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Hydraulic modelling of the vulnerability for compounding high sea levels and high river discharge on the Swedish coastline

- *A case study on the vulnerability of three coastal river catchments by use of hydraulic modelling software LISFLOOD-FP*

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Abstract

Coastal floodplains are at risk for combined high discharge and sea level events. Consequences when they occur can be several magnitudes greater than the impact from any isolated event. In this thesis the compounding of different river and coastal flood combinations at three case study sites were studied through the use of 1D/2D-hydraulic modelling software LISFLOOD-FP. The areas were; Henån, Ängelholm and Sundsvall. They have different physical conditions and were chosen to give an indication of the vulnerability to combined events at river mouths in Sweden. Results from the sites showed very few compounding effects. The exception occurred in a future scenario in Ängelholm where a combined 100-year sea level and 100-year discharge event resulted in a 14% increase of the inundation, compared to the corresponding isolated sea level event. The main conclusion drawn was that one factor is more important to the severity of a flooding at the coastal sites that were studied. Only when both the sea-level rise and the high discharge had significant consequences as isolated events was there a compounding effect when they occurred simultaneously. This is an important conclusion because it may facilitate future mapping of the vulnerability of the Swedish coastline to combined events.

Sammanfattning

Områden där floder mynnar ut i havet kan drabbas av kombinerade händelser av höga havsvattenstånd och höga flöden. När det sker kan konsekvenserna vara betydligt mer omfattande än vid isolerade händelser. I det här examensarbetet har konsekvenser av samtidiga händelser undersökts vid tre fallstudieområden genom det 1D/2D-hydrauliska modellverktyget LISFLOOD-FP. Områdena som valdes att studera var; Henån, Ängelholm och Sundsvall. De har olika fysiska förutsättningar som påverkar deras risk för översvämningar och valdes för att ge en representativ bild av känsligheten för samtidiga händelser i Sverige. Resultaten visade få samtidiga effekter vid de olika fallstudieområdena. Undantaget sågs i ett framtida scenario i Ängelholm med 100-års havsvattenstånd och 100-års flöden där simuleringar visade en ökning av översvämningen med 14% i jämförelse med en framtida havsvattenståndshändelse med återkomsttid på 100 år. Den främsta slutsatsen som kunde dras var att en faktor, havsvattenståndet eller flödet, dominerade utfallet av en översvämningshändelse. Enbart när både havsvattenståndet och flödena gav konsekvenser som enskilda händelser uppstod en samtidig effekt vid en kombinerad händelse. Det här är en viktig slutsats eftersom den kan förenkla det framtida arbetet med att kartlägga känsligheten för samtidiga händelser längsmed Sveriges kust.

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1. Introduction

1. 1 Background on floods and flood forecasting

Floods are one of the most severe natural disasters globally causing loss of human lives, disease and trauma[1], environmental problems such as erosion, landslide and the dissemination of pollution[2] as well as damage to buildings and infrastructure leading to great economical losses every year. Only in the European Economic Area economic losses attributed to floods amounted to more than 170 billion euros in the period 1980-2017, making up one third of the economic losses caused by natural disasters in Europe[3] .

With climate change, the hazards of floods and extreme weather events are expected to increase in most European countries[4]. The last five years (2014-2019) have been the warmest measured in the last 200 years[5]. There has also possibly been an increase of tropical cyclones in recent decades that may imply marine storms will be more frequent and have higher intensity in the future, leading to more extreme temporal variations in sea-levels[6]. Furthermore, a recent study using CoastalDEM[7] elevation data found that up to 630 million people will live below annual flood levels by 2100 because of sea-level rise[8].

Knowledge of how to prevent and forecast flood events can decrease the consequences from floods greatly[9]. Hydraulic models have improved thanks to the incorporation of high resolution and accuracy digital elevation models as well as satellite validation imagery. It is now possible to forecast the

1 *Floods in the WHO European region: Health effects and their* prevention | WHO, 2013
2 Simonsson L. et al., 2017
3 *River floods* | EEA 2020
4 IPCC SROCC, *Chapter 6: Extremes, Abrupt Changes and Managing Risks*, 2019
5 *WMO bekräftar: 2019 är det näst varmaste året som noterats* | SMHI, 2020
6 IPCC SROCC, *Chapter 6: Extremes, Abrupt Changes and Managing Risks*, 2019
7 CostalDEM is an improved Digital Elevation Model where errors in satellite images have been reduced by using neural networks. It is an advantage in global studies when areas are studied where there is no airborne LIDAR (high accuracy elevation) data available (8).
8 Kulp and Strauss, 2019
9 *Floods in the WHO European region: Health effects and their prevention* | WHO, 2013

consequences from floods with higher accuracy and warn for floods through early warning systems.

LISFLOOD-FP is a hydraulic modelling tool developed by Bristol University that integrated with Arcgis aims to create simple yet accurate simulations of floods. It is used in the European Flood Awareness System (EFAS) that warns for floods and flash floods in Europe[10] . LISFLOOD-FP will also be used to derive the impact from floods, as a base for flood warnings, in Sweden in the future.

This project will seek answers on the impact of combined events of high river discharges and high sea levels along the Swedish coastline through the hydraulic modelling of a few selected coastal sites. But it will also be an investigation on how to deal with the special case of combined coastal and fluvial flooding in hydraulic modelling for a new consequence based warning system. In the future all coastal river mouths in Sweden will be modelled and different flood events simulated to find their impact on coastal sites. A strategy for how to deal with combined events will therefore be needed.

1.1.2 Different types of floods and their consequences

There are many factors that induce floods and impact their magnitude and destructiveness towards ecosystems, human life and society. The main sources of floods are pluvial, fluvial or coastal. As may be deduced from their descriptions pluvial floods originate from precipitation, fluvial from high discharges in watercourses and coastal floods from sea-level rise or waves. The origin and condition for floods determine their magnitude and consequences and will be dived into further in this section.

[10] *Home* | EFAS, 2020

Sea level variability and fluctuations

Temporal variations in sea-levels can have many causes. The most severe coastal floods have caused great disruption because of their rapid unfolding in time. The tsunami in 2004, caused by an earthquake at the seabed of the Indian Ocean was one of the most severe natural disasters the last decade and killed approximately 225 000 people[11]. The deadliest tropical cyclone in modern time (or since 1873) according to the World Meteorological Organization occurred in Bangladesh in 1970. The cyclone created a storm surge that in combination with a high tide went in over the coast. 300 000-500 000 fatalities have been estimated, mostly attributed to the high sea levels[12].

In Sweden, coastal floods are usually caused by changes in atmospheric pressure or wind. Tidal variations are small[13] and earthquakes that could induce tsunamis are considered non-existant, even though geologic deformations suggest they have occurred in Sweden's early history[14] . One phenomenon that does occur is what is called seiche, or "standing wave". Seiches are oscillatory waves that occur when there is a partly or wholly enclosed basin of water where a wave goes back and forth. This has been observed in harbors like the one in Gothenburg[15]. Another phenomenon is the wind driven increase of the sea level that can occur in bays where water can be pushed in during longer time periods. This effect varies depending on the structure of the coast and the sea-bottom bathometry[16]

The most extreme coastal flood events in Sweden theoretically occur when different factors for high sea-levels coincide. If high sea-levels are already present and a storm hits a coastal site, there might be extreme sea-levels, but if sea-levels are low before a storm, there may be limited consequences from a sea-level rise caused by a storm.[17]

[11] *Indian Ocean tsunami of 2004* | Facts & Death Toll, 2020
[12] Cerveny et al., 2017
[13] Tides | SMHI, 2020
[14] Mörner, 2016
[15] Johansson SMHI, 2018
[16] Johansson, Gyllenram and Nerheim, 2017
[17] Simonsson L. et al., 2017

Compounding high river discharge and high sea levels

At river mouths there is a risk for a compound effect when high sea levels and high river discharge occur simultaneously. A compound effect is when two events coincide and the impact is greater than the impact from any of the isolated events. Since the compound effect is composite of two variables it is more unpredictable and complex than a single event, and therefore harder to study and forecast.

Historical records of simultaneous events in Sweden are very limited, which is why modelling these scenarios can provide not only potential consequences of such events but also be compared with validation data (in the form of photographs from past events) to see whether compound events are likely to have occurred at a given location and are likely to occur in the future.

In a study made 2018 by Ward et al. the magnitude and correlation of combined events of high river discharge and high sea levels were studied on a global scale. They found that high sea levels were significantly conditional to annual maximum discharges at 56% of the stations that were studied when using a time lag of 5 days. The compound effect was evaluated through the use of statistical (copula) models and joint exceedance probabilities to recommend when flood risk assessment should be carried out in different regions.

For Sweden, no conclusions could be drawn from the study because of limited amount of historical data. There is however a map where the joint exceedance probability at all the stations studied are visualized, where a point in Sweden show a factor of 5. Without explaining the statistics of their methodology, this gives the indication that the compound effect is crucial to study further.[18]

[18] Ward et al., 2018

1.1.3 Climate change and sea-level rise

Climate change is central to the understanding of future impact from floods. Temperatures on earth have increased above pre-industrial levels with approximately 1.15 degrees Celsius (in 2019)[19] and human activity will continue rising the temperature depending on emission levels and uncertainties of synergic effects in the future[20]. 90% of the excess thermal energy from global warming has been taken up by the oceans leading to melting of the polar ice sheets, changes in terrestrial water storages and thermal expansion of ocean water. These changes have led to a sea level rise that will continue for centuries.[21]

How far the sea level rise proceeds the coming century is strongly dependent on the emission path that is taken and land use in the future.[22]. Globally, the mean sea level has been projected to rise between 0.43 to 0.84 meters. Regionally, ocean dynamics, gravitational differences, polar ice melt as well as fresh water content will affect the sea-levels[23].

In Sweden the sea-levels rise will appear different in different regions because of continental rise. The rise of the continent is a leftover from the latest ice-age, from when Scandinavia was partly covered in ice, 10 000-20 000 years ago[24]. The Gulf of Bothnia's coast has the most rapid continental rise in Sweden with an approximately 10 mm elevation of the land per year, currently rising faster than the ocean. The rise of the continent is however constant while the rise of the ocean is increasing[25]. Meaning the ocean will at some point catch up with the continental rise even further north in Sweden.

19 *Climate Change: Global Temperature* | NOAA Climate.gov, 2020
20 *Summary for Policymakers — Special Report on the Ocean and Cryosphere in a Changing Climate A2* | IPCC 2019
21 *Summary for Policymakers — Special Report on the Ocean and Cryosphere in a Changing Climate Figure SPM1* | IPCC 2019
22 *Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities — Special Report on the Ocean and Cryosphere in a Changing Climate* | IPCC 2019
23 *Chapter 4: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities — Special Report on the Ocean and Cryosphere in a Changing* Climate | IPCC 2019
24 *Landhöjning* | Lantmäteriet, 2020
25 *Framtida medelvattenstånd längs Sveriges kust* | SMHI 2017 p.2 and 4

For this reason, sea levels will appear to rise faster in southern Sweden the coming century.

RCP[26]-scenarios are used in climate models to predict future consequences from climate change. RCP refers to the radiative forcing of the atmosphere in 2100 where radiative forcing is the extent of the absorption of energy from radiation, measured in W/m^2, and depends on the concentration of greenhouse gases in the atmosphere. The main RCP-scenarios are RCP 2.6, RCP 4.5 and RCP 8.5. They describe in the order written; the radiative forcing if restrictions on emissions are taken and we have negative greenhouse gases 2100 and a culmination of emissions in 2020, if emissions continue increasing with a culmination in 2040, and lastly, if we continue on the path that we are currently on, regarding emissions and land use, with future CO_2 emissions three times as large as today in 2100[27]. In this study results from climate and hydrological models based on RCP 8.5 will be applied.

1.1.4 Precipitation and climate variability

Along with the sea-level rise and changes to marine, aquatic and terrestrial ecosystems the global patterns of precipitation will and have already been observed to change because of global warming. Precipitation in Sweden is likely to increase with 20-60% by 2100, mostly during winter and to a greater extent further north in Sweden[28]. Another effect of climate change is increased climate variability, seen in the increased frequency of ocean oscillatory events, such as El Niño, and in the increased intensity and duration of extreme events[29]. One such event is the short-duration heavy precipitation that leads to high river discharge.

Another such event is the wind-driven, temporal variation of the sea level, called storm surge. Extreme wave heights have been observed to have

26 Representative Concentration Pathway
27 *Vad är RCP?* | SMHI, 2018
28 *Klimatindikator - nederbörd* | SMHI, 2019
29 Figure 6.5, 6.2 IPCC SROCC, *Chapter 6: Extremes, Abrupt Changes and Managing Risks*, 2019

increased in the Atlantic Oceans.[30] There is however no current scientific conclusion that climate change has increased or will increase sea-level variability along Swedish coasts. Since it so far has been hard to diverge the natural variability with the increase that could be due to climate change.[31]

For both the present and future scenarios in this study sea-level return times will be computed using historical data. A possible increase in the sea level variability in the future, or regional sea-level rise will not be included. To include the future sea level conditions, only the global mean sea level rise will be considered, along with regional continental rise.

Summary

Coastal floods have had great disruptive impact in the past and have the potential to become an even greater threat to human society in the future. The same pattern may be seen for fluvial floods with increased precipitation and seasonal variability as a consequence of global warming. Historical events show a great magnitude difference between global events and events that have occurred in Sweden. However, some extreme scenarios that could affect Sweden may not have occurred or been recorded since they are composed of many extreme events occurring simultaneously. One such rare and possibly severe scenario is the combined high discharge and high sea-level event by coastal river mouths. To invest in the right preparatory measures and warn in the case of danger to societal functions when these events coincide there is a need for further research. Hydraulic modelling is a tool to do so and this thesis will hopefully provide a step towards further understanding of coastal events by the Swedish coastline.

30 *Summary for Policymakers — Special Report on the Ocean and Cryosphere in a Changing Climate A3.5* | IPCC 2019

31 Nerheim, Schöld, Persson and Sjöström, 2017

1.2 Project idea and purpose

This project was conducted at The Swedish Meteorological and Hydrological Institute, responsible for warnings and forecasts of natural events in Sweden and abroad. Hydrological warnings are today based on hydrological model simulations of over 60 000 sub-catchments all over Sweden[32]. For each sub-catchment, yearly extreme values have been analyzed and the time found in which a discharge event is likely to return, referred to hereafter as a return time. Warnings are then issued at three levels based on 2, 10- and 50- year return times of river discharges[33].

The rarity of an event does not imply there are consequences when it occurs. From 2021, SMHI will launch a new warning system which will be based on the predicted impact of a forecasted event. For the new impact based system hydraulic models will be set up nationally. Hydraulic models differ from hydrological models in that they take a flow or surface level at specified points as indata, to simulate inundation and overland propagation in a model domain. Hydrological models take the precipitation and temperature in a catchment and utilize functions and parameters of infiltration rates and topography to model the flow at a specific point or in an area.

Since hydraulic models are computationally heavy, pre-made simulations will determine consequences of flow events at different locations as well as when warnings should be disseminated. Combined events of high river discharge and high sea levels at coastal sites need to be studied separately because of the complexity of combining two events and the number of possible scenarios that may occur.

The Swedish Civil Contingencies Agency[34] has as part of a broader study into combined extremes ordered an investigation by SMHI of how the event of combined high river discharge and high sea-levels will affect the Swedish coastline by the end of the century. When the idea for this project was formed the necessity to further quantify the effects of combined events was one of

32 *Om tjänsten Modelldata per område* | SMHI, 2020
33*Varningsdefinitioner* | SMHI, 2020
34 Myndigheten för Samhällsskydd och Beredskap

the initial purposes along with studying impacts in preparation for the new warning system.

1.3 Aim and problem formulation

The aim of this study was to first develop and improve the set-up and analysis of combined hydrological and hydraulic modelling along Sweden's coastline, and to then understand the vulnerabilities for compound events for a selected number of coastal case study sites. In a larger perspective the aim was to provide further understanding on the impact from coastal events and form the basis of the new warning system for compound events along the Swedish coastline.

The main problems that this thesis seeks to answer are:

- How can coupled hydrological and hydraulic models be used to find vulnerabilities for compounding high river discharge and high sea levels? How can the developed approach be applied at the national scale?
- What is the vulnerability for compound events at a selected set of important catchments? And what do the results imply about the vulnerability of the Swedish coastline?

In order to answer the questions above more specific problems were recognized. These are listed below.

- How should the statistical analysis necessary to find (discharge) and sea level extremes as well as combine events be conducted?
- How should the duration of sea-level and discharge events be specified? How should the development of the events be described in the models?
- How should different possible combinations of high sea-levels and high discharge be considered in a feasible way?
- Are the risks for compounded effects as high in small rivers as in large?
- Do combined events occur in Sweden and are they likely to occur in the future?

1.4 Methodology and materials

In the search for answers to the problems described and to fulfil the aim of this project, LISFLOOD-FP models were set up for the three case study sites Henån, Ängelholm and Sundsvall. Scenarios were formed based on two categories. Present scenarios, that is, scenarios that were estimated using the current situation regarding climate and sea-levels; and future scenarios regarding a certain path in relation to emissions and land use (RCP8.5). Return times for flow and sea-level events, for both the present and future scenarios were computed using historical data.

The data series for sea levels were from SMHI's own measurement stations in Viken, Spikarna and Uddevalla. A python script was received from SMHI's statician, Johan Södling and modified to find return times for sea levels. The discharge time series and return times were taken from HYFO, an information system used internally at SMHI where data from HYPE model simulations are found.

The geographic information software Arcgis was used to create in-data raster files describing the floodplain (2D-model) and channel (1D-model). The base maps and digital elevation model were from the Swedish Land Survey. Parameters used to find average depth and widths of watercourses were based on SMHI measurements in Sweden and estimated by the hydrological forecast unit at SMHI prior to this study.

Python scripts were created for eliminating positive slopes in the 1D-model as well as for reformatting files and restructuring oceanographic data. Python was also used to plot historical data series of sea levels and discharges to find occurrences of combined events. The scripts that were produced can be found in the appendices.

Finally, the hydraulic models for the different sites were calibrated and validated against photographs of previous inundation events. The scenarios were then executed in LISFLOOD-FP to find the extent of inundation and assess consequences of different flooding events. Problems that arose during the simulations and their solutions, boundary conditions and strategies for model runs were developed and described. Thereafter, the simulated results were visualized in Arcgis to find the source of impact in different scenarios.

An analysis was made comparing previous studies of flooding at the case study sites with the results found through the simulations in this study.

The literature study involved previous studies of flooding events at the case study sites, describing the hydraulic functions that constitute the base of hydraulic modelling and more in depth, the hydraulic model LISFLOOD-FP utilized in this study. Furthermore, a background on flooding events and the impact of climate change and rising sea levels was included in the introduction. A brief background on the statistical analysis to find the return times for high discharge and high sea levels was made to explain the choices of boundary conditions.

2. Case study sites

The case study sites are located in different parts of Sweden and represent coastal areas with different topography and location in relation to surrounding water. They were also chosen because of their importance being urban, inhabited regions and because they represent river outlets of watercourses with different size and discharge conditions. Records of their vulnerability to floods have been found in the form of photographs and articles of previous inundation events. In addition, previous studies have sometimes been made of their vulnerability to floods. Validation data in the form of satellite or airplane imagery of past flooding events have not been found. In this chapter the three sites, past inundation events, physical conditions and previous studies will be presented.

2.1 Henån

Henån is the name of a stream and village with 1800 inhabitants in Orust, an island in the archipelago on the west coast of Sweden in the border of Kattegatt and Skagerack in the Atlantic Ocean. Henån is known for its vulnerability to floods and has been subjected to yearly inundation events of the harbor area[35]. In February 2020 two inundation events succeeded each other with a week in between. The first occurred the 10th of February when sea-levels rose with 1.4 meters (from a measurement station in Uddevalla[36]). Consequentially, roads had to be closed, a restaurant by the harbor took in water and cars got stuck at inundated parking-lots.[37] The second event, the 17th of February, had similar consequences and SMHI also issued a warning for high discharges[38]. These events will be discussed further as they are used to validate the hydraulic model for Henån.

The slope of the stream bed in Henån is steeper than the slope of the other watercourses that were studied. It was also smaller with an approximate mean depth of 0.2 meters and width of 1.9 meters[39]. Since Henån is located on an

35 Herold | DN, 2019
36 SMHI's database
37 *Högt vattenstånd - Översvämning i Henån* | NYHETERsto.se, 2020
38 *Efter storm kommer översvämning* | NYHETERsto.se, 2020
39 See chapter 6: Pre-processing; Hydraulic geometry theory

island the river catchment is also smaller than the ones at the other sites. Sea-level observation data for the modelling of flood scenarios in Henån were taken from SMHI's station outside Uddevalla.

In a project made by the County Administrative Board[40] in Västra Götaland to find the vulnerability to sea-level rise along the coast, Henån was used as an example of an area with especial vulnerability in a pre-study[41]. A map was produced to illustrate vulnerability to rising sea-levels. However, the results were only based on a digital elevation model of the area, not a hydraulic model simulation. It was therefore not very useful as a comparison with simulations produced in this study. Besides this investigation few past studies have been found. The county has been investigating methods for decreasing the hazards of floods but no hydraulic simulations of coastal flooding events in Henån have been made.

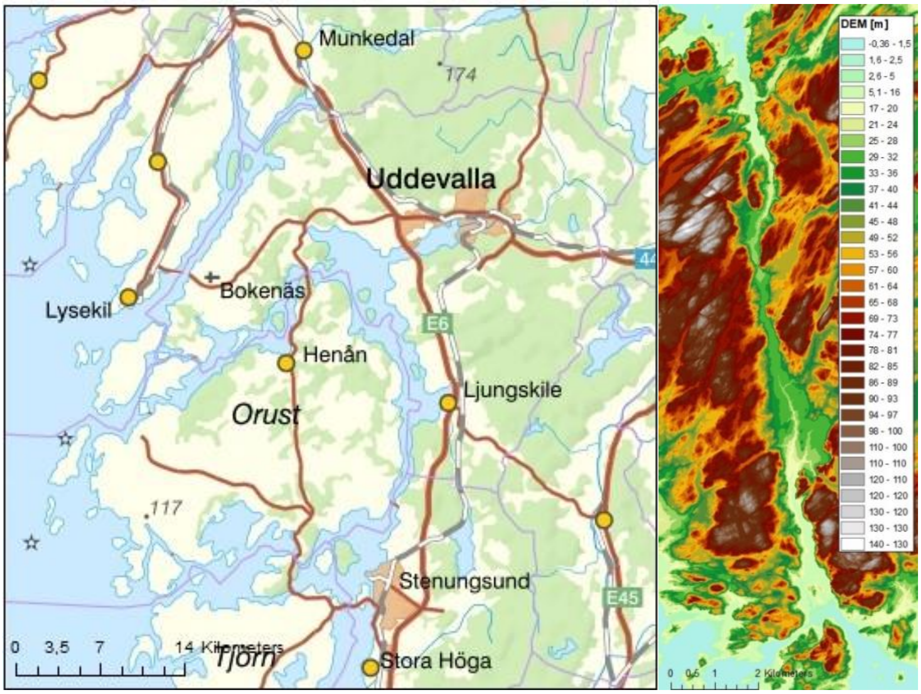

Figure 1. To the left: Map showing location of Uddevalla and Henån. To the right: The digital elevation model of Henån, showing the relatively steep slope of the watercourse.

40 Länsstyrelsen
41 Schaap, 2013

2.2 Ängelholm

Ängelholm is located on the western coast in the south of Sweden, in a bay in Kattegatt. Rönne å is the name of the main river meandering through Ängelholm and there is a tributary stream that connects to Rönne å right before the harbor. Rönne å is larger than the watercourses at the other sites with an average depth of 1.8 meters and width of 46 meters. The slope of the river is relatively flat in the model domain but the stream bed of the tributary river is steeper.

In 2012 SMHI conducted a study ordered by the municipality of Ängelholm to find vulnerabilities to future extreme flood scenarios. They found vulnerability to the scenarios that were tested, and concluded that Ängelholm is vulnerable to both high sea levels and high discharge events. They also found that the impact from elevated sea levels could be disregarded in a combined event with very extreme discharges[42]. There was however no investigation on whether the consequences originated from the coastal or fluvial extremes since all four scenarios that were studied were combined events. In the analysis chapter this will be delved into further.

[42] Björn and Berggreen-Clausen, 2016

Figure 2. Map of Ängelholm.

2.3 Sundsvall

Sundsvall is located on the east coast of Sweden along the Gulf of Bothnia, further north than the other case study sites. The river that flows through the city is called Selångersån. There are a few smaller tributary streams connecting to the main river as well as a lake and wetland area above the inner city. The main depth and width of the watercourse were estimated to 0.81 and 15 meters.

There was a great inundation event in Sundsvall the 11th of September 2001 when sea levels rose 0.44 meters and discharges corresponding to a 100-year event were observed. Consequences were severe with many damaged roads and homes that had to be evacuated. After the 2001 event measures were taken to improve the safety for floods in Sundsvall. A tool for creating 10-day prognosis of the discharge was developed and the dam that had threatened to break during the flood was reinforced. SMHI states in an evaluation of the work to future-safe Sundsvall, after a project conducted by Sundsvalls municipality to prepare Sundsvall for climate change[43], that high flow and high sea levels both were important factors during the 2001 event, and that if higher sea-levels had occurred the consequences would have been even more severe[44].

Figure 3. Map of Sundsvall.

However, 7 years earlier (2010), SMHI conducted a study of the causes of the 2001 event by the use of a 1D hydraulic model (HEC-RAS). They found that high sea-levels did not have an impact during high flows (as seen during the 2001 event). If flows were low however, they had a little impact. The results from this study will be further described and compared to the simulations produced in this thesis in the Analysis (chapter 10). [45]

43 *Klimatsäkring pågår, Klimatanpassa Sundsvall*, 2011
44 *Minskad översvämningsrisk i Sundsvall, fördjupning* | SMHI, 2017
45 Berglöv, 2010

3. Theoretical background

In hydraulic modelling of channel and floodplain flow the shallow water equations are used to find flow velocities and water depths. These are also called the Saint Venant's equations and are partial differential equations that describe unsteady non-uniform flow for open surfaces. Unsteady flow is flow where the water velocity changes with time and non-uniform flow implies the flow velocity varies with distance. In this chapter the equations for 1D-respectively 2D –flow for open surfaces will be described briefly. First, a background to some of the definitions that are important in open surface water hydraulics will be made.

3.1 Defining flows of open surface waters

There are different ways in which flow has been categorized in order to better describe and differentiate its physical behavior i.e. hydraulics. One common methodology of diverging flows is by calculating Froude's number. Froude's number is a measurement of the relationship between inertial and gravitational forces and defines flows as subcritical, critical and supercritical. The flows are categorized by the equation that may be seen below.

$$F_r = \frac{V}{\sqrt{gy}}$$

Where F_r is Froude's number, V is velocity, g is the gravitational constant and y is the flow depth. Subcritical flow appears when the gravitational forces are greater than the velocity, and the water is smooth-flowing. Critical flow is when Fraude's number is equal to 1. Supercritical flow, when Froude's number is greater than 1, appears when water flows are rapid.

When a bump or sudden decrease of slope occurs in a waterway there is sometimes what is called a hydraulic jump. The hydraulic jump refers to the jump between different types of flows that may occur in an open surface water flow. It occurs when a supercritical flow is suddenly turned into a subcritical flow and is characterized by a bulge of the water surface, loss of energy and sudden turbulence.[46]

3.2 The shallow water equations

Hydraulic behavior in LISFLOOD-FP and other hydraulic applications is defined by the shallow water equations. The shallow water equations include the momentum balance equation and the continuity balance equation, governing the conservation of mass and momentum in free flowing water. The mass balance equation describes the rate of exchange and accumulation of stored water in a defined section of the waterbody. The momentum balance equation regards the accumulation and change of momentum within the water section, and takes into account the forces gravity, pressure and friction acting on the mass of fluid water.

There are different forms of the shallow water equations that include or neglect different physical phenomenon. There are also limitations to the full shallow water equations that make it necessary to state the conditions under which the equations are valid.

3.2.1 Assumptions for the 1D shallow water equations

The following assumptions are made in order to apply the 1D shallow water equations.

- The hydrostatic pressure is constant vertically in the watercourse. This is reasonable in watercourses where the celerity (bending) is low.
- The slope of the channel bed is very small.
- The velocity does not vary within the cross-section of the channel.
- The channel is prismatic; meaning the cross-section and slope do not vary with distance.
- Steady state resistance laws can be used to simulate head losses; thus head losses at a given velocity in unsteady flow are the same as the

[46] Chanson, 2004

ones used for steady flow, for example by the use of Manning's equations.

- Water is incompressible and has a constant mass density.[47]

3.2.2 1D unsteady flow

The equations for 1D unsteady flow regard the conservation of mass and momentum in one direction. The equations that describe the rate of change of these states will be presented in the sections below.

The 1D momentum equation

The momentum equation is derived from Newton's second law of motion which states that the acceleration of an object is defined by the net force acting on the object and the mass of the object. Thus the momentum equation describes the change of momentum states or the accumulation of momentum where the three forces gravity, pressure and friction acts on the mass of water. The momentum equation is written below.

$$\frac{\partial V_x}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial h}{\partial x} = g(s_x - s_f)$$

Where V is the velocity, t is time, x is the distance in the x direction, g is the gravitational constant, h is the depth of the watercourse, s_x is the channel slope and s_f is the friction slope. The terms may be rearranged to illustrate the implications of each term;

$$\underbrace{\underbrace{\underbrace{S_f = S_0}_{Steady,uniform} - \frac{\partial}{\partial x}\left(\frac{V^2}{2g} + h\right)}_{Steady,nonuniform} - \frac{1}{g}\frac{\partial V}{\partial t}}_{Unsteady,non-uniform}$$

If there is no friction, thus the friction slope is the same as the channel bed slope, there is no variation in time or space. The flow is steady and uniform.

47 Chaudhry, 2008

If the convective acceleration term; $\frac{\partial}{\partial x}\left(\frac{V^2}{2g}+h\right)$ is added, the flow may vary in space (here in depth and vertical head, describing non-uniform flow) and if the last term is included variation in time is possible, enabling an unsteady, non-uniform flow to be described.

The channel slope is found by taking the sinus of the angle of the x-axis (the channel bed) to the horizontal plane.

$$s_x = sin\ (\theta_x)$$

The friction slope is given by the shear resistance between the bed of the watercourse and the water divided by the weight of the overlaying water and the distance it travels over the surface;

$$s_f = \frac{F_s}{\rho g h \Delta x}$$

Where F_s is the shear resistance, g is the gravitational constant, ρ is the density of water, h is the water depth and delta x is the distance traveled.

The 1D continuity equation

The continuity equation describes the conservation of mass, or rate of exchange of stored water during a given time step.

$$\frac{\partial A}{\partial x} + \frac{\partial Q_x}{\partial x} = 0$$

Where A is the cross sectional area of the flow, Q is the flowrate in the x direction and x is the distance in the x direction.

3.2.3 2D unsteady flow

In the shallow water equations for two-dimensional flow an additional spatial dimension is introduced, perpendicular to the first (x), that will be referred to as y. By adding another dimension, the propagation of the water may be described in two directions at the same given time interval.

The 2D continuity equation

In the continuity equation, describing the rate of change of storage, or the volume entering and leaving the entity of water, is similar to the continuity equation for 1D unsteady flow but has an additional term describing the flow in the y direction.

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} Uh + \frac{\partial}{\partial y} Vh = 0$$

Where U is the mean velocity in the x direction and V is the mean velocity in the y direction.

The 2D momentum equation

The 2D momentum equations describes, just as in the 1D momentum equation, the change in momentum during a given time step. That is a product of the flux of mass entering and leaving the element.

The momentum equation in the x direction:

$$\frac{\partial \mathrm{U}}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial V}{\partial y} + g\frac{\partial h}{\partial x} = g(s_x - s_{fx})$$

Where U is the flow in the x direction, t is the time, x distance in the x direction, V the flow in the y direction, g the gravitational constant, h the height, y the distance in the y direction, s_x the water slope in the x direction and s_{fx} is the friction slope in the x direction.

The momentum equation in the y direction:

$$\frac{\partial \mathrm{V}}{\partial t} + V\frac{\partial V}{\partial y} + U\frac{\partial U}{\partial x} + g\frac{\partial h}{\partial x} = g(s_y - s_{fy})$$

Where s_y the water slope in the y direction and s_{fy} is the friction slope in the y direction.

The terms describe in the order written; the local acceleration ($\frac{\partial V}{\partial t}$ in the y direction), the convective acceleration in the two directions ($V\frac{\partial V}{\partial y}$ and $U\frac{\partial U}{\partial x}$), gravitational forces as well as the channel bottom slope and slope friction.

4. LISFLOOD-FP

The hydraulic modelling software LISFLOOD-FP that was used in this study to simulate inundation and investigate compounding effects will be described in more detail in this chapter, along with the numerical solvers utilized in LISFLOOD-FP to simulate water propagation.

4.1 Background

LISFLOOD-FP was developed by Bristol University and is a raster based 1D/2D-hydraulic modelling software that simulates the inundation of channels and floodplains. It uses a water storage cell structure that is composed of raster grids. At each given time instance hydraulic functions describing the conservation of mass and momentum simulate water depth and velocities in every inundated cell.

The 1D-model consists of a channel and its' pathway in the model domain wherein the flux and water depth is simulated in one direction. When the channel depth exceeds a threshold value the simulation of the floodplain is initiated. The coupling of the model is constituted of the exchange of mass (not momentum) between the channel and the floodplain. In the 2-dimensional floodplain simulation, 1-dimensional functions are applied in two directions (the 2D shallow water equations) for each time instance in each cell. The functions consider the hydraulic propagation of water based on topography and friction surfaces.

LISFLOOD-FP can manage complex topography by the use of high resolution raster grids. It can also be assigned cell-specific friction coefficients. A raster with different friction values for different parts of the model domain are useful in cases where different types of surfaces are present within the same area (urban, rural, agriculture, forests etc.) and to represent buildings in the model. In this study the floodplain friction coefficient and the sub-grid channel friction coefficients are the same for the whole model domain. This was a simplification made to facilitate the modelling but also because of lack of calibration data.

The advantage of a 1D/2D models are that they save computational time compared to a conventional 2D-model but keeps the information of the floodplain that characterizes a 2D-model. Thereby it is able to simulate floodplain inundation more accurately than a 1D-model for more complex floodplains. If the channel depth does not exceed a threshold value and there is no inundation of the floodplain only the "channel", 1D-model will run. If the 2D-model is initiated the computational time is directly correlated to the number of inundated cells.[48]

Boundary conditions and coupling with a hydrological model

Boundary conditions are specified in the hydraulic model to define the extent of discharge and water levels at specified points in the model domain. The discharge and/or water levels defined at the boundary conditions are used to simulate the flow and water depth in the channel and floodplain. By extension the boundary conditions work as a way to couple the hydrological model, that simulates the flow in points (HBV) or sub-catchments (HYPE), with the hydraulic model that uses boundary conditions at specified locations to simulate inundation in the model domain.

4.2 Application of the shallow water equations in LISFLOOD-FP

LISFLOOD-FP utilizes different versions of the full shallow water equations in simulating the flow and depth of waterways. In the format that the momentum 1-dimentional equation is written below the different forces acting on the water body are clearly separated. They are then included or neglected in different numerical solution strategies. The terms describe in the order written the; local acceleration, convective acceleration, water slope and friction slope.

The local acceleration is the rate of change at a given time-step while the convective acceleration is the acceleration caused by the change of location of fluid particles. The water slope is defined by the change of elevation within a vertical distance (x) in the river bed. The friction slope is determined

48 Bates P. Et al. 2013

by Manning's friction coefficient n, which is a sum-up parameter including the loss of momentum from the bathometry of the channel, the surface roughness and obstacles that affect the flow of water[49].

$$\frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q_x^2}{A}\right) + gA\frac{\partial(h+z)}{\partial x} + \frac{gn^2 Q_x^2}{R^{4/3}A} = 0$$

4.2.1 Manning's n

Manning's roughness coefficient n is used to describe roughness of surfaces that are in contact with flowing water. It was defined by the formula below which states that the velocity of a waterbody depends on the roughness and shape of the wet surfaces, the bathometry of the channel or inundated floodplain as well as the energy grade line. The energy grade line or energy head is a common term in hydraulics that describes the evolution of energy in a water body including the state of pressure, velocity and elevation. Manning's n depends on many factors and has a large impact on hydraulic model simulations. In this thesis areas with very different floodplain surfaces were studied; from urban to rural areas with forest and agriculture. Anthropogenic channels and natural streams as well as watercourses with different depth/width relationships were represented.

Manning's equation may be seen below, where V is the water flow velocity, R is the hydraulic radius and S is the slope of the energy grade line.

$$V = \frac{1.486}{n} R^{2/3} S_e^{1/2}$$

The hydraulic radius (R) is the cross sectional area (A) of the flow divided by the wetted perimeter (P).[50]

$$R = \frac{A}{P}$$

49 Dyakonova and Khoperskov, 2018

50 *Guide for selecting manning's roughness coefficient*, 1989

Manning's formula can also be used to define depth and width of a watercourse by finding the hydraulic radius. It is however easier to use hydraulic geometry theory (a methodology that will be described later on) since n in most cases is unknown. N may instead be estimated and calibrated at a later stage with assumptions on the geometry of the channel already made. Thus, this was the methodology for the models in this study.

4.2.2 Channel solvers

In order to simulate the channel flow different "wave approximations" can be applied. A wave, in the context of hydraulics, is defined as the change of water depth over time. To simplify computations of floods some terms in the shallow water equations are sometimes assumed to dominate the behavior of the water flow. These assumptions are truer in some applications than in others. In LISFLOOD, there are different solvers with different degree of complexity in the inclusion of physical terms. These are named the diffusive, kinematic and sub-grid channel solver. The kinematic solver (that utilizes kinematic wave approximations) neglects all terms except the bed gradient and friction slope term in the shallow water equations. It does however assume the flow is uniform in the section that is modeled, the full bottom slope term is not included. The diffusive wave approximation however utilizes the full bed slope term and thus can also handle back-water effects at the water surface. Back-water effects appear when the flow of water is obstructed and leads to a rise of the surface water before a hindrance. In this study the sub-grid channel solver was used for the 1D channel simulations. The sub-grid channel solver utilizes all terms in the shallow water equations except for the convective acceleration. Meaning it deals with all physical elements represented in the equations except for the rate of change of velocity due to particle movements within the fluid.

4.2.3 Floodplain solvers

There are four types of solvers in LISFLOOD-FP for simulating the water propagation over the floodplain, namely; the Routing, Flow-limited, Adaptive, Acceleration and Roe-solver. They neglect different parameters in the 2D-shallow water equations and deal with time steps differently. In this study the floodplain flow will be calculated using the Acceleration solver. The Acceleration solver includes the local acceleration, the water slope as well as the friction slope terms in the full shallow water equations but neglects the convective acceleration. It is also similar to the adaptive solver since it has an adaptive timestep. This will be explained further in the section about time steps.

In a study by J. Neal et. Al. in 2011 different LISFLOOD-numerical solution strategies for simulating inundation were tested for the capability of simulating flow over a bump or sudden drop of elevation. In the test the Roe, Acceleration and Adaptive solvers for floodplain flow were included. Since their base code was the same a comparison could be made of their use of time-steps and formulation of the shallow water equations. Thereafter the extent of complexity needed to simulate flow over different floodplains could be evaluated.

The acceleration solver, utilized for modelling floodplain flow in this thesis, had the most problems when computing the flow in the depression or bump. The friction value that was set to 0.01 for all the models, made the Acceleration solver unstable. The adaptive solver, that lacks the inertial term and thus does not model backwater effects, only simulated the filling of the depression with water while the Roe solver, that consider all terms in the shallow water equations, managed to compute the surface elevation induced by the bump with small volume errors. The Acceleration solver first managed to simulate the flow over the depression and bump when using a higher friction coefficient of 0.03, but exaggerated the overtopping flow creating larger volume errors than the Roe solver.

Thus, the hydraulic jump induced by the depression or bump could not be handled by the Acceleration solver without a higher friction value, but even with the higher friction value there were errors in the simulation. Friction plays different roles in the different solvers because of their different physical representations of reality. In the Acceleration solver, friction has a stabilizing effect.[51]

Another study by de Almeida and Bates, in 2013 also showed that the full shallow water equations are needed in order to correctly simulate flow over steep channels where there are sudden changes of depth, such as would occur in mountain rivers.

4.2.4 Time-steps and the Courant-Friedrich-Lewy condition

Time steps in the acceleration and sub-grid channel solver are adaptive and vary in relation to the Courant-Friedrich-Lewy condition. The Courant-Friedrich-Lewy condition states that the distance traveled within a time-step must be within the size of the computational grid in relation to the Courant number. The computational grid is in this case the resolution of the raster files. So practically the time-step will vary in relation to the flow velocity and depth. Higher flow velocities will generate smaller time-steps in order to fulfill the condition. This methodology, using the CFL-condition to adapt time steps, functions as a way to reduce instability of the numerical methods of the solver and thus plays an important role in the hydraulic models.

The function for describing the time steps in the Acceleration solver can be seen below:

$$\Delta t = C_n \frac{\Delta x}{\sqrt{gh}}$$

Where C_n is the Courant number, Δt is the time step and h is the flow depth. Courant's number is by default 0.7 in the Acceleration solver.[52]

[51] Neal et al., 2011
[52] Neal et al., 2011 pp. 24

4.2.5 Numerical solution strategies

The St. Venant equations are non-linear partial differential equations that do not have one, “closed form” solution. For engineering purposes numerical approximations are usually applied to find solutions to such problems. In LISFLOOD-FP, the grid structure is utilized to create uniform flow where the equations can be discretized in space and the time is discretized through a finite difference scheme.[53] These are solved explicitly or implicitly in hydraulic models. The explicit numerical scheme solves the equations for a later time with conditions of the state of the present time, while the alternative approach; an implicit scheme, has an iterative approach to find approximations based on both the current and the later state.[54] The acceleration floodplain solver in LISFLOOD-FP utilizes a finite, forward difference explicit numerical scheme. In simple terms, the numerical approximations reduce the number of solutions by fixing a variable while deriving the other. This may be done by fixing the time variable to the time-step and the space variable to the grid-size, enabling the functions to be solved analytically.

53 Bates, Horritt and Fewtrell, 2010

54 Chaudhry, 2008 p.372-384

5. Data collection and statistical analysis

In order to provide LISFLOOD-FP with boundary conditions and create in-data raster files, time-series of discharge and sea-levels at the coastal sites were collected and analyzed. In this chapter the data collection of simulated and observational discharges and sea level time series will be presented. Thereafter there will be an explanation of the statistical analysis applied to find return times for sea levels. Finally, the re-composition of HYPE-simulated discharge time series necessary to form realistic representations of the river flow in the models will be described.

5.1 Defining the hydrological and oceanographic year

When analyzing the yearly maximums of hydraulic or oceanographic events the year is reconstructed to consider seasonal variations. It is important in order to not to extract maximums for two succeeding years from the same event. The hydrological year in Sweden is defined between the 1st of October and the 30th of September. In the shift of the hydrological year there is less likelihood of discharge due to snowmelt because of no or little snow accumulation[55]. It is thus the definition of the year that yields the least probability for a correlation between two succeeding years.

The oceanographic year is defined similarly as the hydrological year but in relation to conditions that affect the sea-level. SMHI usually defines the oceanographic year for Sweden to begin the 1st of July and end the 29th of June.

5.2 Return times for discharge and sea level events

The return times for discharges were retrieved directly from HYFO or HYPE and were based on simulation results of HYPE sub-catchments. More specific information on how boundary conditions for discharges were defined may be found in section 5.5; Discharge boundary conditions. The following section will present the statistical analysis and collection of sea-level data. Similar

[55] Smhi.se, 2018

methodologies were used when defining return times for discharges by the use of Gumbel distributions, but since these were not estimations done in this study (only used) their forming will not be presented.

In order to find return times for sea-levels monthly maximums sea levels relative to the regional mean were extracted from SMHI's internal database WISKI. The years were modified from conventional years to oceanographic years using a python script (Appendices; *hydro_year*). Thereafter yearly maximums were found and analyzed.

Sea-level observational data is limited and often time series are too short to analyze statistically with any reliability of the results. This is why data in some cases was taken from a station close to the case study site instead of the site in question. For the Henån-model, there were no observations so sea-levels were taken from SMHI’s station in Uddevalla. Sea levels were assumed to be similar or approximately the same there as in Henån because of their geographical proximity. In Ängelholm observation data from Viken, a coastal area nearby was used since the length of the observations-series in Ängelholm was too short for extreme value analysis. The resemblance of the series seen in Figure 4 implies that observations from Viken could be substituted for sea-levels outside Ängelholm. A report where the correlation of sea-levels was studied showed similar results[56].

[56] Schöld et al., 2017

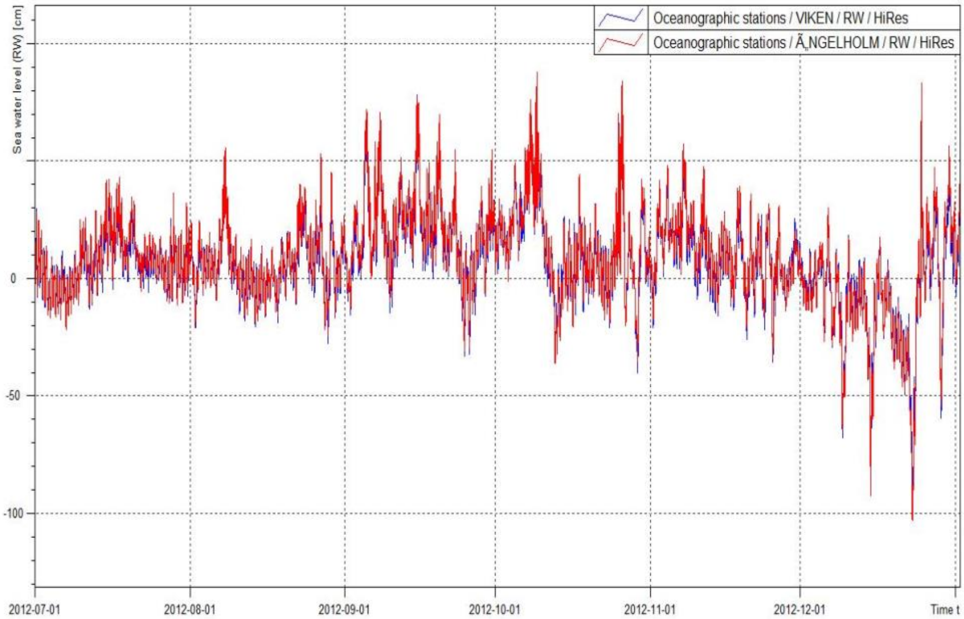

Figure 4. Relative sea-levels in Ängelholm and Viken from July to January in 2012.[57]

5.2.1 Fitting an extreme value distribution to annual maximums

After the yearly maxima time series had been created they were analyzed for return times. Histograms of maximums from each area were fitted to GEV (Generalized Extreme Value), Gumbel, log-normal[58] and inversed Weibull extreme-value distributions by the use of a python script.

The GEV-distribution is a family distribution that is comprised of the three different versions; Gumbel, Frechet and Reversed Weibull in one and adapts to the data it is fitted against. The parameter that diverges these distributions is called Xi, ξ. Xi defines the shape of the distribution curve. For Gumbel where $\xi = 0$, the tail decreases exponentially, in Frechet, $\xi > 0$, the tail shape decreases as a polynomial and in the Reversed Weibull distribution

57 Graph from SMHI's internal database.
58 The log-normal distribution is a distribution where the logarithm is normally distributed. However, it provided the worst fit of the tested distributions and was not used to find return times.

where $\xi < 0$ the distribution has a finite tail[59]. Knowing this the GEV-distribution is a safe choice because of its adaptability. The Gumbel distribution did however fit better to the observations in Ängelholm (Viken) and was therefore used in this case.

The fits of the sea level observations to the different distributions were evaluated based on a KS (Kolmogorov-Smirnov) test where a p-value and D-value are given. The null hypothesis that is tested can be rejected if the p-value is less than 0.05 on a 95% confidence level[60]. In this case the null hypothesis states that the yearly maximums follow a GEV or Gumbel extreme value distribution. The results from the KS-test show that this hypothesis cannot be rejected.

The D-test value is the normalized maximum distance between any observation value and the distribution curve. It is an indicator of how much the data diverges from the distribution. In table 1 where the p- and D-values are listed one may see that the D-value obtained for Henån is higher than the D-values found for the other areas. This may be due to the difference in the amount of data that was analysed. In Ängelholm (Viken) and Sundsvall (Spikarna), 50 years of data from July 1969 to june 2019, laid the basis for the statistical analysis. Return times for sea levels in Henån were estimated based on less than 10 years of data, between December 2010 and September 2019.

In statistical analysis there is higher reliability on results obtained from longer data series since they are more likely to catch the variance of a population (statistical term that here refers to the variation of sea levels).

Table 1. The best fit distribution and respective KS-test values for each area.

Henån: GEV		**Ängelholm: Gumbel**		**Sundsvall: GEV**	
p-value	**D-value**	**p-value**	**D-value**	**p-value**	**D-value**
0.899	0.191	0.933	0.0823	0.897	0.081

59 se.mathworks.com, 2020
60 Statistics (scipy.stats) — SciPy v1.4.1 Reference Guide, n.d.

5.4 Sea-level boundary conditions

In order to define sea level boundary conditions modifications to convert sea levels between different systems were performed. The sea level return times were analysed in relative sea levels. Relative sea levels are adjusted to the long-term changes of continental rise and sea level rise by the use of linear regressions. Mean sea levels in an area a certain year can be added to a relative sea level to form an event with a return time of interest. To form the present scenarios, regional mean sea levels from 2019 were used.

When modeling in LISFLOOD-FP the Digital Elevation Model must also be considered since the sea level boundary condition will be placed in the model domain. The DEM is constructed from a scanning of the area and the sea levels during the day of the scanning may diverge from the mean sea level. In the model, sea levels are represented as elevations in RH 2000. RH 2000 is the national standard height system in Sweden[61]. In order to correctly represent the elevations in the model the sea levels at the day of the scanning of the area were subtracted from the mean sea levels before the relative sea levels were added, see equation 1 below. In such a way, the impact from the sea levels of the day of the scanning were eliminated.

Equation 1

$$SL_{bc} = -SL_{RH2000}^{DEM} + MSL_{RH2000}^{2019} + RW^{x}$$

Where SL_{bc} is the sea level boundary condition, SL_{RH2000}^{DEM} is the sea level recorded on the day of the scanning of the area, thus taken directly from the digital elevation model, MSL_{RH2000}^{2019} is the mean sea-level in the area in year 2019 and RW is the relative water level above the mean sea level for a sea-level with return time x.

[61] RH 2000, Lantmäteriet

5.5 Discharge boundary conditions

The discharge time series were taken from HYPE (Hydrological Predictions for the Environment). HYPE is a hydrological model that takes precipitation and temperature data along with information on topography and infiltration to simulate discharge and transport of nutrients in a catchment. It was developed by SMHI and has open data for Sweden and many other countries globally. The simulated flow and nutrient data is accessible with a daily resolution (in Sweden) and has different historical range depending on sub-catchment.[62]

In this project, pre-calculated return times and means for discharge were taken from HYFO, a version of HYPE that does not have open access to the public but is used internally at SMHI and sold as a hydrological prediction information system. The values are based on the mean and annual maximums from 1981 to 2010. HYFO has more resources and is therefore more accurate than HYPE. However, the simulations originate from HYPE and therefore the source HYPE will be referred to hereafter.

HYPE utilizes catchments and sub-catchments to simulate the flow in the sub-catchment area. In the models created in this project several sub-catchments have been integrated to represent the flow in the model through a series of boundary condition points (with the exception of Henån since it only contains one sub-catchment).

The sub-catchments that were used to create flow boundary conditions in the model may be seen in Figures 5, 6, and 7. An important note is that the flow in any given downstream sub-catchment must be larger than the flow further upstream, since it will include the upstream flow as well as the additional runoff in the catchment in question and eventual tributary streams. To illustrate this the formulation of the discharge boundary conditions for Sundsvall will be explained.

Five sub-catchments were considered when formulating the three inflow points in the domain. Let us call them, HYPE flow A, B, C, D and E where E is the denotation of the catchment the furthest upstream. The same chronology applies to the model flows Q1, Q2 and Q3 where Q1 is the model

[62] Arheimer, SMHI 2013

flow point the furthest upstream. Then the model flows were determined by the formulas below:

Sundsvall flow formulation

Q1 = [HYPE flow E]
Q2 = [HYPE flow C] – [HYPE flow E]
Q3 = [HYPE flow A] – [HYPE flow C]

Control: Q1+Q2+Q3 ≈ [HYPE flow A] = Q_{17563}

As can be seen above, Q1 will be the same as the HYPE flow from the catchment the furthest upstream, but in order to not put in double flows, Flow E is subtracted from flow C, to formulate the next boundary condition, Q2. The last input flow, Q3, is then formed by subtracting HYPE flow C from the HYPE flow from the catchment the furthest downstream the river (HYPE flow A).

Lastly, to make sure the formulation was done correctly, the HYPE flow from the catchment furthest downstream is compared with the sum of the boundary conditions Q1, Q2 and Q3. They should be about the same but may diverge a little because of evaporation, infiltration or other unconsidered in- and outputs to the river that are included in the HYPE simulations.

Table 2. HYPE-flows from the sub-catchments considered in the model for Sundsvall and calculated model flows with different return times. In the first column HYPE-flows are named after their catchment sub-ID. The discharges are given in m^3/s.

Sub-ID	MQ	HQ2	HQ5	HQ10	HQ25	HQ50	HQ100
Q_{17659}[E]	3.5	29.1	37.9	46.1	56.4	64.1	71.7
Q_{17633} [D]	3.6	29.4	38.3	46.6	57.1	64.8	72.5
Q_{17614} [C]	4.5	37.7	49.2	59.8	73.3	83.3	93.2
Q_{17587} [B]	22.9	190.3	248.2	301.9	369.8	420.1	470.1
Q_{17563} [A]	24.9	205.3	267.6	325.5	398.6	452.9	507.0

Q1	17.6	145.6	189.7	230.6	282.2	320.6	358.6
Q2	4.9	42.9	56.3	68.6	84.3	95.9	107.4
Q3	2.3	16.7	21.7	26.3	32.1	36.5	41.0
Control	24.9	205.3	267.6	325.5	398.6	452.9	507.0

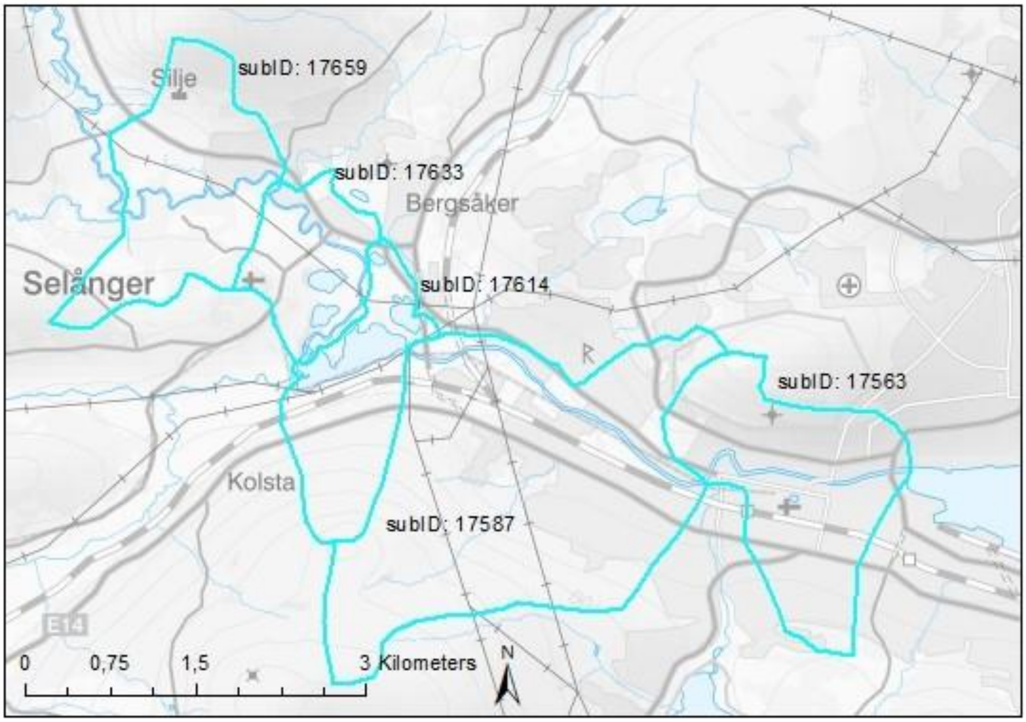

Figure 5. The sub-catchments which were analyzed in order to correctly represent the flow in the model of Selångersån in Sundsvall.

The discharge boundary condition in Henån was easier to define since it only concerned one sub-catchment. Thus, the model flow point value and the catchment's flow were the same.

Table 3. Flow return times for Henån in m^3/s.

subID	MQ	HQ2	HQ5	HQ10	HQ25	HQ50	HQ100
Q_{42167}	0.34	3.19	3.64	4.05	4.57	4.96	5.34

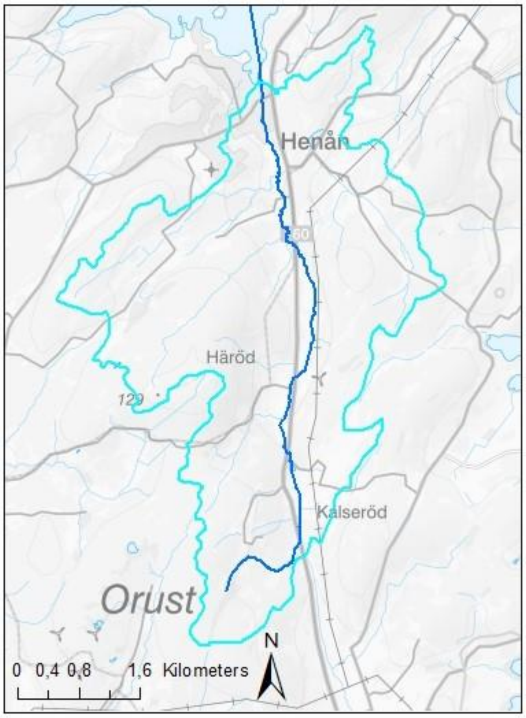

Figure 6. HYPE sub-catchment with sub-ID 42167.

In Ängelholm three sub-catchments were included in the flow formulation of the model. The formulation differed from the other areas because of a tributary stream intersecting Rönne å (river) in the city center. Flows from the sub-catchment with sub-ID 541 were therefore only used to evaluate the result since Q1 in the model and the HYPE flow upstream Rönne å before the intersection of the tributary stream (sub-ID 541), should be roughly the same.

Ängelholm flow formulation

$Q1 = Q_{554} - Q_{564}$

$Q2 = Q_{564}$

Control: $Q1 \approx Q_{541}$

Table 4. HYPE-flows from the sub-catchments considered in the model for Ängelholm and calculated model flows with different return times. The flows are in m^3/s.

subID	MQ	HQ2	HQ5	HQ10	HQ25	HQ50	HQ100
Q_{541}	20.6	96.6	117.3	136.6	160.9	179.0	196.9
Q_{564}	4.0	23.6	27.8	31.7	36.6	40.3	43.9
Q_{554}	24.7	114.6	139.3	162.4	191.5	213.1	234.5
Q_1	20.7	91.0	111.5	130.7	154.8	172.7	190.5
Q_2	4.0	23.6	27.8	31.7	36.6	40.3	43.9

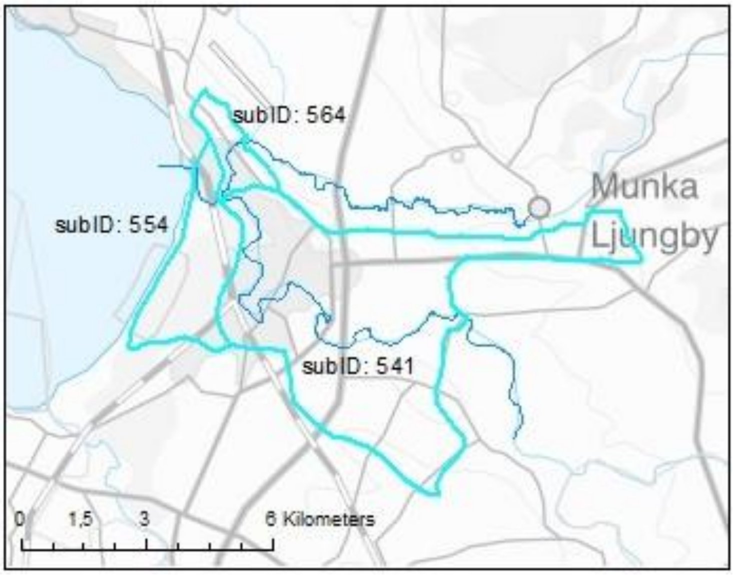

Figure 7. Sub-catchments and rivers that were considered in the model for Ängelholm.

5.6 Future scenarios

The future sea-level and discharge boundary conditions were based on climate and hydrological model results and formed separately based on the data that was available. Future sea-levels are estimated for 2100 but future discharges are based on model results of impact that is projected to occur between 2069 and 2098 in case of RCP 8.5. This is one reason why the future scenarios should not be considered exact entities but more as possible hazards in the future if we continue on the same path regarding emissions and land use that we are on today. In this project they have been used to see whether there are compounding effects with even more extreme events than with those that are included in the present scenarios.

5.6.1 Sea level boundary conditions

The future mean sea-levels were formed based on the global mean sea-level rise in the case of RCP 8.5 that is projected to occur by 2100[63]. The higher 95th percentile of the probability curve was used. Continental rise is constant and therefore easily calculated for the year of interest by multiplication of continental rise per year, with the number of years between the future event, and the year from which the mean sea level is taken. The annual mean sea level of the area and the global mean sea level can be added to form future sea-levels as described in the formula below[64].

Equation 2

$$FMSL = MSL^{z}_{RH2000} + CR_{year} * n + MSLR^{2100}$$

Where FMSL is future mean sea-level in the region of interest, CR_{year} is the continental rise per year in a region, n is the number of years between z and 2100 and $MSLR^{2100}$ is the global mean sea-level rise in 2100 in the 95th percentile of the probability distribution of the climate model results assuming RCP 8.5.

63 *SROCC*, 2019
64 The methodology is described in *Karttjänst för framtida medelvattenstånd längs Sveriges kust*, 2017, but the values have been updated with values from the latest IPCC report, *SROCC*, 2019

Table 5. Continental rise per year in the regions studied.[65]

Area	**Henån**	**Ängelholm**	**Sundsvall**
Continental rise [mm/year]	3.376	1.482	8.900

When creating the boundary conditions for future sea-levels the MSL^{z}_{RH2000} -term in Equation 1 was substituted with the future mean sea level calculated in Equation 2.

Table 6. Sea-levels from DEM and mean sea levels 2019 in meters according to the height system RH2000[66][67].

Area	**Sea level in DEM [m]**	**Mean sea level 2019 [m]**	**MSL 2100 RCP8.5 [m]**
Henån (Orust)	-0.119	-0.029 (Uddevalla)	0.776
Ängelholm	-0.20	0.072	1.004
Sundsvall	0.29	0.021 (Spikarna)	0.365

In a coming up-date of the expected sea-levels SMHI will model regional factors such as gravitational and thermal effects. At the time of writing the levels have not been updated, thus the old methodology was applied.

[65] The values are from the Swedish Land Survey's model for continental rise, NKG2016LU, *Landhöjning* | Lantmäteriet, n.d.
[66] *HAVSVATTENSTÅND 2019 Beräknat medelvattenstånd för 2019 i olika höjdsystem* | SMHI och sjöfartsverket, 2019
[67]*EKVATIONER FÖR MEDELVATTENSTÅNDET I RH2000 Beräknat medelvattenstånd i RH2000 (cm)* | SMHI och sjöfartsverket 2019

4.6.2 Discharge boundary conditions

To create boundary conditions for future discharge levels “future factors” were estimated. They were based on climate and hydrological model results of climate scenario RCP 8.5 in 2069-2098[68]. The future factors are approximations of images visualizing the increase of total runoff in the areas of interest. They should be seen as indicators used to analyze more extreme scenarios, not as exact model results for describing future discharges in the regions.

Table 7. Future factors describing expected change in mean runoff, 10-year runoff and 100-year runoff 2069-2098 in case of RCP 8.5.

	F_{MQ}	F_{Q10}	F_{Q100}
Henån	1.2	1.25	1.25
Ängelholm	1.2	1.25	1.25
Sundsvall	1.25	1.15	1.15

The factors were multiplied with the values for present mean discharge and discharges with different return time to form the future boundary conditions. The methodology is described in the equation below where FQ_{10} is a future discharge with a 10 years return time, PQ_{10} is a present discharge with a 10 years return time and F_{Q10} is the future factor describing how the intensity of such an event is expected to increase in the future considering the scenario that has been explained. The discharges in the future scenarios were otherwise formulated in the same way as the present boundary conditions.

$$FQ_{10}=PQ_{10} * F_{Q10}$$

68 *Länsvisa klimatanalyser* | SMHI, n.d.

6. Pre-processing

LISFLOOD-FP requires in-data raster files for describing topography, and information on channel width and depth. In this chapter the creation of raster-files will be explained. It involved the use of hydraulic geometry theory, raster modifications in Arcgis as well as python scripts to modify and reformat files.

6.1 Hydraulic geometry theory

Hydraulic geometry theory describes the interrelation of a watercourse's depth and width at a given time instance with flow velocity through the use of simple functions[69]. The functions are based on the principle of there existing empirical relationships between channel geometry and discharge. The function constants used in this thesis for finding depth and width of the watercourses were found prior to this study by comparing 372 different stations in Sweden and around 2800 measurement instances of flow velocity and watercourse depth and width relationships[70]. These constants were used along with the simulated flow from HYPE from the day of the DEM scanning of the area to find the corresponding depth and width of the watercourses.

In Sundsvall and Ängelholm where several HYPE sub-catchments were included in the model domain the discharge of the sub-catchment furthest downstream was used to find depth and width of the watercourse. In Ängelholm, where a tributary stream intersects the main stream and is included in the model, the depth and width of the two watercourses have been defined separately based on the discharge in each stream in the sub-catchment furthest downstream before their intersection. Below are the functions describing the hydraulic geometry relationships.

$$width = a * Q^b$$
$$depth = c * Q^f$$

69 Leopold and Maddock, 1953
70 Alpfjord Wylde, 2019

Table 8. Constants for determining width and depth of watercourses in Sweden.

a	10.909
b	0.461
c	0.655
f	0.282

Table 9. Approximations of depth and width based on the simulated HYPE flow from the day of scanning of the digital elevation model, and hydraulic geometry theory.

Area	**Day of scanning**	**$Q_{day\ of\ scanning}$ [m3/s]**	**Depth [m]**	**Width [m]**
Henån	2010-05-03	0.022	0.195	1.88
Ängelholm Rönne å	2010-04-11	23.3	1.78	46.5
Ängelholm, tributary stream		3.45	0.97	19.3
Sundsvall	2012-07-03	1.98	0.81	14.9

6.2 ArcGIS

In order to set up the LISFLOOD-FP models the right indata files had to be prepared. LISFLOOD-FP is made to easily couple with Arcgis since the model domain is described by raster files. Raster is a file format in Arcgis with a square grid system where values are assigned to each square. Arcgis is a software for geographic information systems used to analyse, visualize and interpret geographic data. In Arcgis there is a tool called Modelbuilder which is a useful inbuilt functionality for combining different operations and visualizing the work-process. Modelbuilder was used to create the raster in-data files necessary for the LISFLOOD-FP simulations.

The in-data files required for a successful LISFLOOD-FP run were:

- A digital elevation model (DEM) file for the model domain.
- A riverbed elevation file in the form of a raster showing the path of the river and the riverbed elevation in each river raster cell.
- A river width file showing the path of the watercourse and its average width.
- A boundary condition file with coordinates describing the location of the boundary conditions along with specifics regarding the type and dimension of the boundary condition.
- A par-file calling the other files when executing LISFLOOD-FP, also specifying simulation time, initial time step, friction parameters and what files to write.

Other files that were used:

- A bdy-file describing changes of the boundary conditions over time. In this project a bdy-file was used to slowly increase sea-levels or discharges. Bdy-files can also be used to describe the development of an event.
- A startfile describing initial surface elevation of the watercourse and floodplain.

All the files prepared had a raster-cell size of 5x5 meters. The geographic projection used during the creation of the files was SWEREF99 TM, which is the standard projection used nationally in Sweden[71].

The elevation data used in the DEM-file was according to the height model RH 2000 which is the current national standard in Sweden based on airborne laser-scanning done between 1979- and 2001[72]. RH2000 is an elevation model based on the height at each given point relative an irregular ellipsoidal model of the earth called the geoid. The geoid describes an imaginary sea-level considering the gravitation of different entities.

71 *SWEREF 99, projectioner,* Lantmäteriet n.d.

72 *Enhetligt geodetiskt referenssystem, infobland n:o 3 Nytt Höjdsystem,* Lantmäteriet, 2009

In RH2000, the geoid is placed according to a zero elevation point in Amsterdam in 2000. When comparing historical sea-levels the continental rise can be eliminated by using the relative water level, RW, where the sea-levels are adjusted by a linear regression. This way, long term changes from sea level rise and continental rise may be eliminated and the sea-level variation is comparable between the decades[73].

Descriptions of the methodology of creating the raster in-data files will be described for each file-type in the following sections.

6.2.1 DEM-file

The DEM-file was created by extracting the values from a DEM for Sweden by the use of a Mask of the model domain. Grid-size was specified.

In the model for Sundsvall, the digital elevation model had to be modified because of the existence of a lake in the path of the watercourse. The lake was represented in the model by a polygon with a constant depth of 3.6 meters, which is the mean lake depth in Sweden applied where no other measurements are available. To adjust the DEM file for these changes a polygon file of all lakes in Sweden was intersected into the model domain and the depth subtracted from the digital elevation layer.

[73] *Höjdsystem och vattenstånd* | SMHI, 2010

6.2.2 River-bed elevation file and channel width file

The watercourses of interest were taken from a line shapefile, showing all watercourses in Sweden, through an intersect operation of the model domain. Thereafter unwanted watercourses within the domain were eliminated manually. The lines were reformed into points within every 5 meters. The point values were then used in two different operations[74].

(1) From the river point locations, values were extracted from the DEM in order to create the river-bed elevation file for Henån. In the other models the point furthest upstream and the point furthest downstream were used to interpolate the elevation decrease of the riverbed. Along with the interpolation, the depth, calculated by the use of hydraulic geometry theory, was subtracted.

In the model for Henån the extracted points were corrected by a python script (*loc_tunnel*) before the depth was subtracted and points were incorporated in Arcgis again. Thereafter the channel points with assigned values were used to interpolate a field in the domain using an IDW interpolation technique. IDW stands for Inverse Distance Weighted interpolation and is a method for creating rasters from points where nearest values are used to interpolate values over an entire raster area[75].

(2) The second operation applied on the points was to create a raster mask of the watercourse in the model domain. In the mask the location of the channel was marked by cells with the value 1, all other cells were attributed the value 0 and the grid size was specified to 5 x 5 meters. To create the width file, the estimated width found by Hydraulic Geometry Theory was multiplied with the raster mask of the channel. The result was a file with the width homogenously specified along the course of the channel in the model domain.

The raster mask created was also used to eliminate unwanted values from the IDW field interpolation by a simple raster multiplication of the mask and the

[74] Before the extracted river line shapefiles were used in the operations “unsplit lines” was used to eliminate breaking points in the metadata. They created errors in later operations when interpolating between points.

[75] *IDW—Help* | ArcGIS Pro Documentation, n.d.

IDW-field. From this last operation the raster file describing the path of the channel in the domain and the river bed elevation was finalized.

6.3 Python

Python scripts were used to reformat files exported from ArcGIS, to find extreme values and to remove bridges and other disruptions in the river bed elevation file for the model of Henån (where the river bed elevation was calculated based on values taken directly from the DEM). The Python scripts may be found in the appendices. Short descriptions of the different manipulations that were done will be made below.

6.3.1 Reformattning files

The exported files from Arcgis had decimal separators in the form of commas, whilst LISFLOOD-FP only takes dots. Also nonvalues have to be represented by -9999 in LISFLOOD-FP, but come out as zero's or minus zeros in Arcgis. These where changes applied by the script; *replace_unwanted.*

6.3.2 Finding extreme values

Return times for sea-levels were unknown and had to be estimated for the study areas. In order to do so observation data of monthly maximums were taken from WISKI, SMHI's database, and the year corrected with the script *hydro_year* (may be found in the appendices). Thereafter, the yearly maximums (now from the oceanographic year) were extracted and matched against different distributions to find sea-levels with the return times of interest. A modified version of Johan Södling's (SMHI employee, statistician) script *extreme_value_falsterbo_calc_rp.py* was used. The script also checked whether two yearly maximums occurred within less than 30 days of each other. If this would be the case the maximums may have occurred during the same event and thus, correlate, but be interpreted as two independent events. This was the case on one occasion in Sundsvall. Considering this only happened once the impact of a possible correlation was disregarded.

6.3.3 Localizing and eliminating tunnels and irregularities in the river bed elevation file

In Henån the slope of the watercourse was irregular, implicating that the interpolation between two points to create the bed elevation raster was not representative of the actual bed elevation. Therefore, the surface elevation of the watercourse was taken from the DEM-file. However, this included bridges and other disruptions that do not depict the elevation of the river-bed, therefore a script was created to remove all elevation changes that would create unnatural uphill or positive slopes in the direction of the watercourse. This script was named *loc_tunnel* and may be found in the appendices.

7. Model set up

LISFLOOD-FP was developed for research and is still being improved as problems are highlighted in new applications. As was mentioned in the theory chapter, there are issues with the Acceleration solver that was used in this study that may create problems when modelling certain areas where topography is especially challenging.

Hydraulic modelling is often a balance between complexity and simplicity and in correctly representing channels and floodplains without complicating models to the extent that they are no longer feasible in operational systems. The solvers used in this study only neglect one term in the shallow water equations, but the implications are that other terms play other roles than they would have done otherwise. Friction (as was stated in Neal et al., 2011) has a stabilizing function on the Acceleration solver computations. Increasing the friction parameter also increases inundation which is why the tweeking of this parameter should be handled carefully.

The model set ups were crucial to the stability of the executions. In this chapter the main challenges and implemented solutions will be presented.

The problems that came up as the models were executed arose:

- When there were high sea-levels combined with lower flows.
- When there were high sea levels.
- When there were high flows.
- When the boundary condition was placed close to the domain border.
- When the boundary condition was either on (Ängelholm) or beside (Henån) the waterway in the 1D channel in the domain.
- When the boundary condition for the sea level was placed further out in the sea.
- When the 1D channel passed a lake (Selångersfjärden in Sundsvall)

The following sections will consider the issues that came up for each site and the solutions that were found. Finally, the main problems and solutions will be described.

7.1 Henån

The problems that had to be addressed in order to run the model for Henån occurred in the cases 1, 2, 3, 4, 5 and 6. The first problem was related to the discharge boundary condition and the location of inflow in the 1D-model. A glass wall effect was prevented by placing the boundary condition away from the domain border. Thereafter, more simulations revealed instabilities at higher discharges with the return time of 2 years. Henån is a shallower watercourse than the rivers at the other sites, and the gradient of the river bed is steeper. These are mentioned as possible stability issues for the Acceleration solver in the LISFLOOD Manual.

The gradient is however larger in the beginning of the watercourse and when the boundary condition was located further downstream, the problem was solved. This was a good solution for the 2 year flows combined with a moderate sea-level rise of one meter. When the sea level was increased to 1.2 meters, or the flow was increased to resemble a 5-year return flow (from 3.19 m^3/s to 3.635 m^3/s) the model became unstable again. To deal with these problems a file with initial conditions was introduced, called “startfile”. The startfile is a surface elevation output from a previous simulation that in this case was a scenario of a mean flow event combined with the sea level on the day of the digital elevation model-scanning.

Problems also occurred in the placement of the boundary condition for sea levels and in combining low flows with high sea levels. In the latter case no solution could be found and thus the effect from low versus high discharge in a combined event (with high sea levels) could only be studied comparing high flows with a return time of 10 years with even higher flows with return times of for example 50 years.

7.2 Ängelholm

In Ängelholm, problems arose in the cases of 1, 4, 5 and 6. The first problem related to the placement of the sea level boundary condition. Firstly, it was too close to the model domain border, thereafter, it was too far out to sea, and lastly, placed in the harbor, the model got instable when the boundary condition was placed on the 1D-model channel. This was interesting, considering the placement was the standard for the other models. In the end, the boundary condition coordinates were specified for a cell near the channel where the river flows into the harbor area of Ängelholm.

Another problem that occurred in the model for Ängelholm arose when modelling the future scenarios with high sea levels and low flows. This was first solved by using a startfile from a run where a higher flow was simulated (combined with the high sea level in the related case). The solution could be problematic if the inundation from the more extreme event does not readjust in the simulation of the new event, so that more inundation than would actually be found is simulated. Thankfully this set-up was only needed in the first simulation of Ängelholm, where a future mean discharge and the future sea-level rise were simulated. These results were therefore neglected.

7.4 Sundsvall

In Sundsvall, problems occurred in the cases 3, 4, 5, 6 and 9. The most specific problem that arose was related to modeling the inundation of the lake, Selångersfjärden, which is a part of the path of Selångersån before it flows through the inner city of Sundsvall. In the first model runs, Selångersfjärden was represented as a blank flat surface in the DEM describing the floodplain domain. As soon as the threshold for the 1D-model was reached at higher flow scenarios, the inundation of a large flat area was simulated, treated in the model as the surface of the floodplain. This immediately created instability in the model.

The solution was to engrave the lake in the 2-D domain by the use of a polygon file with average depth of 3.6 meters (for all non-defined or smaller lakes in Sweden) and a few Arcgis operations. A simulation of normal (mean) conditions was performed during 500 000 seconds to fill up the lake with water and create a startfile for the simulations. Thus, the lake was treated like a volume of water instead of a flat surface in the model. This modification was necessary in order to consider the volume storage of the lake in the model.

7.5 Main problems and their solutions

Problems that arose in all models were related to both the location of the upstream (discharge) and downstream (sea level) boundary conditions and the sudden increase of the sea level or discharge values. To address these problems startfiles from the previously modeled and thus similar events were used as well as bdy-files, where the boundary condition could gradually increase. To change the location of the upper and bottom boundary conditions was also effective in many cases, defining the coordinates beside or inside the 1-D model domain, or further from the domain borders.

Another solution that may be applied to decrease instability is setting Froude's number to 1. Forcing critical flow. This solution was suggested and tried in some simulations but did not have any effect. The question is if the solution was not implemented correctly (by use of max_froude in the par file) or if the existence of supercritical flow was not the problem in the first place.

8. Model calibration and validation

In this chapter the methodology and results from the model calibration and validation will be presented. They were done to the greatest extent possible with the limited amount of data from previous events that were available.

Three parameters were calibrated in this project; the friction parameters for the channel and floodplain and the initial time-step. The friction parameters were the main focus since they determine the extent of the flooding. Initial time-steps were only changed when the models became instable, with limited impact since time-steps thereafter were adaptive.

The friction parameters were initially determined based on recommendations provided from a draft of a report from SMHI, describing the methodology for implementing fluvial flood mapping in Sweden.[76] A comprehensive guide from the US geological survey was then used to understand the implications of different elements of the channel and floodplain to the roughness coefficient.[77] Thereafter friction coefficients from previous studies of the case study sites were sought for and visual evaluations made of the land types in the model areas, by use of satellite imagery from google earth. Finally, different friction parameter values were tested and simulations of historical events were compared with photographs. The chosen friction parameters can be seen in Table 10 below. The calibration and reasoning behind their choice will be described for each model in the coming sections.

Table 10. Friction parameters as defined for the different models.

	Henån	**Ängelholm**	**Sundsvall**
SGCn	0.02	0.02	0.025
Fpfric	0.02	0.01	0.04

[76] Alpfjord Wylde, 2019
[77] *Guide for selecting manning's roughness coefficient*, 1989

8.1 Henån

The character of the watercourse flowing through Henån is natural and slightly meandering with vegetation and less urban surfaces than other sites. The friction parameters for Henån were therefore set relatively high. Calibration was not performed since there was no observation value to calibrate against.

The results were however validated with two events that occurred the 10th and 17th of January 2020. At the first event, the 10th of January, SMHI had warned for high sea-levels (a class 2 warning issued for sea levels that increase more than 1.2 meters) in Kattegatt and Skagerack. As can be seen in the graph below (Figure 8) showing relative sea-levels in Uddevalla during this period, sea-levels peaked at 1.4 meters which corresponds to an event with a return time between 2 and 5 years (1.2 and 1.5 meters). One week later, similar high sea-levels may be seen in the measurement data of sea-levels and at this time, SMHI also issued a warning for high flows, class 2, corresponding to a discharge event with return time 2 to 10 years.

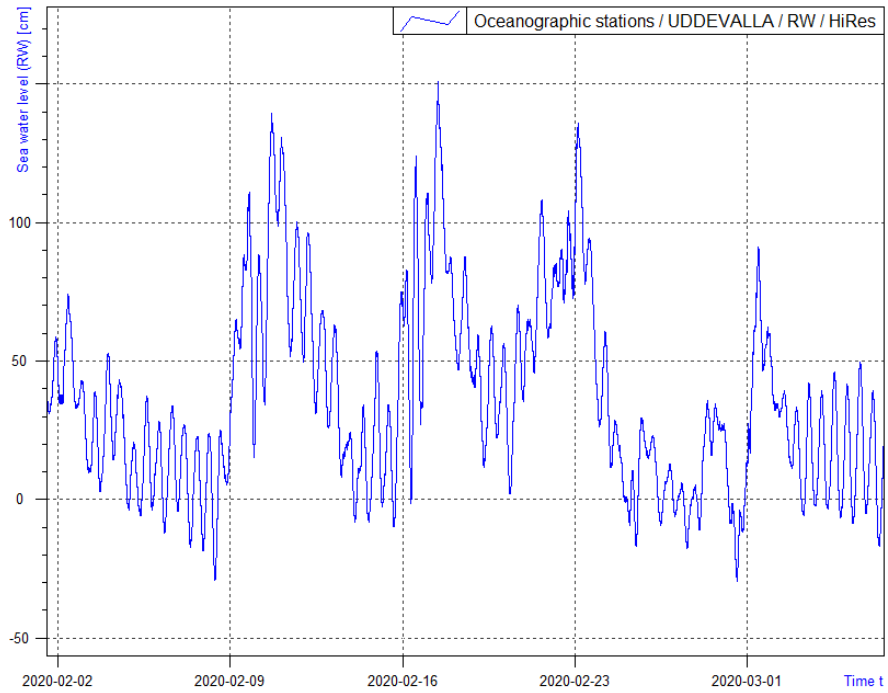

Figure 8. Relative sea-level measurements outside Uddevalla 2/2-2/3 2020.

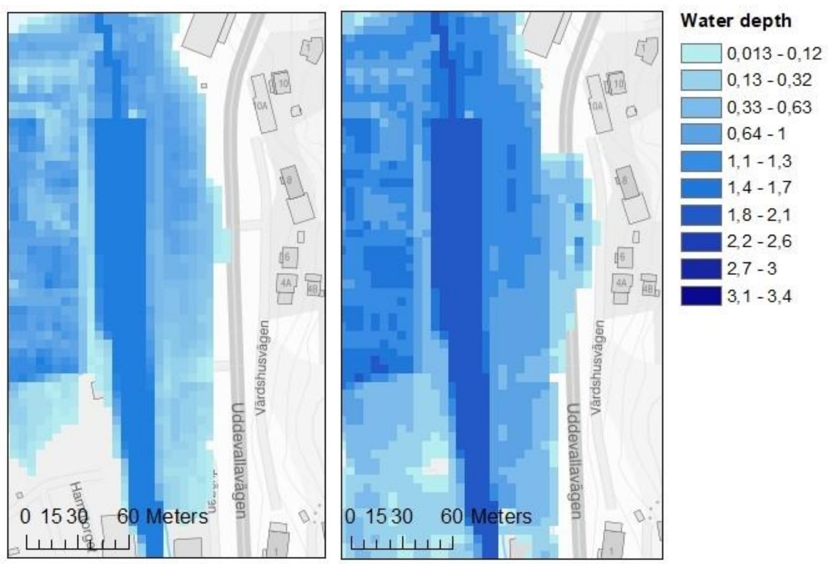

Figure 9. Sea-levels with return times of 2 respective 5 years (1.22.vs. 1.52 meters in RW), the inundation of county road 160 may be seen in the simulation to the right.

The photographs seen from the events in Figure 10 and 11 are similar to the model results showing a simulated 2-year high sea-level event to the left and a 5-year sea-level event to the right (in Figure 9). It was impossible to calibrate the model further without evaluating the development of the events from the 10th and 17th of January more closely in relation to when the photographs were taken. However, looking at the model results and the images one may draw the conclusion that the model is reasonably accurate.

The high flow event that occurred simultaneously the 17th of January was also modeled in the combined event. It did however not have any impact on the extent of the inundation (based on the results that will be presented).

Figure 10. Photographs from Henån the 10th of January 2020 where road 160 may be seen to the far left.[78]

Figure 11. Photographs from Henån the 17 of January 2020 where road 160 may be seen in the middle photograph.[79]

78 *Högt vattenstånd - Översvämning i Henån* | NYHETERsto.se, 2020
79 *Efter storm kommer översvämning* | NYHETERsto.se, 2020

8.2 Ängelholm

Rönne å meanders through Ängelholm city center and is joined by Rössjöholmsån before the harbor. There are both urban and rural areas along the floodplain, and the friction coefficient was set relatively low (0.01). The channel has a natural form and meanders through the city. The friction coefficient was set to 0.02.

The model was validated by comparing a simulated 100-year sea level event with the consequences after Sven, a storm that went in over Ängelholm in December 2013 when sea-levels measured 2.18 meters above normal in the harbor[80]. This was the maximum value that was measured and a 100-year event corresponds to a sea-level rise of 2.02 meters. A comparison of the simulation of the 100-year sea level event with photographs from the event may be seen in Figure 12.

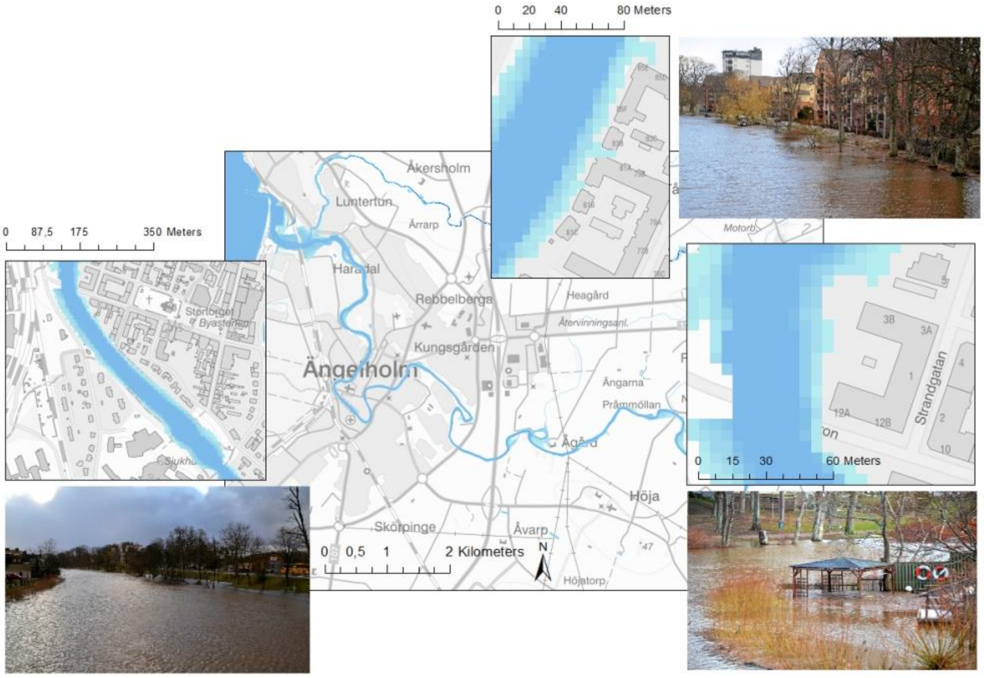

Figure 12. Simulation of a 100-year sea level event and photographs from the event in December 2013.

80 Mauritzson and Scherman, 2013

8.3 Sundsvall

In the model domain for Sundsvall there were both urban and rural areas, but the character of the river is natural with vegetation and irregularities along its bank. Thus the friction coefficients for Sundsvall were higher than those in the other models. The model was also calibrated against a measurement from a known event, something that wasn't available for the other sites. The event was an extreme discharge event that occurred in Selångersån in September 2001 when higher sea-levels were also measured. At a point by the old bathhouse water surface levels were 2.5 meters in RH2000[81]. The point was calibrated in LISFLOOD-FP and validation done with images of the event, seen in figure 13. In this case a scenario with max-levels of the flow (from HYPE simulations) and sea levels (measured at station Spikarna outside Sundsvall) were used to simulate the event. A note on the image: It shows water depth, not surface elevation.

The model for Sundsvall was also validated against an event that occurred the 21st of April 2018. SMHI had issued a warning for level 2 high flows which corresponds to a return time between 10 and 50 years, see figure 14.

81 Berglöv, 2010

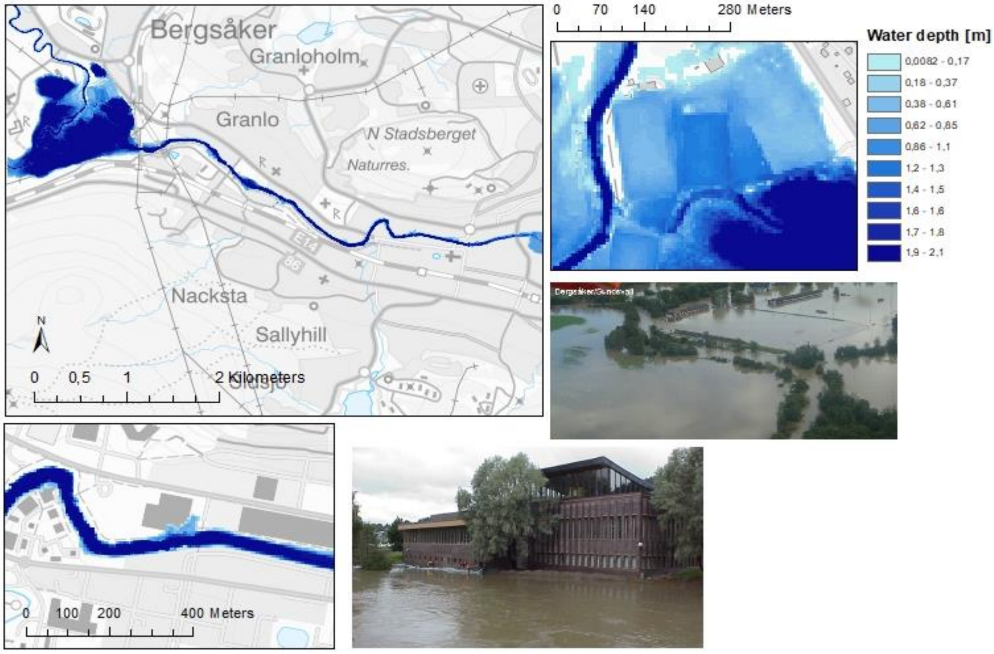

Figure 13. Simulation of extreme event in 2001 (flow: 113 m^3/s, sea level rise: 0.5 meters) and photographs taken during the event.[82]

[82] Jonasson, 2017

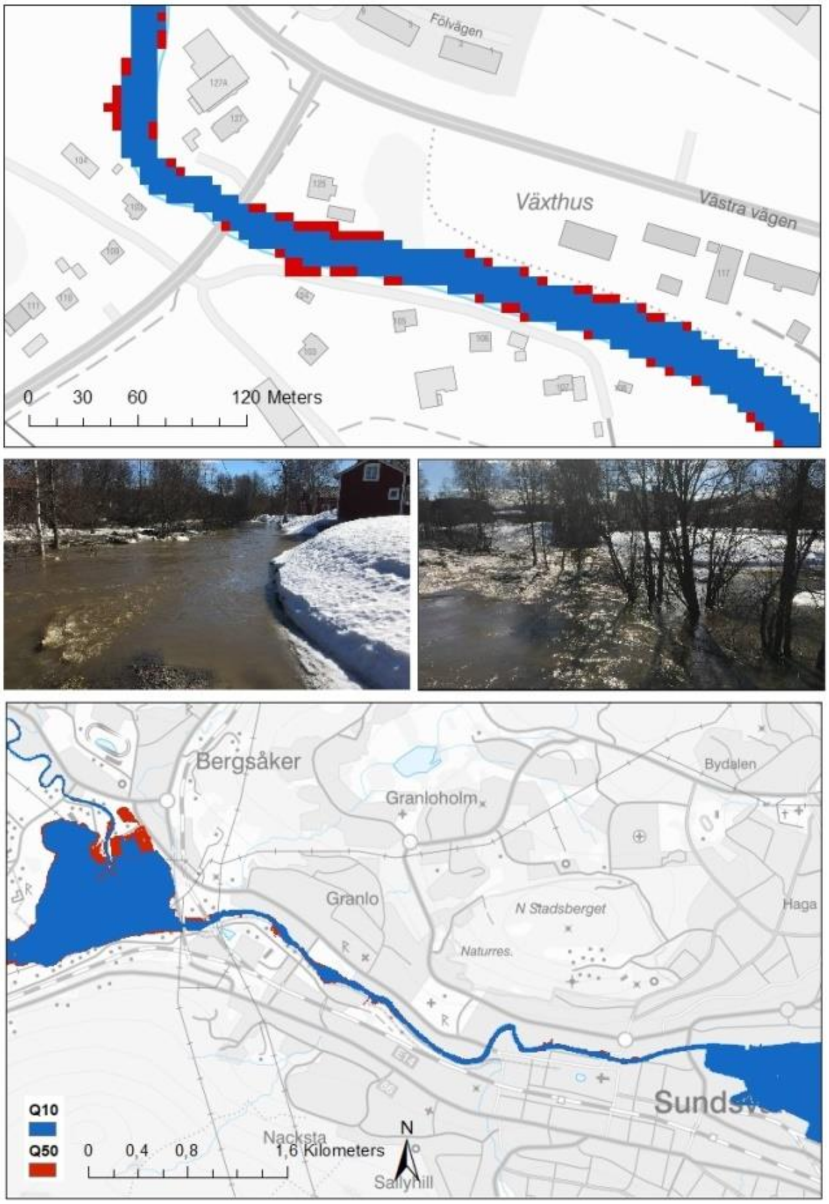

Figure 14. Photographs from the event the 21-23rd of April in 2018 compared with corresponding simulated flow event with return times 10 and 50 years[83]. Approximate coordinates for the location of the images: [E614692, N6922062] (in meters)

83 Israelsson, 2018

9. Results

In this section results from the executions of LISFLOOD-FP will be presented along with details on model runs and boundary conditions. It was found that a maximum of 27 hours, or 100 000 seconds as defined in the model, was more than enough to simulate the extent of a simultaneous high river discharge and high sea level event. The use of start-files to increase stability also had the effect of shortening simulation times.

The results from the model simulations are simplifications of real-life events. Boundary conditions are constant values and thus the development and fluctuations during the events have not been studied. Because of the results of the simulations, with no or very limited compounding effects, there was no need to analyze the time dependencies in regard to the different events and how they co-occurred, only one event was crucial to the consequent inundation, and thus the time duration of this event was the one of interest for predicting the outcome consequences.

Lastly, the plot visualizing the occurrences of combined events in the historical simulated discharge and observational sea level data will be presented.

The following abbreviations will be used to describe the events:

M – mean
Q – discharge
SL – sea level
F – Future
[number] – return time of discharge or sea level event

9.1 Boundary conditions for discharge

Below are the discharge boundary conditions as they were represented in the model with the original flow divided by the cell width, 5 m.

Table 11. Discharge boundary conditions for Henån.

Return time	Q	FQ
MQ	0.0688	0.0826
Q2	0.638	-
Q5	0.727	-
Q10	0.8096	1.012
Q25	0.914	-
Q50	0.9914	-
Q100	1.068	1.335

* Discharge input to model [5*m3/s]

Table 12. Discharge boundary conditions for Ängelholm

	Q1*	Q2*	FQ1*	FQ2
MQ	4.14	0.80	4.97	0.96
Q2	18.19	4.72	-	-
Q5	22.31	5.56	-	-
Q10	26.13	6.34	32.67	7.93
Q25	30.96	7.33	-	-
Q50	34.55	8.06	-	-
Q100	38.11	8.79	47.63	10.99

*Discharge input to model [5*m3/s]

Table 13. Discharge boundary conditions for Sundsvall.

	Q1	Q2	Q3	FQ1	FQ2	FQ3
MQ	0.71	0.20	0.09	0.88	0.24	0.12
Q2	5.83	1.72	0.67	-	-	-
Q5	7.59	2.25	0.87	-	-	-
Q10	9.22	2.75	1.05	10.61	3.16	1.21
Q25	11.29	3.37	1.29	-	-	-
Q50	12.82	3.83	1.46	-	-	-
Q100	14.35	4.29	1.64	16.50	4.94	1.89
2001 event	15.99	4.79	1.83	-	-	-

*Discharge input to model [5*m3/s]

9.2 Boundary conditions for sea-levels

The sea-level boundary conditions were found by the use of statistical distributions, future expected global mean sea level rise in case of RCP 8.5 and continental rise. In this section the found and formulated sea-levels for different return times for present and future events may be found.

Table 14. Return times for sea-levels in relative sea levels, RW and as represented in the model, HFIX (in RH2000).

	Henån		Ängelholm		Sundsvall	
	RW [m]	HFIX [m]	RW [m]	HFIX [m]	RW [m]	HFIX [m]
MSL	0	0.09	0	0.27	0	-0.27
SL2	1.23	1.31	1.10	1.37	0.73	0.73
SL5	1.53	1.62	1.35	1.62	0.92	0.91
SL10	1.73	1.82	1.51	1.78	1.03	1.02

SL25	1.98	2.07	1.72	1.99	1.16	1.15
SL50	2.17	2.26	1.87	2.14	1.25	1.24
SL100	2.35	2.44	2.02	2.29	1.33	1.33

Table 15. Future sea-levels and their return times in relative sea-levels, RW, and as represented in the model, HFIX.

	Henån		**Ängelholm**		**Sundsvall**	
	RW [m]	**HFIX [m]**	**RW [m]**	**HFIX [m]**	**RW [m]**	**HFIX [m]**
FMSL	0.78	0.89	1.00	1.20	0.37	0.075
FSL2	2.00	2.12	2.10	2.30	1.10	1.09
FSL5	2.30	2.42	2.35	2.55	1.28	1.28
FSL10	2.50	2.62	2.51	2.71	1.39	1.39
FSL25	2.76	2.87	2.72	2.92	1.52	1.52
FSL50	2.94	3.06	2.87	3.07	1.61	1.61
FSL100	3.13	3.25	3.02	3.22	1.69	1.69

9.3 Model runs

In this section the model runs will be presented as well as the simulated results from the different areas. The model executions were oriented towards investigating consequences and finding compounding events. Therefore, different combinations have been tested in the different areas after evaluations of previous runs as a strategy in order to avoid simulating all possible scenarios. The tables in this section illustrate how the vulnerability of each area has been investigated. An x in a table represents a simulation with a discharge with a certain return time defined by the row in the table, combined with a sea level with the return time as defined by the column.

9.3.1 Henån

In Henån the sea-level was the dominating factor that determined the severity of an inundation event. Compared to the consequences from a sea-level event the discharge had almost no impact. A simulated isolated 100-year discharge event led to some inundation of a smaller road next to the harbor as well as some broadening of the watercourse higher upstream, but otherwise there were few consequences.

The process of finding the most important factor as well as possible compounding events can be seen in tables 6 and 7 below. Since the sea level was noted to have an impact the discharges were increased to find a scenario when they would have an impact on the inundation.

Table 16. Model runs for present scenarios in Henån.

	MH	H2	H5	H10	H25	H50	H100
MQ	x						
Q2	x					x	
Q5							
Q10		x	x				
Q25							
Q50	x					x	
Q100	x					x	

Table 17. Model runs for future scenarios in Henån.

	FMH	FSL2	FSL5	FSL10	FSL25	FSL50	FSL100
FMQ							
FQ10				x		x	x
FQ100	x			x		x	x

In figure 15 to 17 the extent of inundation for different scenarios in Henån may be seen. In figure 15 the inundation from a 2 and a 5-year recurring sea level event is visualized. As may be seen there is a clear increase of the inundation during the latter event. In the next figure the difference between two more extreme sea levels are seen, with future return times of 50 and 100 years. They are combined with a discharge event with a return time of 10 years. If the discharge in the combined event in figure 16 was increased, from a future return time of 10 years to a future return time of 100 years there was no additional impact from the increased discharge. This was the only way of investigating possible compounding effects since models where lower discharges were combined with higher sea levels were instable.

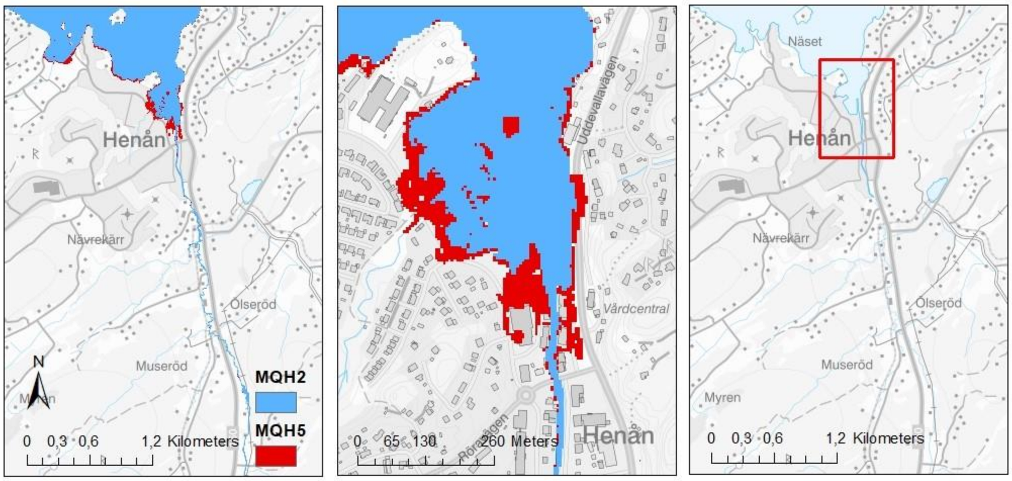

Figure 15. Extent of inundation in simulation of sea-levels with 2, and 5 years return time combined with mean discharges in Henån.

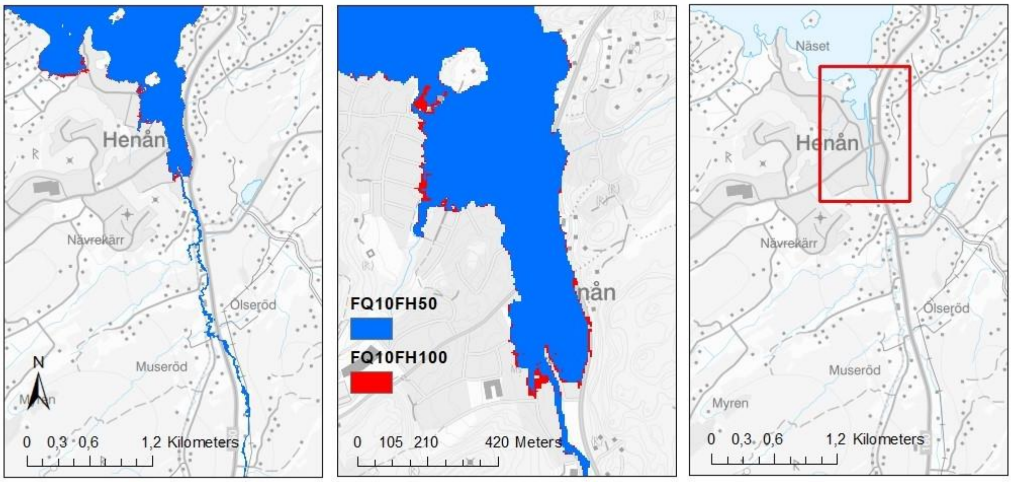

Figure 16. Simulation of future sea-levels with 50 and 100 years return time combined with a future discharge with 10 years return time.

In figure 17 the implications from a discharge respectively a sea level event are shown when a future 100-year discharge event is compared to a present 2-year sea level event. The impact from the sea level event is large with several buildings, the harbor and parking lots inundated. The future 100-year discharge event however is flooding a smaller road next to county road 160 but impacts are otherwise limited.

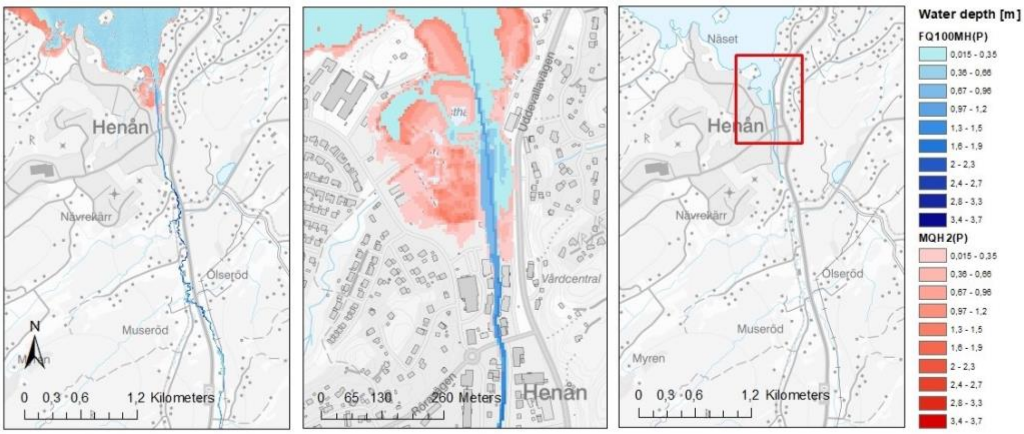

Figure 17. Future discharge scenario with 100 years return time combined with present mean sea-levels, compared to a simulation, in red, of present day mean discharges and sea-levels with 2 years return time.

9.3.2 Ängelholm

In Ängelholm sea-levels had a greater impact on the extent of the inundation than the discharge, for this reason most of the combinations involving discharges with lower return values were not simulated. Instead sea-levels with different return times were compared with a discharge with a 100-year return time to see whether the discharge could have an impact in any combined event. This was also the reason why only more extreme future discharge events were simulated.

Table 8. Model runs for present scenarios in Ängelholm.

	MH	**H2**	**H5**	**H10**	**H25**	**H50**	**H100**
MQ	x						
Q2		x	x	x	x	x	x
Q5		x			x		x
Q10							
Q25							
Q50							
Q100		x			x		x

Table 9. Model runs for future scenarios in Ängelholm.

	FSL	**FSL2**	**FSL5**	**FSL10**	**FSL25**	**FSL50**	**FSL100**
FMQ	x						
FQ10	x	x	x				
FQ100	x	x		x			x

In figures 18-22, simulations of combined and isolated flood events in Ängelholm may be seen.

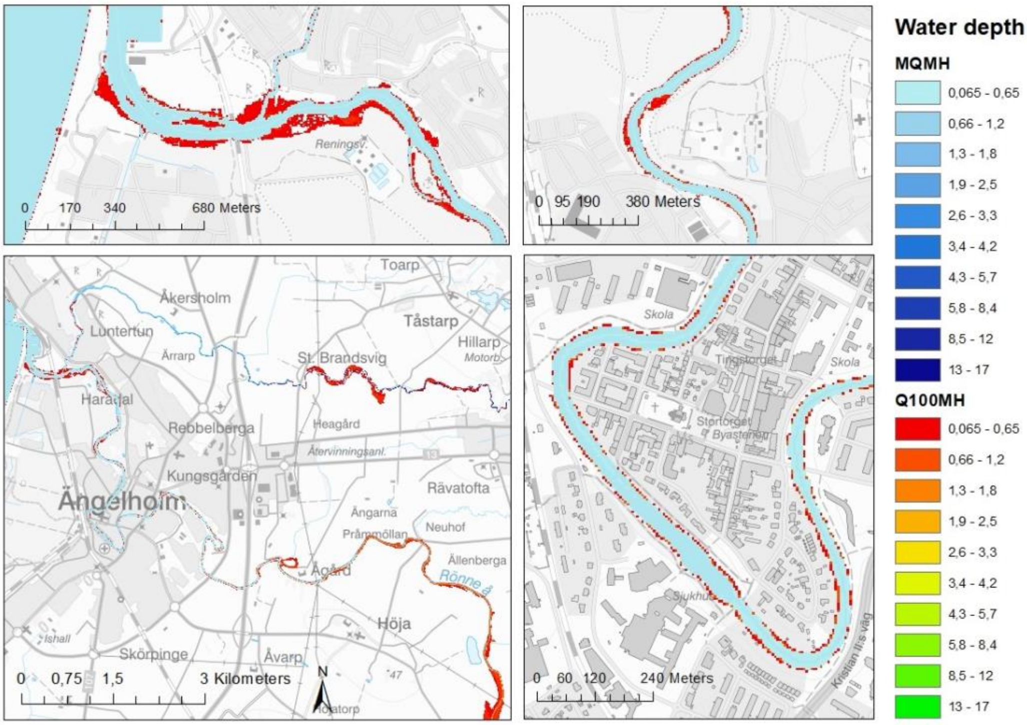

Figure 18. Inundation from discharge with 100 years return time.

In figure 18 the inundation from a discharge event with 100 years return time can be seen. It does not seem to have any severe impact on the city area (as seen in the image in the bottom right corner).

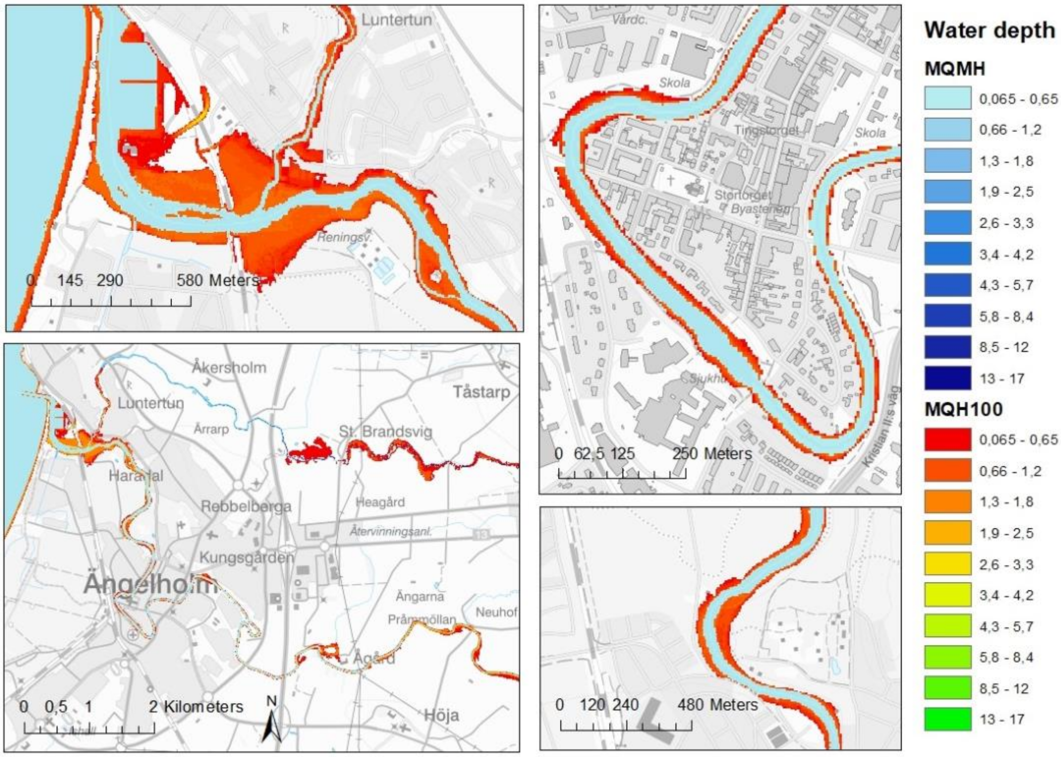

Figure 19. Inundation from sea-levels with 100 years return time.

Figure 19 illustrates the consequences from a 100-year sea level event. The harbor is under water and so is the floodplain around it. The railway may be in danger of inundation. In the next figure, figure 20, the impact from a 100-year discharge event, occurring simultaneously as the 100-year sea level event may be seen. The isolated sea level event from figure 19 is now in blue to visualize the added consequences from the high discharge in the combined event. It is very small or nonexistent in the harbor and city areas.

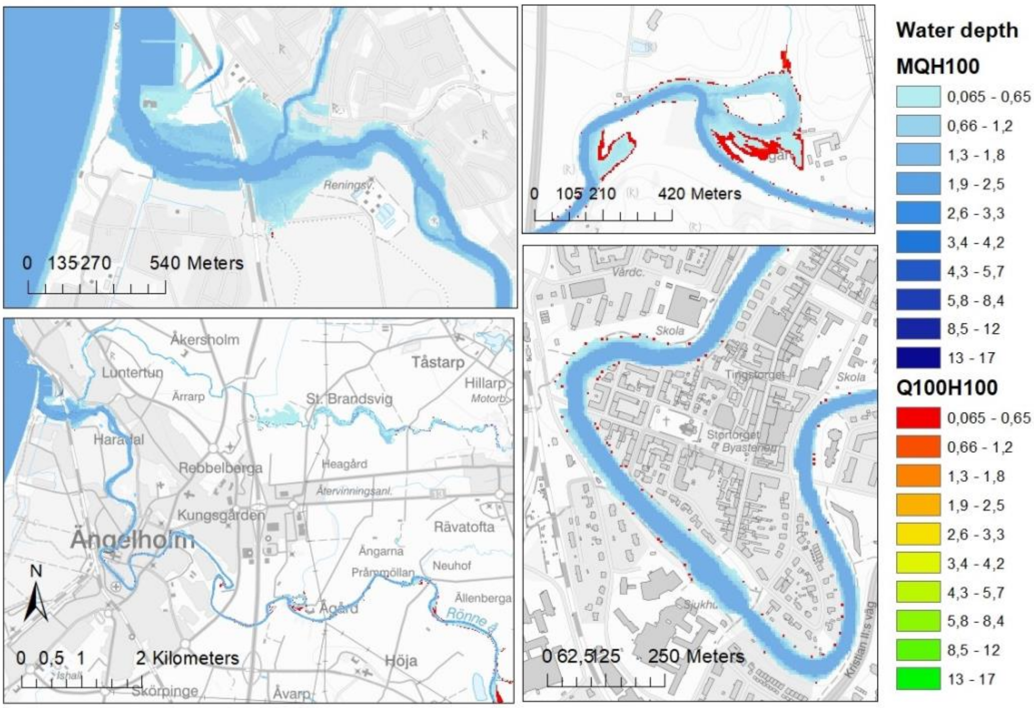

Figure 20. Combined event with 100-year discharge and 100-year sea-levels compared with an event with mean discharge and 100-year sea-levels.

In Figure 21 and 22 the future scenarios may be seen. In the first image the impact from sea levels in a combined event is highlighted, and in the second image, the impact from discharge is. Both are simulations of future 100-year events. As may be taken from the images, sea levels have a much greater impact on the inundation.

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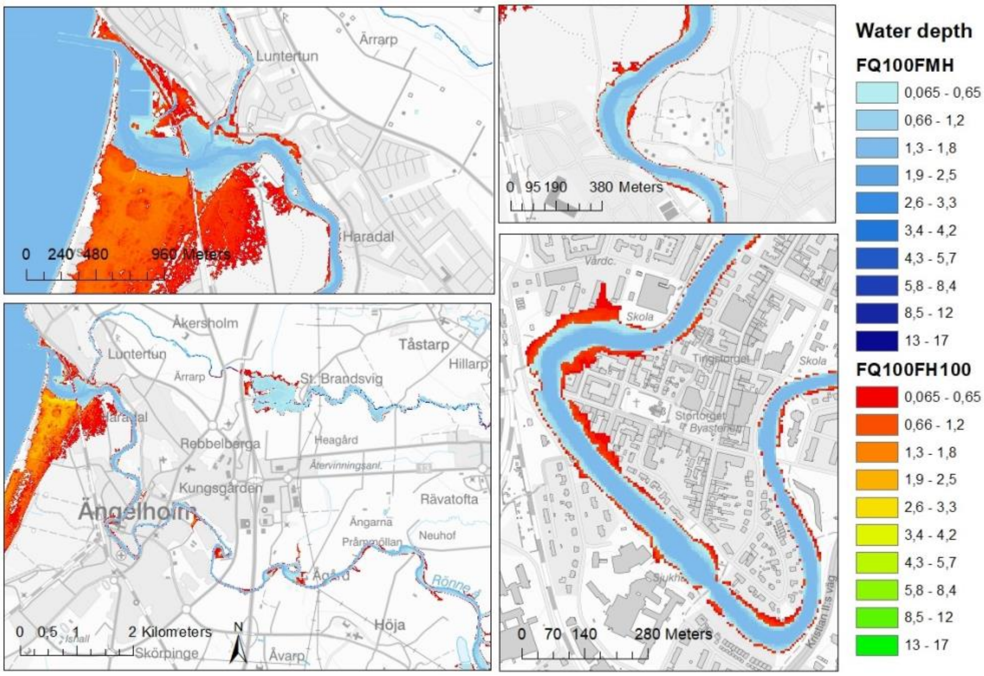

Figure 21. Combined scenario with future sea-levels and discharges that both have 100 years return time compared with a future event with a 100-year discharge and mean sea levels

In figure 21 the added impact from a future 100-year sea level event on a future 100-year discharge event is shown. But since the sea level is the dominating factor, the compound effect can not be deduced by this comparison.

It may also be seen that future discharges with a return time of 100 years, have an impact on the inundation in the isolated event, but consequences are limited.

There are however additional consequences from the discharge in the combined event, that may be seen in figure 22 where the combined event clearly has a larger impact than the isolated sea level event. The inundation from the combined event was 14% larger (in area) than the inundation caused by the isolated sea level event[84]. The addition of high discharge to high sea

84 See calculation in the appendices.

levels lead to greater consequences in the number of inundated buildings, and in the further inundation of the water treatment plant, seen in figure 22 in the upper left corner. Thus, the combined future 100-year events are compounding.

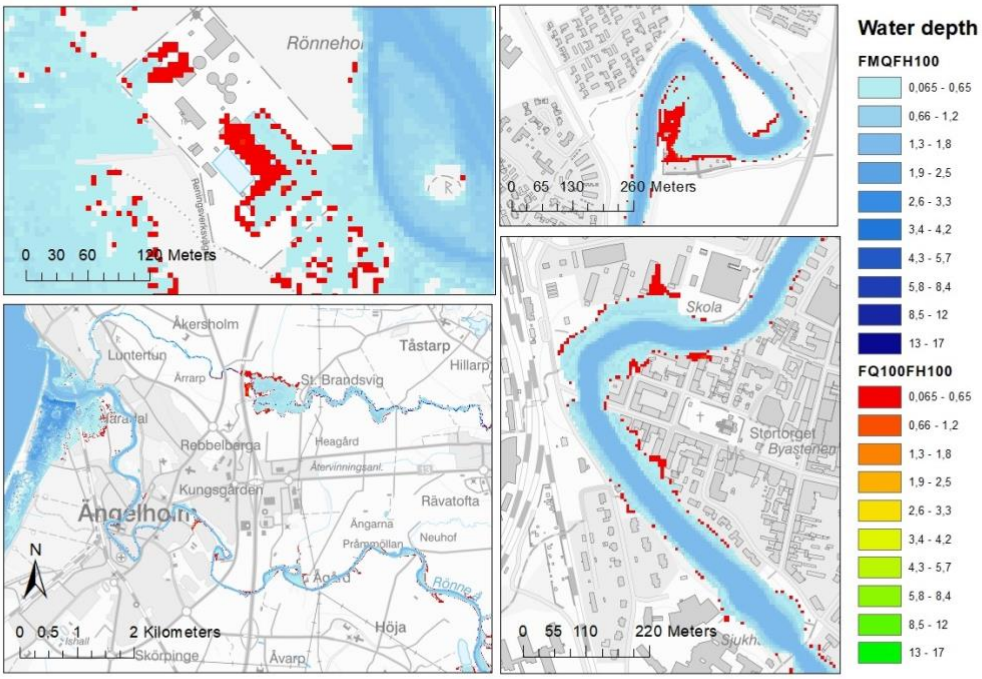

Figure 22. Future event with combined discharges and sea-levels with 100 years return time and future event with 100-year sea-levels and mean discharges.

9.3.3 Sundsvall

In Sundsvall it was first noted that the discharge had an impact on the extent of inundation. Thereafter the runs for investigating the impact from elevated sea-levels were made. But since none of the present scenario sea-levels had any impact on the extent of inundation when combined with a flow with a 2-year return time only the most extreme sea-level with a 100-year return time was applied when searching for compounding effects with other, more extreme discharges.

The same approach was used when looking at the future scenarios where only the more extreme sea-levels (that exceeded the highest sea-levels from the present scenarios) were simulated.

Table 10. Model runs for present scenarios in Sundsvall.

	MH	**H2**	**H5**	**H10**	**H25**	**H50**	**H100**
MQ	**x**						
Q2	x	x		x			x
Q5							x
Q10	x						x
Q25							x
Q50							x
Q100	x						x

Table 11. Model runs for future scenarios in Sundsvall.

	MFSL	**FSL2**	**FSL5**	**FSL10**	**FSL25**	**FSL50**	**FSL100**
FMQ							
FQ10					x		x
FQ100					x		x

In figures 23-25 the results from the simulations may be seen. Figure 23 illustrate the inundation from discharges with different return times, combined with mean sea levels. As may be seen, the inundation increases with discharges with higher return times.

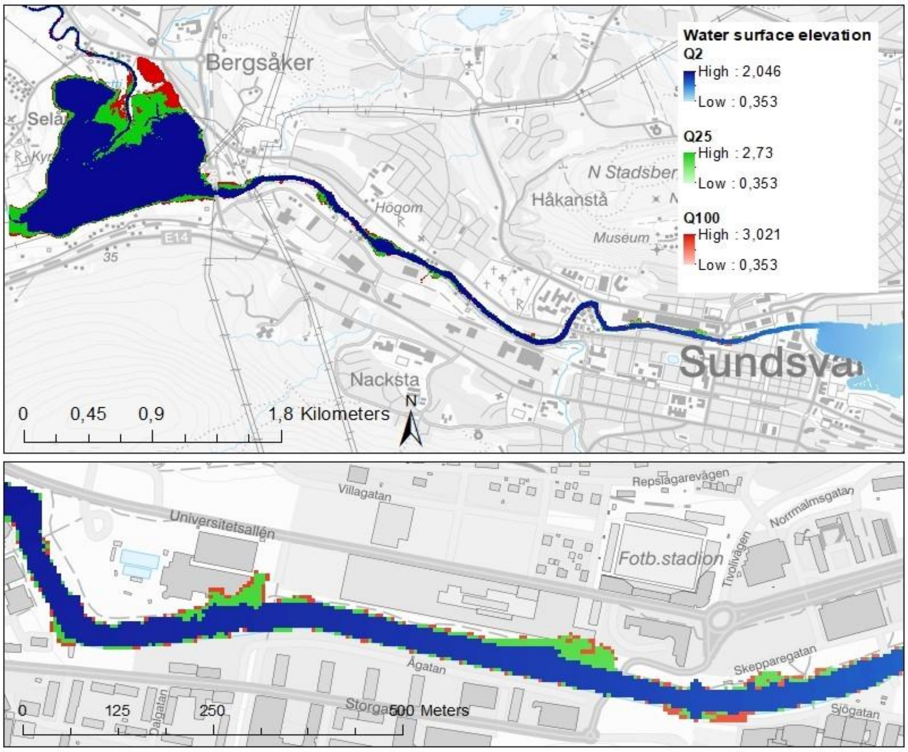

Figure 23. Simulated water surface levels at discharges with 2, 25 and 100 years return time combined with regional mean sea-levels.

In combined scenarios, sea levels did not increase the extent of the inundation, some signs of the rised sea levels could however be seen in isolated sea level events.

In figure 24 there is a simulation of a sea level event with a return time of 100 years combined with mean discharges. As may be seen, the impacts are nearly nonexistent. In the last image future normal conditions are compared with a 100-year future sea level event. Sea levels do have some impact on the inundation for this scenario, but they are not very substantial.

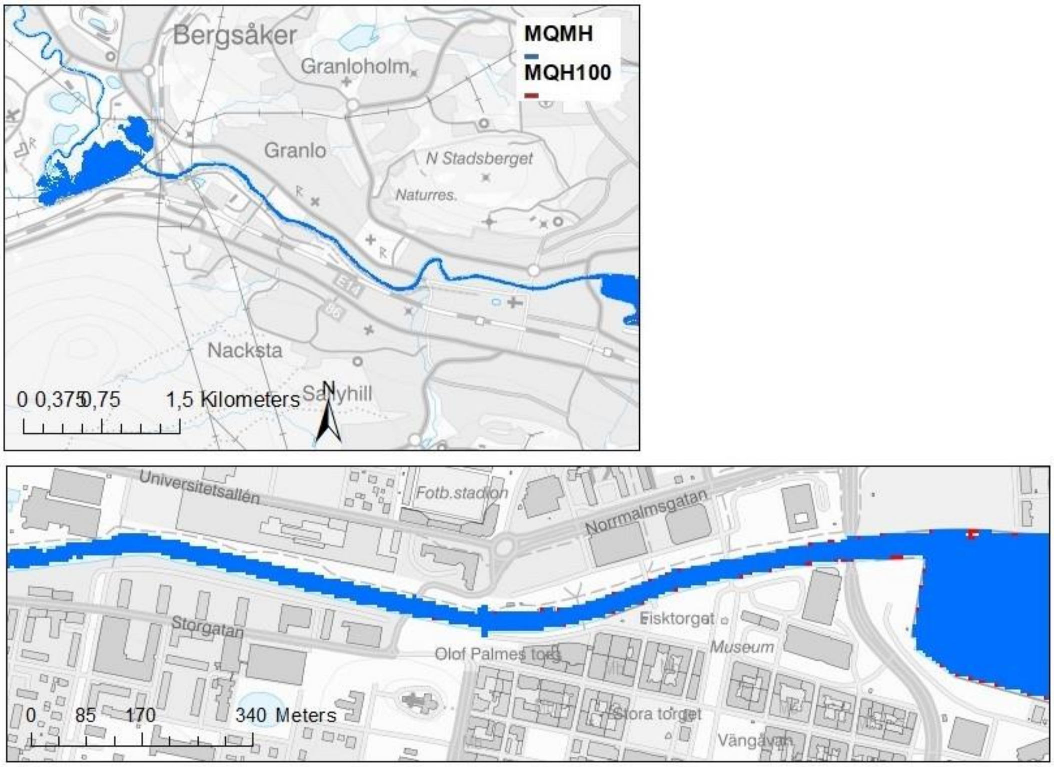

Figure 24. Extent of inundation at mean discharges combined with mean and 100-year sea levels.

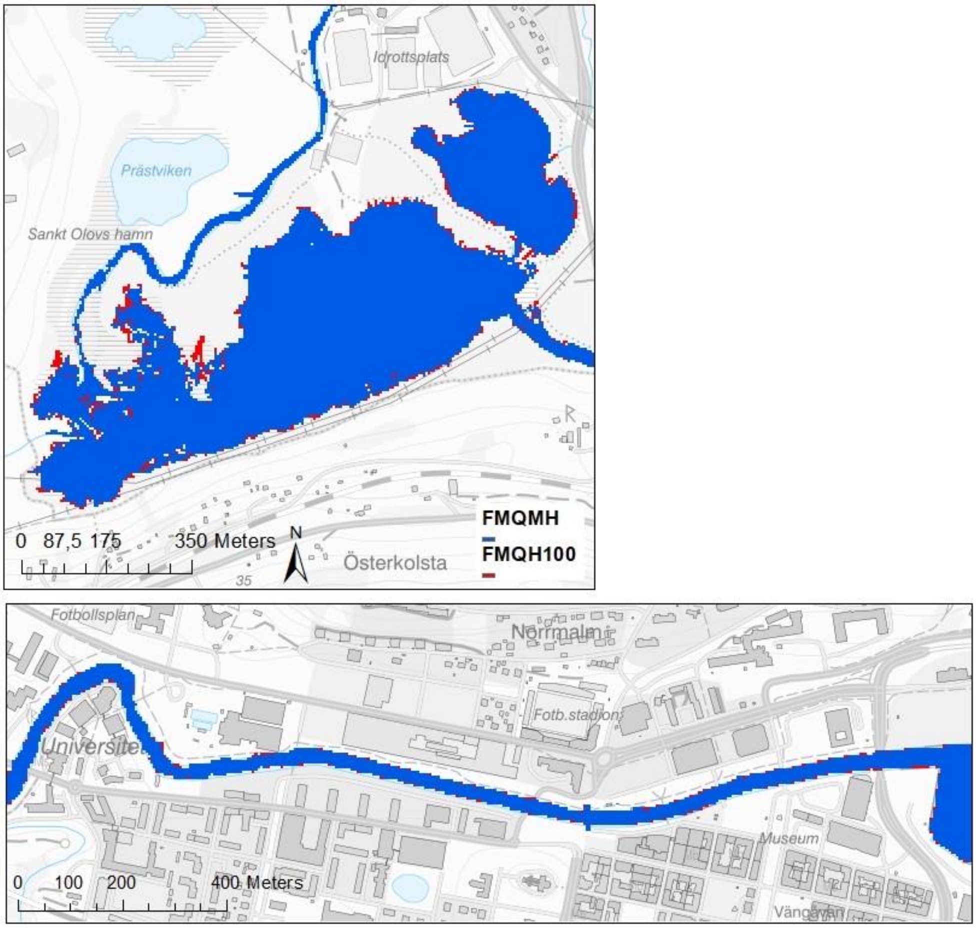

Figure 25. Extent of inundation at mean future discharge combined with regional mean sea-levels compared to sea-levels with 100 years return time.

9.4 Combined events historically

Scatter plots of daily time series of simulated discharge and observational sea levels at the case study sites may be seen below. The lines represent return times where yellow represents a return time of 2 years, orange 5 years and red indicates a return time of 10 years. The mean is shown in the green lines for sea levels and discharges respectively.

As may be seen in the images, there have been few occurrences of combined events on a daily resolution, considering no time lag. However, the direction of the points indicate there might have been more combined events in Henån and Ängelholm than in Sundsvall historically, based on these, relatively short time series. The sea levels are relative to the mean in each region.

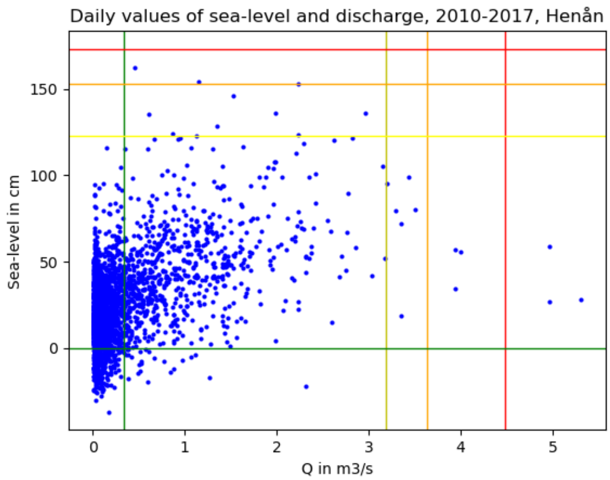

Figure 26. Daily values of sea level and discharge in Henån.

As is shown in figure 26, no day where sea levels and discharges both exceeded 2 years return time may be found in the 7 years of data available from Henån (or Uddevalla from where the sea levels are taken).

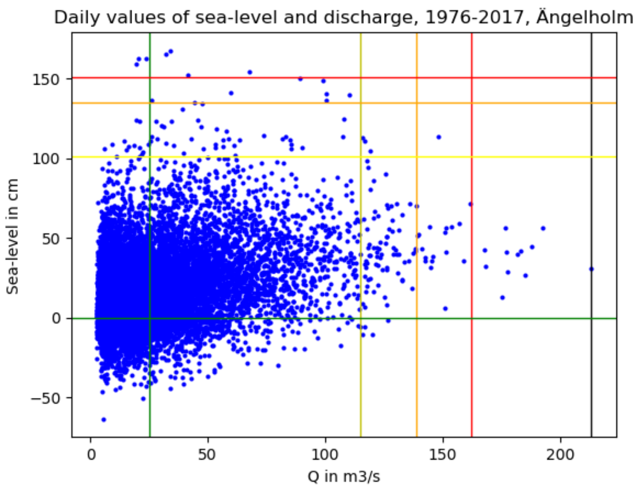

Figure 27. Daily values of sea level and discharge in Ängelholm.

In figure 27, daily sea level and discharge data from Viken and HYPE catchments for Rönne å are compared including 41 years of daily data. From the plot it may be taken that combined events with sea levels and discharge with return times of at least 2 years have occured a number of times, and in at least one event, sea levels with more than 2 years return time occur simultaneously as a discharge with a return time higher than 5 years.

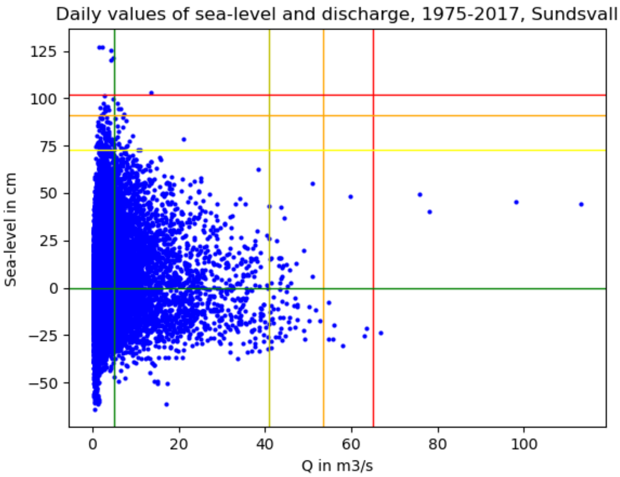

Figure 18. Daily values of sea level and discharge in Sundsvall.

In figure 28, where daily values from Sundvall are plotted, there seem to be a different pattern than in the other plots where less combined events have occured.

10. Comparison with previous studies

For two of the case study sites, Sundsvall and Ängelholm, previous studies of coastal and river floods had been made using hydraulic models. It is notable that some of the conclusions drawn from the previous studies differed from the ones that could be drawn from the results in the current study. They are therefore interesting to illuminate, and could possibly highlight limitations to both the previous studies and this one.

Both previous studies were conducted by SMHI and ordered by their respective municipalities.

10.1 Ängelholm

The first study was conducted by Björn and Berggreen-Clausen in 2016 and regarded the vulnerability of Ängelholm to combined fluvial and coastal floods now and in the future. Important differences and similarities between the studies are listed below.

- Both in the current study and in Björn and Berggreen-Clausen, 2016 sea level observations were taken from SMHI's measurement station in Viken. The estimated return times were however not the same but differed with $\pm$20 cm. For lower return times (2 and 10 years) sea levels were 10-15 cm higher in the previous study but for higher return times (50 and 100 years) sea levels are higher in this study. The differences may be due to how the return times have been calculated, but since no information is given about this in the report no conclusion can be drawn. Another likely explanation is that the three years between 2016 and 2019 that have been added to the observation series contribute to, and change the results from the extreme value analysis.

- Discharges in Björn and Berggreen-Clausen, 2016, were retrieved and analyzed from HBV-simulations, while discharge series and return times in this study were taken from HYPE. Discharges in this study were also separated by their source so that the inflow from the tributary stream entering Rönne å was included in the model. In Björn and Berggreen-Clausen, 2016, only discharges in Rönne å were simulated.

- Neither this report nor Björn and Berggreen-Clausen, 2016, have considered regional effects on the future sea level rise. Björn and Berggreen-Clausen, 2016 has however included wind generated sea level variations. The wind generated sea level rise was calculated for Ängelholm for wind events with different return times. These elevations were then added to the return times of sea level events based on sea level observations from Viken. In this study sea level variations due to wind were neglected, and to a degree assumed to be included in the sea level observations. Extreme sea level observations have possibly occurred during storm surge events, where the wind driven sea level rise is an important factor.

- It is not specified in Björn and Berggreen-Clausen, 2016, which model has been used to perform the simulations, probably because the study was a continuing, improved version of a previous mapping done in 2013. Cross-sections are mentioned implying they are using a 1D-hydraulic model. 1-D models function differently than 2D-models in that they utilize cross-sections to represent the floodplain. In 2D models, where the floodplain topography is fully represented by the DEM, there is more information. Thus it can be more accurate in some circumstances.

The scenarios that were simulated in Björn and Berggreen-Clausen, 2016, were:

- A 100-year discharge event combined with a 25-year sea level event and a 25-year wind event.
- A scenario where the highest calculated discharge was combined with a 100-year sea level event and a 100-year wind event.

- A future 100-year discharge event combined with a future 100-year sea level and a 100-year wind event.
- A 100-year discharge event combined with a 100-year sea level and a 10 000-year wind event.

In numbers the scenarios may be seen in the first two columns in the table below. There are also corresponding levels defined by the system used in this study. As may be seen there is no highest calculated discharge. All discharge events used in this study were based on return times. Another note is that the sea levels are higher in the scenarios from Björn and Berggreen-Clausen, 2016, this is due to the added wind effect. Probably the right way to compare them would be to use sea levels from this study with higher return times.

Table 12: Comparison of scenarios with combined events where sea levels and discharges have the same return time in the two studies. All sea levels are relative to the mean sea level. Flows are written in m3/s and sea levels are in meters.

Scenario*	**Flow***	**Sea level***	**Flow (Q1+Q2)**	**Sea level (without additional wind-factor)**
Q100 +H25+25 Wind	207	1.99	234.5 (191 resp. 44)	1.72
Highest calculated discharge + H100 + 100 Wind	623	2.23	-	2.02
FQ100 + FH100 +100 Wind	248	3.05	293.1 (238 resp. 55)	3.02
Q100 + H100 + 10 000 Wind	207	3.23	234.5 (191 resp. 44)	2.02

*Björn and Berggreen-Clausen, 2016

In the results from the study Björn and Berggreen-Clausen, 2016, conclusions are drawn on the impact from different types of events. They state that the consequence inundation is connected to both high discharge and high sea levels but at the most extreme discharge scenario, sea levels are negligible. In the results that have been revealed through this study another conclusion may be drawn; that high sea levels have the greatest effect on the consequence inundation and that discharge plays a less detrimental role. In the most extreme discharge scenario that was simulated, discharges did however increase the inundation, compounding the effect, when combined with a 100-year sea level event. Discharges as high as in the study by Björn and Berggreen-Clausen, 2016, were not studied.

The highest calculated discharge is several magnitudes larger than any discharge simulated in this study. All events that have been simulated in this study were based on return times, that, due to the length of the observation series, cannot capture the most extreme events that may happen (such as a 10 000-year event). The highest calculated discharge in Björn and Berggreen-Clausen, 2016, was created by feeding the HBV model with the most extreme conditions of precipitation, groundwater and snowmelt conditions.

The conclusions they draw about consequences from the design highest discharge, (that sea levels are negligible) are probably accurate considering how extreme the discharge event is. There is however no investigation on the source of impact in the combined events and thus the conclusion that could be drawn from this study, that sea levels contribute the most to the inundation of the 100-year scenarios, was not visible in theirs. Thus, the studies complement each other. The highest calculated discharge is interesting in the planning of vulnerable functions of society such as hospitals, waste water treatment plants and high-value buildings, where inundation would have large consequences. For most city planning however, a 100-year perspective and probabilities in the dimension of 100-year return times may be enough. This is also a reasoning made in Björn and Berggreen-Clausen, 2016, where the third scenario is declared to have the highest relevance to most city planning.

The compounding effect of two 10 000 year events, such as the highest calculated discharge combined with a “highest calculated sea level” of the same rarity, is too unlikely to be interesting for this study.

10.2 Sundsvall

In 2010, a study was made by Berglöv to map the consequences from floods after the severe inundation event in Sundsvall in 2001. They also sought the source of impact from flooding events in Sundsvall with similar results as those found in the simulations in this study. Below the differences in methodology, results and conclusions are listed.

- A HECRAS 1-D model was used and the 2001 event was represented in high detail in the model with a hydrograph describing the development of the discharge event, taken from HBV simulations, and observation series of sea levels from Spikarna (same station as was used in this study), describing discharge and sea level conditions from August to October. Thus, Berglöv used much longer simulation durations than what could be used in this study.

- In a comment on the results, Berglöv states that high sea levels have an impact during low flow events. There is however no image to illustrate the extent that it affects the floodplain, only a figure with water elevations in the river. In the simulations made in this thesis high sea levels have a very limited impact on the inundation. Future 100-year sea levels had an impact during normal condition flows in the area around Selångersfjärden (the lake above the city), not however in the inner city where there would have been more serious consequences from an inundation. Possibly, the elevated surface levels that were captured by Berglöv, 2010, did not increase the extent of inundation that was evaluated in this study.

- Another conclusion that was drawn in Berglöv, 2010, was that high sea levels had a limited impact when combined with a high discharge event. Something that was also found in the simulations in this study.

- The model in Berglöv, 2010, was calibrated using several measurements taken from the 2001 event while only one measurement was used to calibrate the model in this study.

- In Berglöv, 2010, the friction channel and floodplain parameters were set between 0.05-0.075, and 0.08-0.10, but in this study the corresponding value for the channel was only 0.025, and for the floodplain 0.04.

To conclude, the representation of the 2001 event in the model used by Berglöv, 2010, was much more detailed than the representation that was applied in this study. That does not necessarily mean the model in Berglöv, 2010 was better. A 1D model does not have the same potential as the 1D/2D model, where the floodplain is more fully represented. Additionally, in the evaluation of the 2001 event, neither of these differences seem to have had any impact on the result. The models produced similar results.

The conclusion in Berglöv 2001, that sea levels have an impact during low flows, is based on the surface level in the river. In this study another conclusion was made based on the extent of inundation.

11. Discussion and conclusions

In this thesis three selected study sites were studied. Their vulnerability to compounding high sea-levels and high discharge events was investigated by comparing hydraulic model simulations from different combined and isolated events.

Many modeling challenges have succeeded each other during the course of this project and solutions have been found to different sources of instabilities. In this last chapter possible explanations to the errors and the chosen solutions that were applied will be provided.

The questions posed in the introduction of this project were comprehensive and answers have been found to different extent. The problems included practical aspects in; how to form realistic scenarios by use of observation data and statistical distributions, and how to set-up LISFLOOD-FP models for the case study sites. They also regarded the development of an approach to investigate the vulnerability for compound events, at the case study sites and on a national scale. These aspects were investigated during the course of the project.

Thereafter, the main aim was met by comparing the simulated scenarios to derive sources of inundation during different flood compositions. The results were analyzed in relation to previous studies that were able to reveal some limitations to this study that will be discussed.

In summation, this project has provided some quantification on the knowledge of compounding effects along the Swedish coastline, and hopefully the strategy that has been applied as well as the answers found, will facilitate future national mapping of estuaries and deltas in Sweden.

11.1 Modeling strategy for finding vulnerabilities to compounding events

The simulations were done on an "exclusion principle". If there were no consequences from a simulated scenario, less extreme scenarios of the same type (high discharge and/or sea levels) were not simulated. Thus, simulations of more extreme scenarios were used to determine whether less extreme scenarios should be simulated. Thereby limiting the number of model executions. Since few compounding effects were found when simulating constant and simultaneous scenarios, this strategy also simplified the work on defining scenarios since the durations and timing of combined events did not need to be specified.

The lack of specified durations for different events in the model and the use of start files with initial conditions from less extreme events, led to a loss of the time aspect, and thus the development of the events could not be studied. It was however not the aim of this project to study the development of events if they were not related to compound effects. This may be saved for future studies.

11.2 Model set up

The development of the case study site models involved many rounds of trial and error as well as extensive problem-solving to find solutions to unstable model runs. Problems involved; glass wall effects when the boundary conditions were too close to the domain border, instabilities related to the gradient and shallowness of a river bed, dealing with high sea levels at low flow conditions as well as errors related to the placement of the downstream boundary condition.

The problems may be traced to two possible faults in the model. (1) The first occurred when large areas were inundated simultaneously. When the boundary condition for sea levels was placed outside of the channel the result was inundation of the ocean that in the model was represented as a wide flat surface. The same problem occurred in Sundsvall when the watercourse passed a lake. The solution was to place the downstream boundary condition on the 1D-model channel and respectively, to create a representation of the lake in the 2D-model domain. These solutions may have made the inundation more gradual and natural in the model. In the inundation of a flat surface there may also have been flow velocities where water could pass more than one cell during one time-step. Which leads to the second problem that will be discussed.

(2) The second possible explanation for most of the errors described is possibly related to flow velocities. The model cannot handle water flowing between more than one raster cell per time step. This is why the time step is altered in relation to the Friedrich-Lewy condition, something that reduces instability and decreases computation time. In some circumstances, the FLC is not enough and water flows faster than anticipated in the model, with the result that the model gets unstable. These occurrences may be related to the existence of supercritical flow. The time step in the solvers that were used is based on the gravity wave, ($\Delta t = C_n \frac{\Delta x}{\sqrt{gh}}$), and does not consider the velocity of the flow.

When there are steep gradients or disruptions of the channel bed or inundated floodplain there is a risk for hydraulic jumps and supercritical flow. Supercritical flow occurs when the velocity exceeds the gravity wave, ($F_r = \frac{V}{\sqrt{gh}} > 1$). Hydraulic jumps theoretically happen when Froude's number goes from a value higher than 1 to a value less than 1 and the relationship between the velocity and the gravitational wave is altered. If the channel is shallow and the gradient of the slope is steep, as it was in the model of Henån, the flow will be more easily affected by slope changes of the river bed, and hydraulic jumps are more likely to occur. In the acceleration solver, these effects are in the best cases exaggerated in the simulations, and in the worst, lead to instabilities of the model, as was found in Neal et al., 2011.

This may explain some of the problems with the model for Henån. In Neal et al., 2011, the friction parameter was increased to solve these problems, from 0.01 to 0.03. The model of Henån had friction coefficents of 0.02 for both the channel and the floodplain. This is a relatively low value that therefore may have contributed to the many stability problems that occured in this model.

11.3 Vulnerability to compound events at the case study sites

The main results from the hydraulic models show very limited compounding effects. One event usually had the largest impact on the extent of the inundation in an area and the other factor was negligible in comparison. In this section the vulnerability of each area will be described in more detail and the possible conclusions that could be drawn from the results will be suggested.

Henån was found to be vulnerable to high sea-levels to a much higher degree than to discharges. Sea-levels with return time of 2 years led to inundation of the harbor but in combination with a discharge with a return time of 10 years no additional inundation was seen. When a discharge with a 100-year return time was modeled some inundation was seen by the harbor but nothing of any greater consequence to society. This could be compared to the more serious consequences of a 10-year sea level event that led to inundation of county road 160, inundated buildings as well as an inundated restaurant and parking lot by the harbor.

Ängelholm showed similar vulnerability to high sea-levels. High discharges had consequences on the flooding of river banks in isolated events but in most combined scenarios the effects of high sea-levels eliminated the contribution from discharge. In one extreme future scenario, the most extreme scenario that was studied with future 100-year sea-levels and future 100-year discharges, there was a compound effect that could be seen by comparing the scenario with the corresponding isolated sea level event.

In the study made by Björn and Berggreen-Clausen in 2016, where the impact inundation from four extreme combined events in Ängelholm were studied, a highest calculated discharge was used. The discharge was three times as large as a present 100-year discharge[85] (207 and 623 m^3/s) and more than the double the magnitude of the highest discharge used in this study (293 m^3/s). When the impact from this very extreme discharge was studied,

[85] The 100-year discharge according to their calculations, in the current study the 100 year discharge was higher, 235 m^3/s.

they concluded that the discharge made contribution from high sea levels negligible.

In the other three events, they drew the conclusion that both sea levels and discharges had an impact on the inundation. The results from this study however show that only one of the events; the future 100-year discharge combined with the future 100-year sea level event, had compounding effects. The other scenarios studied (using present 100-year events) did not. For these scenarios, the sea level has the most detrimental role for the inundation consequences and the contribution from discharges can be disregarded. Björn and Berggreen-Clausen, 2016, does however highlight the limitation of the current study. The limitation is the lack of simulations of even more extreme events. They estimated that the highest calculated discharge would have a return time of approximately 10 000 years.

Sundsvall differed from the two other case study sites since discharge played the most important role in determining flood consequences. Here sea-levels were not seen to have any effect except in present and future isolated sea level events with 100-year return times. And even in such scenarios only a small number of grid cells were inundated. This result is important since it contradicts what SMHI stated regarding the impact from sea levels in Sundsvall; that they did increase the inundation during the 2001 extreme flood event and would have enhanced consequences if they had been higher. Hydraulic simulations have now shown that they did not and will not. This is important when tailoring flood warnings and highlights the need for further quantification of combined events along the Swedish coastline.

An important difference between the sea levels that were simulated in Sundsvall compared to ones at the other sites were their magnitude. The highest measured sea level at Spikarna (measurement station in Sundsvall) was 129 cm (in 1984) while the highest measured sea level recorded near Ängelholm was 235 cm (Halmstad 2015).[86]. The highest sea level simulated in Sundsvall, for a 100-year recurring sea level event in a future scenario, was 1.7 meters, the corresponding level in Ängelholm and Henån was roughly 3 meters. If three meters had been simulated in Sundsvall there would have been a larger impact from sea levels on the inundation, considering some

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impact could be seen from the 100-year events simulated, but since the continental rise is faster in Sundsvall than at the other sites (8.9 vs 1.5 and 3.4 mm/year) and the variation of sea levels is smaller, higher sea levels were not simulated.

When analyzing the results from all case study sites one may notice that a compound effect is only seen when there are consequences from both the isolated events of high sea levels and high discharges. In Sundsvall the 100-year sea-level event did not have any consequences (or had very limited consequences), and the impact was the same from the combined sea level and discharge scenario and from the isolated discharge event. Neither was there a compounding effect in Henån, where the isolated event of high discharges had very limited impact. When future extreme scenarios were simulated in Ängelholm there were consequences in the isolated event of high river discharge, but also from high sea levels, and thus when the events were combined, a compounding effect was seen.

11.4 The vulnerability of the floodplains of small and large watercourses

One of the problems that this thesis sought to answer was whether small watercourses are more or less vulnerable to compound events than larger ones. To attempt an answer to this question the results from Henån may be compared with the results from Ängelholm. As was seen in the simulations, the isolated impact from discharges in Ängelholm can be severe in extreme scenarios. This was not true for Henån where a 100-year discharge only led to minor inundation of areas by the harbor.

A difference was thus seen between the larger and smaller watercourse that could be compared. Henån and Ängelholm have more similar conditions in other aspects where Sundsvall differs, which is the reason why Sundsvall was not included in the comparison. The limitation in the scarcity of compared sites, should be considered in the conclusions drawn from the results.

An explanation to the differences may be that discharges of different return time in Henån are comparatively smaller than the ones in Ängelholm, since there is a difference in the size of the catchments, and thus the possible buildup of discharge. In high discharge scenarios, the island and village of Henån would likely also be affected by pluvial flooding, since the buildup in the watercourse originates from precipitation on the island. In Ängelholm, the catchment is much larger and the high discharges can buildup during longer time periods, and be composite of pluvial events that have occurred far away from the city.

Another aspect, not related to the size of the watercourses, that may have affected the extent of inundation from discharge, may be the gradient, that was steeper in Henån. A steeper channel slope would lead to less inundation further upstream the river and less buildup due to discharge.

11. 5 Limitations

An initial decision made in this project was to look at future scenarios to have a grasp of more extreme events that may occur at the study sites in the future. The magnitude of an event with a 100-year return time in future models, assuming the most extreme climate scenario, were considered sufficient to capture possible variations and extremes. In Björn and Berggreen-Clausen, 2016 another strategy was applied. Here the highest possible discharge that the HBV simulations could create in the most extreme hydrological scenario was used.

In impact based warning systems, two factors should be considered. The impact if an event occurs, and the risk that it will occur. If the event is very unlikely, such as an event occurring once every 10 000 years, it is both bordering on, if not impossible to estimate the likelihood that it will occur and to formulate the magnitude and consequences if it does occur. The most extreme events are instead based on the physical possibility of them occurring in the worst case scenario. In this study the combinations of high discharges and high sea levels may be seen as such formulations. For the isolated events, however, the highest extremes are events that are likely to occur once every 100 years in the future. Wind effects and other aspects have not been considered. The extreme design discharge in the study by Björn and Berggreen-Clausen, 2016, is interesting for long term city planning, but maybe not for an operational warning system. If such extremes had been considered for the isolated events, the corresponding combined events would have had return times in a scale that would have made them unreasonable to study.

Another limiting factor was the amount of observational data from past flood events since the effects of different scenarios may vary greatly depending on the calibration of the model. The conclusions that have been drawn regarding the vulnerability to compounding events at the case study sites, should however be accurate, regardless of the possible magnitude difference that a change of parameters may have resulted in.

11.6 Recommendations

In the future hydraulic models will be set up for all catchments in Sweden, including all coastal river mouths. Thus, a methodology is needed for how to deal with sea-levels and combined events. This study has shown three examples of areas with very different physical conditions regarding topography, location and size of river catchments where there has been little to no compound effects. Only one of the events high discharge *or* high sea-levels has been crucial to the inundation consequences. In the cases of compounding events both the sea level and discharge events isolated had an impact on the inundation. If this is general for Sweden combined events only need be investigated when there is a strong risk for a compounding impact.

Since the impact from discharges will be studied regardless, the impact from sea-levels will have to be added in the cases where it is considered likely for them to have an impact. A simple investigation on where this might be needed could be done by looking at low lying land by the coast, through simple GIS layer operations. Combined with an analysis of sea level variability along the coast a good base for finding areas vulnerable to high sea levels could be made. Then coastal areas that are also vulnerable for high discharges could be investigated similarly as the case study sites in this project to find their vulnerability to compounding events.

11.7 Future studies

In order to create scenarios for this project return times for high sea-levels and discharges were found separately. No combined analysis was made except for in a visualization of daily discharge and sea-level data. In this very limited investigation of whether combined events have occurred historically at the locations that were studied, few days where both sea-levels and discharges exceeded a return time of 2 years were found. However, no time lag was considered in this visualization. In Ward et al. 2018, high sea levels were found to be significantly dependent on annual maximum discharge, in 58% of the stations studied when using a time lag of $\pm$5 days.

Research on the correlation of high river discharge and high sea levels may be interesting at sites where events are compounding when they occur simultaneously, since a correlation would increase the likelihood of a combined event occurring. This is interesting research that would be valuable for at least Ängelholm's municipality, since future compounding events were found there in this study. An indication in the scatter plots created was also that combined events are more common on the west coast than on the east coast.

Conclusions

The aim of this project was to simulate inundation from combined events and derive their causes. Additionally, to add insights on the solvers and use of LISFLOOD-FP at coastal sites. The study by Björn and Berggreen-Clausen in 2016 illustrated that the compound effects that have been sought for in this study, were highly related to the scale of the probabilities that were considered. And thus, this study was limited to extremes with 100 years return time, scaled for the future in 2100 (or 2069-98 for the discharges). If more extreme scenarios had been considered, other conclusions might have been drawn, but it is also necessary to analyse events with probabilities in scales interesting for the application.

The set up was very important to the stability of the model. The general conclusion that could be drawn from the many problems that arose was that the Acceleration and Sub-grid solvers used in the simulations are vulnerable to supercritical flow and hydraulic jumps. High sea levels combined with lower flow scenarios were difficult to simulate because of the instabilities that occurred. These were mitigated to an extent by the use of startfiles, bdy-files to gradually increase discharge and sea level values, and by minding the placement of the boundary conditions in the model domain. In some, complex watercourses where the gradient of the bed slope varied, and the channel was shallow, interpolated channel depths may generate more stable model runs, even if they are further from correctly depicting the river bed.

The conclusions that may be drawn on a national level were limited since they were based on only three river outlets. They should therefore only be seen as indicators of what the results from the simulations in this study may imply, and need to be validated further. These indicators pointed towards the conclusions that:

- One factor is more detrimental to the consequences of a combined flood scenario with high sea levels and high discharges at Swedish deltas and estuaries.
- In a compounding event, the corresponding isolated events of high sea levels and high discharges, lead to inundation.
- Larger watercourses/river catchments are more vulnerable to compounding events.
- Areas on the west coast and in the south of Sweden are more vulnerable to high sea levels than areas further north or on the east coast. Impacts from floods in the north of Sweden are more likely from fluvial sources than coastal.

Conclusions that could be drawn on the vulnerability of the case study sites:

- None of the case study sites are highly vulnerable to compounding events.
- Henån and Ängelholm are vulnerable to high sea levels.
- Ängelholm is also vulnerable to high discharge
- Sundsvall is only vulnerable to high discharges.
- In a future scenario in Ängelholm there is vulnerability for a compounding event, indicating combined scenarios like the one simulated, and more extreme scenarios in Ängelholm in the future, will have compounding effects.

In conclusion, more studies are needed in order to fully understand consequences of combined events along the Swedish coastline. This study has illuminated some errors that are likely to occur in the future coastal flood mapping using LISFLOOD-FP, but also some strategies on how to avoid them. The results indicate that the impact from combined events will not be as complicated to forecast as may have been anticipated, since one factor is usually much more important to the consequences than the other. To further investigate and validate this conclusion, the vulnerability for combined events at more coastal floodplains need to be investigated similarly, and measurements from combined events need to be gathered and analyzed in order to validate and improve hydraulic models.

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Appendices

1. Histograms and distribution curves from the sea level extreme value analysis

The visual representation of the yearly maximum sea level data and the distribution density graphs may be seen in the figures below. The sea levels are given in centimeters above the mean sea level.

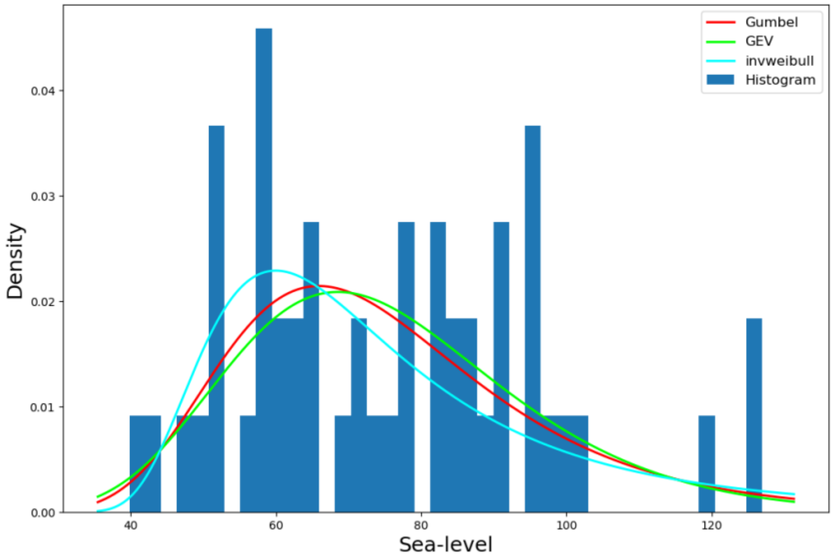

Figure 1. The histogram and fitted distributions for sea level observations in Spikarna, Sundsvall.

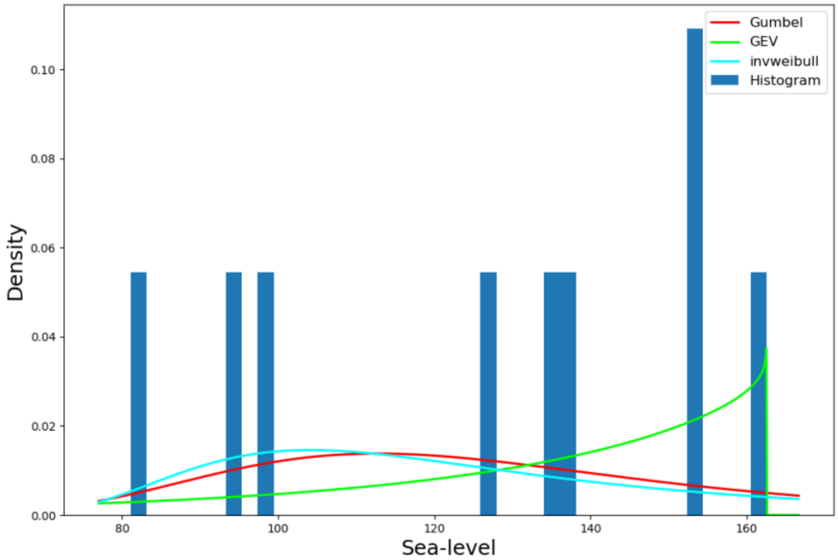

Figure 2. The histogram and fitted distributions for sea level observations from Uddevalla (Henån).

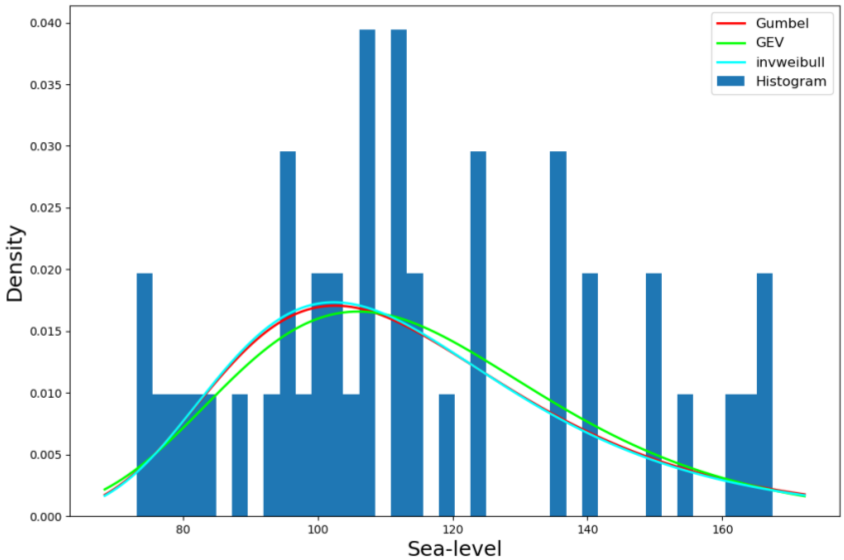

Figure 3. The histogram and fitted distributions for sea level observations from Viken (Ängelholm).

2. Calculation of percentage increase of inundated area in combined event in Ängelholm

The inundated area in Ängelholm from a simulation of a future:

100-year sea level event: 5.7 $*10^6$ m^2.
Combined 100-year discharge and 100-year sea level event: 6.17 $*10^6$ m^2.

The inundated area in Ängelholm from a simulation of (present) mean conditions: 2.33 $*10^6$ m^2.

% Increase from discharge in the combined event:

$$\frac{(6.17-5.7)*10^6}{(5.7-2.33)*10^6} = 0.139$$

3. Python scripts

Here the main python scrips that were created during this project may be found.

They will be presented in the following order:
1. Hydro_year
2. Loc_tunnel
3. Discharge and sea level comparison

3.1 Hydro_year

The following script was used to reformat the dates of monthly maximums in relation to the oceanographic year.

```
#!/usr/bin/env python
# hberk sph Hydroyear


import math
import pandas as pd
import numpy as np
```

```
from datetime import datetime, timedelta
import csv
import time

filename = 'spikarna_rw.txt'
df = pd.read_csv(filename, index_col=['date'], usecols= ['date', 'RW'])
df.index = pd.to_datetime(df.index)
date=df.index
hydro_year=[]

for row in date:
   if row.month>=7:
      hydro_year.append(row.year+1)
   else:
      hydro_year.append(row.year)

df['hydroyear']=hydro_year
df.to_csv('spikarna_hydroy.txt', header=True)
```

3.2 Loc_tunnel

The script below was used to eliminate positive slopes in the river bed point file for Henån. It first identifies a bump in the elevation, and thereafter proceeds to interpolate between the last point before the initial positive increase of the elevation, and the first point after the bump.

```
#!/usr/bin/env python
# hberk sph

import sys
import json
import math
import pandas as pd
import numpy as np
import pylab as pl
from datetime import datetime, timedelta
import csv
import time

def main():

   start = time.time()
   filename = 'C:/Temp/Skripter/riverDEM.txt'
   df = pd.read_csv(filename, index_col=['OBJECTID'], usecols= ['Rowid_','OBJECTID', 'ET_ID', 
'ET_X', 'ET_Y', 'RASTERVALU'])
```

```
points=df.index

road= [] #the identified unnatural elevation of the watercourse that could be a road, buildings etc.
road_block=0 #continues identifying and appending a road even if the new "old" elevation is larger than the elevation (thus road[0] is still not larger than the elevation).
num = 0 #counts the size of the road
act_level=0 #the interpolated watercourse
water=[] #ET_ID, separates watercourses
c=0 #parameter that separates different watercourses

for point in points: #this segment will compare elevation, create "roads" and correct peaks with an interpolation.
    try: # try: deals with point + 1 exceeding the range for the last row

        elevation_old=df.loc[point+c, 'RASTERVALU']
        water=df.loc[point+c, 'ET_ID']

        if df.loc[point+1+c, 'ET_ID'] == water: #makes sure watercourse is the same
            elevation = df.loc[point+1+c, 'RASTERVALU']

            if num > 0:

                if road[0] >= elevation_old: # road end; new values interpolated and saved at location of the road
                    road.append(elevation_old)
                    road_block = 0
                    k=(road[num+1]-road[0])/(num+1)
                    m=road[0]
                    x= 0
                    print('correction made')
                    for each in road:
                        act_level=k*x + m
                        df.at[point + c + x - len(road) + 1,'RASTERVALU']=act_level
                        x += 1

                    road=[]
                    act_level=0
                    num=0

            if ((elevation_old) < elevation or road_block == 1):# road initiated and continued
                road.append(elevation_old)
                road_block = 1

                if len(road) >= 2:
                    num += 1

        else: #ends road if there is a change of watercourse
```

```
            x = 0

            for each in road:
                act_level=road[0] #changes elevation values for the road segment
                df.at[point + c - len(road) + 1 + x,'RASTERVALU']=act_level
                x += 1

            road=[]
            act_level=0
            num=0
            road_block = 0
            c += 1


        except KeyError:
            break

    df.to_csv('riverDEM_improved.txt', header=True)
    end = time.time()
    print(end-start)


if __name__ == "__main__":
                        main()
```

3.3 Discharge and sea level comparison

The script below was created to plot daily discharge and sea levels for the respective areas in scatter plots and thereby reveal historical occurrences of combined events.

```
#Hannah Berk 2020-02-07
#script to take out flow and sea-level values based on date and create graph

import numpy as np
import scipy.stats
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

infile_q_data = '552_m.txt'
infile_SL_data = 'viken2_rw.txt'
#infile_q_data = '17563_m.txt'
#infile_SL_data = 'spikarna_rw_m.txt'
#infile_q_data = '42167_m.txt'
```

```
#infile_SL_data = 'uddevalla_rw.txt'

Q = np.genfromtxt(infile_q_data,delimiter=',',skip_header=1)
SL = np.genfromtxt(infile_SL_data,delimiter=',',skip_header=1)

year_vals_Q = Q[:,0]
year_vals_SL = SL[:,0]

data_vals_Q = Q[:,1]
#yinterval=SL[12876:12847+year_vals_Q.size]
data_vals_SL = SL[0:year_vals_Q.size,1]


#create plot figure and axis
#plt.figure(figsize=(12,8))
#ax = plt.axes()

plt.plot(data_vals_Q, data_vals_SL, 'bo',label='Sea level versus flow')

plt.xlabel('Q in m3/s')
plt.ylabel('Sea-level in cm')
plt.title('Daily values of sea-level and discharge, 1976-2017, Ängelholm')
#plt.title('Daily values of sea-level and discharge, 1975-2017, Sundsvall')
#plt.title('Daily values of sea-level and discharge, 2010-2017, Henån')

#Ängelholm
plt.axvline(c='g', lw=1, x=25)#MQ
plt.axvline(c='y', lw=1, x=115)#HQ2
plt.axvline(c='orange', lw=1, x=139)#HQ5
plt.axvline(c='r', lw=1, x=162)#HQ10
plt.axvline(c='black', lw=1, x=213)#HQ50

plt.axhline(c='g', lw=1, y=0)#HQ
plt.axhline(c='yellow', lw=1, y=101)#2.5
plt.axhline(c='orange', lw=1, y=135)#5
plt.axhline(c='r', lw=1, y=151)#10
plt.show()

#Sundsvall
#plt.axvline(c='g', lw=1, x=4.97)#MQ
#plt.axvline(c='y', lw=1, x=41.046)#HQ2
#plt.axvline(c='orange', lw=1, x=53.5)#HQ5
#plt.axvline(c='r', lw=1, x=65.1)#HQ10

#plt.axhline(c='g', lw=1, y=0)#HQ
#plt.axhline(c='yellow', lw=1, y=73)#2
#plt.axhline(c='orange', lw=1, y=91)#5
```

```
#plt.axhline(c='r', lw=1, y=102)#10
#plt.show()

#Henån
#plt.axvline(c='g', lw=1, x=0.344)#MQ
#plt.axvline(c='y', lw=1, x=3.19)#HQ2
#plt.axvline(c='orange', lw=1, x=3.635)#HQ5
#plt.axvline(c='r', lw=1, x=4.48)#HQ10

#plt.axhline(c='g', lw=1, y=0)#HQ
#plt.axhline(c='yellow', lw=1, y=123)#2
#plt.axhline(c='orange', lw=1, y=153)#5
#plt.axhline(c='r', lw=1, y=173)#10
#plt.show()
#plt.savefig(''
```