Investigating Inundation Impacts Caused by Extreme Sea Level Rise at Nacka Municipality

HILFI AMRI
Investigating Inundation Impacts Caused by Extreme Sea Level Rise at Nacka Municipality

HILFI AMRI
Abstract
Numerous efforts have been employed to explore plausible future sea level rise range as well as improving the ice sheet dynamic that was considered as the biggest challenge in sea level projections. These results in the availability of numerous corresponding Global Mean Sea Level (GMSL), a property that exhibits the problem of deep uncertainty. In the front of deep uncertainty problems, the paradigm “predict then act” is no longer sufficient, as decision makers are prompted with the more recent framework that could encompass the latter problem, in this case, the Robust Decision Making (RDM) approach. Nacka Municipality, one of the rapid growing municipalities in Stockholm, must face future sea level rise problem under this circumstance, which requires an input to be able to act against sea level rise while also sustaining the development in the area.

This work will connect three main methods to provide an appropriate flood map for robust decision-making processes, namely the localization of GMSL, extreme value analysis, and hydrodynamic models. Localizing the GMSL is done by incorporating several important aspects (i.e. Vertical Land Motion, Ocean Dynamics, and Ice Melt Dynamic). Extreme value analysis was conducted to project the extreme value of sea level and the wind according to the desired return period outcome. While hydrodynamic model will provide a more representative interaction between the phase: sea, wind and bed properties. The latter will be done using a product created from the Danish Hydrological Institute (DHI) named MIKE 21 FM. The latter features flexible mesh as the main element and allows to incorporate the momentum equation into place.

Furthermore, results will be based on two scenarios: extreme and low in two different time frame, namely 2100 and 2150. Results will explore the area span of the flood as well as the potentially impacted buildings. Additionally, both scenario results will be adjoined per time frame to provide a span of flood area between the low and the extreme scenarios.
Summary

Several areas in the Nacka Municipality, Stockholm resides on the coast of the Baltic Sea, and within these coastal vicinities exists infrastructure that serves a valuable function to the community. There has been a growing concern that these places are threatened by the changing sea level in the short and long term. This study will examine the effect of coastal inundation in Nacka, on the channel from Ekorren to Solsunda with an in-depth discussion on Fisksätra and Tollare. As a precaution, Länsstyrelsen Stockholm suggests an adaptation measure build valuable infrastructure above 2.7 meters. An estimation of the efficiency of the threshold should also be discussed further.

Sea level change should be perceived as multiple-scenario events that are inadequate to be handled by the “predict then act” paradigm. To address this, the model is designed to assess two contrasting sets of conditions that will act as a range, that is the low and the extreme; as well as two-time frames: 2100 and 2150. Low scenarios assess the low rate of sea level change coupled with extreme value for water level and wind speed that corresponds to 100 years return period. On the other hand, extreme scenario addresses the extreme rate of sea level change as well as a 1000-year return period of extreme sea level and wind speed. Discarding the extreme wind speed element, the future water levels that will be used are as follows: 1.70 m for low-2100; 3.63 m for extreme-2100; 2.15 m for low-2150; and 6.35 m for extreme-2150.

The rate of sea level change uses the value of global mean sea level change that has been adjusted to local sea level change specifically for Stockholm. Physical local attributes are also included such as vertical land motion, sea level, wind and bed resistance from the land cover. To be able to process all these inputs, the study utilizes MIKE 21 Flexible Mesh Hydrodynamic module created by DHI.

Overall, the coastal areas within the scope of the study are less affected by the coastal flood. The latter is a contribution to the steep terrain near the channel. However, several exceptions exist especially on extreme scenarios and worst for the longer term, such as the partial areas of Saltängen, Saltsjö-Duvnäs, Lännersta, and Ekorren. These susceptibilities are evoked by the relatively flat terrain near the channel. The affected buildings in these scenarios are housing, business buildings, and several schools. For the two more concerned areas in this study, Tollare is less affected by the coastal inundation in all scenarios compared to Fisksätra.

Länsstyrelsen Stockholm’s suggestion to build above the 2.7-meter threshold value proves to be adequate in low scenario conditions. In some other cases, the flood model suggested that this rule is inadequate, especially when associated with the extreme scenarios and long-term events. Further, adaptation measures for the longer term need to be reconsidered to be able such an event.
Sammanfattning


Havsnivåförändringar bör uppfattas som händelser som innefattar flera scenarier och som inte går att fullständigt hantera med paradigmet "förutse sen agera". För att ta itu med detta har en modell utformats för att bedöma två uppsättningar villkor som står i kontrast med varandra och som kommer att fungera som ett intervall, det låga och det extrema, samt två tidsramar: år 2100 och år 2150. Ett lågt scenario bedömer den låga förändringen av havsnivån i kombination med extrema värden för vattennivån och en vindhastighet som motsvarar 100 års returperiod. I motsats hanterar det extrema scenariot den extrema förändringen av havsnivån samt en 1000 års returperiod med extrem havsnivå och vindhastighet. När det extrema vindhastighetselementet bortses, kommer de framtida vattennivåer som kommer att användas vara följande: 1,70 m för låg 2100; 3,63 m för extrem-2100; 2,15 m för låg 2150; Och 6,35 m för extrem-2150.

Hastigheten för havsnivåförändringen är tagen från den globala genomsnittliga havsnivåförändringen som har anpassats till lokal havsnivåförändring specifikt för Stockholm. Lokala fysiska attribut ingår också, t.ex. vertikal markrörelse, havsnivå, vind- och båddmotstånd från markskyddet. För att kunna bearbeta alla dessa ingångsvärden använder studien MIKE 21 Flexible Mesh Hydrodynamic modul skapad av DHI.


Länsstyrelsens förslag att bygga över tröskelvärdet på 2,7 meter visar sig vara tillräckliga vid låga scenarier. I vissa andra fall föreslog översvämningsmodellen att dessa regler och begränsningar är otillräckliga, i synnerhet i samband med extrema scenarier och långsiktiga händelser. Vidare måste anpassningsåtgärder på längre sikt omprövas för att kunna hantera eventuella framtida händelser.
Acknowledgements

I would like to offer my sincere gratitude to Zahra Kalantari and Annika Carlsson-Kanyama for the valuable inputs and advice during the supervision sessions. Annika introduced the project and the whole concept of robust decision making. She has been very helpful on providing out the essential existing policies regarding Nacka and the current adaptation measures in place; as well as with great endeavor provides the necessary bathymetry data. Zahra offered great technical knowledge on numerical models, especially the use of MIKE 21. Zahra guidance throughout the establishment of the model and its finalization have been an essential part of the project.

I would also like to thank my examiner, Vladimir Cvetkovic, who has connected me with the thesis project. He too has offered many suggestions and support, as well as encouragement to complete this project. Much appreciation should also be extended to the Land and Water and Resource Department, which has been nothing but helpful throughout the whole master program.

I also wish profound gratitude for those who have been providing the available data and utility: Sjöfartsverket for the sea bathymetry; DHI for the MIKE 21 license; SMHI for the measured water level and wind speed; Lantmäteriet for the DEM and spatial attribute maps. Finally, much appreciation goes to my benefactor, the Indonesian Endowment Fund for Education (LPDP), who has provided me with financial support throughout the whole master program.

Stockholm, June 2017

Hilfi Amri
1. Introduction
This chapter elaborates the need for the study through background description, followed by outlining the aim and objectives of the study.

1.1. Background
The effect of climate change has been one of the problems that have been addressed extensively in the preceding decades. The matter has been remarkably dire that it sparked myriads organizations and conference in multiple levels to discuss or even apply mitigation and adaptation measures. One of the prevailing impacts correlated to the latter is the sea level rise. Sea level rise alarms the world of the resilience of coastal areas worldwide where many strategical and imperative areas are located. Due to rapid economic growth and economic development, the population growth and the urbanization in the coastal areas outstrip the demographic development of the hinterland McGranahan et al. (2007) and Smith (2011). The latter supports Parris et al. (2012) and Hall et al. (2016) assertions that the rising sea level will render more vulnerability towards the growing population, imminent infrastructure related to transportation, energy trade, and the embedded coastal ecosystems.

Sea level rise has been forecasted in many renowned world organizations and researchers (Gregory, 2013; Meehl et al., 2007). There is still no established and agreeable consensus of exact future sea level value, partly due to the embedded uncertainties. One of the uncertainties arises from the future state of the two polar caps, the Greenland and the Antarctica, as scientist has also been working to understand its dynamics (Kuhn et al., 2010; Hay et al., 2014). Nevertheless, assessment towards the effect of the sea level rise towards its coastal vicinity still could be done by admitting these uncertainties in the form of multiple sea level scenarios. It is worth noticing that the effect of sea level rise could vary for different locations depending on the type of coast, ocean, local climate and land dynamics (Andersson and Sjökvist, 2012).

The existing multiple sea level scenarios indicate that sea level rise could be considered as a deep uncertainty phenomenon (Oddo et al., 2017). Multiple frameworks have been developed to be able to adapt and to handle the latter problem, one of which is Robust Decision Making (Walker et al., 2013a). It shifts the paradigm from “predict then act” to consider all possible scenarios regarding the phenomenon (Hall et al., 2016).

The focus of the study is in Stockholm, one of the major capital city located in the periphery of the Baltic Sea. Currently, Stockholm host several high investment areas in close vicinity of its shoreline, some is in the Nacka municipality. The latter is suspected to be susceptible to the rise in sea level in the short term (2100) and mid-term (2150) on several areas. The thesis will model the area span of the flooded area associated with multiple sea level values generated by the use of hydrodynamic models, e.g. MIKE 21 (DHI, 2016). A similar model has been done in South West Australia (Kuhn et al., 2011), Southern Italy (Aucelli, 2016) and Kiel-Germany (Neumann et al., 2013) using MIKE 21. Furthermore, the scenario will be combined to give a span of plausible flood prone area between the lowest scenario and the extreme scenario; allowing the municipality to realize the possible span of impacts and work on robust decision making to solidify a mitigation and adaptation strategy.
1.2. **Aim and objectives**

This study aims to determine the inundated area due to sea level rise in multiple scenarios and assess its impact on land use and corresponding water depths. Thus, the research questions associated with the aim are:

1. What are the flood depths and area span in the inundated areas for each respective scenario in the study area?
2. How does the overarching adaptation measures cope with the various generated scenarios?

Also, as several objectives have been established:

1. Quantify the extreme sea levels, and extreme wind speed based on the available data for the 100-years and 1000-years return period
2. Generate an inundation model for various scenarios
3. Generate flood depth maps that correspond to the scenarios
4. Analyze land use affected by the corresponding sea level scenarios
5. Render an area map between the low and extreme scenario and contrast them overarching adaptation measure
6. Contrast the area span between the scenarios
2. Theory

2.1. Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC, 2011) defines climate change as:

“a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time.”

Therefore, to understand the notion of climate change and its relation to sea level rise, it is important to remark the following historical data: the concentration of greenhouse gas in the global atmosphere, the global mean temperature, and the tide gauge data.

The greenhouse gas has shown an interesting trend for the last two centuries. Several millennia before 1800, carbon dioxide levels ranged from 270 ppm to 290 ppm. However, the concentration spiked to 295 ppm by 1900, 310 – 315 ppm by 1950, 360 ppm in 1995, and 405.34 ppm by January 2017 (Dlugokencky and Tans, 2017). While the earth process also produces greenhouse gasses, the significant increase of greenhouse concentrations has been correlated with human activities (McNeil, 2001) especially due to the use of fossil fuel.

The escalating greenhouse gas concentration has been correlated with the change in the average global temperature (shown in Fig. 1). These gasses, while in certain concentration is needed to retain heat from the sun to create a moderate temperature enabling the survival of life form on earth. Several greenhouse gasses concentrations are directly related to the amount of radiative forcing, which is defined as the difference of energy absorbed and radiated back to earth. In excess amount, the greenhouse gas will render less heat to escape the atmosphere, in other words, an increase in radiative forcing. Hence, a build up heat which will raise the average temperature.

![Global Mean Surface Temperature](image)

*Fig. 1. Global Mean Sea Surface Temperature of recent decades, depicted from GISTEMP Team (2017)*

Over the years, IPCC has commissioned and approved the possible scenarios of multiple greenhouse gas concentrations. The most recent scenario was created at 2013 reported in the 5th Assessment Report (Pachauri et al., 2014). It differs from the earlier approved scenarios. Earlier scenarios were developed by creating socio-economic scenarios that give
rise to alternative future greenhouse gas and aerosol emissions, evaluating these emissions on the climate system and assess the implications of the impact as well as differing socio-economic and other environmental changes on both natural and human system. The process requires ten years to be completed in full linear.

In contrast, the newer scenarios are initiated by taking alternative future values for greenhouse gasses and aerosol concentrations as the starting point. The latter is known as the term Representative Concentration Pathways (RCP) which were named based on the possible range of radiative forcing in the year 2100 about the pre-industrial value (van Vuuren et al., 2011). The radiative forcing and its corresponding RCP is shown in Table 1. Afterward, it could then be utilized in parallel for two processes:

1. Earth System Models to delve into future changes in physical and biogeochemical processes that will affect the atmospheric composition and radiative forcing
2. Integrated Assessment Models which delve into the alternative socio-economic processes that would result in a change in the atmospheric composition.

**Table 1 Radiative forcing level for various corresponding scenarios and CO₂ equivalent (depicted from van Vuuren et al., 2011)**

<table>
<thead>
<tr>
<th>GHG concentration scenario</th>
<th>Description</th>
<th>Radiative forcing level (W/m²)</th>
<th>CO₂ equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP 2.6</td>
<td>Declining pathway after peak before 2100</td>
<td>2.6 (peak at 3)</td>
<td>~490</td>
</tr>
<tr>
<td>RCP 4.5</td>
<td>Stabilization without overshoot pathway, stabilizing by 2100</td>
<td>4.5</td>
<td>~650</td>
</tr>
<tr>
<td>RCP 6</td>
<td>Stabilization without overshoot pathway, stabilizing by 2100</td>
<td>6</td>
<td>~850</td>
</tr>
<tr>
<td>RCP 8.5</td>
<td>Rising radiative forcing pathway</td>
<td>8.5</td>
<td>~1370</td>
</tr>
</tbody>
</table>

Between 1906 and 2005, the global average temperature increased from 0.6 to 0.9 Celsius (NASA Earth Observatory, 2017). The rate of temperature increase has almost doubled in the last 50 years. Scientists estimated that the increase in global temperature would be within the range of 0.5F to 8.6 F by 2100 (IPCC, 2013). It should also be noted that the increase of temperature is not uniform, as some part of the world will have a higher temperature than others (Ji et al., 2014).

### 2.2. Sea Level Rise

The change in climate will have various impacts: change in frost-free season and growing season, change in precipitation patterns, more drought, and heat waves, stronger hurricanes (Shaftel, 2017). One of the most notable effects of climate change that is discussed in this report is the change in global sea level. Unlike other climate change impact, the latter has been observed for some period (Thead, 2016). A robust evidence also shows that not only the sea level itself is rising, the rate of the sea level is also showing increase as well (Lindsey, 2016).

The phenomenon is affected by climate change in two pathways: the dynamics of the ice sheets and glaciers and the thermal expansion of the ocean (Lindsey, 2016). The increasing earth temperature has expedited the rate at which it melts, therefore, expelling more water to the global ocean. The decreasing ice mass weakened the pull factor of the water towards it, which distributes the water more to other places than just concentrated around both polar caps. The increase in the earth temperature also increases the volume of the sea which abides by the law of expansion.
Therefore, to capture the dynamics of sea level and climate change, it is imminent to connect both carbon dioxide and the melting process of the ice caps as well as the ocean’s expansion. Over the years, the focus of the model was concentrated on the prediction of greenhouse gasses following the anthropologic activities and development. In recent years, many research could provide more insights towards the dynamic of the great land ice sheets and atmospheric-oceanographic feedback, resulting in a more representative model for the sea level rise. The following chapter will elaborate two concepts of sea level rise that is essential to this study, namely the Global Mean Sea Level and Local Sea Level.

2.2.1. Global Mean Sea Level
The term Global Mean Sea Level is the average level of the overall surface of the Earth’s ocean. Historically, it is the common concept used in various climate models that predicts its change over time. To understand the concept of GMSL change, it is important to mention a brief background of several preceding GMSL projections. The GMSL change projection is based on the two drivers namely atmospheric and ocean warming which increases the mass of the ocean due to the melting of the ice (in some cases the contribution of anthropogenic activities) and the expansion of the volume of the ocean (Sweet, 2017). In the AR5, IPCC uses the Coupled Model Intercomparing Project Phase 5 (CMIP 5) which allows future projections of climate based on different GHS scenarios associated with the RCP. While the RCP scenario affects the lower and upper boundary, the selection of probability range will also influence these boundaries.

In the AR5, IPCC highest projection of the sea level rise for the global mean sea level ranged around 0.52 to 0.98 meters, under the RCP 8.5 scenario (Church et al., 2013a). The projection did include the contribution of global mean SLR from the collapse of marine-based sectors in the Antarctic. However, the contribution could not be precisely quantified and therefore was given medium confidence values. In one of his notes, Church et al. (2013b) suggest using other value to accommodate for the upper bound, and Hinkel et al. (2015) argued that the derived IPCC global mean SLR not fit to be used as coastal risk management and decision making.

To be able to be used as an input for risk management and decision-making processes, work on the higher range was produced. One of the was the work of Hall et al. (2016) which uses the scenarios from 0.2 meters to 2.0 meters as a default global SLR scenarios. The lower bound was based on a linear estimate of 1.7 mm/year from Church and White (2011) to set the rationale for the lowest scenario of 0.2 m. On the other hand, the upper hand refers to the work of Parris et al. (2012) and Pfeffer et al. (2008) findings. The determination of the upper bound value is restricted by our understanding of the ice-sheet dynamics (Jevrejeva et al., 2014). Despite the continuous improvement of land-ice contributions, Church et al. (2013b) still acknowledge the challenges to accurately quantify the contribution from glacier mass loss, Antarctic surface mass balance, and dynamical responses of Greenland and Antarctic ice sheets.

This study uses the localized values of the GMSL (the referred GMSL change in this study is shown in Table 2). Thus, it is worth noting the latter values that were initially use which is published in the recent study created by NOAA, which puts a higher bound on both lower and upper boundaries and more set of scenarios compared to the work of Hall et al. (2016). The use of higher probability of exceedance is the pretext of this development and has been employed from the probabilistic projections of Kopp et al. (2014).
Table 2 GMSL rise scenarios initiating in year 2000. Only median values are shown. Depicted from Sweet et al. (2017)

<table>
<thead>
<tr>
<th>GMSL Scenario (meters)</th>
<th>201</th>
<th>202</th>
<th>203</th>
<th>204</th>
<th>205</th>
<th>206</th>
<th>207</th>
<th>208</th>
<th>209</th>
<th>210</th>
<th>211</th>
<th>212</th>
<th>213</th>
<th>214</th>
<th>215</th>
<th>220</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.03</td>
<td>0.06</td>
<td>0.09</td>
<td>0.13</td>
<td>0.16</td>
<td>0.19</td>
<td>0.22</td>
<td>0.25</td>
<td>0.28</td>
<td>0.30</td>
<td>0.34</td>
<td>0.37</td>
<td>0.39</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Intermediate-Low</td>
<td>0.04</td>
<td>0.08</td>
<td>0.13</td>
<td>0.18</td>
<td>0.24</td>
<td>0.29</td>
<td>0.35</td>
<td>0.40</td>
<td>0.45</td>
<td>0.50</td>
<td>0.60</td>
<td>0.73</td>
<td>0.95</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.04</td>
<td>0.10</td>
<td>0.16</td>
<td>0.25</td>
<td>0.34</td>
<td>0.45</td>
<td>0.57</td>
<td>0.71</td>
<td>0.85</td>
<td>1.00</td>
<td>1.30</td>
<td>1.80</td>
<td>2.80</td>
<td>3.70</td>
<td>5.10</td>
<td>5.10</td>
</tr>
<tr>
<td>Intermediate-High</td>
<td>0.05</td>
<td>0.10</td>
<td>0.19</td>
<td>0.30</td>
<td>0.44</td>
<td>0.60</td>
<td>0.79</td>
<td>1.00</td>
<td>1.20</td>
<td>1.50</td>
<td>2.00</td>
<td>3.10</td>
<td>5.10</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>High</td>
<td>0.05</td>
<td>0.11</td>
<td>0.21</td>
<td>0.36</td>
<td>0.54</td>
<td>0.77</td>
<td>1.00</td>
<td>1.30</td>
<td>1.70</td>
<td>2.00</td>
<td>2.80</td>
<td>4.30</td>
<td>7.50</td>
<td>9.70</td>
<td>9.70</td>
<td>9.70</td>
</tr>
<tr>
<td>Extreme</td>
<td>0.04</td>
<td>0.11</td>
<td>0.24</td>
<td>0.41</td>
<td>0.63</td>
<td>0.90</td>
<td>1.20</td>
<td>1.60</td>
<td>2.00</td>
<td>2.50</td>
<td>3.60</td>
<td>5.50</td>
<td>9.70</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
</tbody>
</table>

However, it should be noted that both work by NOAA and Hall et al. have not incorporated the newest finding by DeConto and Pollard (2016) which assert a non-linear rate of ice-sheet mass loss. Therefore, it is possible when associated with these findings that the GMSL rise rate could move to higher GMSL rise scenarios.

2.2.2. Local Sea Level Change Adjustment

Solely employing the GMSL change in a specific area is inadequate, since it undermines the several important regional factors such as the vertical movement of the land and interaction between the melting ice based land mass and ocean dynamics. This phenomenon renders a geographically non-uniform distribution of sea level. The importance of GMSL adjustment to the local and regional aspects has been addressed in several assessments, particularly in works of Kopp et al. (2015), Hall et al. (2016) and the 2017 NOAA Report (Sweet et al., 2017). This adjusted GMSL change value is then defined as Local Sea Level change.

Hall et al. (2016) incorporate several factors in their LSL assessment, namely: Vertical Land Motion (VLM); Melting Land-Based Ice; and Dynamical Sea Level. Vertical land motion is a local process that can be caused by tectonic uplift, compaction of sediments, pumping groundwater or oil, and post-glacial response after the retreat of the last ice age or known as Glacial Isostatic Adjustment (Zervas et al., 2013). Due to these processes, the land movements vary spatially dependent on their interactions and the most predominant ones. For example, in Sweden alone, the northern part shows an uplifting trend while the southern part shows land subsidence phenomenon (Andersson and Sjökvist, 2012).

The term melting of land-based ice is straightforward, despite a complex effect it induces. In solid form, the mass of ice sheets applies a gravitational attraction to the water around them (Velicogna and Wahr, 2013). As the ice thaws, the attraction towards the water diminishes and moves away from the melting ice, rendering a counterintuitive impact of lowering sea level on the proximate of the land-based ice mass while raising it in places far away (Mitrovica et al., 2011). Subsequently, the redistribution of mass around the globe also affect the flattening of the spinning globe, which affects the sea-level rise in specific areas (Church et al., 2013a).
Both melting of ice-based land and ocean circulation is often expressed as global pattern scaling and fingerprint which are evaluated on General Circulation Model. Fingerprint is defined as a geographically distinct patterns of sea level change produced by mass changes in a specific ice sheet or glacier (Mitrovica et al., 2011). The acknowledgment of fingerprint effects has experienced a development in recognition through the years (Kopp et al., 2015):

![Fingerprint](image)

*Fig. 2 The ratio of RSL change to GMSL change based on fingerprints on a Greenland ice sheet mass loss b West Antarctic sheet mass loss c East Antarctic ice sheet mass loss and d median glacier mass loss projection from the work of Kopp et al. (2014)*

in IPCC’s Third Impact Assessment Report and the Fourth Impact Assessment, it was dismissed and considered insignificant respectively. It was in the Fifth Impact Assessment Report that fingerprints effect was acknowledged as a complex process (IPCC, 2014). This study utilizes the work of Mitrovica (2011) on the calculated fingerprints accumulated from the calculation of Antarctic Ice Sheet (AIS); Greenland Ice Sheet (GIS); glacier and ice caps (GIC) and oceanographic (OC) processes which includes mean thermal expansion and regional atmosphere.

### 2.3. Robust Decision Making and Deep Uncertainty

Uncertainty has been discussed amply in the field of environment and hydrological projections for some period (Durbach and Stewart, 2012). The latter is comprehended by cumulating the uncertainties in the form of probability distribution embedded in its inputs, parameters, and structure. The latter approach will render what is known as the most probable scenario. However, in the face of uncertain future such as the climate, technological advancement, socio-economic phenomenon and political dynamics, the use of most probable scenario is no longer appropriate (Hall et al., 2016). These types of uncertainties render multiple future projections that could not be assessed regarding probability or ranked in that matter (Kwakkel et al., 2010). One of the common term used to encapsulate this concept of multiple plausible futures is deep uncertainty. Deep uncertainty is defined as:
“...the condition in which analysts do not know or the parties to a decision cannot agree upon: the appropriate models to describe interactions among a system’s variables; the probability distributions to represent uncertainty about key parameters in the models; and/or how to value the desirability of alternative outcomes” (Lempert et al., 2003; Walker et al., 2013b). Hallegatte et al. (2012)

Due to the developing comprehension of deep uncertainties, the use of ‘predict then act’ framework is regarded as perilous, as it takes scenarios as literal future imagery and disregards other possible scenarios (Lempert et al., 2006). The latter not only defies the whole idea of deep uncertainty, but it also would not provide an inadequate insight in the front of deep uncertainties conditions, nor to be taken as an input towards a decision-making process (Weaver et al., 2013).

While many frameworks have been developed to be able to incorporate deep uncertainty conditions in the decision-making process (e.g. adaptation pathways (Haasnoot et al., 2011), adaptive policy making (Ranger et al., 2010)), this study will focus on creating insightful input for the Robust Decision Making (RDM).

RDM is a framework that involves an iterative process that aims to help the identify a potential robust strategy along with an evaluation of its vulnerabilities and tradeoffs (Lempert et al., 2007; Croskerry, 2009). Ideally, a robust decision-making process would explore all the possible combinations and scenarios of an observed event (Weaver et al., 2013). However, due to computational limitations, the study focuses on the extreme case scenarios represented by the event of storm surge. Therefore, it is imminent to create scenarios that would be a valuable input for the stakeholders for the latter to develop a sound strategy to accommodate possible future levels of sea levels. However, to abide by the latter construct the model would require more time and computing power as well as more time needed to post-process the results. The approach is taken to provide a befitting input to the Nacka municipality is to provide a map that shows the span of the area between the lowest scenario and the most extreme scenario based on both extreme surges, wind and GMSL rise scenario.

### 2.4. Frequency analysis

Succeeding the work of Hall et al. (2016), to localize the impact of sea level rise, this study will use the extreme sea water level in which allows the data to be statistically processed using extreme value theories and projections. Extreme sea water level in this considers the effects of storm surge and astronomical tides. A storm surge is defined as an abnormal rise of water created by a storm, over and exceed the predicted astronomical tide. Its maximum height is dependent on several different factors. According to NHC-NOAA (2017), a storm surge is sensitive to the slightest change in storm intensity, forward speed, size (radius of maximum winds), the angle of approach, central pressure, shape and characteristics of coastal features, as well as width and slope of the continental shelf.

The magnitude of extreme sea level and the extreme wind is inversely correlated to its frequency of recurrence. Frequency analysis serves to relate the magnitude of an extreme event to its recurrence interval. To achieve the latter purpose, the sea level, and wind data is fit to a probability distribution function and later is contrasted with the data to gain the suitable type of distribution.

A probability distribution function signifies the occurrence probability of a random variable. It is also common to illustrate it as a Cumulative Density Function (CDF), which is a graph that shows an outcome could be either smaller or equal to a certain value (Chow et al., 1988).
2.4.1. Assumptions
To enable the calculation of frequency analysis; there are two assumptions that the data must abide (Hamburg University of Technology, 2010). First, it is assumed that both extreme surge and extreme wind represents independent data. An independent data is data that is not correlated with adjacent observations. Second, the data comes from the same population and inherent similar statistical properties (also known as the homogeneity assumption).

2.4.2. Return Period
The concept of return period or recurrence interval or repeat interval is a hypothetic period where a magnitude of an event will be exceeded its threshold. It could also be expressed as an inverse of probability. As an example, the return period of a flood is 50 years or expressed as a probability of occurrence is 1/50 or 2% in any one year (also known as Annual Exceedance Probability). However, the latter does not mean that after the magnitude is exceeded, it would recur corresponding to its interval. Instead, it means that in any year there is always 2% that it will occur, regardless of when the similar event was. The concept of return period can be often misleading id it is interpreted as an actual time sequence of an event (Beven, et. al., 2011).

Other events such as extreme wind and extreme storm surge could also be treated with this concept. Chow (1988) states that the equation could determine the probability of a flood (or in this case, it could infer as other extreme events) with a return period of T years to occur a minimum of one in a period of N years.

\[ P(X \geq x_t \text{ at least once in } N \text{ years}) = 1 - \left(1 - \frac{1}{T}\right)^N \]

2.4.3. Selection of Distribution Fitting
There are ample of varying theoretical distribution functions that could be opted to fit the measured tide gauge and wind station data. To process tide gauge data, several distribution theories has been chosen to be applied based on other preceding research, namely: General Extreme Value (Caires, 2011), Gumbel Type I (Caires, 2011), Log Pearson III (Caires, 2011), and Log Normal (Caires, 2011). Formula and parameters requirement is shown in Table 3.

Similar to the estimation of extreme sea level, this study will approach the estimation of extreme wind speed using the distribution analysis. Extreme wind speed data have been used in many environmental studies, i.e. climatology, hydrology, developing wind energy facilities and agricultural management and structure designing (Lopez, 1998; Gomes et al., 2003). From earlier work, the calculation for extreme wind speeds has also been chosen from several distributions GEV (Palutikof, 1999; Rajabi, 2008). However, there are fewer distribution types used compared to the extreme sea level. The main type of distribution used in the calculation of extreme wind speed is the Gumbel Distribution (El-Shanshouri et al., 2012).

Table 3 Type of Distributions and their respective formulas and parameters

<table>
<thead>
<tr>
<th>Type of Distribution Function</th>
<th>PDF Formula</th>
<th>Definition of parameters and requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gumbel (Extreme Value Type I)</td>
<td>( f(x) = \frac{1}{\alpha} \exp\left{ \frac{x - u}{\alpha} - \exp(-\frac{x - u}{\alpha}) \right} )</td>
<td>( \alpha = \sqrt{6\Delta_x} ) ( \mu_y = \bar{y} )</td>
</tr>
<tr>
<td>Log Normal</td>
<td>( f(x) = \frac{1}{x \sigma \sqrt{2\pi}} \exp\left{ \frac{-(y - \mu_y)^2}{2\sigma^2} \right} )</td>
<td>( \mu_y = \bar{y} )</td>
</tr>
</tbody>
</table>
### Type of Distribution

<table>
<thead>
<tr>
<th>Function</th>
<th>PDF Formula</th>
<th>Definition of parameters and requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log Pearson Type III</td>
<td>[ f(x) = \frac{\lambda^\beta (y - \varepsilon)^{\beta-1} e^{-\lambda (y - \varepsilon)}}{\lambda \beta \Gamma(\beta)} ]</td>
<td>[ \sigma_y = s_y ] [ \mu &gt; 0 ] [ \lambda = \frac{s_y}{\sqrt{\beta}} ] [ \beta = \left[ \frac{2}{C(y)} \right]^2 ] [ \varepsilon = \bar{y} - s_y \sqrt{\beta} ] [ C(y) \geq 0 ] [ \log x \geq 0 ]</td>
</tr>
</tbody>
</table>

## 2.5. Hydrodynamic Modelling

Over the years, numerous quantitative models have been conducted to assess the effect of sea level rise and storm surge. One of the known approaches is through a hydrodynamic model, in which is a tool that could represent the motion of a fluid using the Navier–Stokes equation. In coastal modeling, this equation is simplified with the specific properties which result in shallow water equation – since in an ocean and estuary environment the scale feature in the horizontal axis is greater than the vertical counterpart. Several examples of preceding hydrodynamic models include MIKE 21 and MIKE FLOOD (Sto. Domingo et al., 2010), ADCIRC (Lin et al., 2010), and ANUGA (Van Drie, 2010).

The local sea-level change could vary significantly from the GMSL rise. Thus, to be used for adaptation and risk management, a more localized assessment. The spatial variations of LSL could arise from several components. This study essentially tries to adjust GMSL change models to the localized factors while also acknowledging the suggestion given by Hall et al. (2016). He asserts that to localize further assessment of sea level rise by considering the hydrodynamic aspect of the local ocean and other involved interaction. Such approach is necessary to include the wave effect on the sea level as preceding research have disregarded the wave aspect. Using hydrodynamic model also enables the integration on the effect of the land cover towards the water movement in the land.

To achieve the aim and objectives of the current study, hydrodynamic model was done through Mike 21. It is a modeling package software that focuses on two-dimensional flow and transport model (Ting, 2010). Mike 21 is often used to model lateral water movement, as such it can model sea dynamics, river dynamics, and inland flooding (Warren and Bach, 1992). Two types of module could be used to simulate hydrodynamic phenomenon, namely the Mike 21 Classic Grid and Mike 21 Flexible Mesh. Despite being principally akin, the Mike 21 FM allows the more sophisticated approach to formulating the problem which allows a greater detail of inputs compared to its counterpart. However, the setback of adding the complexity is it hampers integration with other applications compared to Mike 21 Classic which has a more straight-forward workflow (Salmonsson, 2015).

Mike 21 utilizes a construction of a non-orthogonal triangular (also known as a triangular irregular network) mesh (Toppe, 1987) which enables flexibility in the resolution across the area compared to a strict raster grid used in Mike 21 Classic. The flexibility also allows the user give higher resolve on certain areas than the others especially where there are needs to represent small areas with a complex bathymetry or a fair representation of structures that significantly contributes to the hydraulic phenomenon (DHI Water Environment UK, 2012). This implies that the flexibility also allows the user to less concentrate on other
areas and diminish the resolution. A diminished resolution will generate fewer mesh elements and therefore enables a curtailed computation time.

Mike 21 FM is based on the numerical solution of two-dimensional incompressible Reynolds-averaged Navier-Stokes equation that uses Boussinesq and hydrostatic pressure assumptions (Néelz and Pender, 2009). Mike 21 also uses the cell-centered finite volume method, which is commonly used in computational fluid dynamics (Jose and Stone, 2006). A Riemann solver is also employed to compute convective fluxes which enable the handling of discontinuous solutions (Toro, 2013). The primary variables that represent the total water depth and velocity components are stored in the cell center (Mike, 2016b). Given these circumstances, the model may consist of equations that characterize continuity, momentum, temperature, salinity and density. In this study, solutions regarding temperature, salinity, and density are not of any concern. However, this study includes other solutions such as: bed resistance, wind resistance and flood-and-dry. Further explanation about these solutions as well as the fundamental equations involved could be found in the scientific documentation (Mike, 2016a) and step-by-step (Mike, 2016b).
3. Methods

The methods used in this study are both adaptation and combination of earlier methods on mapping coastal floods, i.e. Kopp et al. (2014), Brydsten et al. (2009), and Sto. Domingo et al. (2010). The methods were created to be able to localize the global mean sea level as well as other confounding local physical attributes. The method could be divided into three parts: pre-processing, processing and post-processing. An illustration of the steps taken is shown in Fig. 3.

**Fig. 3. Logical flow of methods used to map the extreme scenario coastal inundation in Nacka**

The preprocessing stages involve an intensive use of extreme value calculations, geographical information system process and acquiring the local sea level rise for Stockholm from literature. Extreme value calculations were generated using frequency factors for water level and wind speed data. The geographical information system was used to assign Manning values to the corresponding land use, and amalgamating land elevation and sea bathymetry into a unified study area bathymetry. The goal of the preprocessing stage is to deliver the required input for the MIKE 21 FMHD to run.

Before using the MIKE 21 FMHD module, scenarios were generated to satisfy the goal of this study. The scenarios will determine different model settings in the interface. Results generated will then be analyzed in two ways: flood maps which species the area span and depth of the flood in the area; and screen maps which address the area span with other related attributes.
3.1. Area Description

Nacka is one of the municipalities situated in Stockholm, has approximately 100,000 inhabitants (Nacka kommun, 2017b) and is one of Stockholm’s most extensive county municipalities as forecast projects an inhabitant of 131 000 in 2020 and an increasing population even after (EVRY, 2017). The latter implies the existence of high demands to build new and attractive housing, to provide the services the new residents need and improve communications e.g. a subway extension to the center of Stockholm. The municipality has a land area of 9,550 hectares, half of which of urban land (Nacka kommun, 2012) and a long coastline (100 km, Nacka kommun, 2012), which is predominantly built on due to the huge demand for seaside accommodation.

The study focus is the coastal area around a channel that extends from Ekorren to Solsunda. While it may be called a channel, but the water body is a part of the Baltic Sea. Therefore, it has similar attributes to the latter sea. Several places around this channel are shown in Fig. 4, e.g. Ekorren, Fisksätra, Lannerstam Ostervik, Drevinge, Tollare, Sagtorp,

![Fig. 4 Insert maps and the scope of the study area. Name shows distinctive developed area (Lantmäteriet, 2016)](image)

Hojedn, Saltjo-Duvnas, Saltangen, Eknas and Solsunda. Almost all of these areas currently attribute valuable property that held important function for the community, primarily housing and business building.

The study gives special concerns to Fisksätra and Tollare which are located within the Nacka municipality and the modeled channel. This came after a consultation meeting with the municipality (Nacka kommun, 2017a). Both coastline areas consist of residential areas, harbors, schools and several places of interest. In Fisksätra, a place called Fisksätra Folkets Hus Förening or the Fisksätra People’s House Association is one of the interests of the stakeholder. Fisksätra Folkets Hus Förening is a meeting hub owned by the Nacka Municipality with the intention for the community to meet, socialize and provide a welcoming nuance (Fisksätra Folkets Hus, 2017). In Tollare, currently, an ongoing project
called Tollare I Nacka, which is a joint development by multiple housing developers. The project will offer various types of housing such as detached houses, penthouses, small, well-appointed apartments, and townhouses. Overall, there will be 1100 housing units by the year 2020 (Tollare I Nacka, 2017). Thus, it is necessary to understand the risk of extreme coastal flooding associated with these areas.

A part of the model is the Baltic Sea, located in the Northern Europe and bordered by the surrounding nine countries: Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Germany, and Denmark. The Baltic Sea is a semi-enclosed water body in which water flows in and out through the Skagerrak Strait to and from the North Sea. The latter is 386,680 km² in size and serve as an imminent economic function as well as recreational and leisure.

According to Meier (2006), the amplitudes of tides are negligible, and the risk of coastal flooding is smaller compared to those of the North Sea. However, it also acknowledges that some of the areas are more vulnerable than others, such as in the south and east. The report also acknowledges that storm surges have occasionally occurred and impacted human life and coastal infrastructure.

Pressure and winds are the main factors that create variations in the water level of the Baltic Sea. Low pressure and onshore winds render higher water, while high pressure and land breeze give lower water levels. The extreme level lasts a few hours. How high the extreme level will be based on a given weather situation also depends on the starting position. A powerful storm does not involve critical levels of water initially is low. On the other hand, assumes a higher-level sea rise locally high at more moderate wind forces. This occurred, for example, in the winter of 2006 - 2007 when the entire Baltic Sea was filled with much more water than normal.

To understand the adequacy of current policy and the various sea levels, it is crucial to understand the response that was prepared by the municipality to combat climate change and specifically sea level rise as its consequence. In Nacka Municipality overview plan, the main response taken by Nacka on climate change is related to efforts on reducing emission (Nacka kommun, 2012). The initiative to reduce greenhouse as emission is mainly reflected in the transportation sector. As the municipality pursues a more climate-friendly means of transportation that could be done by increase opportunities for walking or cycling and increase access to climate-adapted fuels (Nacka kommun, 2012). Nacka Municipality has not emphasized in detail on plans related to climate-adaptation means. In the overview plan, it is briefly mentioned the importance of highlighting the flood risk and other consequences related to climate change during the planning process.

An overarching and specific adaptation response to coastal flooding is published by Länsstyrelsen Stockholm or The County Administrative Board of Stockholm. The Board delivers a suggestion to construct new cohesive settlements and community functions of significant importance should be above 2.7 meters (Länsstyrelsen Stockholm, 2012). The 2.7-meters value was based on SMHI’s regional climate report for Stockholm country, which includes 100-year water levels for a global sea level rise of 1 meter for 2100 adjusted with the land rise and safety margins.

3.2. Bathymetry

The bathymetry data is the central part of the model inputs. The term bathymetry refers to the description of the physical form (depths and shapes) of the surface under water (National Ocean Service, 2015). Since the model will bring forth the hydrodynamics features to the land, therefore the bathymetry that is used in the model is a combination of two sets of data: the digital elevation model and the sea bathymetry data. The zero level in
the Height System 2000 (RH2000) defined by Normaal Amsterdams Peil (NAP), which is a point in Amsterdam that is used as the 0-point in other European countries, while SWEREF 99 TM is used as the national georeferenced system proceeding the ETRS89 (Lantmäteriet, 2017a).

The sea bathymetry data is obtained from the Sjöfartsverket (2017), shown in Fig. 5. It uses the SWEREF 99 TM as the georeferenced and RH 2000 as the height datum. In some areas, the resolution of the bathymetry is 1 m while in some areas it varies. The difference of resolution is caused because the bathymetry data is used to navigate the ship through the sea. The shape of the waterbody exemplifies a channel that acts according to oceanic patterns since its tethered to the Baltic Sea.

**Fig. 5. The spread of shoal depth data across the modeled sea. Observe the different densities of bathymetry points, where darker areas show higher resolution bathymetry (Sjöfartsverket, 2017)**

Aside from the sea bathymetry, the digital elevation model (DEM) is a crucial input feature of the model. The digital elevation model will act as a complementary to the sea bathymetry, especially if the sea elevation has risen above 0 m or moves across the predefined land. The digital elevation model is available from the Lantmäteriet (201b) and openly available in the 2-meter resolution.

The creation of combined land and sea bathymetry begins using GIS to cut out the elevation values in the water land use area. The land value was then converted to a format that could be accepted by Mike Mesh Generator. Land boundaries in the mesh were determined based on elevation value since a great number of elevation data will be a waste of time and energy since a coastal flood could only affect some extent of the elevation. Trimming the higher elevation areas will cut running time as well as allocating more mesh. Additionally, segmentation is done to assign a higher number of mesh in the land areas and several narrow water areas compared to the general sea.
To create a continuous bathymetry needed to be able to be used by the MIKE 21 FMHD, an interpolation was done using the MIKE Mesh Generation (Fig. 6). Since the mesh was formed in a triangular shape, a triangle interpolation using the nearest neighbor method was chosen.

![Image](image.png)

**Fig. 6 Left the adjusted land boundaries Right the different mesh size. Illustration from DHI (2016)**

### 3.3. Projected Sea Level Change

It was acknowledged that in a specific area assessment of coastal flood, the localized value of sea level change (in this study known as LSL) is more important than the GMSL change. An adjustment needed to be done to abide by the criteria. Thus, a global scaling is used to adjust the sea level change; which is a ratio of LSL to GMSL in this case between Stockholm and global. Note that the scaling refers to the work of Kopp et al. (2014). In which, he identified the global scaling values of 0.83. This implies that when adjusted locally, the projected LSL in Stockholm will be lower than the GMSL. The lower value could be attributed to the fact that in spatial terms, Stockholm is situated closer to the Green Land ice sheet.

<table>
<thead>
<tr>
<th>Table 4 Projected Local Sea Level Change for Stockholm, Sweden (Background: -5.01 + 0.12 mm/yr) from Kopp et al. (2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RCP 8.5 (cm)</strong></td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>2030</td>
</tr>
<tr>
<td>2050</td>
</tr>
<tr>
<td>2100</td>
</tr>
<tr>
<td>2150</td>
</tr>
<tr>
<td>2200</td>
</tr>
</tbody>
</table>

### 3.4. Frequency Analysis

A preliminary requirement to run the MIKE 21 FMHD is to provide appropriate inputs. One of the inputs that require more processing is the wind and sea surface elevation. To represent the events of the extreme case of both type of data, an extreme value analysis is conducted to predict the value of the sea levels and the wind in correspondence with the
100-year and 150-year return period. Both return values are chosen to represent two of the main model time frame, 2100 and 2150. The Extreme Value Type II is chosen as a method to calculate both inputs per the expected return periods.

There are several types of known type of analysis that could be used to estimate the value of extreme surge events, e.g. the Annual Maximum Method (Walton, 2009; Mkhandi et al., 2015), Peaks Over Threshold (Mkhandi et al., 2015), Joint Probability Maxima (Ochi, 2016), Revised Joint Probability Method (Tawn and Vassie, 1989), etc. The study will utilize the Annual Maximum Method to calculate the extreme value for both wind and storm surge from the historical data. The AMM utilizes frequency analysis to calculate the extreme surges corresponding to the return period by selecting the uppermost value of each year event (Pugh and Vassie, 1978). Several distribution types that have been used to accommodate the use of maximum annual year are Log-Normal (Walton, 2000), Log Pearson III (Dong et al., 2009), and Extreme Value type I or Gumbel (Walton, 2000; Huang et al., 2008). A further explanation on these distributions is presented below:

**Frequency Factor for EV Gumbel I (Chow, 1989)**

\[ x_T = \bar{x} + K_T s \]

\[ K_T = \frac{\sqrt{6}}{\pi} \left( 0.5772 + \ln \left( \frac{T}{T-1} \right) \right) \]

The term \( x_T \) is the estimated sea level magnitude. The latter is the addition between \( \bar{x} \) (the sample mean) and the product of s (the sample standard deviation) and \( K_T \), frequency factor that corresponds to the return period (T).

**Frequency Factor Method for Log Normal (Chow, 1989)**

\[ z = w - \frac{2.15517 + 0.802853w + 0.010328w^2}{1 + 1.432788w + 0.189269w^2 + 0.001308w^3} \]

\[ w = \left( \ln \left( \frac{1}{p^2} \right) \right)^{0.5} \]

\[ p = \frac{1}{T} \]

\[ y_T = \bar{y} + z s_y \]

\[ x_T = 10^{y_T} \]

**Frequency Factor for Log Pearson Type III (Chow, 1989)**

\[ K_T = z + (z^2 - 1)k + \frac{1}{3}(z^3 - 6z)k^2 - (z^2 - 1)k^3 + zk^4 + \frac{1}{3}k^5 \]

\[ k = \frac{C_s}{6} \]

\[ y_T = \bar{y} + K_T s_y \]

\[ x_T = 10^{y_T} \]
3.5. Sea Level Data
The SMHI tide gauge station provides an hourly recorded sea level with an RH 2000 datum. The station has been recording the hourly sea level data since 1889. The tide gauge station name is “Stockholm”, with an identifier number of 2069, located near the Skeppsholmen area. It approximately contains 1.2 million durational sea level data, and is currently active. A statistical summary of the tide gauge station data is shown in Table 5, and the trend of the yearly data is shown in Fig. 7.

Table 5 Several explorative parameter statistics from the measured sea level data (SMHI Oppna data, 2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AM Sea Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of data</td>
<td>128</td>
</tr>
<tr>
<td>Minimum</td>
<td>61.8</td>
</tr>
<tr>
<td>Maximum</td>
<td>149.8</td>
</tr>
<tr>
<td>Mean</td>
<td>96.0289</td>
</tr>
<tr>
<td>Standard of Deviation</td>
<td>18.169</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.392</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.201</td>
</tr>
</tbody>
</table>

Fig. 7. The annual maxima and the annual average of sea level data between 1889 to 2016 (SMHI Oppna data, 2017)

3.6. Wind speed data
The wind speed and wind direction data are acquired from SMHI wind station located at Skarpö A in meter/second and degree consecutively. The wind station has acquired an approximate of a hundred and seventy thousand wind speed, and direction data started from the year 1976. A statistical summary of the wind speed station data is shown in Table 6, and the trend of the yearly data is shown in Fig. 8.
Table 6 Several explorative parameter statistics from the measured wind speed data (SMHI Oppna data, 2017b)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AM Wind Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of data</td>
<td>41</td>
</tr>
<tr>
<td>Minimum</td>
<td>10.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>20.4</td>
</tr>
<tr>
<td>Mean</td>
<td>16.39</td>
</tr>
<tr>
<td>Standard of Deviation</td>
<td>2.165</td>
</tr>
<tr>
<td>Skewness</td>
<td>-0.426</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Fig. 8 The annual maxima and the annual average of sea level data between 1976 and 2016 (SMHI Oppna data, 2017b)

3.7. Bed Resistance

To be able to assign Manning’s value, a land use data, as well as several kinds of literature, are needed. Land use data in this study refers to the raw satellite data that has been classified into land use categories. The land used data originated from Lantmäteriet (2017c) and provided valuable insight on determining the extent of various land cover and function, e.g. urban, forest, and agriculture. Land use data will be used for as an input data for the model and the post-processing analysis. The insight delivered by the land use data is used to approximate the corresponding Manning value (M) to the land cover and will be used as one of the input value for the Mike 21. The provided land use data is available in vector shapefile format.

Manning’s number (M) is used to represent the bed resistance. These values were chosen based on their feature in the land use map and their corresponding Manning’s number.
available in the literature. The study will use the Manning-Land use classification based on the work of Kalyanapu et al. (2009) that is shown in Table 7, while spatial assignment of such value is exemplified in Fig. 9.

Table 7 Associated land cover and their respective Manning number from the work of Kalyanapu et al. (2009)

<table>
<thead>
<tr>
<th>Land Cover</th>
<th>n</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed, low intensity</td>
<td>0.08</td>
<td>12.5</td>
</tr>
<tr>
<td>Developed, high intensity</td>
<td>0.15</td>
<td>6.67</td>
</tr>
<tr>
<td>Developed, medium intensity</td>
<td>0.15</td>
<td>6.67</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.035</td>
<td>28.57</td>
</tr>
<tr>
<td>Pasture</td>
<td>0.04</td>
<td>25</td>
</tr>
<tr>
<td>Mixed forest</td>
<td>0.16</td>
<td>6.25</td>
</tr>
<tr>
<td>Deciduous forest</td>
<td>0.16</td>
<td>6.25</td>
</tr>
</tbody>
</table>

Fig. 9 Manning number classification in the study area based on Kalyanapu et al. (2009) work

3.8 MIKE 21 FMHD Modelling
The Mike 21 FMHD utilizes a flexible mesh approach which has been refined for oceanography, coastal and estuarine environment. A similar approach could also be used to study overland flooding. Mike 21 Flow Model FM is grounded on two/three-dimensional incompressible Reynolds-averaged equation using the Boussinesq and hydrostatic pressure.
3.8.1. Scenario Creation
To achieve the aim and objectives of the study, several scenarios were composed by selecting corresponding localized sea level change projections, extreme water level, and extreme wind data. The expected corresponding scenarios are divided into two categories based on the severity of the expected impact: low and extreme. Also, since the input is intended to help long-term decision-making process in the associated areas, two categories are also created based on the expected time frame, namely 2100 and 2150. The summary of the combination of the events is shown in Table 8.

For the calculation of the extreme water levels in the future, added average water level rise before the statistical calculation is made for the future climate. The methodology assumes that the distribution of extreme water level is the same as today and that the entire increase in water level is due to the average water level rise.

Table 8 A summary of scenarios and its corresponding attributes

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Attribute 2100</th>
<th>Attribute 2150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>• Localized low projection sea level for Stockholm at 2100 • 100-years return period extreme water level • 100-years return period extreme wind speed</td>
<td>• Localized low projection sea level for Stockholm at 2100 • 100-years return period extreme water level • 100-years return period extreme wind speed</td>
</tr>
</tbody>
</table>

| Extreme  | • Localized low projection sea level for Stockholm at 2100 • 1000-years return period extreme water level • 1000-years return period extreme wind speed | • Localized low projection sea level for Stockholm at 2150 • 1000-years return period extreme water level • 1000-years return period extreme wind speed |

3.8.2. Model Set Up
The set up refers to the configuration of the MIKE 21 FM interface. It is composed of the parameters that were used as an input to the model.

- Domain: The domain specified in the module is the interpolated bathymetry mesh preprocessed before.
- Module selection: The hydrodynamic module and inland flooding was chosen in this model
- Solution technique: The shallow water equation is configured to be solved with high-order time integration and space discretization. The minimum time step, which refers to the shortest time step the calculations can use to achieve the critical CFL number, was set to 0.01 second. The desired CFL number was set to 0.8. The maximum time step was set up to 30 seconds. These values was chosen to satisfy the stability of the model and produces less running error as possible.
- Standard flood and the dry module were chosen with a drying depth of 0.005 meters, flooding depth of 0.05 meter and wetting depth of 0.1 meters. Lowering the flooding depth any further would result higher the chance of the violation of CFL numbers as well as unrealistic velocity and crashed programs.
- Eddy viscosity was set up to the default number, 0.08 m²/s.
• Bed resistance: The dfs-2 file with embedded Manning’s number was chosen
• Initial condition for the surface elevation was adjusted based on the specified level used as an input. Additionally, u and v velocity used zero as its initial value.
• Outputs: Two outputs were set. A 2D result disc-file and the inundation dfsu-file

The simulation period was set to 48 hours and the used simulation time steps are 5 minutes. The duration was determined to be able to incorporate storm surge event while the simulation time step ensures the stability of the numerical calculation. The computation time per simulation is approximately ten hours, a normal duration for a flexible mesh model. However, a flexible mesh computation duration could be shortened to eight hours by bypassing the calculation through the graphical processing unit (GPU).

Since the focus of the study is the locality of Fisksätra and Tollare, the model boundary was drawn in the northern and eastern part of the water body. The northern boundary of the model exists near Ekorren while the eastern boundary is situated at Solsunda. The northern and eastern boundary embeds a specified level, which is an input of sea level on a 48-hour period adjusted with the scenarios. Aside from those, all delimiters are assigned as land boundaries.

3.8.3. Other Assumptions

While this study is intended to give a more robust coastal inundation assessment using the hydrodynamic model, the execution of the latter needs several assumptions to be able to be completed. Several determined assumptions are:

• It is assumed that the future land use in 2100 and 2150 are identical to the land use data obtained from the Lantmäteriet (2017c). This might change depending on further plans of development in the future, especially since Nacka Municipality is an alluring area that tends to develop its areas further. Several future land uses have been allocated within the scope of this study for several years to come. However, the extent of the plans is diminutive compared to the time extent of this study.
• It is also assumed that there is no sedimentation process in the ocean, which suggest for a similar value of both Manning’s value (M) and the distribution of depth.
• In this study, while the input value of tide gauge is taken from the values of the extreme sea level rise and localized sea level change, the wind data only takes into account the extreme wind speed event.
4. Results

4.1. Frequency Analysis for Extreme Water Level

Extreme Sea Level value was calculated using four methods: Log-Normal, Gumbel (Method of Moments), Gumbel (Frequency Analysis), and Log-Pearson III (Frequency Analysis). The results are shown in Table 9. The frequency analysis was done under the assumption that the continuous data is homogeneity, consistent and stationary (Dahmen and Hall, 1990).

Table 9 Frequency factor results for Maximum Annual Water Level Data with their respective return period and methods (in cm)

<table>
<thead>
<tr>
<th>Return Period (years)</th>
<th>Log Normal (cm)</th>
<th>Gumbel (cm)</th>
<th>Log Pearson III (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>94.36</td>
<td>93.04</td>
<td>94.74</td>
</tr>
<tr>
<td>5</td>
<td>110.48</td>
<td>109.10</td>
<td>110.72</td>
</tr>
<tr>
<td>10</td>
<td>119.99</td>
<td>119.73</td>
<td>120.39</td>
</tr>
<tr>
<td>25</td>
<td>131.04</td>
<td>133.16</td>
<td>131.64</td>
</tr>
<tr>
<td>50</td>
<td>138.70</td>
<td>143.13</td>
<td>139.46</td>
</tr>
<tr>
<td>100</td>
<td>145.98</td>
<td>153.02</td>
<td>146.88</td>
</tr>
<tr>
<td>200</td>
<td>152.97</td>
<td>162.87</td>
<td>154.03</td>
</tr>
<tr>
<td>500</td>
<td>161.89</td>
<td>175.88</td>
<td>186.31</td>
</tr>
<tr>
<td>1000</td>
<td>168.46</td>
<td>185.70</td>
<td>225.37</td>
</tr>
</tbody>
</table>

Table 11 shows statistically calculated levels for return times 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years. These corresponds to 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, 0.2% and 0.1% probability that the extreme water level exceeds each individual year. The extreme water level with 100 years of return time is 145.98 cm, 153.02 cm, 146.88 cm; Log Normal, Gumbel and Log Pearson III, respectively. The highest measured extreme water level, 149.8 cm corresponds to an approximate return time between 100 – 200 years in Log Normal; 50 – 100 years in Gumbel; and 100 – 200 years in Log Pearson III. Note that the uncertainty is high when the return time is much longer than the database. In this case, values exceeding a return period of 128 years will yield more uncertainties.

4.2. Frequency Analysis for Extreme Wind

The extreme value analysis for the wind speed data is processed using the Extreme Value Analysis Type I or Gumbel distribution. The result and its corresponding return period value are shown in Table 10.

Table 10 Frequency factor results for Maximum Annual Wind Speed Data (m/s) with their respective return period

<table>
<thead>
<tr>
<th>Return Period (years)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>16.04</td>
</tr>
<tr>
<td>5</td>
<td>17.95</td>
</tr>
<tr>
<td>10</td>
<td>19.22</td>
</tr>
</tbody>
</table>
Table 10 shows statistically calculated levels for return times frequency analysis for 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years. These corresponds to 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, 0.2% and 0.1% probability that the level is exceeded each Individual year. The extreme wind speed with 100 years of return time is 23.19 m/s. The highest measured wind speed, 20.4 m/s corresponds to approximately a return time of 10 – 25 years. Due to the shorter extent on the number of the data, higher uncertainty exits in higher return period times beyond 41 years.

### 4.3. Flood Maps

Fig. 10 and Fig.11 depicts which areas will be flooded if the sea levels abide by the low and extreme scenario in 2100. The consequences of the low scenario are relatively small compared to the extreme counterpart. Low scenario mostly shows floods with the depth between 0 to 1 meter. On the other hand, extreme scenario yield wider span of flood and deeper flood depth in some places. Depth could extend to three meters in the latter scenario and yield impact to urban areas that is represented with grids. It could also be observed that several roads are inaccessible which could hinder traffic to the area.

<table>
<thead>
<tr>
<th>Return Period (years)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20.82</td>
</tr>
<tr>
<td>50</td>
<td>22.01</td>
</tr>
<tr>
<td>100</td>
<td>23.19</td>
</tr>
<tr>
<td>150</td>
<td>23.87</td>
</tr>
<tr>
<td>200</td>
<td>24.36</td>
</tr>
<tr>
<td>500</td>
<td>25.91</td>
</tr>
<tr>
<td>1000</td>
<td>27.08</td>
</tr>
</tbody>
</table>
Fig. 10. Comparison of flood maps generated from the results of MIKE 21 FM for 2100
Fig. 11. Comparison of detailed flood maps for 2100. Focusing on both Ficksatra and Tollare

Fig. 12 and Fig. 13 shows inundated for each scenario in the year 2150. The low scenarios reflect more shallow floods as the inundated areas has a depth between 0 to 2 meters. Several flooded roads are more visible compared to its predecessor 2100 counterpart. The extreme parallel shows a significantly deeper and more extensive flood, such that it distinctively overlay with urban areas in several places. Under this scenario, flood depth could reach more than four meters. In such case, the areas affected will not only suffer material damage, but it is also more likely that residents will have to evacuate and activities related to specific building function will have to halt.
Fig. 12. Comparison of flood maps generated from the results of MIKE 21 FM for 2150 scenario.
Fig. 13. Comparison of detailed flood maps for 2100, Focusing on both Ficksatra and Tollare

4.4. Screening Map

Fig. 14 and Fig. 15 are the results of adjoining scenarios based on their respective time frame. It intends to give more contrasting extent of the flood span which will screen out areas that are not currently identified as prone flood areas even under the extreme circumstances. Another feature of the screening map is to illustrate the extent of the current bearing rule to adapt to the coastal flood. Stockholm Lan asserts an adaptation rule which to construct no building below 2.7-meter elevation unless further detail investigation is proven otherwise. A contour feature was added to screening map which
shows an increment of 5 meters and 20 meters. Contours will provide basic imagery of the overall land terrain in the modeled area.

Fig. 14. Screen maps for both low and extreme in the year 2100 and 2150

Apart from providing a more general area span of the coastal flood and their associated scenarios, the screen maps also illustrate the areas that should be avoided for further construction. This is to incorporate Länsstyrelsen Stockholm suggestion that all new cohesive settlements should be built above 2.7 meters RH-2000 elevation. Utilizing this value and raster calculation procedures, an area span representing this value was created to further the contrast the adequacy of the adaptation response.
Fig. 15. Detailed screen maps for both low and extreme in the year 2100 and 2150. Focusing on both Ficksatra and Tollare

4.5. Impact on land use
A simple land use analysis is done by overlaying the inundation map from the model and the available land use map that has been classified by Lantmäteriet (2017c). The latter was done for each scenarios. The overlay results embed the land use types that could be broken down according to these types. In the overlay results, five types of land use that come about, namely low developed, high developed, open land, forest, and water. However, the water land use was discarded during the analysis since it provides no additional insight, as due to the assumption of a non-changing land use, the calculation regarding this land use
remains the same. The breakdown of the land use types to its associated land use is available in Table 11.

**Table 11 Land-use breakdown matrix. Land use classification follows the spatial data produced by Lantmäteriet (2017c)**

<table>
<thead>
<tr>
<th>Area inundated (m$^2$) per land use type</th>
<th>Total Area (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area inundated (m$^2$) per land use type</td>
<td>High</td>
</tr>
<tr>
<td>Developed</td>
<td>Developed</td>
</tr>
<tr>
<td>2100</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-</td>
</tr>
<tr>
<td>Extreme</td>
<td>457.058</td>
</tr>
<tr>
<td>2150</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-</td>
</tr>
<tr>
<td>Extreme</td>
<td>9171.702</td>
</tr>
</tbody>
</table>
5. Discussion

5.1. Flood Maps

Overall, both extremes in the 2100-time frame do not yield a significant difference in area span. The steep terrain surrounding the channel contributes to the none significant difference between the modeled range of sea level rise. Nevertheless, the area between Saltängen and Saltsjö-Duvnäs shows more coastal propagation compared to the other areas. This also applies to some part of Lännersta and Ekorren. The greater propagation in these areas contributed to the flat attribute of the terrain on certain elevation. The contour figure also shows the latter as there is a wide distance separating the contours in the area.

Visually, enlarged results focused on Tollare shows almost no change in a flood area. However, it does suggest there are changes in the flood depth, in which the extreme-2150 scenario generates deeper flood depth. The latter increase is attributed to the increasing level of sea level. On the other hand, the observation between Low-2100 and Extreme-2100 in Fisksätra shows an increase in the coastal flood propagation. The wider area span in the extreme 2100 scenario inundates several local buildings. As a comparison, the extreme 2100 scenario is roughly 2.43 bigger than its low counterpart.

The comparison of both extremes in 2150 illustrates more significance regarding the difference in the size area affected by the flood as well as the flood depth. The total flooded area of the Extreme-2150 is approximately three times larger than the its low counterpart. Much like the case in 2100, the area between Saltängen and Saltsjö-Duvnäs, Lännersta and Ekorren also illustrate a greater flood propagation contributed to the terrain that is relatively flat compared to the other areas in the vicinity.

In the 2150-time frame, both of scenarios exemplifies a more extensive flood along the coastal areas and more of it falls into a deeper depth range. It is worth noticing that in the extreme-2150 scenario, Fisksätra suffers more flood propagation with deeper depths ranging from 0 to more than 4 meters. On contrast, low-2150 scenario illustrates depth ranging between 0 to 1 meter and in some areas, reaches up to 2 meters. In this area, the latter scenario illustrates no substantial difference even when contrasted to the low-2100 and extreme-2100 scenarios regarding size. The significant increase in size suggests that the area is sensitive to an increase of extreme sea level.

5.2. Screen Maps

Comparison between the Länsstyrelsen Stockholm suggestion (marked by areas below 2.7 meters) and the scenarios yield differing results. When compared to the low scenario in 2100 and 2150, the Länsstyrelsen suggestion area is proven to be adequate to address the response to prevent further damage implicated by the coastal flood. However, upon comparison to the extreme scenarios, the Länsstyrelsen suggestion is exceeded by the propagation of the flood. In the 2100-time frame, only several averted-construction areas are exceeded. The exceedance is distinctively shown upon compared with the extreme-2150 scenario, in which the flood propagates the Länsstyrelsen suggestion. The latter signifies the importance of adjusting these threshold value depending on the time frame that the planners will work with, or in this case the predetermined age of planned infrastructure.

On Tollare, only several small areas of the land where the flood propagates exceeded the Länsstyrelsen suggestion areas during the 2100-time frame. Those that exceeded the threshold represent the flood generated from the extreme scenario. During the 2150-time frame, it is evident that the extreme scenario flood propagates further than the extreme-
2100 scenario. However, the additional propagation is relatively minor compared to the more sensitive areas such as Saltängen, Saltsjö-Duvnäs, Lännersta and Ekorren.

On Fisksätra, the extreme-2100 flood propagates more in one area than the other. However, the span of the coastal flood is beyond any of the Tollare cases. In the extreme scenario, building close to the channel is affected due to the flood. In a certain area of Fisksätra, the extreme-2150 propagates more than the preceding 2100-extreme scenario. It even shows a similar trend to the case of the sensitive areas. The phenomenon implies a relatively flat terrain exists beyond a certain sea level that the land becomes inundated extensively. The further span of the flood cause several more buildings were inundated near the coast of Fisksätra.

5.3. Land Use
The tabulation of land use analysis shows that in 2100, there is a significant increase in the inundated area between the low and the extreme scenarios. The amount of the total inundated area in the extreme scenario is roughly 2.5 times to that of the low scenario. While all type of land use increases, however, the open land is the most affected by the coastal flood. Also, it is worth noticing that in the extreme scenario, an additional distinct high developed land use exists with a value small relatively to the other land use counterpart.

A construction of similar observation for the 2150-time frame scenarios implies a higher increase exists between the low and extreme compared to its 2100 counterpart. The total inundated area of the extreme area is approximately three times more of its low counterpart. The breakdown also shows that in the extreme case, the forest is the most impacted land use competed to the open land. The high developed land is also more impacted; it attributes 20 times more to its 2100 counterpart.

The breakdown also shows quantitatively that low scenarios yield less increase in the area impacted by the flood inundation contrasted to the high scenarios. Even though the latter is the contribution of lower sea level in the scenarios, another important aspect to be considered is that the coastal areas are steep in this ranges. The results of higher scenario suggest that the existence of a relatively wide flat terrain in the range of higher scenario sea levels. In the event of a sea level exceeding a certain elevation value, coastal flood propagates more extensive in these terrains.

5.4. Suggestions for Future Work
This study approached the improvement of the upon suggestions of Parris et al. (2012) and Kopp et al. (2014), which suggests for a localization of global sea level change and the use of hydrodynamic for a localized assessment. However, the current study still embeds several rooms that could be improved in future research.

The land use analysis assumes the non-changing land use over the years, based on the available Lantmäteriet data (2017c). However, this might not be the case in actuality. It was clear that Nacka Municipality is one of the fast-growing parts of Stockholm hence the latter is inadequate to be used as a base to assess the future impact of the flood. Not only it would result in a better assessment of the impacts associated with land use, but it will also act as a more representative bed resistance input for the model.

While the change in the sea level is one of the primary concerns in the method of this study, the change in the maximum gust affected by the latter is not addressed. Since climate change will affect the overall global temperature, it would affect the pressure and therefore wind patterns over the years to come. In this study, extreme wind calculated
primarily using the frequency analysis for a predetermined return periods. It should also be noted that the wind input also consists of direction factor aside from the magnitude. The direction of the wind could be addressed as one of the uncertainty factors that could be addressed using Monte Carlo analysis in the future work.

Screen maps in this study designed to visualize the range of possible flood inundations from the low to the extreme scenario. In the future work, a probability map could be generated instead. A probability map would illustrate more focus on the probabilistic range rather than being misinterpreted as a combination of two scenarios. To approach this as a quantitative probabilistic map, a Monte Carlo analysis could be used to generate the area-span of each simulation. The user needs to list the uncertainties embedded in the inputs as well as their probability distribution function approximations. However, in doing so, it requires a massive computational power and storage drive, taking into account the size of the study area and the decision to use the flexible mesh.
6. Conclusion

This study models the propagation of coastal floods in Nacka that corresponds with two contrasting sets of conditions: low and extreme. The model considers fingerprints in the sea level rise as well as local physical attributes such as vertical land motion, extreme sea levels, the wind, and surface resistance from various land cover. These aspects were included in the shallow equation that acts as the main driver of the model.

While there are several areas where flood propagates extensively (e.g. Saltängen, Saltsjö-Duvnäs, Lännersta, and Ekorren), the overall Nacka Municipality in the context of the modeled coastal areas is considered not significantly affected by the sea level rise. However, attention should still be given to those several areas that are more prone than others, as these areas still possess functions to the community: such as schools and housing. Tollare is an example of a less affected area by sea level rise, while Fisksättra shows sensitive areas to extreme sea level rise.

As expected, low scenario coupled in short term time frame shows the least flood propagation throughout the area. On contrast, an extreme scenario in a further time scenario shows the most flood propagation. While there are contributions from extreme events and surface resistance, the propagation of coastal flooding is primarily affected by the sea level rise. This is affected by the dynamics and contributions of ice sheets which have always been an ongoing research. It is possible that the sea level change values will change compared to that of the study in the future.

Furthermore, this study gives an example on one of the ways to present an input for the robust decision-making framework from MIKE 21 results. The method of handling sea level rise selection, frequency analysis using frequency factors for extreme storm surge and extreme wind, as well as scenario building are relevant results of the study.

By discarding the depth aspect, screen map visualizations focus on giving a range of flood propagation rather than representing two contrasting scenarios. It is also a representative way to contrast between the model and the suggestions from Länsstyrelsen Stockholm. Low scenario related sea level rise events are addressed adequately compared to the extreme ones. Long term extreme event proves to exceed several of the construction-averted areas, suggesting that threshold should also be addressed for the long term.
References

Andersson, M., Sjökvist, E., 2012. RAPPORT NR 29 Dimensionerande havsvattennivåer vid Södra Värtan (REPORT NO 29 [Dimensioning sea water levels at Södra Värtan, in Swedish] SMHI: Stockholm


DHI. 2016. MIKE 21, Release 2015 64bit. Copenhagen, Denmark: Danish Hydrological Institute


Gregory, J., 2013. Projections of sea level rise. *Climate Change*


Holly Shaftel, 2017 The Consequences of Climate Change
https://climate.nasa.gov/effects/, Accessed at 18 April 2017


Jose, F. and Stone, G.W., 2006. Forecast of nearshore wave parameters using MIKE-21 Spectral wave model.


Lantmäteriet, 2017b. Höjddata [Elevation data, in Swedish]. © Lantmäteriet
Lantmäteriet, 2017c. Fastighetskartan [GSD Swedish Land Cover Data, in Swedish]. © Lantmäteriet
Länsstyrelsen Stockholm, 2012. Rekommendationer för lägsta grundläggningsnivå längs Östersjökusten i Stockholms län – med hänsyn till risken för översvämning [Recommendations for the lowest foundation level along the Baltic Sea coast in Stockholm County - considering the risk of flooding, in English)] Stockholm: Länsstyrelsen Stockholm


Nacka kommun, 2017a. Discussion on flood prone areas in Nacka [Meeting] (Personal communication, 23 February 2017)


UNFCCC, 2011. Fact sheet: Climate change science - the status of climate change science today. United Nations Framework Convention on Climate Change: Bonn, Germany


