Effects of future sea level rise – the example of the island of Gotland, Sweden

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Abstract—**Sea level rise is confirmed to be an upcoming and pressing issue; on a global as well as local scale; and with it comes the necessity to adapt. Using the local case study of the island of Gotland, Sweden, we investigate the effects of future sea level rise on a multitude of features combined and thereby assess the overall impact on the environment and infrastructure of the island. Sea level is expected to rise 1 - 2 m until 2100** [1]**. We analyze what percentage of Gotland's total land surface will be submerged under the given scenario, using ArcGIS environment using LIDAR elevation data. Through successive overlay analysis of both raster and vector data, we then quantify the loss of infrastructure; including wells, roads, industrial areas and gas stations. Secondly we investigate what percentage of Gotland's natural and cultural heritage will drown.**

In this ongoing study we found that about 3% of Gotland's land area will drown. Future pressures of water extraction will yield increased risk of saltwater intrusion for a considerable part of the population. For southern Gotland, projections show that about 30% of the wells will be associated with high risk of saltwater intrusion. Furthermore, around 90% of the wells would be at medium or high risk of saltwater intrusion in that case. Even a minimum predicted sea level rise will drown the entire shore meadows and the associated breeding places for birds. We expect that current quantifications of the impact of sea level rise on multiple environmental and anthropogenic features can provide a scientifically sound basis for assessment of main consequences and costs of direct losses.

I. INTRODUCTION

Sea level rise is confirmed to be an upcoming and pressing issue; on a global as well as local scale; and with it comes the necessity to adapt. The pace at which sea level will rise is not clear, but undoubtedly, it will drown areas along the world's coasts - where we find most of our settlements and infrastructure. A natural first step towards managing this change is the investigation of the consequences of sea level rise; reversible and irreversible, on humans, nature, and connected issues such as sea water pollution by drowning contaminated areas and salt water intrusion in wells.

Several studies have considered the impact of sea level rise on a variety of environmental and anthropogenic features [2], [3] yet often they fail to take on the multi-consequential characteristic of this subject. This paper aims to fill that gap. Using the local case study of the island of Gotland, Sweden, we try to investigate the effects of future sea level rise on a multitude of features combined and thereby assess the overall impact on the environment and infrastructure of the island. Gotland is a politically stable, comparatively well-suited area, with many means to prepare for future sea level rise. Still some valuable areas like shore meadows and the connected bird life will be irreversibly lost. Still, moving towns and sanitizing of contaminated areas like gas stations will be costly and difficult, and in cases not even possible. If we see Gotland as a "miniature world", the study is extrapolated to illustrate what effects sea level rise could have globally, given rather an underestimate of the possible consequences of sea level rise.

II. SEA LEVEL RISE ON GOTLAND

Gotland is located in the Baltic Sea east of Sweden (Figure 1) and the main island has a total land area of 3 140 km², which makes it the largest island of Sweden. Administratively

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Gotland is both a county and a municipality of its own and it has a population of almost 60 000 people. It is an island with complete infrastructure with rich tourism, agriculture, mining and food industry [4]. The coastline of the island, which stretches 77 km, harbors unique flora and fauna and is an important economic asset as well as a valuable resource for residents and travelling visitors [5]. Sea level here, according to the fifth report of IPCC, is expected to rise 1 - 2 m until 2100; mainly as a result of the slow but ongoing and irreversible collapse of the West Antarctic Ice Sheet (WAIST) [1].

The initial analysis, which examines what percentage of Gotland's total land surface will be submerged under the given scenario, is performed in an ArcGIS environment using LIDAR elevation data. Through successive overlay analysis of both raster and vector data, we then quantify the loss of infrastructure; including for example built-up areas, wells, roads, industrial areas and gas stations. Secondly we investigate what percentage of Gotland's natural and cultural heritage will drown, including for example shore meadows, cultural grazing fields and rune stones.

Based on this information the paper then takes the overall perspective and discusses the possible environmental as well as economic implications. It considers for example saline water intrusion and the reduction in beach meadow area and in bird life; and then possible economic consequences arising from e.g. decreasing tourism, the restoration of infrastructure and of polluted areas. Discussion then finally addresses which of these losses are irreversible and which might actually be mended or prevented.

Results show that a future sea level rise between 1 and 2 meters would result in inundation of 2 to 3% of Gotland's current land area. In the relatively flat, southern part of the island, the expected inundation is twice as high. More generally, the fact that the population density is relatively high near the coast implies that a considerable part of important infrastructure will be submerged.

Application of developed models of salt water intrusion [6] furthermore shows that future pressures of water extraction, in combination with density driven intrusion of relatively heavy saltwater beyond the new future coastline will yield increased risk of saltwater intrusion for a considerable part of the population. For instance, for southern Gotland, projections show that about 30% of the wells will be associated with high risk of saltwater intrusion given a future sea level rise of 1m. Furthermore, around 90% of the wells would be at medium or high risk of saltwater intrusion in that case.

In order to quantify how conditions can change in the future, the results of the future projections are compared with current risks of salt water intrusion. Presently, the high-risk area of sea water intrusion covers 214 km^2 and contains 807 drinking water wells. Results show that 82 of these will be completely flooded given a sea level rise of 1m. Despite this loss of land, the high-risk area of the remaining part of the island would increase to 245 km^2 and contain 947 wells (in addition to the 82 in submerged ones). For a sea level rise of 2m, 165 wells would be submerged, the high risk area of remaining land would increase to 279 km^2 and contain 1081 wells.

The above quantification examples illustrate that, in addition to direct and irreversible loss of land and infrastructure such as roads, industrial land and drinking water wells, the remaining part of the island may be more vulnerable to risks such as salt water intrusion. This is due to modified hydrological and hydrogeological conditions; a larger area of the remaining island will contain low lying land, for instance. The problem could be further accentuated by pressures from increasing population and/ or population density of the coastal zone (as the island shrinks). Even the minimum predicted sea level rise will consume 99% of Gotland's shore meadows [7], a breeding place for a high variety of bird species. With the shore meadows and archeological sites disappearing, not only unique natural and cultural values, but also, as a consequence, tourism will decrease drastically.

With regard to industrial activities, the region that will be submerged by expected future sea level rise contains contaminated industrial land and infrastructure that may have adverse environmental effects such as gas stations. Sea level rise can hence imply that costs for mitigation measures addressing Gotland's current environmental problems may change due to changing environmental conditions; for completely submerged regions, costs for remediation may even become too high to be feasible, due to an increased inaccessibility of flooded or partly flooded land.

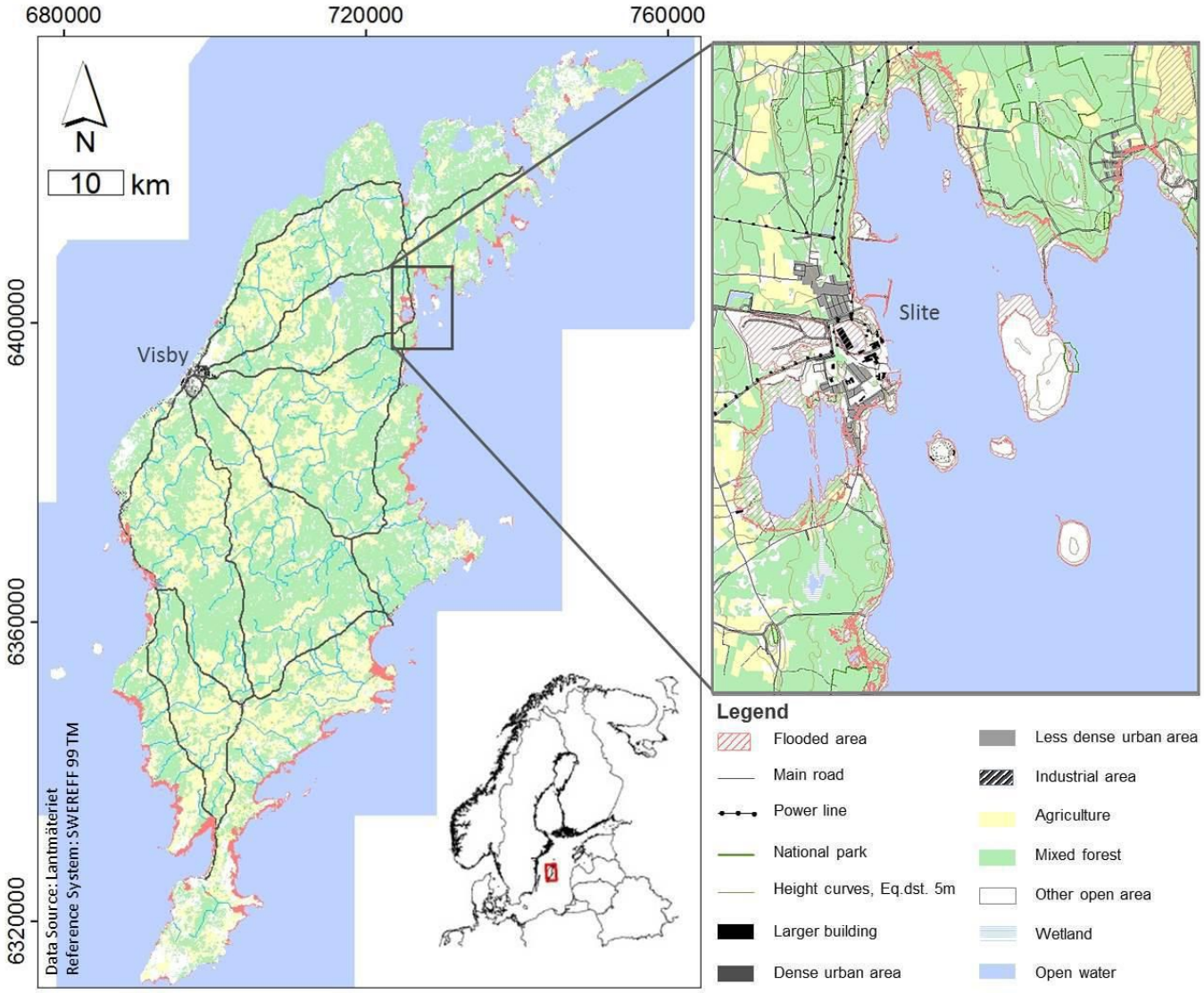

Figure 1. Gotland's land area would diminish with 3% as consequence of a 2m sea level rise. Urban areas and nature reserves would be severely affected as the majority of settlements and cultural heritage sites in Gotland are situated at the coast. In our project, we quantify the percentage of disappearing sites and discuss the long-term consequences of sea level rise. Inset map shows Gotland's location in Fennoscandia.

We expect that current quantifications of the impact of sea level rise on multiple environmental and anthropogenic features can provide a scientifically sound basis for assessment of main consequences and costs of direct losses (of land and infrastructure) and potential future costs associated with increased vulnerability, which potentially can lead to increased costs of maintaining a sufficient water security, for instance.

Notably, such knowledge can also contribute to preventing some of the expected adverse effects, by prioritized remediation of contaminated land at risk of flooding, for instance.

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