has been done for several reasons throughout the report, e.g. to inspect the sensitivity of the data to seasonality or for better demonstration as in the case of Figure 14 below. The diagram showing the distribution of monthly extreme sea levels between June 1942 and May 1998 is available as Figure 14, where it can clearly be seen that extremes of extreme values occur during late autumn and winter months.

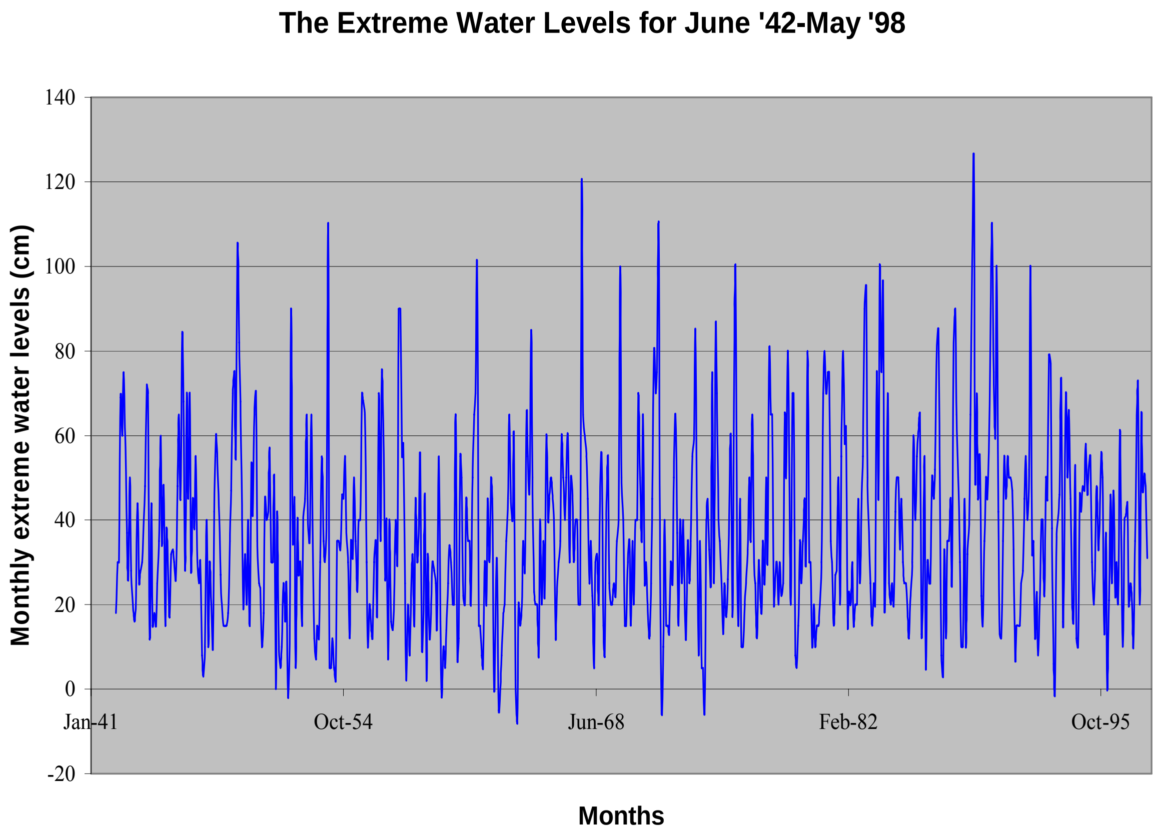

Figure 14. The Diagram showing the distribution of monthly extreme water levels from June 42 to May 98

The next step in the analysis was to decide on a distribution which is thought of fitting the data set of extremes. The selection of distribution is a matter of engineering judgement to some extent. As explained in the previous section, ordinary normal distribution is usually not adequate to model the behaviour of the extreme events properly. Therefore, Gumbel distribution was chosen for this purpose. The reasons behind this preference are the self-check for suitability feature of Gumbel, proven well performance of Gumbel in extreme value representation and practicality because of simple method. Since the graphical solution was going to be utilized, the procedure emphasized in detail under the heading of 'The Gumbel Method' was followed. This monthly maximum frequency analysis by extreme value method was started by adjusting the extracted data, which is nothing but simply ranking the data so that the highest event value has a rank (r) of 1, the second highest one 2, and so on down to the lowest which has a rank of N, where N is the number of values in the series. If two values of the maximum event happened to be identical, then they were given the same rank and the following rank was omitted.

Having ranked the monthly extreme sea level values, the probability of occurrence (P) of each of these previously ranked values was calculated using one of the appropriate equations available for this purpose. This process can also be referred as determination of the plotting positions. Two of the equations to get the probability of occurrence (or to find the plotting positions) are called Weibull and Gringorten [28]:

Weibull Formula: $P = r / (N + 1)$……………………………………........................*(2)*

Gringorten Formula: $P = (r – 0.44) / (N + 0.12)$...*(3)*

The Weibull equation is more often employed, just because it is simple, but it can easily be stated that in many case studies available in the literature, there is little difference in the results obtained by Weibull and Gringorten equations, anyway. For the frequency analysis by extreme value technique on sea levels in this study, Weibull formula was used to get the corresponding plotting positions, which refer to probabilities in the Gumbel method. [27]

After determining the plotting positions for every extreme value in the data set, the next stage was to plot the selected extreme sea level measurements against their calculated percentage probabilities. To be able to obtain a straight line graph as much as possible so that extrapolation for the desired time period can be made easier, different special graph papers are used for different choice of distributions. The type of paper to be made use of varies according to the length of the data record and the distribution that the data set fits, i.e. whether it will be assumed that the data series are normally distributed or not. In this study, since only the method required by the Gumbel method was taken as a reference, the probability graphs were made on Gumbel paper.

In the Gumbel method, extreme water levels were drawn on a linear scale against so-called Gumbel reduced variate, y, which is given by:

$y = -\ln(-\ln(1 - P))$……………………………………………………….....................*(4)*

In this way, the representation transforms the Gumbel distribution into a straight line. Since the data points seemed to lie on a straight line, a linear regression was applied to get the return periods for different extreme sea water levels. Equation (1), $P = 1 / T$, was used to calculate the values of P from return period, T. Then, these probability values were inserted into the Equation (4), $y = -\ln(-\ln(1-P))$, to determine Gumbel reduced variate. Afterwards, by using the y-values, the water levels corresponding to 20 (for which y value is equal to 3) and 100-year return periods (for which y value is equal to 4.6) were determined from the graph as 77.5 cm. and 106 cm. respectively, as can be seen in Figure 15 below. The 20 and 100-year time periods were chosen as return periods in this study so that the results would be indicative for both the near future and relatively long time after. As mentioned several times, the data points tended to scatter on a straight line when Gumbel paper was used for the analysis, confirming that monthly extreme sea level data in Falsterbo between 1942 and 1998 conforms to the Gumbel distribution. Otherwise, the distribution would have to be changed and the same procedure would be repeated to find the most suitable distribution so that the obtained results would be trusted.

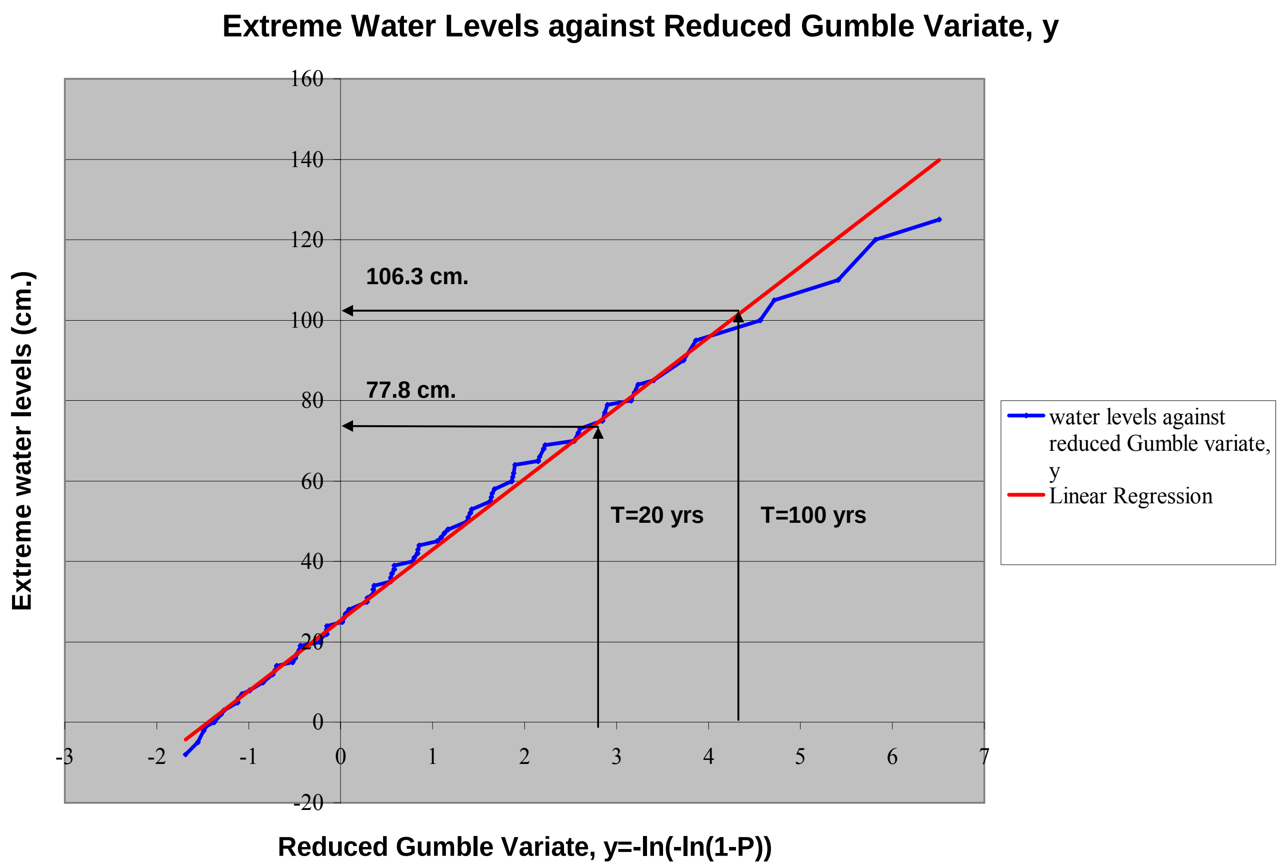

Figure 15. Graph showing extreme water levels against reduced Gumbel variate (or probabilities)

The extreme value analysis, thus the results obtained, do not take the mean sea level increase, the trends existing within the data, time variability into consideration. The data set need to be revised for dealing with these issues. The following subsection covers the issue of trend removal. After having the trends removed, the extreme value analysis will be repeated.

4.2.1 Removing the temporal trends

The main purpose of trend analysis in the statistical studies is to detect if any temporal trend is present, looking for a negative or positive change in data not due to randomness. [31] The long duration of the observational sea level record in the study also includes potentially significant contributions from mean sea level rise and from a temporal trend existing within the data itself. For the Falsterbo case, both of them are considered to be present and to be of enough magnitude to demand attention in the extreme value analysis conducted. They do not just constitute random influences, for this reason; they should be removed from the data set to establish a net data record free of temporal influence (time variation) prior to the analysis.

It can not be said that there is a single procedure or test for investigation of the trends that is superior to the others in all cases. It is very situation and purpose-dependent to decide which test is the most suitable. Some of the methods available in the literature are the classical approach, Man-Kendall test, the predictive Bayesian approach, etc. In the present study, the classical approach was taken as a reference for trend detection. This method was based on a parametric model, ($\alpha + j\ \beta$), where j denotes time. Within this approach, the null hypothesis is represented by the statement, $\beta=0$ and $\beta\neq0$ implies that there is temporal trend in the data. [31] Test of the null hypothesis was conducted by trying to fit a regression line (or curve) throughout the trend analysis, and the trend was assumed to be equal to β (cm/year or cm/month).

First of all, the trend existing in the original data (daily sea level measurements) should be subtracted from the chosen extremes. This trend exists due to the historical rise in mean sea level. However it can not be regarded that this historical trend will be representative for future estimates (or extrapolations into the future), since it is valid only for the duration between the years of 1942 and 1998. Instead of this value, the mid (or the best) estimate for the future sea level rise in 'the future sea-level rise estimation graph stated by IPCC (Intergovernmental Panel on Climate Change) in 1996', which was given as Figure 3, was included as can be seen in the next subsection. By means of this process, it was anticipated that the effect of future increase in mean sea level in Falsterbo would be included in a much more global manner.

For the inspection of the trend, firstly, the daily sea level measurements of 1942 to 1998 (raw data) were plotted and the linear regression was applied on the graph to get the linear trend, which was found to be equal to 0.07 cm/yr or 0.006 cm/month as shown in Figure 16 below.

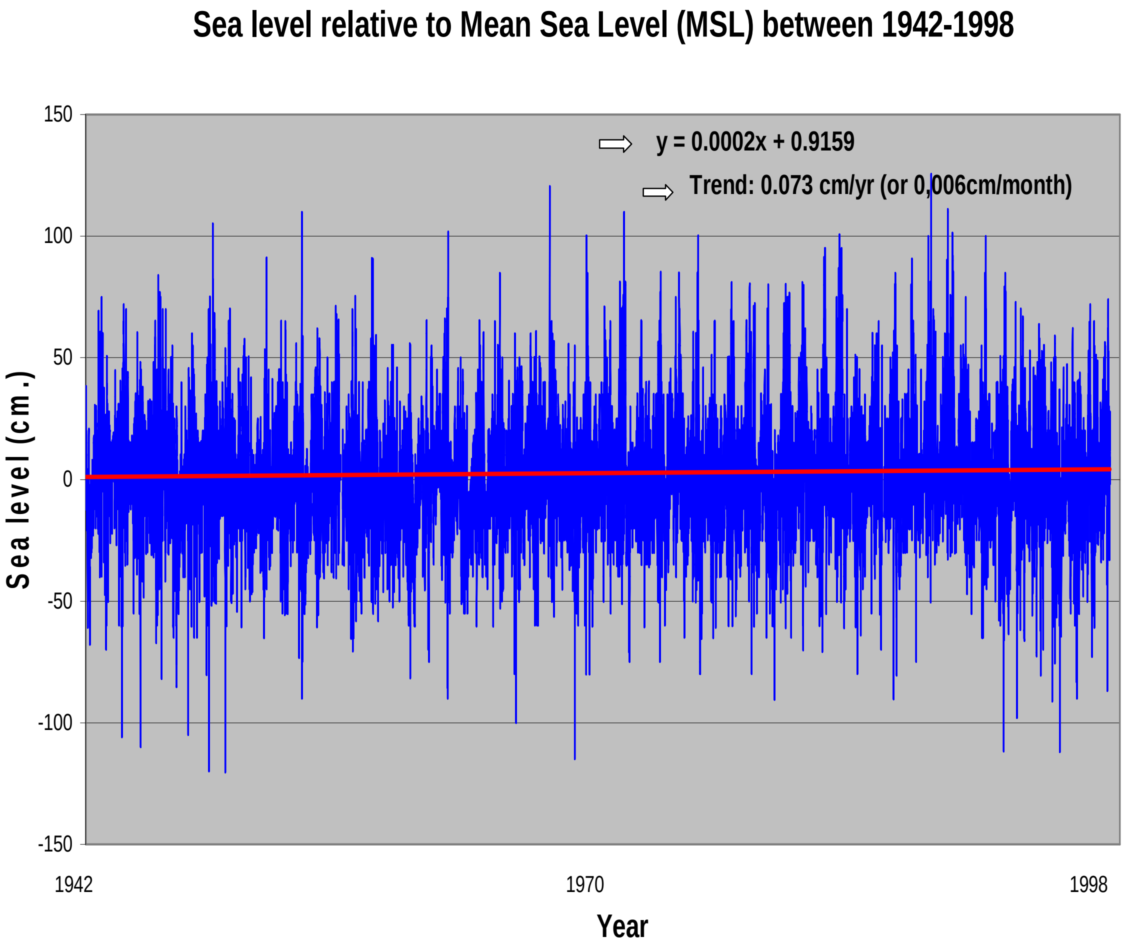

Figure 16. Daily sea level measurements between the years of 1942 and 1998, together with the calculated trend for mean sea level increase

As an alternative way of investigating the pattern in mean sea level (MSL) increase in this data set, the annual MSL were extracted. In this case, the consistency between the trend of daily measurements and annual means was the focus. To see how including all the stormy months within 1 year affects this trend, the year was taken as both calendar year, and a climate year starting in June while plotting the data. After that, polynomial trend analyses were performed on the graphs drawn. The graphs together with the added trend curves and equations are available as Figure 17 and 18, for calendar year, and climatic year, respectively.

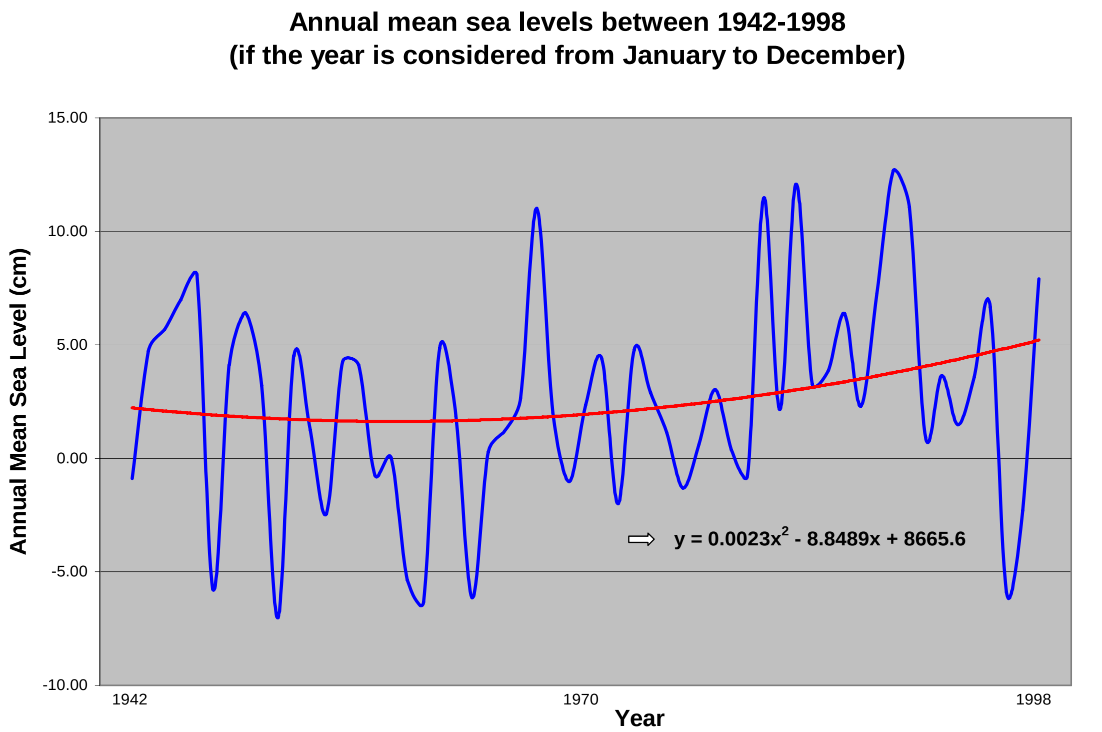

Figure 17. Annual mean sea level values between 1942 and 1998, together with the added polynomial trend curve and corresponding equation (the year is from January-December)

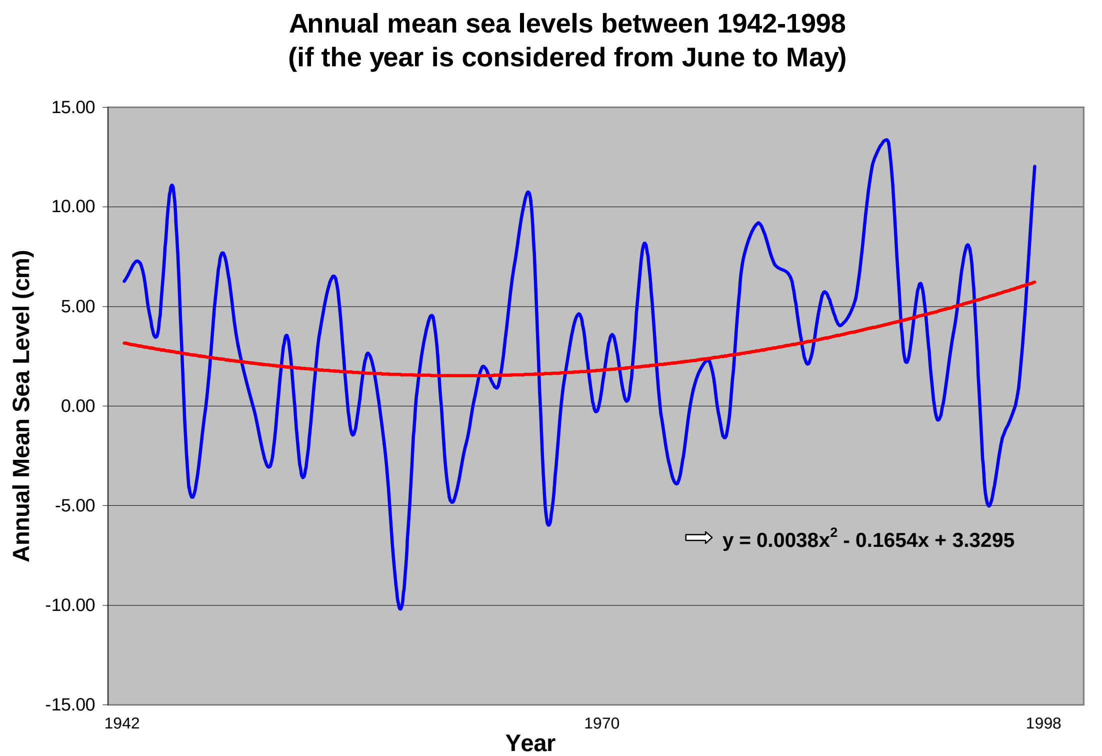

Figure 18. Annual mean sea level values between 1942 and 1998, together with the added polynomial trend curve and corresponding equation (the year is assumed from June to May)

When polynomial trend (or regression) was applied to the graphs, it was observed in both cases that trend first tends to decrease and around the year of 1970, it starts to increase up to 1998. As illustrated in Figures 17 and 18, the curves fitted do not make it possible to see the future extrapolation of the trends from the graphs. So, the results obtained are not applicable on the analysis. However, they are still useful to emphasize that there is a general increasing trend in the data set since they are consistent with the previous trend inspection done on daily sea level measurements from this point of view.

The MSL trend obtained from the graph in Figure 16, which was 0.073 cm/year, was subtracted from the monthly extreme sea level measurements data individually. By means of this, MSL increase trend was removed from the data set. The resulting monthly extremes after the adjustment according to the MSL trend and the difference between unadjusted and adjusted monthly extreme sea level observations are clearly observed in the graphs given as Figure 19 and 20, respectively.

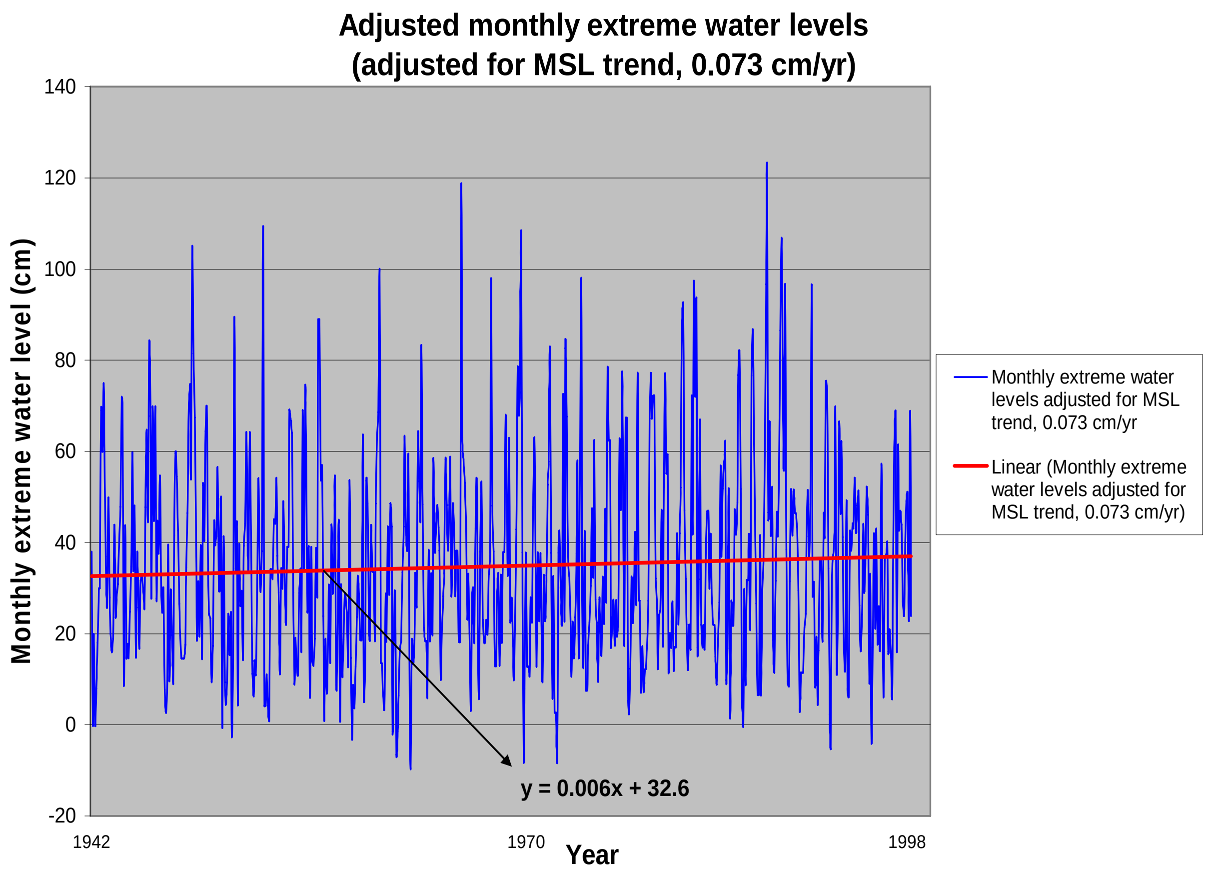

Figure 19. Monthly extreme water levels adjusted according to the trend, 0.073 cm/yr

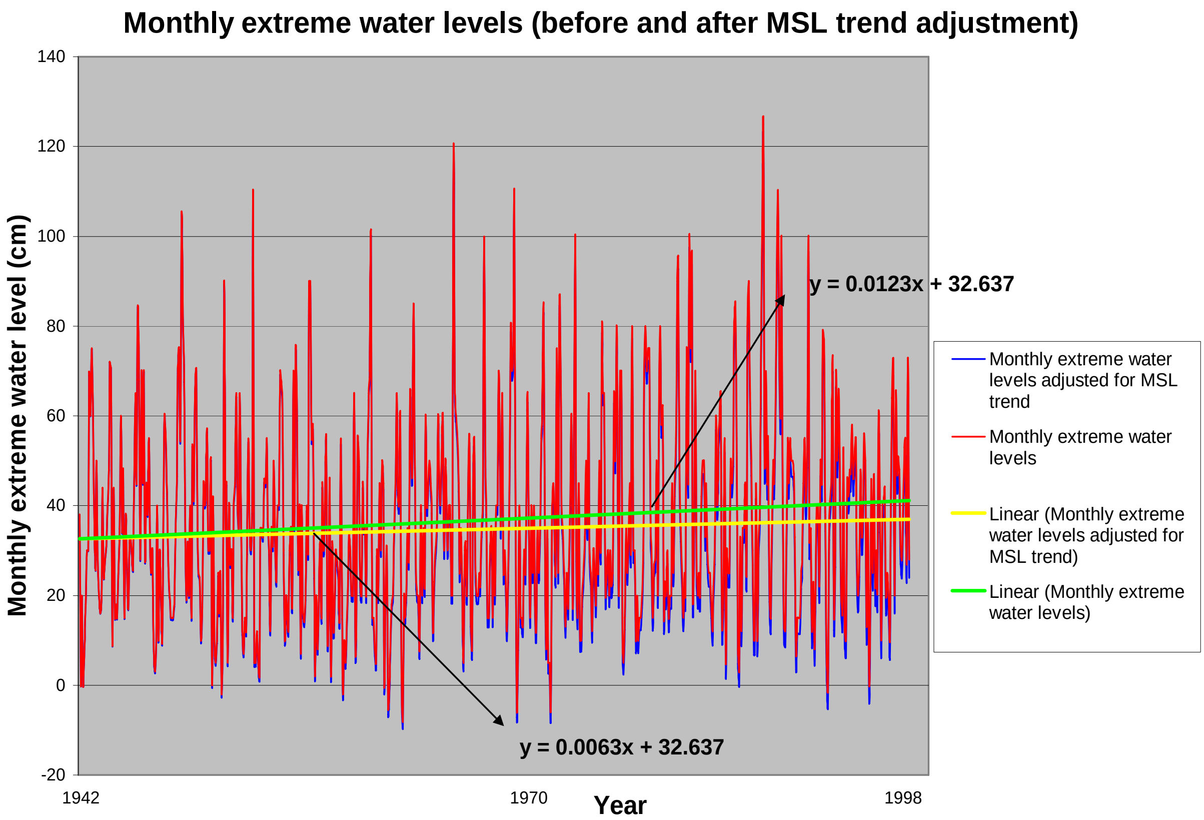

Figure 20. The graph showing the difference between the unadjusted and adjusted monthly extreme sea levels

The second step in the trend analysis was to detect the trend in the adjusted data set, which was obtained after having revised the original data according to the mean sea level rise increase. The trend in the already-adjusted extreme monthly sea-levels data was determined from the graph again in the same way by applying a linear regression as seen in Figure 19 above. Interestingly, this trend (EWL trend) was also found to be equal to approximately 0.072 cm/year. Next, this value was subtracted from the already-adjusted data set so as to have a net data free of trends. The resulting graph is seen in Figure 21 below. As can be observed in the graph, the null hypothesis β=0 (its value, $4*10^{-5}$, is slightly greater than 0, but it can very well be neglected and assumed as 0) was proven true, indicating no trend in the source data set of this graph.

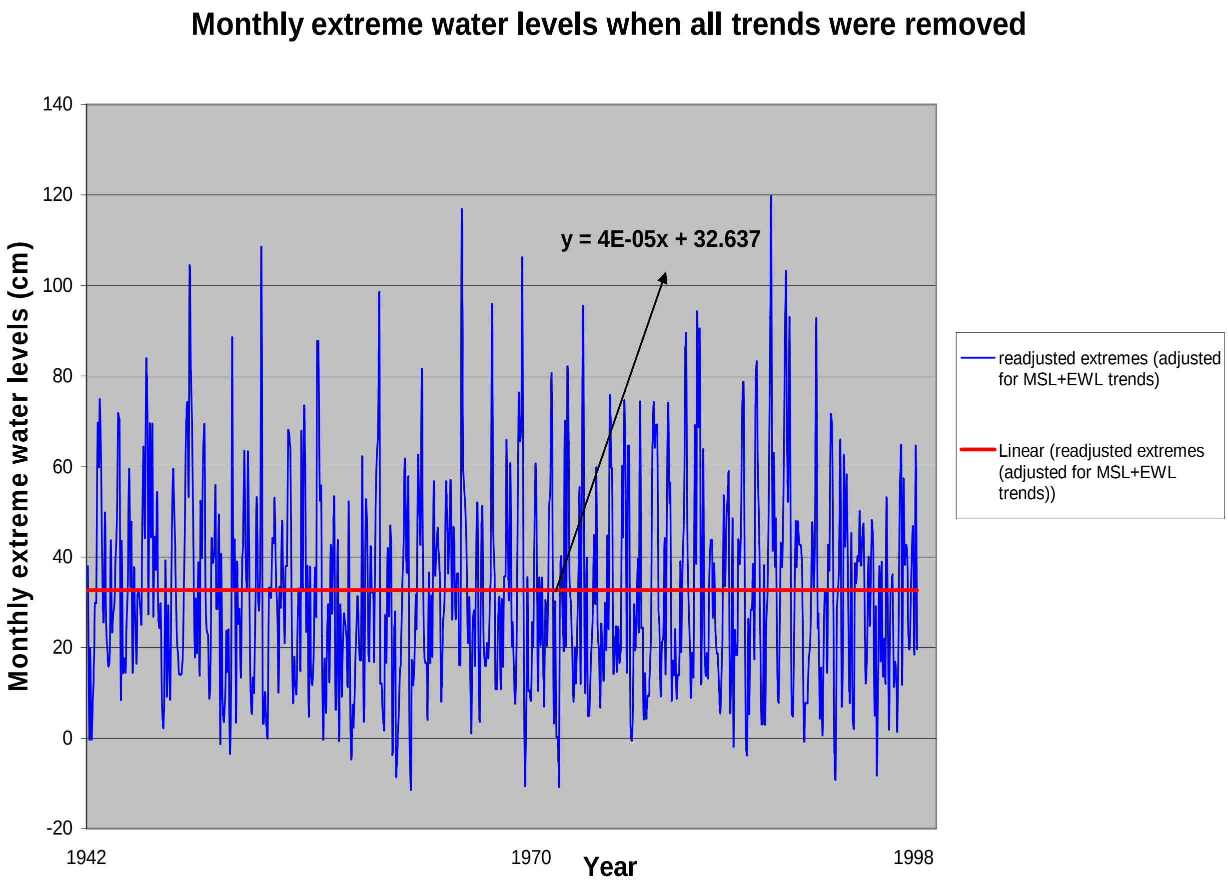

Figure 21. Net data set of monthly extreme sea levels in Falsterbo

The data set of extreme water levels plotted in this graph (Figure 21) is free of temporal trends. In addition to that, standard deviation values of the consecutive 14-year periods were put on a graph as seen in Figure 22 below. It can be observed on the graph that there is much more variation happening between the years of 1970 and 1984. However the record is not long enough to predict the pattern and remove this trendy pattern in standard deviation values, if there is any.

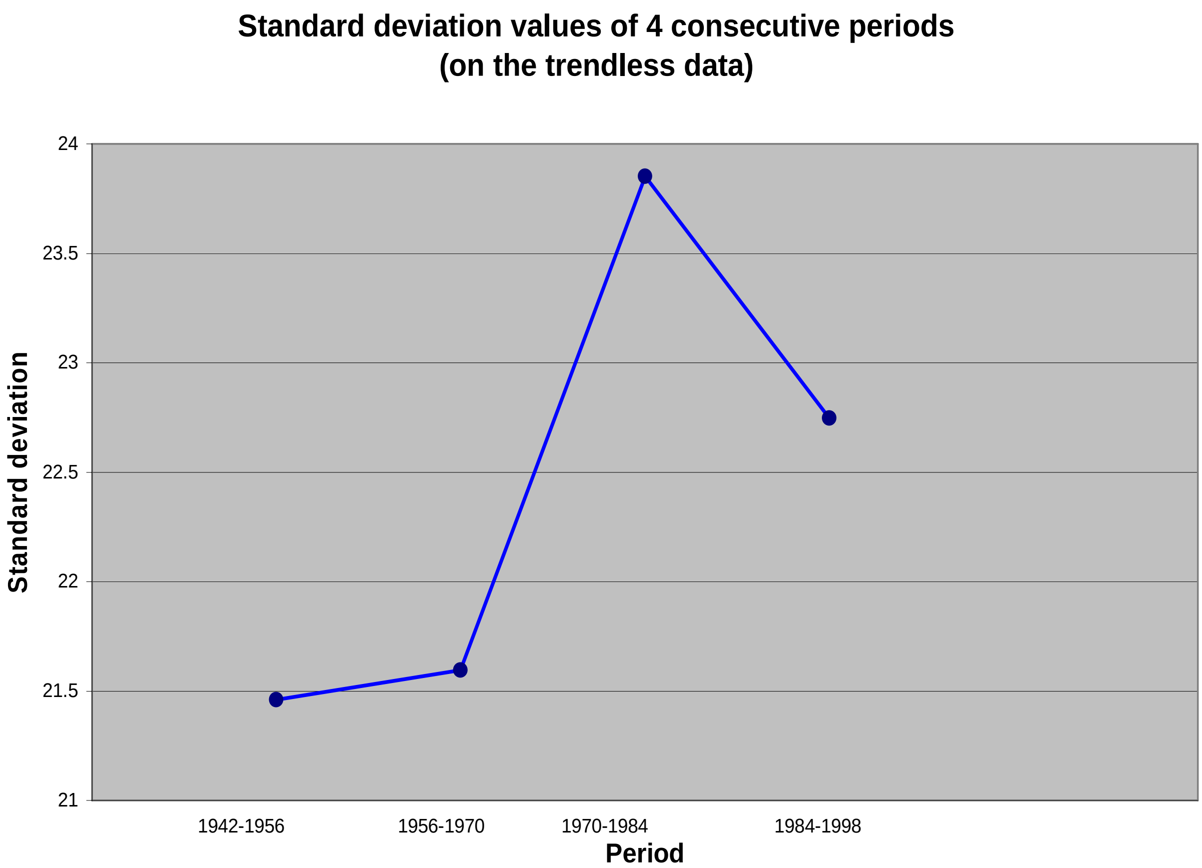

Figure 22. The plot of standard deviations of four consecutive periods in the trendless data

The extreme value analysis with the net data set of extreme water level measurements in Falsterbo, Sweden will continue with the trend readjustment process in the next subsection and then, the desired future sea levels will be determined.

4.2.2 Trend readjustment

The final step in the estimation of the extreme maximum water levels corresponding to the specified return periods is the re-introduction of a deterministic trend for the global mean sea level increase. In this study, as mentioned earlier, the mid (or the best) estimates for the mean sea level increase given by IPCC (Intergovernmental Panel on Climate Change) were introduced. The values that should be added to the net (or trendless) data for conditions in 2020 and 2100 are 7 cm. and 49 cm. respectively. These values can be seen in Figure 2 of the subsection 2.1. For estimating the conditions in 2020 7 cm. were added and for conditions in 2100 49 cm were added. By using the net data set free of MSL trend and EWL trend, Gumbel plot was prepared again in the same way as explained before. Therefore, three different source data sets were obtained. Next, these data sets were plotted against the reduced Gumbel variates computed, y, given by the formula, -ln (-ln (r / N+1)), r denoting corresponding rank value, and N number of extremes in the set. After having plotted the data sets on the paper, linear regression technique was applied to fit representative lines and their equations. The lines together with the equations can be seen in Figure 23.

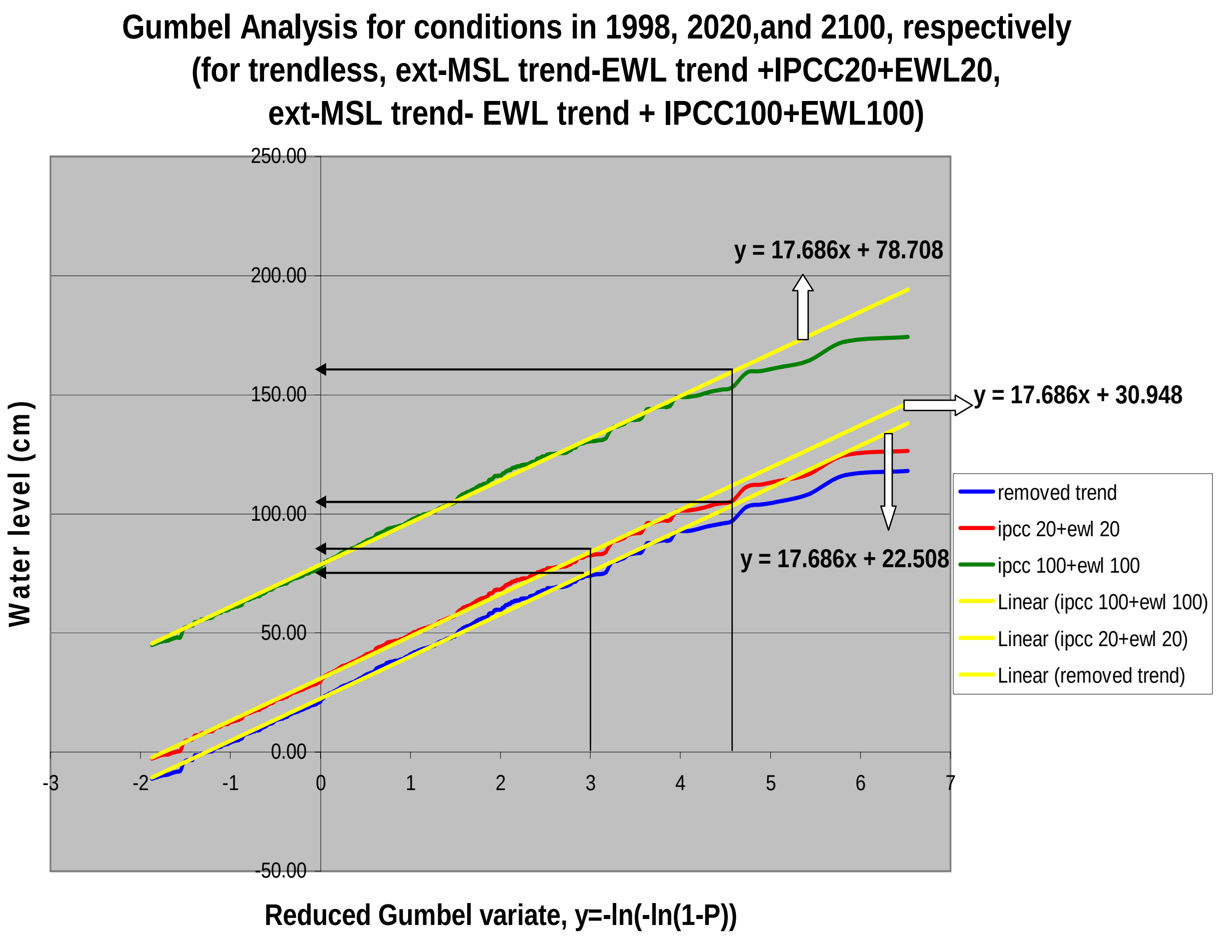

Figure 23. Gumbel analysis plot for the determination of conditions in 1998, 2020 and 2100, respectively (for trendless (ext.-msl-trend), trendless+IPCC20+EWL20, trendless+IPCC100+EWL100 data sets)

In the Gumbel method reduced Gumbel variate was formulated as y = -ln (-ln (1-P), where probability, P, can be defined as 1 / T (return period). So, by putting the desired return periods, in 2020 and 2100, into this equation, corresponding y values were calculated. Then, these values were used in the linear equations determined by linear regression to get the extreme sea-levels. All the results were summarized in Table 2 below.

Table 2. Table showing the results of Gumbel analysis on trendless and trendless + IPCC values + EWL trend for conditions in 1998, 2020 and 2100

Return Period	**Reduced Gumbel variate, y**	**Extreme water level for trendless data set**	**Extreme water level, including IPCC prediction in the years 2020 and 2100**
20 years	**3**	**76 cm.**	**84 cm.**
100 years	**4.6**	**104 cm.**	**160 cm.**

The most realistic estimates of future extreme sea levels in Falsterbo are the ones which are taking also IPCC prediction for mean sea level rise and EWL trends into account. In this way, global values for mean sea level rise, which has been used in most of the studies as the most reasonable value, were included. Apart from that, this adjustment together with the trend adjustment secured the analysis from the effects of variation over time. As illustrated in Table 2 above, the extreme sea level values for 2020 and 2100 conditions were calculated to be equal to 84 cm. and 160 cm. after extreme value analysis by Gumbel method.

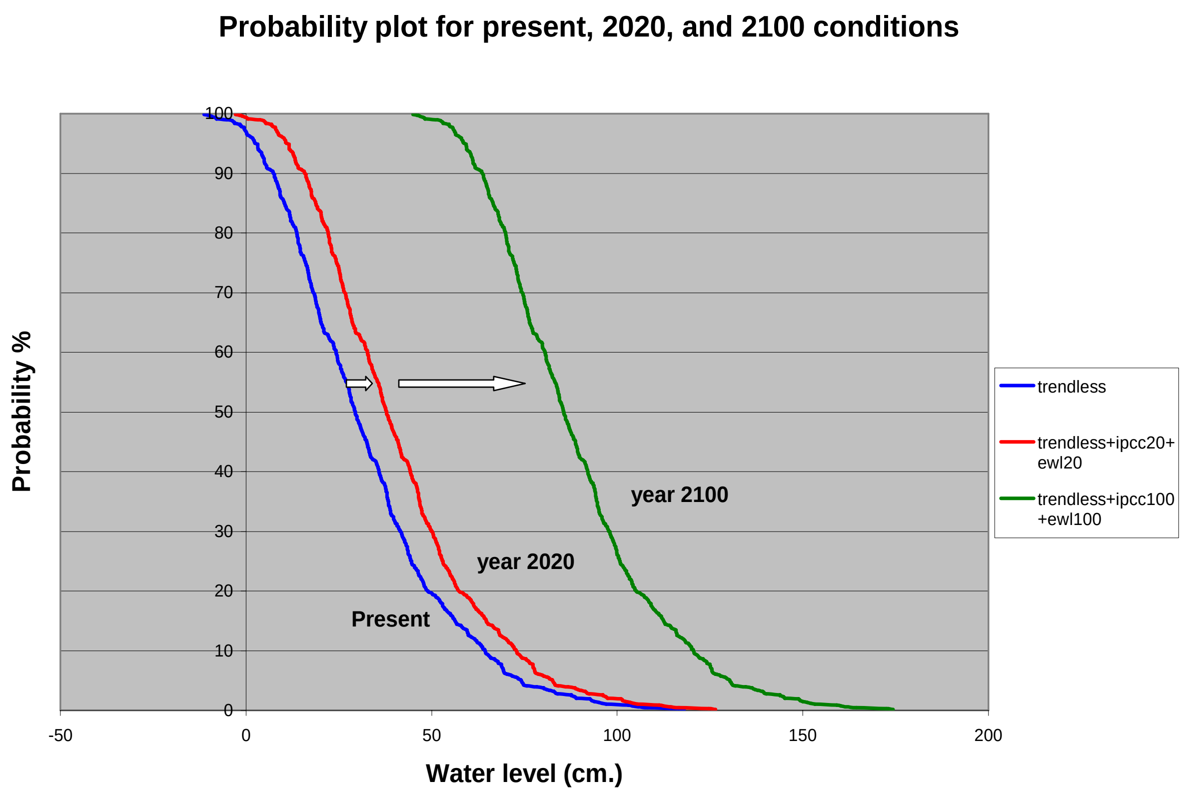

Figure 24. Probability of occurrence plot for extreme water levels for present, 20 years later (2020) and 100 years later (2100) conditions

In Figure 24 above is shown the probability plots for the occurrence of extreme water levels for present conditions, the year 2020, and the year 2100. This plot clearly shows the transformation of the water level together with its probability of occurrence from present to the years 2020 and 2100.

5 Wave prediction from wind data and run-up height analysis

In this chapter, wave hindcasting (predicting wave properties from available wind data), and run-up height analysis for Falsterbo coast are discussed. Wave hindcasting was accomplished by means of a computer code, and after having determined wave heights, the corresponding run-up heights were computed within the same code by engaging the related run-up formula. The resulting run-up heights were combined with the water level observations, so that an extreme value analysis similar to the one done on extreme water levels could be performed on these values, as well. The data, the methods utilized and the results of the analyses are given as separate sections and subsections as follows.

5.1 Wind climate

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As mentioned above, fetch length is a very significant factor in the generation of wind waves. Because of this, two points with different fetch lengths (different land blocking effects for the waves) were chosen in Falsterbo peninsula. This approach is also good from the point of view that two different sides of the peninsula were assessed for the wave action.

5.1.1 Wind data

Wave hindcasting for the purpose of getting corresponding wave heights for Falsterbo peninsula of Sweden was made by using the wind data set measured by SMHI (Swedish Meteorological and Hydrological Institute) in the area. The wind data set available covers the years between 1961 and 2005. The measurements are available on a daily basis and for every 3 hours, 8 times a day, starting from 00.00 o'clock. The data file also includes the direction of the wind as clockwise rotation from 0 degree, i.e. 180 degree indicates the wind direction of south. 16 compass directions referred in the data set can be seen in Figure 25 below.

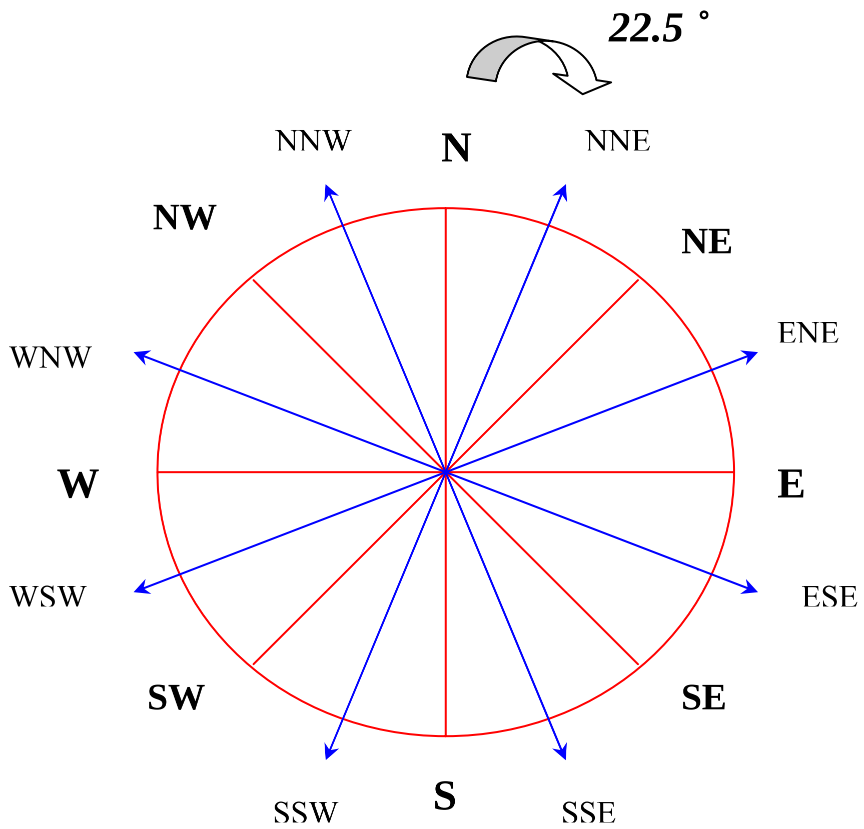

Figure 25. 16-point compass rose, showing the 16 directions used in the wind-wave analysis

Since the main purpose is to combine the water level measurements with the run-up heights which are calculated from the wave data (wave height, period, and length), the frequency and the length of water level and wave data sets should be the same. As mentioned in Chapter 4, water level measurements were made once a day, and between the years of 1941 and 1998. Therefore, from the wind data available, a new data set of daily measurements covering the period between 1961 and 1998 was extracted. The wind speed and direction at noon was regarded as representative for the day. After this process, a data set of daily wind speeds with directions and water level for 38 years between 1961 and 1998 were obtained to be used in both wave hindcasting and run-up analyses.

When 16 directions from which the wind blows were investigated, it was seen that the directions SW, W, WNW are dominant ones. The frequency diagram of wind directions in Falsterbo is shown as Figure 26. In this figure, STL stands for no-wind situation. On the other hand, wind speeds vary between 0 and 25 m/sec in this data set. Almost 80 % of the wind speeds are between 3 and 11 m/sec. There are missing values for some days. However, these missing values do not need to be completed or estimated, since they are ignorable when their percentage in the data set is taken into account. All these can be observed clearly in Figure 27, which gives the occurrence frequencies of different wind speeds.

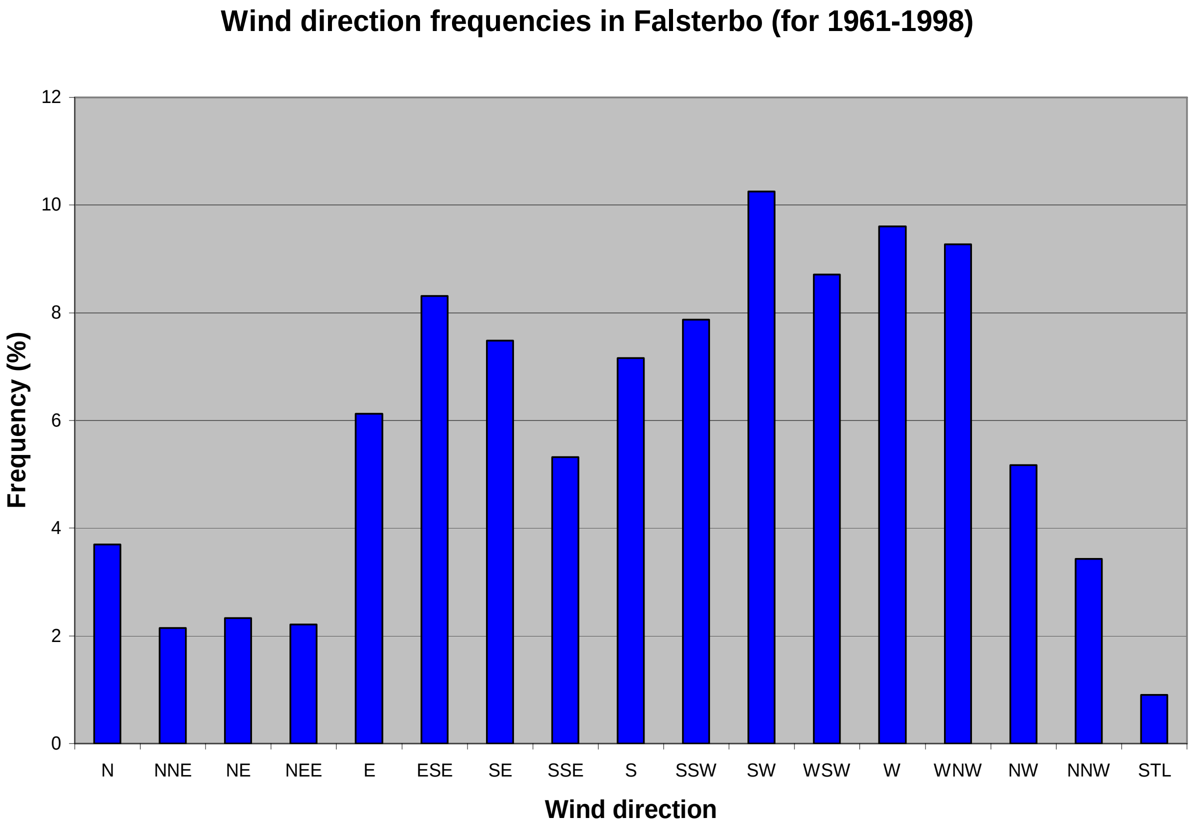

Figure 26. Chart showing the corresponding frequencies of 16 wind directions for 1961-1998

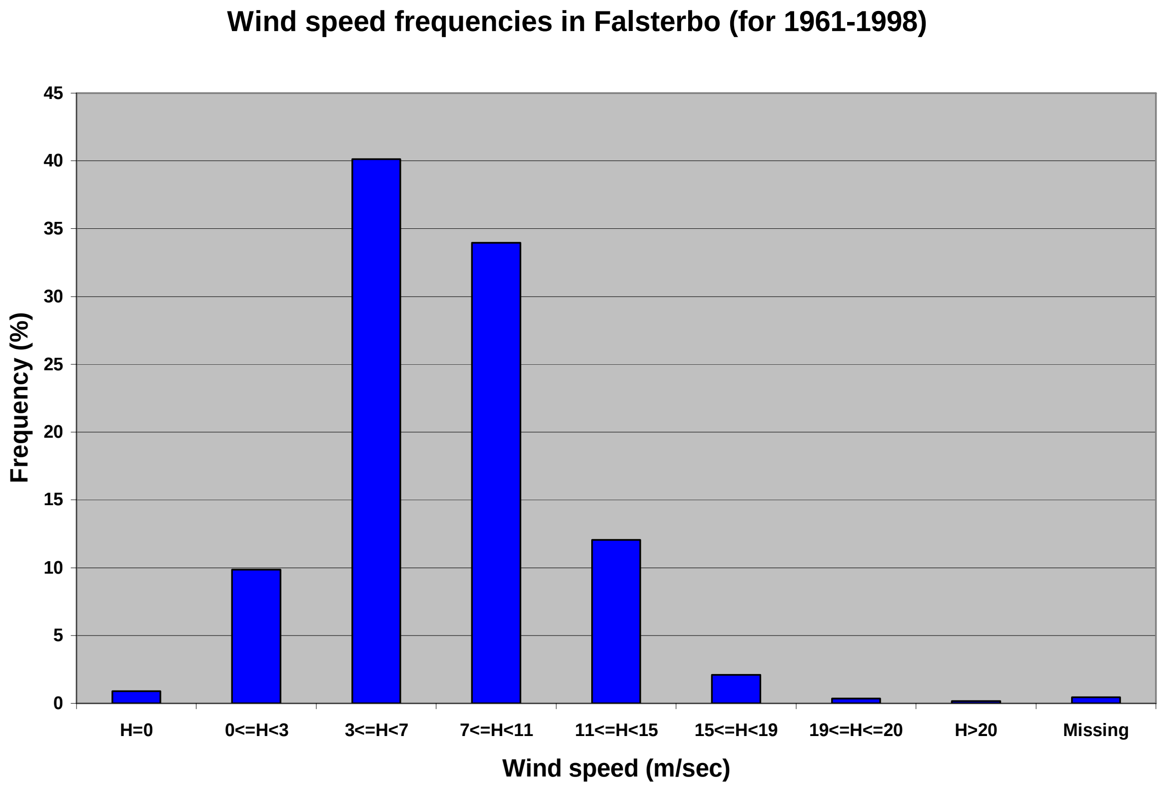

Figure 27. Chart showing the corresponding frequencies for different wind speed intervals for 1961-1998

The wind speeds in the extracted set have values ranging from 0 up to 25 m/sec. When yearly average wind speeds were calculated, it was observed that they do not differ from each other greatly. Only the years 1963 and 1996 can be classified to have relatively lower values compared to the others. Also the yearly averages did not depart drastically from the calculated total mean, 6.78 m/sec, as seen in Figure 28. This graph confirms that no abrupt change in the wind regime or no malfunctioning in the measuring device, which can affect the accuracy of the analysis, took place over the observation period.

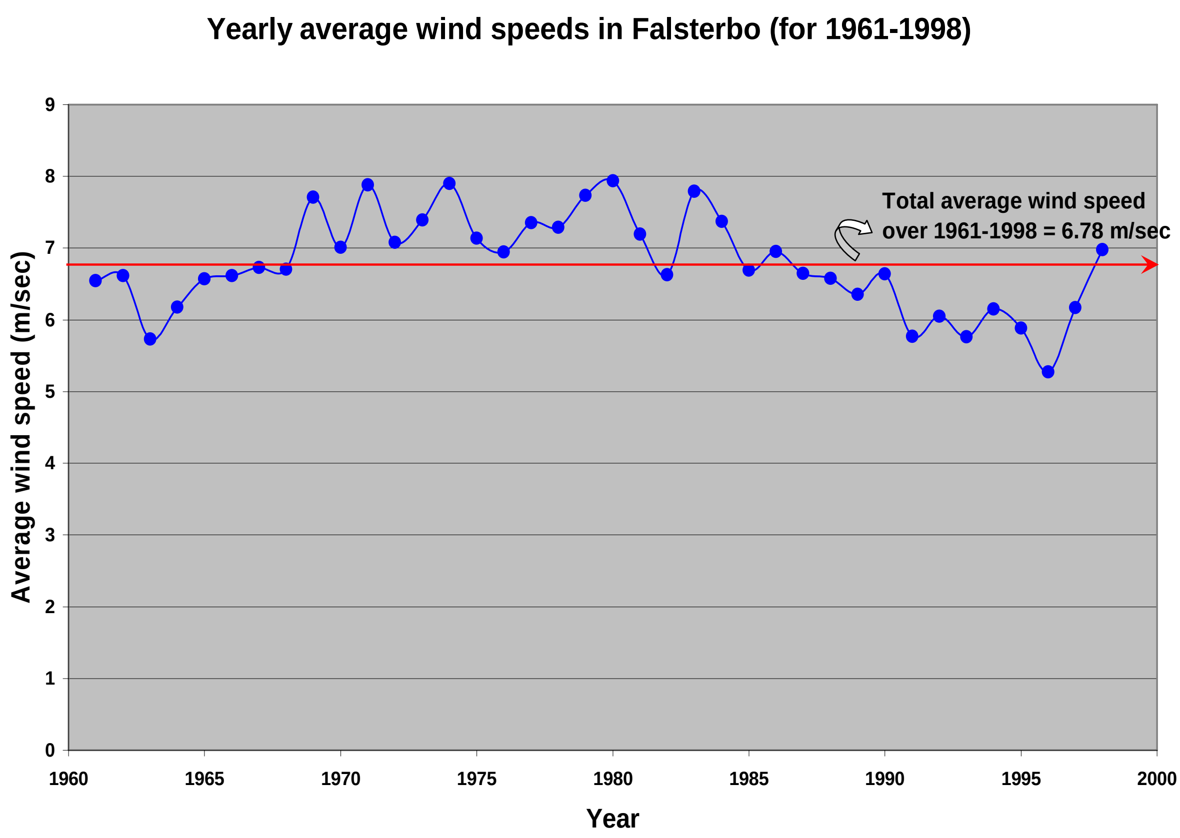

Figure 28. Graph showing the yearly average wind speeds together with the total average wind speed for the years between 1961 and 1998.

5.2 Wave climate

5.2.1 Wind-wave model

Wave hindcasting is the procedure of estimating the wave characteristics from the wind data. As outlined in the former parts of the report there are several methods available in the literature for this purpose, e.g. usage of empirical relations, spectral models, and numerical models. In this report, wave data was estimated by a computer code written in FORTRAN. The computer code was designed in a way so that it also computes the run-up heights, in combination with the water level measurements. This computer code employed is available as Appendix 1. This version can be named as a 'numerical model' due to its computing algorithm. It consists of basic wave generation and run-up formulas as well as the checks for the state of the sea, which can all be seen in the code together with brief explanations. It does not take wave growth/decay into account, but includes a randomization of the wind direction to avoid that some angle bins become 'over-represented' in the analysis. The model is a modified version of the model recommended by U.S. Army Corps of Engineers.

Fetch length and average water depth are two parameters required by the model as input information. They differ according to the points chosen in the area of interest. The analyses, of wave and run-up, were made for two points in Falsterbo so that situations in different parts of the peninsula could be revealed. First point was chosen in the Skanör Harbor side of peninsula and the other one was selected to be close to Falsterbo Bay. These points were marked as number WP and SP in the Falsterbo map, respectively, shown in Figure 29. They will be called western point and southern point throughout the rest of the report.

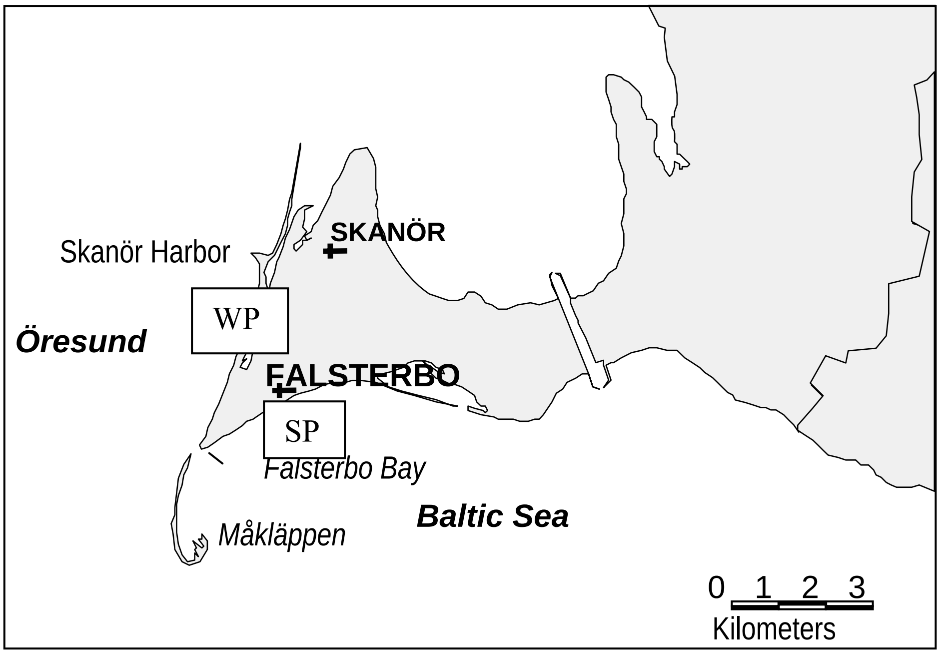

Figure 29. The points (western point, WP, and southern point, SP) chosen for wind-wave and run-up analyses in Falsterbo map

5.2.2 The run-up model

The run-up height is defined as 'the upper level reached by a wave on a beach or coastal structure, relative to still-water level' by U.S. Army Corps of Engineers. [32] Wave run-up height and consequently overtopping are two decisive phenomena when the height of coastal structures like seawalls, sea dykes or breakwaters are considered. In the design phase of breakwaters, the maximum wave run-up height is the most important factor for the decision of breakwater height, whereas the mean wave run-up height plays significant role for breakwater crest design. [33]

In this study, two run-up height models for overtopping risk were considered. These models are called Hunt's model and Mase-Iwagaki model. Both models are mainly similar in principle but they differ from each other when it comes to the definition of beach slope. The results obtained from both formulas will be compared and one of two will be classified as 'more suitable run-up model' for Falsterbo.

Hunt's run-up model formulates run-up height simply in terms of the wave height, wave length and beach slope. It was taken as basis for many others formulas offered afterwards. The run-up equation is expressed as follows;

$$R / H_0 = \tan\beta / (H_0 / L_0)^{1/2} \qquad (5)$$

Where;
R = run-up height
H_0 = significant wave height
L_0 = significant wave length
$\tan\beta$ = the beach slope.

In Hunt's formula, the beach slope is referring to the slope of the swash zone (or the dry part of the beach slope), named as m_d in Figure 30, showing a typical configuration of the parts of the beach slopes.

Second run-up height formula used within the computer code of this study is called Mase-Iwagaki formula, which is a run-up height model on gentle slopes valid for random waves. [34] This model considers the fact that the gentler the slope of the beach gets, the more significant the interaction between back-rush and up-rush becomes. The model is based on Equation 6, to calculate the maximum wave run-up height, R_{max}.

$$R_{\max} / H_0 = d\,(\tan\beta / (H_0 / L_0)^{1/2})^{e} \quad (6)$$

(Mase & Iwagaki, 1984) [35]

Where;

R = run-up height

H_0 = significant wave height

L_0 = significant wave length

$\tan\beta$ = the beach slope

$d = 2.319$

$e = 0.771$.

The constants *d* and *e* were taken from special tables prepared for 'Crest Method' presented in the corresponding reference. For more details, this journal should be referred. [34] In the Mase-Iwagaki model, the maximum wave run-up heights were taken into account, since extreme value analysis is the main purpose. It is also beneficial to calculate the maximum wave run-up heights so that the worst-case scenario can be visualized.

All the variables in both formulas are available after the wind-wave analysis, except the beach slope, which is the most problematic element and should be calculated separately and inserted. As mentioned above, while in Hunt's formula the slope in swash zone is of interest, Mase-Iwagaki model requires the beach slope to be defined 'as the average slope between the breakpoint and the run-up limit'. [35] There are several ways to calculate (or approximate) this slope. In this study, respective beach slopes were calculated or averaged by using the beach profiles plotted in a previous study by Hanson and Larson (1993). [36] In their study, some points were selected in Falsterbo peninsula and beach profiles were drawn. In the report, numbers of different profiles are present for every point. For the beach slopes, according to the wave breaking distances from the shore, the beach profiles available for the western point, indicated by number 7 in Figure 28 above, were analysed. Out of the different beach profiles for this point, a representative one was chosen and the slopes were approximated on the graph. These slopes were assumed to be representative also for the southern point, number 13 in the Figure 28, since the grain size distribution is not expected to differ from each other greatly in these two points. The calculation process of the equivalent (or representative) slope to be used in Mase-Iwagaki formula is shown schematically in Figure 30. The reason for calculating two different equivalent slopes is taking the wave breaking distance from the shore into the consideration. This issue will be explained in more detail when the slope calculation results are given in the next sub-section.

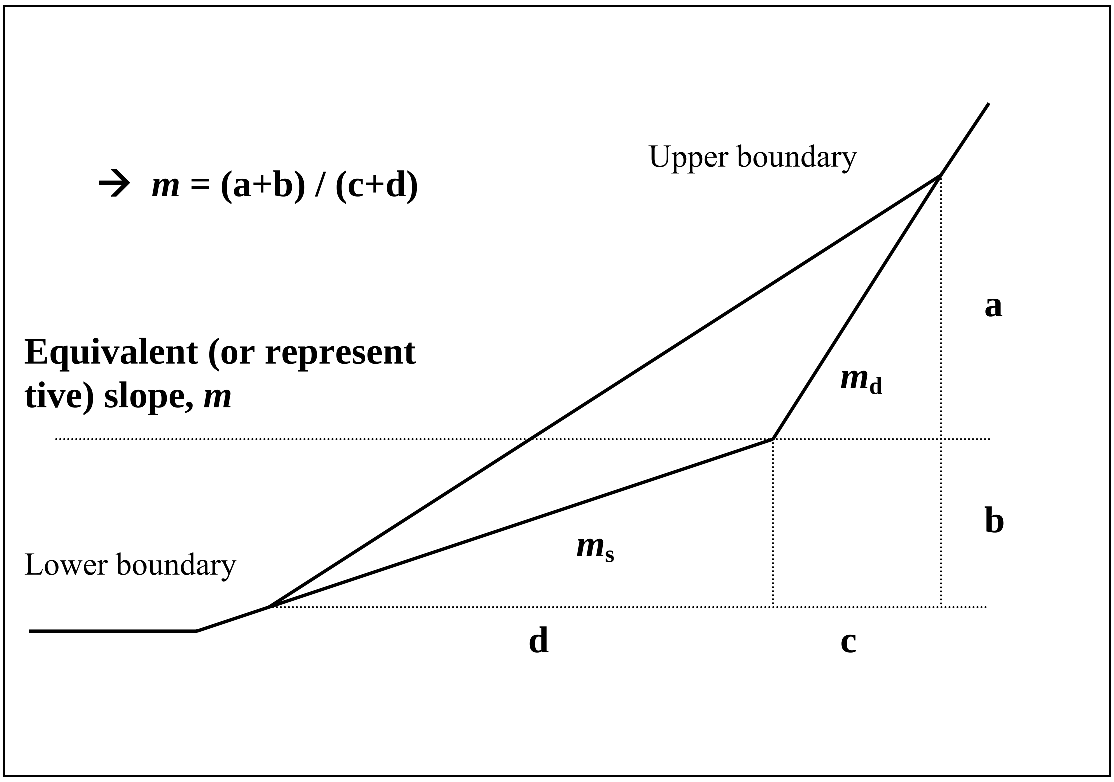

Figure 30. Calculation of the equivalent slope of a beach

5.2.3 Wave prediction (by wave hindcasting) and calculation of run-up heights

In this subsection of the report, the process of wave prediction together with run-up calculation, and the results obtained were analysed for the two points separately.

5.2.3.1 The western point

This point lies on the western side of the peninsula where Skanör Harbor is located. It is thought that the analytical results obtained by taking this point as a base would give an idea about wind-wave relations and run-up characteristics of the Öresund region. As discussed before, fetch length and the water depth are two major input parameters required by the model. The fetch lengths calculated by means of an interactive atlas ([37]) for wave estimation from wind data are shown in Figure 31.

Figure 31. The map showing the fetch lengths in the western point of Falsterbo

Water depth values were read from a special ´depths and heights in meter map, which consists of water depth cells for different parts of Baltic Sea. Table 3 shows the fetch lengths and water depths calculated in directional wise

Table 3. Table showing the fetch lengths and average water depth of wind directions for western point in Falsterbo

Wind Direction	Fetch Length (km)	Average water depth (m)
N	51	9
SW	30	14
WSW	25	11
SSW	50	18
W	31	11
WNW	40	10
NW	27	10
NNW	25	6

The third and last element to be inserted into the model manually is the beach slope. Determining a representative beach slope is not an easy task as said before. In the present study, beach profiles drawn for Falsterbo were taken as reference. Not only in this previous study, but also in the literature, there is a lack of information about beach profiles for the southern part of Falsterbo although the western part of the peninsula is fairly well-known from the beach profiles point of view. Therefore, a beach profile for the western point of Falsterbo was selected so as to determine the slope. (Figure 32) At this point, it is thought that reading two slopes from this profile would be beneficial for Mase-Iwagaki formula so that different wave breaking distances would be able to be included. For instance, the waves that are breaking before 200 m far away from the shore and the ones breaking before the 300 m line should be treated with different slopes according to this profile. For this purpose, one steep, m_4, and one mild slope, m_3, which are covering these both distances, have been read from the profile as shown in detail in Figure 31. Slope m_3 was calculated to be the equivalent slope of m_1 and m_2 according to the principle in Figure 29 above. These slopes are equal to;

$\boldsymbol{m_3}$ (mild slope) = 0.018

$\boldsymbol{m_4}$ (steep slope) = 0.023

In Hunt's formula, the slope of the dry part of the beach (so-called swash zone) is employed. Therefore the slope m_l in Figure 32 was determined;

$\boldsymbol{m_1}$ (swash zone slope) = 0.100.

These calculated slopes can be said to be in good agreement with the average slope value ranges, given in literature for Falsterbo region and its surroundings.

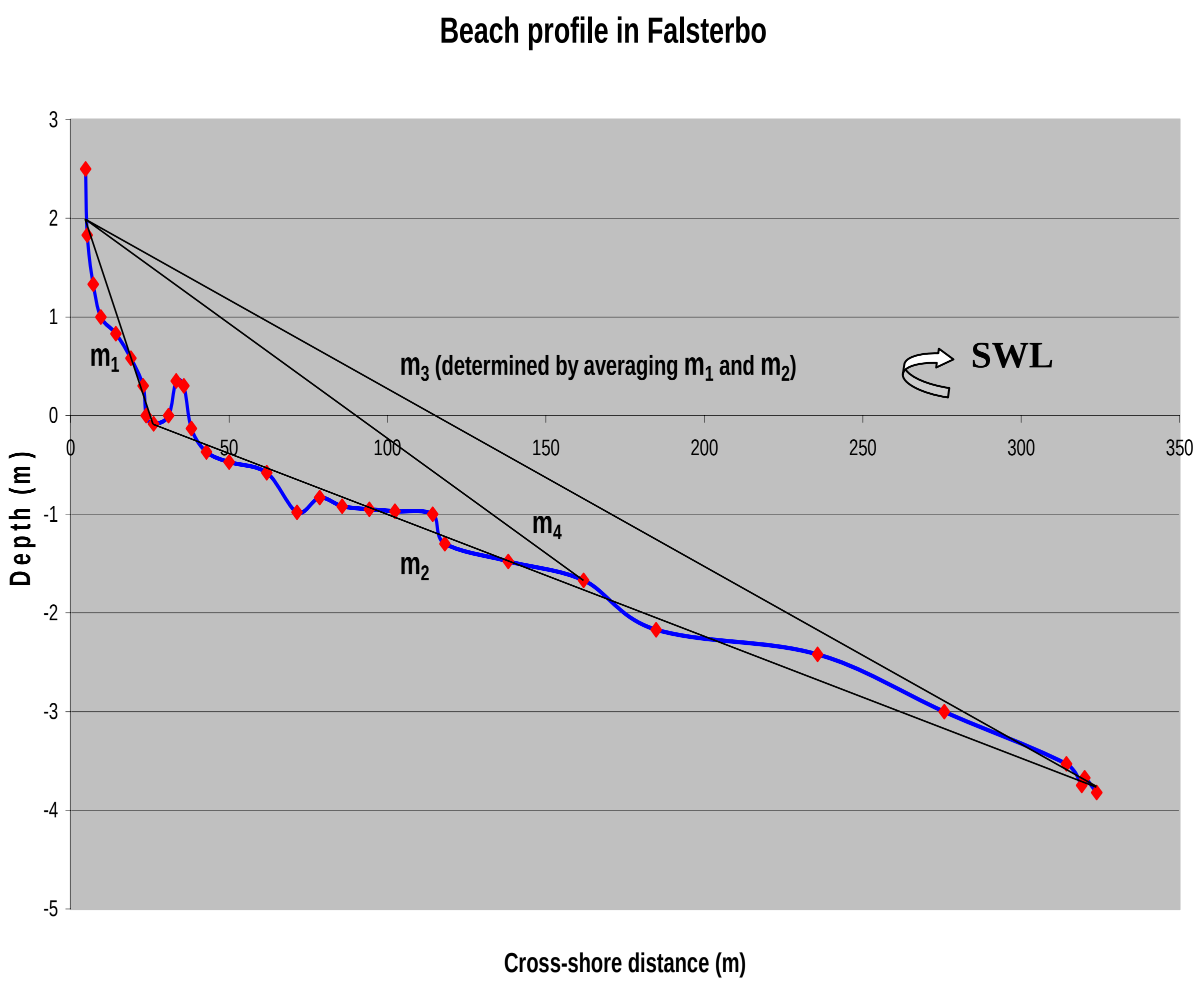

Figure 32. Selected graph illustrating field measured beach profile in the western point of Falsterbo (modified after Hanson and Larson, 1993) [36]

Having obtained the fetch lengths, water depth values and having decided on the slopes, it was possible to run the model to get wave characteristics and run-up heights. The model has been run for the western point three times, applying Hunt's run-up formula with the swash zone slope and employing Mase-Iwagaki formula considering so-called mild and steep slopes. Since slope value does not have any influence on the computation of wave characteristics, namely wave height and period, waves propagating to the shore are of the same characteristics for all three cases.

In the western point, in more than 40% of the time, no wave development was observed. Otherwise, the wave height values generally hovered between 0 and 2 m. The biggest wave height observed in this region was 3.05 m. These are shown in the frequency chart given below in Figure 33.

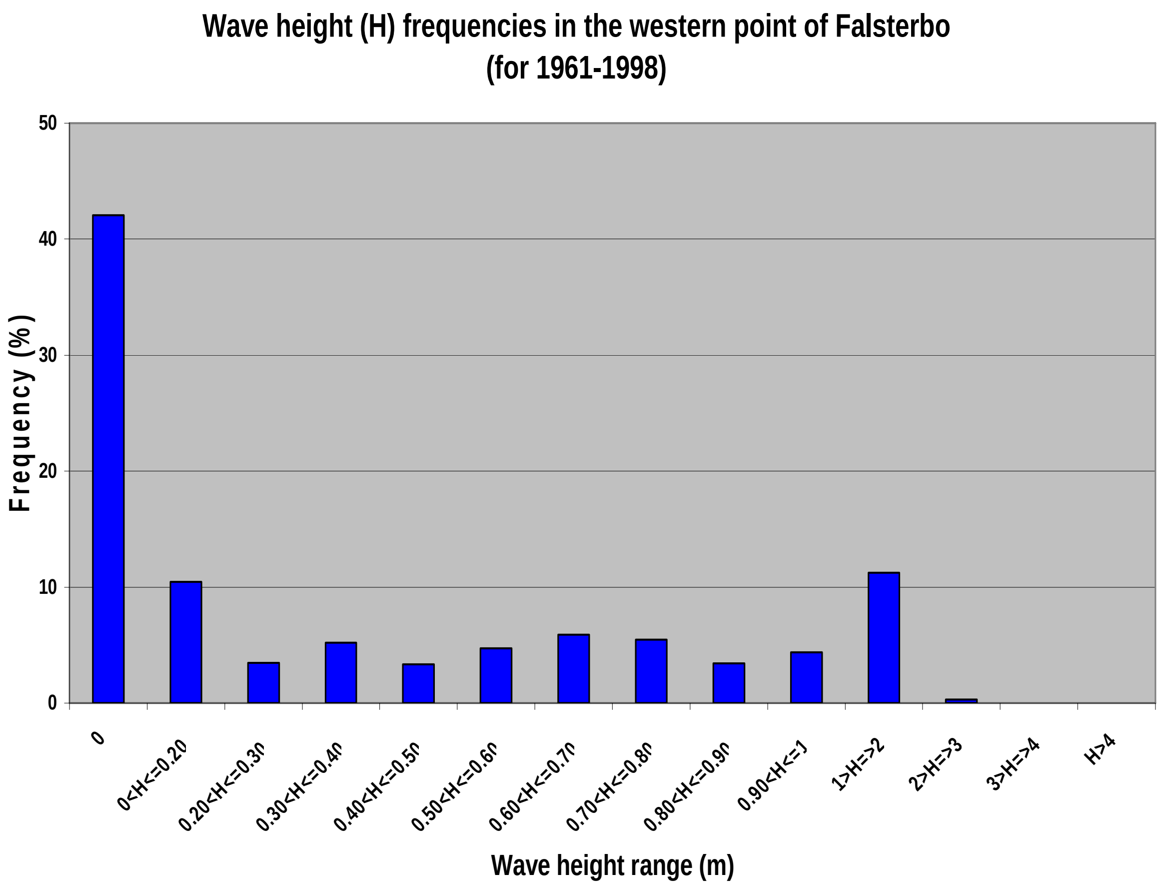

Figure 33. Wave height frequency diagram in the western point for the years 1961-1998

Regarding the run-up height computation, the effect of beach slope is seen. Since in both run-up formulas slope value is required and calculated in different ways, the model was run for three cases of different slopes, namely ´western Hunt run-up`, ´western Mase-Iwagaki mild run-up`, and ´western Mase-Iwagaki steep run-up`. The results are presented for these cases separately.

For the western-Hunt-run-up case, the maximum run-up height encountered came out to be 1.35 metre. Not surprisingly, maximum run-up occurred in the day of maximum wave height, since there is a direct correlation between these two in the formula. No run-up situations were observed frequently in the output file again because of the presence of no wave conditions. In addition, it can be remarked that many of the largest wave heights, thus the biggest run-up heights, were observed during the year 1973. The graph given as Figure 34 illustrates the resulting run-up heights according to the Hunt's run-up formula in the western point.

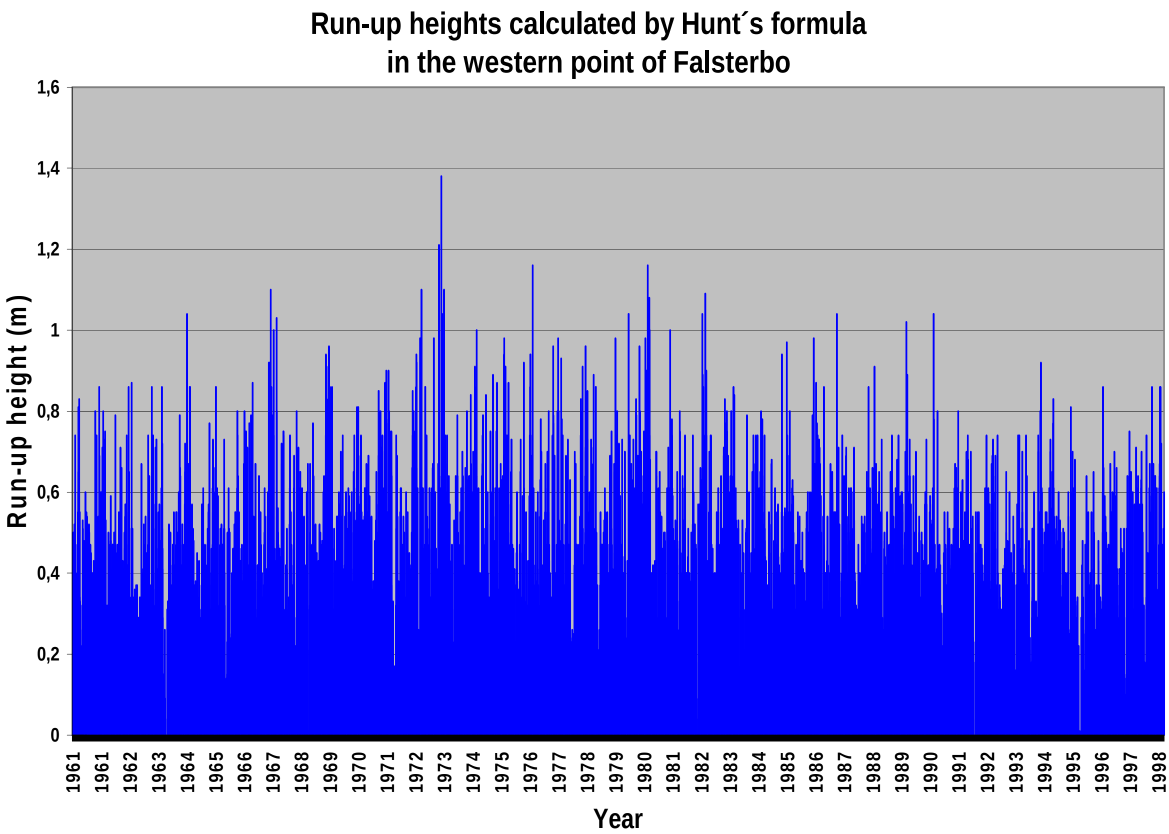

Figure 34. The graph showing the calculated run-up heights by the Hunt's formula in the western point

The relationship between wave heights, run-up heights and the water levels is worth to mention. For this purpose, the run-up heights larger than 1.00 m were extracted together with the corresponding wave height, water level and the date of occurrence. All these events can be seen in a chronological order in Table 4, as most of them occur in winter period. As Table 4 reveals, whenever a run-up height is larger than 1 metre (which corresponds to a wave height larger than 2 m in most of the time), water level value of this day tends to be relatively low compared to the whole data set. Sometimes water level falls below 0-level, otherwise it does not exceed +30 cm. Hence this can be concluded as follows: the larger the run-up height in the beach becomes the calmer the state of the sea tends to be.

Table 4. Table showing simultaneous large wave heights, run-up heights and low water levels

Date	Wave Height (m)	Run–up Height (m)	Water Level (cm)
13/12/1964	2.23	1.04	-8
29/10/1967	2.37	1.10	25
11/01/1968	2.15	1.03	12
13/02/1973	2.37	1.10	-25
09/10/1973	2.65	1.21	-35
06/11/1973	3.05	1.38	-30
20/11/1973	2.24	1.04	30
11/12/1973	2.37	1.10	-25
29/12/1976	2.51	1.16	-15
19/04/1980	2.24	1.04	-90
14/01/1981	2.51	1.16	15
03/02/1981	2.33	1.08	20
10/12/1982	2.23	1.04	30
18/01/1983	2.46	1.09	0
07/09/1987	2.24	1.04	12
26/01/1990	2.31	1.02	-30
06/01/1991	2.23	1.04	15

For both the western Mase-Iwagaki steep run-up and the western Mase-Iwagaki mild run-up cases, a clear decrease in run-up heights was observed when they are compared to the results obtained by Hunt's. Although the incoming waves were of the same wave heights, because of the beach portion that was assumed to be influenced by the waves, the computed run-up heights came out to be smaller. Moreover, it is thought that the difference in run-up heights computed by these two run-up models is also due to the difference in characteristics of the formulas.

When it comes to the comparison of run-up heights in steep and mild slopes, as could be expected, larger run-ups were encountered in the steep slope case. For western Mase-Iwagaki steep run-up case, the largest run-up height was 1.24 m, which is 0.22 m more than the largest of the western Mase-Iwagaki mild run-up case. The differences in run-ups can be clearly seen on the graph showing the run-up heights computed by Mase-Iwagaki formula for both slopes simultaneously. (Figure 35)

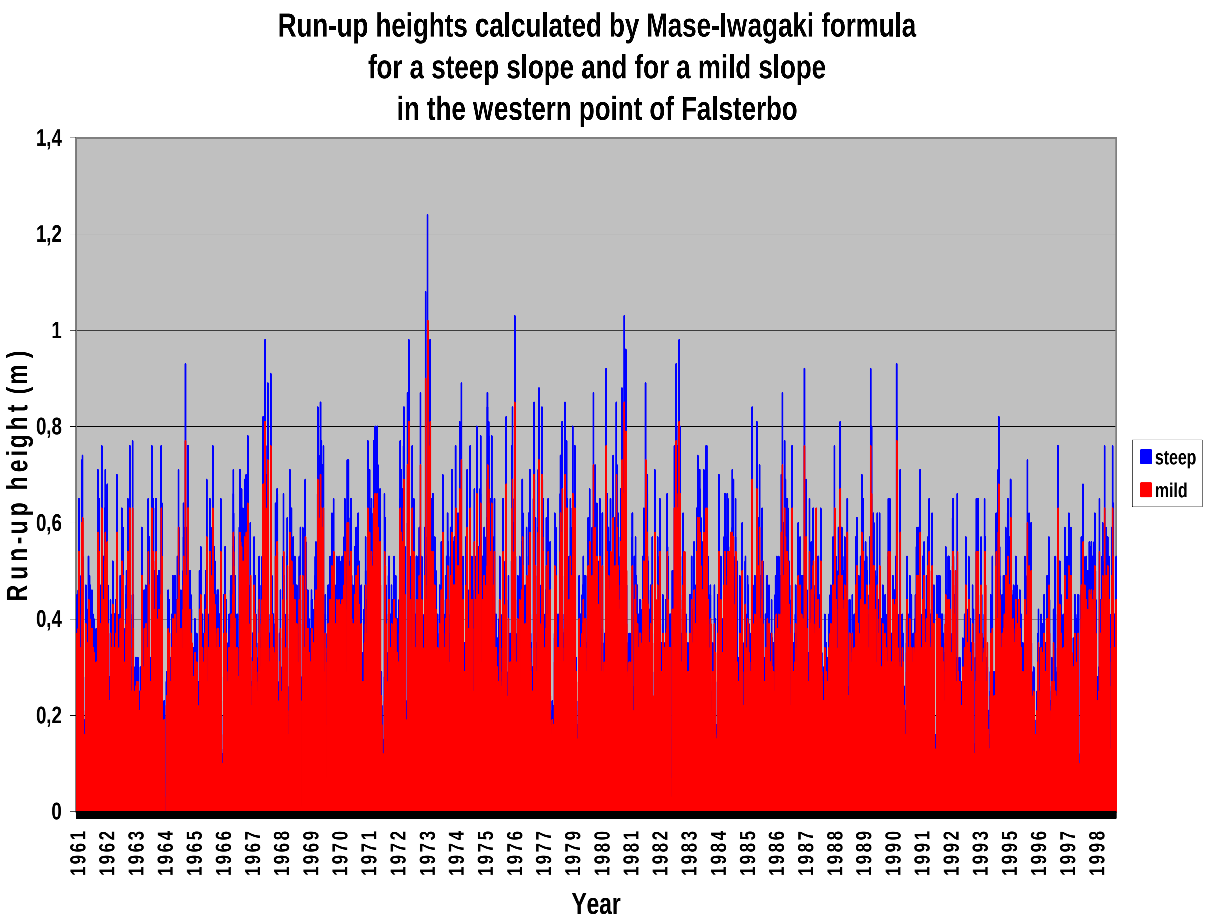

Figure 35. The run-up heights calculated by Mase-Iwagaki formula for both steep and mild slopes

As outlined above, the run-up heights determined from Hunt's formula and Mase-Iwagaki formula can be mentioned to differ greatly from each other since 20 cm increase or decrease in run-up means a lot to a very low-lying peninsula like Falsterbo, which has a very mild overall slope. In a previous study conducted on the Ystad coast, which is very closely located to the peninsula, by Dahlerus and Egermayer [38] it was stated that Hunt's formula gives better and more reliable results on run-up calculations in the area. This statement was decided to follow in this report as well. Hence run-up calculations and run-up analyses from this point on will be based on Hunt's run-up formula.

5.2.3.2 The southern point

This point was chosen in the southern face of the peninsula, very close to Falsterbo Bay. Since fetch lengths are greatly larger than the ones in the western point, the wave action, thus its impacts, are stronger. It is expected that the consequences in this point are important as they represent the situation on the Baltic Sea side of the peninsula. In addition to these, the opportunity of comparing the results in different parts of the peninsula arises.

The same methodology as in the western point was followed for the southern point to run the model for the purpose of getting wind characteristics and computing run-up heights. The same sources were utilized while applying the same procedure. First of all, fetch lengths (Figure 36) were measured. Next, average water depths were calculated for the directions for which fetches were measured. Measured fetch lengths together with the depth values in respective directions are given as Table 5 below.

Figure 36. The map showing the fetch lengths in the southern point of Falsterbo

Table 5. Table showing the fetch lengths and average water depth of wind directions for southern point in Falsterbo

Wind Direction	**Fetch Length (km)**	**Average water depth (m)**
ESE	**257**	**40**
SE	**202**	**25**
SSE	**105**	**30**
S	**106**	**30**
SSW	**49**	**18**
SW	**54**	**12**

For the beach slope value in the southern point, the slopes calculated for the western point were utilized. Previous studies also indicate that there are no adequate data sets on beach profiles in the southern part of the peninsula. However, the grain size distribution of the beaches and grain characteristics in the southern part are not expected to show a great deviation from these of western beaches as discussed before. This fact, thus, is considered to enable one to use the same slopes for the run-up determination.

In the next step, the model was employed with the presence of fetch lengths, water depths and the slopes in the same way as it was done for the western point. The wave heights computed by the model were demonstrated in a frequency diagram. (Figure 37). The main difference is the bigger percentage of days with no wind. Besides, the maximum wave height experienced in the western point was computed to be equal to 5.70 m, which is almost 1.5 m larger than the maximum wave height of the western point. It is also one of the outcomes of the frequency diagram that larger wave heights propagate towards to the southern coast. The frequency of waves of 1-2 metre is almost 20% in the southern point, while this value could not exceed 11% in the western point. This difference in wave heights are due to the fact that the southern coast of the peninsula has much longer fetch lengths compared to the western coast. As mentioned in the background of the generation of wind waves, the longer the fetch length gets, the larger the wave heights become.

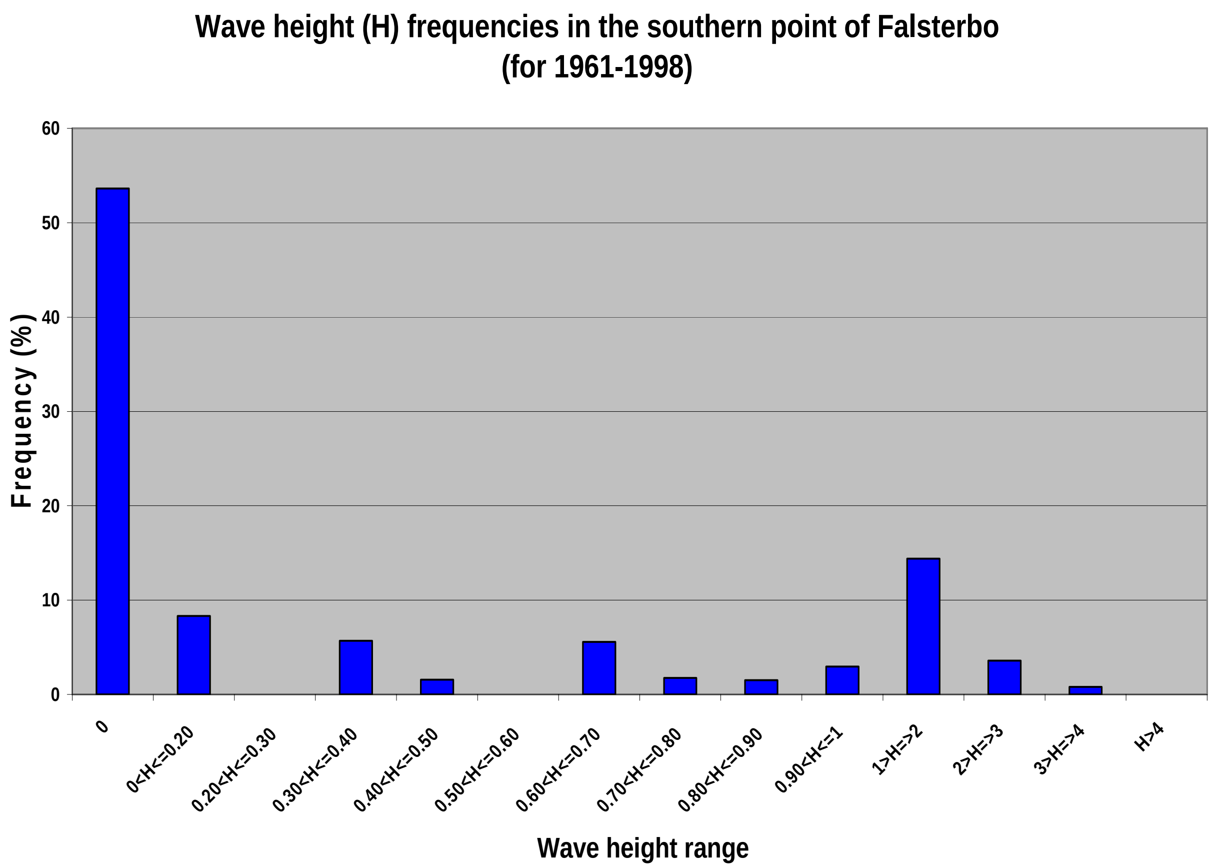

Figure 37. Wave height frequency diagram in the southern point for the years 1961-1998

Run-up heights in the southern point were determined to be larger than the ones in the western point. As emphasized in the wave height comparison, because of the fetch length difference larger run-ups occurred. Maximum run-up height was found to be 2.82 m, taking place twice throughout the data period. The years 1977 to 1980 holds the biggest wave heights, thus the largest (or the most severe) run-up heights. These can be observed in Figure 38 on which computed run-ups in the southern point of Falsterbo is shown. On the other hand, Figure 39 below is important from the point of view that it illustrates the remarkable difference in between the run-up heights computed for two different parts of Falsterbo.

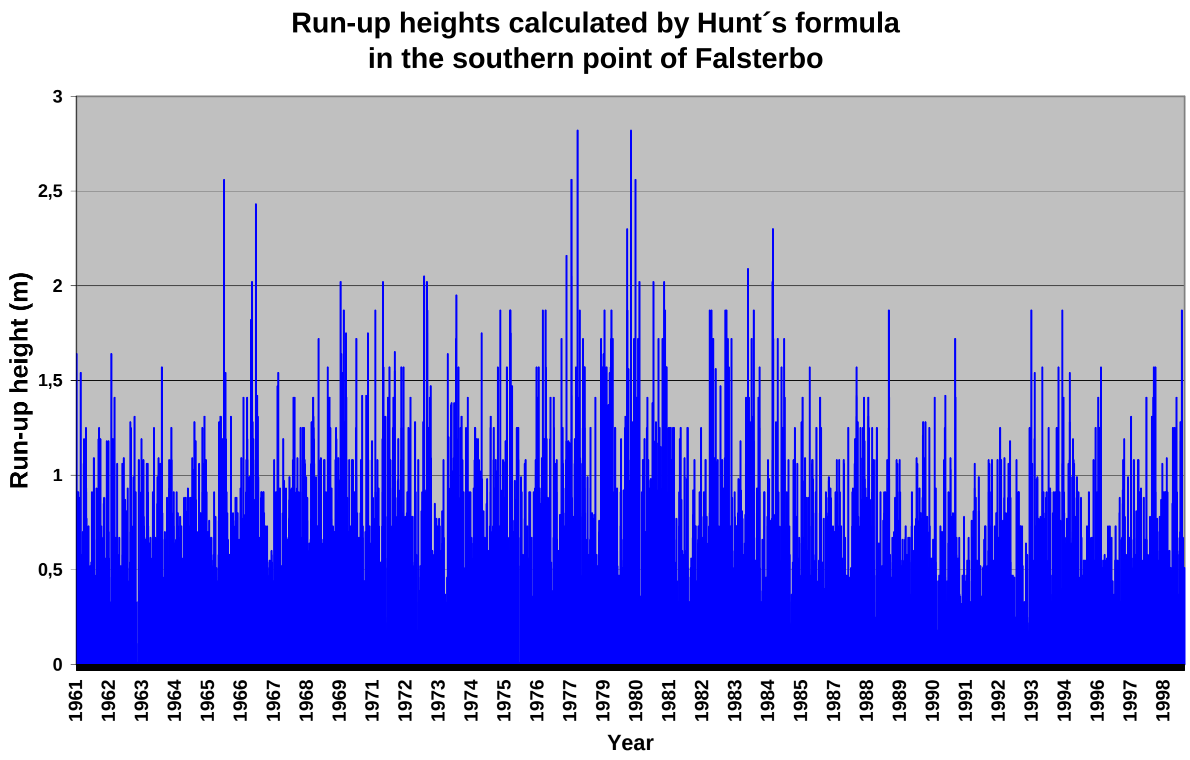

Figure 38. The graph showing the calculated run-up heights by the Hunt's formula in the southern point

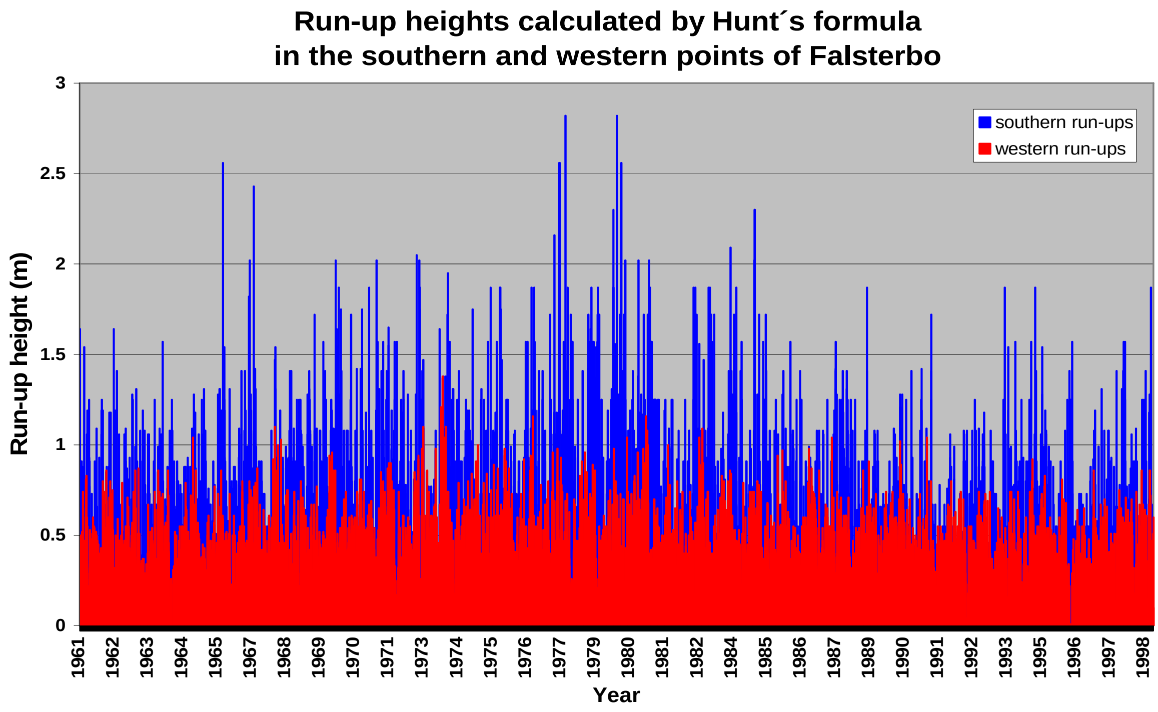

Figure 39. The graph showing run-up heights calculated by Hunt's formula for both the southern and western points

The relationship between the run-up heights and the state of sea level was investigated for this point as well. The run-up heights larger or equal to 2.30 m were chosen and listed together with their date of occurrence and wave height and water level of this date. (See Table 6)

Table 6. Table showing simultaneous large wave heights, run-up heights and low water levels

Date	**Wave Height (m)**	**Run–up Height (m)**	**Water Level (cm)**
01/01/1966	**5.16**	**2.56**	**30**
30/01/1967	**4.88**	**2.43**	**30**
08/12/1977	**5.16**	**2.56**	**40**
10/12/1977	**5.16**	**2.56**	**15**
23/02/1978	**5.70**	**2.82**	**15**
14/12/1979	**5.70**	**2.82**	**55**
09/02/1989	**5.16**	**2.56**	**0**
16/11/1984	**4.60**	**2.30**	**50**
17/11/1984	**4.60**	**2.30**	**40**

It is evident in this table that the same relationship between run-up heights and water levels specified in the western point is not valid for the southern point. That is, there can not be observed an obvious trend in the sea level values to be low while the corresponding run-up heights are at their maximums. This phenomenon can be explained as follows: Although the same wind and water level data are applied to both points, because of their locations and orientations they have different fetch lengths and wind directions. Therefore crucial differences in wave and run-up heights arise due to these facts. Since the interaction of wind direction, fetch-length affected wave height and run-up height, and water level is not of the same characteristics as in the western point, the calmness of sea state can not be associated with the large run-up heights for the southern point. However, sea level does not also tend to be in its extreme levels, instead it can be said to be ranging within middle level values.

Thus, it was concluded from this discussion that the dependency of sea levels on simultaneous run-up heights can not be generalized. This dependency should be investigated in a point or a region-wise manner.

5.3 Extreme value analysis of water levels and run-up heights combination

After calculating the wave and run-up heights by means of numerical model and making a comparison of the results obtained in two different parts of the peninsula, extreme value analysis on (water levels + run-up heights), (WL + RU), will be introduced in this section. In the analyses, the water level condition combined with run-up phenomena in 2020 and 2100 will be determined in both the western and southern points of Falsterbo, respectively.

5.3.1 The western point

The western point is located in the Öresund region and it is hit by relatively smaller waves compared to the other point thanks to shorter fetch distances as mentioned in the previous parts of the report.

The data set resulting from the numerical wave hindcasting model was comprised of daily (WL + RU) for 38 years between 1961 and 1998. Firstly monthly maximums were extracted out of these daily values, which are available as a graph in Figure 40.

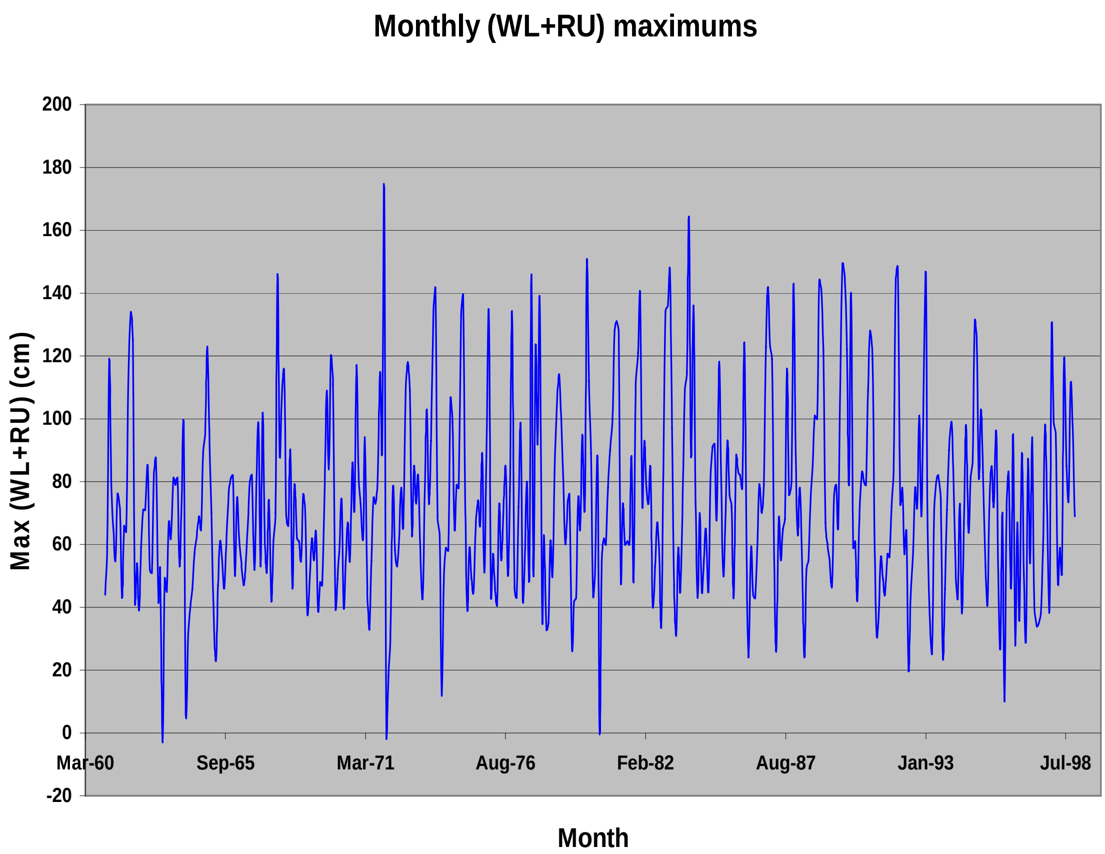

Figure 40. The graph showing the monthly (WL+RU) maximums in the western point

The methodology followed in extreme value analysis for water levels only in section 4.2 was also kept up in extreme value analysis of (WL+RU). In the beginning of the analysis the temporal trends had to be removed from the data set so that the present conditions could be reached prior to projection into the future. In this respect, increase in mean sea level (MSL trend) and timely variation in (WL+RU) values (WLRU trend) were regarded as the temporal trends to be dealt with. As the first step in trend removal phase, MSL trend was removed. MSL trend calculated in the previous extreme value analysis on the water levels for 1941-1998 was taken into account here was well since it not only includes the period of interest, 1961-1998, but also represents a more general prediction of the trend. This MSL trend value, 0.073cm/year, was subtracted from the monthly data set accordingly, resulting in the graph shown in Figure 41 below.

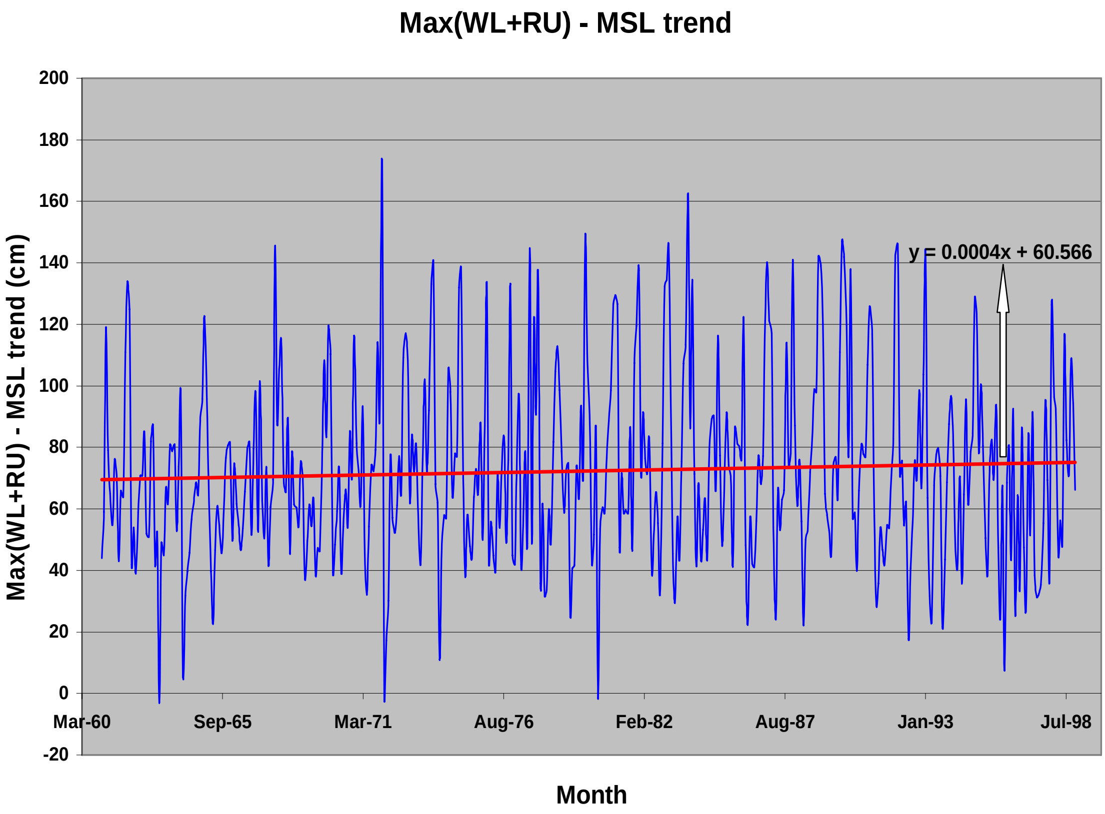

Figure 41. The monthly maximum (WL+RU) after MSL trend removal for the western point

Once the MSL trend was removed from the data set, trend removal was completed with excluding WLRU trend which was calculated and shown in Figure 41 to be 0.0048 cm/year (or 0.0004 cm/month). The net data set ready to perform an extreme value analysis for future estimates is available in Figure 42. A linear regression on this graph still caused having an increasing trend. This is considered to be due to the fact that MSL trend value was referred from a data set of longer period. The data set shows significant variations in itself and it is sensitive to the exclusion of even few years. For instance, the individual trends of consecutive 10-year periods differ greatly from each other.

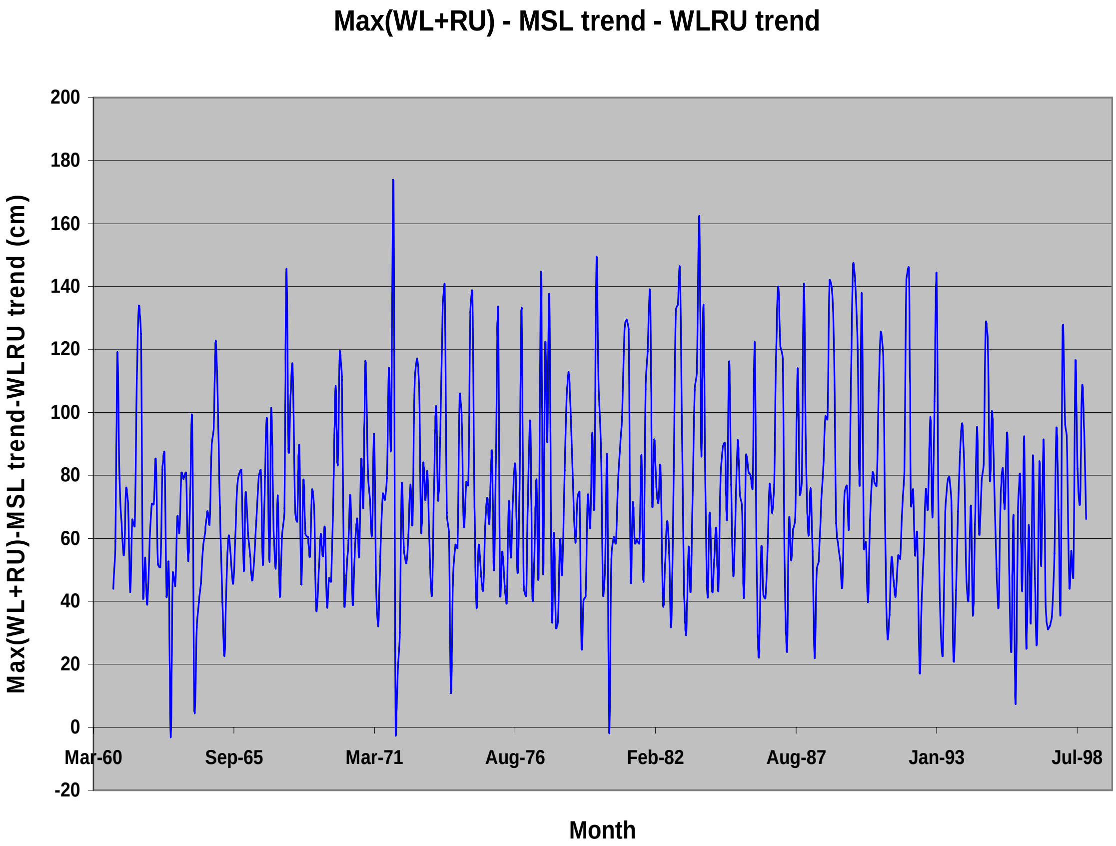

Figure 42. The net data set free of temporal trends for the western point

The trend removal phase was followed up by a trend readjustment process so as to reach present condition. IPCC values as in the case of extreme value analysis on water levels were employed for MSL trend. Whereas WLRU trend was compensated by adding it back to the data set as a constant value. IPCC20 (7cm) and IPCC(49 cm) for MSL trend, WLRU of 20 years and WLRU of 100 years were inserted for the purpose of simulating the conditions in 2020 and 2100, respectively.

Having completed the trend analysis, an extreme value analysis on monthly (WL+RU) maximums by Gumbel method was performed by applying the same procedure and rules as explained in detail in the previous sections of the report. The graph in Figure 43 reveals (WL+RU) levels in 2020 and 2100 on a Gumbel plot together with the associated probabilities. On the other hand Figure 44 illustrates the probability of occurrence curves of (WL+RU) for these years.

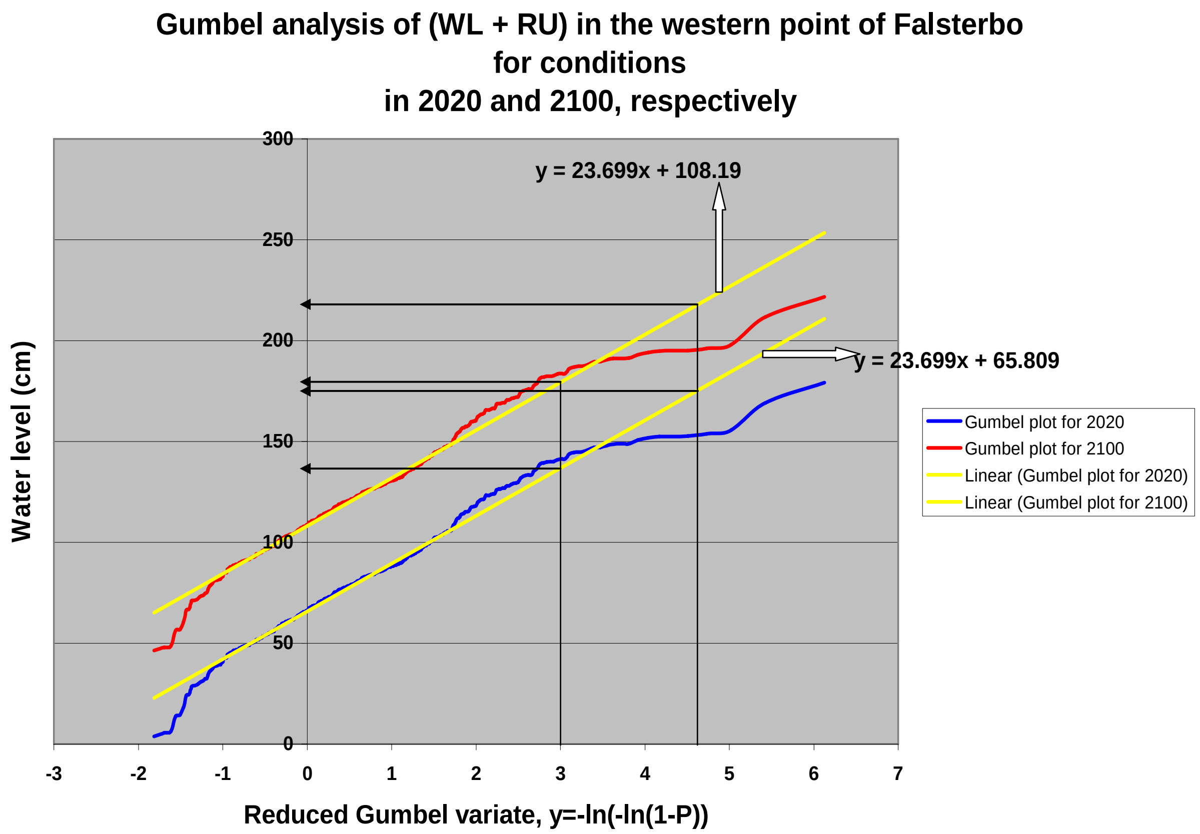

Figure 43. Gumbel analysis plot for the determination of conditions in the western point in 2020 and 2100, respectively

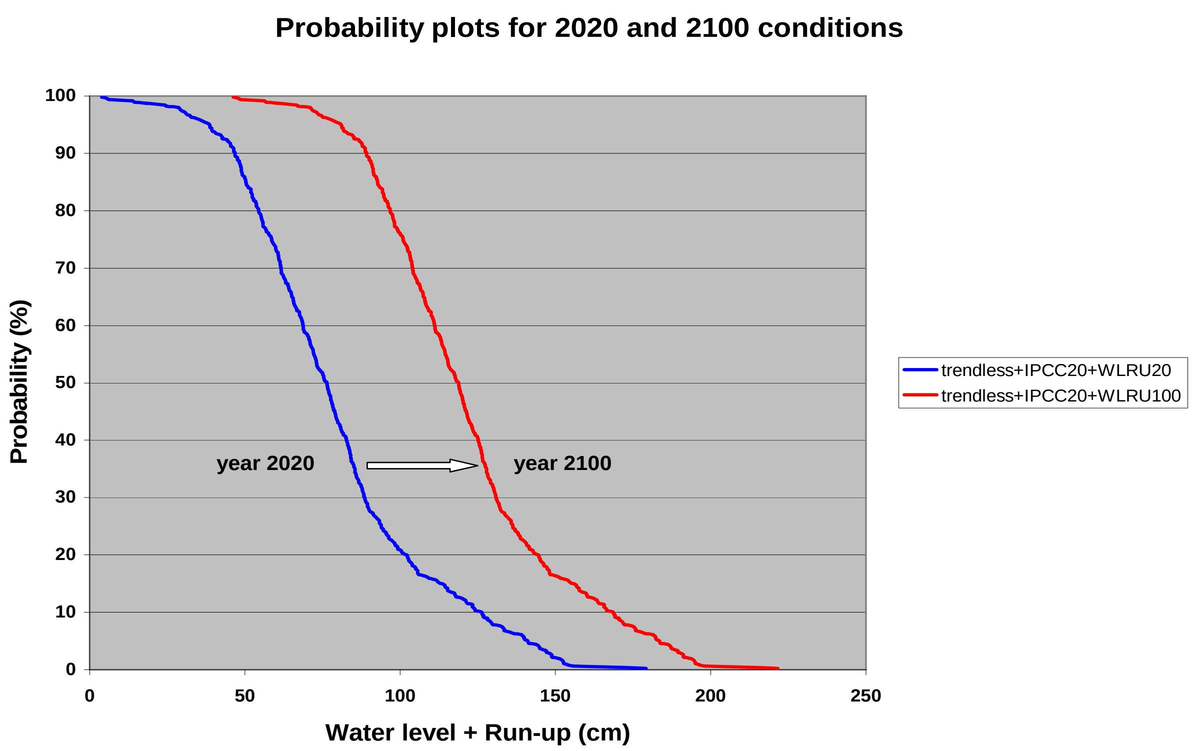

Figure 44. Probability of occurrences of (WL+RU) for the years 2020 and 2100 in the western point

(WL+RU) heights in the years 2020 and 2100 were determined from the linear regression lines fitted on the Gumbel analysis plot in Figure 42. They were calculated to be 137 (with 20-yr return period) and 175 cm (with 100-yr return period) for 2020 and 179 (with 20-yr return period) and 217 cm (with 100-yr return period) for 2100. The results are shown together with the corresponding reduced Gumbel variate values used for getting the desired levels in Table 7.

Table 7. Table showing the results of Gumbel analysis on trendless + IPCC values + WLRU trend for conditions in 2020 and 2100 in the western point

Return Period	**Reduced Gumbel variate, y**	**Extreme water level, including IPCC prediction in the years;**	
		2020	**2100**
20 years	**3**	**137 cm.**	**179 cm.**
100 years	**4.6**	**175 cm.**	**217 cm.**

It can be observed in Figure 42 that linear regression lines automatically fitted to the Gumbel plots for the years 2020 and 2100 are a bit overestimating for (WL+RU) levels bigger than 160 cm. It can be classified to do with the effect of seasonal variation effect, i.e. the maximums of winter and autumn months are considerably larger than the ones of summer and spring months. Seasonal variation can be overcome by making use of an appropriate threshold value or by fitting a better line on the Gumbel curves. An extreme value analysis on annual maximums may be a beneficial alternative to be able to compare the results and to see the differences in between monthly and annual analyses.

5.3.2 The southern point

The southern point lies in the Baltic Sea side of Falsterbo peninsula. This portion of the peninsula has longer fetch lengths than the ones the western point has. Therefore, it is continuously exposed to larger wave and run-up heights, thus facing higher danger of flooding and overtopping. The initial data set of (WL+RU) was treated exactly in the same way as mentioned in the previous subsection to have monthly maximums, which are available on the graph as Figure 44 below.

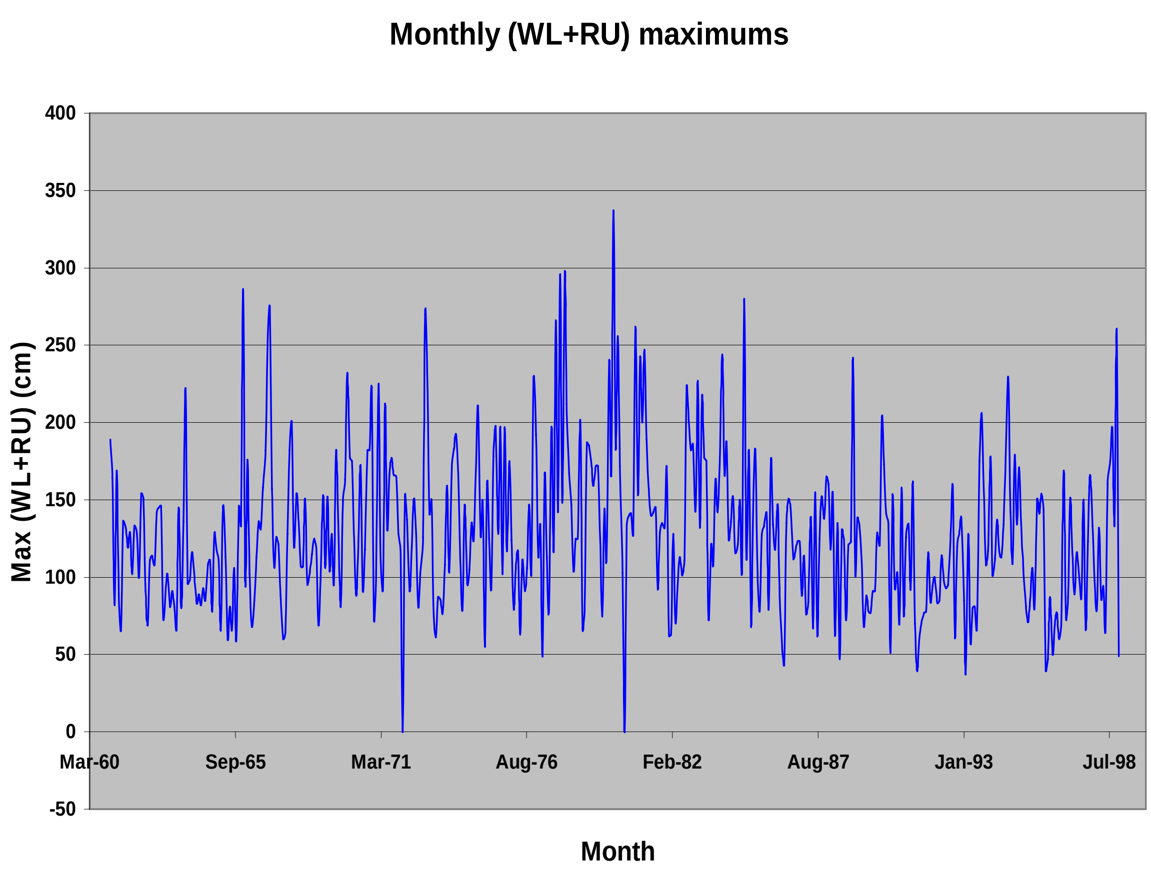

Figure 44. The graph showing the monthly (WL+RU) maximums in the southern point

Next, the MSL and WLRU trends were removed and then trend readjustment was accomplished by means of inclusion of IPCC prediction for MSL and WLRU trend as constant for WLRU trend. The data set from which the MSL trend was removed and net data set which is thought of having no temporal trends are shown in figures 45 and 46, respectively below.

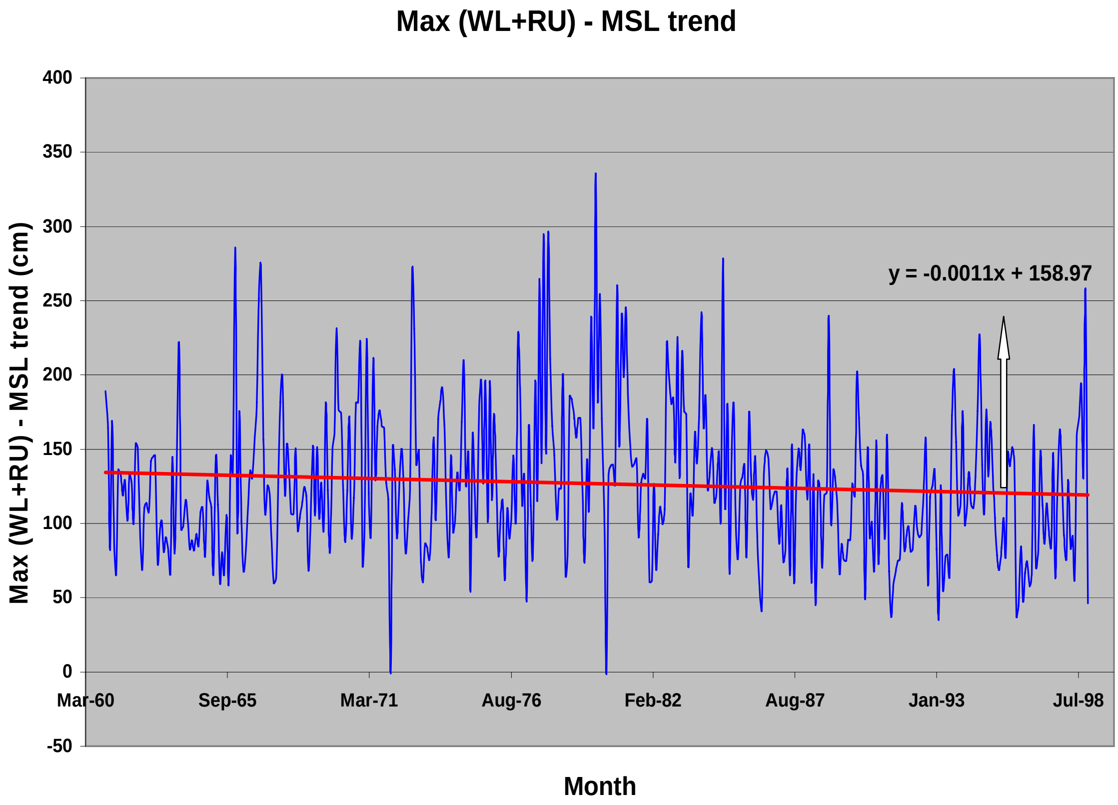

Figure 45. The monthly maximum (WL+RU) after MSL trend removal, together with the WLRU trend for the southern point

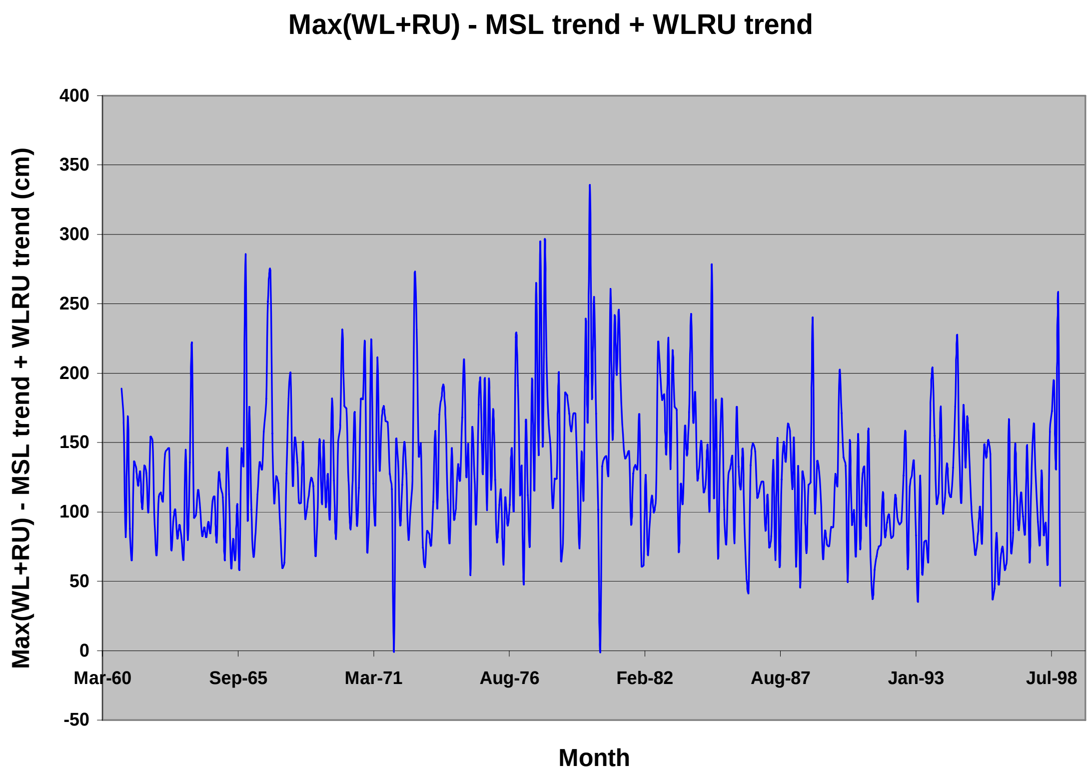

Figure 46. The net data set free of temporal trends for the southern point

There was a remarkable difference in the trend analysis of the southern point. WLRU trend was determined to be negative (or decreasing). (See Figure 45). This situation was come up with since the negative trend in run-up values is bigger than the positive trend of water levels in this point. Therefore, removing WLRU trend was completed with an addition process instead of subtracting, which has always been the case in the previous analyses. Similarly, WLRU trend readjustment was nothing but addition of WLRU trend as a constant to the data this time. This difference in trend analysis once again confirms that the wind and wave characteristics completely differ from each other for different geographic locations.

After trend analysis, an extreme value analysis on monthly (WL+RU) maximums in the southern point was conducted. Once again, Gumbel method was taken as the reference throughout the analysis and the conditions in 2020 and 2100 were aimed. For this purpose, Gumbel plots were prepared and fitted by linear regression technique as it was done for the western point. The resulting graph can be observed in Figure 47. On the graph, the equations of fitted lines are also indicated.

It is remarkable that automatic linear regression conforms very well to the Gumbel curve. There are again some overestimating portions of the line in both curves; however, they do not constitute a problem since the estimations were not made by depending on these portions as can be observed in Figure 47.

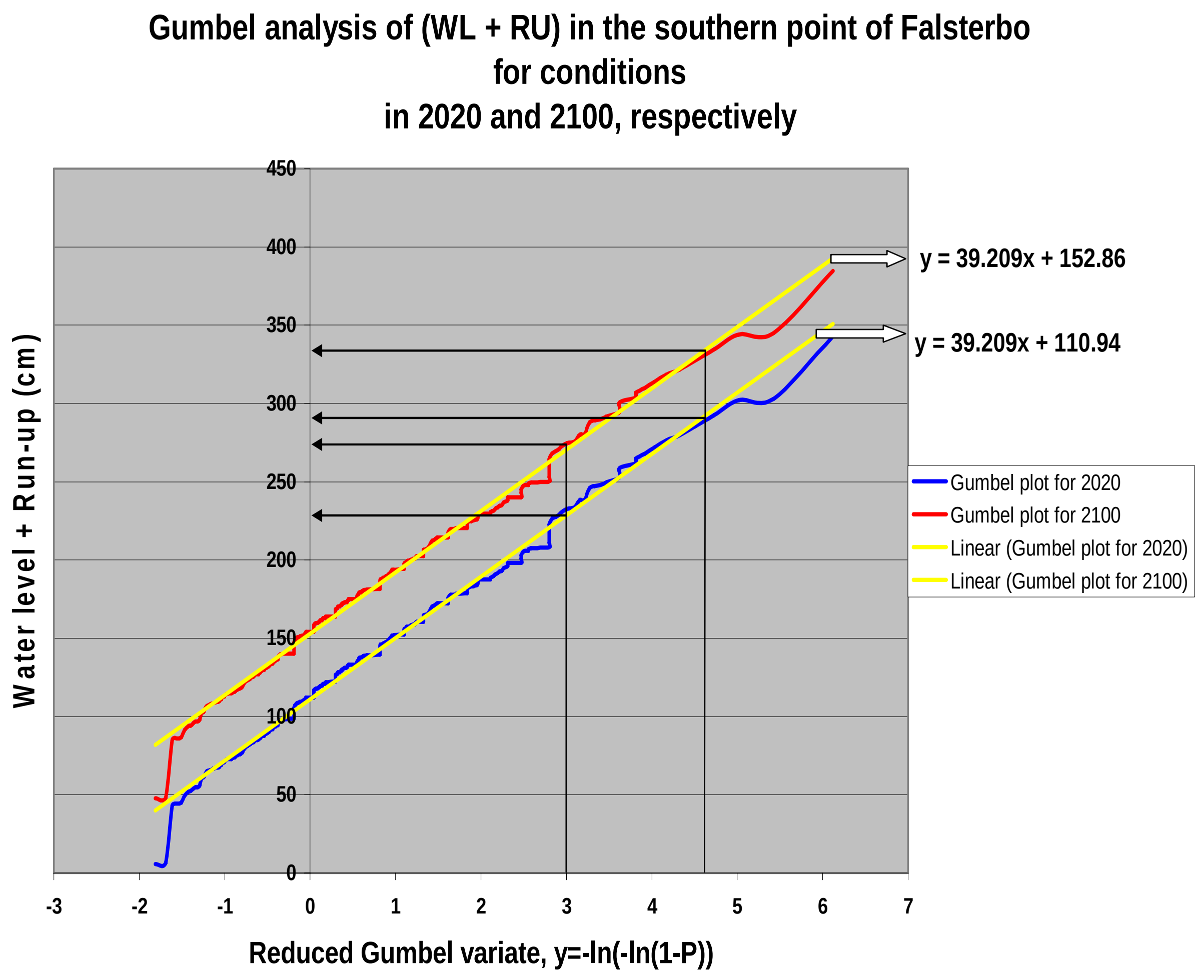

Figure 47. Gumbel plots showing (WL+RU) levels in 2020 and 2100 in the southern point

(WL+RU) levels by the monthly extreme value analysis in southern point were predicted to be equal to 229 and 291 cm for 2020 conditions and 270 and 333 cm for the conditions of 2100. The probability of occurrence plot for these years was shown in Figure 48 below. Furthermore, the resulting levels were clearly demonstrated with the proper explanations in Table 8 below too.

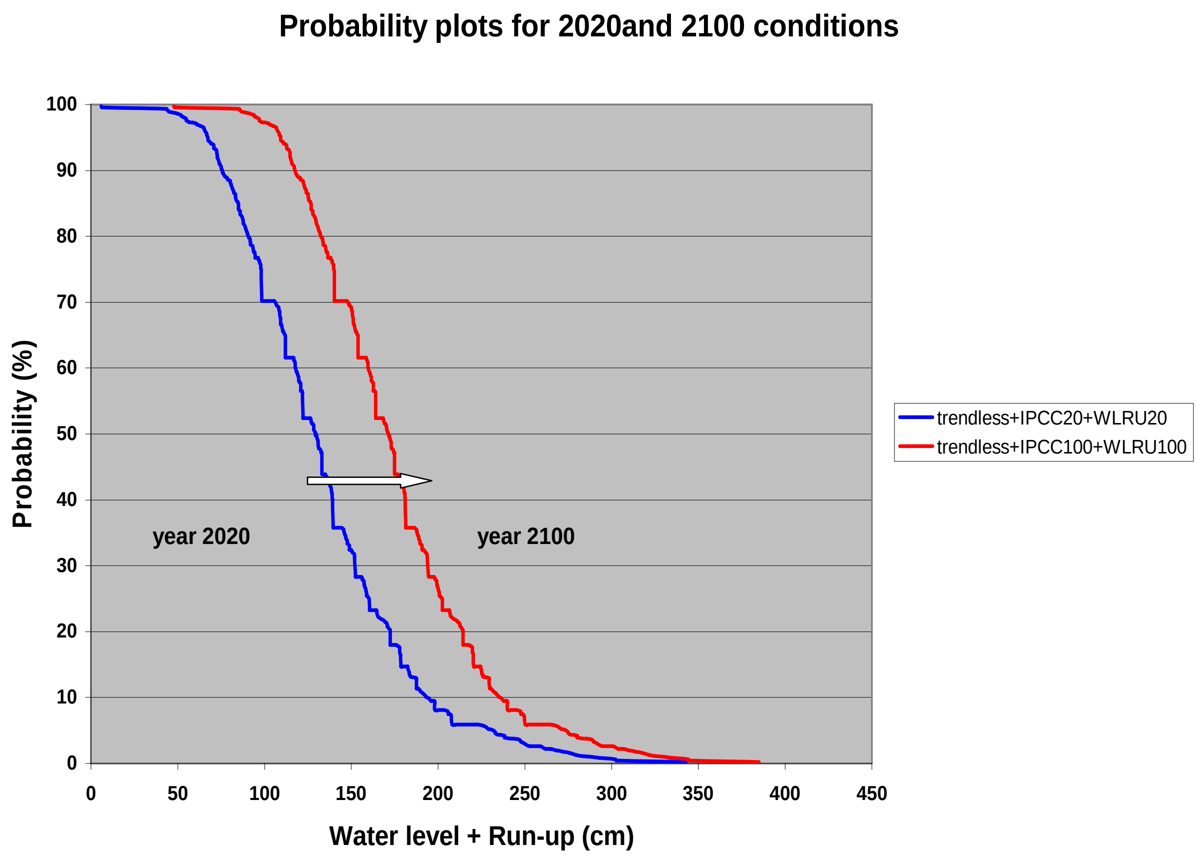

Figure 48. Probability of occurrences of (WL+RU) for the years 2020 and 2100 in the southern point

Table 8. Table showing the results of Gumbel analysis on trendless + IPCC values + WLRU trend for conditions in 2020 and 2100 in the southern point

Return Period	**Reduced Gumbel variate, y**	**Extreme water level, including IPCC prediction in the years;**	
		2020	**2100**
20 years	**3**	**229 cm.**	**270 cm.**
100 years	**4.6**	**291 cm.**	**333 cm.**

6 Discussions and conclusion

The main aim with this study was to calculate the extreme water level values in the future, specifically in the years 2020 and 2100, and to evaluate the flooding risk in Falsterbo peninsula of Sweden considering the levels obtained and the geographical characteristics of the study area. For these purposes the sea level rise phenomenon, especially in connection with climate change (global warming) and wave action, were defined. Possible consequences of these occurrences on the coastal zone were indicated within this context. Then, the study area and its characteristics from several points of view were discussed. After that extreme value analyses followed. Firstly, extreme value analysis on water levels in Falsterbo was performed and possible water heights over the present sea level in 2020 and 2100 were estimated. Secondly, this was followed by extreme value analyses on the water levels but this time with the inclusion of run-up distances. These analyses on two different points of the peninsula again gave rise to having (water level + run-up) values for 2020 and 2100.

The future projections of water level over the mean sea level calculated out of three different analyses, namely water levels, western (water levels + run-ups), southern (water levels + run-ups), are summarized in Table 9 below.

Table 9. Table showing calculated water level values throughout analyses conducted in the report

Water Level (cm) by Extreme Value Analysis on	Years			
	2020		2100	
Water Levels	84		160	
Water Levels + Run–ups (Western)	20-yr return period	100-yr return period	20-yr return period	100-yr return period
	137	175	179	217
Water Levels + Run–ups (Southern)	229	291	270	333

One of the outcomes as presented in Table 9 is the effect of run-up height on the level reached in the future. The predicted level implicated significant increases when water level was combined with run-up phenomena. The levels, therefore, are important because they illustrate what happens when the coupled effect of both water level and waves are taken into account. As can be observed in the table, an analysis where only water levels were considered resulted in having 84 and 160 cm of water height for the years of 2020 and 2100, respectively. Whereas, another analysis which was dealing with combination of water levels with run-ups, which can be said to be the most realistic approach, ended up with levels up to 229 and 270 cm for the same years and for the same return period values. The increase in the levels with the same probability (or return period) is around 50 cm depending upon the point. These future sea level heights are, no wonder, seriously threatening the peninsula, which is below 3-meter water level with 90% of its area. In this perspective, the simultaneous occurrence of high water levels with the waves is a very crucial subject to be able to estimate or foresee their combined effect on the coastal zone and to plan new or to renovate existing sea defense structures.

Another conclusion worth to emphasize from looking at Table 9 is the difference in results obtained in the western and the southern points. As the table indicates, higher future water levels are predicted for the southern point of the peninsula than the western point. Actually this difference should not be surprising, because although the same water level observations are applied to both points, southern point in Falsterbo experiences waves of larger wave heights in connection with its longer fetch lengths through the Baltic Sea. Larger wave heights cause the coastal zone to have higher run-up distances. Thus, combination of the same water level data with the point-specific run-up data normally creates such a big difference in the future projection of water levels. It would, for example, be interesting to observe and record the water level oscillations and wind occurrences in both points separately, and repeat the analyses for these data sets unique for the points of interest. It can be concluded from this discussion that, because of the geographic location of Falsterbo peninsula, any future water level and wave analyses are recommended to be conducted specifically for the points. Besides, as the southern point represents more critical case in this study, in general southern coast of Falsterbo peninsula should be expected to be more vulnerable to water level rise and wave action.

Furthermore, the dependency between water level and wave height deserves more attention. In this study, these two variables were regarded as completely independent. However, this approximation can rarely be classified as a good one since they are usually partially dependent if not completely. So, studying this dependency and remaking all the extreme value analyses without ignoring this dependency would be a very interesting potential study topic, although multivariate extremes turn out to be a very difficult environment to make predictions out of.

This study led to determination of possible water levels in the near future. Results vary in a range from 84 to 333 cm depending on the analysis and the place. These levels are very significant for a low-lying peninsula like Falsterbo as they may result in flooding on the coast and no wonder these levels, if formed, will be the cause of diminishing of attractive and important sandy beaches. Nonetheless, the flooding may even proceed to the residential areas and disrupt life routines in this prestigious area. An example of such disruption would be the flooding of only road connecting Falsterbo to Malmö. Thus this study together with its analyses and results is a good indicator of the future scenarios in sea water levels and the risk associated. It is thought that in the light of findings of this study, grounds for further research and planning of appropriate protection measures and design of necessary sea defense structures against indicated potential dangers are laid.

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Appendix I

```
C* VARIABLE DECLARATION
C*

      INTEGER I,ITER,IANT,IY,IM,ID,IH,NRF

      REAL FETCH(17),WSPEED,WL,DEPTH(17),DUR,FEFF,XOLD,XNEW,
     &HMO,TM,TIME,HM,T,HMAX,TMAX,T1,T2,HWR,TWR,WDIR,L0

      CHARACTER*3 DIR,CDIR(17)

C*
C* INPUT DATA ON FETCH LENGTH (IN KM; ONE LENGTH PER COMPASS
DIRECTION)
C

      DATA FETCH/0,0,0,0,0,257,202,105,106,49,54,0,0,0,0,0,0/

C*
C* INPUT DATA ON AVERAGE WATER DEPTH (IN M; ONE LENGTH PER
COMPASS
DIRECTION)
C

      DATA DEPTH/1,1,1,1,1,40,25,30,30,18,12,1,1,1,1,1,1/

C*
C* DURATION OF WIND INPUT
C*

      DATA DUR/86400./

C*
C* DEFINITION OF COMPASS DIRECTIONS
C*

      DATA CDIR/' N ','NNO',' NO','ONO',' O ','OSO',' SO','SSO',
     #          ' S ','SSV',' SV','VSV',' V ','VNV',' NV','NNV',
     #          'STL'/

C*
C* INPUT AND OUTPUT FILES
C*

      OPEN(UNIT=10, FILE='WIND_WL_FALSTERBO.DAT')
```

```
      OPEN(UNIT=20, FILE='RUN-UP SOUTHERN MILD.DAT',
STATUS='UNKNOWN')

C*
C* INITIALIZE RANDOM NUMBER GENERATOR
C*

      CALL RANDOM_SEED

C*
C* READ WIND INPUT DATA
C* (NOTE: WATER LEVEL HAS BEEN PUT IN THE WIND FILE TO ALLOW
FOR
C* SIMULTANEOUS PRINT OUT AND SUBSEQUENT ANALYSIS)
C*
C* PRESENT INPUT STRUCTURE (MAY BE CHANGED)
C*
C* IY = YEAR
C* IM = MONTH
C* ID = DAY
C* IH = HOUR
C* WDIR = WIND DIRECTION (IN DEG)
C* WSPEED = WIND SPEED (IN M/SEC)
C* WL = WATER LEVEL
C*

      IANT=0

            READ(10,*)

66    READ(10,*,END=99) IY,IM,ID,IH,WDIR,WSPEED,WL

C*
C* SKIP MISSING VALUES
C* (MIGHT BE PRESENT IN THE FILE)
C*

         IF(WDIR.LT.-900.OR.WSPEED.LT.-900) GOTO 66

         IF(WDIR.GT.900.) GOTO 66

         IF(WL.GT.900) GOTO 66

         IANT=IANT+1

C*
C* RANDOMIZE WAVE DIRECTION
C*

         CALL RANDOM_NUMBER(SS)
```

```
      WDIR=WDIR+10.*SS-5.0

      IF(WDIR.LT.0) WDIR=360.+WDIR

      IF(WDIR.GT.360.) WDIR=WDIR-360.

C*
C* COMPASS DIRECTION
C*

      NRF=NINT(WDIR/22.5)+1

      IF(NRF.GT.16) NRF=1

      DIR=CDIR(NRF)

      IF(WSPEED.EQ.0) DIR=CDIR(17)

C*
C* ASSIGN FETCH LENGTHS AND CONVERT TO METERS
C*

      FFF=FETCH(NRF)*1000.

C*
C* DETERMINE WIND STRESS FACTOR UA
C*

      UA=0.71*(WSPEED)**1.23

C*
C* WAVE PREDICTION FOR DEEP WATER
C* ------------------------------
C*

      HMO=5.112E-4*UA*SQRT(FFF)

      TM=6.238E-2*(UA*FFF)**0.3333

      IF(UA.GT.0)THEN

        TIME=32.15*((FFF)**2/UA)**0.3333

      ELSE

        TIME=0.0

      ENDIF
```

```
C*
C* CHECK IF WAVE GROWTH IS DURATION LIMITED
C*

      IF(DUR.LT.TIME)THEN

        FEFF=SQRT(UA*DUR**3/33231)

        HMO=5.112E-4*UA*SQRT(FEFF)

        TM=6.238E-2*(UA*FEFF)**0.3333

      ENDIF

C*
C* CHECK IF SEA IS FULLY DEVELOPED (WIND SPEED LIMITING)
C*

      HMAX=2.482E-2*UA**2

      TMAX=0.83*UA

      IF(HMO.GT.HMAX) HMO=HMAX

      IF(TM.GT.TMAX) TM=TMAX


C*
C* WAVE PREDICTION FOR SHALLOW WATER
C* ---------------------------------
C*

      IF(UA.GT.0)THEN

        T1=TANH(0.530*(9.81*DEPTH(NRF)/UA**2)**0.75)

        T2=TANH(0.00565*SQRT(9.81*FFF/UA**2)/T1)

      ELSE

        T1=0.0

        T2=0.0

      ENDIF

      HM=0.0288*UA**2*T1*T2

      IF(UA.GT.0)THEN
```

```
        T1=TANH(0.833*(9.81*DEPTH(NRF)/UA**2)**0.375)

        T2=TANH(0.0379*(9.81*FFF/UA**2)**0.3333/T1)

      ELSE

        T1=0.0

        T2=0.0

      ENDIF

      T=0.7686*UA*T1*T2

      IF(UA.GT.0)THEN

        TIME=54.74*UA*(9.81*T/UA)**2.333

      ELSE

        TIME=0.0

      ENDIF

C*
C* CHECK IF WAVE GROWTH IS DURATION LIMITED
C*

      IF(DUR.LT.TIME)THEN

        T=(UA**1.33*DUR/11191.)**0.429

        DUM=1.301*T/UA/T1

C*
C* NEWTON-RAPHSON TO SOLVE FOR FEFF
C*

        ITER=0

        XNEW=1.

77        XOLD=XNEW

        XNEW=XOLD-(TANH(XOLD)-DUM)*(COSH(XOLD))**2

        ITER=ITER+1

        IF(ABS(XNEW-XOLD).GT.1E-3.AND.ITER.LE.20) GOTO 77
```

```
      IF(ITER.GT.20)THEN
        WRITE(*,*) 'AAAAAAAARGH, NOT CONVERGING'
        STOP
      ENDIF
      FEFF=(T1*XNEW/0.0379)**3/9.81*UA**2
      T1=TANH(0.530*(9.81*DEPTH(NRF)/UA**2)**0.75)
      T2=TANH(0.00565*SQRT(9.81*FEFF/UA**2)/T1)
      HM=0.0288*UA**2*T1*T2
    ENDIF
    HWR=HM
    TWR=T
    IF(HMO.LT.HM) HWR=HMO
    IF(TM.LT.T) TWR=TM
    IF (TWR.GT.0) THEN
        L0=1.56*(TWR)**2
    R=HWR*2.319*(0.0178/((HWR/L0)**(0.5)))**0.771
        ELSE
        R=0
        ENDIF
    WRITE(20,100) IY,IM,ID,IH,DIR,WSPEED,HWR,TWR,WL,R,R+WL
100   FORMAT(' ',I4,3I3,TR3,A,F10.1,5F10.2)
20    CONTINUE
  GOTO 66
99  STOP
  END
```