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Study on Environmental Consequences of Sea Level Rise on Areas along the Göta Älv in Gothenburg

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ABSTRACT

That the significant increase of the “green house effect” is caused by human activities is widely accepted among scientists. However, they cannot agree upon how fast regional sea levels will rise and how severe the impact will be. This thesis aims at analyzing the impact of sea level rise on the environment of Gothenburg, Sweden based on different estimations of sea level rise (0.1-0.9 m). Based on these estimations, three scenarios are created for fourteen riverside districts (“stadsdelsnämnd”) of Gothenburg in the next hundred years: the zero-increase, moderate-increase and maximum-increase. The study area is along the Göta Älv - the city’s river - which will be affected the most when sea level rise occurs and the environmental consequences in focus are landslides and saltwater intrusion. Data from different reliable sources are integrated into a GIS map and then analyzed by the software ArcGIS 9. Product maps for the scenarios support the discussion about potential measures against sea level rise in the future.

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ABBREVIATIONS

BASMAA	Bay Area Stormwater Management Agencies Association
DEM	Digital elevation model
DTM	Digital terrain model
GIS	Geographic Information System
IPCC	Inter-governmental Panel on Climate Change
MW	Mid-tide
HHW	Highest recorded tide
NAO	North Atlantic oscillation
PSMSL	Permanent Service for Mean Sea Level
SGI	Swedish Geotechnical Institute
SGU	Sveriges geologiska undersökning (Geological Survey of Sweden)
SMHI	Swedish Meteorological and Hydrological Institute
SRES	Special Report on Emissions Scenarios
SuDS	Sustainable Drainage Systems

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1. INTRODUCTION AND RESEARCH QUESTIONS

This section is to introduce sea level rise as a problem which will become more and more severe for many countries in the hundred years to come. Predicting the future always faces uncertainties. So what have scientists come up with for the last decade in order to deal with these uncertainties? We will see how effective current scenarios used for estimating sea level rise are and then examine recent research of relevance. After that, a few niches for this thesis will be considered and its research questions and outline will follow.

During the next century, the global average sea level is expected to rise because of thermal expansion (Cazenave and Llovel, 2010) but local sea levels may fluctuate due to the change in ocean density and dynamics (Solomon *et al*., 2007, Chap. 10). Therefore, it is not easy to study the problem globally and produce a unique answer for all countries and territories. Different nations may have to come up with different approaches to adapt to the changes of sea levels in their own regions. Specifically, some must invest a large portion of their national budgets in protecting their coastline against the higher rate of sea level rise while others would experience a slow increase in the local sea levels for the next hundred years and therefore can save money for other more important objectives instead (World Bank, 2009). Furthermore, the complexity can also occur at the national level when one country experiences a change from decline to rise in the relative sea level, i.e. the level of the sea relative to the land at a specific region [e.g., Rennie and Hansom (2011)]. Such phenomenon may happen where the sea level increases at a faster degree than the tectonic uplift, which is "the raising of the Earth's surface across broad plateau or mountain regions" (Ruddiman, 1997).

Climate change, its negative impacts, such as floods, droughts, erosion and sediment transport (FitzGerald *et al*., 2008; Kundzewicz *et al*., 2007), and the vulnerabilities, such as that of freshwater resources and biodiversity (Nicholls *et al*., 2007), imply many potential problems and uncertainty about future development. This makes the future consequences hard to predict. Before addressing these uncertainties, one can first categorize them into one of the three following groups: unpredictability, structural uncertainty, and value uncertainty (IPCC, 2005).

1. Unpredictable uncertainties are those that result from non-determined systems like social or political systems (such systems can change their future development).

2. A structural uncertainty is one resulting from a shortcoming of the model which should be criticized by the authors themselves at the end of the research. In fact, because science is in essence a process of self-correction, plenty of models were created and improved over time (Solomon *et al*., 2007, Chap. 1) and they had different levels of complexity ranging from the most comprehensive to the simplest ones (Solomon *et al*., 2007, Chap. 8).

3. Value uncertainties are related to the error that occurs during the data-acquiring and data-analyzing process although they can be minimized with measuring tools of high precision or good analyzing software. An example of value uncertainties of GIS features is the contour interval (Fig.6).

Vafeidis *et al*. (2008) described the process of establishing a new global coastal database for impact and vulnerability analysis to sea level rise which underpins the Dynamic Interactive Vulnerability Assessment (DIVA) model for computing relative sea level rise scenarios (Carter *et al*., 2007).

To deal with uncertainties, scientists have invented various methods to characterize the future, for example using scenarios or sensitivity analyses (Carter *et al*., 2007). Unlike predictions or forecasts in which the outcomes are more likely, scenarios tend to draw possible or wanted future states of the world with, frequently, "extreme colors" yet in the "frame" of plausibility. Scenarios can help to identify different paths of problem solution and development. This means that using a scenario, one can leave all the details behind, think outside of the box, and hopefully find potential problem-solving approaches which cannot be revealed based on the "business-as-usual" mindset. For instance, based on Special Report on Emissions Scenarios or, in abbreviation, SRES (Nakicenovic *et al*., 2000), Hansen (2010) has built three scenarios for assessing the impact from sea level rise on coastal zone urban development at Aalborg, Denmark; and Johansson *et al*. (2004) have applied SRES-based sea-level scenarios for the Finnish coast taking into consideration the global mean sea level, local land uplift, and estimates of the water balance of the Baltic Sea. Outside Scandinavia, scenarios were also frequently used in research, e.g. Tian *et al*. (2010), to forecast the effects of sea level rise. Doing a sensitivity analysis is, on the other hand, like "decorating" some parts of the picture and then seeing how the whole would be transfigured. In fact, sensitivity analysis is done by trying to change one or more variables in order to study how the outcomes would differ according to this change.

There is still ongoing controversy whether there will be significant sea level rise in Gothenburg, Sweden or not. Therefore, the thesis is an attempt to look deeper into this issue. For guiding the literature review, these research questions have been raised:

1. What are the possible effects of sea level rise on the Swedish west coast?

2. What are the possible effects of sea level rise (combined with storm surges) on the coastal and river areas in the city of Gothenburg?

2. RESEARCH AND LITERATURE ABOUT SEA LEVEL RISE AND ITS CONSEQUENCES FOR COASTAL AREAS

Due to limited time and resources for a master thesis, no in-depth review of literature and research can be done. Only the newest (i.e. within three years' time) and most relevant papers (i.e. the article shares the same topic and its research area has the characteristics closest to those of the coastline of Sweden and, particularly, Gothenburg) are reviewed in the following chapter to describe the state-of-the-art in the field. However, the focus on one area and region, i.e. Gothenburg and the Swedish west coast, makes a review easier – there is not much specific research about the themes of this thesis in that area, and all relevant research documents from the area are used (see below, chapter 3).

Two studies on the impact of sea level rise on coastal ecosystems reveal that sea level rise can have a two-sided effect on the muddiness of a coral reef, i.e. adding sediment to or reducing it from the mud belt (Ogston and Field, 2010), and might cause erosion landward (Hanson *et al*., 2010). Moreover, Peterson *et al*. (2010) found that a species that is seriously affected by climatic changes is not necessarily seriously affected by marine intrusion and *vice versa*. In other words, marine biodiversity can be threatened separately by the direct climate effects and the indirect marine intrusion effects. Also concerning the preservation of marine ecosystems, Niang *et al*. (2010) criticized that hard protection structures can constrain the growth of mangroves at brackish waters and suggested beach nourishment methods instead. *According to both papers, one must not take for granted that climatic changes will homogeneously affect the whole study area.* Sánchez-Arcilla *et al*. (2008) presented their results in a comprehensible manner to introduce another climate change research on land erosion and salinity intrusion in Europe.

The last paper reviewed from research outside Sweden concerns the city Nagoya, Japan, which is a large coastal city (similar to Gothenburg, Sweden). In Pokharel *et al*. (2009), four models, i.e. sea model, river model, overland flood flow model and sewer model, are connected to perform analyses on urban inundation. There are four simulation cases in total: 0.00, 0.50, 0.95 and 1.50 m increase in the sea level. Flooding in the cases of 0.50 and 0.95 m of sea level rise is mainly because water spreads out of manholes; however, in the case of 1.50 m it is due to the overflow from the river. The maximum inundation is achieved when the peak of rainfall and that of tidal wave concur. The capacity of sewer systems of Nagoya is analyzed with the assumption that the rainfall and tidal wave both reach their maxima (the scenario with the largest inundated area) so as to see if more money should be invested in building higher dykes.

The aforementioned studies show that *there is currently a strong need for research concerning impacts of climate change as well as local vulnerability and plans for mitigation and adaptation*. Different nations have chosen different approaches to collectively mitigate the effects of climate change at the global scale and at the same time to adapt their people to live with its consequences (Fisher *et al*., 2007). Both aspects have constantly been of interest to many scholars but it is the authors' choice that this thesis focuses on the adaptation side.

There are various factors which may aggravate or ease the consequences of sea level rise, e.g. storm surges or land uplift can increase or decrease respectively the risk of flooding. *This thesis therefore attempts to investigate the influence of storm surges which did not receive sufficient attention in many locations in the past* (Carter *et al*., 2007). Even among the limited amount of studies integrating storm surges in their models, there still exist uncertainties in detailed patterns and magnitudes of variations in extreme water levels (Nicholls *et al*., 2007). Furthermore, in some cases, uplift may hinder the effect of sea level rise up to a point; however, when the uplift halts, it will then leave the local people much more vulnerable to the continuously rising sea level. For Sweden, while land in the northern part is still rising (with the rate of 7-8 $mm \cdot yr^{-1}$), in the south it is relatively stationary (-0.1-0.2 $mm \cdot yr^{-1}$) or even sinking at the southernmost areas (Vestøl, 2006).

Further elaboration on why the study area is the Swedish west coast (including Gothenburg) will be presented in the next chapter. After that follows the description of methodology, estimations of sea level rise until 2100, and description of the scenarios. Thereafter the results will be demonstrated regarding vulnerability maps and suggestions for policy-makers. The thesis will end with the discussion section and conclusions.

3. RESEARCH IN THE STUDY AREA: IMPACTS OF CLIMATE CHANGE ON THE SWEDISH WEST COAST

3.1. The Swedish Commission on Climate and Vulnerability

The Commission on Climate and Vulnerability (2007) has published a detailed report on the consequences of climate change and extreme events in Sweden and presented support and instruments for reduced vulnerability. In the report, many extreme events that happened in the past are listed together with costs for damage expected. Some of these events were around the Swedish west coast (as summarized in Table 1).

It is essential to use the experiences from previous extreme events to prepare for the future ones. Hence, two scenarios were created in the report for estimating the costs and savings in relation to climate change. They are called the High scenario and the Low scenario which are for ranging loss and benefit from different aspects until 2100 (see Table 2).

Besides suggesting many adaptive measures, the report introduces practical support and instruments for reduced vulnerability, such as mapping of floods, landslides and erosion, databases, warning systems, physical planning, grants for preventive measures, insurance, training, research, and collaboration at EU level.

Table 1. Extreme events near the Swedish west coast during 1977-2007.

Year(s)	Event	Effects and damage costs
1977	Tuve landslide	Great loss in human lives and properties
1994-2001	Heavy precipitation	Landslides and flooding (mainly in Western Götaland)
1995	Heavy snowstorm in Gothenburg	Traffic obstruction
1999	Storm Anatol	Cost: SEK 970 million as damage compensation covered by insurance
2002	Rainstorm in Orust	Flooding. Cost: SEK 123 million as damage compensation covered by insurance
January 2005	Storm Gudrun	Air traffic disruption. Disconnection of telecommunication systems and electricity transmission network. Direct cost: SEK 500 million to Telia, a Swedish telecommunication company, mainly for rebuilding fixed access networks. Other costs: SEK 650 million to electricity subscribers
December 2006	Large landslide in Munkedal	Main road disconnection. Direct cost: SEK 120 million. Other costs: SEK 60 million
January 2007	Storm Per	Disconnection of telecommunication systems. Cost: the replace by wireless access

Source: Adapted from Commission on Climate and Vulnerability (2007)

Table 2. The High scenario and the Low scenario for estimating costs and savings in relation to climate change until 2100.

	Low scenario	High scenario
Railways	Half as much damage as for the High scenario	Three large landslides and two large storms
Shipping	25% decrease in ice-breaking costs	50% decrease in ice-breaking costs
Electricity and telecom networks	Minor increase in damage due to forest destroyed by storms	5 "Per"-size storms, 2 "Gudrun"-size storms, and 2 bigger storms
Hydroelectric power	Increase of 14%	Increase of 20%
Wind power	No increase	Increase of 10%
Drinking water supplies	Half the cost of the High scenario	More damage to pipes and increase in water treatment cost
Flooding in coastal areas	Half the size of that in the High scenario	Inundation of all buildings in threatened areas
Coastal erosion	10% of threatened areas eroded	40% of threatened areas eroded
Landslides	Increase of 50%	Increase of 100%
Storms	No cost for local authorities	5 "Per"-size storms, 2 "Gudrun"-size storms, and 2 bigger storms

Source: Adapted from Commission on Climate and Vulnerability (2007)

Based on the report, Storbjork and Hedren (2011), with a case study approach done in an institutional perspective, have studied what factors have prevented adaptive measures from being more integrated, strategic and proactive. These factors are described in the diagram below (Fig.1). In the case of Coastby where Storbjork and Hedren studied, while local key actors (individuals) possess a strong external networking capacity, weak coordinating capacity is found in the internal municipality administration (the organization). In other words, some individual actors dominate and organizational performance is therefore hindered. As a result, the adequate capacity to coordinate for example the activities of erosion managers, planners and environmental officials cannot be achieved. Moreover, the vertical interplay between national, regional and local actors is weak with a rising concern about "tensions and unsettled relations" between them. On the basis of their findings, Storbjork and Hedren also suggest that the political administrative system should find and solve institutional conflicts among key actors (e.g. colliding agendas, values and priorities) to obtain more integrated, strategic and proactive adaptive measures. Such actors need to cooperate more to exchange their respective experiences as well as to utilize their proficiency and authority. This kind of interaction has also been investigated in Stauffacher *et al*. (2006) from a pedagogical angle.

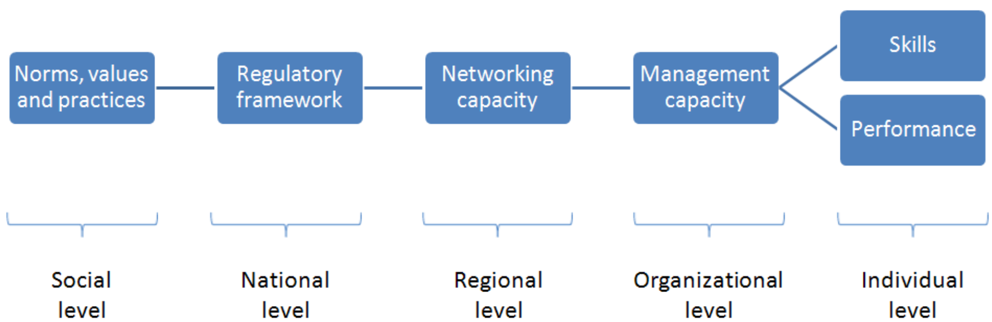

Figure 1. Five interdependent aspects of institutional capacity-building. They are relevant factors for the management of sea level rise. Source: Adapted from Storbjork and Hedren (2011).

In response to the report, many operational activities have been carried out as illustrated in Johansson and Mobjörk (2009). For example, the county administrative board of Västra Götaland and Vattenfall AB agree to adopt a new regulation strategy on Lake Vänern whose highest levels would be lowered by 40%; Lantmäteriet, the Swedish mapping, cadastral and land registration authority, has launched a project worth SEK 200 million to improve its elevation database; and County Administrative Boards of Stockholm, Uppsala, Södermanland, Östergötland, Värmland, Örebro and Västmanland have recommended that no buildings should be sited under the 100-year flood level (except garages, outhouses and other simple buildings). Those counties that choose not to adopt any adaptive strategies because of the lower "costs of inaction" (OECD, 2008) must ensure that they have considered thoroughly these problems in estimating costs of inaction: uncertainty, irreversibility, discount rate, substitutability, equity and distribution, and behavioral responses and adaptation. Additionally, many current models make "smooth adjustments". Hence when one tries to apply these models to calculate extreme weather events (like those in Table 1), the mismatch between prediction and reality would be significant.

3.2. Swedish west coast

The interest in future sea levels had not been high along the Swedish west coast. Indeed, research regarding impacts of climate change (Gustafsson and Nordberg, 2002; Larsen *et al*., 2009) and sea level changes (Jensen *et al*., 2002; Lohne *et al*., 2007; Helle, 2008) around the Swedish west coast had been rather focusing on the past than trying to predict what may happen in the near future. On the other side, studies of the relevant topic did not examine the west coast but chose the east instead (Näslund and Lindborg, 2009; Scotto *et al*., 2009; Storbjork and Hedren, 2011). Based on the sources of news media, Jönsson (2011) concludes that the closer to the Baltic Sea, the more frequently topics related to the sea would appear on local newspapers. With the east and south-east being studied thoroughly, and the rocky northern Sweden being less prone to sea level rise thanks to land uplift (European Commission, 2009), only the west and southwest of Sweden are left for further investigation.

Among ecological researchers, Cossellu and Nordberg (2010), with an interdisciplinary approach, explain the mechanism behind "opportunistic explosions". Opportunistic explosions happen when anthropogenic eutrophication adds to the large storage of nutrients in the sediment. Such storage is enlarged due to decrease in winter sea-ice that results from winter temperature increase. This study could be a development of the findings in Nordberg *et al*. (2000) concerning the lack of oxygen concentrations in the bottom-water of Gullmar Fjord, Sweden which is thought to be related to the North Atlantic oscillation (NAO).

For the physical and agrochemical assessment of the impacts of climate change on the Swedish west coast, there are recently two notable studies. One of them is from Persson *et al*. (2007) whose pore pressure prediction model was under development at that time. They conclude that it is possible to simulate groundwater levels using the HBV model, a rainfall-runoff model by the Swedish Meteorological and Hydrological Institute (SMHI, 2006), as well as to predict how the slope stability will be affected by climate change. Their study area is Harestad, located on the Swedish west coast, approximately 50 km north of Gothenburg. Follow-up research can be found in Swedish Geotechnical Institute (SGI) publications [e.g., Report 73 - Persson (2008)]. In addition, Wright *et al*. (2006) have studied fourteen sites around Europe one of which is Gårdsjön, located 12 km inland on the Swedish west coast. They have found that Gårdsjön may face the threat of the so-called "seasalt effect" which is explained in the text quoted below:

> "An indirect impact of climate on water quality innear-coastal areas occurs as a consequence of the 'seasalt effect'. Seasalts, entrained from sea surfaces during periods of high wind, are deposited on catchments in wet or dry deposition. Whereas the major anion, chloride (Cl) is usually very mobile in soils and is flushed out in runoff, the accompanying base cations (mainly sodium (Na) and magnesium (Mg)) are in part retained on the soil cation exchange complex, by cation exchange including the acid cations hydrogen (H^+) and inorganic aluminium (Al^{n+}). The result is depression of ANC [acid neutralizing capacity] in runoff, but an increase of the percent base saturation (%BS) of the soil." (p.158)

Out of paleoclimatological studies, there are two relevant ones closer to present time, only some hundreds of years from now (200 and 500 years, respectively). Firstly, Hünicke (2008) aims at predicting the impact of atmospheric factors on the past sea-level variations (up to 200 years) in the Baltic Sea. The relationship between the sea-level records and climatic datasets [i.e. sea-level pressure (wind), air-temperature and precipitation] is analyzed statistically with the support from 30 observation stations covering the whole region of the sea (including the Swedish west coast). The results indicate that wind forcing is the main factor explaining average (Baltic) sea level variability. Moreover, sea level variability in the Kattegat region in summer cannot be explained by temperature and precipitation. To improve the precision of analyses, two regression models are designed separately for summer and winter. Secondly, the doctoral thesis of Eriksson (2009) is a collection of useful information about the Baltic Sea, such as oceanographic description and climate. One of the results is that reconstructed ice and river runoff dominantly contribute to the changes in atmospheric circulation. In addition, the precipitation dataset was still imperfect because nil was assigned to all the cell values regarding precipitation on the sea. Sea precipitation data may be left out without generating any bias in the results of some other research; however, in his study, Eriksson points out that ten percent of total freshwater input into the Baltic Sea originates from sea precipitation and this amount can to some extent affect salt balance in the sea. Thus, sea precipitation is relevant to saltwater intrusion and needs to be measured in the future studies.

Meier *et al*. (2004) also share the same problem regarding insufficient datasets as the grid resolution of their ocean model is so low that it leads to the underestimation of the extreme weather (e.g. storm surges) in the Western Baltic Sea. Moreover, waves are excluded from their model which is applied for simulating future sea levels as well as for hindcasting, i.e. comparing the results simulated by the model with the previous records to test the model ("backtesting").

The last two studies reviewed for the Swedish west coast are about storm surges as an impact of climate change: Semadeni-Davies *et al*. (2008) and Sztobryn *et al*. (2005). In the later, a storm surge is defined as "the occurrence of a water level at least 1 m above the generalized mean sea level" (p.5). This study which listed the most dangerous storm surges during 1976-2000 was the preparation for future collaboration in research between Germany and Poland. Besides, Semadeni-Davies *et al*. have raised a new issue, the "urbanization on drainage", and combined it with the impacts of climate change (stormwater) in their model. The study area is Lussebäcken catchment near Helsingborg which is a city by the west coast of Sweden.

The institutional framework for coastal management in Sweden as far as it is relevant for the thesis can be described briefly as followed: At the regional level, the County Council (i.e. "Västra Götaland County" for Gothenburg) does not have much formal responsibility for coastal management. On the contrary, at the municipal level, the municipality (or "kommun" – in this case, "Göteborgs Kommun" or "Göteborgs Stad") is the most important institution that makes a decision on sector-specific coastal management proceedings including physical planning (Morf, 2006, Chap.8).

3.3. Gothenburg

Göteborgs Stad, the municipality of Gothenburg, seems to be highly interested in protecting the environment of Gothenburg according to the documents it published. The "little book" about the environmental work in the city summarizes all the thirteen objectives that Gothenburg aims at for a better environment in the future (Göteborgs Stad, n.d.). These objectives are also listed in Göteborgs Stad (2009a) together with a comprehensive plan regarding how to achieve them. As a result, year after year, more and more environmental activities were added to the annual reports of the city, under the section "Environment and climate adaptation" (Göteborgs Stad, 2007; Göteborgs Stad, 2008; Göteborgs Stad, 2009b).

Göteborgs Stad provides administrative and planning documents for Gothenburg but it is necessary to have more scientific research in the Gothenburg area. One study by Löfgren *et al*. (2011) introduces a modern technique in measuring sea levels at a site 33 km south of Gothenburg. On a side note, Thorsson *et al*. (2004) examine the relationship between the thermal environment, park use and behavioral patterns in the recreational areas of Gothenburg.

There will be an increase in flood risk in Gothenburg as confirmed in European Commission (2009). Also realizing the fact that Västra Götaland region (including Gothenburg) is one of the most vulnerable areas to inundation and erosion in Sweden, Keskitalo (2010) reviews in her chapter the development of adaptation policy and measures on the regional and local levels. According to the Commission on Climate and Vulnerability (2007), if the land level changes are taken into account, the rise in 100-year water level 2071-2100 in relation to that of today would be 0.90 m for Gothenburg. This would probably make 9.13% of the areas studied in the report under water costing SEK 7 500 million of insurance payouts. Interestingly enough, just a few years ago, survey results illustrated by thematic maps from the ESPON Project 1.3.1 about "the spatial effects and management of natural and technological hazards in general and in relation to climate change" (2003a; 2003b) still indicated a very low chance of flooding in Västra Götaland, even though high risks of landslides and storm surges were identified. To produce the thematic map of flood recurrence, the amount of large flood events was recorded and assigned to each region, such as Västra Götaland. According to ESPON analysts, the "very low" chance of flooding in a region results from the fact that there has been no large flood event there during

1987-2002. In other words, the chance is determined by counting past events within only a sixteen-year period. Therefore, the result from ESPON would not hold true for flooding chance at a smaller scale (Gothenburg) and for much longer time afterwards (a hundred years).

In the future, while some parts of Gothenburg could be susceptible to temporary flooding due to storm surges, the main concern is the possibility of permanent inundation caused by sea level rise. The global mean sea level during 2090-2099, as IPCC (2007) estimates, would increase 18-59 cm compared to the level since 1980-1999 (on average, 1.8-5.9 $mm \cdot yr^{-1}$). Regression analyses mentioned in Hammarklint (2009) also support a 3 $mm \cdot yr^{-1}$ rise of the sea level along the Swedish coasts during 1980-2009. When referring this to the average rate of 1.5 $mm \cdot yr^{-1}$ rise since 1886, one can realize the evident acceleration of sea level rise. However, the sea level rise in Gothenburg cannot be easily recognized only based on the tide gauge data (see subchapter 4.6) as it is nullified by the 3 $mm \cdot yr^{-1}$ rate of land uplift since 1887 according to Hammarklint. Thus, when the rate of sea level rise accelerates and outpaces that of land uplift – and it will as confirmed by the latest results, low-lying areas in Gothenburg especially those next to the coast could be perpetually flooded.

The consequences that concern Gothenburg at the moment are land erosion (main) and salinity intrusion (secondary) both of which would be escalated by flooding due to sea level rise and storm surges – the impacts of climate change. Furthermore, there are few suggestions that it is necessary to include waves as a variable and examine storm surges as well; if the spatial dataset includes sea precipitation values, it would allow for better conclusions.

4. MATERIALS AND METHODS

4.1. Generation of a flood risk map

Based on the method presented in Chust *et al*. (2010), the following procedure is performed in order to produce a flood risk map:

- Choosing a study area
- Estimating sea level rise
- Searching for a digital elevation model
- Classifying urban land use types

The study area serves as a starting point to look for relevant datasets. If the study area is well-defined, i.e. having exact coordinates and a distinct boundary with the surroundings, and based on an administrative unit (e.g. districts in Gothenburg), it would be time-saving for requesting data support from the providers such as SGU and Lantmäteriet. The more specific the request, the faster it will be handled.

With the study area already determined, the next step can be divided into three main phases as sketched in Fig.2:

(1) Estimating sea level rise. For example, a projected sea level rise of r meters is estimated for the study area for the next hundred years which means the present annual mean sea level, s_1, will become the new s_2 whereas $s_2 = s_1 + r$.
(2) Making a digital elevation model. For example, two grounds are measured in height and they are h_1 and h_2 meters high.
(3) Generating the initial flood risk map. For example, assuming that $s_1 < h_1 < s_2 < h_2$, we have A_1 is the area with a risk for being flooded in the future as the new s_2 is higher than the height h_1 of the ground and, in contrast, A_2 is the area that can be to some extent safe from future flooding as $s_2 < h_2$ (except during extreme events like storm surges where the water can get to an abnormally high level).

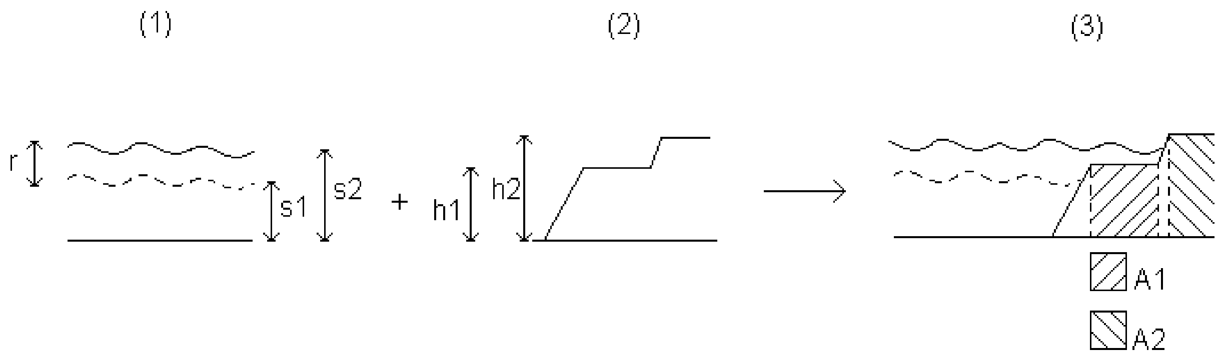

Figure 2. Three main phases of generating a flood risk map: estimating the rise, measuring the elevation and combining these data. A_1 is the area with flood risk while A_2 is safe for the moment. Source: Own drawing.

After the initial flood risk map is obtained, it can be improved with the classification of land use. For the areas that may be flooded in the future, their land use types are of interest. Indeed, inundated areas with different uses can result in different damage costs; for instance, the damage cost of a farm being flooded is different from that of a harbor so being.

Furthermore, the previous records from tide gauges are often needed in some cases so that the redistribution of sediment along the coast can be calculated with the Bruun formula (Douglas *et al.*, 2000). This calculation can be performed in parallel with the generation of the flood risk map to see whether or not the latter has underestimated the shoreline recession process since a 1-cm rise of the sea level could push back the coast 50-100 cm landward depending on the character of the soil according to the Bruun Rule. However, as the total area of sand beaches in the study area is insignificant (see Fig.8.2 and 9), the estimation of the shoreline recession process can be safely left out in this study.

4.2. Study area

The site of interest is the city of Gothenburg where a major harbor of Sweden is located. With its strategic location in the whole Scandinavian region, Gothenburg plays an important role in the future development of Sweden. However, the city growth currently faces many threats such as biodiversity loss, scarcer freshwater, and more frequent landslides due to climate change. Moreover, the construction of new structures along the river on one hand restricts people from enjoying the riverside scenic view and on the other poses a threat of unsustainable development as in the future these places can be flooded.

To adhere to the objective of this thesis, the study area stretches from the coast (near Långedrag) to the farthest bridge landward (the Angered Bridge) embracing the Göta River and including the fourteen riverside districts ("stadsdelsnämnd", in Swedish): Angered, Backa, Bäckebols, Brunnsbo, Brämaregården, Carl Johan, Domkyrko, Lundby, Masthugg, Nylöse, Oscar Fredrik, Sankt Pauli, Torslanda, and Älvsborg (Fig.3). This district division was outdated because in the new division, which has been in force from January 2011, there are only 10 districts in total. However, at the time the data were collected, no updated map has yet been available.

These districts are chosen based on the two reasons: First, the ones that are closest to the coast are studied but at the same time those that are farther yet may still be affected by saltwater intrusion would not be excluded. Second, using the district unit allows the inclusion of the district area, population etc. in the analysis.

4.3. Estimation of the next hundred years' sea level rise

Göteborgs Stad had SMHI mandated to calculate future climate changes in Gothenburg for the next hundred years. According to the estimations generated by a regional-specific atmospheric-oceanographic model of Rossby Center (RCAO), the future sea level in Gothenburg would increase from 0.1 to 0.9 m relative to the present mean sea level. If the rate of land uplift is taken into consideration, i.e. 0.1 m, the rise would be 0-0.8 m (Göteborgs Stad, 2006). That is to say, there would be a chance that the sea level in Gothenburg may not increase until 2100.

According to SMHI, sea level records from the two local stations (Torshamnen and Klippan) show that the mid-tide (MW) level of Gothenburg is 9.96 m and that the highest recorded tide (HHW) levels are 11.47 m and 11.65 m at Torshamnen and Klippan, respectively. Combining these data with the prediction about sea level rise, we can assume that Gothenburg would have the mid-tide level at 9.96-10.76 m and the highest recorded tide level at 12.27-12.45 m around 2100. Based on Torshamnen and Klippan locations, it is reasonable to expect the predicted 12.27 m tide level at the coastal area of Gothenburg (near Torshamnen) and the 12.45 m one in the central (near Klippan). However, the different HHW values recorded at these two sites could result from the differences in the periods of recording, i.e. 1969 – 2009 for the former and 1887 – 1968 for the latter (PSMSL, 2011a; PSMSL, 2011b). Thus, to be on the safe side, one can apply the predicted 12.45 m tide level for the whole area.

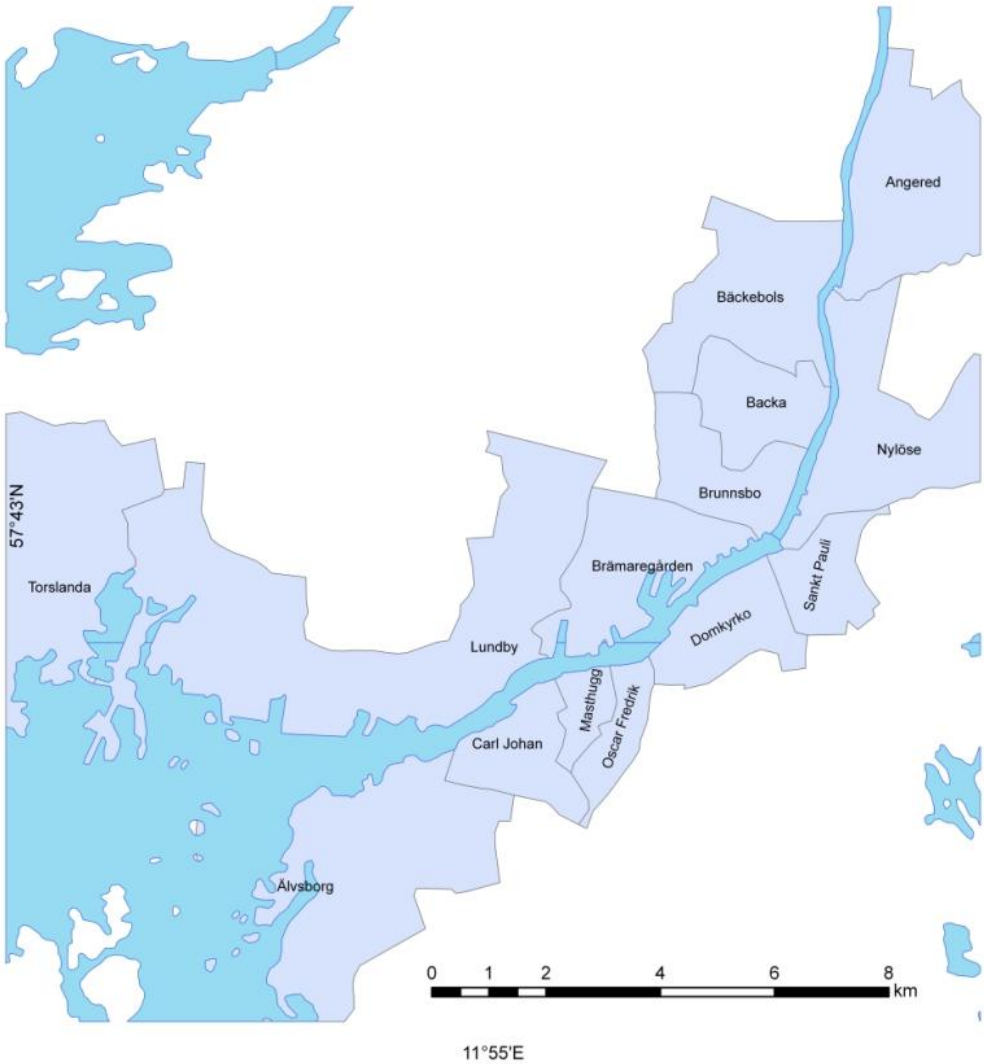

Figure 3. The study area including the fourteen districts of Gothenburg. Source: Original spatial data was retrieved from Digitala Kartbiblioteket (Digital Map Library), www.metria.se

4.4. Digital elevation model of Gothenburg

A digital elevation model (DEM) describes an area of the earth's surface and consists of a set of polygons with a height value for each polygon. It is a requirement for investigating how flooding caused by sea level rise could affect the area (see Phase 2, subchapter 4.1). Though Chust *et al*. (2010) suggested the use of a LiDAR-based digital terrain model (DTM) for generating a flood risk map, the use of a DEM is more appropriate in this case. Many believe the two terms DEM and DTM can be used interchangeably. However, Butler and Davies (2011) point out that a DTM serves as the topographic model of the ground surface only while the DEM based on this DTM also takes into account the elevation of buildings.

An example of a DEM for Frihamnen, a harbor in Gothenburg, is illustrated in Fig.4 where we can see many sets of different polygons with different colors (the darker color represents the higher surface). This DEM is just a small part of the larger DEM used in this thesis. The whole DEM belongs to UGOT, a research group in the University of Gothenburg, working within the EU-level project called SECOA (Solutions for Environmental contrasts in COastal Areas).

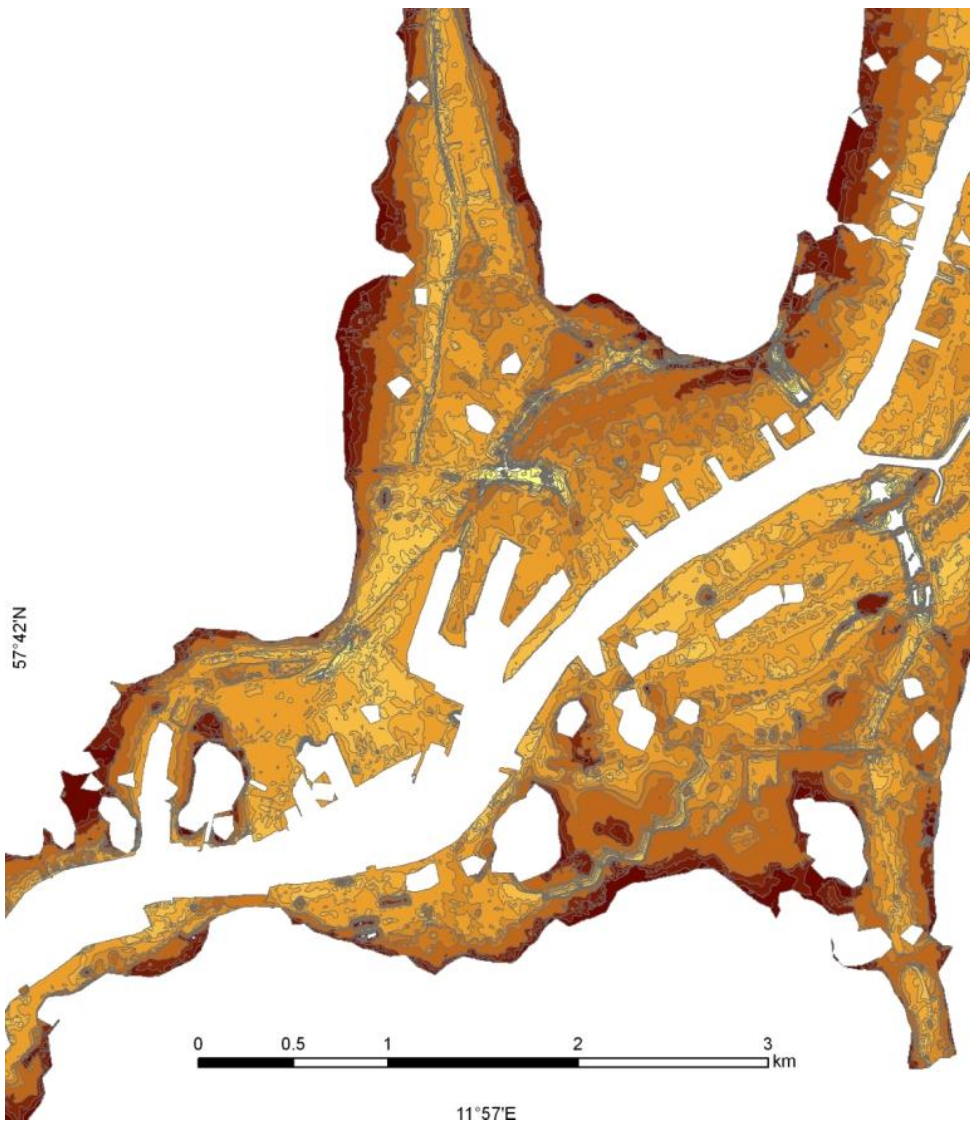

Figure 4. An example of a DEM for Frihamnen's area. Source: UGOT, University of Gothenburg. With ArcMap, one can classify the polygon features by quantile: the darker the color, the higher the surface.

The polygons seen in Fig.4 can be generated from a raster image which is obtained from a scanning technique called LiDAR (Light Detection And Ranging). The LiDAR technicians make use of an aerial platform (an airplane, for example), whose accurate position (longitude and latitude) is determined with the help of a GPS (Global Positioning System) device, to send a pulse of laser light towards the ground and receive the returning signals with the elevation information (Olsen, 2007). Therefore, for every cell in the raster image, its coordinates (*x*, *y*) describe the actual longitude and latitude while its value *z* indicates the height of the piece of land it represents (see Fig.5).

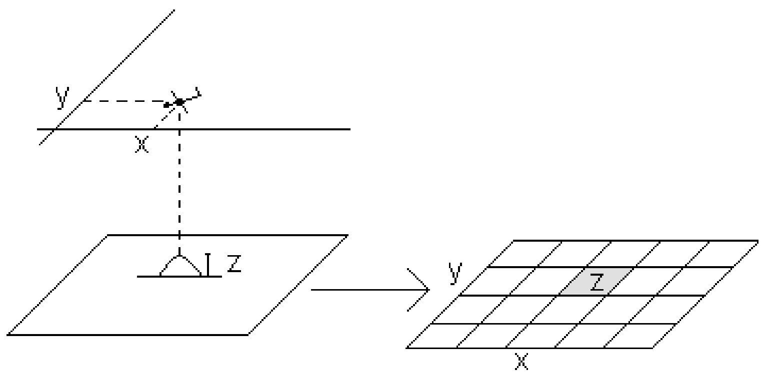

Figure 5. The construction of a raster image. Source: Own drawing. A quality raster image, i.e. with high accuracy and resolution, can now be obtained by modern devices specialized for remote sensing. Due to huge investment in these tools, original raster images are expensive but, regardless of the high price, they are always in demand by not only geologists but also environmental scientists, city planners and businessmen.

The raster image is in fact a grid structure which is preferred for describing continuous surfaces; however, to effectively analyze them (e.g. spatially categorizing them by elevation), one needs to transform them into geometric objects, i.e. points, lines and areas. One of the prevalent methods to convert a grid structure into a vector structure (consisting of points, lines and areas) is to make contours out of the grids (see Fig.6).

The accuracy of the analysis depends largely on the resolution of the original raster image and the contour interval of the converted vector graphics. While the former determines how closely the image resembles the reality, the latter directly affects the precision of the analysis. For example, the data from SECOA are regional contours and their interval is 0.3-0.5 m which means for every difference in the elevation that goes beyond 0.5 m a new contour line is drawn. Therefore, an assumption of sea level changes that falls into this span (0.3-0.5 m) would be appropriate. In other words, an assumption of a 0.2 m change in the sea level can cause errors to the analysis if the reality is like Fig.7.b instead of Fig.7.a and, on the other side, presuming a 0.6 m change would be an inefficient use of the quality data.

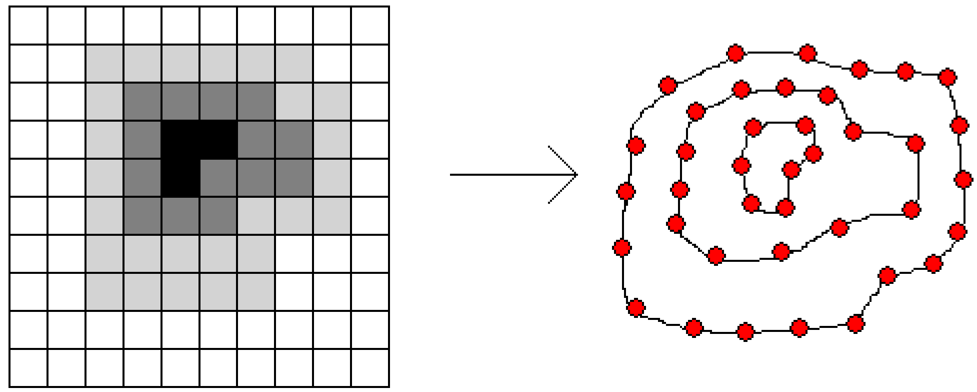

Figure 6. From raster to contour. Source: Adapted from Heywood *et al*. (2006), Fig.3.9. The contour interval chosen will influence the accuracy of the output feature. The smaller the interval, the higher the accuracy will be, at the cost of a larger file size though.

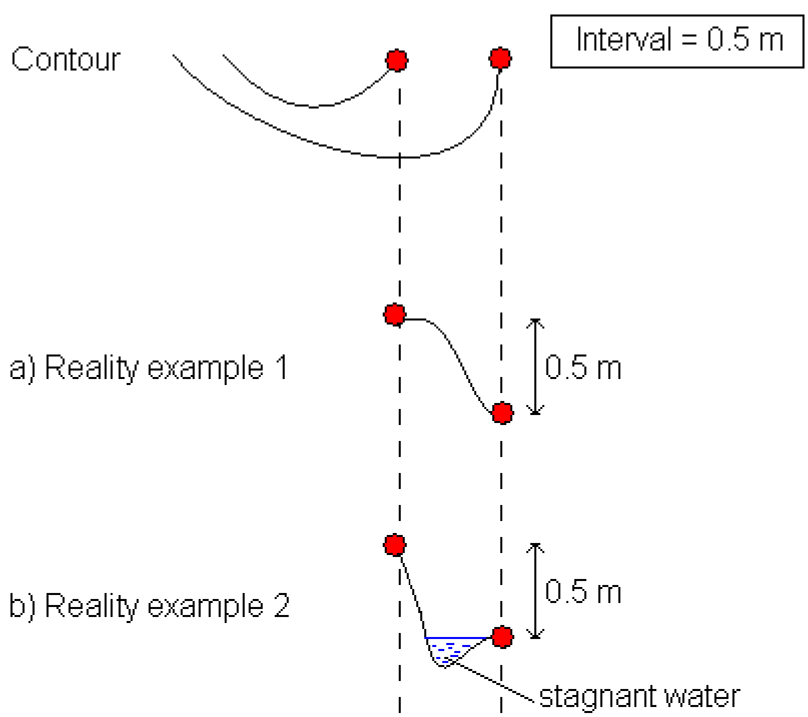

Figure 7. Two typical examples of reality that can be interpreted from the same contour sample (its contour interval is 0.5 m): a) the decline is linear; and b) the decline is steep at first and then the land rises up to form a small crater whose height is less than 0.5 m. In the latter case, if the area is examined by using its upper limit, it is seen as non-flooded but if the lower limit is used, it can be seen as partially flooded. Source: Own drawing.

For this thesis, the upper limits are used for all the regional contours and sea levels are assumed to vary 0.4 m from scenario to scenario. Particularly, there are three main scenarios:

1. The zero-increase scenario: Gothenburg's mid-tide (MW) level is assumed to remain unchanged at 9.96 m;

2. The moderate-increase scenario: Gothenburg's MW level is assumed to rise 0.4 m and stay at 10.36 m; and

3. The maximum-increase scenario: Gothenburg's MW level is assumed to rise 0.8 m and stay at 10.76 m.

These scenarios will serve the purpose of calculating permanent inundated areas in the future. Temporary flooded areas can also be calculated in the maximum-increase scenario by applying the predicted highest recorded tide (HHW) levels, i.e. 12.27 and 12.45 m, respectively for the coastal and central area of Gothenburg.

4.5. Urban land use types

The dataset concerning urban land use types is retrieved from the website of European Environment Agency. It is a component of GMES Urban Atlas (http://www.eea.europa.eu/data-and-maps/data/urban-atlas) which covers the period 2005-2007. The CORINE Land Cover dataset, 2000 (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vector-database-2) and 2006 (http://www.eea.europa.eu/data-and-maps/data/clc-2006-vector-data-version), supplements to the urban atlas in term of temporal coverage. Further, the urban atlas comes with the better resolution while the CORINE dataset possesses a more accomplished set of land use types (see Fig.8.1 and 8.2).

4.6. Soil properties and bedrock capacity to drain water

SGU - Sveriges geologiska undersökning or the Geological Survey of Sweden - provides data concerning the soil properties (Fig.9) and bedrock capacity to drain water (Fig.10).

For soil property map, SGU indicates that the samples are extracted from soil that is as low as one meter below the land surface. Besides, the website of SGU clearly describes and gives examples of the soil types like "svämsediment", "morän", "urberg" etc. (http://www.sgu.se/sgu/sv/geologi/jord/tolka-karta/index.html). This helps a lot to understand the Swedish terms used for labeling soil properties in the SGU dataset. Therefore, the soil nature can be interpreted precisely to perform the multi-criteria assessment (in subchapter 5.3).

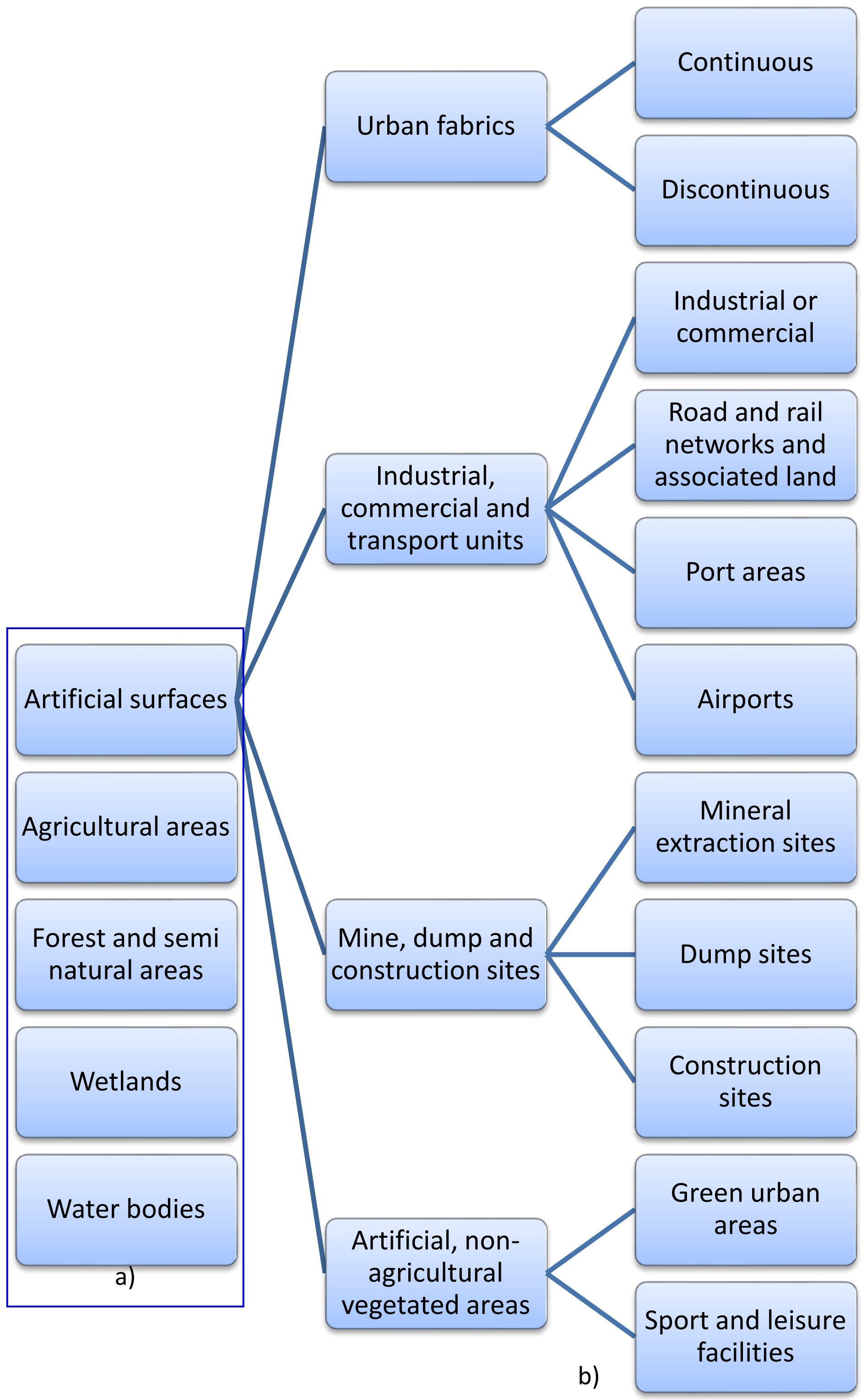

Figure 8.1. Land cover types: a) Main classes; and b) Subclasses of "Artificial surfaces" which is a dominant class in the study area. A continuous urban fabric is the land over 80% of which is covered by structures and the transport network. A discontinuous urban fabric is mostly covered by structures where the vegetated areas are significant but discontinuous. Source: CORINE.

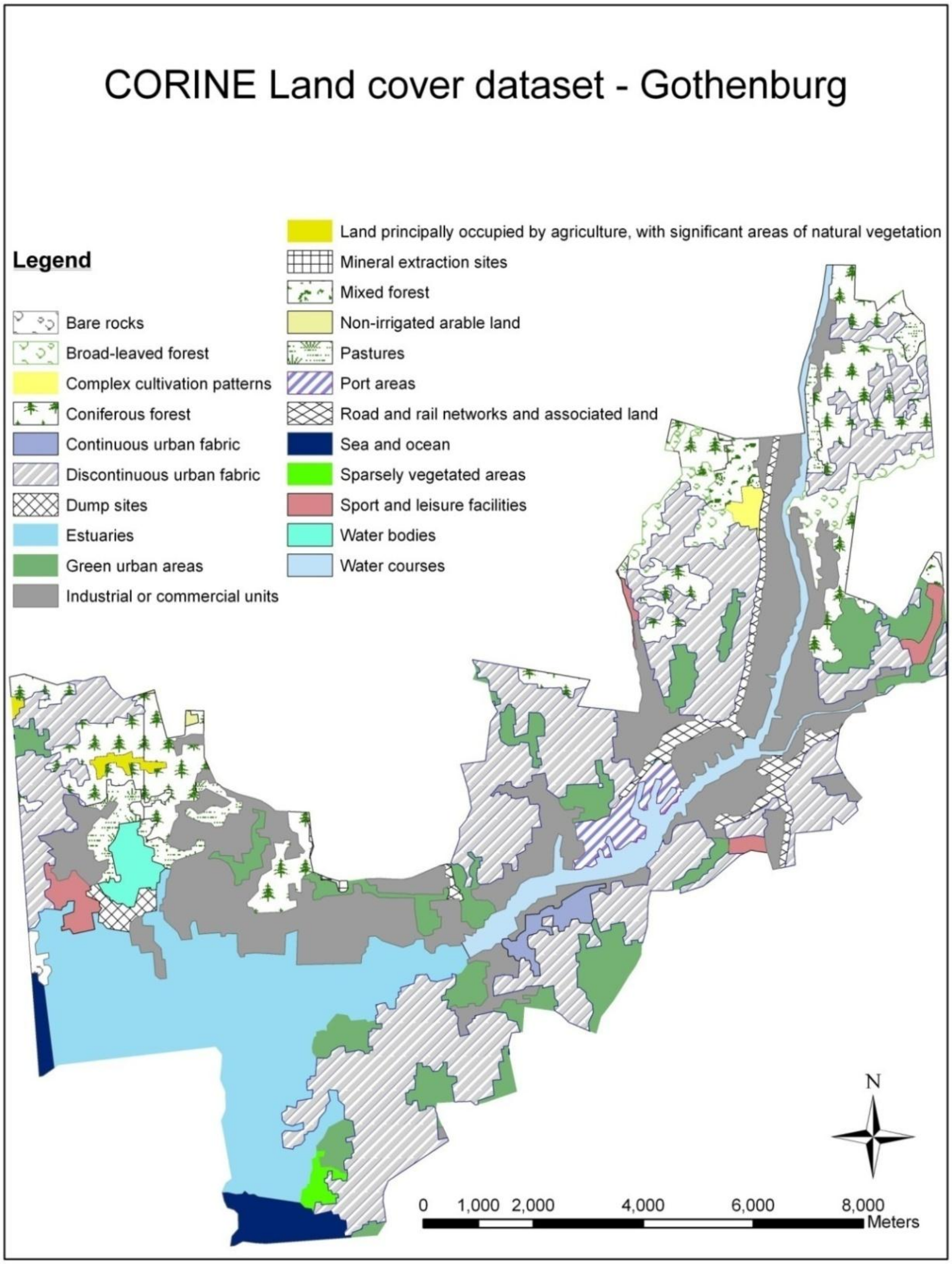

Figure 8.2. Land cover dataset 2006 for the study area. Artificially surfaced areas constitute 76% of the total land area of the fourteen districts of Gothenburg. Areas with paved surfaces such as ports, roads and urban fabrics could reduce ground absorption and intensify surface flow (Pareva, 2006). Source: CORINE.

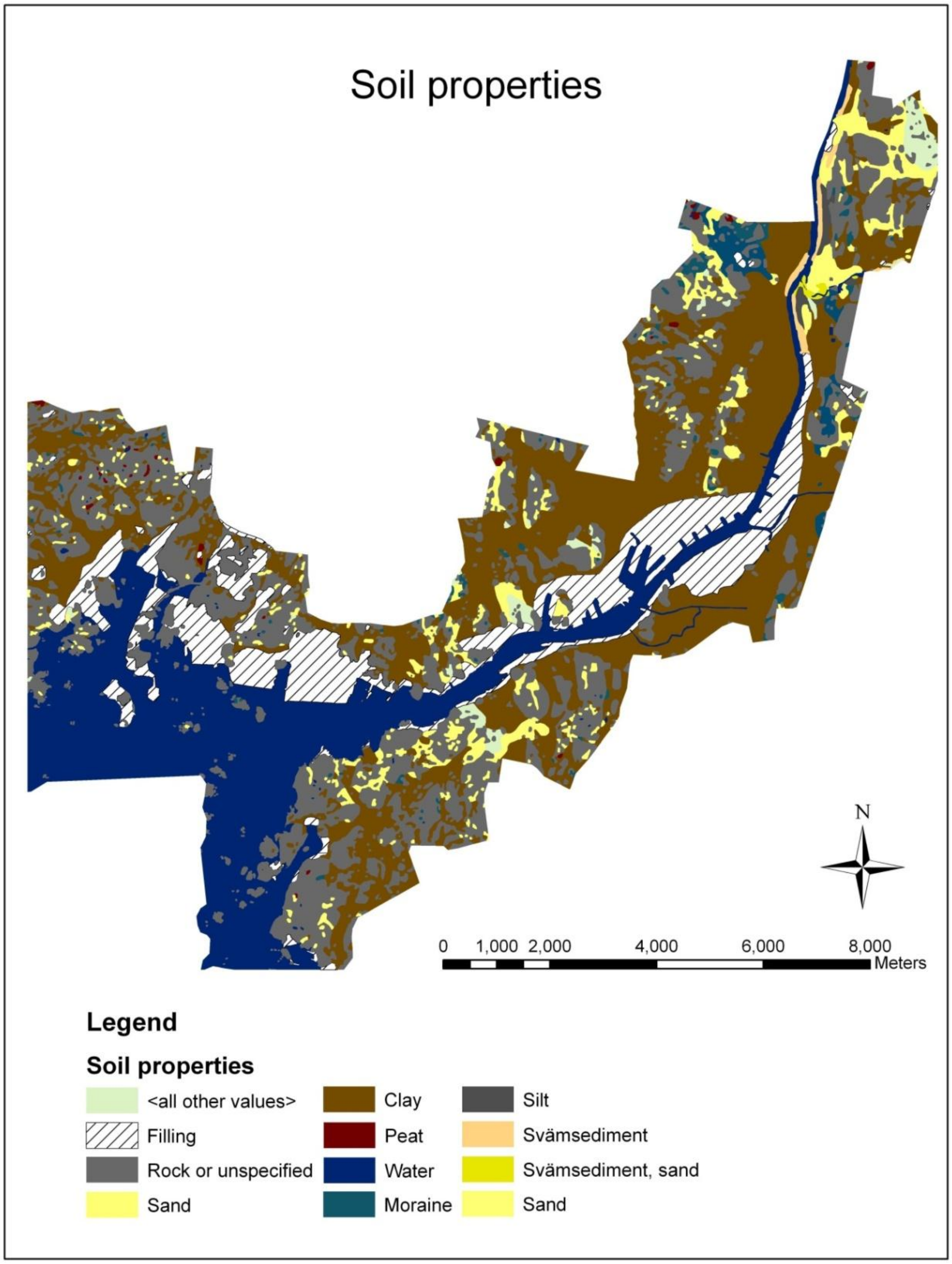

Figure 9. Soil properties. Source: SGU. A large area that possesses clay and filling soil embraces the river. This will slow down to some extent the speed of drainage in case of flooding. According to Scheyer and Hipple (2005), due to pore spaces, sand lets water drain through the fastest, silt slower, and clay the slowest among the three.

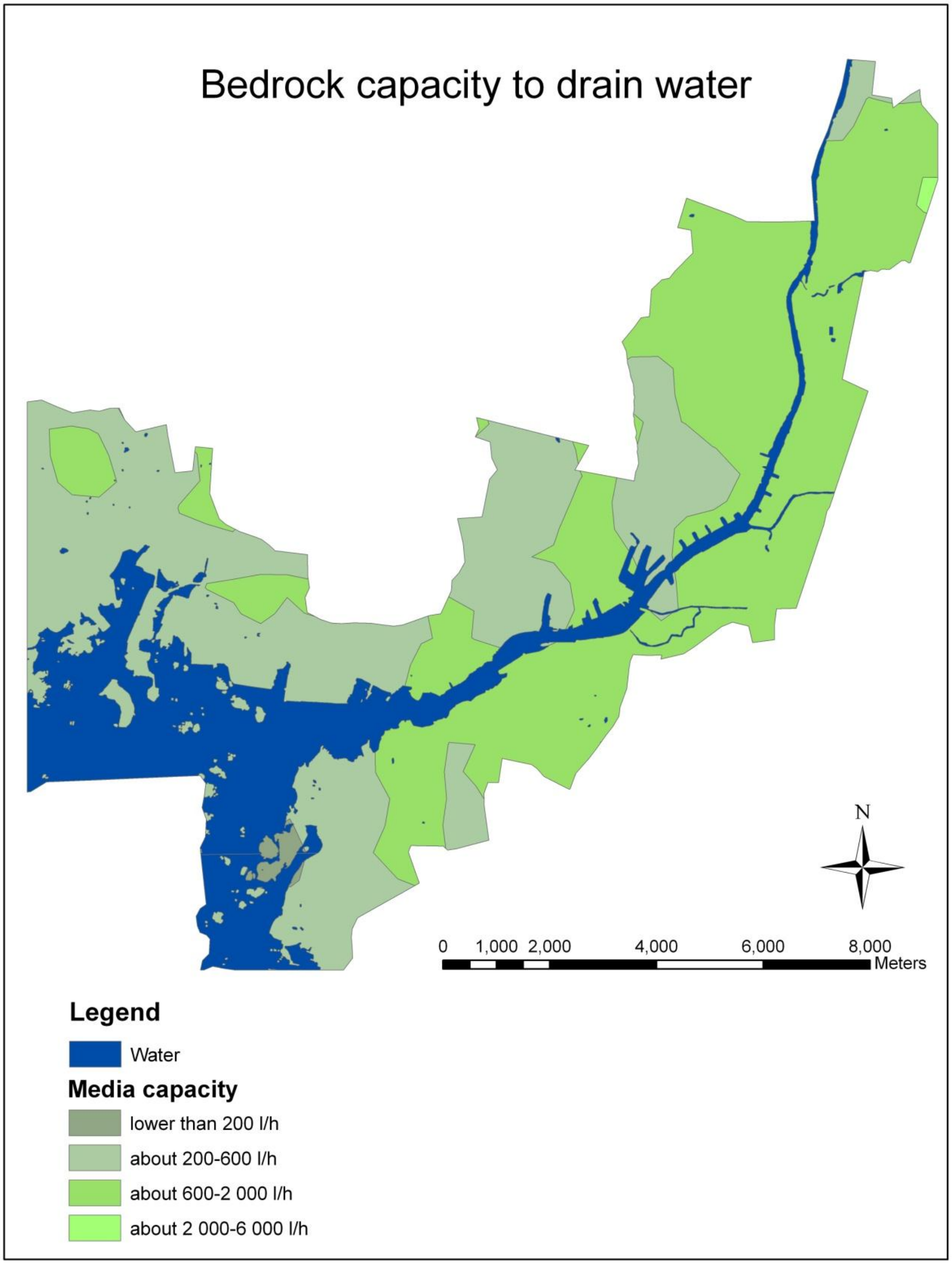

Figure 10. Bedrock capacity to drain water. Source: SGU. Most of the study area is located on the bedrock which is capable of draining 200 - 2000 liters of water per hour.

This thesis will aim at generating a flood risk map based on estimations of sea level rise (subchapter 4.3) and a digital elevation model (subchapter 4.4) for the study area and then intersecting the flooded areas with the layers of district borders (subchapter 4.2) and land use types (subchapter 4.5) for calculating the total flooded area for different districts and land uses. To make such an estimation closer to reality, it is interesting to examine the duration of inundation and the speed of floodwater drainage, which will require the combination of data from the DEM and land cover type as well as the soil properties and bedrock capacity to drain water (subchapter 4.6). After that, some proposed measures to cope with the future urban flooding will be presented.

5. RESULTS

5.1. Initial flood risk maps

Table 3 lists the percentage of the total land area of the fourteen districts that would be affected by flooding, permanently for the first three cases and temporarily for the last one, in 2100 based on the three scenarios and the special treatment for the maximum-increase scenario (see subchapter 4.3 and 4.4 for the description of the scenarios).

Table 3. Status of estimated inundation for the study area. From 0 to 0.4 m, it is hard to recognize the change in the impact of sea level rise (from 0.001% to 0.03% of land affected). However, the area flooded increases dramatically in the maximum-increase scenario (0.8 m) with the total of 0.33% of land affected. That the flooded area grows exponentially with sea level rise can, at the first stage, falsely assure many people of the “harmless” sea level rise and, later, hit them hard when they are not prepared.

Scenario / Treatment	Zero-increase (0 m)	Moderate-increase (0.4 m)	Maximum-increase (0.8 m)	Highest tide levels (12.27-12.45 m)
Percentage of flooded land	0.001%	0.03%	0.33%	12%

While the actual damage caused by permanent inundation would not be extensive, even for the maximum-increase scenario (see Fig.11), the temporarily flooded areas seem large and problematic due to the vital infrastructure in the center being affected (see Fig.12). Thus, the special treatment of the highest tide levels needs to be analyzed further in the following subchapters 5.2 and 5.3.

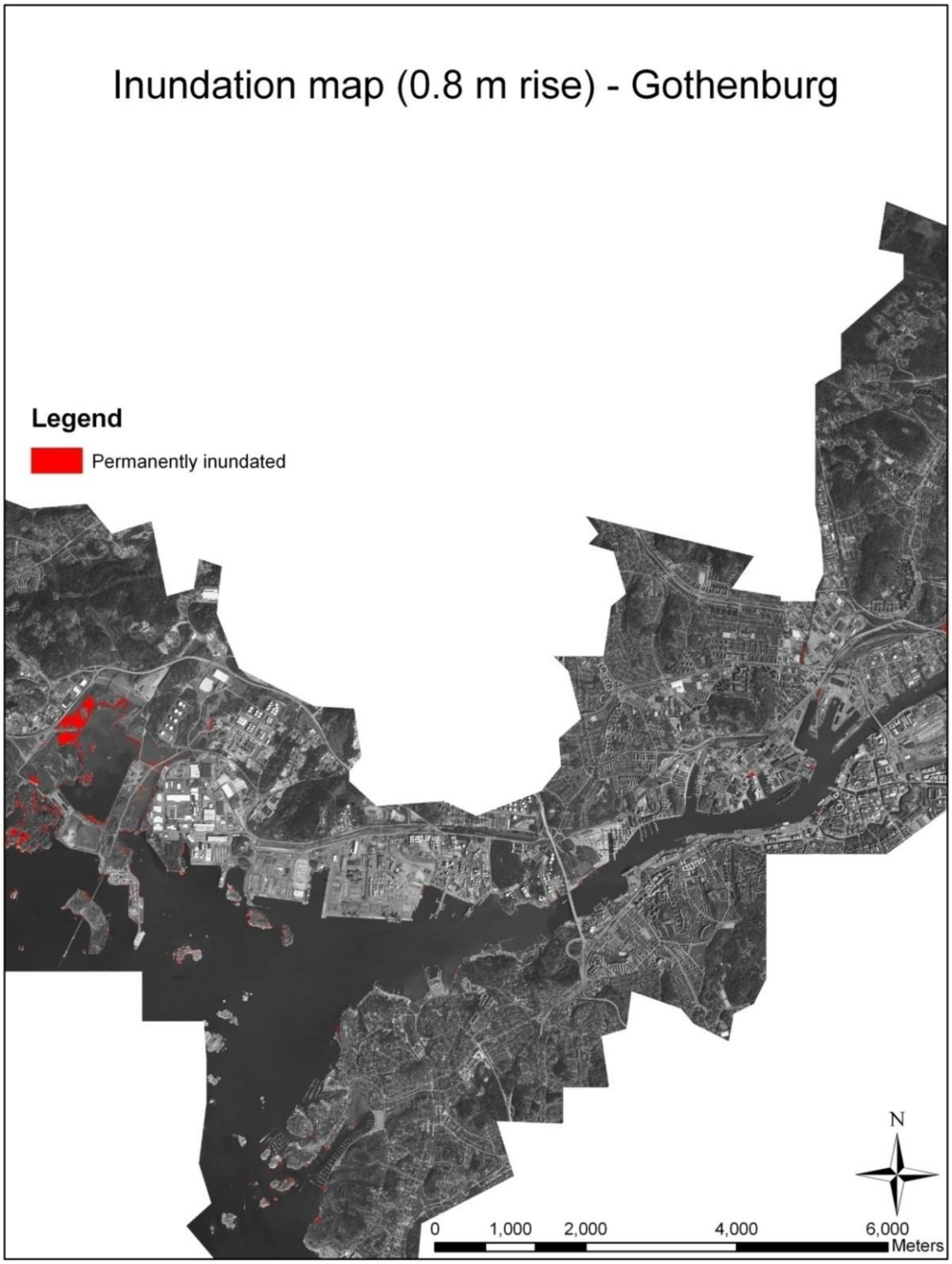

Figure 11. Inundation map for the maximum-increase scenario (0.8 m). Permanently-flooded areas would not spread over a large area in Gothenburg but be confined to tiny local areas along the coast and river. Source: Orthophoto from Digitala Kartbiblioteket.

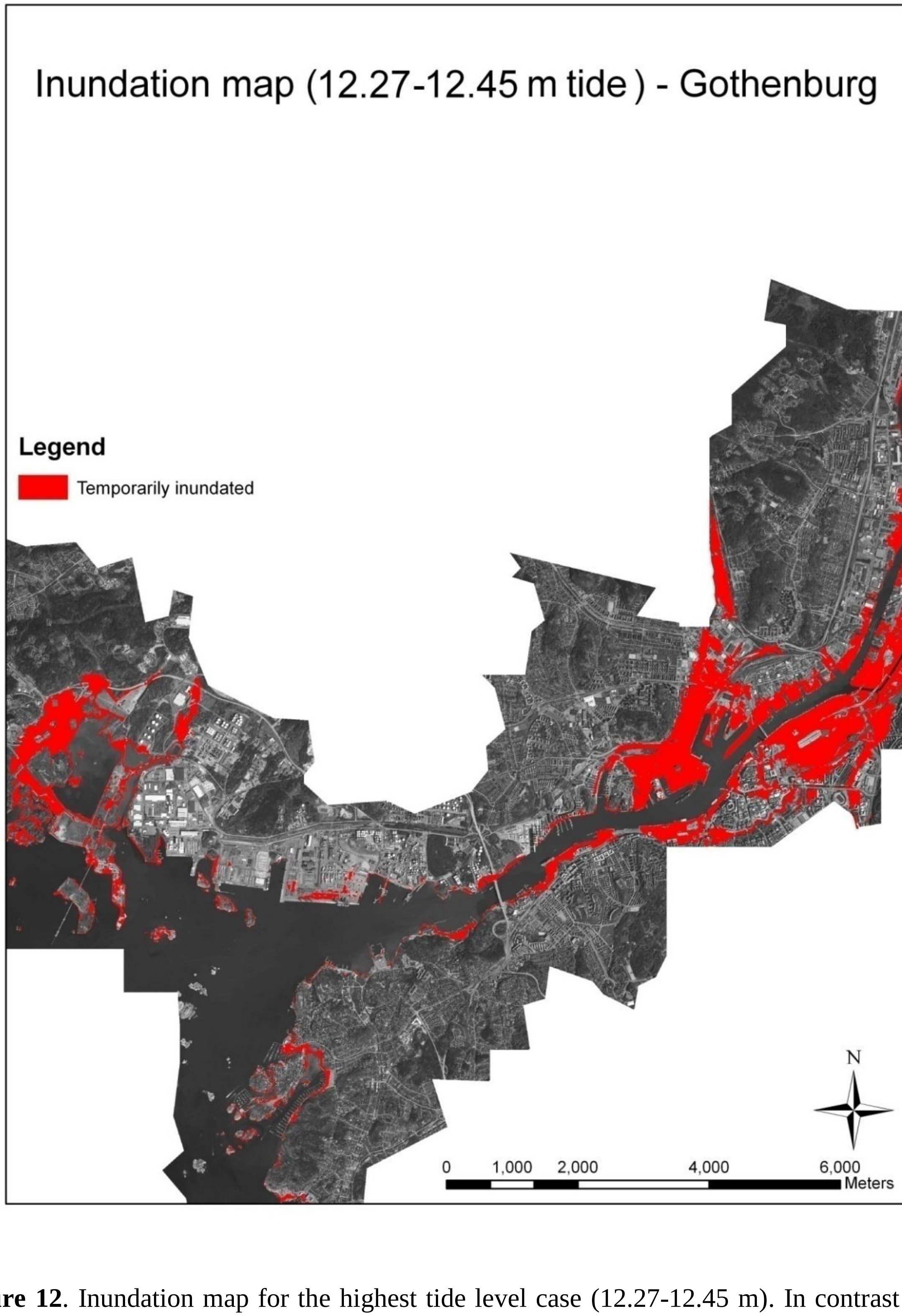

Figure 12. Inundation map for the highest tide level case (12.27-12.45 m). In contrast to those under the threat of constant flooding, temporarily-flooded areas would be huge and problematic. Source: Orthophoto from Digitala Kartbiblioteket.

5.2. Temporarily-flooded area sorted by land use types and districts

The highest tide level case could deal a significant damage to the study area; therefore, it is interesting to see how such damage can be attributed to different land use types and districts. The top ten most-affected land use types are listed in Table 4. Similarly, Table 5 shows the top five most-affected districts in terms of the percentage of the total district area that would be inundated.

Table 4. Affected areas listed by land use types. Most of the types which are the products of urbanization (marked in bold) rank high in this table since Gothenburg is a metropolis. Source: Own calculation.

Rank	Land use type	Affected area (m^2)
1	**Industrial or commercial units**	6,000,000
2	**Discontinuous urban fabric**	2,000,000
3	**Port areas**	1,200,000
4	Pastures	700,000
5	**Road and rail networks and associated land**	370,000
6	**Sport and leisure facilities**	300,000
7	Broad-leaved forest	150,000
8	**Dump sites**	140,000
9	Green urban areas	120,000
10	Bare rocks	60,000

Table 5. Affected areas listed by districts. Domkyrko and Brämaregården could see half of their land under water if nothing is done to prepare for the extreme events around 2100. Source: Own calculation.

Rank	District	Affected area (%)
1	Domkyrkofg i Gbg	57
2	Brämaregården	47
3	Sankt Pauli	35
4	Nylöse	17
5	Torslanda	16

Those statistics outline the situation of Gothenburg under extreme weather like storm surges. A broad view on the problem is the preparation for a deeper look into it. The next subchapter will be an attempt to consider a few important factors that can influence the speed of floodwater drainage.

5.3. Inundation time and floodwater drainage speed

There are many research on urban stormwater management and drainage that list important data for calculating inundation time (Butler and Davies, 2011, Table 20.4; Debo and Reese, 2003, Table 6.1). Based on available data for this thesis, several important factors can be examined, i.e. the floodwater depth (computed with the DEM and estimation of sea level rise), the (CORINE) land cover type, and the soil property and bedrock capacity to drain floodwater (data from SGU). Fig.13 roughly shows how these factors can be arranged spatially in a flooded zone.

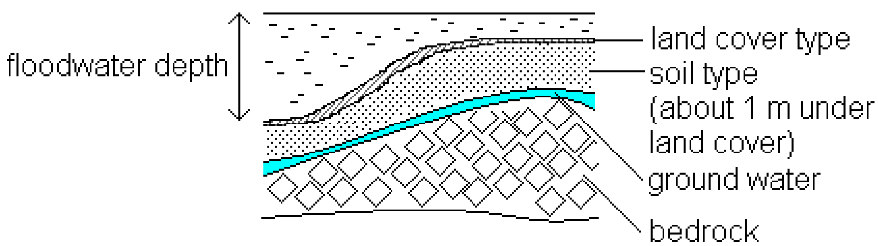

Figure 13. Sketch of a cross section to introduce different factors in the multi-criteria assessment. Source: Own drawing. At inundated areas, the floodwater depth can be calculated by subtracting the elevation from the sea level. Together with the floodwater depth, the land cover type, soil property and bedrock capacity to drain floodwater are some of the main factors that influence the length of inundation. These factors are considered because of the following facts:

- More water means longer it takes to withdraw them all (floodwater depth);
- Paved surface cannot drain water as fast as vegetated one (land cover type);
- Clay cannot let water infiltrate as quickly as sand (soil type); and
- There are differences concerning bedrock capacity to drain water.

After normalizing the aggregate score of all the four factors (i.e. floodwater depth, land cover type, soil property and bedrock capacity to drain floodwater), we can obtain the nominal value of duration of inundation (see Appendix). This value ranging from 0 to 1 represents the relative time that floodwater would remain at a site after the flood. The relative sense here means to compare between areas in Gothenburg. For instance, Frihamnen the port has the value of 0.375 while the Central Station 0.408. This suggests that if both areas are inundated at the same time and floodwater stays at Frihamnen for 375 minutes (roughly 6 hours), the Central Station would be flooded for 408 minutes, assuming that there is no human intervention, for example by using water pumps, to remove floodwater faster. Fig.14 could serve as a mental picture for administrative units of the city to know where to dredge or upgrade drainage systems to prepare for the future flooding. The zones in the darker blue would need more attention because floodwater would stay there longer compared to some other places with the lighter blue.

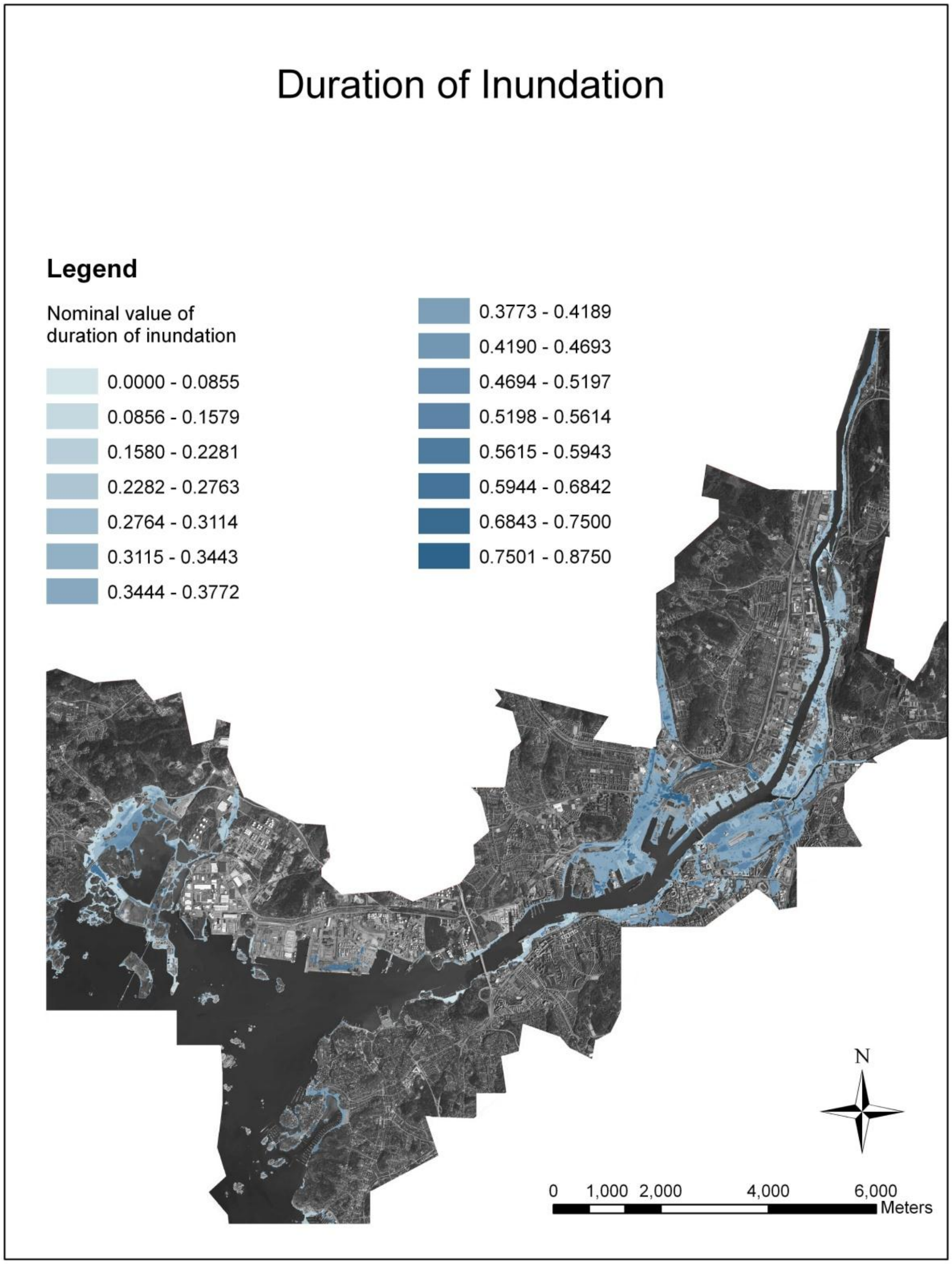

Figure 14. Duration of inundation due to temporary flooding. This multi-criteria assessment approach provides new insight into the impact of temporary flooding in Gothenburg, taking into consideration the depth of floodwater, land cover types, soil properties and bedrock capacity to drain water. The darker the blue, the longer floodwater would stay. Source: Orthophoto from Digitala Kartbiblioteket.

5.4. Proposed measures

In this subchapter, three main categories of measures for managing stormwater will first be listed. After that, they will be discussed within the context of the study area. Particularly, some of the measures will be illustrated by examples drawn on the map.

The three main categories of measures that will be mentioned are Sustainable Drainage Systems (SuDS) options for stormwater management, preventive measures against storm events and system design techniques.

Since the enforcement of the Water Framework Directive, existing practices for draining floodwater have shown much ineffectiveness in maintaining water quality during flood times. SuDS appears as a promising solution to this problem because they are rather flexible (Butler and Davies, 2011, Chap.22; Dublin City Council, 2005). Table 6 lists the SuDS options as potential measures for Gothenburg regarding stormwater management.

Table 6. SuDS options for stormwater management. Source: Adapted from Dublin City Council (2005). These measures have the minor impact on the environment and can be maintained for a long time.

SuDS options	Description
Water conservation and re-use	Collecting and re-using surface water with water butts, rain tanks and rooftop greening
Infiltration systems	Allowing stormwater to infiltrate the ground and filtering pollutants during the infiltration process with infiltration trenches, basins and permeable paving
Filtration systems	Capturing heavy metals, grease, oil, nutrients and sediment with swales, bioretention systems, and filter strips
Retention systems	Retaining pollutants with retention ponds
Detention systems	Reducing runoff rate with detention basins and filter channels
Constructed wetlands	Filtering stormwater, reducing runoff rate and providing wildlife habitat by making stormwater wetlands

Conventional methods which are still widely in use nowadays are the preventive measures against storm events (Pareva, 2006). They are favored in terms of governability from construction to maintenance (Table 7).

Table 7. Preventive measures against storm events. Source: Adapted from Pareva (2006). Most of these measures are related to certain administrative units in a city.

Preventive measures	Description
Construction of flood protection structures	Such as barriers, mobile pumping, channels and dams
Drainage improvement	Desilting, cleaning roads, and upgrading drainage systems
Rain water harvesting	Deepening drainage to store more water, building artificial recharge trenches or check dams, expanding or deepening ponds, and using retention basins
Planting of sturdy trees	To reduce soil erosion

A proper combination of multiple measures is more effective than a single one. Therefore, BASMAA (2003) focused on the techniques for system design (Table 8).

Table 8. System design techniques. Source: Adapted from BASMAA (2003). This approach is a systematic view on the combination of different measures for stormwater management. A single item in the list does not make much sense but when all is integrated into the same measure package, the collective effectiveness is compelling (Fig.15).

System design techniques	Description
Micro-pool	To keep the rest of the basin dry and sediment-free
Basin side slope	To prevent bank erosion
Forebay	To prevent soil erosion
Low-flow channel	To regulate water flow
Vegetation	To control erosion and enhance sediment entrapment
Maintenance access	To keep things in good shape (by cleaning and dredging)
Multiple uses	To combine flood control, recreational facilities and wildlife habitats into one measure package.
Aesthetics	To make scenic views for pedestrians and cyclists

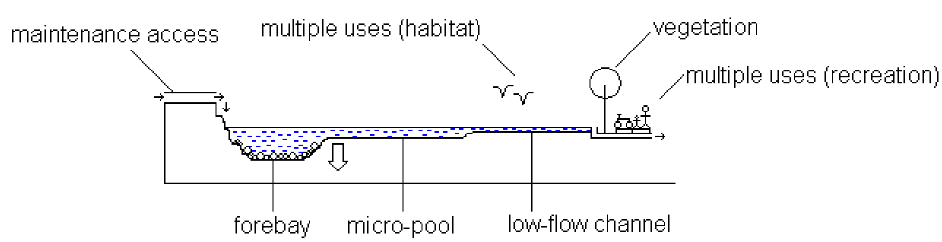

Figure 15. Illustration of system design techniques. Source: Adapted from BASMAA (2003). When several measures are combined correctly, they can achieve an enthralling result.

Each measure in Table 6, 7 and 8 will be discussed critically to see which ones are adequate for the study area (summarized in Table 9).

Table 9. Suitability of the measures for the study area. Source: Own analysis.

Measures	Suitability for the study area
Water conservation and re-use	Rooftop greening is appropriate for the city as it has many houses. However, the renovation cost can be high. Water butts and rain tanks can also be effective if locations to install these devices can be found in the city area most of which is already occupied.
Infiltration systems	Permeable paving can be made in small distinct areas in the city to avoid traffic jam. If well-executed, this measure can have a huge impact in drain water management because the city is covered with many paved surfaces (Fig.8.2). Infiltration trenches and basins are quite hard to construct as at the moment the riverside is overly filled with ports and industrial areas.
Filtration systems	Swales and bioretention systems should be established at suitable sites, such as hollow or sand areas, to bear a feasible cost. The areas satisfied these criteria are rare (Fig.4 and 9). Therefore, filtration systems can be applied but would not influence much.
Retention systems	Retention ponds for pollutants should be located near industrial areas and marked as restricted areas. Overall, this could be developed into an effective measure.
Detention systems	Detention basins and filter channels can be connected to and built on existing channels along the river. Overall, this could be developed into an effective measure.
Constructed wetlands	Stormwater wetlands are suitable at the lower coastal areas where there exist a few green urban areas and vegetated land but not at the upper where industrial and commercial units are dominantly situated (Fig.8.2). Since the wetlands are artificially built, they need constant care to maintain the ecological balance among aquatic plants.
Construction of flood protection structures	Dams were constructed in the upper Göta Älv to control the water flow; hence, another one downstream is unnecessary. Instead, building barriers and mobile pumps are more desired to prevent overflow from the river and to drain water out of inundated areas.
Drainage improvement	Drainage improvement is practical and should be performed periodically.
Rain water harvesting	With the same purpose as that of the sustainable "water conservation and re-use", rain water harvesting costs more. Therefore, it should be prioritized below water butts, rain tanks and rooftop greening.
Planting of sturdy trees	Existing clusters of sturdy trees in the green urban areas (Fig.8.2) can be expanded and connected to each other to form a natural belt along the river and prevent soil erosion.
System design techniques	The whole package of measures is highly suitable for using in existing parks in the study area, such as Slottsskogen. If the package is materialized, a small section of the urban fabrics blocking the riverside will be removed, letting the citizens enjoy a scenic view of the river.

Most measures are suitable but a few are not because they require huge alteration to the terrain. The methods such as setting side slopes flatter, planting vegetation (BASMAA, 2003), creating infiltration and detention basins (Butler and Davies, 2011, Chap.22) can also be used but cost-benefit analyses should be done beforehand. These analyses are necessary for ensuring that the dramatic changes to the environment would enhance amenity and habitat or, at least, can bring the desired benefits to compensate for their negative impacts on the ecosystem.

As a common trend, current preventive measures, i.e. construction of flood protection structures, improvement of drainage efficiency, and rain water harvesting (Pareva, 2006), have become more systemized and been integrated into already-built structures at the site to minimize the changes to the natural environment. A systematic view on new measures regarding stormwater management was found in BASMAA (2003). The measures presented in BASMAA (2003) and Pareva (2006) are interesting but for this thesis the measures within Sustainable Drainage Systems (SuDS) are chosen to be studied more closely because of their relevance for adaptation to sea level rise. They will first be discussed as groups of measures and each of them will later be analyzed in terms of strengths and weaknesses.

Specifically, there are two groups of measures that are proposed for the study area. The first one is to create filtration systems close to the source of pollutants (Dublin City Council, 2005). During normal events as well as extreme ones, such systems can prevent the pollutants of the dump site (see Fig.16) from infiltrating the soil, into the groundwater. Second, Dublin City Council (2005) suggests the integration of preventive measures into existing structures. For example, a big unused tank in the study area can become a rain tank to store excessive rainwater, some houses can green their rooftops to hold a little amount of rainwater, and some pavements can be made permeable to decrease surface water runoff (see Fig.16). One should not underestimate the effectiveness of these small-scale measures as they can be highly effective when used in combination with others in a well-designed system (Dublin City Council, 2005). Another reason is that many different measures on an extensive area can raise the awareness of the people in Gothenburg. After all, public awareness is an important factor for carrying out sustainable drainage practices successfully (Dublin City Council, 2005).

Basically, we have examined in detail four proposed measures each of which comes with its own strengths and weaknesses. First, the use of filtration systems, such as filter strips, near the dump site can prevent contaminants from permeating the soil and therefore increase groundwater quality. However, these filter strips require constant inspections and cleansing to ensure that they are not blocked or full because clogged filter strips can become pervious and dangerously let polluted water run freely. After all, it is better to keep the waste away from rainwater than to rely on filtration systems. Like in the SuDS "treatment train" concept, first comes "good housekeeping", then "source controls". The second measure proposes the reconstruction of an unused tank into a rain tank. This will take advantage of an abandoned site and put it into good use by storing excessive rainwater. Nonetheless, the problem that may arise is from its owners. They may come up with a new use for their tank as it has recently been repaired by Tidermans

Hyrmaskiner AB – a construction and renovation company in Gothenburg. Third, green roofs, which are planted vegetation on the tops of buildings, can retain a large amount of rainwater which will gradually evaporate after the rain. Moreover, according to Liu and Minor (2005), a green roof can help regulate the temperature of the room underneath. The disadvantage of this measure is the high initial cost for installing the roofs although the cost can be shared among the residents who might also receive from the municipality an endowment for promoting a sustainability measure. Last, permeable paving can effectively reduce runoff volume and therefore increase soil quality and decrease bank erosion risk. Its effectiveness however can be weakened if there is too much litter.

6. DISCUSSION

6.1. General view on the results

The first research question mentioned in Chapter 1 "What are the possible effects of sea level rise on the Swedish west coast?" has been answered mainly based on the literature review in Chapter 2 and 3. No specific analysis or calculation is done regarding the Swedish west coast. However, the second question "What are the possible effects of sea level rise (combined with storm surges) on the coastal and river areas in the city of Gothenburg?" has been resolved in detail with both the literature review and estimations for sea level rise consequences in Gothenburg in 2100.

To improve the results by means of better analyses, the input data must have a better resolution and, preferably, be in a raster format. To make more holistic conclusions, social aspects of the issue must be included in addition to the physical ones that have been studied mainly through the previous chapters. Further, other climate-related hazards should be included besides sea level rise since a disaster and an extreme weather event can happen at the same time and produce a compounding effect. For instance, when heavy rainfall combines with an earthquake, landslide risk will get to a higher level compared to when only one of the two events happens (Yasuhara *et al*., 2011).

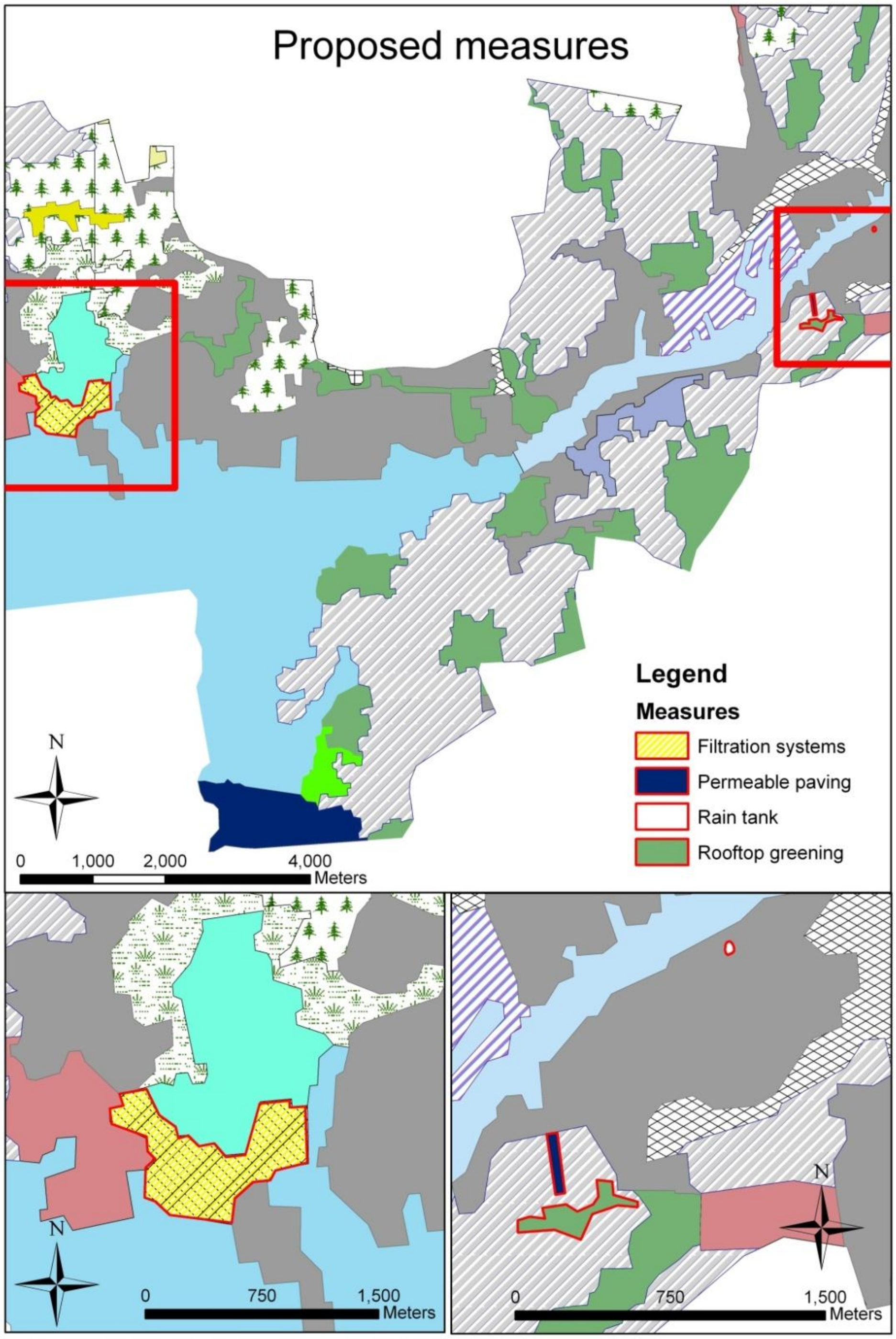

Figure 16. Proposed measures. Sustainable Drainage Systems would be a good choice for Gothenburg to be in compliance with legislation such as the Water Framework Directive (Dublin City Council, 2005). A few measures are proposed in order to cope with sea level rise in the study area: filtration systems at a dump site, a rain tank at an abandoned tank, and permeable paving and rooftop greening at a residential area. All of them are experimented at places of heavy flooding that are suggested in Fig.14. Source: Land cover layer from CORINE.

The holistic approach in adaptation to sea level rise and inundations is gaining more and more attention from scholars as only physical adaptation and protection cannot solve the problem effectively. Birkmann *et al*. (2010) suggest "a paradigm shift to move from the dominant focus on the adjustment of physical structures towards the improvement of planning tools and governance processes and structures themselves". Also at the governmental level, the main perspective on the issue is to consider all disasters as separate events which will happen one at a time. Thus, risk and economic loss analyses for compound catastrophes that will be likely to happen more frequently in the future of climate change are necessary according to Yasuhara *et al*. (2011). While Birkmann, Yasuhara *et al*. emphasize that holistic approaches combine entities long separated in previous research, Romieu *et al*. (2010) found that such approaches can also eliminate the unnecessary overlap between certain concepts, e.g. climate change and natural hazards. With the holistic approach that integrates adaptive governance, compound disaster management and improved vulnerability analysis, the actors will have more chance to find a better locally-adapted strategy.

To apply the holistic approach for the case of Gothenburg whose adaptation to sea level rise and inundation has been continuously improved to reach the level of adaptation strategies presented in Birkmann *et al*. (2010), the following four changes in the perception are required. The first one is the replacement of the "physical adaptation" thinking by the "adaptive governance" thinking which implies the improvement of city planning. Second, climate change should no longer be all about "rural" – the city and its citizens must also play an important role. The city must be seen as a complex social-ecological system in which the social system components (the inhabitants and their activities) are crucial. Third, Gothenburg has many ethnic and social groups that have different cultures and norms; therefore, when working with different social groups, the informal measures will be necessary to complement the formal ones. Last, coastal risk assessment should be refined by an improvement in the vulnerability analysis which is in turn done by reducing the gaps between climate change and natural hazard contexts (Romieu *et al*., 2010).

6.2. Detailed discussion

In this thesis, the questions how much land might be flooded and how fast floodwater might withdraw can be answered in a sense; however, the more complex ones, such as how much damage there might be in monetary terms, would need further investigations. For instance, the maps can show that a building is flooded but whether floodwater does enter the house or not is unclear. This depends largely on its structural integrity to withstand the floodwater pressure. Hence, if water remains outside the building, it would not be that costly to recover after the flood. Otherwise, insurance payment for pumping out water and cleaning the debris would be high. It is also important to remember a good side of flooding that it can bring nutrition to agricultural land and therefore generate profits through crops. Moreover, the current analysis itself is not at a complete state since some important factors are not considered such as the slope of terrain (which affects the speed of surface water runoff), the hydrodynamic and meteorological parameters (which direct the movement of floodwater and have a strong impact on evaporation process, respectively), and the capacity of the city's manhole-pipe drainage system (which influences the drainage speed of floodwater on urbanized and paved surfaces). That the analysis is not at its desired level of accuracy may reduce the preciseness of monetary calculations which frequently demand a high level of accuracy. Hence, monetary studies on such a large area at this stage can be rather challenging.

For proposed measures in this thesis, the number is limited as the focus of the thesis was on data collection and analysis to produce flood risk maps. However, potential measures for the study area have been fully listed and critically discussed. The reason why some measures are specifically proposed is explained.

For the discussion, it is interesting to compare measures for Gothenburg with those for Ho Chi Minh City, one of the few cities for which detailed planning and adaptation measures can be found [proposed in Birkmann *et al*. (2010)], as well as to combine measures against sea level rise with those against natural disasters that may accompany sea level rise (like storms). Table 10 and 11 will illustrate these in more detail.

Table 10. Measures of sea level rise adaptation for Gothenburg and Ho Chi Minh City. Source: Own proposal and Birkmann *et al*. (2010). These cities are the two contrasting examples: one is from a metropolitan area in a developed country in the north while the other from a developing country in the south.

Gothenburg	Ho Chi Minh City
New barriers	New dykes
Construction of new stormwater wetlands	Protection of mangrove forests
Dredging of channels	Clearance of canals
(No equivalent measures)	Improved early warning for floods, storms and tidal waves, resettlement, promotion of drought-resistant crops and production patterns
Rooftop greening, permeable paving	Resilient housing and infrastructure

Ho Chi Minh City has more different measures than Gothenburg. It could be due to the fact that the former has recently faced the consequences of sea level rise to a larger extent than the latter.

Table 11. Combination of measures against sea level rise and adaptation strategies against climate change-related natural disasters. Source: Adapted from Yasuhara *et al*. (2011). Protection, accommodation, and evacuation are the three main groups of measures used for combining with measures against sea level rise.

Protection	Additional banking, water protection work, early warning system and evacuation system*, construction of shelter*, monitoring and lowering of the groundwater level*, soil improvement and reinforcement, protective pile
Accommodation	Hazard map, appropriate land use, regulation of land use in hazardous area*, insurance
Evacuation	Restriction of development, evacuation from dangerous area*, public support for evacuation*

*Note: Measures that have not been listed as the measures against sea level rise.

Table 10 and 11 show that the measures used in Ho Chi Minh City and Gothenburg are mainly protection-oriented and less accommodation- and evacuation-oriented. One exception is the promotion of drought-resistant crops and production patterns in Ho Chi Minh City which is an accommodation-oriented measure.

7. CONCLUSIONS

The thesis has touched upon an aspect of climate change impact, i.e. sea level rise. With this, Gothenburg can have some options to deal with the issue of flooding due to storm surges. Flooding can become highly problematic for Gothenburg for many years to come but at this time the city faces the threats of erosion and salinization. To solve these three problems and other potential ones, there are a lot of tasks to complete, ranging from the local to the regional level and including urgent missions as well as long-term goals.

The most obvious effect of sea level rise along the Swedish west coast is inundation but the two current issues in Gothenburg are land erosion and saltwater intrusion. However, to what extent land uplift will counteract the rate of sea level rise is still uncertain and requires the implementation of regional climate models to estimate. One thing for sure at this point is that the farther to the south, the more likely flooding will happen since the rate of land uplift decreases in Southern Sweden. In addition, when implementing measures against flooding, we should not be confined to only solving the inundation issue but need to try solving the two main concerns in Gothenburg: land erosion and saltwater intrusion. In fact, the two are closely connected to flooding. Flooding can affect groundwater levels which in turn increase the risk of erosion and salinization. Storms can also combine with sea level rise to bring salt water deep into the lakes that are used to supply drinking water for the city. More importantly, land erosion and saltwater intrusion are happening now while it would take some time for inundation issues to become critical in the future. Furthermore, when we consider inundation, land erosion and saltwater intrusion as a group, the overlap between measures against each of them can be reduced.

From the local to the regional scale, Gothenburg seems to have a lot of work to do to cope with the impacts of climate change. Firstly, in Gothenburg, fourteen coastal and riverside districts are chosen to be studied in detail how they could be affected by sea level rise. The results indicate that permanent flooding would not be as severe as temporary flooding. Urbanized areas should be affected the most and among them Domkyrko and Brämaregården are the two typical examples. The follow-up multi-criteria assessment suggests that floodwater may remain for quite a long time around Frihamnen and the Central Station. Four measures (i.e. filtration systems, rain tank, permeable paving and rooftop greening) are proposed for experiment at crucial spots of flooding. If they can prove effective, multiplication of such measures will certainly be promising. Secondly, at the regional scale, Gothenburg should cooperate with other municipalities nearby to mitigate the impacts of climate change. The implementation of Sustainable Drainage Systems, if successful, will be just the small part in a larger system of solutions to the problems. Such a system was once mentioned as the term "managed realignment" in French (2006). Further research requires the inclusion of in-depth resilience and vulnerability studies.

A well-organized system of measures will be needed but for now increasing public awareness remains as a principal task. To solve the problems of land erosion and saltwater intrusion as well as the other climate change-related issues that may arise in the future, a well-designed system of solutions is required. It will not only help to solve multiple issues at the same time but also save the cost for construction and management. The long-term trend as everywhere is towards integrated and transdisciplinary approach. However, the important lesson at the moment is the need of raising people's awareness of sea level rise and it is even more decisive for the case of Gothenburg because of the two following reasons. First, the damage of sea level rise will increase exponentially over time: the change is hard to recognize at the beginning and when we can actually feel it, it is too late to defend against the flood. Second, the rise is masked by land uplift and therefore many were not convinced by an increase in sea levels.

REFERENCES

Scientific resources

Birkmann, J., Garschagen, M., Kraas, F. & Quang, N. (2010) 'Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change', *Sustainability Science*, 5: 185-206.

Butler, D. & Davies, J. (2011) Urban drainage (3rd edition). London: Spon Press.

Carter, T., Jones, R., Lu, X., Bhadwal, S., Conde, C., Mearns, L., *et al*. (2007) 'New assessment methods and the characterisation of future conditions.', in M. Parry, O. Canziani, J. Palutikof, P. van der Linden & C. Hanson (eds), C*limate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC*. Cambridge: Cambridge University Press.

Cazenave, A., & Llovel, W. (2010) 'Contemporary sea level rise', *Annual Review of Marine Science*, 2: 145-73.

Chust, G., Caballero, A., Marcos, M., Liria, P., Hernández, C., & Borja, Á. (2010) 'Regional scenarios of sea level rise and impacts on Basque (Bay of Biscay) coastal habitats, throughout the 21st century', *Estuarine, Coastal and Shelf Science* 87 (1): 113-124.

Commission on Climate and Vulnerability (2007) 'Sweden facing climate change–threats and opportunities', *Final report from the Swedish Commission on Climate and Vulnerability.* SOU 2007:60.

Cossellu, M. & Nordberg, K. (2010) 'Recent environmental changes and filamentous algal mats in shallow bays on the Swedish west coast – A result of climate change?', *Journal of Sea Research*, 63: 202-12.

Debo, T. & Reese, A. (2003) Municipal stormwater management. Florida: CRC Press.

Douglas, B., Kearney, M., & Leatherman, S. (2000) Sea level rise: History and consequences. New York: Academic Press.

Eriksson, C. (2009) Characterizing and reconstructing 500 years of climate in the Baltic Sea Basin. University of Gothenburg.

Fisher, B., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., de la Chesnaye, F., Hourcade, J.-Ch., *et al*. (2007) 'Issues related to mitigation in the long term context', in B. Metz, O. Davidson, P. Bosch, R. Dave, L. Meyer (eds), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the IPCC*. Cambridge: Cambridge University Press.

FitzGerald, D., Fenster, M., Argow, B., & Buynevich, I. (2008) ‘Coastal impacts due to sea-level rise’, *Annual Review of Earth and Planetary Sciences*, 36 (1): 601-47.

French, P. (2006) 'Managed realignment-The developing story of a comparatively new approach to soft engineering', *Estuarine, Coastal and Shelf Science*, 67 (3): 409-423.

Gustafsson, M., & Nordberg, K. (2002) ‘The impact of climate and shore-level displacement on the late-Holocene environmental development of Havstens Fjord and Koljö Fjord, Swedish west coast’, *The Holocene,* 12 (3): 325-38.

Hansen, H. (2010) ‘Modelling the future coastal zone urban development as implied by the IPCC SRES and assessing the impact from sea level rise’, *Landscape and Urban Planning*, 98: 141-9.

Hanson, S., Nicholls, R., Balson, P., Brown, I., & French, J. (2010) ‘Capturing coastal geomorphological change within regional integrated assessment: An outcome driven fuzzy logic approach’, *Journal of Coastal Research*, 26 (5): 831-42.

Helle, S. (2008). Early post-deglaciation shorelines and sea-level changes along Hardangerfjorden and adjacent fjord areas, W. Norway. Doctoral thesis.

Heywood I., Cornelius S. & Carver S. (2006) An introduction to geographical information systems (3rd edition). Pearson Prentice Hall.

Hünicke, B. (2008) Atmospheric forcing of Baltic Sea level variability in the last 200 years: A statistical analysis. GKSS – Forschungszentrum Geesthacht GmbH.

IPCC (2005) Guidance notes for lead authors of the IPCC Fourth Assessment Report on addressing uncertainties. United Nations Environment Programme.

IPCC (2007) Climate Change 2007: Synthesis Report – An Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press

Jensen, J., Petersen, K., Korandi, P., Kuijpers, A., Bennike, O., Lemke, W., & Endler, R. (2002) ‘Neotectonics, sea-level changes and biological evolution, in the Fennoscandian Border Zone of the Southern Kattegat Sea’, *Boreas*, 31: 133-50.

Johansson, B. & Mobjörk, M. (2009) Climate adaptation in Sweden: Organisation and experiences. FOI-R—2725—SE.

Johansson, M., Kahma, K., Boman H., & Launiainen, J. (2004) ‘Scenarios for sea level on the Finnish coast’, *Boreal Environ. Res*., 9: 153-66.

Jönsson, A. (2011) ‘Framing Environmental Risks in the Baltic Sea: A News Media Analysis’, *AMBIO*, 40: 121-32.

Keskitalo, E. (2010) ‘Adapting to Climate Change in Sweden: National Policy Development and Adaptation Measures in Västra Götaland’, in E. Keskitalo (ed), *Developing Adaptation Policy and Practice in Europe: Multi-level Governance of Climate Change*. London: Springer, pp.189-232.

Kundzewicz, Z., Mata, L., Arnell, N., Döll, P., Kabat, P., Jiménez, B., Miller, K., Oki, T., Sen, Z. & Shiklomanov, I. (2007) ‘Freshwater resources and their management’, in M. Parry, O. Canziani, J. Palutikof, P. van der Linden & C. Hanson (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to The Fourth Assessment Report of The Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Larsen, N., Knudsen, K., Krohn, C., Kronborg, C., Murray, A., & Nielsen, O. (2009) ‘Late Quaternary ice sheet, lake and sea history of southwest Scandinavia–a synthesis’, *Boreas*, 38 (4): 732-61.

Liu, K., & Minor, J. (2005) ‘Performance evaluation of an extensive green roof’, *Greening Rooftops for Sustainable Communities*.

Löfgren, J., Haas, R., & Johansson, J. (2011) ‘Monitoring coastal sea level using reflected GNSS signals’, *Advances in Space Research*, 47: 213-20.

Lohne, Ø., Bondevik, S., Mangerud, J., & Svendsen, J. (2007) ‘Sea-level fluctuations imply that the Younger Dryas ice-sheet expansion in western Norway commenced during the Allerød’, *Quaternary Science Reviews*, 26 (17-18): 2128-51.

Meier, M., Broman, B., & Kjellström, E. (2004) ‘Simulated sea level in past and future climates of the Baltic Sea’, *Climate Research*, 27: 59-75.

Morf, A. (2006). Participation and planning in the management of coastal resource conflicts. Case studies in West Swedish Municipalities. University of Gothenburg.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., *et al*. (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Pacific Northwest National Laboratory and Environmental Molecular Sciences Laboratory.

Näslund, J., & Lindborg, T. (2009). Expected extreme sea levels at Forsmark and Laxemar–Simpevarp up until Year 2100. Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co).

Niang, I., Dansokho, M., Faye, S., Gueye, K., & Ndiaye, P. (2010) ‘Impacts of climate change on the Senegalese coastal zones: Examples of the Cap Vert Peninsula and Saloum Estuary’, *Global and Planetary Change*, 72: 294-301.

Nicholls, R., Wong, P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S., & Woodroffe, C. (2007) ‘Coastal systems and low-lying areas’, in M. Parry, O. Canziani, J. Palutikof, P. van der Linden & C. Hanson (eds), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to The Fourth Assessment Report of The Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Nordberg, K., Gustafsson, M., & Krantz, A.-L. (2000) ‘Decreasing oxygen concentrations in the Gullmar Fjord, Sweden, as confirmed by benthic foraminifera, and the possible association with NAO’, *Journal of Marine Systems*, 23: 303-16.

Ogston, A., & Field, M. (2010) ‘Predictions of turbidity due to enhanced sediment resuspension resulting from sea-level rise on a fringing coral reef: Evidence from Molokai, Hawaii’, *Journal of Coastal Research*, 26 (6): 1027-37.

Olsen, R. C. (2007) Remote sensing from air and space. Society of Photo Optical.

Persson, H. (2008) Estimation of pore pressure levels in slope stability calculations: Analyses and modelling of groundwater level fluctuations in confined aquifers along the Swedish west coast. Linköping: Swedish Geotechnical Institute.

Persson, H., Alén, C., Lind, B. (2007) ‘Development of a pore pressure prediction model’, in R. McInnes, J. Jakeways, H. Fairbank, E. Mathie (eds), *International Conference on* “*Landslides and Climate Change*”. Isle of Wight, pp. 229-35.

Peterson, T., Navarro-Sigüenza, A., & Li, X. (2010) ‘Joint effects of marine intrusion and climate change on the Mexican Avifauna’, *Annals of the Association of American Geographers*, 100: 908-16.

Pokharel, P., Takeda, M., & Naoki, M. (2009) ‘Inundation analysis in the coastal area considering climate change due to global warming’, *Water Air Soil Pollution: Focus*, 9: 393-401.

Rennie, A. & Hansom, J. (2011) ‘Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland’s coast’, *Geomorphology*, 125:193-202.

Romieu, E., Welle, T., Schneiderbauer, S., Pelling, M. & Vinchon, C. (2010) 'Vulnerability assessment within climate change and natural hazard contexts: revealing gaps and synergies through coastal applications', *Sustainability Science*, 5: 159-170.

Ruddiman (1997) Tectonic uplift and climate change. Plenum Publishing Corporation

Sánchez-Arcilla, A., Jiménez, J., Valdemoro, H., & Gracia, V. (2008) ‘Implications of climatic change on Spanish Mediterranean low-lying coasts: the Ebro Delta Case’, *Journal of Coastal Research*, 24 (2): 306-16.

Scheyer, J. & Hipple, K. (2005) Urban Soil Primer. United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.

Scotto, M., Barbosa, S., & Alonso, A. (2009) 'Model-based clustering of Baltic sea-level', *Applied Ocean Research*, 31 (1): 4-11.

Semadeni-Davies, A., Hernebring, C., Svensson, G., & Gustafsson, L. (2008) 'The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater', *Journal of Hydrology*, 350 (1-2): 114-25.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., & Miller, H. (eds) (2007) IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

Stauffacher, M., Walter, A., Lang, D., Wiek, A., & Scholz, R. (2006) 'Learning to research environmental problems from a functional socio-cultural constructivism perspective: The transdisciplinary case study approach', *International Journal of Sustainability in Higher Education* 7 (3): 252-75.

Storbjork, S., & Hedren, J. (2011) 'Institutional capacity-building for targeting sea-level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby', *Ocean & Coastal Management*, 54: 265-73.

Sztobryn, M., Stigge, H.-J., Wielbińska, D., Weidig, B., Stanisławczyk, I., Kańska, A. *et al*. (2005) Storm surges in the Southern Baltic Sea (western and central parts). BSH – Bundesamt für Seeschifffahrt und Hydrographie.

Thorsson, S., Lindqvist, M., & Lindqvist, S. (2004) 'Thermal bioclimatic conditions and patterns of behaviour in an urban park in Göteborg, Sweden', *International Journal of Biometeorology*, 48 (3): 149-56.

Tian, B., Zhang, L., Wang, X., Zhou, Y., & Zhang, W. (2010) 'Forecasting the effects of sea-level rise at Chongming Dongtan Nature Reserve in the Yangtze Delta Shanghai, China', *Ecological Engineering*, 36: 1383-8.

Vafeidis, A., Nicholls, R., McFadden, L., Tol, R., Hinkel, J., Spencer, T., *et al*. (2008) 'A new global coastal database for impact and vulnerability analysis to sea-level rise', *Journal of Coastal Research*, 24 (4): 917-24.

Vestøl, O. (2006) 'Determination of postglacial land uplift in Fennoscandia from leveling, tide-gauges and continuous GPS stations using least squares collocation', *Journal of Geodesy*, 80 (5): 248-58.

Wright, R., Aherne, J., Bishop, K., Camarero, L., Cosby, B., Erlandsson, M., *et al*. (2006) ‘Modelling the effect of climate change on recovery of acidified freshwaters: Relative sensitivity of individual processes in the MAGIC model’, *Science of the Total Environment*, 365: 154-66.

Yasuhara, K., Komine, H., Yokoki, H., Suzuki, T., Mimura, N., Tamura, M. & Chen, G. (2011) 'Effects of climate change on coastal disasters: new methodologies and recent results', *Sustainability Science*, 6.

Non-scientific documents

BASMAA (2003) Start at the Source – Chap.5: Drainage Systems. Retrieved May 2, 2011, from Bay Area Stormwater Management Agencies Association: http://strawberrycreek.berkeley.edu/pdfs/Start@Source/sats5drainagesystems.pdf

Dublin City Council (2005) Regional Drainage Policies – Vol.3 – Chap.6: Sustainable Drainage Systems. Retrieved May 2, 2011, from Dublin City Council: http://www.dublincity.ie/WaterWasteEnvironment/WasteWater/Drainage/GreaterDublinStrategicDrainageStudy/Documents/Vol%203%20-%20Chapter%206%20-%20Sustainable%20Drainage%20Systems.pdf

ESPON (2003a) The European Spatial Planning Observation Network (ESPON): SE0A2-Västra Götalands län. Retrieved March 9, 2011, from ESPON: http://www.espon.eu/export/sites/default/Documents/ScientificTools/ESPON2006Tools/DatabasePublicFiles/ESPONProjectIndicators/12_environment_nuts_3.xls

ESPON (2003b) The European Spatial Planning Observation Network (ESPON): Natural hazards. Retrieved March 9, 2011, from Geologian tutkimuskeskus (Geological Survey of Finland): http://www.gsf.fi/projects/espon/natural.htm

European Commission (2009) The economics of climate change adaptation in EU coastal areas. Retrieved February 13, 2011, from European Commission: http://ec.europa.eu/maritimeaffairs/climate_change/sweden_en.pdf.

Göteborgs Stad (2006) Extrema vädersituationer - Hur väl rustat är Göteborg? Retrieved April 15, 2011, from Göteborgs Stad: http://www.goteborg.se/wps/wcm/connect/1a78480042171f9c9edcff3d2a09bb7a/huvudrapport_extrema_vadersituationer_maj+2006.pdf?MOD=AJPERES&CONVERT_TO=URL&CACHEID=1a78480042171f9c9edcff3d2a09bb7a

Göteborgs Stad (2007) City of Gothenburg | Annual Report 2007. Retrieved February 1, 2011, from Göteborgs Stad:

http://www.goteborg.se/wps/wcm/connect/439013004216e2a09bb8ff3d2a09bb7a/annualreport07_low.pdf?MOD=AJPERES&CONVERT_TO=URL&CACHEID=439013004216e2a09bb8ff3d2a09bb7a.

Göteborgs Stad (2008) City of Gothenburg | Annual Report 2008. Retrieved February 1, 2011, from Göteborgs Stad: http://www17.goteborg.se/english/documents/annual_report_2008.pdf.

Göteborgs Stad (2009a) Comprehensive Plan for Göteborg: Summary. Retrieved February 1, 2011, from Göteborgs Stad: http://www17.goteborg.se/english/documents/Gothenburg_comprehensive_plan.pdf.

Göteborgs Stad (2009b) City of Gothenburg | Annual Report 2009. Retrieved February 1, 2011, from Göteborgs Stad: http://www17.goteborg.se/english/documents/Annual_Report_2009.pdf.

Göteborgs Stad (n.d.). Gothenburg and the Environment. Retrieved February 1, 2011, from Göteborgs Stad: http://www5.goteborg.se/prod/Miljo/Miljohandboken/dalis2.nsf/vyFilArkiv/GoAndEnviro_enkelsid.pdf/$file/GoAndEnviro_enkelsid.pdf.

Hammarklint, T. (2009) Swedish Sea Level Series - A Climate Indicator. Retrieved March 2, 2011, from SMHI: http://www.smhi.se/polopoly_fs/1.8963!Swedish_Sea_Level_Series_-_A_Climate_Indicator.pdf

OECD (2008) Costs of Inaction on Environmental Policy Challenges: Summary Report. Retrieved March 1, 2011, from OECD: http://www.oecd.org/dataoecd/60/45/40501169.pdf

Pareva, M. (2006) Urban flooding and its management. Retrieved May 2, 2011, from India Disaster Management Congress (IDMC): http://nidm.gov.in/idmc/Proceedings/Flood/B2%20-%2036.pdf

PSMSL (2011a) Goteborg - Klippan. Retrieved April 20, 2011, from PSMSL: http://www.psmsl.org/data/obtaining/stations/74.php

PSMSL (2011b) Göteborg - Torshamnen. Retrieved April 20, 2011, from PSMSL: http://www.psmsl.org/data/obtaining/stations/1236.php

SMHI (2006) The HBV model. Retrieved February 12, 2011, from SMHI: http://www.smhi.se/sgn0106/if/hydrologi/hbv.htm (Updated on May 3, 2006).

World Bank (2009) The costs to developing countries of adapting to climate change. Retrieved February 10, 2011, from World Bank: http://siteresources.worldbank.org/INTCC/Resources/Executivesummary.pdf.

APPENDIX

Calculation of relative inundation time

Relative inundation time at a site is calculated by the four variables: floodwater depth, land cover type, soil property and bedrock capacity to drain floodwater. In ArcGIS, these variables are denoted as WATER_DEP, LAND_COV, SOIL_PROP, and BEDROCK respectively. They are defined as followed:

- WATER_DEP: Float, Range = [0 .. 3.8]
- LAND_COV: Short Integer, Range = { 0, 1, 2, 3 }
- SOIL_PROP: Short Integer, Range = { 0, 1, 2, 3, 4 }
- BEDROCK: Short Integer, Range = { 0, 1, 2 }

For each variable, higher numbers mean that it will takes longer for the site to drain all the floodwater. With the assumption that all variables have equal contribution to the duration of inundation at the site, the relative inundation time, denoted as AVG_VALUE, is calculated by this formula below:

$$AVG\_VALUE = \frac{\frac{WATER\_DEP}{3.8} + \frac{LAND\_COV}{3} + \frac{SOIL\_PROP}{4} + \frac{BEDROCK}{2}}{4}$$

The relative inundation time of each site in the study area is then represented in a thematic map as seen in Fig.14. Here is an example of how the calculation looks like in ArcGIS: