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Exploring vegetation as coastal protection during extreme storm conditions

Case study: Kivik waste water treatment plant

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Picture from Kivik waste water treatment plant

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Abstract

Scania has always been susceptible to damages caused by storms along its coasts which also holds true for the east coast in Scania where there is a great need of coastal protection for households and infrastructure alike. One example is the Kivik waste water treatment plant (WWTP) which is a newly built establishment with glass windows situated 30 meters from the east coast and provides its services to 7500 people. However there are new challenges for coastal protection with climate change causing the sea to creep closer and extreme storms occurring more frequently . This was made painfully clear on the 20:th of October when the storm Babet that hit Kivik with waves that reached height of 3.6 meters and water levels reaching 116 cm above the mean sea level.

Damages were abundant along the coast and even though Kivik WWTP came out unscathed there were rocks and pebbles along the glass facade that warned of the possibility of failure. The protecting rock revetment had also been undermined during the storm which leads to the need of new protection.

The possibility to use vegetation as coastal protection is fairly unexplored but can be a viable solution in many parts of the world. A model in the modeling software XBeach was created to simulated the dampening effect three different types of vegetation had. The plants that were decided to be simulated were willow trees, low reeds in form of a salt marsh and bushes. The model showed that the reduction in wave height could reach around 50% through the 13 meter long vegetation field, a number that was similar regardless of which plant that was simulated. It was therefore concluded that vegetation is a viable option as coastal protection. It was not clear however which type of plant that would be best suited for the local conditions at Kivik WWTP. To determine this, it is recommended to do throughout experimentation with the vegetation that is planed to be used for every case that wants to utilize vegetation as coastal protection.

Sammanfattning

I södra Sverige har det historiskt sett alltid funnits behov för kustskydd för att skydda viktig bebyggelse och infrastruktur från de stormar som annars kan driva stora vågor till att skada bebyggelse som befinner sig längsmed kustlinjen. Denna problematik förstärks dagligen av havsnivåstigningen som gör att havet kryper sig allt närmare den befintliga bebyggelsen. Detta gör att nya förhållanden uppstår när planering av kustskydd utförs men i dagsläget används samma angreppsmetoder som tidigare fast med större dimensioner. Runtom i världen har det blivit aktuellt att undersöka en annan typ av lösning än de hårda lösningarna. I anknytning till stormen Babet, som drog över Sverige den 20:e oktober 2023, fick Skåne ett smakprov på de konsekvenser som havsstigningen kan leda till. Simrishamn kommun var hårt drabbad av stormen Babet som drog med sig ett flertal skador till kustområdet till följd av det höga vattenståndet och vågor.

Ett exempel är Kiviks reningsverk som är ett nybygge precis intill Kiviks hamn med modern reningsteknik som klarar av läkemedelsrester och renar vatten från 7500 PE. Byggnaden klarade sig utan några skador men längs med glasfasaden låg det både sten och grenar som hade spolats upp och slått mot fasaden vilket tyder på en tydlig risk för skador i framtiden ifall en mer extrem storm skulle ske.

Tre typer av växter har därav undersökts för att kunna bedöma ifall vegetation kan funka som kustskydd och vilken typ av vegetation som är lämpligast för Kivik. De tre typerna är buskage, pilträd och vass. Genom att simulera dessa tre typerna av vegetation indivudellt i programvaran XBeach under de förhållanden som rådde under Babet samt med motsvarande vattenstånd 2050 fanns det en tydlig dämpningsförmåga av våghöjden på cirka 50% hos växterna när vågorna propgerade genom ett 13 meter långt fält. Däremot gick det inte att avgöra vilken typ av vegetation som lämpade sig bäst för förhållandena utanför Kivik

Notation

Symbols

C_g - Wave group velocity [m/s]
E - Wave energy density [J/m^2]
ϵ_v - time-averaged vegetation-induced rate of energy
dissipation per unit horizontal area [-]
C_D - Drag coefficent [-]
H_S - Significant wave height [m]
$R_{u2\%}$ - Elevation exceedence of all runup during a time period [-]
T - Period [s]
h - Water depth [m]
ξ - Iribarren number for runup [-]
L_0 - Deep water wave length [m]
x - cross shore distance [m]
$H_{\max}$ - Maximum wave during a time period [m]
N - Vegetation density - [plants/m^2]
ah - height of plant [m]
bv - stem width of the plant [m]

Abbreviations

WWTP - Waste Water Treatment Plant
PE - Population Equivalent
MSL - Mean Sea Level
SWL - Still Water Level
NbS - Nature based Solution
GEV - Generalized Extreme Value
SLR - Sea Level Rise

Contents

1 Introduction

The south of Sweden has always been susceptible to the threat that extreme weather events poses on the infrastructure at the coastline. However, it is uncertain if current infrastructure will be resilient enough when climate change causes both sea level rise and extreme storm events to occur more frequently. The methods to counter these changes remains the same but with larger dimensions. Is this method a valid approach or if other methods are more beneficial.

A term that has been used more frequently lately is nature-based solutions (NbS) which is defined as:

"Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions." [1]

The extent of this definition is wide and includes coastal protection with dunes, vegetation beach nourishment etc.

Another common solution besides NbS is to use hard structures as coastal protection. Examples of hard structures that are often used are rock revetments, breakwaters and vertical walls. However, NbS has some added benefits compared to hard structures which is that they compromise the ecosystems and does not disturb the natural movement of sediment across the shoreline.

Scanea, which is located in the south of Sweden, was hit by an extreme storm on the 20th of October named Babet. Heavy damages was caused at infrastructure along the coastline which also holds true in the municipality of Simrishamn. The aftermath of this storm left them with several structures which needed repairing and a worry of the susceptibility of vital infrastructure. One example is the wastewater treatment plant at Kivik which is located right at the coast. After the storm there were branches, pebbles and smaller rocks that had gather alongside the glass facade which shows how it had endured several hits from the waves. Kivik WWTP will therefore be used as a case study for simulating the effect of vegetation.

Figure 1.1: Geographical position of Kivik in the Baltic Sea (Figure taken and edited from Lantmäteriet [2])

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1.1 Aim of study

The necessity of robust coastal protections along coastlines that are exposed to extreme storms is showcased on occasions when damages occur such as from the aftermath of Babet. Furthermore, hard structures may have unforeseen environmental impacts and cause damages coastal habitats by ecosystem degradation. Harbour constructions can also cause anoxic conditions by water stagnation [3]. Having the alternative to consider different solutions depending on the local conditions is a powerful tool for coastal engineers which is why it is important to understand how to implement these solutions. This study aims to further widen the understanding of implementation of vegetation as coastal protection during extreme storm events to hopefully promote further experimentation's and implementation of vegetation as coastal protection. The study will therefore try to answer these questions:

- Is it possible to utilize vegetation as coastal protection?
- Which type of vegetation is best suited for the case study?

The municipality of Simrishamn have been adamant that increased care have to be taken into preparation for extreme storm event which is why they reached out to the coastal engineers at LTH who suggested Kivik WWTP as a case study.

1.2 Kivik WWTP

The newly added extention of the wastewater treatment plant in Kivik was set into operation in 2019. Not only is it treating the water as a conventional treatment plant but it also features a process which uses carbon to remove medical residuals from the wastewater and is providing this service to 7500 PE. This number is sure to increase as Österlen VA, which are the owners of the building, are planning to connect a new pipeline which will include an additional 166 real estates by 2026 [4]. The WWTP is situated 30 meters from the coast according to SGI if RH2000 is the reference point for the water level. However, the distance can vary heavily depending on the local condition. The elevation in RH2000 is approximately 1.8 meters when measured at the seaside front of the WWTP. There is a flat low-lying area in front of the WWTP with scarcely spread out vegetation of reeds and a couple of trees. The seabed is rocky and the beach contains fine sediment with a relatively large amount of medium sized rocks.

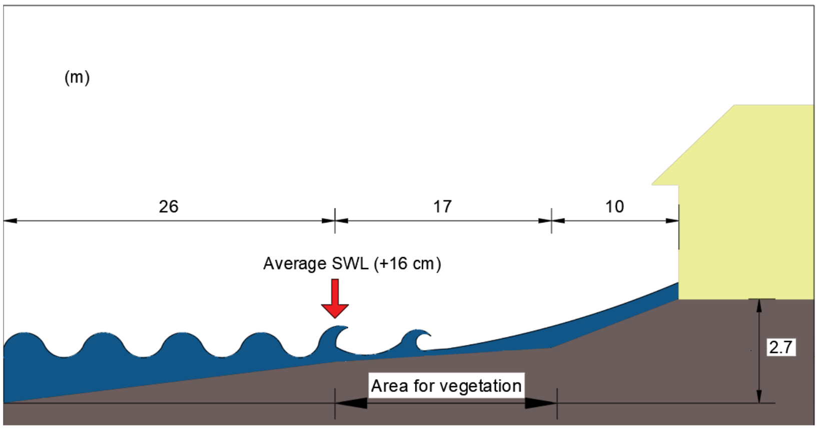

Figure 1.2: Kivik WWTP with the incoming waves and runup from Babet. Slopes are three times larger in the picture to showcase the elevation clearer

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The current coastal protection is a stone revetment which is designed by Sweco [5]. The design made by Sweco was based on a return period of 100 years and the still water level by 2050 which is estimated by SMHI to be at +18 cm. The significant wave height used was 0.94 meters. The dataset used for wave data was taken from the measuring station at Simrishamn which is run by SMHI. The station has been active since 1982, hence, it has 37 years of data. After the storm, damages to the structure were visible at several places in the form of rocks that were misplaced, clear erosion on the front-side of the structure and visible geotextile. Pictures were acquired from a site study that was made the 11th of March 2024. Figure 1.3 showcases some of the aforementioned damages to the rock revetment.

Figure 1.3: Erosion along the top of the rock revetment at Kivik WWTP

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1.3 The Baltic Sea

The WWTP is situated at the Baltic Sea which is a semi enclosed body of water and is connected to the Atlantic ocean through three straits, Öresund, Little Belt and Great Belt which makes it to an inland sea. The Baltic Sea has a limited water exchange with the Atlantic ocean which makes it susceptible to preconditioned water setup which is when water is squeezed into the basin, in this case the Baltic Sea. The water level is heavily dependant on the wind setup, for Kivik this means that eastern winds will push water towards the coast causing higher water levels. The dependence of significant wave heights on wind directions can be seen in the wave rose in figure 3.3 where the measuring point 440 meters outside of Kivik WWTP only identifies H_S from north-east and east north-east.

The wave climate in the Balitc sea i generally calmer than for instance the Atlantic which is due to the fetch length. Fetch length is the length of which a wave can be generated and can be limited by either the duration of the storm or the length of the basin in which the storm was generated. However estimates shows that significant wave heights can in some cases reach up to 10 meters [6].

1.4 Study area

The study will be conducted within the nearshore area of the WWTP which in this study is defined as 440 meters offshore perpendicular to the coastline. As mentioned before, it is situated on the east coast of Scanea, south of Sweden. The reason for the angle of incidence that is used is further explored in section 3.2.1. The angle of incidence for the propagating waves and the study area can be seen in figure 3.1. A cross shore section at the coastline outside the WWTP can be seen in figure 1.4.

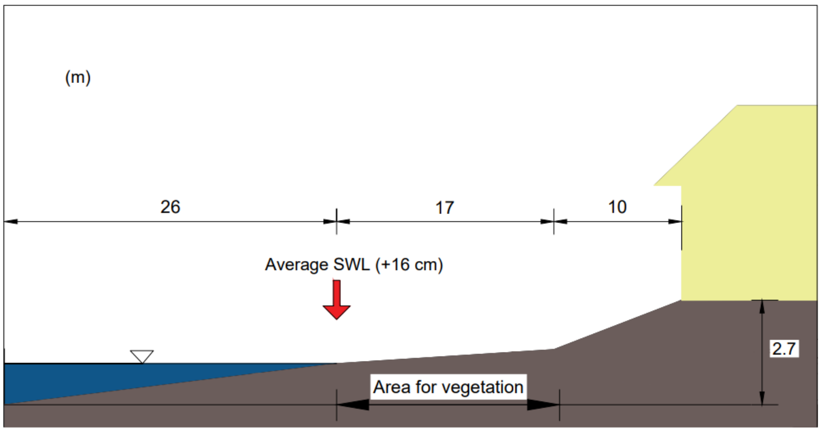

Figure 1.4: Nearshore profile for Kivik WWTP for MSL of +16 cm

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A picture from the area featured in Figure 1.4 was taken on December 22nd, 2023 which is showcased in figure 1.3.

1.5 1872 Baltic sea flood

The sea flood that occurred 1872 (called Backafloden in Sweden) ravaged through the Baltic Sea washing away ships and buildings alike along the coasts of Sweden, Germany and Denmark. The conditions in the Baltic Sea were set up for disaster, western winds had forced large quantities of water into the Baltic Sea through the three straits. The Baltic Sea had also began to sieche east to west and a low pressure area emerged in Germany resulting in higher water levels. Then on November 13th, came the eastern winds pushing water inside the basin towards the coasts in the southern Baltic Sea leading to hundreds of casualties [7]. The highest measured water level was recorded in Germany and reached 3.5 meters above sea level. The Falsterbo peninsula in the west of Scanea had recorded water levels of 2.4 meters, however the most severe damages in Sweden occurred in the east of Scanea which includes Kivik and Simirshamn. The effect of this storm surge is unparalleled for the area in recorded history. This event showcases how severe a storm theoretically can become in the Baltic Sea.

1.6 Babet

The storm Babet that swept over the south of Sweden between the 20th to 21st October 2023 caused damages to the south and east coast of Scanea. It originated from the Atlantic ocean and affected the British Isles and northwestern Europe, including Denmark, Germany and Sweden. In the south Baltic Sea, the storm caused eastern winds which accumulated record high storm surges along the eastern coasts of the previously mentioned countries. A measuring station owned by SMHI located in Simrishamn registered the MSL to be at +132 cm in RH2000 which is the second highest measurement for the station besides one made 2017. The costs of restoration for the municipality of Simrishamn was estimated to 60 million SEK which excludes damages to roads such as Tittutvägen. Some damages will not be repaired either as it was deemed too expensive for the municipality to restore. This is according to Magnus Lembke who works at Simrishamn municipality as a harbour engineer.

The extent of the reach Babet had at the WWTP can be seen in figure 1.5 where the water level of +132 cm is marked in light blue and the dark blue line is the observed runup level. The observation was made by the municipality through identifying sand deposits and seaweed deposits. The dark blue line is situated at an elevation of 2.3 meters to the right of the WWTP.

Figure 1.5: The observed effects of Babet at Kivik WWTP

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1.7 Method

The study will be initiated by examining previous studies associated with dampening by vegetation and the local conditions of the Baltic Sea. From the information gathered of the Baltic Sea environment, input parameters can be studied with the use of different plots of data series for significant wave heights etc. Input parameters for the modeling software will be acquired by analyzing the information in this manner. Different vegetation can be considered to determine which plant that is most suitable based on its dampening effect. Previous studies will be the point of reference for the plants' characteristics in the model.

2 Theoretical background

Information presented in this chapter will be used extensively in the report and is therefore important for the reader to take part of the reasoning used in later chapters. This will include what linear wave theory is, what extreme value analysis means and what type of nature based solutions that could be applicable.

2.1 Linear wave theory

Linear wave theory was introduced to simplify the process of calculating and modelling the behavior of waves and is based on the following assumptions made by George Airy 1845 [8]

- The fluid is homogeneous and incompressible; therefore, the density ρ is a constant.
- Surface tension can be neglected.
- Coriolis effect can be neglected.
- Pressure at the free surface is uniform and constant.
- The fluid is ideal or inviscid (lacks viscosity).
- The particular wave being considered does not interact with any other water motion.
- The bed is a horizontal, fixed, impermeable boundary, which implies that the vertical velocity at the bed is zero.
- The wave amplitude is small and the waveform is invariant in time and space.
- Waves are plane or long crested (two dimensional).

These assumptions will lead to a sinusoidal oscillatory wave, which is a condition for linear wave theory. Its utility has been proven to be accurate as long as the wave is not steep enough which would render linear wave theory useless [9]. There are four parameters that are the most essential when describing this type of wave. Its length $\boldsymbol{L}$ (from crest to crest), its height $\boldsymbol{H}$ (the distance from crest to trough), its period $\boldsymbol{T}$ (the time it takes for a wave length to travel) and the depth $\boldsymbol{h}$ (at which the wave is passing). It is now possible to derive expressions for the equations used in linear wave theory. Two different types of equations will be used when deriving the equations that will be used, (1) the mass balance equation and (2) the momentum balance equation.

Together with the assumptions used in linear wave theory, this will yield an equation for the dispersion relationship.

$$\omega^2 = gktanh(kh) \quad \text{or} \quad L = \frac{gT^2}{(2\pi)}tanh(\frac{2\pi d}{L}) \tag{2.1}$$

2.1 To see how it is derived, please read the following source: [9]. In equation 2.1, ω is the angular frequency ($\omega = \frac{2\pi}{T}$) and k is the wave number ($k = \frac{2\pi}{L}$). The wave number is the correlation between angular change and wave length, meaning that a longer wave length will yield a smaller wave number. Furthermore if the equations 2.1 are combined one can see that $\frac{L}{T} = \frac{\omega}{k}$ which will be the expression for the phase velocity.

$$c = \sqrt{\frac{g}{k}tanh(kh)} \tag{2.2}$$

2.2 The depth (d) will affect the equation and can therefore be defined for deep water velocities as c_0

$$c_o = \frac{g}{2\pi}T \quad \text{or} \quad c_0 = 1.56T \tag{2.3}$$

2.3

and the shallow water velocity will become

$$c_{shallow} = \sqrt{gh} \tag{2.4}$$

2.4 When individual waves move with different velocities they will inevitably interact and gather in groups. When this happens, the wave energy will be regarded for the gathered wave group rather than the individual waves. The group velocity will be defined as the velocity of the wave in front however the wave crest will move faster from the back of the wave group to the front. The difference in velocity is described by the correlation ($\frac{c_g}{c}$) and is assigned with the letter n. This number will vary between 0.5 to 1 depending on if wave group is situated in deep water or in shallow water (read 2.2.1). These parameters are the fundamental part of describing waves and the wave climate, it is the base of which models are built and data is gathered. This will also be the case going forward which will not be mentioned unless it is deemed necessary to do so.

2.2 Wave behaviour

Several different phenomenon will start to occur when waves enter the coastal area due to the effect of the seabed. These effects are important to take into account when calculating design wave heights nearshore and subsequently how accurate the model will become. Therefore, descriptions of the different phenomena will be presented in this section.

2.2.1 Shallow water & deep water

Waves can be defined differently depending on if they are in coastal waters or deep waters. Equation will differ significantly depending on this fact. Whether the wave is in deep water or shallow water depends on the water depth and the wave length according to 2.5.

$$\text{Deepwater}: \quad \frac{h}{L_0} < \frac{1}{2} \quad \text{Shallowwater}: \quad \frac{h}{L} < \frac{1}{20} \tag{2.5}$$

2.2.2 Shoaling & wave breaking

As waves enter coastal waters they will become affected by the seabed which leads the wave to slow down. Because the wave energy is constant, a gradual increase in amplitude and steepness will occur as the wave approaches the shoreline (see figure 2.1. The steepness of the wave could theoretically approach infinity if there were no physical boundaries. However, when the particle velocity exceeds the wave celerity the wave will become unstable and collapses upon itself, a phenomena that is refers to as the wave breaking.

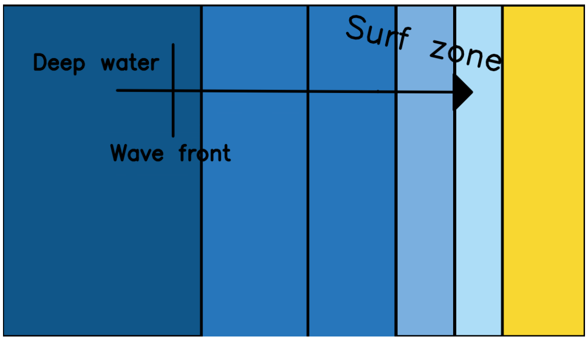

Figure 2.1: The nearshore conditions when shoaling occurs

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2.2.3 Wave breaking

Waves breaking can be observed nearshore as the phenomena occurs when the friction forces induced by the seafloor slows down the propagating wave. When the wave breaks it collapses and loses a significant amount of its energy in the process which means that waves that is year to break carries a higher amount of energy and are therefore more destructive, especially when the energy is realised (when it breaks). The exact conditions for a wave to break is dependant on the nearshore condition but generally it is around 0.78 which is called the breaker index [9].

2.2.4 Refraction

If a wave is propagating with an angle towards the shoreline there will be a lag in time for when the wave reacts to the seabed depending on its position relative to the depth contour. This will cause the part of the wave that is closer to the shoreline to slow down and the rest of the wave will slowly catch up. This phenomena is called refraction which causes waves to alter there course and bend towards the shoreline which can be seen in 2.2

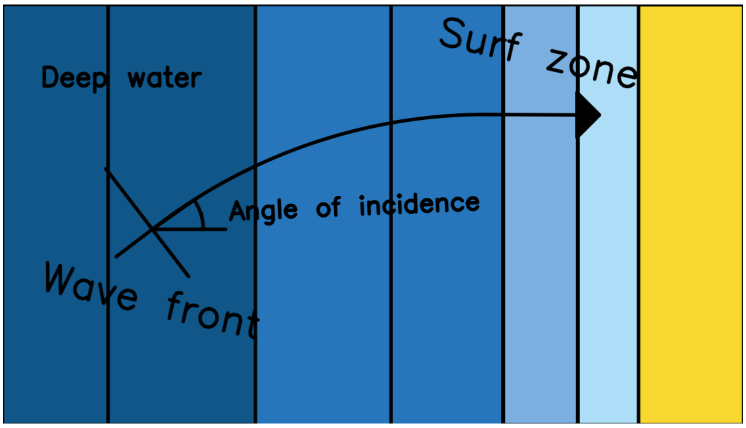

Figure 2.2: The nearshore conditions when refraction occurs

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2.2.5 Wave runup

The runup for a wave is defined by how far a wave reaches on the beach in relation to the still water level. It is divided into two components, the wave setup and the swash. The wave setup occurs due to the wave breaking and results in an increase of the still water level at the shoreline. The swash is defined as the intersection of the wave and the beach at a certain point of time. The swash is the standing component of a wave and is the wave energy that is not dissipated when the wave is breaking. The steepens of the beach will play a heavy roll in the dissipation of the wave energy. A steeper slope will dissipate most of the energy along the slope of the beach while a less steep slope would dissipate wave energy along the surf zone. A first order of magnitude is estimated by using the following formula [10].

$$R \sim \eta_u + H_s\xi \quad \text{where } \eta_u \sim 0.2H_s \quad \text{and } \xi = \frac{tan(\alpha)}{\sqrt{\frac{H_s}{L}}} \tag{2.6}$$

Another factor that determines the runup is the friction that the seabed enforces upon the wave. The material of the seabed will therefore govern the friction loss for a certain beach. One could choose to regard a sandy beach which would lead to the use of the Stockdon method [11]. The following equations are used when calculating by the Stockdon method:

$$R^2 = \begin{cases} 1.1\eta_u + 0.5(S_w^2 + S_{ig}^2)^{\frac{1}{2}}, & \text{if } \xi \geq 0.3, \\ 0.043\sqrt{HL}, & \text{if } \xi < 0.3, \end{cases} \tag{2.7}$$

$$\eta u = 0.35H\xi \tag{2.8}$$

$$S_w = 0.75H\xi \tag{2.9}$$

$$S_{ig} = 0.06\sqrt{HL} \tag{2.10}$$

Another alternative is to regard the coastal area as rocky which would prompt one to use the Eurotop manual for runup on an impermeable rubble mound revetment[12].

$$\frac{R_{u2\%}}{H_{m0}} = 1.75 \times \gamma_b \times \gamma_f \times \gamma_\beta \times \xi_{m-1} \tag{2.11}$$

There are three gamma values in equation 2.11, γ_b, γ_f and γ_β which represents influence factor for berm, influence factor for surface roughness and influence factor for oblique wave angle respectively. The values that are used for a rock revetment with no berm and an angle of incidence that is perpendicular to the revetment is 1 for the berm, 1 for the angle and 0.55 for the friction.

The bathymetry will also affect the runup which leads to the runup behaving differently for every individual beach. To take this into account, models have been developed where bathymetry and local wave conditions are used as input. This will be further explored in section 4.1.

2.3 Sea level

The point of reference for SWL that is most commonly used in Sweden us the RH2000 as it is the national height system. Its point of reference, also known as the vertical datum, is the MSL the from the year 2000 and has its point of reference in Normaal Amstedams Pieal (NAP) [13]. The current SWL according to RH2000 is on average +16 cm which is sure to increase with climate change as a driving factor.

In some cases, especially when making statistical analyzes, the relative water level is used which is another point of reference that disregards the effects of sea level rise. The relative water level is calibrated from the measured value in RH2000 by either removing the added sea level for the years post 2000 or adding the difference in average sea level when regarding years prior to 2000.

2.4 Vegetation

Using vegetation as coastal protection is a NbS that is multi beneficial for a plethora of reasons but is also difficult to model. This is due to the fact that local condition will govern how the plants will establish and their wave damping capabilities. Geomorphology, ecology and hydrodynamics are some of the in situ conditions that will make comparison of NbS for different locations difficult [14]. Furthermore, implementation of vegetation as coastal protection is mainly preformed at cites where the wave energy is weaker. The plants are sensitive to greater forces as the vegetation-wave interactions are highly dynamic, damages to the vegetation can occur by the stem breaking or the plant being swept away. The diversity of plants in different environments is a testament to the variability that plants has in dampening effect and robustness [15]. Vegetation is able to dissipate the wave energy due to the force being directed at the vegetation which causes dampening similar to drag. The wave energy conservation equation for the vegetation can be be expressed as:

$$\frac{\partial E_{\mathrm{cg}}}{\partial x} = -\epsilon v \tag{2.12}$$

The swaying motion of the vegetation is also a factor that can be taken into account when observing submerged vegetation. Another property of the vegetation that can be considered is the elasticity of the vegetation, especially when considering salt marsh vegetation.

Models were originally including this effect in the drag coefficient and comparing the calculated values with seaweed experiments that were analyzed in a controlled environment. To obtain knowledge of the attenuation of vegetation, some build physical models which will generate accurate effects of the vegetation. One conclusion that was drawn form laboratory experiments is that stiffer vegetation will have a higher dampening effect compared to the flexible vegetation [16].

The inclusion of vegetation is complex to consider as seen by the aforementioned examples, furthermore there are effects of vegetation that is yet to be understood. A suggested method to circumvent these difficulties is to use the drag coefficient (c_D) as parameter that can be calibrated to describe the local conditions accurately [17]. The C_D coefficient can be put in relation to Kuelegan-Carpenter number, **K**, with equation 2.13.

$$C_D = 0.47 \exp(-0.052K), \quad 3 < K < 59 \tag{2.13}$$

The coefficient is within the range of 0.01-0.52 depending on vegetation and circumstance according to the model used by F. Mendez and I. Losada. In their experiment, seagrass was used with a calibrated C_D value of 0.2. In the case where calibration is not an available option a comparison of different locations is necessary to build a robust model that can predict results without previous measurements.

Despite the difficulties with describing the effects of vegetation there are advantages to vegetation (and NbS in general) compared to hard structures such as rock revetments. For example, when considering a rock revetment that is exposed to a storm event. If said storm event is more severe than the design storm damages to the structure could render the coastal protection useless. In contrast, a salt marsh will be damaged but the damages will occur gradually.

Trees

Wave attenuation with the use of trees is a viable option in many parts of the world. More tropical environments allows mangrove trees to grow which benefits the coastal areas both from its attenuating properties and also the biodiversity it brings for fisheries etc. The mangrove forests have a dampening effect on storm surges and do also collect carbon dioxide. However, these trees are not capable of survive in freezing temperatures and are therefore not an option for the studied part of the world.

An option that has been explored in the colder parts of the world is planting willow trees which has been proven to dampen waves [18]. They grow naturally in Skanea and is able to grow close to brackish water which would make them suitable for plantation in front of the WWTP (see figure 2.3).

Figure 2.3: The nearshore conditions when shoaling occurs

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An experiment was constructed by Bregje K. van Wesenbeeck et. al looked at the effects of willow trees for an extreme storm event [18] . The model contained 32 willow trees, two rows with 16 trees each with a length of 40 meters with the trees being 15 years old. The canopy of the trees were relative close to the water but was also altered to understand the ideal distance for maximum attenuation. The waves were generated within a basin with the incoming waves being at a $H_{\max}$ of 2.5 meters. The maximum attenuation effect was measured to 22% with the ideal condition being a full canopy with leaves and the wave hitting the middle of the canopy and a stem height of 0.3. The wave dampening was put into relation to runup with the conclusion that the reduction effect was similar. The experiment also analyzed the C_D value when $\mathbf{K}$ approaches high numbers, showing that C_D will approach 1.2 in relation to the $\mathbf{K}$. The estimated C_D for the study was between 0.4-1.2.

The roots of willow trees can in some cases prove problematic as its roots can penetrate pipes to ensure water supply for the plant. However as the trees will be situated at the coast they will have enough water supply to not affect the WWTP.

Mangrove trees are by far the most understood type of vegetation for coastal protection meaning that models have been centered around them. As previously mentioned, they will not establish in freezing temperatures however the properties of the canopy could somewhat be compared to bushes and shrubs as the branches and leaves have similar flexibility which is strongly connected to the drag. The comparison is also made due to the lack of data for usage of bushes as coastal protection. A study regarding attenuation through a mangrove forest estimated that C_D values would range between 0.5-1.5 for the studied case[19].

Salt marshes

A salt marsh is an environment that is dominated by halophytic plants, meaning that they are capable of growing in a saltwater environment with the roots situated in the saltwater along the shore or in the soil adjacent to the saltwater [3]. A diverse set of studies have concluded that salt marshes can dissipate wave energy, with one lab experiment showing that the wave height reduction can be as high as 60%. This experiment was conducted by [20] used a 300 meter long flume where the studied area was a patchwork of marsh blocks. The blocks were submerged 2 meters below the water level and exposed to wave heights up to 0.9 meters. After the experiment, there were no noticeable damages to the planted salt marsh patchwork. The experiment was analyzing extreme storm conditions for a salt marsh.

Another study on the same topic was also analyzing the attenuating effect of salt marshes. The study concluded that a 50% attenuation would occur for a wave H_S of 1.55m and 70% for a H_S of 0.8m. The average characteristics of the salt marsh was a stem thickness of 5mm, a stem density of 344 per m^2 and a height of 71 cm[21].

2.5 Extreme Value Analysis

Commonly when constructing shore protecting structures one will consider a storm event with a certain return period that will govern the input parameters for significant wave height, still water level and time period. The significant wave height is the average of the top 1/3 of waves, the return period is defined as 1/probability of exceedance, therefore a method of acquiring the probability of exceedence is required. To do this, probability distributions are applied to the dataset which will reveal the probability depending on the wave height or storm surge levels. Generalized Extreme Value (GEV) distribution is an alternative that is common to apply (see equation 2.14). Alternatively, a Weibul distribution or a Gumbel distribution could be more accurate depending on the input parameter ξ [22].

$$G(z) = \exp\left(-\left(1+\xi\left(\frac{z-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right)\right) \tag{2.14}$$

GEV plots are beneficial when analyzing the return period of storm events that have occurred and can also predict the return period for each wave height by plotting the data series. Therefore a longer data series will yield results with a higher accuracy. The accuracy may diminish for extreme storms with a high return periods as they are outliers, thus they may stray away from the fitted distribution. This is important to keep in mind when deciphering the return period of extreme storms, especially those that overshoot the distributed GEV plot. The input in a GEV distribution is the peak storm for every year of the data series. An option to determine the fit of the curve to the input values is to regard the coefficient of determination (R^2 value) which indicates just that, the calculation for R^2 can be seen in equation 2.15. It can vary between 0 and 1, 0 indicating no fit and 1 indicating perfect fit.

$$R^2 = 1 - \frac{\text{Variance explained by the model}}{\text{Total variance}} = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2} \tag{2.15}$$

When using input data for a SWL GEV distribution it is important to use the Relative sea level. This is due to the RH2000 point of reference increasing with the rising sea levels meaning that a storm that causes +80 cm of SLR 1980 and one 2020 will have different values as the mean sea level has increased during those years. This will corrupt the data, thus, using the relative sea level will be suitable instead as it disregards the effects of SLR.

However, when the distribution is completed it is important to take sea level rise into account. This is because SLR will increase the mean sea level and therefore affect forecasts of extreme events by the added height in sea level. Predictions for SLR can be found on the swedish meteorological and Hydrological institute (SMHI) and have been produced by IPCC. They have made calculations for several different scenarios depending on future predictions of carbon dioxide emissions and how far into the future one would look. Average sea levels in 2024 are at a level of +16 cm which should be taken into account when making predictions. In summary this means that the increase in mean sea level since the year 2000 should be added to the SWL reading from the year of interest.

3 Finding the design storm

To accurately predict the runup at the WWTP and to see how different plantations will affect the runup the numerical model XBeach will be used. The input data needed will therefore be the bathymetry, the topography in front of the WWTP, wave data, wave runup and vegetation. Fortunatley, data for bathymetry and topography are available for the public at Lantmäteriet. This data can then be treated in QGIS by merging the two different measurements ensuring that the data is interpolated and consistent. The merged topography and bathymetry will be extracted as a matrix with point values from QGIS which is nescessary to run the data in XBeach. XBeach is furhter explored in chapter 4.1.

Wave data has been modeled by LTH [23] and calibrated with nearby measuring points to assure its accuracy. The chosen point of reference is situated 440 meters offshore of Kivik WWTP. The dataset extends from 1958 to 2023 with 1 hour intervals and includes significant wave heights, direction of the wave rays, time period and some other parameters that will not be used. SMHI provides data for the still water level which is acquired by a measuring station at Simrishamn. Simrishamn is located 16 km from Kivik which makes this measuring station viable as input data. The dataset is from 1982 and the station is still active. The data can be analyzed in Python to determine input parameters for the wave conditions at at the coastal area outside of the WWTP.

3.1 Bathymetry and topography

QGIS is a geographic information system that is commonly used to generate or analyze maps of different sorts. Data can be expressed as either rasters or vectors. For topography, rasters will be preferable as they are expressed as 2D pixels which is convinient when explaining height variations.

In QGIS, one will be able to treat bathymetry and topography to merge the maps (rasters) to have a consistent transition between land and water which is required to analyze the runup effects in XBeach. To do so, rasters were acquired from existing measurements of the area. However measurements of bathymetry is not preformed in the same way as the measurements for topography which leads to a gap of information between the different zones. This is due to topography is taken with LIDAR scanning which measure how fast the light is reflected from an airplane to the ground and then back. The same can not be done for the bathymetry as the water will reflect the light causing the water surface to become the output data for the bathymetry. Measurements for bathymetry is instead preformed by echo sounders, which are placed at a ship's hull and will instead measure the time it takes for the sound to travel from the hull and back[24].

When acquiring the raster for topography from Lantmäteriet, a squared area has to be marked in front of the WWTP which will include values for the ocean as well. As mentioned above, the values for the ocean from LIDAR measurements are inaccurate and will therefore be cut out from the initial raster. This is done with the raster calculator where the function“AND” allows you to acquire a raster where both rasters align. This will be used to a template when removing the ocean from the topography raster. In QGIS, the cutting tool is easier to use on vector layers, thus a transformation of the raster layer to a vector layer was made to yield the desired raster for the topography. The merge tool was then used to have a consistent layer to export to XBeach, however some cells did not align perfectly where the two layers met which led to cells with no data. These values can be changed to zero which will not be a perfect representation of reality. Fortunately the data that will be extracted for QGIS is a one dimensional cross section perpendicular to the WWTP. Therefore these error points will not be accounted for in the actual model as long as the cross section does not intersect one of the error cells. The figure that is produced will include these error point but a 1x1 pixel will not be visible on the figure which means that leaving them as zero is a viable option that will not affect the results or the figure.

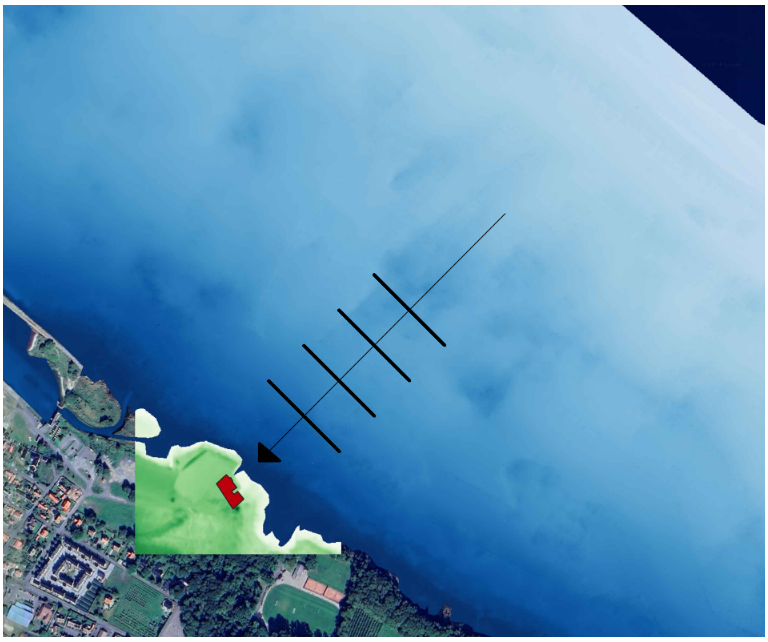


Figure 3.1: The bathymetry (the blue raster) and topogrophy (the green raster) included in QGIS. The area marked in red is the WWTP building.

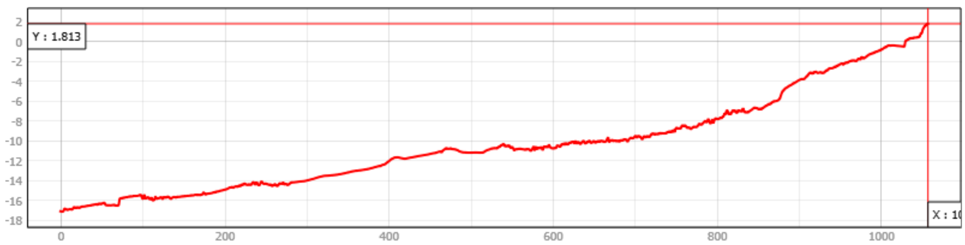


Figure 3.2: The corresponding cross section for the wave propagating towards Kivik WWTP with the direction perpendicular to the WWTP
. the elevation is shown in the y axis.

3.2 Hydrometeorological conditions

The raw data that is given is far too extensive to be able to draw any conclusion from without somehow being treated or plotted. Python is a programming language that will be able to plot the data and gather specific data points by assessing the csv-files. This enabled the data to be utilized for several types of plots which would not be possible by simply using excel. For instance, a wave rose could be plotted which gave the valuable information of which direction the waves would propagate. This information will give the angle of incidence that will be used in the one dimensional XBeach-model and a line for the incoming waves could be drawn in QGIS. Python operates by installing packages that creates environments for the user to customize which functions that should be included. Matplotlib is an example of an environment that includes packages that allows functions such as plt.plot to be used to plot figures easily. The supply of packages is varied and allows for some operations that otherwise would be difficult to preform.

3.2.1 Wave rose

As mentioned above, the wave rose is a visual tool to aid with determining the angle of incidence for the wave propagation. The code to do so was already available from Github [25] and could be adjusted for the data for Kivik. If Python is to be able to utilize the csv file, one has to create a path for Python to find where on the computer the file is stored. Another adjustment that was made to the code was increasing the threshold for the significant wave height. This is to eliminate waves that are measured during calm conditions as the angle of incidence is only interesting for rough conditions. By having a threshold of significant wave height of 0.8 meters the following waverose was plotted.

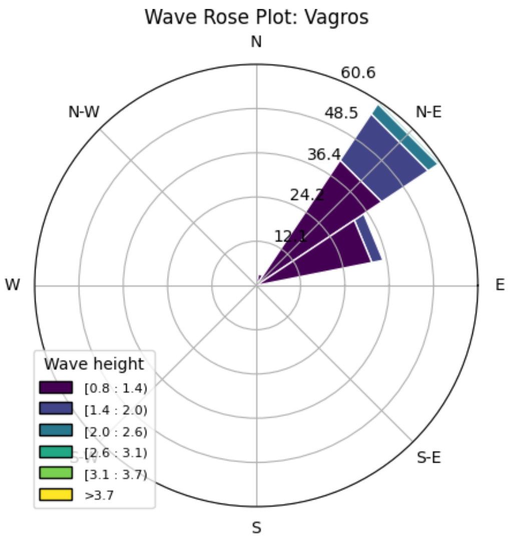


Figure 3.3: Direction of incoming wave 440 meters offshore of Kivik WWTP

3.2.2 Scatterplot

The use of a scatterplot is beneficial to determine the correlation between wave height and still water level at the vicinity of Kivik. To do so, the data can only be plotted for the time series where the data is available for both measurements which occurs between 1982-06-01 and 2023-12-31.

3.2.3 Extreme storms and water levels

A comparison of the four most extreme storm events is of interest to put Babet into perspective to other storms that have occurred during the time series. A satisfactory method to achieve this is to create a plot which contains the significant wave height in the y-axis and the storm duration in the x-axis. Finding the extreme storms from the time series is done by filtering the time series to only choose values over a certain threshold. Three meters was used in this case as this yielded only a handful of storms. When the storms are found, 25 values from each storm are chosen (representing 24 hours of the storm event) and plotted in the same graph. The results of this plot can be seen in figure 3.5a. A similar approach can be made when considering extreme water levels. The x-axis can still be an interval of 24 hours while the y-axis can contain the SWL in the RH2000 system. The acquired plot can be seen in figure 3.7a.

3.2.4 GEV plots

Python includes packages for aiding with linear regression and GEV. For linear regression there exists the package sklearn.linear_model and for GEV there is the package pyextremes. The pyextremes package also enables a way to calculate the return period and visualizing the data, provided that the matplot.lib package is installed [26].

3.2.5 Wave runup

The runup was calculated for each hour of Babet with the use of python with the Stockdon and Eurotop method being used (see equation 2.6, 2.7, 2.10 & 2.11). The result was plotted to compare the methods which will showcase both when the runup is most severe and how comparable the used methods are compared to the measured value of 2.3 meters. The resulted plot and table can be seen in chapter 3.3.3. The slope of the shore used in calculations is 1:40 which is used in the report made by Sweco in their calculations [5].

3.3 Results & Discussion of the wave climate

Results for the different Python plots will be presented in this chapter. Results that has been acquired from the literature study will be included in the discussion chapter of the thesis (Chapter 5. The conclusion drawn from these results will be used as input in the XBeach model (see chapter 4.1).

3.3.1 Bathymetry

The bathymetry was already measured previously so the bulk of the result is from the simplification made from interpolating the values between the bathymery measurement and the topography measurements. The cross section that is used in the XBeach model is plotted in figure 3.2.

3.3.2 Extrme storms & GEV

Significant wave heights outside of Kivik WWTP can be seen in figure 3.4 in relation to the still water level. The scatterplot includes all hourly measurements from 1982-06-01 until 2023-12-31 and is plotted using the relative water level as described in section 2.3.

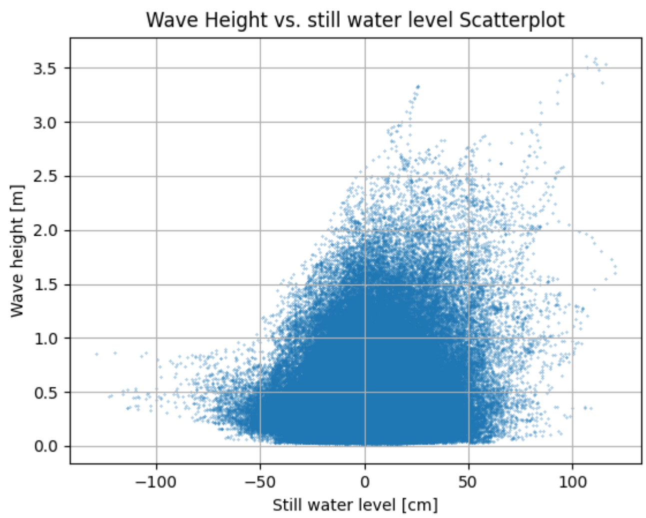
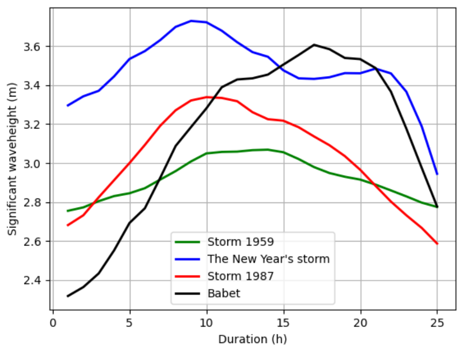


Figure 3.4: Scatterplot for the measurement point situated 440 meters offshore of Kivik's WWTP.

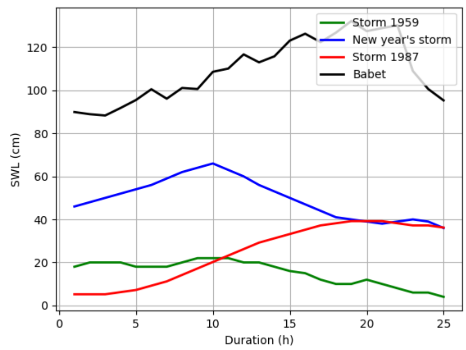
The plot has several tall waves that are located to the right of the figure. The highest H_S for the scatterplot which occurs for SWL below zero is at 2.5 meters which showcases the correlation between H_S and SWL and in extension the correlation between H_S and eastern winds.

Significant wave height

To give some clarity to the storm events that produced the highest H_s, figure 3.5a was plotted that includes the four storm events with the highest H_s within the dataset. The SWL was also plotted for the same period as each storm event in figure 3.5b to gauge if there is any connection between the two.



(a) Comparison of the four most extreme storm events when regarding H_s since 1959. The measured point is situated 440 meters offshore of Kivik's WWTP.



(b) Corresponding SWL for the extreme H_s seen in figure 3.5a.

Figure 3.5: The four highest SWL since 1982 shown in figure 3.5b with the corresponding H_s shown in figure 3.5a.

Although wave heights are in the same range for the four storms it is evident when looking at figure 3.5a that the severity of Babet is far greater due to the difference in SWL during the storm event. Note that data for SWL is used for a time period prior to 1982 for both the new year's storm and the 1959 storm which is not included in the dataset. The data is instead gathered to an somewhat adjacent measurement satiation located in Ysatd (south shore of Sweden). The data is therefore not as trustworthy for these two event as variations in SWL can be relatively significant for these storm events but not enough to offset the clear difference between these storms and Babet which is why no further investigations are made.

A general trend for the return period for the significant wave height is plotted in A GEV distribution to gain insight in the risk of an event to repeat. Each point marks the peak significant wave height for a year in the data series. The R^2 value for the plot is calculated to 0.991.

All values are not encapsulated in this plot as there is an exceedance for a 100 year return period which can be seen from the exclusion of H_S levels above 3.5 meters. This means that both the new year's storm and Babet is excluded. The return period for both of these wave heights are above 100 years. This is how the code associated with the figure operates further exlporation could be made in this department to get a more accurate return period for the events that are excluded.

Still water level

Determining the four highest still water levels from the series is also executed by plotting them in a joint graph and showcasing the corresponding H_S (figure 3.7a). Figure 3.7b shows that there are many occations when the sea level reaches high levels however the siginificant wave heights during these occations do not reach the same extremes except for Babet. The difference in significant wave height is 1.5 meters

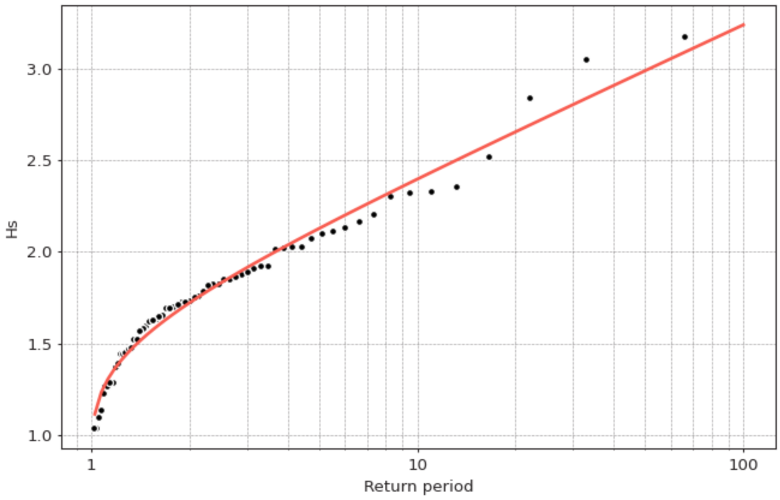
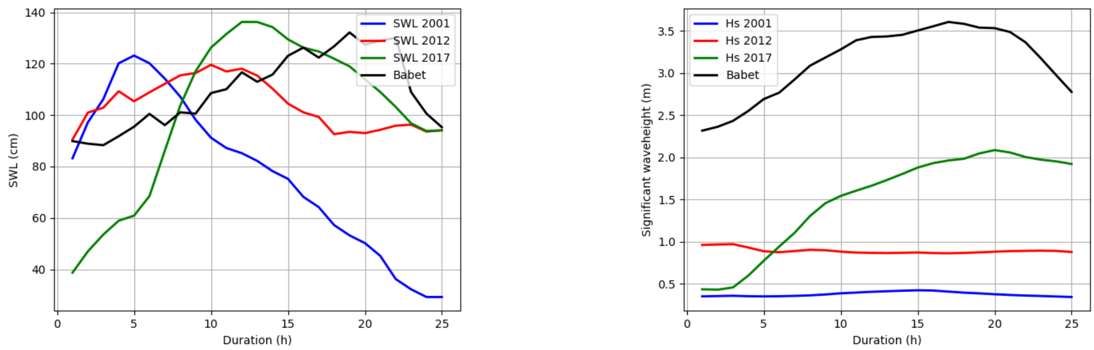


Figure 3.6: A GEV distrubtuon with a 100 year return period for the H_s.



(a) Comparison of the four most extreme SWL since 1959

(b) Corresponding H_s for the extreme SWL seen in figure 3.7a

Figure 3.7: The four highest SWL since 1982 shown in figure 3.7a with the corresponding H_s shown in figure 3.7b

between the 2017 storm and Babet.

A GEV distribution is made in the same manner as for the significant wave height to grasp the return period for this occurrence. The plotted graph can be seen in figure 3.8 where each point is the peak SWL for every year of the data series and the R^2-value is 0.997 indicating a good fit.

The return period for Babet will correspond to the point located at a relative water level of 116 cm which can be seen as the second highest point in the series. The highest point represent the relative water level of the 2017 storm.

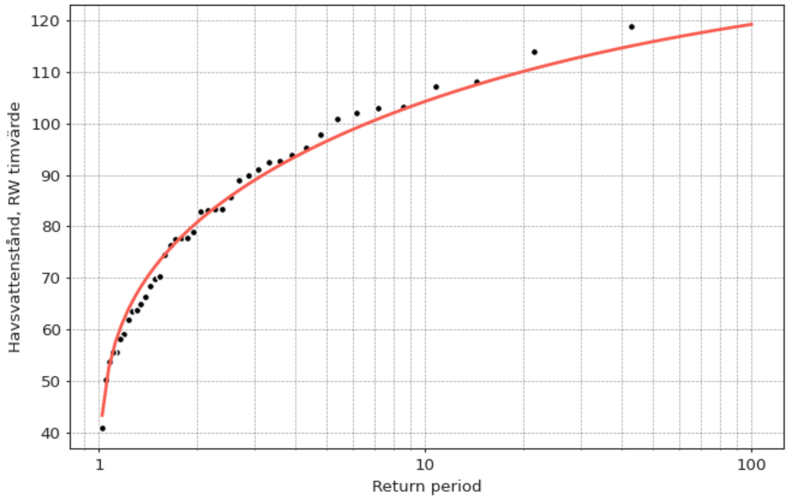


Figure 3.8: A GEV distrubtuon with a 100 year return period for the SWL.

3.3.3 Runup

The runup was calculated using the Eurotop method and the Stockdon method to understand the similarity to the observed runup-level seen in figure 1.5. Figure 3.9 was therefore created to compare the different runup levels with the two approaches and to validate the observed runup.level of 2.3 meters. The runup-level is independent to the SWL which means that the SWL should be added to the calculated runup-level which is presented in Table 3.1. Another approach to calculate runup is to do a joint probability analysis which will combine the likelihood of the H_S and SWL while regarding the conditional probability. However this is difficult to manage and unnecessary for the purpose of this report as the most interesting parameter is the parameters of the storm event not the exact probability of its occurrence.

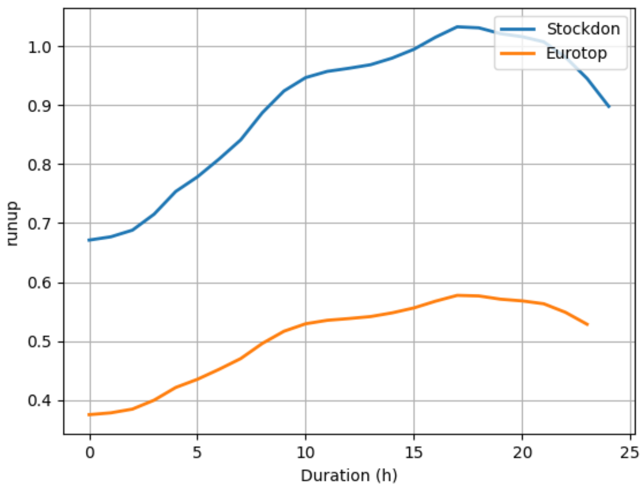


Figure 3.9: The runup for Stockdon and Eurotop simulations at Kivik WWTP for Babet.

Table 3.1: Peak runup heights from the three approaches with corresponding Tp (meters)

	Stockdon	Eurotop	Observed
R2%	1.02	0.58	1.04
R2% + SWL	2.28	1.84	2.30
H_s	3.61	3.61	3.61
Tp	9.95	9.95	9.95

.

3.4 Conclusion for the design storm inputs

It is evident that the most severe storm from the data series was Babet as it has a combination of the second to highest SWL from the data series and the second highest H_S as can be seen in figure 3.5a & 3.7a.

From the plot of the calculated Runup with both Stockdon and Eurotop the highest runup occurs at hour 17 of the time series which corresponds to the vales shown in row two of Table 3.2, therefore, the values $H_S = 3.61$ m and SWL = 126.3 cm will become the design parameters for the storm which can be read in figure 3.9 and read in A Appendix. Babet being the outlier in the data series can be seen in the scatterplot (figure(3.4) where the dots in the top right corner represents the storm.

Table 3.2: Design parameters gathered from Babet (in the middle row)

H_S [m]	SWL [cm]	Tp [s]
3.55	123.1	9.82
3.61	126.3	9.95
3.58	122.4	10.12

The return period for Babet regarding H_S is above 100 years and when regarding SWL 40 years when looking at the GEV distrubutions in figure 3.7a and figure 3.8. The combined likelihood of Babet would therefore be at a minimum 100x40 = 4000 years if these events would be independent. However eastern winds causes both significant wave heights and SWL to increase simultaneously which as shown in the waverose (figure 3.3) is a requirement for high waves thus the return period of 4000 would be inaccurate.

Choosing an event with lesser impact than Babet would be unnecessary as the WWTP withstood the wave forces generated by the storm. It could be argued however that if a storm of the same caliber were to hit Kivik WWTP there would be higher consequences as the protecting rock revetment got damages during the storm. Furthermore, with SLR in mind the same storm would automatically reach higher levels from the extra elevation from the added sea level. The accuracy of SLR forecasts will become more unstable the further one looks into the future. The estimate of SMHI made of +18cm in added MSL for 2050 will therefore be analyzed to have a somewhat secure point of reference.

Designing for an extreme storm is somewhat arbitrary as the consequences of failure is a factor that is evaluated by the perceived value of the structure that one wants to protect. Basing it of the perceived value makes the process opinionated in its nature. However in this case, although the WWTP is important for the population in the municipality, no further adjustments are made to the incoming waves. This is motivated by the predicted recurrence of Babet being extremely low according to the GEV-plots.

The 1872 Baltic Sea flood is not considered in design as even though it occurred, the likelihood of an equally severe storm occurring is slim to none and the event would flood the WWTP regardless of protection purely by the SWL being situated 60cm above the base of the WWTP.

4 Xbeach modeling for vegetation

Modeling for vegetation is possible after acquiring values for the design storm. Simulations for both current water levels and water levels for 2050 is considered for the inputs for Babet. Bathymetry remains the same during all simulations as the effect of sediment transport is neglected due to the sea bed consisting mainly of rocks.

4.1 XBeach

Xbeach is an open source numerical model that was created with the purpose of predicting the effect of hurricanes at sandy beaches, mainly the impact of hydrodynamic and morphological processes. It is developed by UNESCO-IHE, Deltares, Delft University of technology and the University of Miami. XBeach has been extended to take into account several different effects at the coast such as vegetation or hard structures. It has been proven to be trustworthy by comparing the model to laboratory experiments and comparing the results [27]. XBeach is also able to take the runup into account and the attenuating effects of vegetation when making simulations which is the main reason as to why it will be used for modeling the runup at the WWTP.

4.1.1 Input values

To run XBeach, a bat-file is created that is calling to the Xbeach program (xbeach.exe). The program will initiate by reading a parameter file that has to be named params.txt. Within the params.txt is where one specifies the condition for the area of interest. Examples of parameters that can be contained in the params.txt according to the XBeach manual are bathymetry, wave input, flow input and morphology input. A parameter can be specified directly in the params.txt or call to another file that stores a dataset. The extent of parameters that can be used is much wider, this study will utilize the vegetation parameters as well as parameters for water levels.

XBeach uses default values for non specified parameters to aid the user when creating the model. This is a necessity as there are a plethora of parameters in XBeach that can be modified which if done manually would be time consuming. However, there are some values that are required to be defined by the user, namely the wave input, the grid and the bathymetry.

The grid can be 1D or 2D which in modeling languages can be somewhat deceiving as 1D is the wave input from a straight line, hence the name 1D. However, the depth is still taken into account in the actual model which would make it 2D when plotted. The confusion in the definition occurs is because the grid and the bathymetry are defined separately in the model which means that the grid is 1D but the result in the model will be seen as 2D.

The wave input is not directly written in the params.txt file, instead, a txt file that is called Jonswap.txt is created to contain the wave parameters.

The effects vegetation will have regarding dissipation is taken into account in XBeach. The user defines the vegetation by calibrating the input parameters. In the XBeach manual the different input parameters for vegetation are defined as " nsec, ***ah***, C_D, ***bv*** and ***N*** that represents the number of vertical sections, height of vegetation section relative to the bed, the drag coefficient, stem diameter and vegetation density per vegetation section, respectively" [27] . The manual also includes a figure that showcases how different parameters can be implemented.

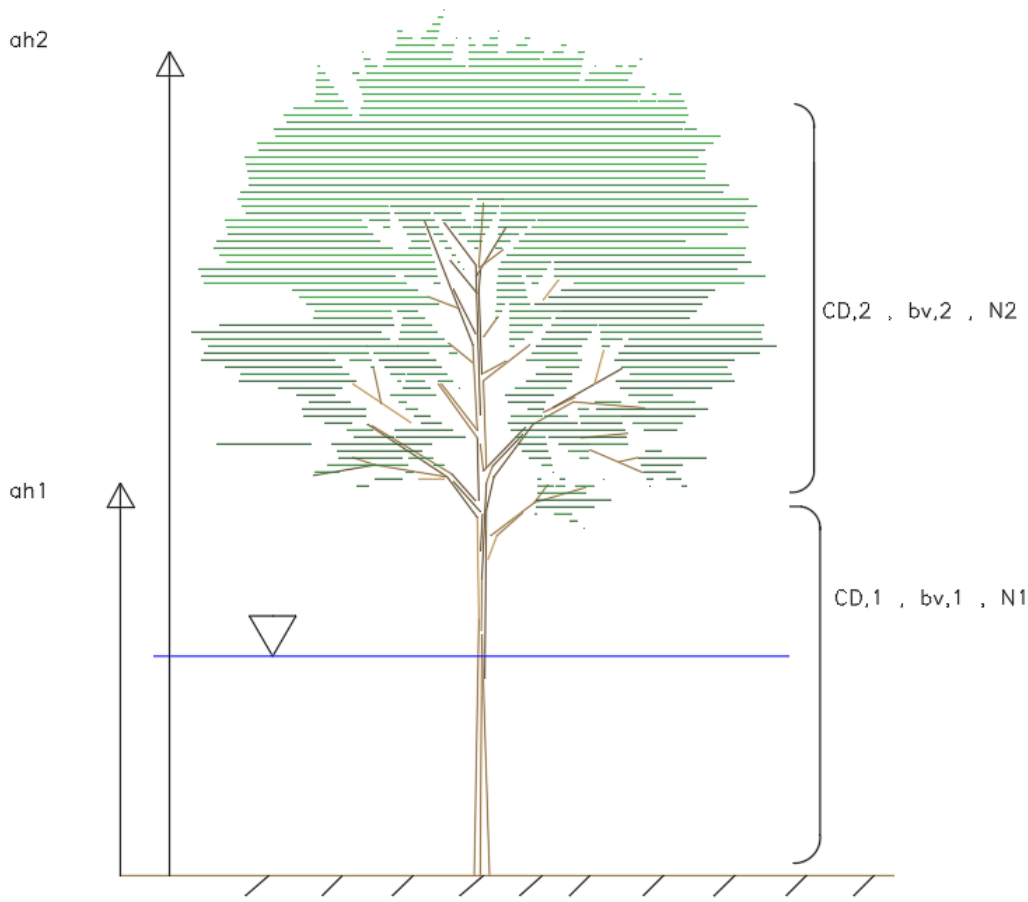


Figure 4.1: A modified figure from the XBeach manual which showcases how vegetation is used as an input in the software [27]

The benefit with the nsec function is the ability for the user to dissect the plant into different sections which is favourable when modelling non uniform vegetation such as willow trees. The parameters for the vegetation is defined in a .veg file which can have an arbitrary name chosen by the user. The position of the vegetation in the grid is defined in veg.bed where each value corresponds to an element on the bed.dep. Therefore, the length of bed.dep and veg.bed will be equal. The elements in veg.bed should be interpreted as the number of species at a certain point on the grid, the number of species is distributed by stating the number, for example, if no vegetation is supposed to be contained at the first coordinate on the bed.dep one would write 0 in the veg.dep file.

4.1.2 Used Inputs

Previous studies on dampening effect have been used to find a satisfactory set of input parameters for the vegetation and what vegetation that should be used. A combination of perceived effectiveness, available information and possibility of establishment have been weighed when making this choice. Three main candidates have emerged, namely salt marshes, willow trees and leave bushes. Both willow trees and salt marshes had previous studies with promising results and bushes is deemed to have similar properties to a mangrove canopy which would imply that the dampening effect would be satisfactory. The chosen input parameters for the plants can be seen in Table 4.1 where the willow tree is dissected into the stem's properties and the canopy's properties (see figure 4.1).

Table 4.1: Input parameters for vegetation in XBeach

	Bushes	Saltmarsh	Willow tree canopy	Willow tree stem
C_D	0.5-1.5	0.25-1.2	0.4-1.2	0.2-0.6
N	15	400	40	5
ah	1.5	0.4	1.7	0.3
bv	0.05	0.03	0.005	0.2

Values for height (ah) and plant density (N) is based on gathering information of previous XBeach modeling and assumptions of how the specific plant would establish for the conditions outside of Kivik WWTP. C_D values are purely based on other experiments as descried in chapter 2.4.

As mentioned in chapter 2.4, a range of 0.4-1.2 is expected for the C_D of the willow tree. An example in the XBeach manual put the relation of the canopy friction and the stem friction to 2:1, therefore, the stem was assigned a range of 0.2-0.6. The experiment used branches with a thickness of 3 cm which is why the bv value is assigned to 0.03.

The veg.bed included vegetation from where land meets the ocean up to 10 meters in front of the WWTP which is roughly 17 meters long . This is the flat area which currently is occupied by a low density patchwork of reed and trees. The same stretch is is used for all vegetation for the results to be consistent when comparing the dampening effect.

4.1.3 Output parameters

The output parameters that is produced in XBeach is chosen by the user by indicating these in the params.txt as well as the number of output parameters which is desired. Output parameters that is always included, and the same ones that are used for this model, is $\boldsymbol{H}$, $\boldsymbol{zs}$ and $\boldsymbol{zb}$. $\boldsymbol{H}$ is the significant wave height along the x-grid, $\boldsymbol{zs}$ is the Water level and $\boldsymbol{zb}$ the bed level. H_S is the desired output as the reduction in Significant wave height in a model which includes vegetation and one which simulates the current condition will yield the effectiveness of the vegetation. The result will be presented as the percentage of wave height reduction as it is tangible to the reader and is a common way of representation in other articles on the subject.

4.2 Model Calibration

A stretch adjacent to the WWTP was used for calibration as this is the spot where the measured runup height of 2.3 meters was situated. The stretch runs parallel to the used bathymetry seen in figure 3.1 and was acquired from the same QGIS raster that was used in the figure. The stretch is used for calibration as washed up seaweed can be identified which indicates the reach of the runup during Babet. This can not be done in front of the WWTP as the structure blocked water to reach further which is why the runup is calibrated with a stretch that does not have any obstacles. As both the bathymetry and the angle of incidence for the chosen stretch are the same and the lines are close to each other it is deemed reliable to use this stretch for calibration.

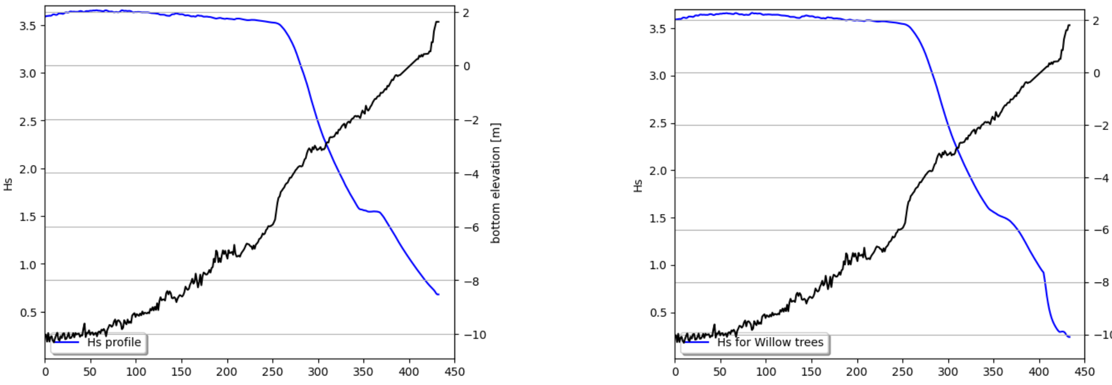
The original strategy was to use the XBeach specific output parameter runup as point of reference but unfortunately there were errors within the params.txt that prevented this method. The other option was to utilize the H_S output which will not be as describing of the actual hydrodynamic processes for runup but would still be able to tell the dampening of the wave height in the later stages of the model which made the use of H_S an available option. The difference of measured and simulated runup after calibration was 2 cm which is deemed sufficient in this case.

4.3 XBeach results

Results from the simulation of the peak hour of Babet without considering any added vegetation can be seen in figure 4.2a. The same simulation was made for a SWL of 143 cm to simulate the effects for 2050. The bathymetry and the H_S-profile are ploted in the same graph to visualize the effect of the bathymetry on the wave evolution.

Three different types of vegetation was considered (leafy bushes, salt marshes and willow trees) with the SWL for Babet and the SWL for 2050 for each type of plant. This yields 6 simulations but it was decided that the range of the drag coefficient was too great to only analyze the average value which led to the inclusion of simulations for both higher C_D-values and lower C_D-values (see figure 1.2 for planed area of vegetation). Therefore a total of 18 scenarios was simulated with the results being shown in table 4.2. The wave dampening is showcased in the table and is calculated as the relation of the reduction of H_S and the H_S prior to establishing vegetation where the point of reference is chosen in front of the added vegetation. The cells is the percentage of the dampening effect. Values just outside of the WWTP were also calculated and can be seen in Appednix B but these were discarded as the values were not following the expected increase in wave dampening that comes with higher C_D-values.

A plot of the relation between the original evolution of the H_S and the evolution for



(a) Evolution of the H_S for Babet's unaffected conditions during peak hour

(b) Evolution of H_s for willow trees for high C_D-values

Figure 4.2: Evolution of the H_S as the profile approaches the WWTP for SWL = 126 cm.

Table 4.2: Dampening of H_S (%) from the vegetation for all simulations after the established vegetation

	Bushes	Saltmarsh	Willow tree
C_D low, SWL 1.26 m	56	34	49
C_D mid, SWL 1.26 m	57	55	56
C_D high, SWL 1.26 m	61	62	62
C_D low, SWL 1.43 m	44	25	49
C_D mid, SWL 1.43 m	55	50	55
C_D high, SWL 1.43 m	61	59	60

H_S when vegetation is included to showcase the effects outside the WWTP. This can be seen in figure 4.3 where the vegetation is included from 406 to 422.

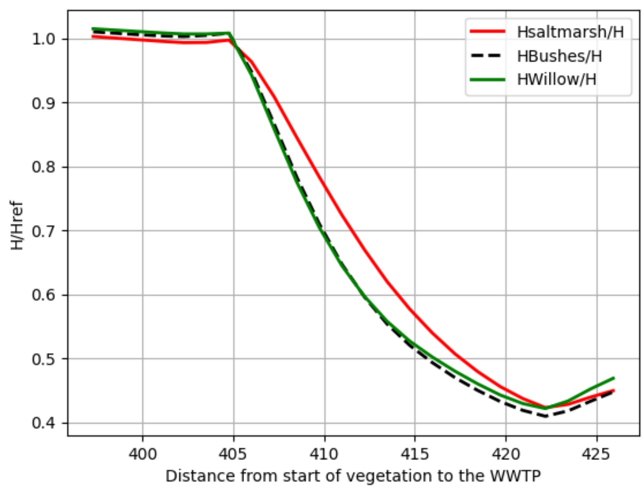


Figure 4.3: The effects of Willow trees, reeds and bushes for wave dampening showcased by H/H_{ref} C_D=1.2 and SWL = 1.43 m

The plot shows a similar pattern for all types of vegetation for a high C_D value which also can be seen in table 4.2 in the bottom row. The difference in attenuating effect is the greatest at the middle of the planted stretch where the salt marsh is not dampening with the same efficiency. However this difference is disappearing at the end pf the vegetation. This could indicate that reeds as vegetation would prove to be more efficient if there were room for a longer plantation. This could be further explored and evaluated for a different case study.

5 Discussion

5.1 Conclusions from the outputs

The XBeach output for nearshore conditions for significant wave height is similar to the significant wave height that was calculated by Sweco (0.94 m) when designing the rock revetment. This, alongside the calibration yielding similar runup levels as the observed runup-level, would indicate that the model is properly mimicking the attributes of the nearshore conditions at Kivik WWTP. The difference in C_D seems to have greater effect for a SWL of 1.43 meters compared to a SWL of 1.26 meters. This is natural for both the bushes and willow trees as they will be more submerged for a greater SWL but this does not hold true for the salt marsh as the vegetation will be fully submerged in both cases. Instead the cause of the difference in dampening effect could be contributed to the observation made by [18] where flexible vegetation that is exposed to greater forces will compromise the attenuating effect. Another explanation is that the percentage of vegetation that is exposed to the incoming water is diminished when the water level rises as there is a higher water level but no change in the height of the vegetation.

From figure 4.3 one can see how the slope from 406 meters flattens out the further the wave moves into the planted vegetation. This means that planting a extremely long vegetation field would give diminishing returns the longer it is. This property of the vegetation can be used to more easily find the design length of the vegetation field when considering extreme storms. A similar observation was made by [14] where a salt marsh had its first 2.5 meters dampening 50% of the wave height and 100% at 30 meters. Granted, this was for a wave height of 0.18 meters but the pattern still remains the same.

The most accurate calibration of the model can be in relation to the willow trees, where it can be seen that dampening is very high, especially for the added water level. This might be caused due to the flexibility of the willow tree branches not being considerd. The model would in this case, be overestimating flexible vegetation.

5.2 Comparing solutions

The optimal solution is acquired by evaluating the aspects of wave dampening capability, resilience to wave climate and opportunity for establishment from an ecological perspective. A heavier consideration has been taken to low C_D values as this is the worst case scenario which is the recommended method of choosing design scenarios. Another reason to consider low C_D-values is that overestimation of C_D is common in models, such as seen in [18] where many seem to overestimate C_D. This overestimation can occur due to several factors regarding assumptions made about the C_D-value for example the extent of the flexibility for the used plant. Experiments are also carried out in flumes which causes drag forces to occur when water moves along the walls. The different aspects for each plant is described in the next subsections.

5.2.1 Bushes

When evaluating bushes as coastal protection there are not many local examples of species that grow at coasts on beaches with the soil type that is present outside of Kivik WWTP. There is not the same extent of studies made on the subject either which further increases the uncertainty of both attenuating effects and possibility of establishment. Bushes that have been used are for example *Acacia longifolia subsp. sophorae* (Coastal Wattle) which is native to Queensland Australia and have been utilized in Portugal for example. However introducing non-native species can often end in failure. Sometimes the ecology will not support the plant as intended and in some cases it can lead to the plant becoming invasive which can disrupt the local ecosystem [28].

The properties of the foliage will determine its susceptibility to saline conditions which is another unexplored aspect of plantation of bushes that should be further researched before making any real suggestions or conclusion of the usability of this type of vegetation.

In summary, comparing bushes to mangroves is not sure to be valid. If bushes were to seriously be considered for wave dampening, one would have to make validation with real experiments such as one that was made in the case of [18] to understand if the vegetation is capable of establishing in the local conditions.

5.2.2 Salt marshes

Salt marshes thrives in conditions with large tidal ranges and an abundance of fine grain sediments with mild wave conditions. Therefore, the ideal conditions for salt marshes do not align with the conditions at the beach of Kivik WWTP as there is negligible tidal effects and a limited amount of fine sediment. There still seems to be an opportunity for developing reeds as there was an area adjacent to the WWTP which had a relatively dense patchwork of reed and they were also growing scarcely in front of the WWTP. The question then becomes whether the condition on average is calm enough for development of resilient plants and if extra sediment has to be introduced in the area. Further studies for the specific area should be made to gain deeper insight. Even after plantation, there will be a need of great monitoring to optimize the odds of successfully implementing a salt marsh.

5.2.3 Willow trees

The use of willow trees have shown promising results in the conducted study by [18] both in terms of resilience to wave climates during extreme storm events and the dampening effect of the canopy. The results from the XBeach model yielded similar conclusions in dampening effect with estimations reaching a reduction in significant wave height of roughly 50%. Furthermore the existence of trees at the sight proves that it is possible for vegetation of this size to establish properly and also endure the storm condition of the same, if not greater, magnitude as Babet. Willow trees are also able to flourish in the environment both according to previous studies and also by their presence along the same stretch of coast.

5.3 Limitations of the study

Before choosing the optimal vegetation, some aspects of the vegetation has to be acknowledged which XBeach will not consider in the model. Firstly, plants in the model is assumed to remain rooted during the simulation which does not hold true in reality. The wave forces which is inflicted on the vegetation will most likely uproot some of the vegetation regardless of the option that is chosen. The experiments presented in chapter 2.4 did not observe this to occur but the vegetation was exposed to non breaking waves which makes the scenarios vastly different because of the difference in forces.

Secondly, the input parameters for the vegetation is based on previous studies and not from experiments carried out for the specific case. The variation of the dampening effect is considered in the simulation by the variation in C_D which gives a greater perspective when considering alternatives. However, only one solution can be adapted, thus, to give a proper recommendation, one would experimentally test if the suggested input parameters can be achieved and the plant's resilience to uprooting and stem breaking.

Thirdly the possibility to establish coastal vegetation is a process that takes careful planing to not fail. Furthermore, there is a need of monitoring to gauge the success of the plantation and adjust the course of action accordingly. It requires a sufficient understanding of both the ecology and hydrology, for example, there may be a need to fertilize the plants but this could cause algies to grow in the nearshore area which could lead to problem as oxygen deficiencies in the nearshore area. Another example is the sediment transport which could compromise the sediment that is needed for the plants.

Even though the runup could not be studied in a desired way, wave heights have been a standardized measuring tool for the wave dampening effects in both laboratory experiments and modeling aspects. Therefore a comparison of the wave height reduction can be made in front of the planted vegetation as seen in table 4.2. The model would also be able to run correctly for this case as they are planted at an elevation of 0.87 meters which commonly will be at land but when the designed extreme storm hits, they will be submerged by the SWL of 1.26 which means that the modelling approach that is commonly adapted emegrent vegetation will be valid.

It is important to mention that the acquired dampening effect of 50 % is deemed high for a attenuating distance of 13 meters compared to other studies. Unfortunately there is no way of validating the results to which is a common problem for vegetation as coastal protection. It is often a trial and error method that will yield a successful protection.

5.4 Conclusion

The aim of this study was to answer these questions:

- Is it possible to utilize vegetation as coastal protection?
- Which vegetation is best suited for the case study?

5.4.1 Is it possible to utilize vegetation as coastal protection?

It is possible to utilize vegetation as coastal protection as shown by the dampening effect of the significant wave height reaching up to 60%. However it is a complex process that requires careful planing. It is quintessential when planing a coastal protection with vegetation to have a thorough understanding of three aspects, the coastal conditions, the ecology and the input parameters for the plant. With a lacking understanding of any of these there is no guarantee that the vegetation will establish or how it will fare against extreme storm conditions. Therefore it is recommended to make an throughout study of the specific area when utilizing vegetation.

Other then planing one must also safeguard the plantation. The planted solution can not be left to its own devices after the protection is built as supervision is required to guide the planted vegetation to become a self sufficient ecosystem. The vegetation will not have the same input parameters through its entire lifetime either with the biggest changes occurring in the plant's first years. This is why it is recommended to plant vegetation that already has been grown to a proper size and have it trimmed somewhat frequently so the height remains the same ensuring emergent trees.

5.4.2 Which vegetation is best suited for the case study?

It is unclear for this study how the vegetation will react to the environment at Kivik WWTP as this aspect is poorly explored without doing any physical experiments. There can therefore not be any realistic conclusion drawn as to which plant is best suited. However if a suggestion is to be made it would be to further experiment with willow trees in future studies.

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A Appendix

Table A.1: Hourly values for Babet between 2023-10-20 05.00 to 2023-10-21 05.00

H_S [m]	SWL [cm]	Tp [s]
2.32	86.7	8.2
2.36	89.9	8.2
2.43	88.9	8.2
2.55	88.3	8.3
2.69	91.8	8.5
2.77	95.5	8.7
2.92	100.5	8.8
3.09	96.1	8.9
3.18	101.1	9.3
3.28	100.6	9.5
3.39	108.6	9.6
3.43	110.1	9.6
3.43	116.7	9.7
3.45	113	9.7
3.51	115.8	9.7
3.55	123.1	9.8
3.61	126.3	9.9
3.58	122.4	10.1
3.54	126.8	10.2
3.53	132.2	10.1
3.49	127.5	10.1
3.37	128.9	10.2
3.18	130.2	10.2
2.98	109	10.2
2.78	100.6	10.0

B Appendix

	Bushes	Saltmarsh	Willow tree
C_D low, SWL 1.26 m	60	29	59
C_D mid, SWL 1.26 m	62	60	62
C_D high, SWL 1.26 m	65	66	65
C_D low, SWL 1.43	49	32	53
C_D mid, SWL 1.43 m	53	55	53
C_D high, SWL 1.43 m	59	57	57

Table B.1: XBeach results H_0/H_S at WWTP

C Appendix

Listing C.1: Python code for extracting output parameters from XBeach

```
# -*- coding: utf-8 -*-
"""
Created on Fri Oct 20 14:23:16 2023

@author: bjorn
"""

# import default modules
import matplotlib.pyplot as plt
import sys
import os
import netCDF4
import numpy as np


# method to import xbtools with try routine
try:
    import xbTools
except ImportError:
    print('**no xbTools installation found in environment,
    adding parent
    path of notebook to see if it works')
    sys.path.append(os.path.abspath(os.path.join('..', '..',
    'xbeach-toolbox')))

## import xbeach tools
#sys.path.append(os.path.abspath(os.path.join('..')))
from xbTools.xbeachpost import XBeachModelAnalysis



file3 = 'xboutput.nc'
filepath = r'C:\xbeach\calibrering_runup'
filepath_veg = r'C:\xbeach\calibrering_runup'

results = XBeachModelAnalysis('Test som 2', filepath)

wav2 = netCDF4.Dataset(os.path.join(filepath, file3))

wH2 = np.sqrt(2)*wav2.variables['H_mean'][-1].compressed()  #waves
zb = wav2.variables['zb'][0,0,:].compressed()
```

```
wav2veg = netCDF4.Dataset(os.path.join(filepath_veg, file3))
wH2veg = np.sqrt(2)*wav2veg.variables['H_mean'][-1].compressed()
#waves
zbveg = wav2veg.variables['zb'][0,0,:].compressed()
print(wH2)
#print(zb)
# Create the first figure and axis
fig, ax1 = plt.subplots()

# Plot the first data on the first y-axis
ax1.plot(wav2.variables['globalx'][:].compressed(), wH2veg,
label='sqrt(2)*Hmean_surfbeat', color='blue')
ax1.plot([765.75-757, 765-592, 765-488, 765-390, 765-270, 765-202],
[1.83, 1.74, 1.75, 1.70, 1.58, 1.33], 'o', color='red'
            , label='Hmo, wave sensors')



# Create a second y-axis on the same figure
ax2 = ax1.twinx()

# Plot the second data on the second y-axis
ax2.plot(wav2.variables['globalx'][:].compressed(), zb, color='black',
label='Second Y-Axis Label')

# Combine the legends from both axes
ax1.legend(loc='lower left', shadow=True, facecolor='white')
ax1.set_ylabel('H_mean [m]')
ax2.set_ylabel('bottom elevation [m]')


# ax2.legend(loc='upper right')

plt.tight_layout()
# plt.savefig('no_OffshoreExtent.png', dpi=150)

#Load XBeach model output

zs = results.load_modeloutput('zs')

ny, nx = results.var['globalx'].shape

#results.load_modeloutput('point_zs')

zs = results.get_modeloutput('zs')
point_zs = results.get_modeloutput('point_zs')
```

```
[t, zs] = results.get_modeloutput_by_station('zs','point001')

## change coordinates of plots to local coordinates:
#results.set_plot_localcoords(True)
## only plot a certain Area Of Interest of the complete grid
#results.set_aoi([20,445,20,220])

# example usage map plotting
fig, ax = results.fig_cross_var('H_mean', 0, iy=0, coord=None,
plot_ref_bathy=True, zmin=-15)

# Create the first figure and axis
fig2, ax21 = plt.subplots()
ax21.plot(wav2.variables['globalx'][:].compressed(), wH2,
label='H_veg / H', color='blue')
#ax21.plot([-200,400], [1,1], ':', color='red')

# Create a second y-axis on the same figure
ax22 = ax21.twinx()

# Plot the second data on the second y-axis
ax22.plot(wav2.variables['globalx'][:].compressed(), zb, color='black',
label='bottom')

# Combine the legends from both axes
ax21.legend(loc='lower left', shadow=True, facecolor='white')
ax21.set_ylabel('H_eelgrass/Ho [-]')
ax22.set_ylabel('bottom elevation [m]')
ax21.set_ylim(0.01,3.7)
ax21.set_xlim(0,450)


# ax2.legend(loc='upper right')

plt.tight_layout()
plt.savefig('Diff_WaveHeight_eealgrasVSnone.png', dpi=150)
Langd=list(range(len(wH2)))
#plt.plot(Langd, wH2 )
plt.show()
```

Listing C.2: Python code for Runup

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import csv
```

```
#Inparametrar
#Tp=10
#Hs=3
h=10.1
g=9.81
gammaf=0.55
tanalpha=0.025
#Babet
df1=pd.read_csv('Exceldata/VagdataKivik.csv', usecols=['Hs','Tp'])
Hs=df1.loc[563692:563716, 'Hs']
Tp=df1.loc[563692:563716, 'Tp']
Tp_values = []
Hs_values = []
for value in Tp:
    Tp_values.append(value)
for value in Hs:
    Hs_values.append(value)
hBabet = list(range(24))

#Eurotop RR
L_deep=[]
L_shallow=[]
epsm=[]
runup=[]
for i in range(24):
    L_deep.append(1.56*Tp_values[i]**2)
    L_shallow.append(np.sqrt(g*h)*Tp_values[i])
    epsm.append(tanalpha/np.sqrt(Hs_values[i]/L_deep[i]))
    runup.append(1.75*gammaf*epsm[i]*Hs_values[i])

#Stockdon
L_stock = []
eps_stock = []

for value in Tp_values:
    L_stock.append((g*value**2)/(2*np.pi))

for i in range(len(Hs_values)):
    eps_stock.append(tanalpha/np.sqrt(value/L_stock[i]))




n_stock = []
Sw = []
Sig = []
```

```
for i in range(len(Hs_values)):
    n_stock.append(0.35*Hs_values[i]*eps_stock[i])
    Sw.append(0.75*Hs_values[i]*eps_stock[i])
    Sig.append(0.06*np.sqrt(Hs_values[i]*L_stock[i]))

R2 = []
for i in range(len(Hs_values)):
    if eps_stock[i] > 3:
        R2.append(1.1*(n_stock+0.5*np.sqrt(Sw[i]**2 + Sig[i]**2)))
    else:
        R2.append(0.043*np.sqrt(Hs_values[i]*L_stock[i]))

plt.plot(R2, linewidth=2, label="Stockdon")
plt.plot(runup, linewidth=2, label="Eurotop")
plt.xlabel("Duration (h)")
plt.ylabel("runup")
plt.legend(loc='upper right')
plt.grid(True)
plt.show()

# print(R2)
```