IMPACTS OF MORPHO-DYNAMICS AND SLR ON EXTREME WATER LEVEL STATISTICS AND IMPLICATIONS FOR CLIMATE CHANGE ADAPTATION STRATEGIES IN COASTAL DENMARK

Carlo Sørensen
Senior coastal engineer (M.Sc.), Danish Coastal Authority, Lemvig, Denmark
E-mail: cas@kyst.dk

Thorsten Piontkowitz
Senior coastal engineer (M.Sc.), Danish Coastal Authority, Lemvig, Denmark
E-mail: tpi@kyst.dk

Abstract

One advantage of extreme water level statistics is that the natural variability in climate and associated storm surge heights may be described in a simple and useful manner for coastal planning and climate change adaptation. SLR, morpho-dynamic changes, land movement and other factors, however, may also have an impact on extreme water levels and on the statistics and their application. The Danish statistics based on tide gauge records from 68 stations are presented together with two case studies. One case contains a comprehensive modelling effort looking into the effect of morpho-dynamic changes on extreme water levels and provides updated statistics based on bathymetry-corrected water levels in the area considered, whereas the other case relates to the use of statistics in climate change adaptation by including land movement and SLR into a "dynamic" DEM, adjusted to better represent future conditions in relation to coastal flooding hazards.

Apart from considerations on the statistical approach, changes in the above parameters may yield a different picture of coastal flooding hazards and the challenges ahead. In the studied areas SLR only ranks third in importance after subsidence and morpho-dynamic changes at an intermediate time scale. Due attention to these matters is therefore advocated in conjunction to the calculation and communication of extreme water level statistics and climate change adaptation in Denmark.

1. INTRODUCTION

There are indeed challenges related to the production and use of extreme water level statistics from tide gauge measurements. Challenges may relate to the instrumentation (type and design, deployment site, data collection and transmission, data quality and processing, benchmarking and datum corrections) and human attention to these matters; to the choice and application of statistical methods (including, amongst others, aspects of precision and representation in historical data) and to the actual use in relation to present and future coastal flooding hazards. This may seem trivial from a technical and scientific point of view, nevertheless considerations about these aspects are important in the overall assessment, use and communication of the statistics. No matter how good and robust the statistical approach is, the results still depend on the validity of data and thorough consideration about their applicability and use is needed.

Although many aspects may be accounted for in the statistics, we still face limitations in our work due to a lack of data and/or knowledge. Here, following a brief presentation and discussion of the Danish extreme water level statistics, results related to morpho-dynamic changes and land movement are presented from two case studies. They draw attention to the representativity of historical extremes and to the use of the present statistics in climate change adaptation, respectively.

2. THE DANISH EXTREME WATER LEVEL STATISTICS

The Danish extreme water level statistics (Sørensen *et* al, 2013a) cover 68 locations along the Danish coastline and are based solely on measured extremes in tide gauge records. The tide gauges are owned and maintained by different authorities, e.g. the Danish Meteorological Institute, the Danish Coastal Authority (DCA), the Danish Nature Agency and local municipalities and harbours.

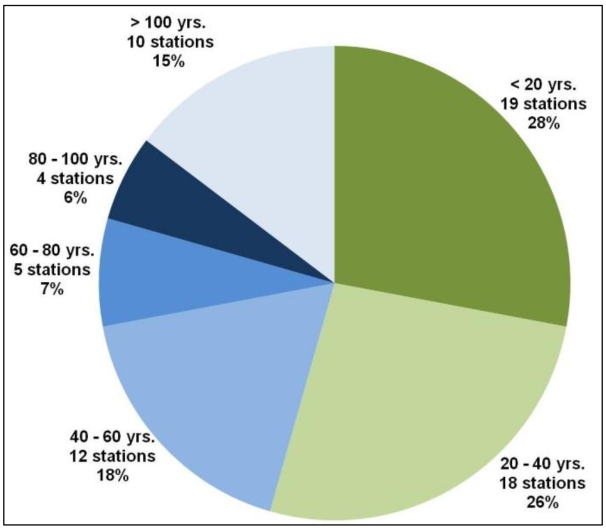

Figure 1 Distribution of data periods (n = 68) used in the extreme water level statistics.

The data series in individual statistics range from 11.6 to 139 full years (total 3228 yrs.) where 31 statistics are based on more than 40 years of data, figure 1.

Some statistics based on only 12 - 15 years of data have been included also to promote into society and to decision-makers the actual usefulness of tide gauge data and to emphasize that its takes at least a decade of sound measurements to have somehow valid time-series for extreme value analysis.

The statistics are widely applied in climate change adaptation, coastal planning and management, in relation to the implementation of the EU Floods Directive and in the assessment of extreme events by the Danish Storm Council where citizens may be eligible for economic compensation for flooding damages on property on occasions exceeding a 20 year event.

2.1. Methodology

Data come in a digital form from a large variety of tide gauges (laser, radar, float, pressure transducer) of which some time series are in a poor condition regarding maintenance, datum, drift etc. Some older data series are kept in an analogue form, whereas from other series only the extreme values exist making a reassessment of data quality difficult or even impossible.

All data are first evaluated, corrected and related to the Danish datum DVR90 (basis in 1990). Extremes, selected above a certain threshold, are then de-trended to mean sea level in the year of occurrence. In practice, a linear interpolation between the former Danish datum of DNN (mean water level around 1890) and DVR90 is used at all stations except in the Limfjord, refer below. Tides are not considered.

In the selection of extremes a time factor of independency between individual events of 36-72 hours is used together with conditions of a normalized water level between events. Further, the independency is checked manually within individual water compartments. Extremes are then compared between neighbouring stations and the spatial distribution of the event is resolved and evaluated.

Statistics are then calculated using a basic POT method for Log-Normal (Wadden Sea and Limfjord) or Weibull distributions according to Sørensen *et* al (2013a) and Sørensen & Ingvardsen (2007) in which the choice of cut-off level is made manually and thus is liable to some subjectivity. Whereas the extremes fit the distribution very well at some locations, the fit is fair to poor at others due to different meteorological and hydrodynamic conditions being the cause of extreme events.

In order to make the statistics as useful and transparent as possible results from individual stations are presented as return levels for 20, 50 and 100 year events with standard errors, graphics showing the distribution function and a Quantile plot of the fit together with a list of the extremes. Further, the cut-off level, the intensity of occurrence and parameters of the applied distribution are stated together with other station-specific information on data quality, data period etc.

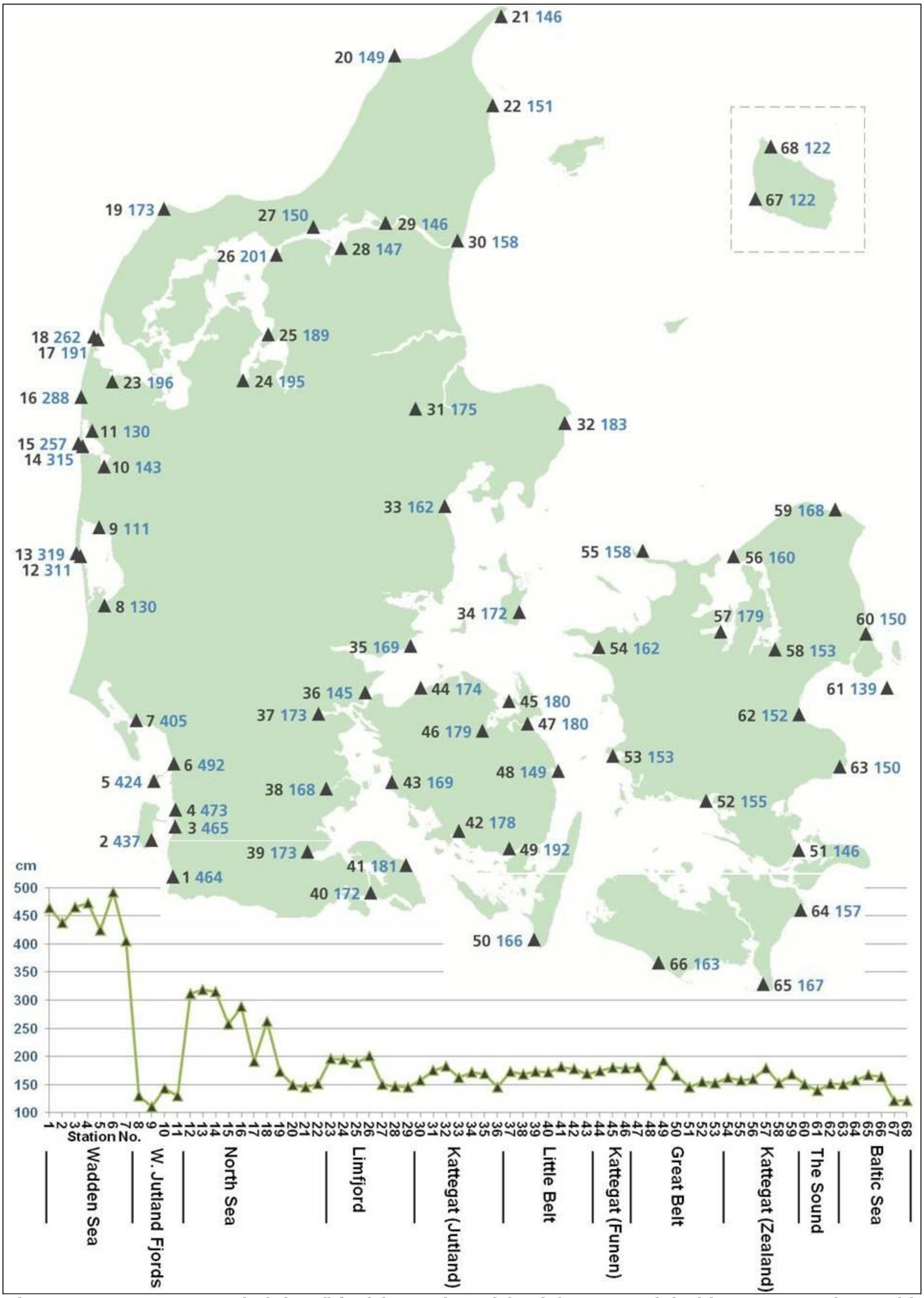

Figure 2 100 year return heights (blue) in cm (trend-free) for 68 Danish tide gauge stations with the spatial variation in extremes between water compartments sketched (bottom).

2.2. Spatial variations in extremes

Figure 2 shows the 100 year return heights from the tide gauge locations around Denmark. As the results are de-trended to 1990 a couple of centimetres, in general, should be added to the numbers to relate these to DVR90. Any possible acceleration in SLR since 1990 is unaccounted for.

In the Wadden Sea the 100 year return heights are between 405 and 492 cm. Along the North Sea coast extremes are in the order of 300 cm and decreasing to the north to about 150 cm. In most of the remaining water bodies the 100 year return heights are 150 - 200 cm with some variation between stations. In the sluice regulated West Jutland fjords 100 year return heights are below 150 cm as is the case on the island of Bornholm situated in the Baltic Sea (insertion in figure 2).

In the Wadden Sea and on the North Sea coast there is a fairly straightforward relationship between the meteorological forcing and storm surges occurring at more or less regular intervals, whereas the picture is more complex in the Inner Danish Waters (comprising Kattegat, The Sound and Belts and the Baltic Sea). Very severe events are infrequent and tend to occur only a few times every century in relation to wave phenomena and/or local surges in the narrow parts of the Baltic Sea – North Sea transition. The most extreme water level(s) may thus be considerably higher than the remainder based on "normal" bad weather conditions. The statistics' representation of a 100 year event may thus be difficult to evaluate and correspondingly may yield a poor fit in the statistics. For example did the surge levels in the 1 - 2 November 2006 event by far exceed any other registration even in some long (> 100 yrs.) tide gauge series. Adding to this, as the water level excursions are smaller in the Inner Danish Waters, the differences in both relative and absolute values between, say, a 20 year and a 100 year event are also small. This, of course, calls for caution when interpreting and using the statistics for planning purposes.

The statistics do however show a consistent distribution function pattern within individual water compartments as exemplified here from the Wadden Sea, figure 3, where the lines are almost parallel and vertical displacements between stations to a large extent can be explained by the positions of the tide gauge stations within the Wadden Sea.

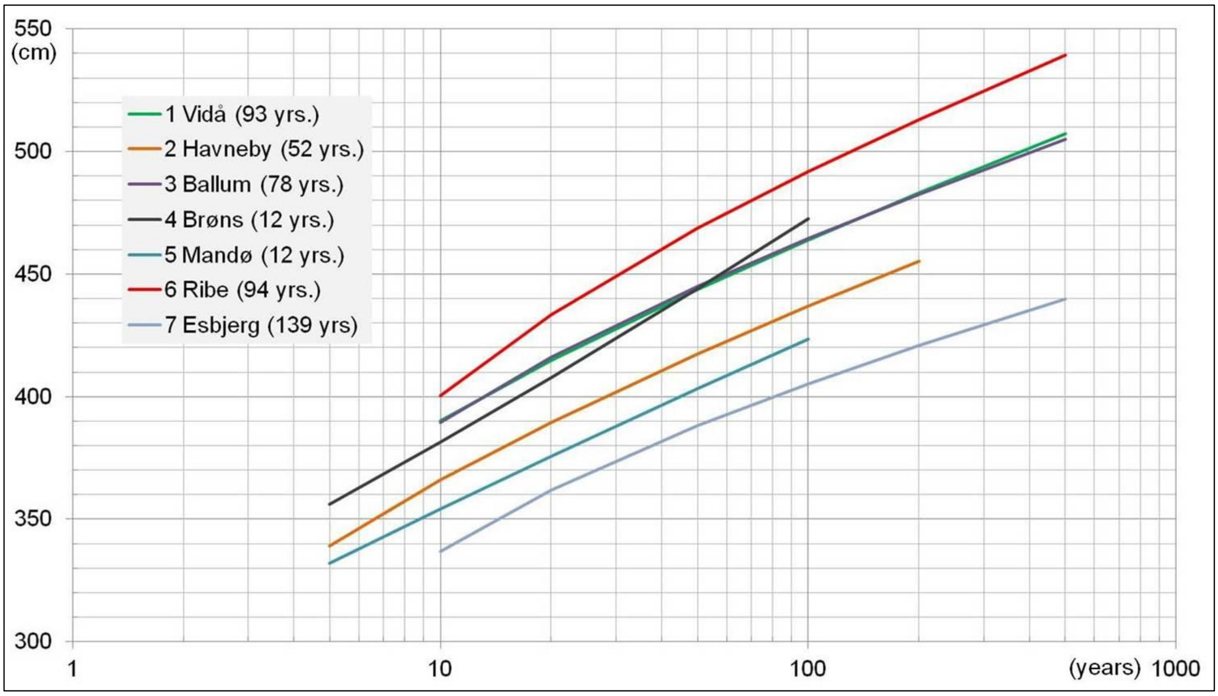

Figure 3 Distribution functions (Log-Normal) of extreme water level statistics at the tide gauge stations (station no., location, and length of time series) in the Wadden Sea. Refer to figure 2 for positions of stations.

3. MORPHO-DYNAMICS

Physical and morphological changes, sudden or gradual, may affect the extreme surge levels on a local to regional scale. One consequence of this is that historical extremes may no more be representative in extreme water level statistics.

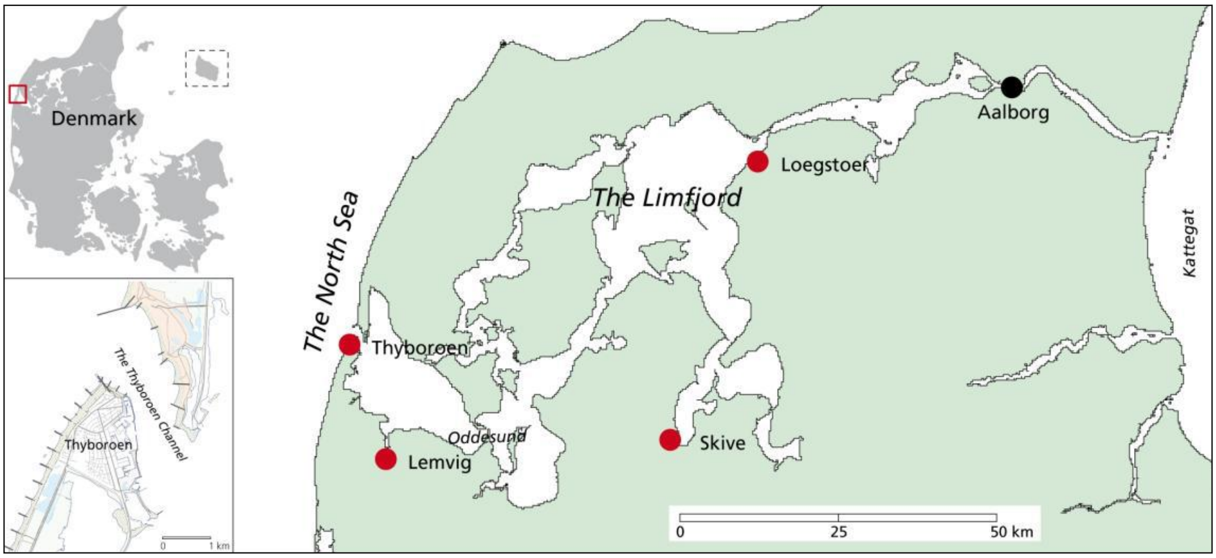

Figure 4 The Limfjord. Insert (bottom left) shows the town of Thyboron and the Thyboron Channel connecting the Limfjord to the North Sea.

An apparent gradual increase in extreme events over the last decades in the Limfjord, figure 4, that could not be explained meteorologically led the DCA to initiate an investigation into the possible causes and magnitudes of change. As the main water exchange in the Limfjord occurs through the Thyboron Channel to the North Sea changes in morpho-dynamic parameters in the channel were in focus from the beginning. Further, the current annual import of sand to the Limfjord amounts to approximately $1*10^6$ m^3 of which the majority settles on the extensive flood tidal delta inside the channel, figure 5. Please, refer to Christensen (2011a, 2011b), Ingvardsen *et* al (2012), Knudsen *et* al (2011, 2012) and Sørensen *et* al (2013b) for detailed information on methodology, results and recommendations of the investigation.

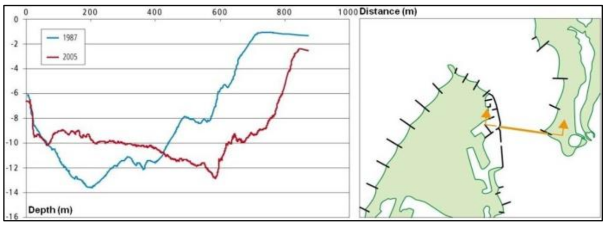

Figure 6 Depths in transect of Thyboron Channel in 1987 (blue) and 2005.

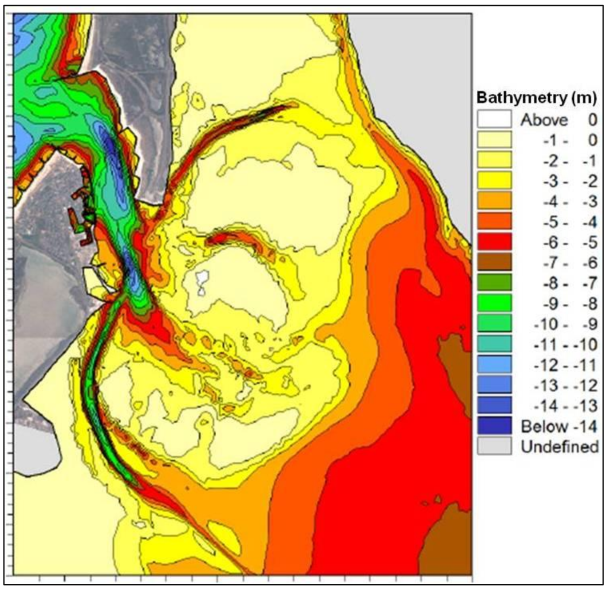

Figure 5 Section of model bathymetry representing 2011 conditions at Thyboron.

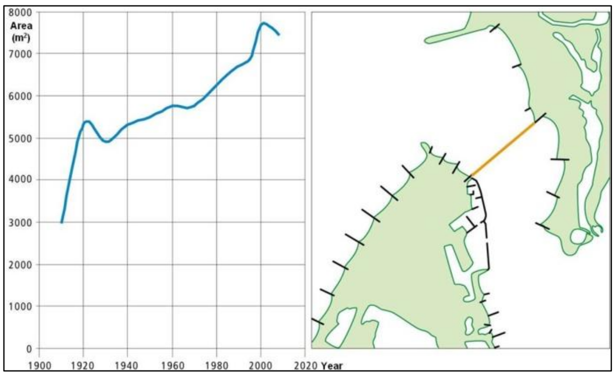

Figure 7 Development in the cross-sectional area of Thyboron Channel since 1910.

3.1. Methodology and results

Knudsen *et* al (2011) found a shift towards east of the deeper parts of the channel since 1987, figure 6, and an increase in the cross-sectional area of the channel from 3000 m^2 to 8000 m^2 since 1910, figure 7.

A detailed MIKE21 HD model of the entire Limfjord was set up in close collaboration between the Danish Hydraulic Institute (DHI) and DCA and calibrated for 6 recent storm events including data for the entire Limfjord area on bathymetry, wind, water levels, waves and tides. Thorough sensitivity analyses of the importance of waves, wind direction, depths in the channels and on the flood tidal delta, storm intensity, MSL, impulse effects (related to sudden increases in water level in the North Sea) etc were evaluated and showed that changes in the Thyboron Channel, by far, was the factor having the largest impact on storm surge levels in the fjord.

To quantify effects of the changes in the Thyboron Channel on extreme water levels, modelling was carried out using channel bathymetries from 1958, 2005 and 2060, where the 2060 bathymetry was constructed by assuming that the current development of the channel will continue.

The suite of models on calibrated bathymetries was used to establish bathymetry-corrected extreme water level statistics from 1958, 2005 and 2060 for 20 locations in the Limfjord by simulating storms representing 31 high water level events in a 33 year period. The 20 most extreme water levels at each location entered the statistical extreme value analyses to secure a consistent basis for comparison in time and space (the general method is in accordance with the one presented in chapter 2). For the four locations with established extreme water level statistics/tide gauge records at the time of investigation (Thyboron, Lemvig, Skive and Logstor) recalculations based on the bathymetry-corrected water levels were performed on individual storms to minimize the errors on the water level corrections and to better represent the actual effect today (2005) and in the future (2060).

For each of the 20 locations a trend-relation has been established between extreme water levels in the 1958, 2005 and 2060 bathymetries as exemplified by Lemvig in figure 8. The representation of an extreme water level back and forth in time can then be made by interpolation of the trends in relation to the year of occurrence.

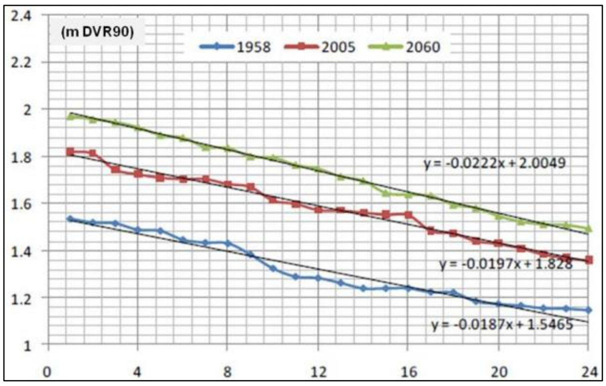

Figure 8 Trend-relations for the modelled storms in Lemvig ranked by surge levels.

In general, it was found that the increase in extreme water levels in the period 1958 - 2005 is larger than the increase in the period 2005 - 2060. Although the impact of the morpho-dynamics on the extreme water levels varies between different areas within the Limfjord, the general picture is clear and significant inasmuch as the natural development has led to an increase in the extreme water levels in the entire Limfjord (perhaps except the easternmost more channel-like parts) since the 1950s.

Table 1 100 year return heights (cm) from extreme water level statistics.

Statistics	Lemvig	Skive	Logstor	Source
1958 modelled and corrected	173	183	199	Christensen (2011a)
2005 modelled and corrected	199	197	203	Christensen (2011a)
2060 modelled and corrected	238	209	220	Christensen (2011a)
2007	183	193	194	Sørensen & Ingvardsen (2007)
2012 corrected	196	195	201	Sørensen *et* al (2013a)

Selected levels for a statistical 100 year return height at Lemvig, Skive and Logstor in table 1 show a marked increase between 1958 and today. For reference the calculated statistics from 2007 (Sørensen & Ingvardsen, 2007) and 2012 (Sørensen *et* al, 2013a), the latter including bathymetry corrected water levels in the statistics, are also shown.

Differences between the 2005 and 2012 statistics are small and are mainly due to the inclusion of all extremes in 2012 and with cut-off levels decided individually at each station. As the statistics have all been related to MSL, SLR must be added to give true number for 2060 in DVR90 and subtracted from 1958 water levels, respectively. At Logstor, the small difference between 1958 and 2005 is mainly due to local off-shore shoals that lead to high surge levels in the town. The largest magnitude of change is found in the Lemvig statistics, where the estimated 100 year return height has increased 13 cm between the last two official DCA statistics (2007 & 2013) and a dramatic increase in storm surge levels is found between the 1958, the 2005 and the 2060 statistics, respectively.

Although many additional morpho-dynamic changes may occur on a local level and modelling has its limitations, too, the results are believed to yield a solid picture of the actual impacts of change in the Limfjord.

4. INCREASED FLOODING HAZARDS DUE TO SLR AND SUBSIDENCE

A study in Thyboron in collaboration between the Danish Geodata Agency, DCA, DTU-Space and the Lemvig Municipality set out to explore uses of the Digital Elevation Model (DEM) in relation to land movement and future storm surges, hereby integrating into coastal climate change adaptation extreme water levels, SLR, glacio-isostatic adjustment (GIA), local subsidence and flooding hazards (Sonne *et* al, 2012; Vognsen *et* al, 2013). Being a methodology study preliminary assumptions have been made which are currently being dealt with in relation to qualification of methods, causes, solutions, and with a task to make the method more widely applicable (e.g. Broge *et* al, 2013).

4.1. Methodology and results

The precision of the DEM (resolution 1.6 m) was evaluated from levelling of manhole covers of the sewer system. Based on 136 of a total of 349 measurements, where the slope gradient was below 0.7° and thus considered representative of the DEM, figure 9, a deviation of +23 mm (std. dev. = 4 mm) was found and used for adjustment of the DEM.

From precise national levelling campaigns, GPS-measurements and GIA models a glacio-isostatic uplift in the Thyboron area of 1 mm/y is found (Knudsen & Vognsen, 2010; Knudsen *et* al, 2012) and the current absolute rate of SLR at Thyboron from tide gauge measurements (Knudsen & Sørensen, 2013) is established at 3 mm/y (for use in this study).

Figure 9 General elevation pattern (right) and surface slope map. Manhole covers are either in areas with slope gradients <0.7° (green dots), typically in the middle of roads, or > 0.7° (red).

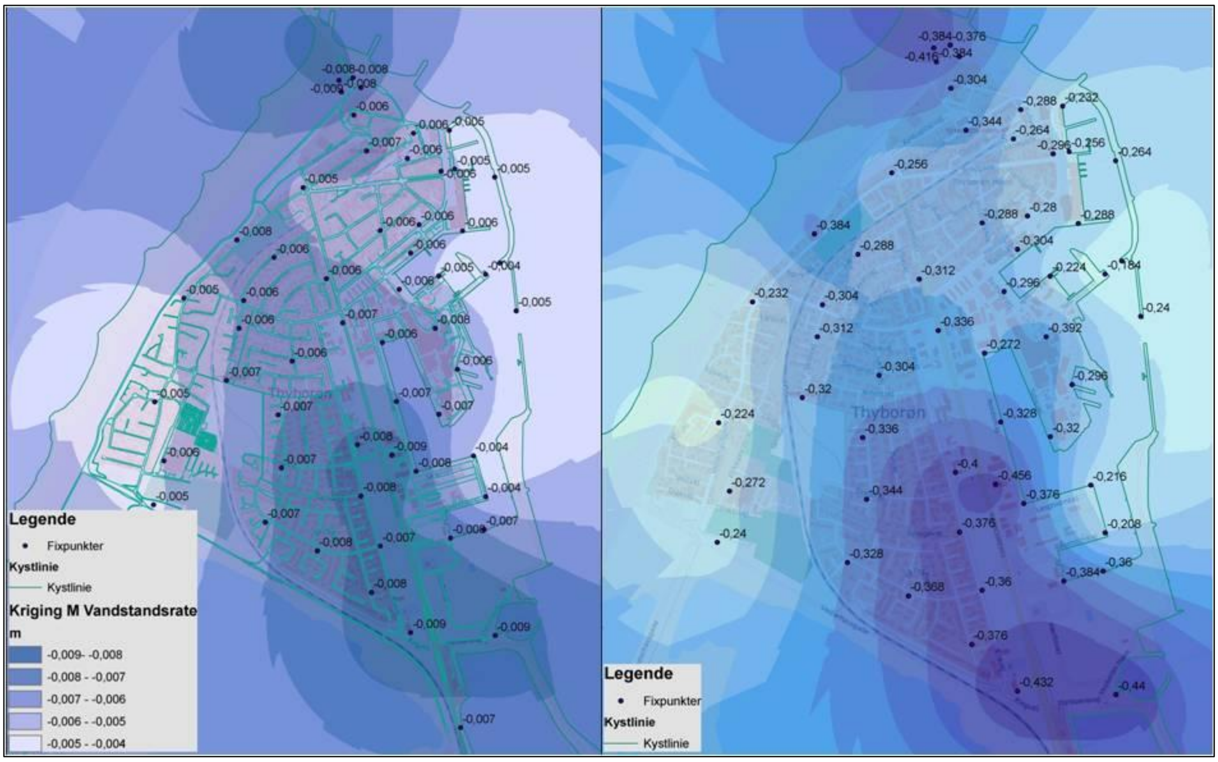

Figure 10 Relative change (m/y) between the land surface and mean sea level today (left) in Thyboron and accumulated change by 2060 provided that rates of change remain constant.

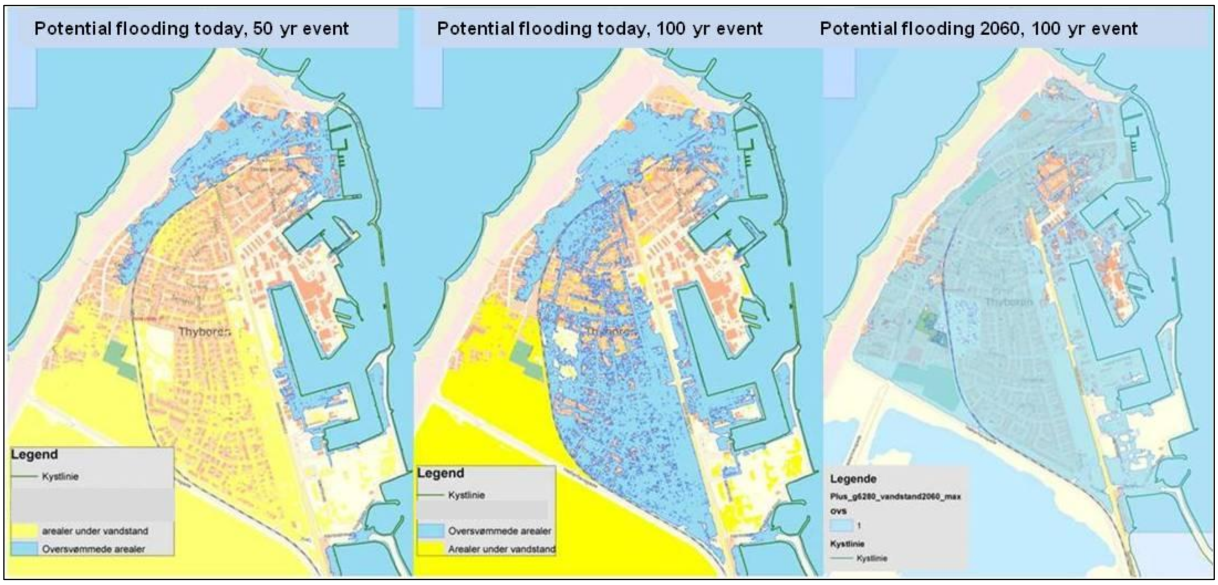

Figure 11 Maximum potential extent of flooding (blue) in Thyboron for 50 yrs (187 cm DVR90) and 100 yrs (193 cm DVR90) return heights today, and a 100 yrs return height in 2060 related to the adjusted DEM (right). Yellow areas are not flooded but lie below maximum water level.

Levelling campaigns in 2012, 2009 and 2006 to a closely spaced grid of benchmarks (and inclusion of previous campaigns in 2003, 1998, 1985 and 1970) show a very consistent pattern of local subsidence in Thyboron of 2 - 8 mm/y. This subsidence is largest in areas with landfill but is also governed by the underlying geology. Adding up the individual contributions, the vertical reduction between MSL and land surface in Thyboron is 4 - 10 mm/y as mapped in figure 10 (left) using a kriging interpolation.

If the changes are projected linearly into the future (assuming constant rates of SLR and land movement) they add up to a maximum of almost half a meter by 2060, figure 10 (right). This assumption is not strictly valid but is considered sufficient on a 50 year timescale for illustration purposes.

Turning to the extreme water level statistics, figure 11 (left and middle) some flooding today may be anticipated already at a 50 year event and increasing at a 100 year event, when the time factor is not considered. This probably is not the case and may be due to the DEM; however some immediate attention is probably needed in relation to flooding protection. Again, assuming that SLR will not affect the extreme water level statistics, the DEM is made "dynamic" in time and adjusted to the known and projected changes in MSL and land movement to yield a result for the potential flooding extent in 2060, figure 11 (right). Almost the entire town is then at risk.

The above example thus shows the ability to model SLR and land movement in the DEM to give more realistic future flooding scenarios. It also shows that, in addition to extreme water levels and the potential consequences of SLR, local subsidence may locally be the most important parameter of change at an intermediate timescale. Further, the example emphasizes that attention cannot be given solely to areas in the immediate vicinity of the coastline in coastal climate adaptation as areas further inland may also be susceptible to change over time.

5. DISCUSSION AND CONCLUSIONS

Based on the presented results a simplified conceptual set-up for the location-specific relative change in extreme water levels may be stated as:

$$\Delta WL_{(rel)extreme} = (\Delta MET_{\text{extreme}} + \Delta PHYS_{\text{extreme}}) + (\Delta SLR_{abs} + \Delta GIA_{abs} + \Delta LOW_{abs}) \quad (1)$$

The first bracket contains effects from a potential increase in future storminess and from physical/ morpho-dynamic change and the second bracket relates to SLR and to land movement due to regional glacio-isostatic adjustments and to local subsidence. The second bracket adds corrections to the de-trended extreme water level statistics for use in assessing the future change but may also affect the water level excursion in extreme events.

The impact in the statistics due to climate change is not dealt with explicitly here, but projections give a hint as to how the future may look and the effects can be modelled or calculated. The influence of morpho-dynamic changes can also be modelled provided that sufficient data is available and one knows what to look for, and local subsidence rates can easily be measured but most often we do not have enough data and knowledge present at hand. The presented studies show, however, that the impact of morpho-dynamics and local subsidence can be significant with contributions by far exceeding the effects of SLR both back in time and in coming decades.

In relation to the Danish statistics both the method applied and the extreme water level data may need a re-evaluation and update, and in relation to storm surge heights it is intriguing to await the future. Nevertheless, Denmark is in the midst of making climate change adaptation plans at the municipality level where robust statistics are "a must" in evaluating current and future flooding hazards. Focus is still often on the uncertainties in projections of SLR and on what to believe in, however.

In relation to the impacts of morpho-dynamics in the Limfjord changes occurred almost unnoticed for decades and local subsidence has not been a major issue there or elsewhere up till now. From a managers point of view this means that projected or believed safety levels against coastal flooding are in many places not met, especially where benchmarks are old and have not been related to a fixed datum for perhaps several decades. Considerations about potential morpho-dynamic changes and local subsidence are therefore advocated in relation to extreme water level statistics, flooding hazards and climate change adaptation in Denmark.

The current work on making a "dynamic" DEM by adjusting the model to future conditions based on (1) seems very promising and may prove a viable and easily accessible tool in relation to flooding issues and e.g. planning and maintenance of sewer systems. Mapping of areas in Denmark potentially susceptible to submergence has been initiated and will, together with the ongoing national flooding hazard mapping based on extreme water level statistics and extreme water level curves, form a solid basis for coastal climate change adaptation in Denmark.

Finally, an integration of the two case studies is desirable in relation to the upcoming tasks of determination and implementation of measures to reduce the extreme water levels in the Limfjord area.

6. ACKNOWLEDGMENTS

Co-authors Bo Brahtz Christensen (DHI), Holger Toxvig Madsen (DCA) and Søren Bjerre Knudsen (DCA) are acknowledged for their work on the Limfjord investigations as is Signe M. Ingvardsen (DCA). In relation to the work on land movement and the "dynamic" DEM appreciation primarily goes to Karsten Vognsen, Ian B. Sonne and Niels Broge from the Danish Geodata Agency and to Per Knudsen from DTU-Space for an exciting collaboration containing a multitude of facets that still need to be addressed and investigated.

7. REFERENCES

Broge, N, Sonne, B., Vognsen, V., Knudsen, P. and Sørensen, C. (2013). *Integration af lokale sætninger i klimatilpasning og risikokortlægning*. Dansk Kystkonference 2013, 11. - 12. september 2013, Køge, Danmark.

Christensen, B.B. (2011a). *Stormflodsundersøgelse i Limfjorden. Modelgrundlag, kalibrering og følsomhedsanalyse*. Teknisk Notat. Udarbejdet af DHI for Kystdirektoratet. 265 p + Appendices.

Christensen, B.B. (2011b). *Stormflodsundersøgelse i Limfjorden.– ny bathymetri og uddybning til 10 meters vanddybde*. Teknisk Notat. Udarbejdet af DHI for Kystdirektoratet.

Ingvardsen, S.M., Knudsen, S., Toxvig Madsen, H., Sørensen C. and Bisgaard C. (2012). *Thyborøn Kanal og Vestlige Limfjord*. Teknisk rapport. Kystdirektoratet.

Knudsen, P., Engsager, K., Khan, A., Andersen, O.B., Sørensen, C., Vognsen, K., Sonne, I.B. and Broge, N. (2012). *Landbevægelser i Danmark og deres betydning i forhold til fremtidig havspejls-stigning*. Højdedata - til klimatilpasning og beredskab, Holckenhavn Slot, 2. oktober 2012.

Knudsen, P. and Vognsen, K. (2010). *Metode til at følge vandstandsstigningstakten i de danske farvande*. KMS Technical report no. 08. Danish National Cadastre, Copenhagen.

Knudsen, S.B., Ingvardsen, S.M., Madsen, H.T., Sørensen, C. and Christensen, B.B. (2012). *Increased water levels due to morphodynamic changes; the Limfjord, Denmark*. *Coastal Engineering Proceedings* [Online], ICCE 2012, Santander, Spain, Vol. 1, 33.

Knudsen, S.B., Sørensen, C., Toxvig Madsen, H. and Ingvardsen, S.M. (2011). *Thyborøn Kanal 2009 – Teknisk rapport*. DCA, Lemvig.

Knudsen, S.B. and Sørensen, C. (2013). *Vandstandsmåling og vandstandsudvikling langs Jyllands centrale vestkyst*. Teknisk rapport. Kystdirektoratet.

Sonne, I.B., Broge, N., Vognsen, K., Borg, C., Knudsen, P. and Sørensen, C. (2012). *Dynamisk fremskrivning af Danmarks Højdemodel (DHM) ud fra højde- og vandstandsmålinger i Thyborøn. Højdedata -til klimatilpasning og beredskab*, Holckenhavn Slot, 2. oktober 2012.

Sørensen, C. and Ingvardsen, S.M. (2007). *Højvandsstatistikker 2007*. Kystdirektoratet.

Sørensen, C., Madsen, H.T. and Knudsen, S.B. (2013a). *Højvandsstatistikker 2012*. Kystdirektoratet.

Sørensen, C., Knudsen, S.B., Madsen, H.T., Ingvardsen, S.M. and Christensen, B.B. (2013b). *Thyborøn Kanals indvirkning på stormflodsvandstande i den vestlige Limfjord*. DNO. *17. danske Havforskermøde*, Roskilde, 21.-23. januar 2013.

Vognsen, K., Sonne, I., Broge, N., Sørensen, C. and Knudsen, P. (2013). *Metode til fremskrivning af oversvømmelsesomfang ved stormflod*. Geodatastyrelsen. Technical Report.