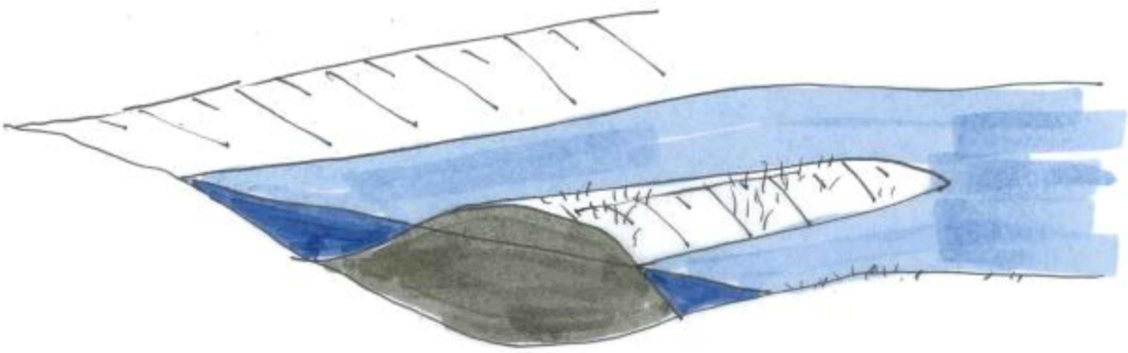
IMMERSE

Implementing measures for sustainable estuaries

WP3.10

Regional dynamic flood protection measure in the Roskildefjord and Isefjord



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1. INTRODUCTION

In the North Sea Region (NSR), the estuaries are intensively used for a wide range of activities such as industry, agriculture, fishery, recreation, and tourism. NSR estuaries are also valuable habitats and ecosystems protected by European legislation. At the same time, the pressure from rising sea-levels and more intense storm-surges is already occurring and is expected to increase in the future.

The challenge is to sustainably and cost-effectively manage and adapt the estuaries to the changing hydrodynamic pressures while preserving or improving the functions of the estuarine system. Flood protection is also on the political agenda both locally, regionally and on a national level. However, flood defence systems on a regional level have not been systematically investigated and it is not straight forward due to the sensitivity of the areas.

This study uses numerical models to investigate the effects of measures in sensitive shallow tidal estuaries. Together with stakeholder integration and political commitment, this project aims at improving development and accelerate implementation of large-scale measures at NSR estuaries leading to better accessible and more sustainable estuaries.

More specifically this project focuses on:

- Overview of existing and anticipated/future pressures and trends
- Analysis of flood protection measures to deliver identified benefits
- To control risks of flooding and climate change while conserving sufficient ecosystems
- Investigate transferability of the measures to other estuaries

2. STUDY AREA

The estuary consists of two fjord systems, Isefjord and Roskilde Fjord – both characterised as micr

otidal estuaries with tidal ranges of 0.1-0.2 meters.

Isefjord is 35 km long fjord with a total area of 305 km^2 and an average depth of 5-7 meters. Isefjord is a “threshold fjord” with a large central basin as well as several separate smaller fjords counting Lammefjord, Holbæk Fjord and Tempelkrog. The salinity of the Isefjord rises in the winter period (1,8-2,6 %) and drops in the summer period (1,6-2,0 %). Stratification occurs periodically because of intrusion of saline water from the Kattegat Sea.

In the hinterland to the Isefjord, several land reclamations have been established in the bays, where dams and water from the reclaimed areas is pumped into the fjord. The largest reclamation project is Lammefjorden, which constitutes an enclosed area of approx. 6000 acres. The reclaimed area is situated 7.5 meters under mean sea level (MSL). The plant is Northern Europe's largest reclaimed area.

At the southern part of Isefjord lies the town of Holbaek (Figure 1) with approx. 30.000 inhabitants. There are summer cottage areas close to the fjord, where some of the ground levels are below 2 metres from MSL.

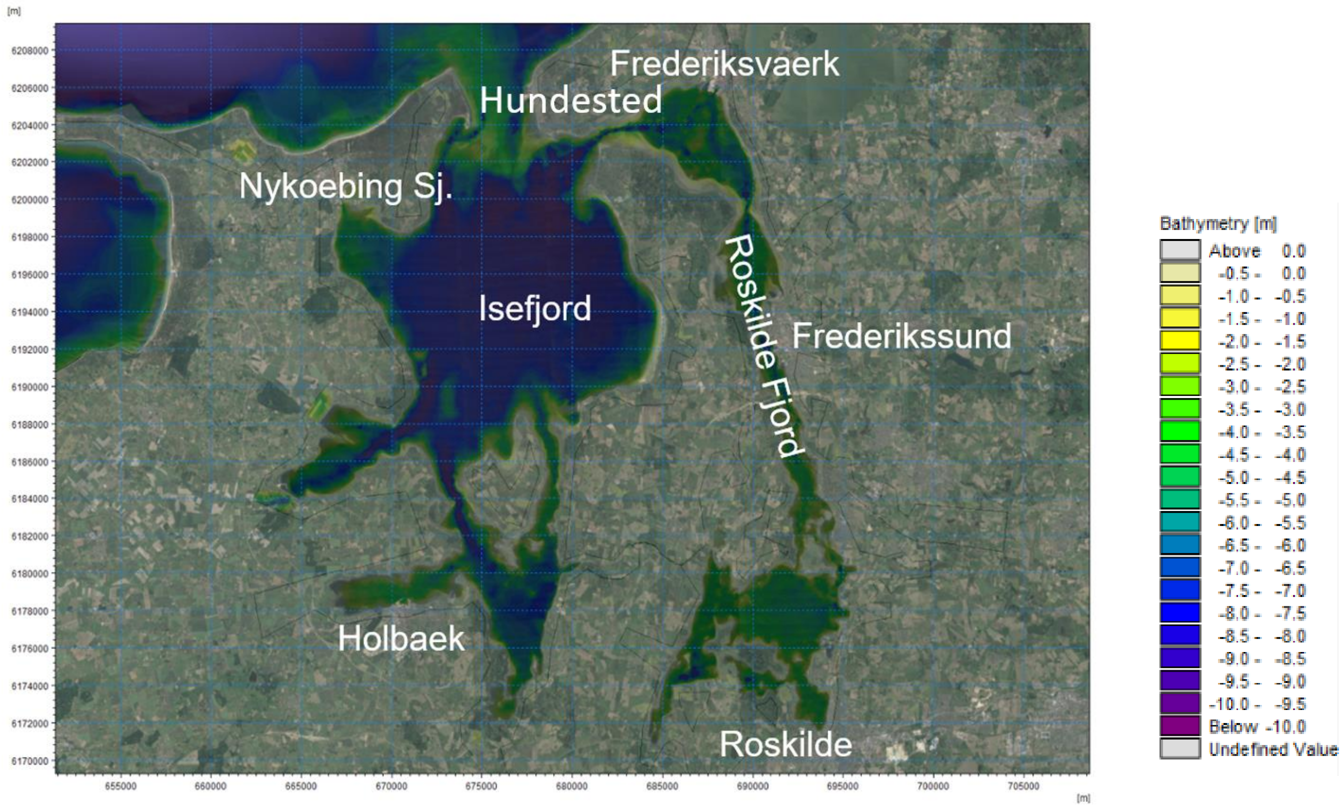


Figure 1 Aerial photo of the sensitive shallow estuary system with Isefjord and Roskilde Fjord.

Roskilde Fjord has a length of approx. 42 km and an area of 74 km^2 and is a relatively shallow fjord with a depth of approx. 5 meters in most places, but also has some deep areas where it is approx. 29

m deep. The Fjord partly consists of narrow stretches as well as wider broads such as the Frederiksværk Broad and Roskilde Broad. A shallower threshold splits the fjord in two at “Eskildsø” (Eskilds Island) resulting in a salinity of 1,2 – 1,4 % in the southern half of the fjord and slightly higher with a salinity of 1,6 – 1,8 % in the northern half. Stratification can occur temporarily in the case of saltwater intrusion, but for most of the time the water column is fully mixed.

There are several small undisturbed islands in the fjord, some of them designated as EC bird protection areas and EU habitat areas. At the south-east coast of the fjord is the town of Roskilde with approx. 50.000 inhabitants. Frederikssund and Jyllinge are larger towns along the eastern coast in the fjord.

The area Jyllinge Nordmark where Værebro Å (water course) runs through has been heavily influenced by floods in recent years. Here we also find Risø, Denmark's only nuclear power plant, which is now closed, but which now stores the nuclear waste produced through the years.

The regional topography reflects a geomorphology resulting from the last glaciation where glacial till and outwash plains were deposited. The coastal zone of the estuaries is dominated by low-lying marine foreland, reclaimed areas and saltmarsh. As the estuaries are micro-tidal one entrance estuaries, the approach is to develop and test large scale measures for flood protection of sensitive shallow tidal estuaries.

2.1. Hydrodynamic pressures

2.1.1. Water level data

There are water level data from Roskilde since 1992 and for Holbaek since 1972. These water level stations are operated by Danish Meteorological Institute (DMI). The locations of the water level stations are shown in Figure 2.

Figure 2 Water level stations at Roskilde and Holbaek.

2.1.2. Extreme water levels

The Isefjord and Roskilde Fjord estuary system has experienced severe flooding of many houses during the last approx. 10 years. The worst storm was the 2013 storm named Bodil, which flooded major parts of the estuary. The flooding level was 2.06 m in Roskilde and 1.94 at Holbaek (Table 1). In response to the frequent flooding events, local solutions for flood protection have been initiated and some places completed.

Measured peak water levels at Roskilde and Holbaek from the three most recent storm-surges are given in Table 1 and the extreme value analysis from the Danish Coastal Authority are given in Figure 3.

Table 1 Peak water levels from the national extreme water level statistics, Ref. /1/.

	"Bodil" 06-12-2013	**"Egon" 11-01-2015**	**"Urd" 27-12-2016**
Roskilde [m DVR90]	2.06	1.34	1.52
Holbaek [m DVR90]	1.94	1.25	1.59

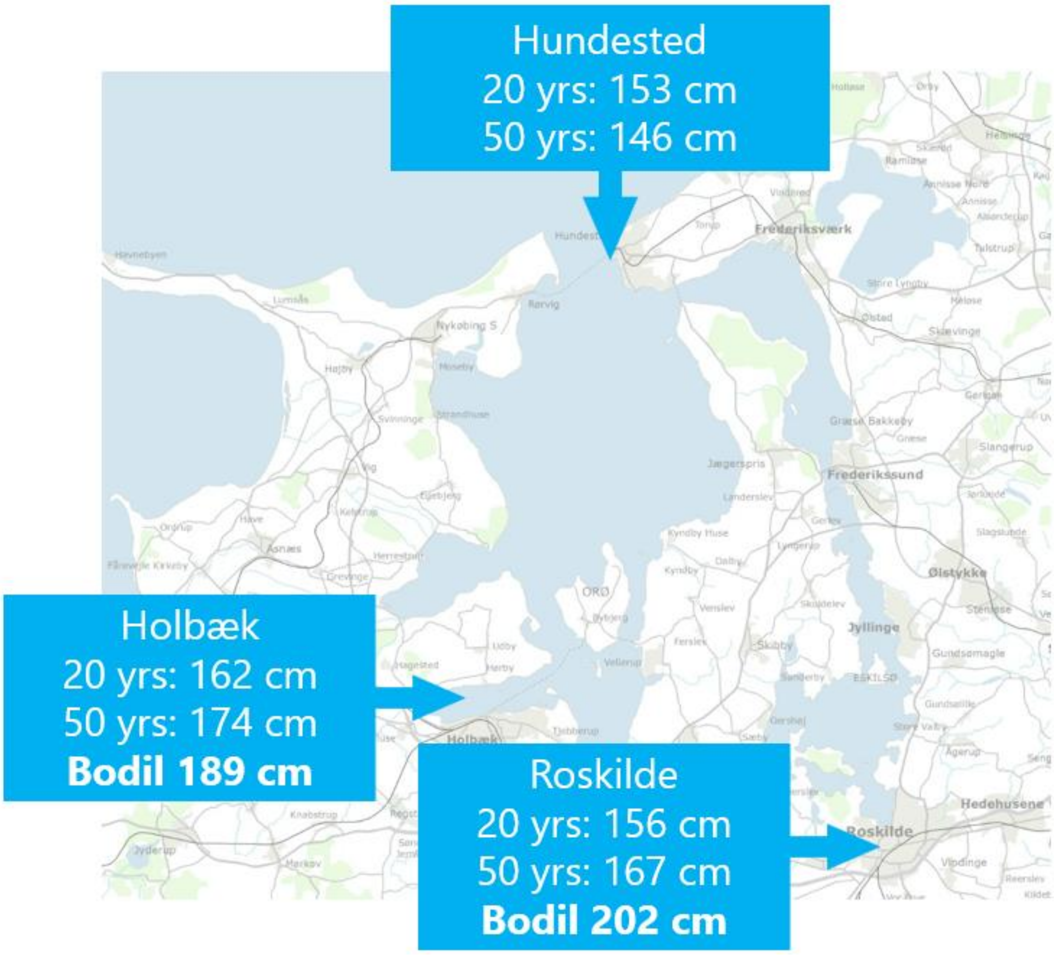


Figure 3. Extreme value analysis at three locations, Ref /1/.

2.1.3. Sea level rise

According to Ref. /2/ it is recommended that when planning beyond year 2050 the RCP8.5 scenario should be used. However, it is also possible to use the RCP4.5 scenario as a basis for planning to-wards 2050 if it would be cost-effective to raise the security level of the storm-surge protection measures.

For the coastline in the Isefjord the expected change in mean water level is 31 cm (median value) with a deviation up to 63 cm for the RCP4.5 scenario for the end of this century 2071-2100. For the RCP8.5 scenario the values are 52 cm to 96 cm at the end of this century 2071-2100. Along the coastline of the Roskilde Fjord the change in mean water level is expected to be between 27 cm to 60 cm for the RCP4.5 scenario and 51 to 96 cm for the RCP8.5 scenario, Ref. /2/.

2.1.4. Tides

The astronomical tide in the estuary is semi-diurnal and can be characterized as micro-tidal. In Holbaek the spring tide tidal amplitude is 30-35 cm and 10-15 cm at nip tide. At Roskilde the tidal amplitude is 5-10 cm with minor variations between spring- and nip tide.

2.1.5. Isostatic processes

Due to the last glaciation, there is an ongoing uplift at the estuary area between 1.2-1.4 mm/year see Figure 4. This gives over 50 years (2020-2070) a landrise between 0,060 – 0,070 m, which must be subtracted when designing security levels of storm-protection measures.

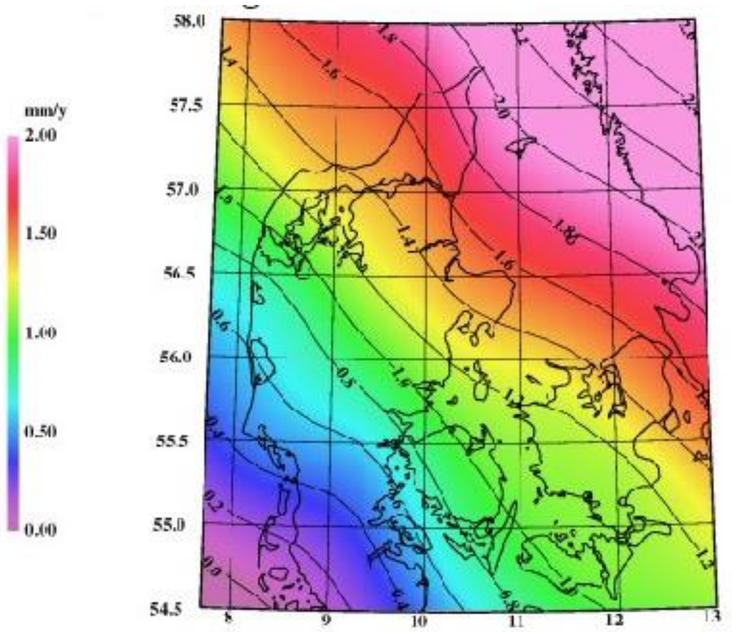


Figure 4 Absolute uplift speed in Denmark in mm/year. At the Roskilde and Isefjord estuary it is between 1.2-1.4 mm/year. Ref. /5/.

2.1.6. Waves

Wave impact must be expected to vary along the individual coastal stretches of the estuary depending on the fetch, the current wind direction, and the wind speed.

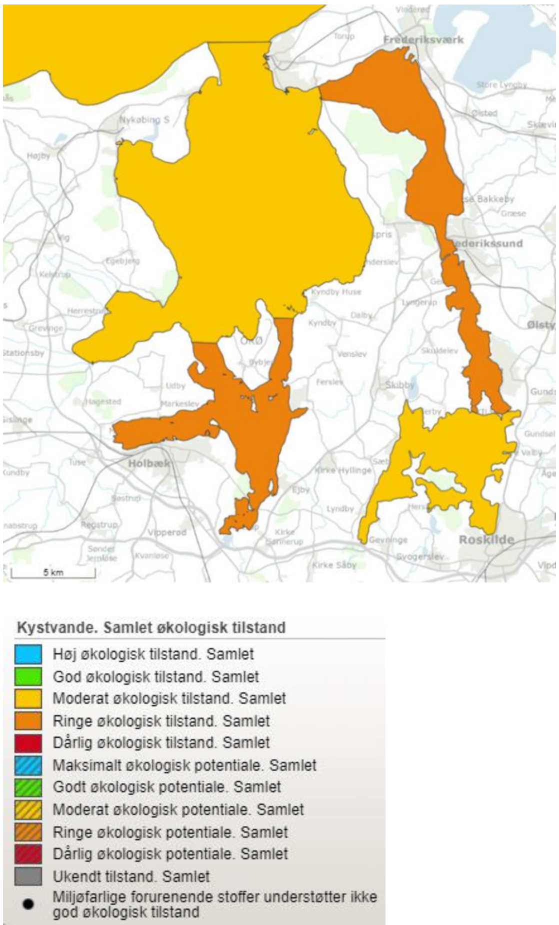
2.1.7. Example of design criteria for storm-surge protection measures

Based on the above, a design elevation criteria can be determined for potential storm-surge protection measures at Roskilde and Holbaek. It basically consists of a 100-year extreme water level, the expected sea-level rise and land uplift.

2.2. Water quality

According to the Danish implementation of the Water Framework Directive, i.e. river basin management plans, the current ecological status of the inner parts of Roskilde Fjord is classified as moderate ecological status while the outer northern part of the fjord is classified as poor ecological status based on monitoring of chlorophyll a, eelgrass and benthic invertebrates.

The ecological condition at the inner part of Isefjord is classified as poor ecological status (Figure 5) based on monitoring of chlorophyll a and eelgrass while the outer northern parts of Isefjord is classified as moderate ecological status based on monitoring of chlorphyll a, eelgrass and benthic invertebrates.



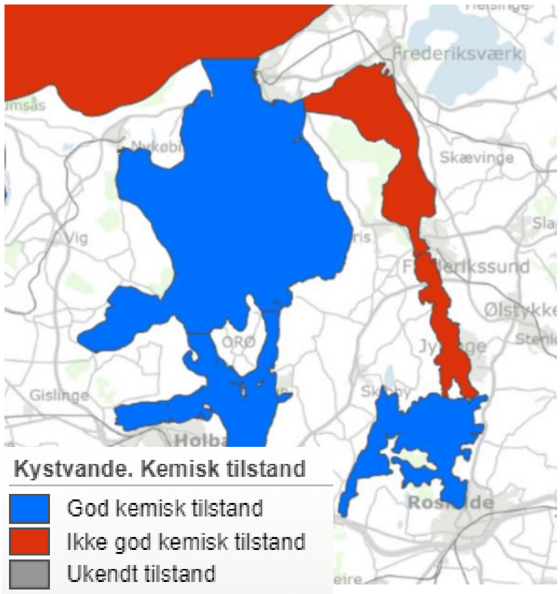


Figure 5. Ecological status (left) and chemical status (right) of coastal water bodies.

When looking at the chemical status of the water bodies in the estuary, the chemical status at the inner part of Roskilde Fjord is good based on monitoring of mussels while the outer part is classified as bad chemical quality based on monitoring of mussels caused by BDE mercury.

The Isefjord is classified as good chemical quality both at the inner and outer part based on monitoring of mussels.

2.3. Sources of pollution

Public and industrial wastewater from the catchment area is treated in 71 public wastewater treatment plants (WWTPs) and 26 private plants discharging treated wastewater to the fjords resulting in elevated concentrations of nutrients and organic matter.

The total annual discharge in 2009 was 190 tonnes of Nitrate and 26 tonnes of Phosphorous. In the urban areas several Combined Sewer Overflows (CSOs) discharge diluted wastewater to water bodies resulting in heavy nutrient loading of fjords.

In addition to this, about 8000 households in the catchment area are not connected to the public sewer. Household wastewater from these properties is treated locally in “septic tanks” or by infiltration to the soil also affecting the water quality of waterbodies in the estuary system.

In addition to the domestic wastewater, several larger industrial companies have separate outlets to the fjords. These industries comprise food, steel, concrete, transportation, and chemical industry.

The nitrate discharge is the dominant factor regarding the water quality of the marine waters. Several of the larger WWTPs and industries have direct outlet to the fjords, while the CSOs and discharge from rural areas discharge to streams eventually leading to the fjords.

WWTPs and industry are the major point sources of pollution of the fjords. Rural areas are the primary contributor of organic matter while CSOs and rural areas together contribute with most of the phosphorous pollution.

Diffuse pollution sources degrade the water quality as a result of leaching of nutrients primarily from agriculture. The nutrient load has been declining since the 1980’s with the implementation of the water environment plans.

Roskilde Fjord and Isefjord are currently not fulfilling the objectives of the WFD of good quality. This is, as mentioned above, primarily due to leaching and outlet of nutrients (nitrate) primarily from agriculture and domestic WWTPs, hazardous substances and heavy metals primarily from industry, agriculture and ship traffic.

A lot of the initiatives initiated by the EU directives (Wastewater Directive, Nitrate Directive, Water Framework Directive) etc. to improve water quality are still ongoing.

2.4. Ecology

Shell-harvesting up until the 90's in the Roskilde Fjord has influenced the seabed physically. Several holes in the seabed are still present. The holes have been used for dumping of soil material from minor harbours. In Isefjord one dumping site for unpolluted soil is still in function.

Dredging of bottom sediments are performed on a regular basis to maintain fairways for ship traffic in both fjords. This practice has a negative physical impact on the bottom flora and fauna.

Across Isefjord and the northern part of Roskilde Fjord fishing for mussels by a "scraper" removes part of the bottom vegetation (eelgrass), rocks and fauna, deteriorating the ecological quality of the fjord.

Heavy nutrient loads leading to oxygen depletion has a negative effect on the bottom fauna. Although in recent years, oxygen depletion has not been recorded, and oxygen levels seem to be improving.

High concentrations of hazardous substances in the sediment, water and mussels exceed international limit values.

2.5. Natura 2000 areas

The Natura-2000 areas in the river catchment area comprise meadows, freshwater marshes, and saltwater marshes. Furthermore, several wetlands and moist natural areas outside the Natura 2000 areas rely on the water ecosystems in the river basin. Some of these are habitat to wildlife of high value including characteristic and/or rare species of flora and fauna.

Within the river basin there are 16 Natura 2000 areas with a total area of 25.000 acres (Figure 6). Of these, 11.000 acres are situated in sea and fjord areas. Almost the entire area of Roskilde Fjord is designated as Natura 2000 area as well as 8 stretches of the coastal line of Isefjord.

About 30 bird species breeds on the vacated islands of Roskilde Fjord.

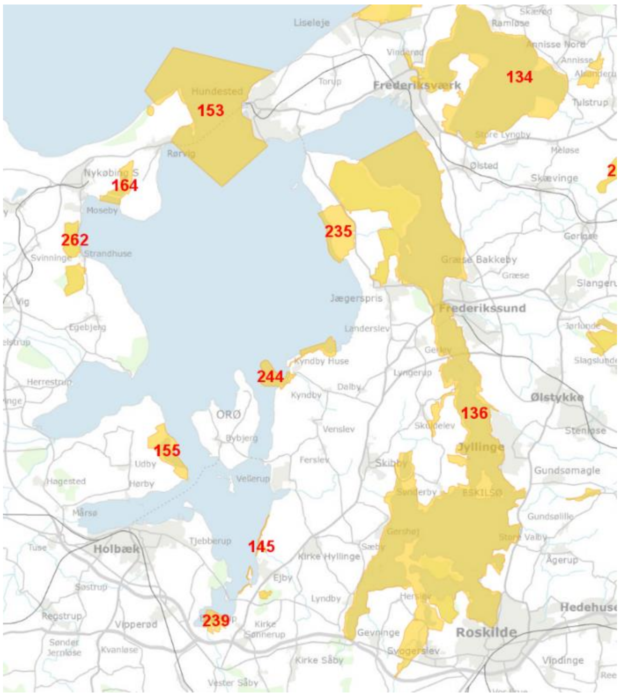


Figure 6 Natura 2000 areas around Roskilde Fjord and Isefjord.

2.6. Coastal protection and flood protection measures

According to the Danish Coastal Authority's coastal atlas, Ref. /6/, the coastlines along the estuary system consists of both coastal protection and flood protection measures. The coastal protection along the estuary coastlines consists of a mix of dikes, breakwaters, groynes, seawalls, etc.

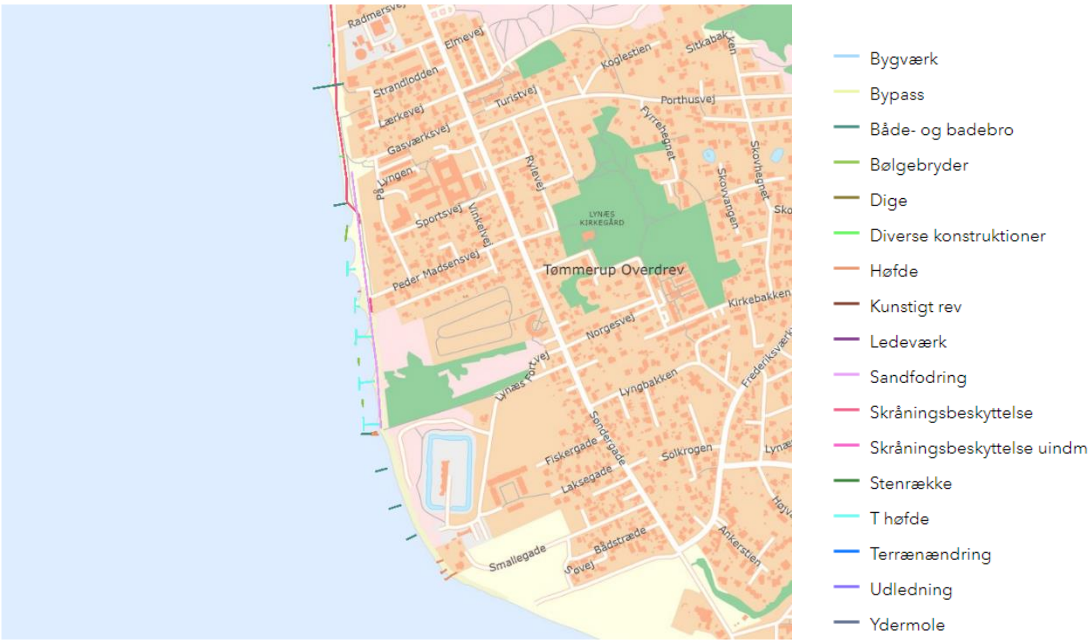


Figure 7. Example of different coastal protection measures at Tømmerup Overdrev. The coastal protection schemes here are: nourishment (pink), breakwaters (light blue), groynes (dark green/orange) and slope protection (red), Ref. /6/.

Also, more recreational structures such as bathing bridges are widely distributed across the estuary. At some places sand nourishments have been used to protect the coastline from erosion and improve the recreational value in the area.

Other hard structures in the estuary cover slender members such as piles, pipelines and large structures such as bridges, piers and docks.

3. MODEL SET-UP

The numerical model (MIKE 21) is used for hydrodynamic simulations in a regional model and a more detailed local model covering the estuary fjord system. The models were run with an hourly time step interval. The model set-up is shown in Table 2.

Table 2 Model set-up of regional and local numerical models.

Regional model		Local model	
Solution technique	Low order, fast algorithm	Solution technique	Low order, fast algorithm
Depth correction	No depth correction	Depth correction	No depth correction
Flood and dry	0.0005/0.1	Flood and dry	0.0005/0.1
Density	Barotropic	Density	Barotropic
Eddy viscosity	Smagorinsky (0.28)	Eddy viscosity	Smagorinsky (0.28)
Bed resistance	Manning map	Bed resistance	Manning map
Coriolis forcing	Varying	Coriolis forcing	Varying
Wind forcing	Varying	Wind forcing	Varying
Ice	Specified	Ice	No
Precipitation/evapor.	Specified	Precipitation/evapor.	No
Rivers discharge	Specified	Rivers discharge	No

The regional and local domains are based on bathymetric scatter data covering the North Sea, Inner Danish Waters and the Baltic Sea. The bathymetric data is from EMODnet and scatter data from digital elevation models is also applied to the local model. The models are forced by a 40-year hindcasted wind and pressure data timeseries from the ERA-5 model (ECMWF). ERA5 provides hourly estimates of many atmospheric, land and oceanic climate variables. It is a high-resolution reanalysis developed by ECMWF which is the European Centre for Medium-Range Weather Forecasts. The data cover the Earth on a 30 km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions. The dataset is continuously extended since 1979 and is freely available. Data is hourly sampled.

3.1. Regional model

The regional model has been set up for investigating the long-term hydrodynamic behaviour and supplying boundary conditions (BCs) to the local model. The regional model covers the North Sea, Baltic Sea and Inner Danish Waters. The regional model takes tides, river runoffs, winds and precipitation into account and covers a period from 1979 to date. Two boundary conditions were applied to the model. The model is bounded by a northern BC between Norway and the UK and a southern BC at the English Channel between France and UK (Figure 8).

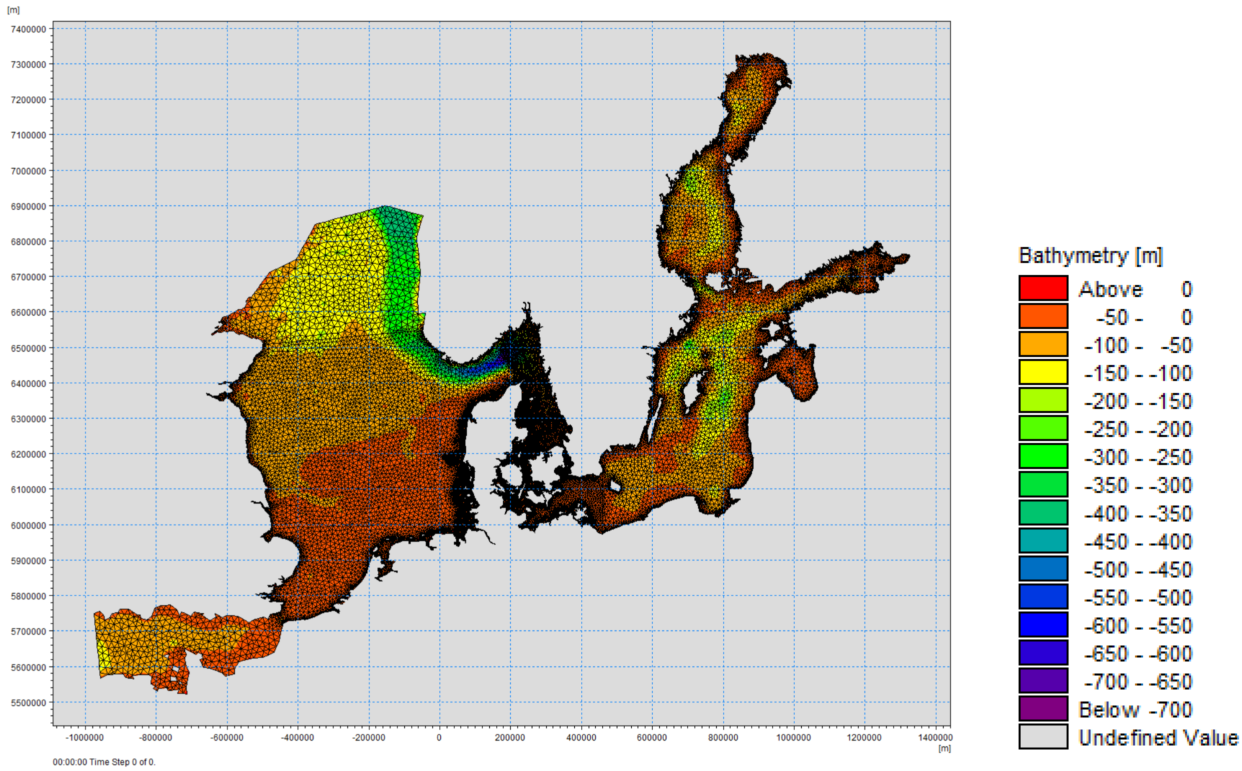


Figure 8. Regional mesh covering the North Sea, Inner Danish Waters and Baltic Sea.

The mesh was drawn with gradually finer resolution zones around areas of interest and in nearshore areas. A triangular mesh approach was applied to the model with local maximum areas varying from 2e+08 in the northern part of the North Sea to 1e+08 at the central North Sea and Baltic Sea. In the Inner Danish Waters, the triangular mesh resolution was set to 1e+07 and 4e+06 in nearshore areas.

3.2. Local model

The local model covers the estuary fjord system, Isefjord and Roskilde Fjord. BCs were drawn from the regional model. A northern BC and a western BC in Kattegat and a southern BC in the strait of Øre-sund were applied to the model.

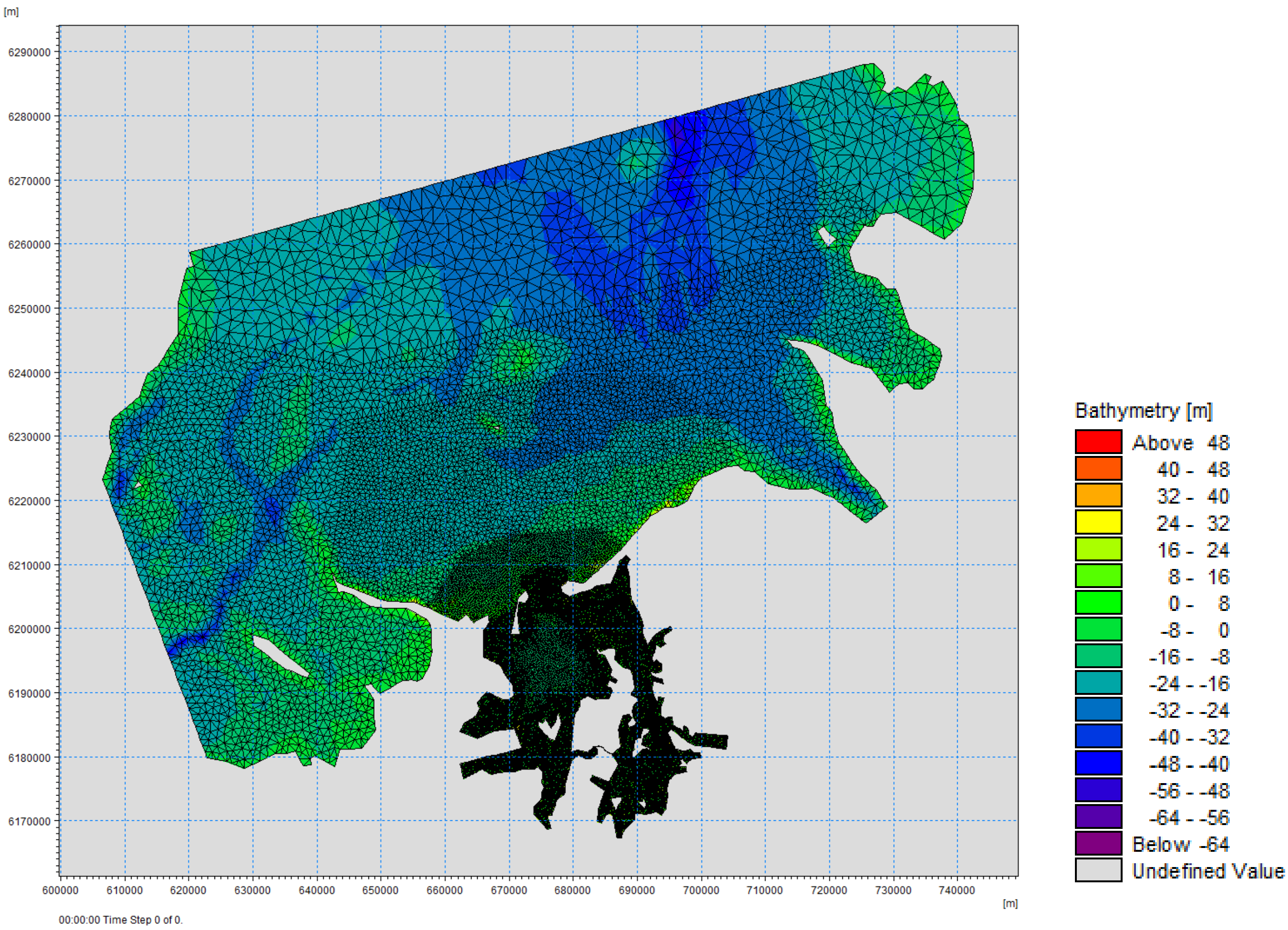


Figure 9. Local mesh covering the southern part of Kattegat and the estuary fjord system.

The local model was calibrated against the measured water level timeseries from Holbaek and Roskilde. Special emphasis was given to the storm event “Bodil” 6th of December 2013 where peak water levels in Roskilde was 2.06 and 1.94 in Holbaek (Danish Coastal Authority, 2017).

The mesh was drawn with gradually finer resolution zones around specific areas of interest, i.e. where the measures are introduced and in the channel of Roskilde Fjord (Figure 9). A triangular mesh was applied to the model with local maximum area just outside the estuary mouth set to 125000 and 100000 at the central part of Isefjord. The nearshore areas in the estuary were set to 35000. A quadrangular mesh was applied to the model at the tidal channel in Roskilde Fjord and in the areas where the estuary barrier measures are applied (Figure 10).

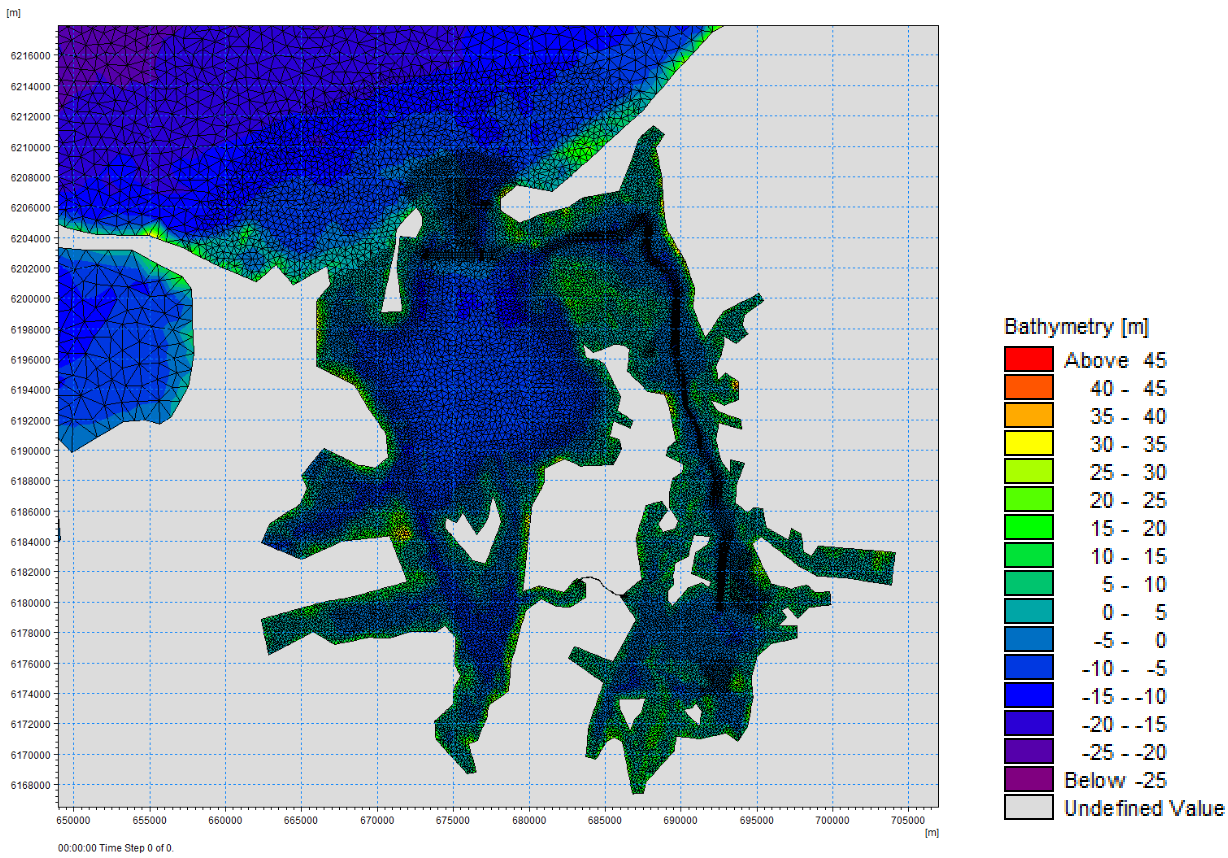


Figure 10. Local mesh covering the Isefjord and Roskilde Fjord estuary.

4. CALIBRATION

The regional and local numerical models were calibrated from measured water level timeseries distributed across the regional and local model domains. The calibration was completed by regulating the Manning numbers, mesh resolution and approach (triangular/quadrangular) until the measured and modelled water levels reached acceptable deviations.

4.1. Regional model

The Manning numbers for the regional model were set to 55 m$^{(1/3/s)}$ for the North Sea, 60 m$^{(1/3/s)}$ in Skagerrak, 40 m$^{(1/3/s)}$ in Kattegat, 20 m$^{(1/3/s)}$ Inner Danish Waters and 45 m$^{(1/3/s)}$ in the Baltic Sea. The regional model was calibrated against measured water level data from distributed stations across the entire regional model.

Three water level stations, Drogden, Skagen and Gedser, are shown in Figure 11 to Figure 13 with comparison of measured/modelled extreme values for specific high water level events.

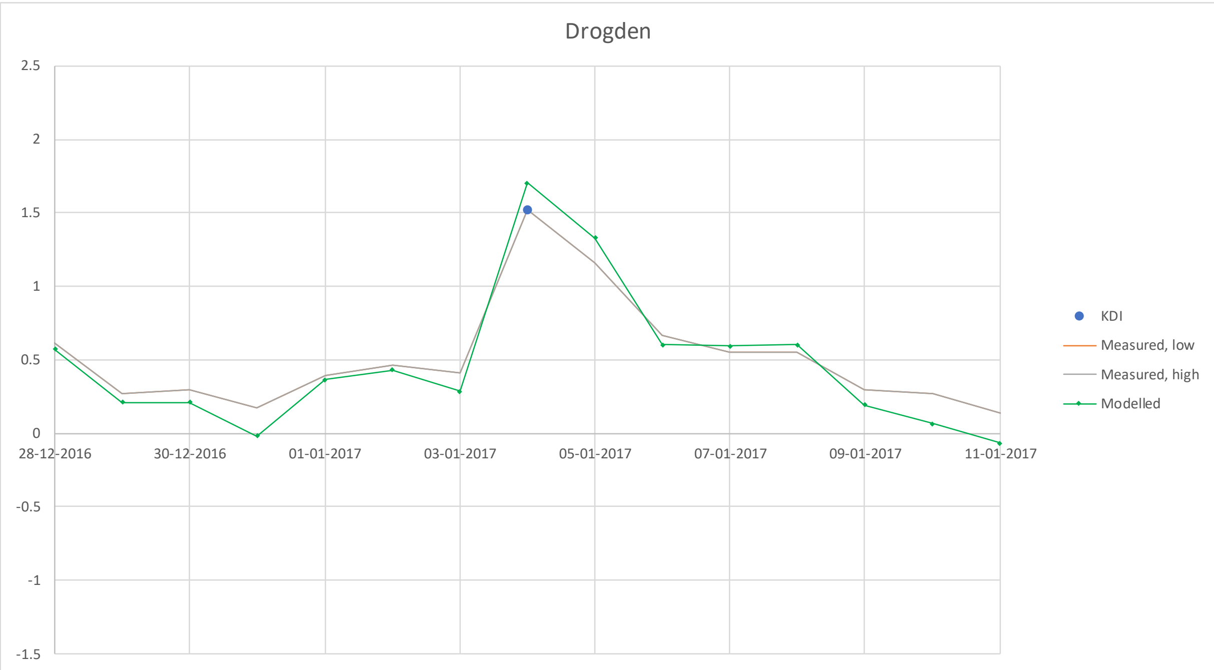


Figure 11. Timeseries of measured and modelled water levels (m) at Drogden during a peak event between 03-01-2017 and 07-01-2017.

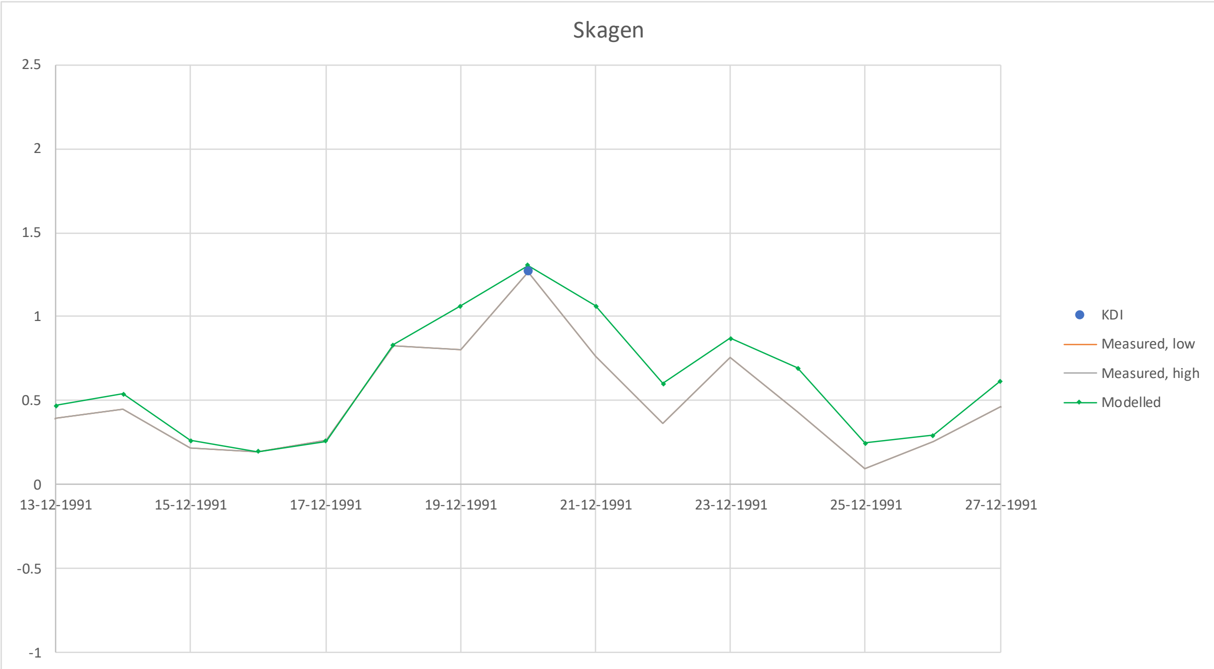


Figure 12. Timeseries of measured and modelled water levels (m) at Skagen during a peak event between 17-12-1991 and 22-12-1991.

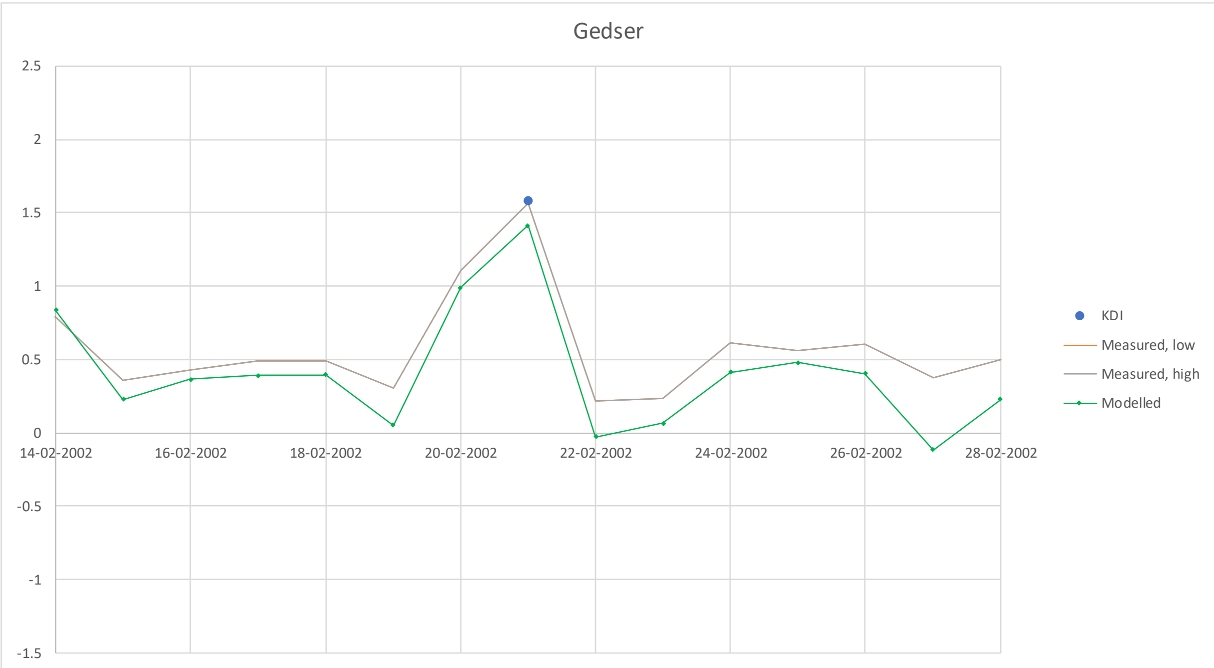


Figure 13. Timeseries of measured and modelled water levels (m) at Gedser during a peak event between 19-02-2002 and 22-12-1991.

The measured and modelled values are compiled in Figure 14 based on the national extreme water level analysis from 2017 from the Danish Coastal Authority where the 20 most extreme situations are compared with modelled.

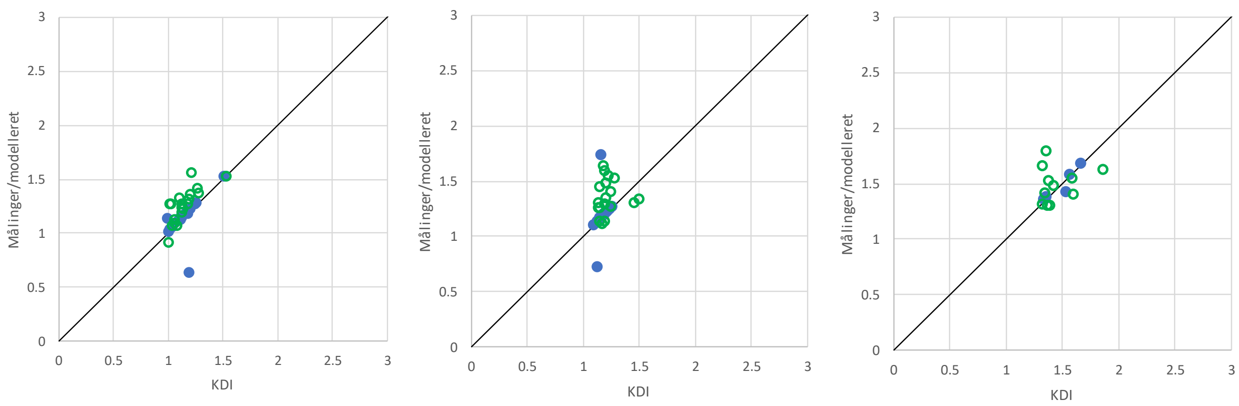


Figure 14. Measured/modelled water level (m) values at Drogden (DK). Left panel: Drogden (DK). Mid panel: Skagen (DK). Right panel: Gedser (DK). Blue dots: measured water levels. Green dots: modelled water levels.

Both measured and modelled values are reduced to daily min/max due to computational efficiency. The calibration is also checked at the largest storm where measured and modelled values are compared.

4.2. Local model

The Manning numbers for the local model are 32 m$^{(1/3/s)}$ outside the estuary and 25 m$^{(1/3/s)}$ inside the estuary. An assessment of the mesh approach, i.e. triangular vs. quadrangular, was applied in the calibration process where it was found that the local model gave the best results when applying rectangular mesh resolutions in the Roskilde Fjord tidal channel.

A comparison of measured vs. modelled timeseries of two water level stations, Roskilde and Holbaek, are shown in Figure 15 for the storm Bodil on December 6th 2013.

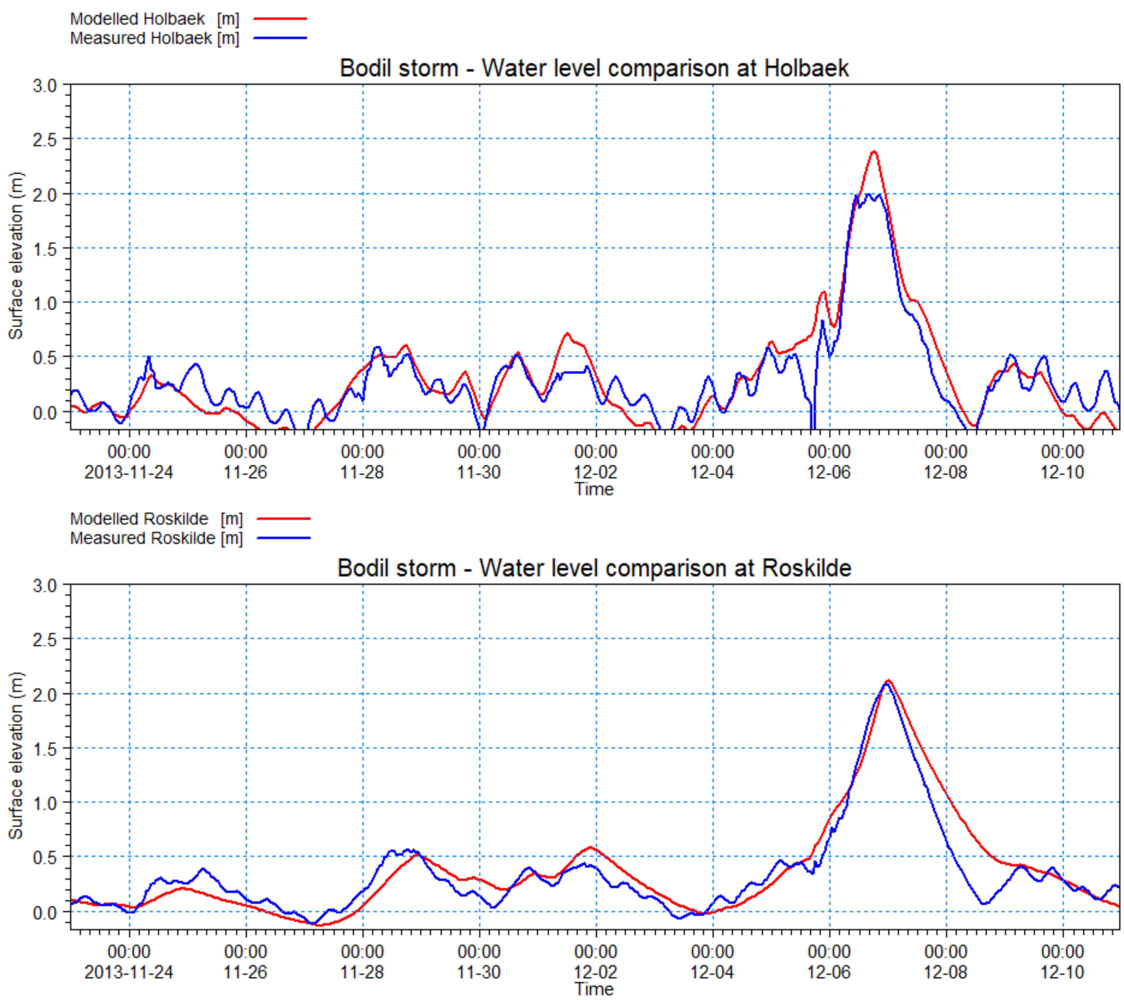


Figure 15. Timeseries of measured/modelled water level timeseries for Holbaek (upper) and Roskilde (lower) during the Bodil storm event on December 6th 2013.

The timeseries at Roskilde show minor deviations between the measured and modelled data. Peak water levels at Holbaek, however, show deviation which was possibly caused by failure during the measured peak water levels of the tide gauge.

Measured and modelled extreme water level values for Roskilde and Holbaek are shown in Figure 16 covering the period 2012-2018. The extracted values are based on the annual maximum method.

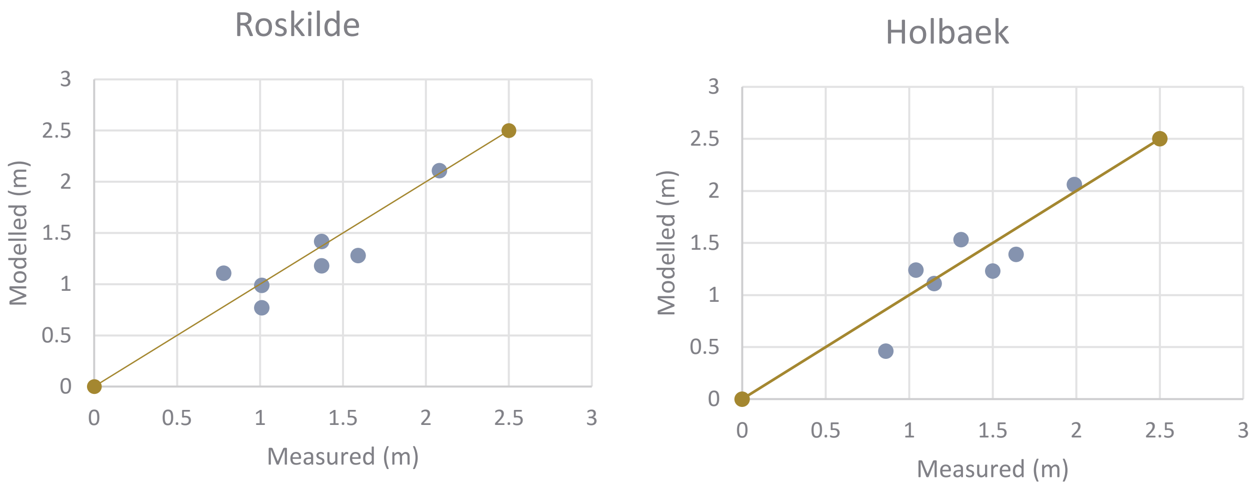


Figure 16. Measured vs. modelled annual maximum water level values at Roskilde and Holbaek from 2012-2018.

When comparing all timesteps (hourly) for the period 2012-2018 it gives an index of agreement of 0.86 for Holbaek. This same analysis for Roskilde gives a value of 0.87. The index of agreement is calculated as:

$$\text{Index of agreement} = 1 - \frac{\sum_{i=1}^{N}(\text{OBS}_i - \text{SIM}_i)^2}{\sum_{i=1}^{N}(|\text{SIM}_i - \overline{\text{OBS}}| + |\text{OBS}_i - \overline{\text{OBS}}|)^2}$$

4.3. Wind effects

Futhermore an evaluation of the wind effects from land has been assessed in the model. An extraction of the wind field from Isefjord and Kattegat has been completed during the Bodil Storm to see the effects from land on wind speed in the estuary. The results are shown in Figure 17.

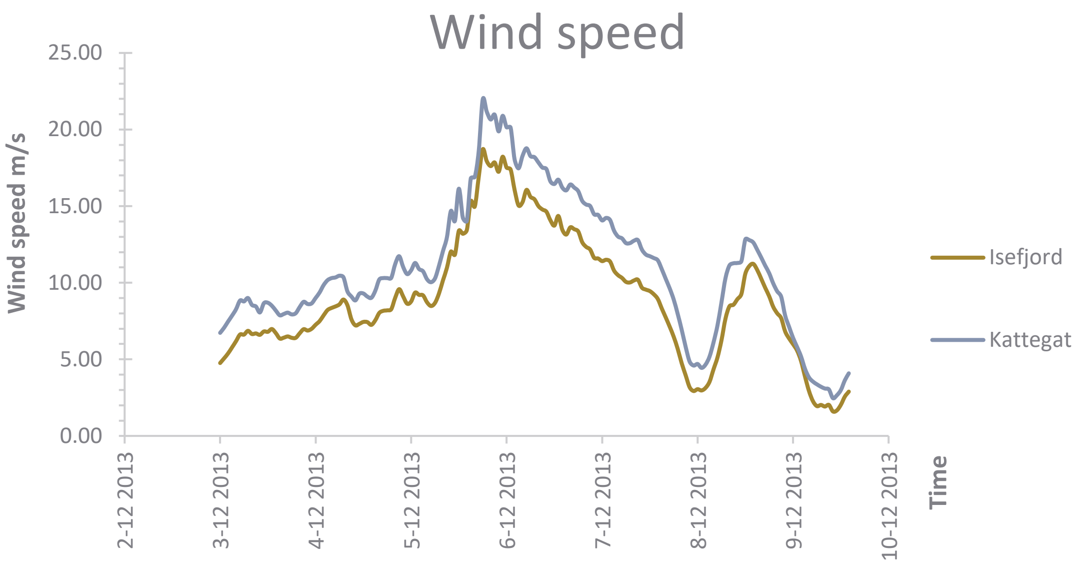


Figure 17. Plot of wind speed extracted from Kattegat and from the estuary (Isefjord).

Figure 17 shows that the effects from land are incorporated in the model and simulations. The wind speeds are higher outside the estuary (Kattegat) compared to within the estuary (Isefjord).

4.4. Calibration conclusions

Since the regional model and local model have been calibrated up against measured extreme annual maximum values and on specific storm events for a long period of time, from 1979-2018 for the regional model and from 2010-2018 for the local model supports the conclusion that both models can be perceived as reliable and used for the purpose.

5. FLOOD PROTECTION MEASURES AND CLIMATE CHANGE IMPACTS

Selected storm-surge protection measures are tested in the local model which gives a detailed technical insight into the effects of the specific measures and how the estuary responses to the measures as a holistic system. When testing the measures, sea level rise and relative effects of large-scale morphodynamics are considered.

5.1. Simulated scenarios

The numerical models are used to investigate the effects of different flood protection measures and natural estuary dynamics. In Table 3 are given the specifications of each of the tested measures such as measure type, location, dimensions, and simulation period. Each measure is marked with a scenario number. Scenario 1-6 are flood protection measures, i.e. structures and physical modifications, while scenario 7-11 represents simulations of estuary dynamics such as sedimentation and sea-level rise. Scenario 13-16 covers simulations of the robustness of the measures during sea-level rise.

Table 3. Simulations of flood protection measures at the estuary.

	Scenario	Flood protection measure	Location	Dimensions	Simulation period
Flood protection measures	Scenario 1	Estuary barrier	Hundested – North of Skansehage	Height: 6 m Length: 3.8 km	06-12-2013 07:00 – 07-12-2013 23:00
	Scenario 2	Estuary barrier	Lynæs - Rørvig	Height: 6 m Length: 6.2 km	06-12-2013 07:00 – 07-12-2013 23:00
	Scenario 3	Submerged dike	Korshage - Tærsklen	Height: 1 m Length: 2.0 km	15-11-2013 07:00 – 14-12-2013 11:00
	Scenario 4a and 4b	Permanent solution with open (a)/closed gates (b)	Frederikssund	Adjusted to channel	15-11-2013 07:00 – 14-12-2013 11:00
	Scenario 5a and 5b	Permanent solution with open (a) /closed gates (b)	Kulhuse	Adjusted to channel	15-11-2013 07:00 – 14-12-2013 11:00
	Scenario 6	Flood storage channel	Across Hornsherred	Width: 25 m Depth: -2 m	15-11-2013 07:00 – 14-12-2013 11:00
SLR and morphodynamics	Scenario 7	Sedimentation in tidal-channels at estuary mouth	Lynæs - Rørvig	Elevated tidal channel bottom level	01-01-2013 00:00 – 01-01-2014 00:00
	Scenario 8	Sedimentation rate 0.25 m	Storesand and Korevle	Elevated bed level 0.25 m	01-01-2013 00:00 – 01-01-2019 00:00
	Scenario 9	Sea level rise 0.52 m (2071-2100)	Isefjord and Roskilde Fjord	Applied to BC in regional and local model	01-01-2013 00:00 – 01-01-2014 00:00
	Scenario 10	Sea level rise 0.96 m (2071-2100)	Isefjord and Roskilde Fjord	Applied to BC in regional and local model	01-01-2013 00:00 – 01-01-2014 00:00
	Scenario 11	+/- 3 storm delay	Isefjord and Roskilde Fjord	Applied to BC in local model	15-11-2013 07:00 – 14-12-2013 11:00
	Scenario 12	Constant 25 m/sec wind from true north	Isefjord and Roskilde Fjord	Regional model	15-11-2013 00:00 – 16-12-2013 06:00
Me asu	Scenario 13	Estuary barrier + SLR	Hundested – North of Skansehage	Height: 6 m Length: 3.8 km	06-12-2013 07:00 – 07-12-2013 23:00

	Scenario 14	Estuary barrier + SLR	Hundested – North of Skansehage	Height: 6 m Length: 3.8 km	06-12-2013 07:00 – 07-12-2013 23:00
	Scenario 15	Estuary barrier + SLR	Lynæs - Rørvig	Height: 6 m Length: 6.2 km	06-12-2013 07:00 – 07-12-2013 23:00
	Scenario 16	Estuary barrier + SLR	Lynæs - Rørvig	Height: 6 m Length: 6.2 km	06-12-2013 07:00 – 07-12-2013 23:00

The tested flood protection measures (scenario 1-6) are shown in Figure 18.

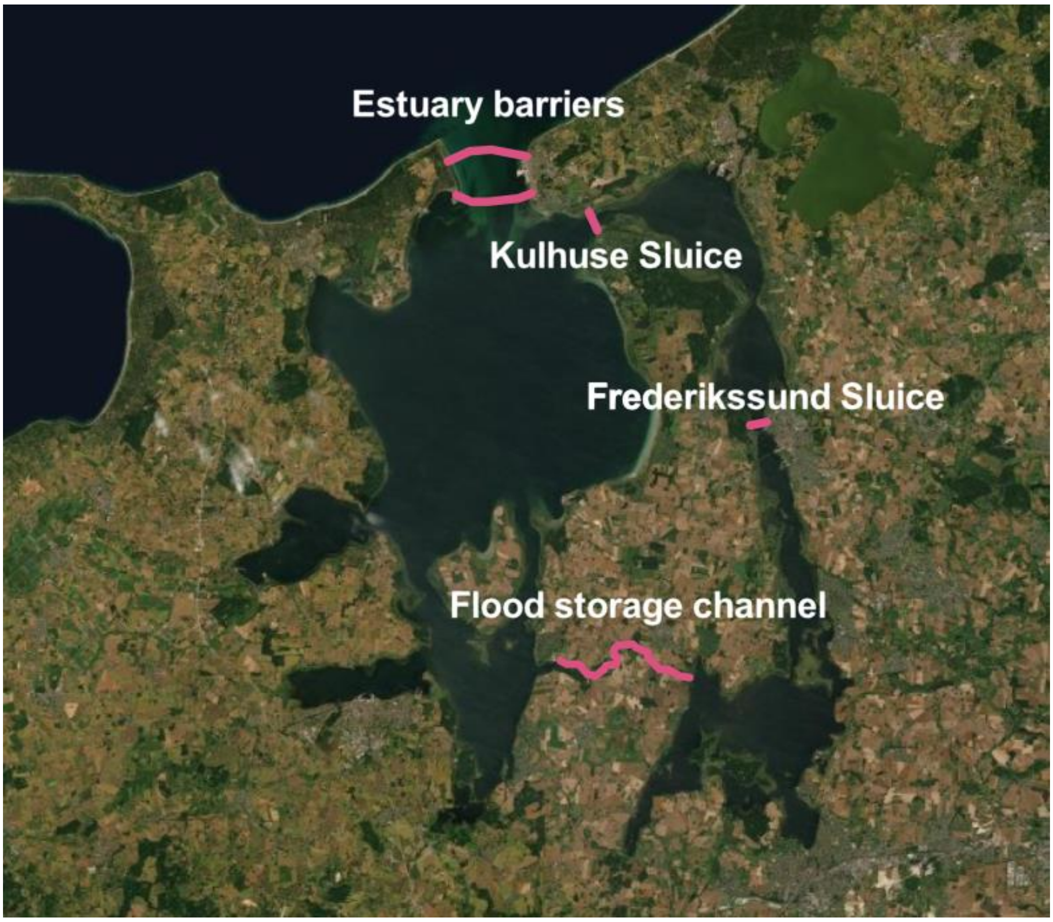


Figure 18. Overview of the tested flood protection measures.

Contour plots and cross-sections of all scenarios are given in appendix 9.1-9.6.

6. RESULTS

In this section the results from numerical modelling of applied storm surge measures are presented. Scenario 1-6 covering the flood protection measures are presented in section 6.1-6.4.

Scenario 7-12 covers the natural dynamics such as SLR and morphodynamics and are presented in section 6.5-6.9.

Scenario 13-16 shows the results from simulations of northern and southern estuary barriers under different sea-level rise scenarios.

Scenario 1-2 includes the simulations of an estuary barrier across the estuary mouth in the local model. The storm protection is only activated during extreme water levels and storm-surges. The free water exchange is ensured through the tidal channels and there are more placement options.

Scenario 3 covers simulations of a submerged dike across the left half of the estuary mouth in the local model. The flood protection is more permanent construction.

Scenario 4(ab) and 5(ab) are permanent solutions in the Roskilde Fjord tidal channel applied to the local model. The tested flood protection measures are adjusted to the tidal channel and simulations were run with open and closed gates, respectively.

Scenario 6 includes a flood storage channel across the peninsula of Hornsherred that separates Isefjord from Roskilde Fjord. The flood storage channel applied to the model is 25 m wide and 2 m deep and is placed in the low-lying areas across Hornsherred south of the town of Skibby.

Scenario 7 represents a simulation of where the morphodynamic changes results in sedimentation of the tidal channels at the estuary mouth in the local model. The bed levels of the tidal channels at the estuary mouth have been raised to the surrounding bed levels.

Scenario 8 indcludes simulations of sedimentation rate of 0.25 m at the sand banks, Storesand and Korevle, at the estuary mouth run in the regional model.

Scenario 9-10 covers modelling of sea-level rise scenarios applied to the boundary conditions (BC) in the regional model. Two sea-level rise scenarios have been applied to the BC – 0.52 (change in mean water level) and 0.96 m (uncertainty interval) – based on DMI's regional sea-level rise prognoses based on RCP 8.5 for the estuary system.

Scenario 11 shows simulations of a displacement of the timing of the Bodil Storm. Simulations are run with displacement of the water level boundary conditions 3 hours forward/back in time while the wind forcing is kept the same.

Scenario 12 is a constant wind simulation from true north with 25 m/sec to see the wind setup at different places in the estuary system.

Scenario 13-16 considers the estuary barriers under sea-level rise. The two estuary barriers (north and south) are tested under a sea-level rise scenario of 0.52 m and 0.96 m, respectively.

6.1. Scenario 1-6 (flood protection measures): Roskilde

Several flood protection measures (scenario 1-6) are shown in Figure 19 together with the baseline scenario (solid black) at Roskilde. The figure shows that the estuary barrier (blue and light green dotted) dampens and delays the storm surge signal under the Bodil Storm from app. 2,08 m to 1,92 m and app. 6 hours delay.

A permanent solution with open gates at Frederikssund (dark green dotted) and Kulhuse (yellow dotted) gives the highest effect and dampens the storm surge signal from app. 2,08 m to 1,76 m when introducing a permanent solution at Frederikssund and from app. 2,08 m to 1,60 m when introducing a permanent solution Kulhuse. Closed gates at Kulhuse (grey dotted) and Frederikssund (orange dotted) prevents the water from entering Roskilde.

The submerged dike (red dotted) shows a negligible effect and the flood storage channel through Hornsherred (pink dotted) increases the storm surge signal at Roskilde.

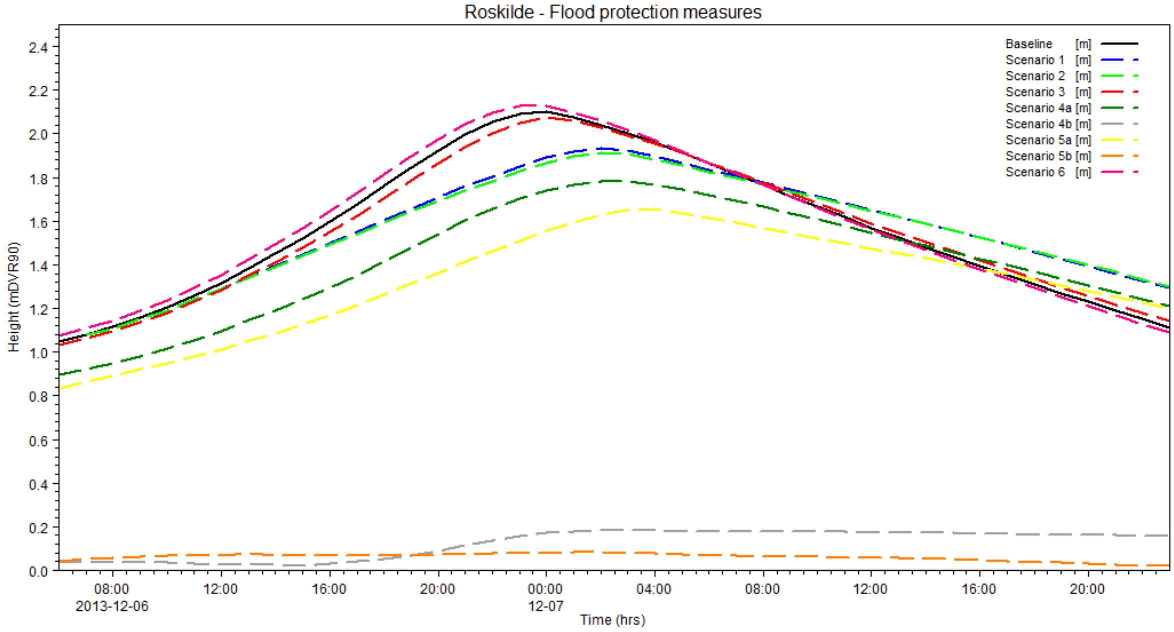


Figure 19. Effects from flood protection measures (scenario 1-6) on peak water levels during the Bodil-storm at Roskilde.

6.2. Scenario 1-6 (flood protection measures): Holbaek

The effects from different flood protection measures (scenario 1-6) at Holbaek are shown in Figure 20. It shows that the estuary barrier (blue and light green dotted) dampens and delays the storm surge signal under Bodil Storm from app. 2,36 m to 1,96 m and approximately a 5-hour delay.

A permanent solution with closed gates at Frederikssund (orange dotted) increases the storm surge signal at Holbæk from app. 2,36 m to 2,44 m and a permanent solution with closed gates at Kulhuse (grey dotted) increases the storm surge signal at Holbæk from app. 2,36 m to 2,40 m. The open gate scenarios do not have a significant effect on the storm surge signal at Holbæk.

The submerged dike (red dotted) shows a negligible effect and delays the flow of water out of the estuary. The flood storage channel through Hornsherred gives a negligible effect.

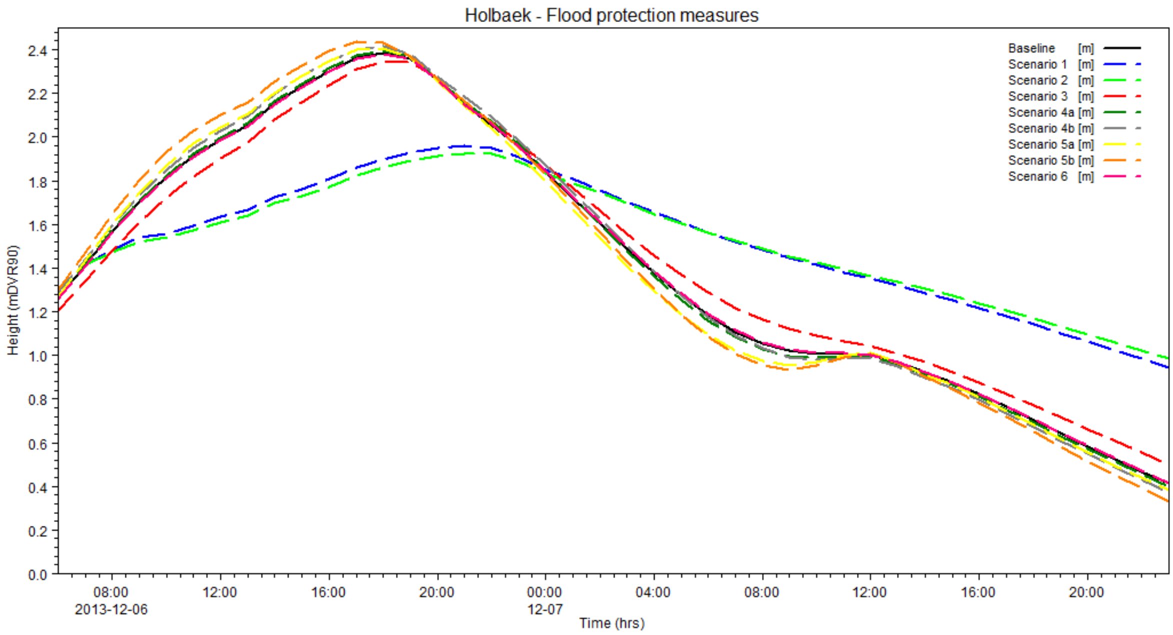


Figure 20. Effects from flood protection measures (scenario 1-6) on peak water levels during the Bodil-storm at Holbaek.

6.3. Scenario 1-6 (flood protection measures): Frederiksvaerk

Different flood protection measures (scenario 1-6) and their effects on Frederiksvaerk are shown in Figure 21. The figure shows that the estuary barrier (blue and light green dotted) dampens and delays the storm surge signal under Bodil Storm from 2,24 m to 1,88 m and approximately a 7-hour delay.

A permanent solution with closed gates at Frederikssund (grey dotted) increases the storm surge signal at Frederiksværk from 2,24 m to 2,36 m. A permanent solution at Frederikssund with open gates (dark green dotted) also increases the storm surge signal at Frederiksvaerk from 2,24 m to 2,32 m. Closed gates at Kulhuse prevents the water from entering Frederikssund (orange dotted). A permanent solution with open gates a Kulhuse is the most effective measure in order to dampen the storm surge signal at Frederiksværk (yellow dotted) from 2,24 m to 1,60 m.

The submerged dike (red dotted) gives a negligible effect and delays the flow of water out of the estuary. The flood storage channel through Hornsherred gives a negligible effect.

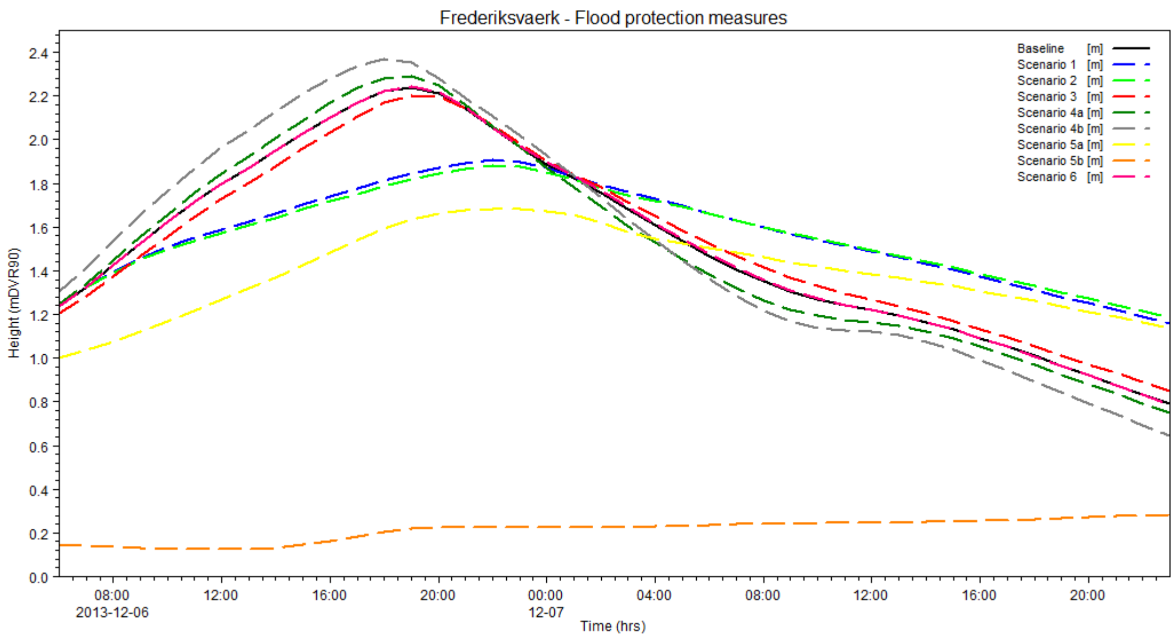


Figure 21. Effects from flood protection measures (scenario 1-6) on peak water levels during the Bodil-storm at Frederiksvaerk.

6.4. Scenario 1-6 (flood protection measures): Nykoebing Sj.

The tested flood protection measures (scenario 1-6) are shown in Figure 22. The figure shows that the estuary barrier (blue and light green dotted) dampens and delays the storm surge signal under the Bodil Storm from 2,24 m to 1,80 (blue) and 1,76 (green) m and approximately a 9-hour delay.

A permanent solution with closed gates at Frederikssund (grey dotted) increases the water levels at Nykoebing Sj. to 2,32 and closed gates at Kulhuse (orange dotted) increases the water level at Nykoebing Sj. to 2,36 m.

A permanent solution at Frederikssund with open gates (dark green dotted) and at Kulhuse with open gates (yellow dotted) does not increase the water levels at Nykoebing Sj. significantly.

The submerged dike (red dotted) gives a negligible effect and delays the flow of water out of the estuary. The flood storage channel through Hornsherred gives a negligible effect.

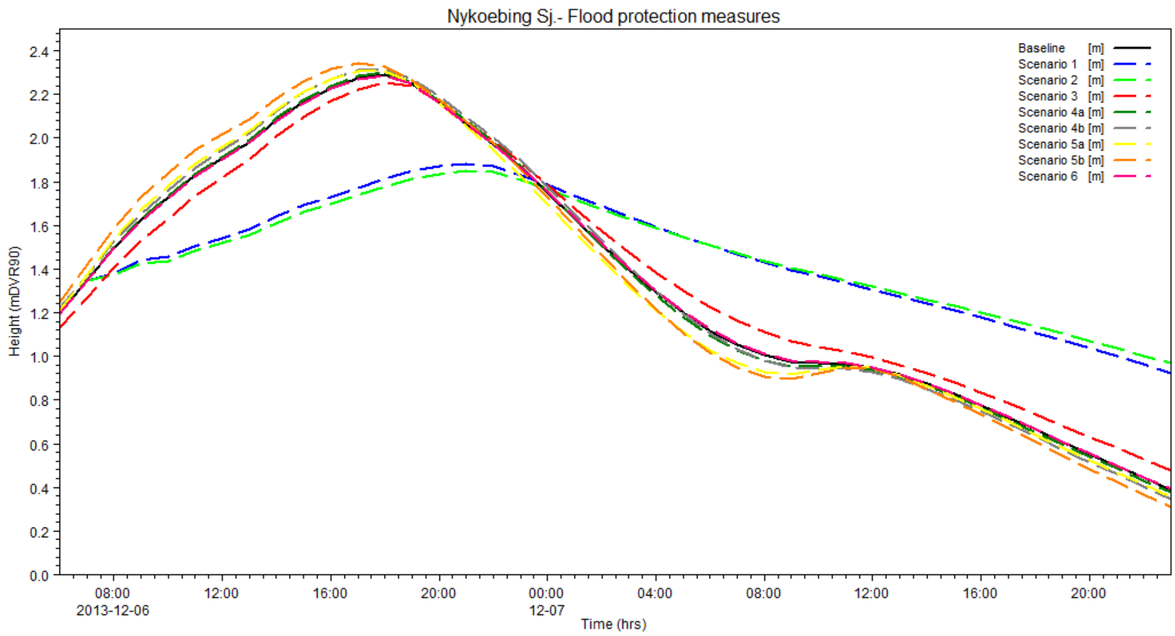


Figure 22. Effects from flood protection measures (scenario 1-6) on peak water levels during the Bodil-storm at Nykoebing Sj.

6.5. Scenario 7 – Sedimentation in navigation channels

Simulations of increased sedimentation in the navigation channels at the estuary mouth are presented in Figure 23 for the Bodil Storm.

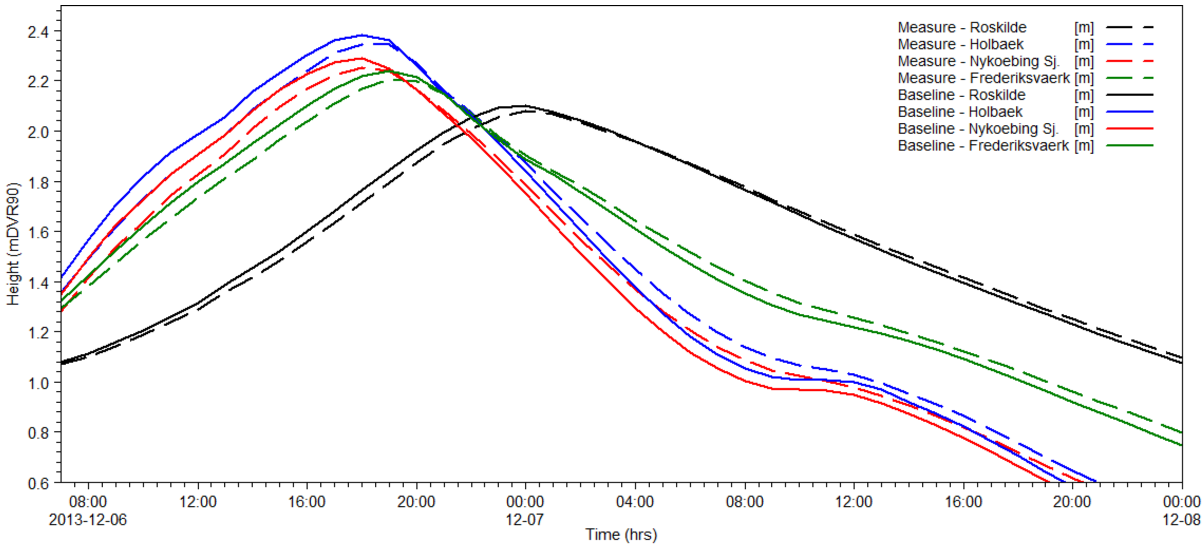


Figure 23. Effects from sedimentation in navigation channels.

Figure 23 shows the same tendency for all locations with slightly increased storm surge water levels due to increased sedimentation. When the wind changes, the water level begins to decrease with a delay compared to baseline.

Extreme values were extracted from the timeseries (baseline vs. measure) using a peak-over-threshold method with a threshold level of 0.5 at Roskilde and 0.6 at Holbaek and the inter-event time was set to 36 hrs and inter-event level to 0.5. The values are given in Table 4.

Table 4. Sedimentation in navigation channels, extreme values 2013.

Roskilde			Holbaek		
Date	Baseline	Measure	Date	Baseline	Measure
[dd-mm-yyyy]	[mDVR90]	[mDVR90]	[dd-mm-yyyy]	[mDVR90]	[mDVR90]
04-01-2013	0,66	0,65	04-01-2013	0,70	0,69
31-01-2013	0,88	0,88	31-01-2013	0,85	0,84
05-02-2013	0,97	0,96	05-02-2013	1,02	1,02
23-05-2013	0,54	0,55	23-05-2013	0,71	0,69
02-09-2013	0,57	0,57	02-09-2013	0,65	0,63
06-11-2013	0,88	0,88	29-10-2013	0,71	0,67
28-11-2013	0,52	0,52	05-11-2013	0,97	0,97
01-12-2013	0,58	0,58	01-12-2013	0,71	0,68
07-12-2013	2,12	2,08	06-12-2013	2,39	2,34

Table 4 and Figure 23 shows very little effect from sedimentation of navigation channels at the peak-water levels. This is probably due to the very limited area in the channels compared to the total cross-section area of the estuary mouth.

6.6. Scenario 8 – Sedimentation at estuary mouth sand banks

Simulations of increased sedimentation at the sand banks at the estuary mouth are presented in Table 5 for the period 2013-2018.

Table 5. Sedimentation at the estuary mouth sand banks, extreme values 2013-2018.

Roskilde			Holbaek		
Date	Baseline	0.25 m sediment	Date	Baseline	0.5 m sediment
[dd-mm-yyyy]	[mDVR90]	[mDVR90]	[dd-mm-yyyy]	[mDVR90]	[mDVR90]
04-01-2013	0.66	0.65	04-01-2013	0.70	0.69
31-01-2013	0.88	0.88	31-01-2013	0.85	0.84
05-02-2013	0.97	0.96	05-02-2013	1.02	1.02
23-05-2013	0.54	0.55	23-05-2013	0.71	0.69
02-09-2013	0.57	0.57	02-09-2013	0.65	0.63
06-11-2013	0.88	0.88	29-10-2013	0.71	0.67
28-11-2013	0.52	0.52	05-11-2013	0.97	0.97
01-12-2013	0.58	0.58	01-12-2013	0.71	0.68
07-12-2013	2.12	2.08	06-12-2013	2.39	2.34

Table 5 shows that increased sedimentation at the estuary mouth sand banks does not affect the peak water levels significantly under storm-surges.

6.7. Scenario 9-10 – Sea-level rise

Two scenarios of sea-level rise have been applied to the boundary conditions of the regional model. Annual maximum values have been extracted from the model. The results from the regional sea-level rise simulations are presented in Table 6 for the period 2010-2018.

Table 6. Annual maximum values from SLR simulations, regional model.

Holbaek				Frederiksvaerk			
Date	Baseline	SLR 0,52	SLR 0,96	Date	Baseline	SLR 0,52	SLR 0,96
[dd-mm-yyyy]	[mDVR90]	[mDVR90]	[mDVR90]	[dd-mm-yyyy]	[mDVR90]	[mDVR90]	[mDVR90]
01-03-2010 14:00	0,95	1,67	2,11	18-09-2010 10:00	1,19	1,76	2,2
10-12-2011 03:00	1,36	2,03	2,5	10-12-2011 03:00	1,51	2,15	2,6
04-01-2012 20:00	1,27	1,83	2,29	04-01-2012 19:00	1,37	1,95	2,4
06-12-2013 16:00	2,49	3,22	3,67	06-12-2013 16:00	2,47	3,19	3,64
17-03-2014 01:00	1,03	1,69	2,14	17-03-2014 01:00	1,18	1,81	2,24
11-01-2015 14:00	1,58	2,08	2,53	10-01-2015 18:00	1,73	2,35	2,81
27-12-2016 03:00	1,56	2,14	2,58	27-12-2016 02:00	1,64	2,24	2,69
29-10-2017 21:00	1,57	2,17	2,62	12-01-2017 12:00	1,52	2,16	2,62
23-10-2018 23:00	1,19	1,76	2,21	22-09-2018 12:00	1,21	1,85	2,31

It can be seen from the results that the global eustatic sea-level rise propagates into the Danish Waters and into the Isefjord and Roskilde Fjord system. The simulations cover the high climate RCP8.5 scenario from the median value up to the upper limit of the uncertainty level.

6.8. Scenario 11 – Displacement of storm-surge timing

The timing of the Bodil storm-surge have been investigated in the regional model. This was done by displacing the water level boundary conditions +/- 3 hours and extracting data in the middle of the Isefjord.

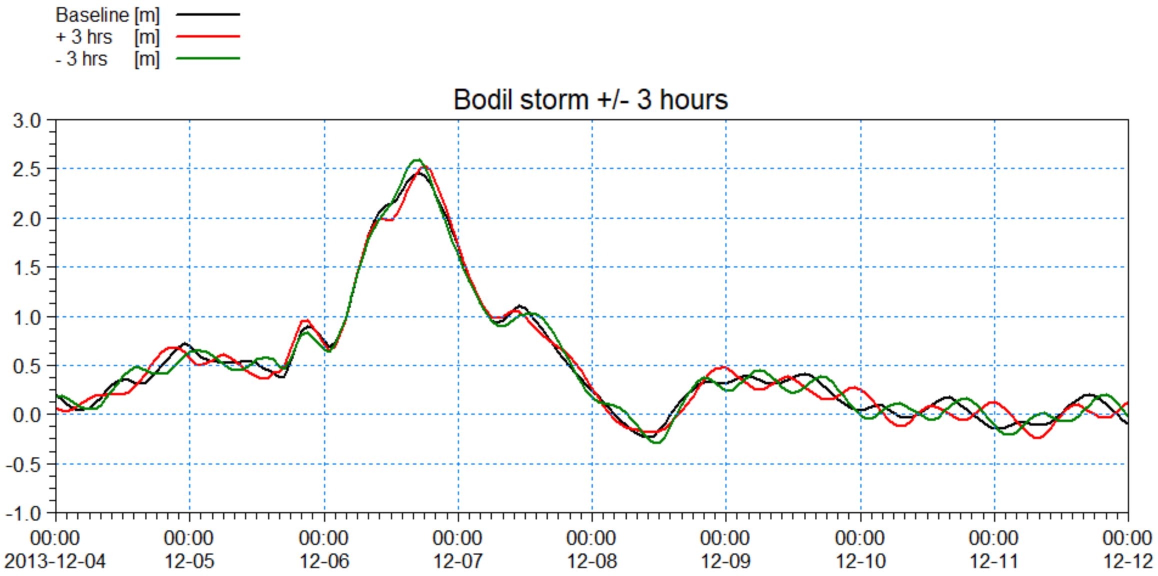


Figure 24 Effects from displacement of the timing of the Bodil Storm +/- 3 hrs simulated in the regional model.

Figure 24 shows baseline and a 3 hour +(red) / - (green) displacement of the timing of the Bodil Storm. A displacement of the timing of the Bodil Storm with +3 hours shows a slightly increase in peak water level compared to the baseline situation while a displacement –3 hours also slightly increases the peak water level. This indicates that the displacement propagates into the large volume of Kattegat and gives minor effects on the storm-surge signal.

6.9. Scenario 12 – Constant wind pressure from north

To investigate the potential water level set-up driven by the wind, simulations with constant winds from the north have been completed. These simulations involve a constant wind blowing from the north over a month with 25 m/sec . The results from the constant wind simulations are shown in Figure 25.

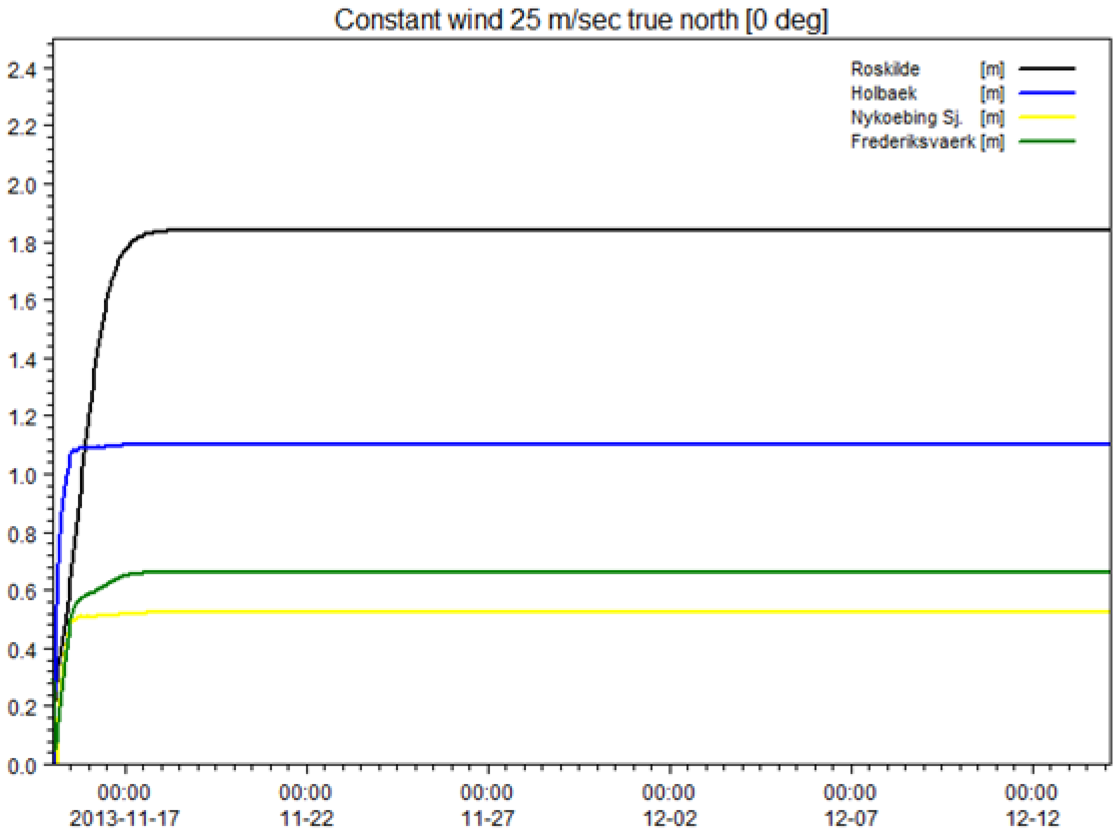


Figure 25. Simulations of constant wind pressure from true north [0 deg].

Figure 25 shows a variety in the wind driven water-level set-up distributed across the estuary coast-lines varying from 0.5-1.8 m. The simulated water level set-up is app. 0.4 at Nykoebing Sj and 0.6 m at Frederiksvaerk. According to the simulations the highest set-up in water level is at Roskilde and Holbaek. The highest water level set-ups are observed at the bottom of the fjords since the conditions for a wind-driven set-up is largest here.

6.10. Scenario 13-14 – Effects from SLR 0.52 and 0.96 m on northern estuary barrier

As this study focuses on measures to reduce the storm-surge signals under current and future conditions climatic conditions, the effectiveness of the measures have also been analysed under two sea-level rise scenarios: 0.52 and 0.96 m.

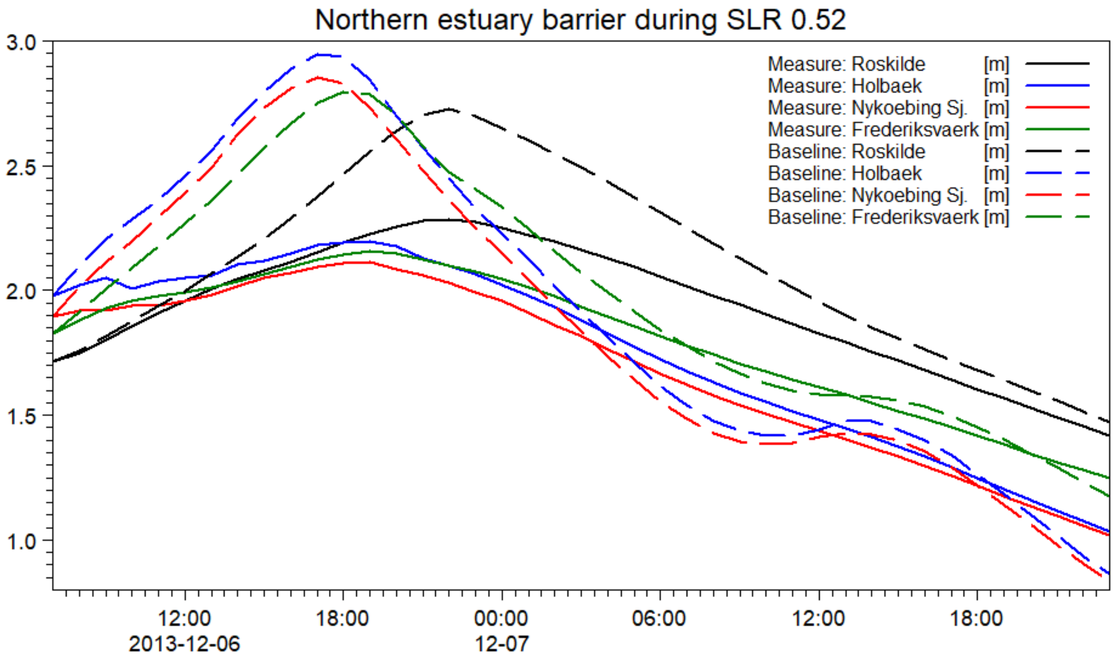


Figure 26. The robustness of the northern estuary barrier under SLR 0.52 m.

Figure 26 shows the effectiveness of the northern estuary barrier under a projected Bodil Storm into the end of this century based on the median value of the high emission climate scenario RCP8.5. A projected storm-surge signal into year 2071-2100 shows peak values varying between 2.72 m at Roskilde to 2.95 m at Holbæk. The greatest effect between baseline and measure level was found to be at Holbaek with a difference of 0,77 m while it was 0,76 m at Nykoebing Sj. and 0,73 m at Frederiksvaerk. The worst performance of the introduced measure under sea-level rise was found to be at Roskilde where the difference between the baeline and measure level was found to be 0,44 m.

Figure 27 shows the effectiveness of the northern estuary barrier under the Bodil Storm projected to the upper deviation limit of the RCP8.5 climate scenario at the end of this century 2071-2100. The peak values varies between 3.25 m at Roskilde to 3.41 at Holbaek. The greatest difference between the baseline and measure level is 1,05 m at Holbaek and Nykoebing Sj. while it is 0,94 at Frederiksvaerk and 0,79 at Roskilde.

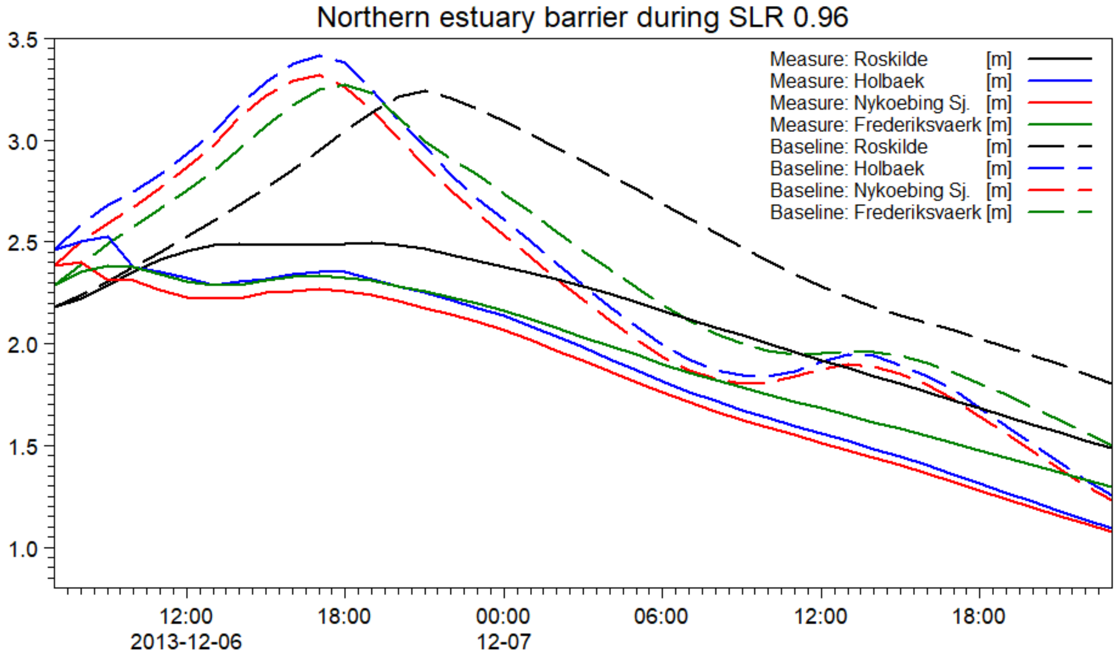


Figure 27. The robustness of the northern barrier under SLR 0.96 m.

6.11. Scenario 15-16 – Effects from SLR 0.52 and 0.96 m on southern estuary barrier

Simulations of the southern estuary barrier at the estuary mouth have also been completed for the 0.52 and 0.96 m sea-level rise scenarios to evaluate this measure's robustness towards the changing climatic pressures to the estuary.

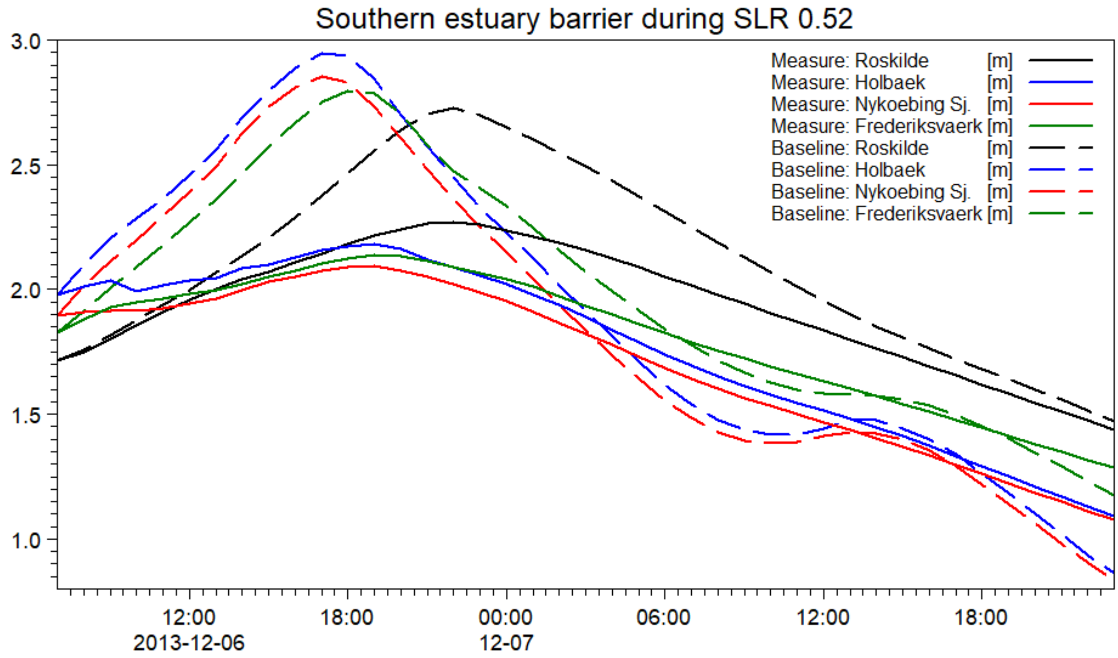


Figure 28. The robustness of the southern estuary barrier during SLR 0.52 m.

Figure 28 shows the effectiveness of the southern estuary barrier under a projected Bodil Storm into the end of this century based on the median value of the high emission climate scenario RCP8.5. A projected storm-surge signal into year 2071-2100 shows peak values varying between 2.72 m at Roskilde to 2.95 m at Holbæk. The greatest effect was found to be at Holbaek where the difference between the baseline and measure level was found to be 0,79 m at Holbaek and 0,78 m at Nykoebing Sj while it was 0,67 m at Frederiksvaerk. The worst performance was found to be at Roskilde where the difference between the basline and measure level was 0,45 m.

Figure 29 shows the effectiveness of the southern estuary barrier under the Bodil Storm projected to the upper deviation limit of the RCP8.5 climate scenario at the end of this century 2071-2100. The peak values varies between 3.25 m at Roskilde to 3.41 at Holbaek. The greatest difference between the baseline and measure level is around 1,09 m at Nykoebing Sj. and 1,06 at Holbaek while it is 0,95 at Frederiksvaerk and 0,78 at Roskilde.

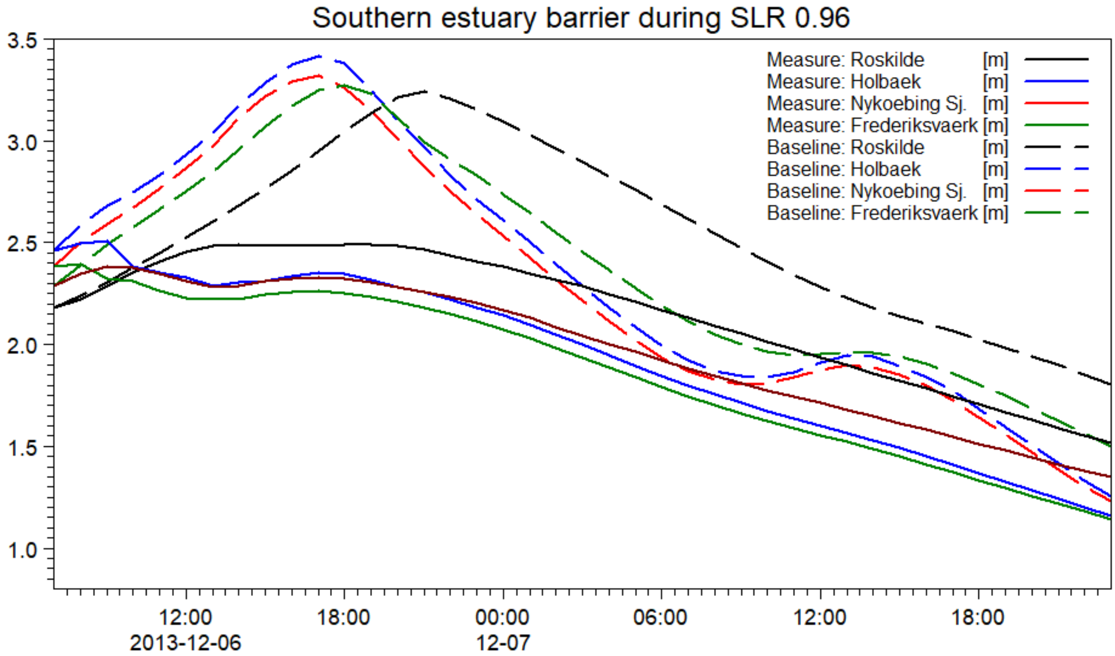


Figure 29. The robustness of the southern estuary barrier during SLR 0.96 m.

7. DISCUSSION

This project investigated the Isefjord and Roskilde Fjord estuary system with specific emphasis on getting an overview of pressures and trends, analysis of flood protection measures to control the risks of flooding and climate change while conserving the sufficient ecosystems. Finally, the transferability of the flood-protection measures to other estuaries are discussed.

7.1. Pressures

The estuary system is affected by several anthropogenic pressures and future trends. The anthropogenic pressures cover both physical-chemical and hydromorphological pressures. The physical-chemical pressure to the estuary system comes from both public and industrial wastewater treatment plants, which are widely distributed across the estuary system discharging both nutrients and organic matter into the estuary. In addition to this, the pressure from app. 8000 households and combined sewer overflows affects the water quality of the estuary system. This is reflected in the chemical status in outer Roskilde Fjord which is categorized as “bad chemical quality” while the chemical quality status for the other parts of the estuary is defined as “good chemical quality”. The initiatives initiated in relation to the EU water directives (Water Framework Directive, Nitrate Directive, etc.) are still ongoing to improve the water quality of the estuary system that will benefit the ecology of the estuary on a longer term.

The estuary system is also affected by hydromorphological elements such as coastal and flood protection schemes, recreational structures, and larger infrastructure. Along the coastlines of the estuary are found both ‘hard’ and ‘soft’ coastal protection schemes. Among the ‘hard’ coastal and flood protection measures are a mix of dikes, breakwaters, groynes, seawalls and slope protections. The ‘soft’ coastal protections consist of sand nourishments typically observed in combination with ‘hard’ structures. In the estuary system larger infrastructural structures can be found e.g. the two bridges across Roskilde Fjord – “Kronprins Frederiks Bro” and “Kronprisesse Marys Bro” and the ports in the cities of Frederiksvaerk, Hundested, Rørvig, Holbaek and Roskilde. The estuary system consists of local coastal- and flood protection schemes. From an economic perspective it could be cost-effective to investigate the total investments in local coastal- and flood protections both from municipalities, companies, citizens and compare it with the costs of a regional solution e.g. an estuary barrier at the estuary mouth or local sluice solutions in the Roskilde Fjord system.

7.2. Flood protection measures

A more extreme climate with expected stronger winds and higher water levels is expected to give an increased pressure from the sea to the estuary in terms of more frequent and more powerful floods. These floods make life in the coastal zone more vulnerable and therefore it is important to explore the possibilities of making our cities and communities more resilient to climate change and future storm-surges.

The purpose of this study was to develop and test large-scale flood protection measures. This was done using a regional hydraulic MIKE 21 model providing the boundaries for a more refined local model. In the local model it was prioritized to include land contours. In a more detailed study, the land bed roughness should be detailed to get more precise results with respect to the time aspect of land flooding. It was chosen to use a 2D model since this study is a basis study and it is a relatively shallow estuary. When completing more detailed studies including ecology it is recommended to use a 3D model.

7.3. Future trends

The future trends in the estuary have been investigated both in terms of hydrodynamic and morphological changes. The hydrodynamic future trends cover rising sea-levels, storm-surges, tides and waves. IPCC have predicted a global sea-level rise based on different climate change scenarios. This study simulated the sea-level rise based on a high emission scenario RCP8.5 and concluded that the global sea-level rise will propagate into the estuary. In addition to the sea-level rise, an expected increase in storm-surges both in intensity and frequency is expected in the future.

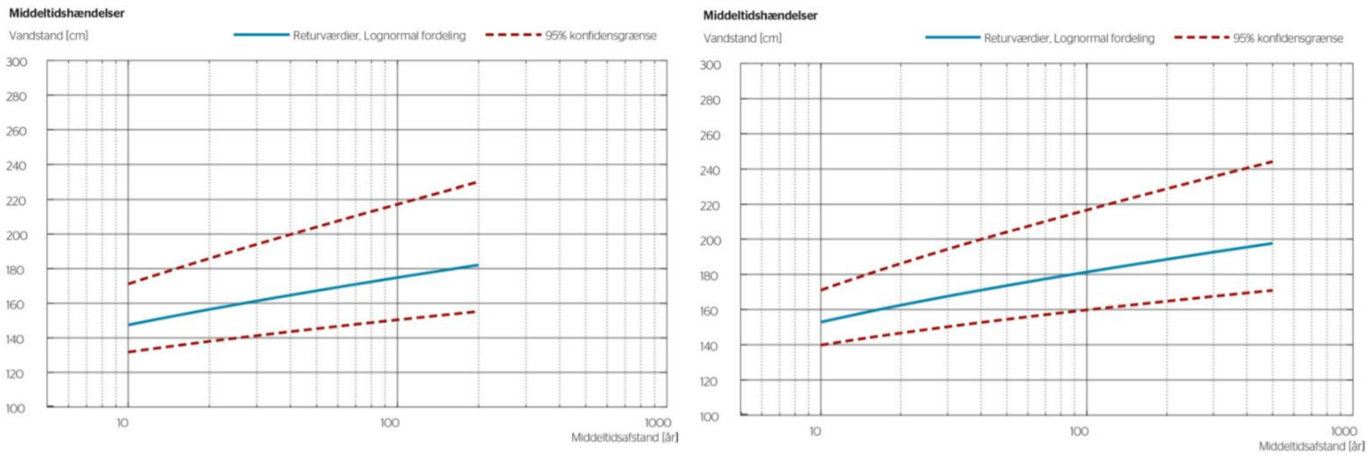


Figure 30. Extreme water level statistics at Roskilde (left) and Holbaek (right), Ref. /1/.

Today a 100-year return period storm is i.e. 175 cm at Roskilde and 181 at Holbæk. When these extreme values are projected into the future the blue line (Figure 30) is vertically shifted upwards. This results in increased frequency in the storm-surge values we observe today and higher peak storm-surge levels in the future.

When designing flood protection measures, the extreme water level statistics, sea-level rise, waves and land uplift should be taken into account. Waves are varying across the estuary dependent on the fetch, wind speed and wind direction. Since the fetch is varying across the estuary, waves are not included in the following example.

An example of a design criteria for storm-surge protection measures in the estuary for a design water level based on a 100-year storm-surge projected into year 2070 is presented in Table 7.

Table 7. Design water levels for a 100-year return period projected to year 2070 without waves.

Parameters	Roskilde	Holbæk
100-year extreme water level, Ref. /1/	175 cm	181 cm
Sea-level rise, RCP8.5 2071-2100, Ref. /2/	+52 cm	+51 cm
Land uplift	-6,5 cm	-6,5 cm
Design water level – 100-year return period projected to year 2070	**+220,5 cm**	**+225,5 cm**

The effects from tides are included in the water level data as the basis for the national extreme water level analysis published by the Danish Coastal Authority. Due to this, it is not necessary to include the effects of tides when designing security levels of storm-protection measures when using the national extreme water level statistics. A design elevation criteria can be determined for potential storm-surge protection measures at Roskilde and Holbaek. However, the vertical shift of the blue line in Figure 30 is not included in this analysis.

When looking into the environmental protection legislation several areas in the system are designated as Natura 2000 areas covering meadows, freshwater marshes and saltwater marshes. Furthermore, several wetlands and moist natural areas outside the Natura 2000 areas rely on the water ecosystems in the river basin.

The present N2000 areas protect today's habitats and species, but nature is not necessarily static because of climate change such as floods, droughts and acidification. Furthermore, more detailed studies should look into a potential change in salinity as a consequence of the introduced flood protection measures to the system and how this affects the species and habitats. These (climate change and potential anthropogenic) effects should be considered under future nature assessments.

7.4. Climate adaptation strategies

The UN's International Panel on Climate Change have developed different climate adaptation strategies to mitigate the societies to the increased pressure from the sea because of climatic changes. The panel's three climate adaptation strategies are:

- Protect: Keep the water away
- Accommodate: Live with the water
- Retreat: Gradually phase out buildings etc.

The protection strategy typically covers the classic approach to climate adaptation of coastal areas. This strategy covers damming and drainage of land areas as well as both soft coastal protection in terms of sand nourishments, biological coastal protection, planting of dunes etc. Hard coastal protection structures are also typical measures in this strategy e.g. sea walls, breakwaters, groynes and dikes. In the Roskilde and Isefjord estuary, as well as many places in Denmark, this is the dominant strategy, which is also reflected in the local coastal protection schemes along the coastline of the estuary.

The accommodation strategy involves reacting to climate change by adapting the coastal areas to learn to live with periodically occurring floods. For example, the houses can be raised by the use of poles. Another measure within this strategy could be an increased emphasis on the emergency planning and the use of mobile coastal protection schemes such as water tubes, sandbags, pump systems etc. This is a temporary flood protection strategy that is widely used in Denmark as we saw during the Malik-storm on 29-30 of January 2022 at Roskilde where citizens were evacuated after watertube breach causing a potential dangerous situation. There is also a tendency within this strategy of establishing "blue districts" by inviting the water into specific areas of a city or community that is designed to have periodic flooding events. This is e.g. seen in Lemvig where the houses on the seaside of the flood protection measure in the city are built on poles and are not flooded during storm-surge events. As part of this strategy the local community learn to live with the forces of nature instead of fighting against it.

Out of this way of thinking comes the tendency to work naturebased, where humans to a greater extent adapts to the forces of nature by bringing e.g. soft coastal protection measures into play rather than fighting against nature.

The retreat strategy is a more drastic climate adaptation strategy and have consequences for the local communities in a short-term perspective. Retreat can be planned, market driven or disaster-driven. A planned retreat will provide an opportunity to consider recreational potentials and create more marine nature areas. A market-driven retreat can be caused be falling house prices or increased insurance prices to vulnerable coastal areas. The disaster driven retreat can be caused by extreme flooding events where the local flood protection schemes are not able to keep out the water.

7.5. Stakeholder involvement

A thorough stakeholder involvement has been consistent throughout the project, where the latest results from the project have been presented and discussed with municipalities, landowners, regions, universities, consultants, contractors, politicians and many more.

Based on the stakeholder involvement, funding is pointed out as a challenge. According to the Danish coastal protection act (LBK nr 705 29/05/2020) it is the landowner’s responsibility to protect its own property. The public involvement points out that it should be the society’s responsibility to adapt to the changing climate and the state should contribute more economically. In this perspective it would benefit the agenda to study the damage costs and the costs of local vs. regional coastal protection. It is challenging to agree on distribution keys and coastal protection belongs to the Danish finance law. In addition, there has been a loss of knowledge due to the transfer of the responsibility from the Danish Coastal Authority to the municipalities. In connection to this it was pointed out that there is a need for inter-municipal / regional coastal knowledge centers.

There is general interest in a regional solution in the form of a barrier between Hundested and Rørvig considering the water exchange, but that the solution must be further specified in more detailed projects. It was also noted that there is a need for a national withdrawal strategy in a longer term, just as there should be a minimum limit for complaints. From a sustainability perspective, the focus in coastal protection projects should also be on minimizing the carbon footprint.

7.6. Transferability to other estuaries

The detailed knowledge of the effect of the measures can be transferred to other estuary systems for use in the design of solutions for storm surge protection. This knowledge is particularly relevant for fjord systems with narrow openings such as the Thyborøn Canal and the Western Limfjord as well as other fjords with a natural narrowing, such as Sakskøbing and Skælskør, where initial work is ongoing to investigate the possibilities of introducing regional storm surge protection solutions. Of other fjord systems where it may be relevant to study regional solutions could be several of the East Jutland fjords such as Mariager, Haderslev and Randers Fjord, while it could also be interesting to investigate the possibilities for a regional storm surge protection solution in e.g. Odense and Nakskov Fjord.

This study has as a basic study studied the effect of various regional measures for storm surge protection of fjord systems, which can form the basis for more detailed studies around both Danish and European fjord systems, in which it will also require other relevant factors such as the environmental, nature and socio-economic are illuminated.

In general, the project has shown that transfer of knowledge between nations within this field is highly valuable and keep developing the best solution. Cross border cooperation is needed also from the perspective that we are all at risk (to some point) by the future water levels. The transnational exchange labs run under this project has developed a network for experts within this field.

8. CONCLUSIONS

The results show that regional solutions can be the way forward for adapting larger estuary systems such as Roskilde and Isefjord to climate change.

Our modeling has shown that a narrowing of the estuary opening between Hundested and Rørvig, which still allows the daily currents in the tidal channels, could take the top of the storm surges today. At the same time, our models indicate that permanent solutions at Kulhuse and Frederikssund can solve the flooding problem more locally while allowing water passage under normal conditions. However, the studies also show that a submerged dike at the estuary mouth and a flood storage channel across Hornsherred will not solve the pressure from storm surge to the estuary.

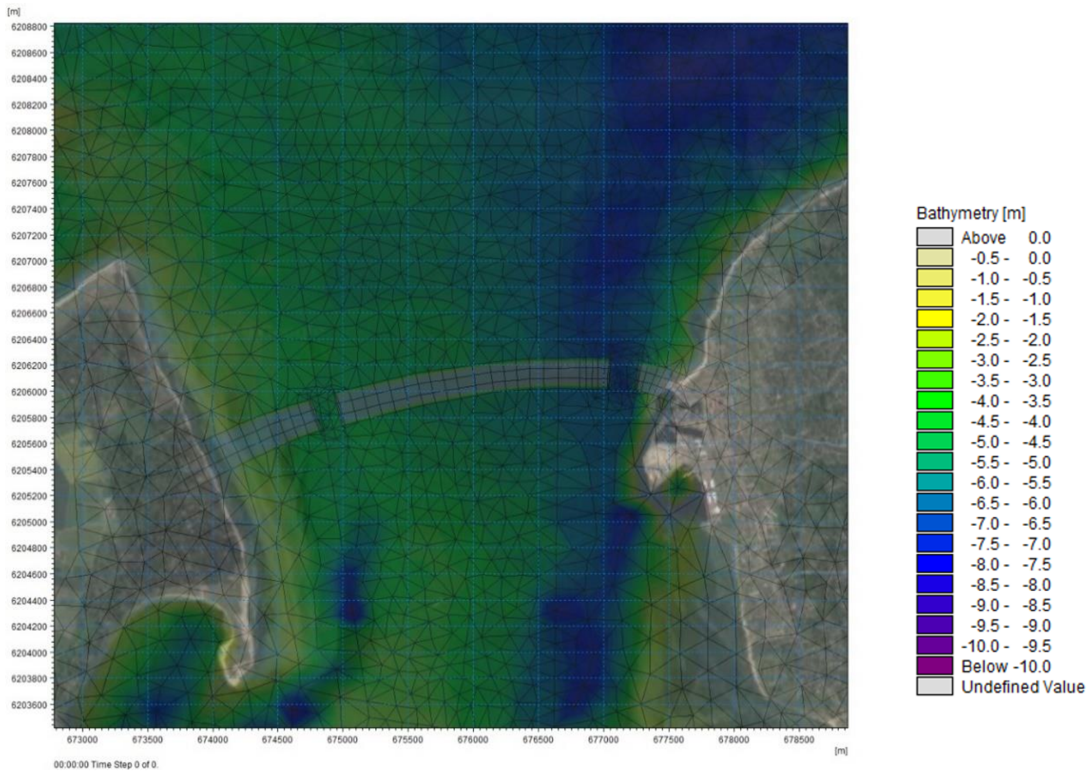
When we investigate the future, our models indicate that the global sea level rise will propagate through the Kattegat and into Roskilde and Isefjord and that the natural sedimentation dynamics at the fjord mouth will hardly save the estuary from the storm surges. When the models are used to look to the future with expected sea level rises, they point out that the solutions at the fjord mouth will probably be able to keep the peak levels around the levels we know today from e.g. the Bodil storm on 6 December 2013 and Malik storm on the 29-30 of January 2022.

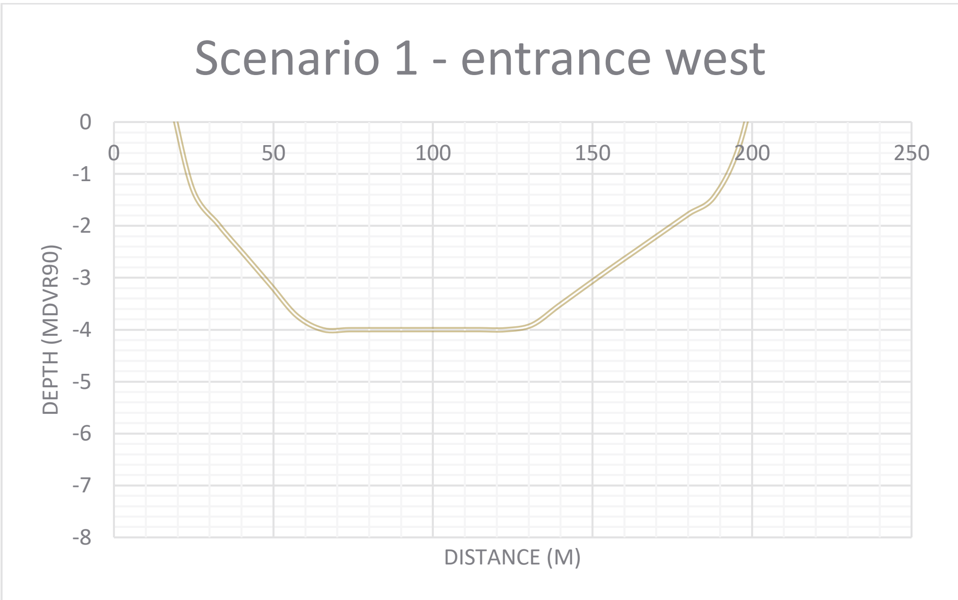
In general, this project has contributed to distribute knowledge between stakeholders and has raised the knowledge level wider than seen in normal initial pre-studies. Based on IMMERSE it has been possible to increase awareness of the impacts by future storm surges. However, the project has also shown that cooperation between regional units is difficult and is governed by many different agendas (protection of nature><personal property, local >< regional solutions far away from the most affected area etc.).

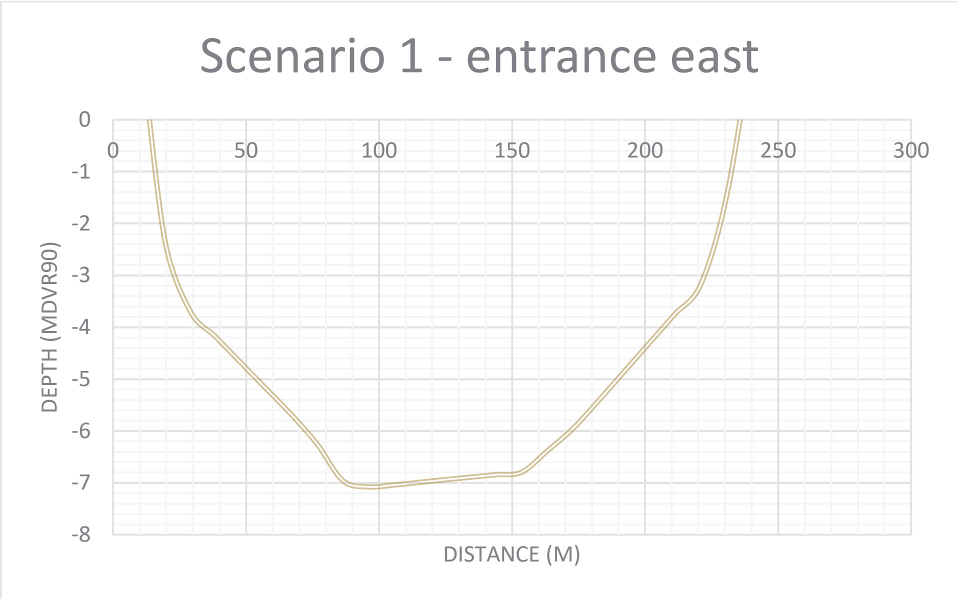
The Transnational cooperation has been valuable in sharing knowledge to find the best solutions to this difficult topic. Based on the project a highly competent network between experts from all along the North Sea region has been able to discuss the challenges and solutions on the Transnational Estuary Exchange Labs and in the partner group in general. This is invaluable for future cooperation to secure the North Sea region with the most efficient solutions.

9. APPENDICES

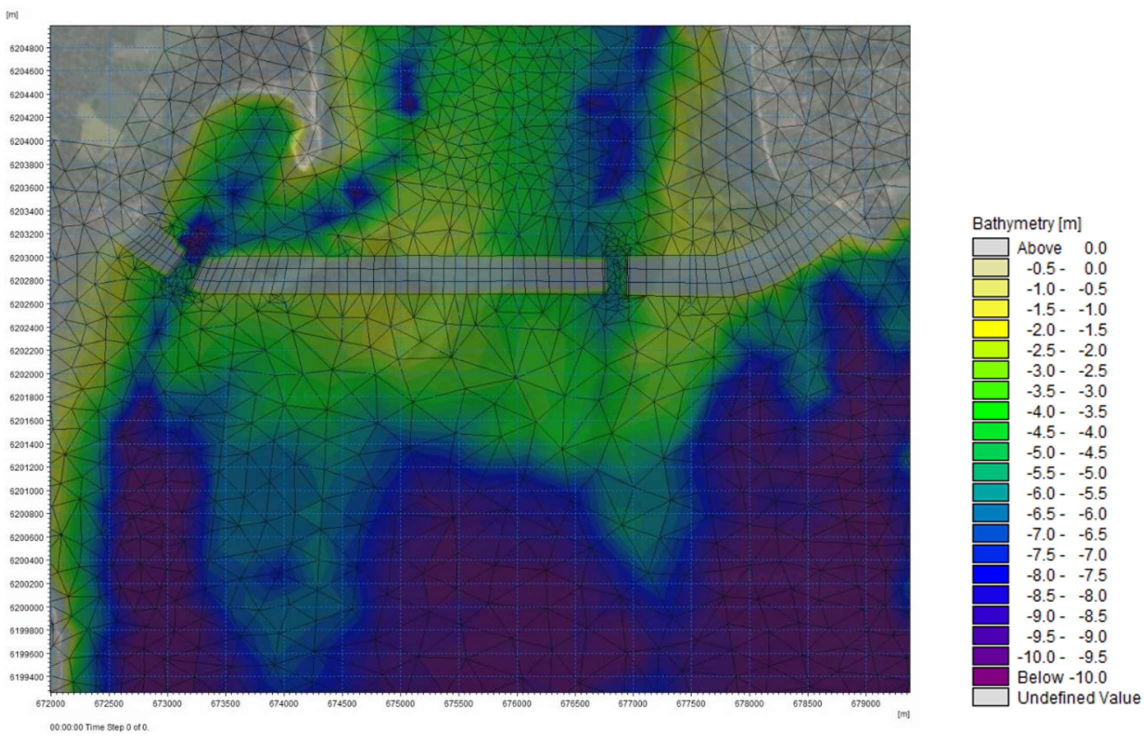
9.1. Contour plots - Scenario 1



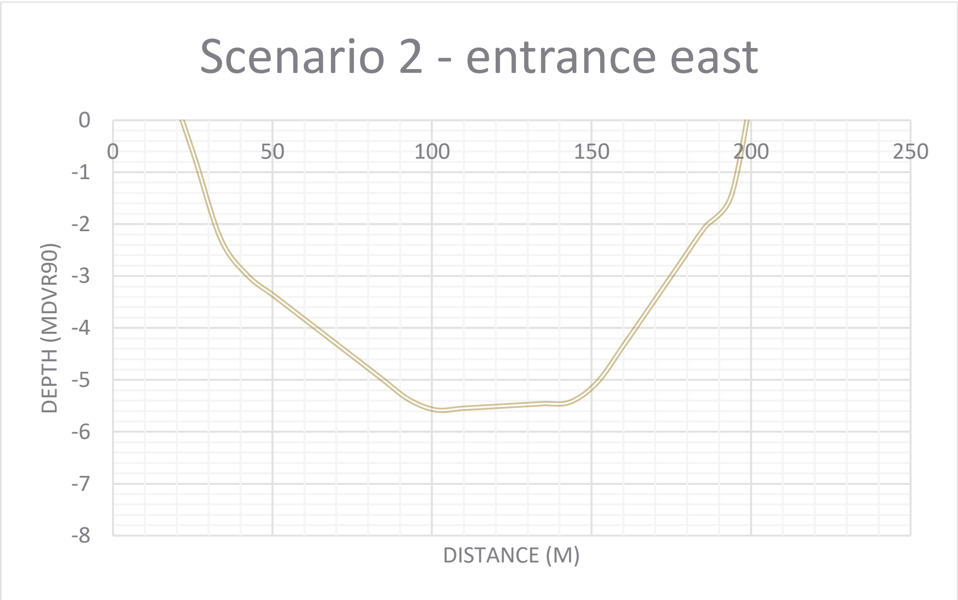




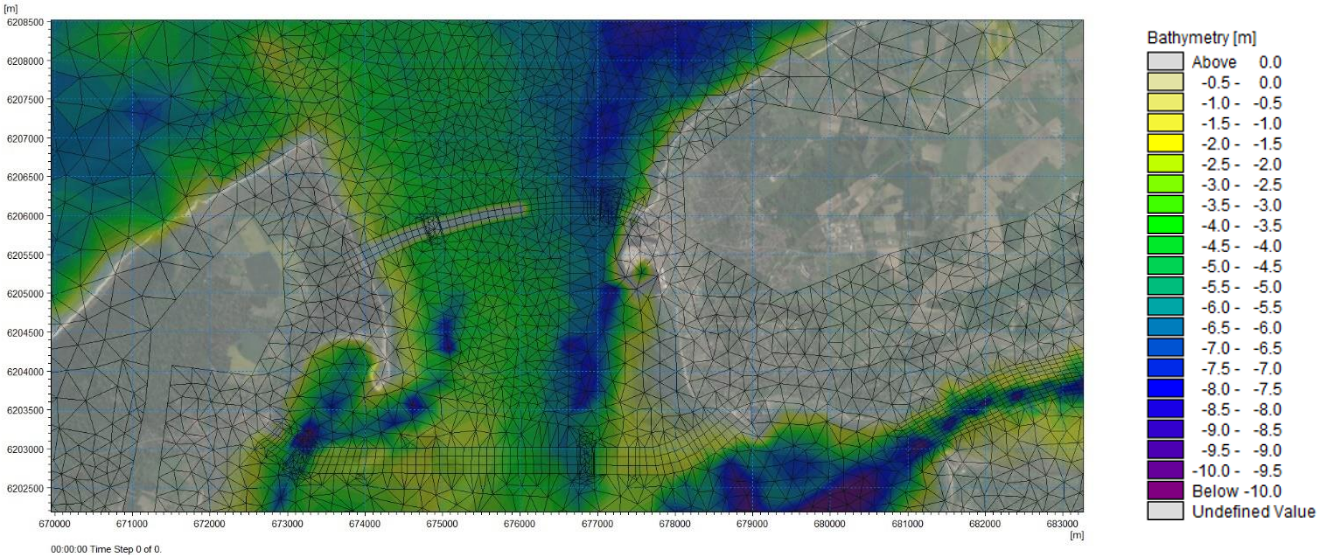
9.2. Contour plots - Scenario 2



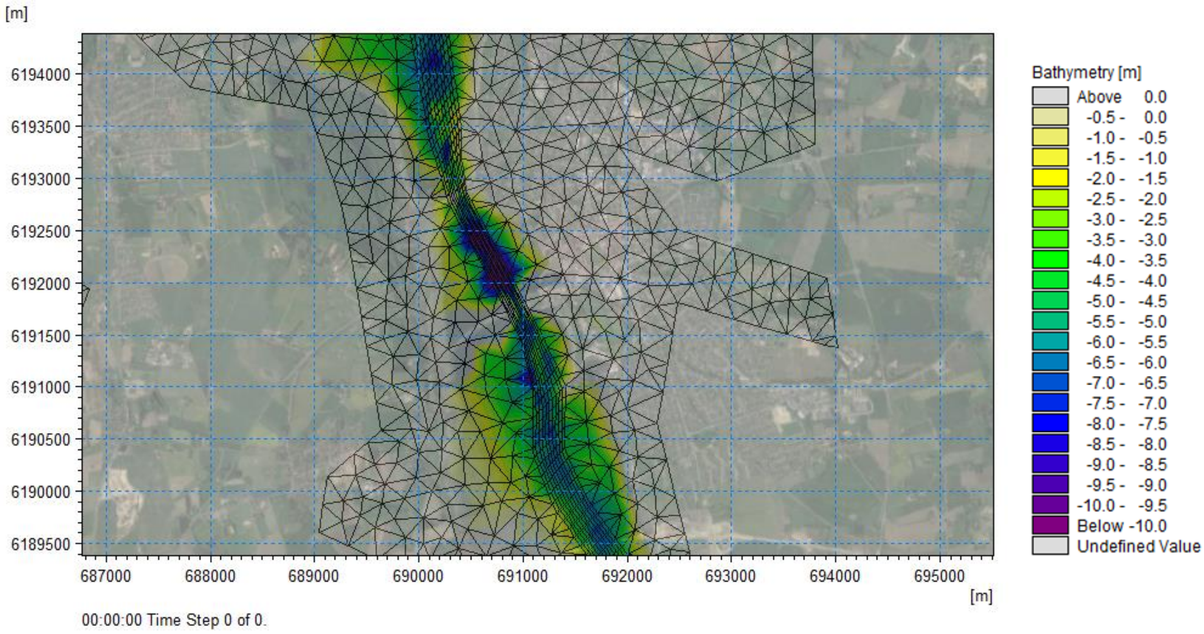

Scenario 2 - entrance west
DEPTH (MDVR90)
DISTANCE (M)
0
-1
-2
-3
-4
-5
-6
-7
-8
0
50
100
150
200
250


Scenario 2 - entrance east
DEPTH (MDVR90)
DISTANCE (M)
0
-1
-2
-3
-4
-5
-6
-7
-8
0
50
100
150
200
250

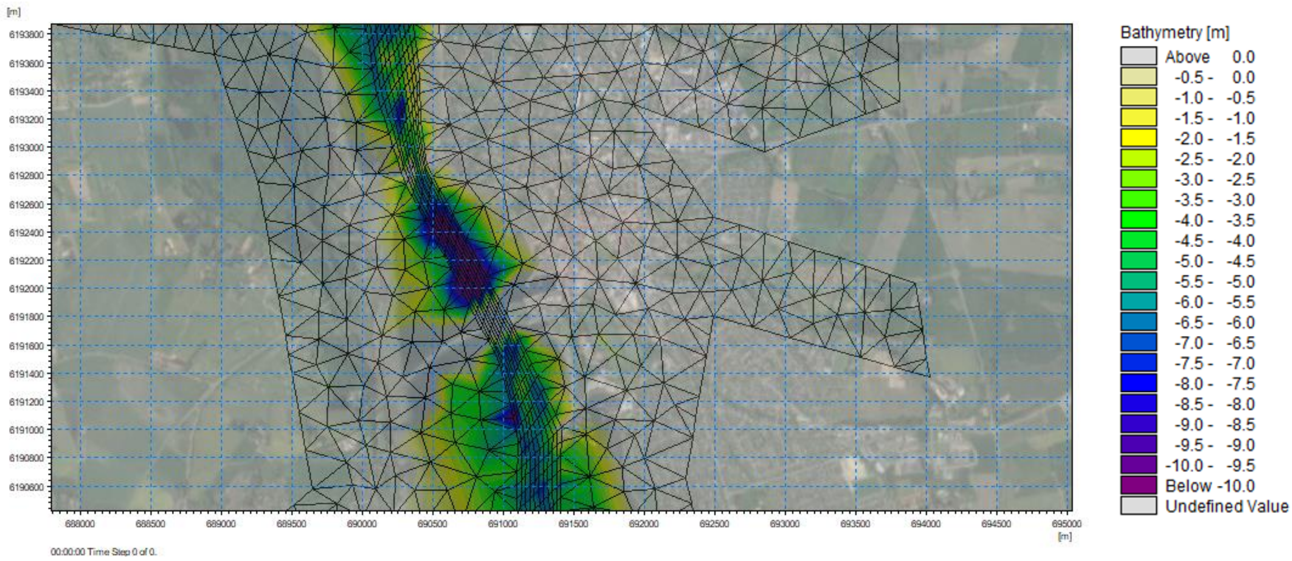
9.3. Scenario 3



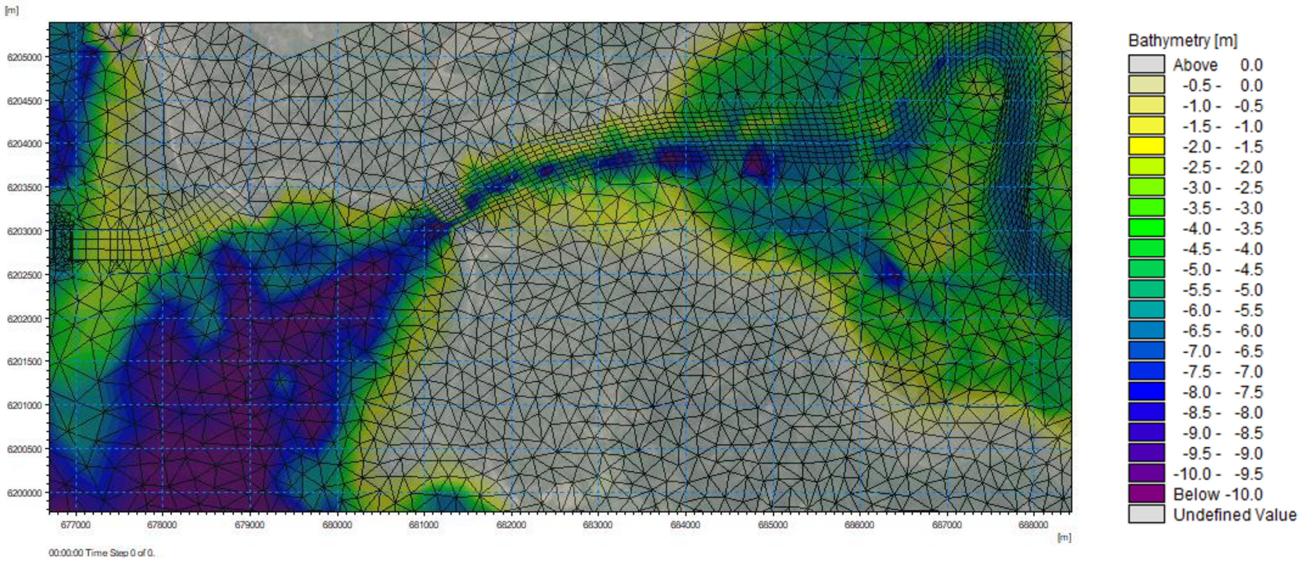
9.4. Scenario 4-5



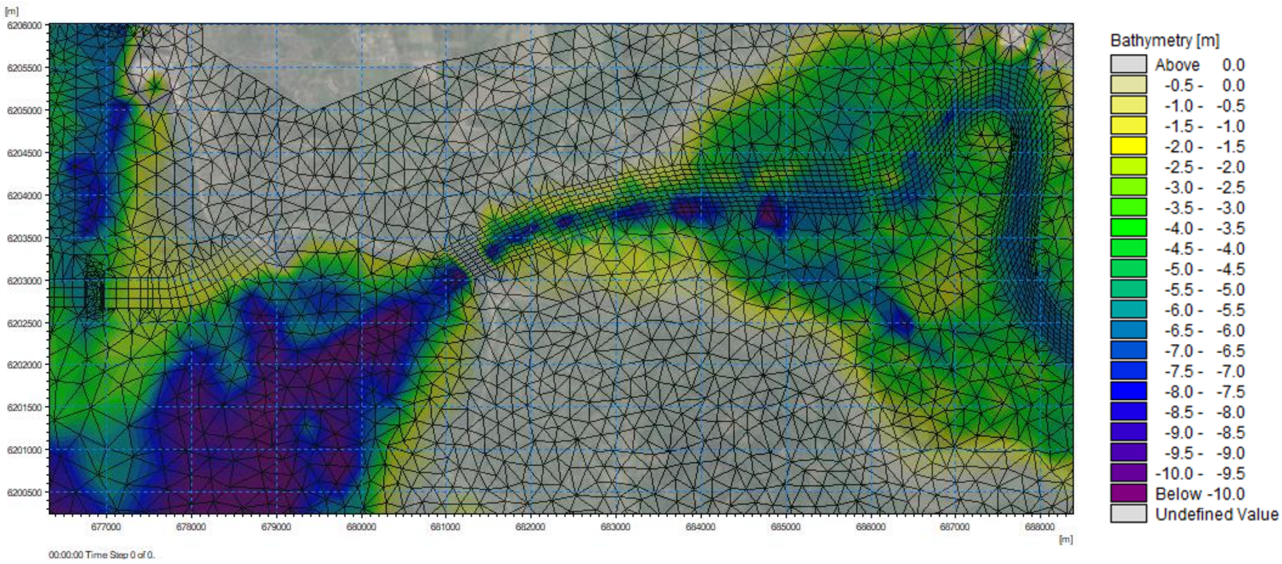
Frederikssund open gates



Frederikssund closed gates



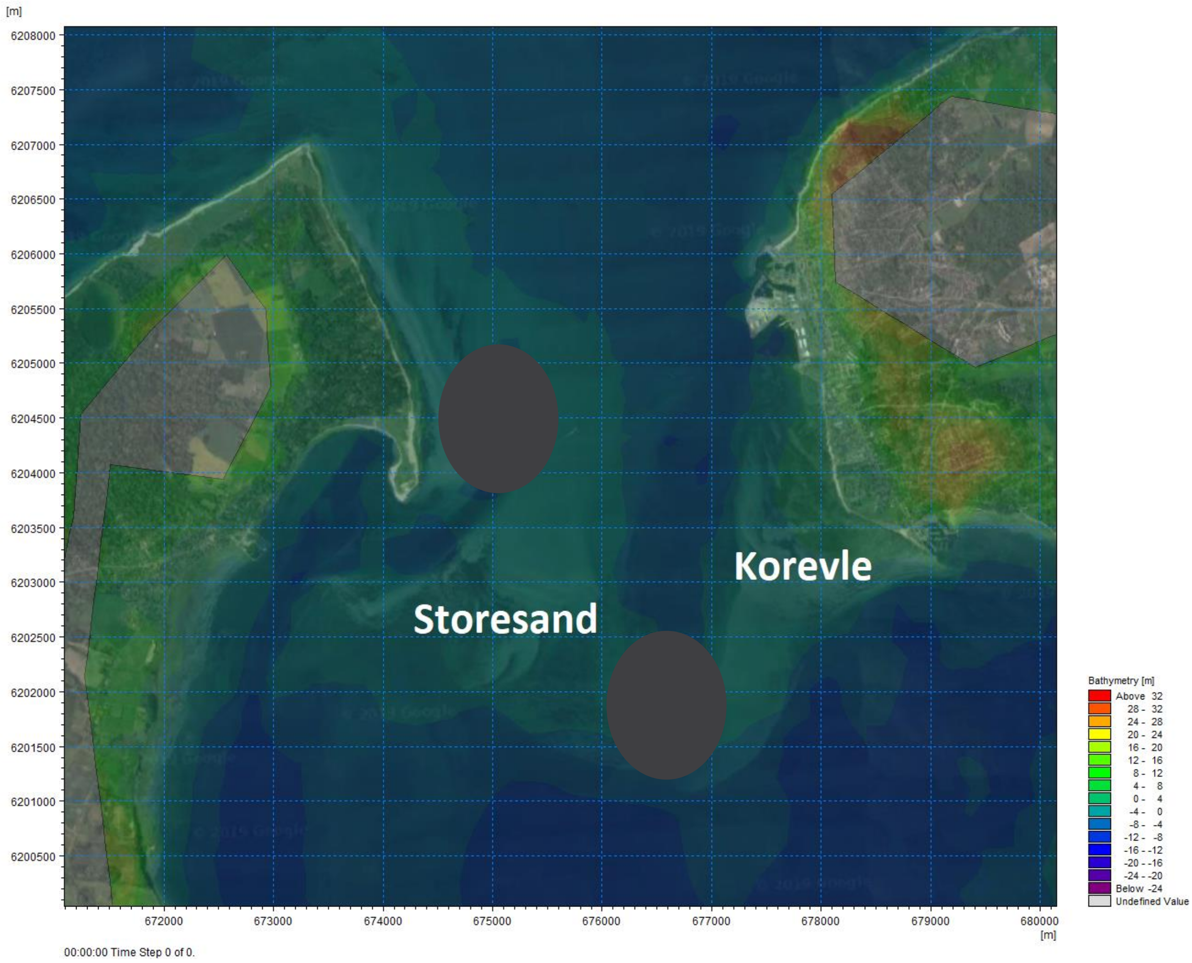
Kulhuse opgen gates



Kulhuse closed gates

9.5. Scenario 6

9.6. Scenario 8



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