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STATISTICAL ANALYSIS OF EXTREME SEA WATER LEVELS AT THE FALSTERBO PENINSULA, SOUTH SWEDEN

Statistisk analys av extrema vattenstånd vid Falsterbohalvön

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Abstract

Falsterbo Peninsula on the south coast of Sweden is low-lying and exposed to flooding. In 1872 the extreme storm surge *Backafloden* caused large devastation on the Swedish, Danish, and German coasts in the South Baltic Sea. For the Falsterbo Peninsula, the peak storm surge level is estimated to have been 240 cm above normal. If a similar event happened today, the consequences would be far worse, as extensive flood prone areas have been developed since 1872. Due to climate change, the mean sea level is expected to rise and increase the flood risk unless preventive measures are taken. This paper discusses the occurrence of extreme sea levels at the Falsterbo Peninsula and design levels for coastal protection. Sea level observations from Skanör, Klagshamn, and Ystad are analysed with General Extreme Value and General Pareto Distribution models to estimate sea levels with return periods of 100–500 years. The estimated return period of the 1872 event, based on these models, resulted in an unrealistically low probability. To better understand the statistical behaviour of extreme storm surges of this magnitude on the Swedish south coast, development of more advanced statistical models will be required.

Key words – Extreme sea levels, Coastal flooding, The Falsterbo Peninsula, South Baltic Sea, General Extreme Value distribution, General Pareto Distribution, Backafloden, 1872 storm surge

Sammanfattning

Falsterbohalvön på Skånes sydkust är lågt belägen och riskerar att översvämmas vid höga havsvattenstånd. År 1872 inträffade en storm känd som Backafloden som orsakade stora skador längs den svenska, danska och tyska kusten i Södra Östersjön. På Falsterbohalvön uppskattas att vattennivån under stormen som högst nådde 240 cm över normalvattenståndet. Om samma händelse inträffade idag, skulle konsekvenserna bli betydligt värre eftersom stora arealer inom översvämningskänsliga områden har exploaterats sedan dess. Till följd av klimatförändringen väntas havsnivån stiga och ytterligare öka översvämningsrisken, såvida inte skyddsåtgärder vidtas. I den här artikeln diskuteras förekomsten av extrema vattennivåer på Falsterbohalvön och designnivåer för kustskydd. Vattenståndsobservation från Skanör, Klagshamn och Ystad analyseras med extremvärdesmodellerna »General Extreme Value» och »General Pareto Distribution» för att bestämma högvattennivåer med 100–500 års återkomsttid. Baserat på dessa modeller skattades även återkomsttiden för den extrema havsnivån 1872 vilket resulterade i en orimligt låg sannolikhet för händelsen. För att bättre förstå den statistiska fördelningen av den här typen av extrema högvatten på Sveriges sydkust behöver mer avancerade statistiska modeller utvecklas.

1 Introduction

Extreme high sea levels cause coastal flooding and damage to houses, infrastructure, and coastal environments. In severe cases, they pose a threat to human lives. In order to protect flood prone areas, different types of coastal protection measures may be implemented. When designing coastal protection, the design condition is normally a combination of water level and wave conditions. In this study, however, we are only focusing on extreme still water levels.

Early in the planning process it has to be decided which probability of flooding (or return period) the protection should be designed for and the corresponding still water level. The return period should be chosen based on risk, which is defined as probability × consequence. Thus, if the consequences are small, a higher probability (shorter return period) can be accepted. The design process should be iterative as costs, environmental impact, and other effects on the society needs to be considered, to find a balance between risks and benefits (Pullen et al., 2007).

Extreme sea levels can be estimated statistically by extreme value analysis of water level observations. This can be a challenging task as data records commonly are short compared to design return periods. In this study we explore the applicability of extreme value analysis for flood defence design with the Falsterbo Peninsula as a case study. However, the applied methods and discussed strategies for determining design levels have a general applicability and the need for coastal protection in other parts of south Sweden is expected to increase with rising sea levels and further development of coastal areas.

The Falsterbo Peninsula (Figure 1), in Vellinge municipality in the south of Sweden, is low-lying and prone to flooding (e.g. Blomgren, 1999; Pakkan, 2006; Persson et al., 2012). To protect the peninsula from extreme storm surges and rising sea levels, the municipality follows a protection plan (Landberg et al., 2011) that is stepwise implemented, with measures on short term (current situation), medium term (50 year perspective), and long term (100 year perspective). Currently, measures for the medium term flood protection are being implemented, with the purpose to protect urban areas from flooding from today until year 2065.

The Falsterbo Peninsula is especially vulnerable as the outer part can be cut off from the mainland if roads are flooded, thus hindering the inhabitants to leave Skanör and Falsterbo and impede access for rescue service. Therefore, initially long return periods, longer than 100 years, should be discussed and possibly with varying return periods for different areas based on vulnerability.

In this paper sea level data and historical records for the Falsterbo Peninsula are analysed with the General Extreme Value (GEV) and General Pareto Distribution (GPD) models. The objectives of the study is to estimate water levels with return periods of 100–500 years at the Falsterbo Peninsula and to analyse the probability of oc-

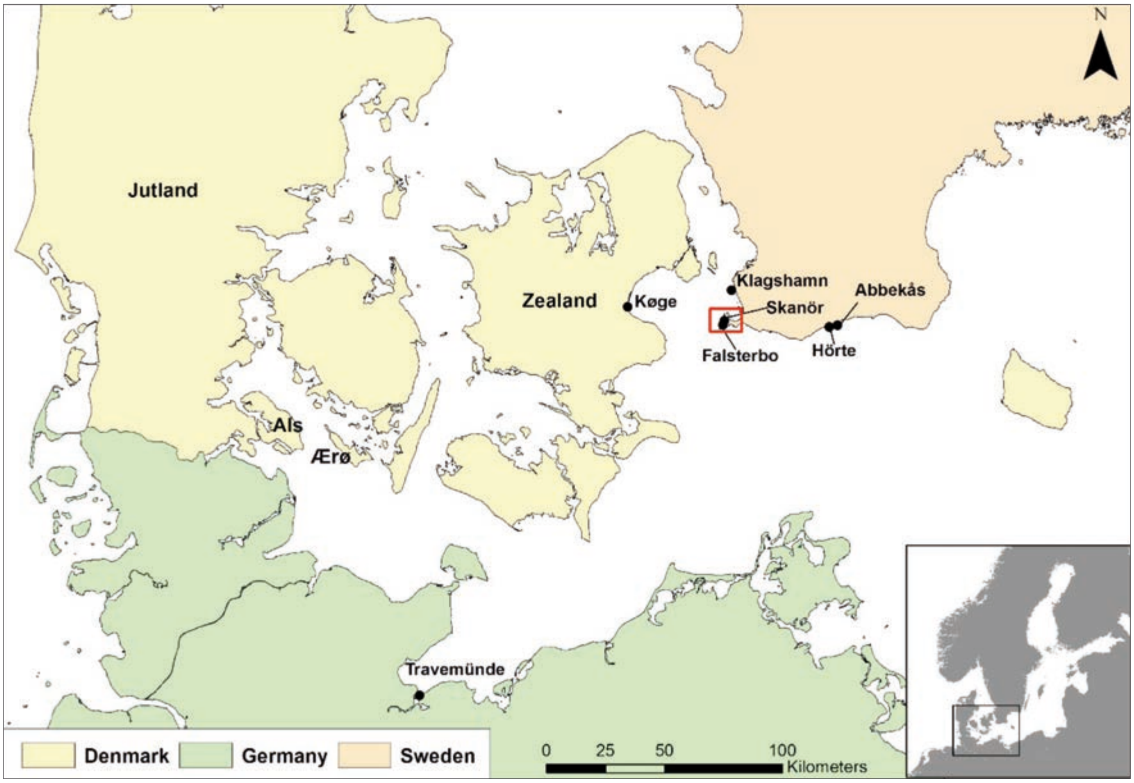

Figure 1. *Map overview; the Falsterbo Peninsula is marked with a red rectangle.*

Figure 2. *Memorial of the 1872 storm reading: To the foot of this memorial stone reached the storm surge in November 13, 1872.*

currence for a storm that occurred in 1872, which is the most severe known storm surge in the area in recent history.

First, a background on coastal protection design, extreme water levels on the south coast of Sweden, the extreme storm in November 1872, and the impact of climate change is given. Thereafter data analysis is performed and extreme value analysis methods are described. The results of the analysis are presented followed by a discussion on the application of extreme value analysis for flood protection design in a Swedish perspective.

2 Background

2.1 Design return periods for coastal flood protection

Flood protection is commonly constructed to withstand a design storm with a specific return period (or recurrence interval). The return period, T, is a way of describing the probability of occurrence, p, where $T=1/p$. Recurrence intervals are often presented in years and tells us the average probability of exceedance of an associated water level in any particular year.

In Sweden, there are few examples of implementation of protection against coastal flooding. Most of the coastal protection has so far been constructed with the purpose to counteract erosion. Examples of municipalities actively working with coastal flood defence in Sweden are Gothenburg (Göteborgs stad, 2015), Kristianstad (Kristianstads kommun, 2016), and Lomma (Almström and Fredriksson, 2014), where the first two are primarily focusing on the combined effect of high river flow and extreme sea levels. In Lomma and Kristianstad design still water levels in the sea are determined for a return period of 100 years and in Gothenburg of 200 years. From an international perspective, 100 and 200 years are relatively short return periods for design of coastal flood defence (see Table 1).

According to the EurOtop manual's (Pullen et al., 2007) guide on design life and level of protection, "Majority of coast protection or sea defence walls" should have a protection level of 50–100 years return intervals and "Flood defences protecting large areas at risk" a protection level of 100–10 000 years return intervals. We estimate that the Falsterbo Peninsula should be placed in the lower range of the second category, hence return periods of 100–500 years are calculated in this study.

The International Levee Handbook (CIRIA, 2013) does not provide guidelines on specific return periods but recommends that risks under different scenarios should be investigated. It also states that design levels based on return periods can be tricky to use as they continuously change as more data is collected.

2.2 Extreme sea levels on the south coast of Sweden

The Baltic Sea is a nearly closed system connected to the North Sea by the Danish belts and a narrow sound between Sweden and Denmark, Öresund, limiting the flow exchange between the seas. The narrowest section

Table 1 Example of design return periods for coastal protection in other European countries.

Country	Return period coastal flood protection
The Netherlands	4000–10 000 years, depending on risk*
Denmark	100–500 years, depending on population density*
Poland	100–500 years, depending on population density*
Great Britain	Low probability: 1000 years, medium probability 200–1000 years (Pullen *et al.*, 2007)
Germany (Baltic Sea coast)	The 1872 storm (Jensen and Müller-Navarra, 2008)

* Workshop Meeting of Kring of Coastal Engineers in Gdansk 5–6.

in the sound, the Limhamn threshold (indicated in Figure 4), separates the extreme sea levels regime in the sound from the regime in the South Baltic Sea (Jensen and Müller-Navarra, 2008). During the Advent storm in November 2011 and the storm Sven in December 2013, which caused flooding along the coast in Öresund, the sea level south of the Limhamn threshold was approximately 2 meters lower than on the north side (SMHI, open data).

During strong wind conditions water can be transported between the north and the south part of the Baltic Sea. Hanson and Larson (2008) analysed the correlation of wind direction and water levels on the south coast of Sweden and found that high water levels were associated with northerly and north-easterly winds while westerly and south-westerly winds generated low water levels. However, storm surge conditions in the South Baltic Sea are rather complex and can be influenced by westerly winds in at least two ways. During events with strong westerly winds the inflow to the Baltic Sea can be substantially larger than normal. After longer periods with westerly winds, water is pushed into the Baltic Sea and may give rise to an increase of the sea level by up to 0.5 m (Hünicke et al., 2015). Westerly winds may also cause seiches in the entire Baltic Sea basin which can affect the sea level with a few decimetres (Jensen and Müller-Navarra, 2008). The period of the seiches are approximately 24–27 h (Hanson and Larson, 2008). Differences in atmospheric pressure over the Baltic basin can cause further increase of the still water level with approximately 25 cm (Hellström, 1941).

When all these four processes interact, large water volume, seiches, pressure differences, and wind setup, the most extreme water levels are generated.

2.3 The November storm 1872

On November 13, 1872 the most severe storm surge on record caused huge devastation on the Danish, German, and Swedish Baltic Sea coast, costing the life of 271 people, leaving 15000 persons homeless and destroying 2800 buildings (Feutcher et al., 2013). The still water level reached up to 3.4 m above normal in Travemünde, Germany (Jensen et al., 2008), and up to 3.3 m above normal in Denmark with the highest observations from Als, Ærø, and the south-east coast of Jutland (Nielsen et al., 2015). In Køge, on the east coast of Zealand, the sea level reached 2.8 m (Nielsen et al., 2015).

The extreme storm surge in 1872 was caused by an unusual interaction of pressure systems (Feuchter et al., 2013). First a low pressure system over the North Sea generated strong westerly winds which pushed water through the sound and belts into the Baltic Sea, rising the sea level in the entire basin. Thereafter a high pressure system established over Scandinavia while a low pressure system moved over Central Europe generating strong north-easterly to easterly winds reaching hurricane strength. Water was pushed to the south-west Baltic Sea and the strong winds generated high waves that coincided with the storm surge peak.

In Sweden the storm is known as *Backafloden* and there are several eye witness reports from the incident, however, there are no trustworthy observations of the still water level as no, for us today known, water level gauges were operated at that time. We have found no reports of deaths in Sweden, but there are several reports about damaged houses on the south coast. In Hörte old fishermen's houses made of clay and straw were destroyed (Mårtensson, 1984) and in Abbekås several houses and parts of the harbour were damaged (SMHI, 2009). According to the Swedish Meteorological and Hydrological Institute, SMHI, (2009) the water level in Abbekås reached 3.6 m above normal. However, this observation is contradicted by descriptions of the storm event in Skanör and Falsterbo (Dufberg, 1994).

Dufberg (1994) has estimated the water level to 2.4 m above normal based on eyewitness stories. For this study we have controlled his estimation by comparing the information with the national digital elevation model (New National elevation model, NNH). Today the mean sea level in Skanör is +15.5 cm relative to the elevation system RH 2000. In 1872, the mean water level was approximately 10 cm lower, meaning that 2.4 m above normal corresponds to an absolute level of +2.45 m (RH 2000) at that time. According to Dufberg (1994) houses in Skanör was flooded but not in Falsterbo, were the historical centre is located above +2.5 m (RH 2000). Further, there is a description of how the old square *Rådhustorget*in Skanör, which has a ground elevation of +2.4–2.6 m (RH 2000) was flooded during the surge peak for half an hour.

Hellström (1941) has studied the 1872-storm and calculated wind setup and the effect of pressure differences based on meteorological observations. Hellström estimated the wind setup to 2.10 m, an additional 0.20 m due to pressure gradients and a maximum water level of 2.26 m above mean sea level, corresponding to approximately +2.3 m relative RH 2000, based on a measurement of a memorial stone over the flooding in Skanör. However, a new control measurement of the stone for this study indicate that the surge level should have been +2.5 m (RH 2000). The memorial stone has been moved from its original position (Dufberg, 1994) so it is uncertain whether the level today exactly corresponds to the level at the time the stone was erected. But according to Hellström (1941) several trustworthy persons have confirmed that the level should be correct al-

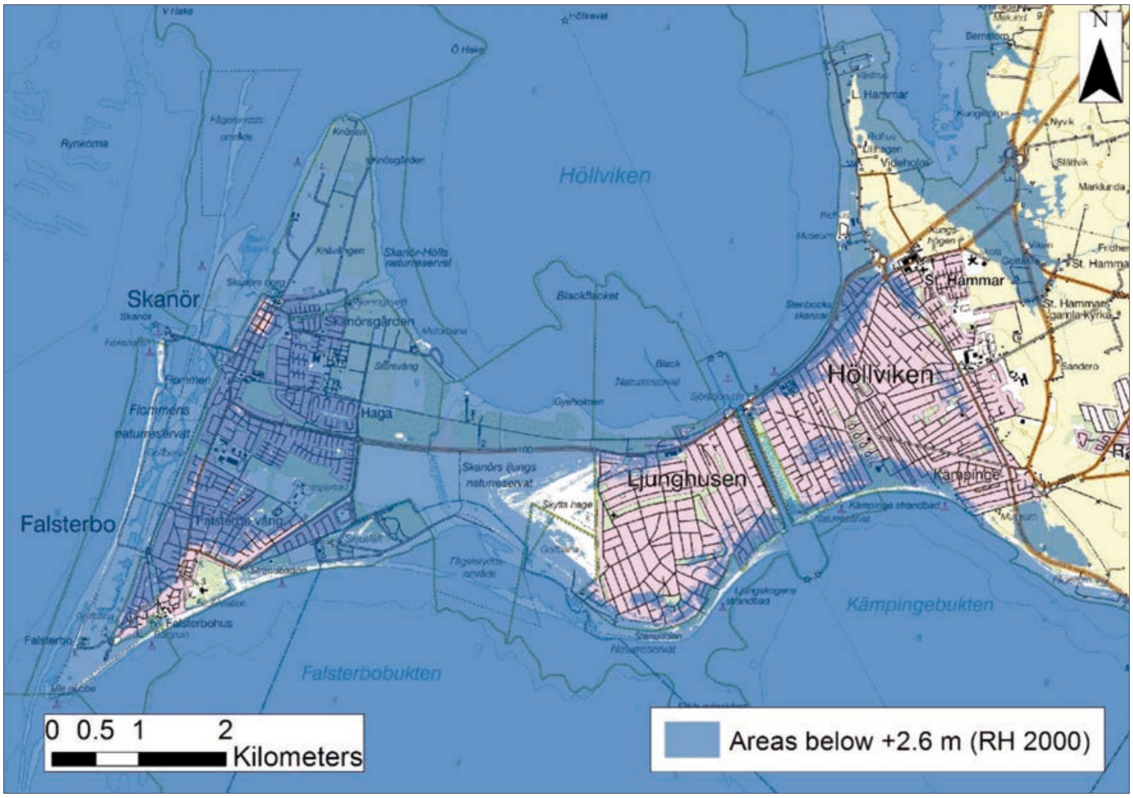

Figure 3. *Flooded areas if the 1872 storm would happen today (©Lantmäteriet [I2014/00579]).*

though the memorial stone has been moved twice. From Hellström's study (1941) we may also conclude that the water level should have been higher in Skanör and Falsterbo than in Abbekås, which is located east of the Falsterbo Peninsula, since the water level in the Baltic Sea was increasing in westward direction. Thus, the observation of a water level 3.6 m over normal in Abbekås (SMHI, 2009) is most probably incorrect.

Our estimation is that the water level in Skanör reached approximately 2.4 m above mean sea level which would correspond to about +2.6 m (RH 2000), if the same storm event would happen today. In Figure 3 is the flooded area during such an event displayed. Today, the effects would have been much larger than in 1872 as extensive low-lying vulnerable areas have been developed since then.

In the literature there are large differences in the estimates of the return period on the German coast ranging from 180–200 years (Niemeyer et al., 1996) up to 3400–10 000 years (Hünicke et al., 2015). Differences in analyses depends on methods used and whether other historical events outside gauged time series are taken into account or not.

2.4 Other extreme storm surges

The highest measured water level on the Swedish south coast is from Ystad, where 1.66 m above normal was measured on December 31, 1904 (Nerheim, 2007), which corresponds to a level of +1.85 m (RH 2000) with the present mean sea level. Notes in the logbook from Klagshamn indicate that the water level there was 1.85 m above normal (Hellström, 1941), which would correspond to +1.98 m (RH 2000) with the present mean sea level.

In Germany and Denmark, further historical surge levels are documented (Jensen et al., 2008). In Travemünde, where the 1872 storm reached 3.4 m above normal, the second highest known peak dates back to 1320 when the water level reached 3.1–3.2 above normal. In the 17th century 2.84 and 2.86 m above normal was observed in 1625 and 1694, respectively. In Denmark, there are no precise measurements of the surge levels, but also here the 1625 and 1694 storms are described in historical documents (Petersen, 1924).

The historical records, especially from Travemünde, indicate that the storm surge in 1872 is an extreme but not unique event in the south Baltic Sea.

2.5 Climate change

For permanent coastal flood protection, design lives of 30–100 years are normally considered (Pullen et al., 2007). Horizons for spatial planning and development of coastal zones may be even longer, up to 200 years. When estimating design storm surge levels climate change and climate variability should therefore be considered.

Climate change can affect storm surge levels in at least two ways, through increase in the mean sea level and through changes in the weather patterns and storminess. For the latter case, climate variability is important and for northern Europe the rather large variations in storminess between decades dominate over long-term trends (Rutgersson et al., 2015). For example the 1960's and 1970's were calm periods compared to the 1880's and the last decade (Rutgersson et al., 2015).

Most climate models predict an increase in the mean wind speed, but the result is not consistent (Christensen et al., 2015). No prediction of future wind directions have been found for this study. For extreme storm surge levels, wind direction is an important parameter and changes of predominant wind directions have been found in data records. For example, a change from predominant east and south-easterly winds to west and south-westerly winds occurred in southern Sweden in the mid-19th century (Jönsson and Holmquist, 1994).

Sea level prognosis are more in agreement to predict rising levels. However, increase rates are uncertain and will not be discussed in detail here.

In Sweden sea level rise is compensated or partly compensated by the glacial isostatic adjustment. However, in Scania this effect is small and in Skanör the sea level is already rising faster than the post-glacial rebound, causing a net increase of mean sea level of about 0.7 mm/year today (Persson et al., 2011). For the Falsterbo Peninsula, a rough estimate of the sea level rise until year 2100 is 1 m (SMHI, 2011) and until 2065 approximately 0.5 m can be considered a reasonable estimate (Almström and Fredriksson, 2014). In spatial planning and design of coastal protection the large uncertainties in the predictions can be dealt with by constructing flexible and adaptive solutions that can be adjusted stepwise according to new predictions.

3 Data

For this study, SMHI open access data with hourly values has been available from three stations in the vicinity of the Falsterbo Peninsula (Figure 4). The stations are located in Klagshamn (operated since 1929), Skanör (operated since 1992), and Ystad (operated 1886–1987).

There has also been data available from the Falsterbo Canal, with daily measurements at noon. Peaks of extreme sea levels are often short, on an hourly scale, thus daily measurements are likely to underestimate the extreme levels. Data from the Falsterbo Canal has therefore been omitted from the study.

SMHI assess the quality of the data points as green or yellow, where green stands for controlled and approved values and yellow for suspicious or aggregated values. For the measurement station in Ystad, there is no information about data quality. For the stations in Klagshamn and Skanör there is no information about data quality until 2010 and thereafter all measurements are green.

The data has been analysed for missing values to assess the applicability for extreme value analysis. The Ystad series is complete. In Figure 5 and Figure 6 missing values from the Klagshamn and Skanör series are indicated with circles. Most extreme water levels occurs from October to March and if values are missing in this period, there is a risk that the most extreme values are absent in the data. Based on this analysis, no data from before 1960 from Klagshamn will be used in the extreme value analysis. Even years where no data is missing during winter time will not be used as it is possible that the data

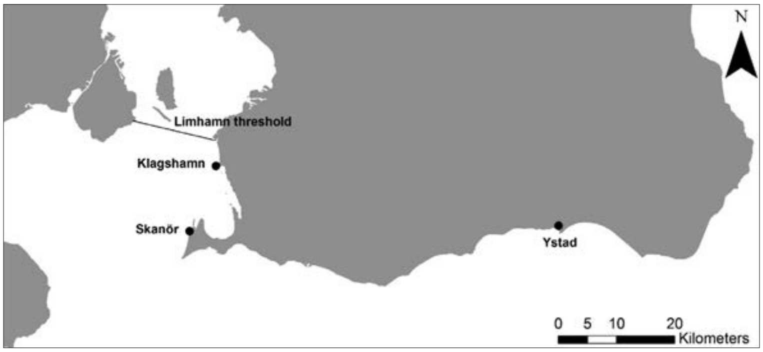

Figure 4. *Water level measurement stations in Klagshamn, Skanör and Ystad. The Limhamn threshold is a narrow section in Öresund, dividing the different extreme sea level regimes in Öresund and the South Baltic Sea.*

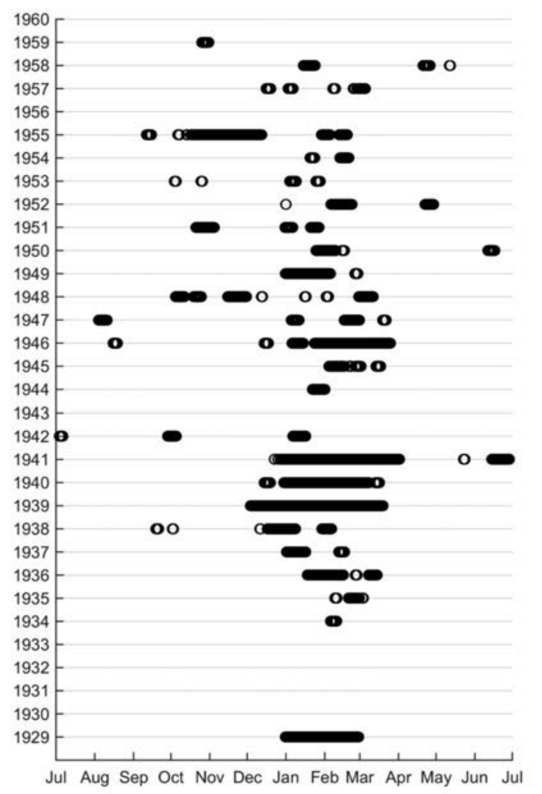

Figure 5. *Missing values in the time series from Klagshamn.*

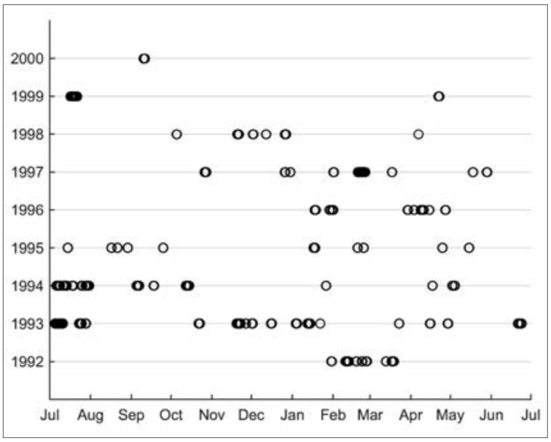

Figure 6. *Missing values in the time series from Skanör.*

is biased and that those years have been unusually calm. In the Skanör series there are fewer values missing during winter time and the missing values are assumed to be negligible in the analysis.

Blomgren (1999) analysed yearly maxima from Klagshamn and found an increasing trend by 4.5 mm/year, in addition to the rising mean sea level trend. When considering the data from 1960 onwards, omitting the years with missing data points, there is no significant trend in yearly maxima.

4 Method

Extreme value theory is used to analyse data and to predict events with low probabilities. By extrapolation, levels can be predicted for return periods that are longer than the data series itself.

The theory is based on some general assumptions about the tail of an unknown distribution which, with some mathematical arguments, lead to different types of distributions. These distributions can be used to make inference on large values of the observed random samples. For instance, hourly or daily measurements of sea levels have distributions that are generally unknown, but the tail with the highest values follows an extreme value distribution.

The highest observations are selected either as block maxima, for example the highest observations during each year, or as values exceeding a threshold value. Block maxima are assumed to follow a Generalized Extreme Value distribution (GEV) and peaks over thresholds to follow the Generalized Pareto Distribution (GPD), under the condition that the observations are independent and identically distributed.

The following description of the method employed is based on extreme value theory as presented in Coles (2001).

The extreme value analysis is performed in R software (R Core Team, 2016) using the packages extRemes (Gilleland and Katz, 2011) and its graphical interface in2extRemes.

4.1 Generalized Extreme Value distribution

A GEV distribution function describes the distribution of block maxima, M_n, which is defined as $M_n=max(X_1, \ldots,X_n)$ where n is the number of observation within each block. Here, sea level observations are hourly so the yearly maxima are determined for $n=365.25\times24$ values. Block maxima are selected from July to June (similar to a hydrological year) to avoid the dependence between consecutive observations, as extreme water levels rarely occur during the summer months.

We are normally interested in determining the return period, T, for a specific extreme event, in this case the

1872 storm. Alternatively, one could calculate a return level, x_p, corresponding to a specific return period for example 100 years. The return period is the inverse of the probability of exceeding the return level (p) *i.e.* $T=1/p$.

To the observed block maxima a GEV family distribution is fitted, of the form:

$$G(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

where μ is a location parameter, σ is a scale parameter, and ξ is a shape parameter. The value of the shape parameter determines which type of distribution within the GEV-family that fits the data best. If $\xi = 0$ the GEV distribution is said to be of a Gumbel type, if $\xi > 0$ a Fréchet type, and if $\xi < 0$ a Weibull type. The Gumbel distribution function, also called double exponential, has the form:

$$G(x) = \exp\left[-\exp\left\{-\left(\frac{x-\mu}{\sigma}\right)\right\}\right]$$

When the parameters have been estimated by fitting the GEV-distribution to observed values, the return level x_p can be determined for an associated return period $1/p$:

$$x_p = \mu - \frac{\sigma}{\xi}\left[1-\{-1\text{n}(1-p)\}^{-\xi}\right] \quad \text{for } \xi \neq 0 \text{ and,}$$

$$x_p = \mu - \sigma\, 1\text{n}\, \{-1\text{n}(1-p)\} \quad \text{for } \xi = 0$$

An important difference between the different types of GEV-distributions is that Gumbel has an infinite range, while the Weibull and Fréchet distributions have finite right and left endpoints, respectively.

4.2 Generalized Pareto Distribution

As mentioned above, extreme value theory concerns approximation of the tail of an arbitrary distribution. It follows that all large observations in the observed sample should be used to make inference about the tail.

A disadvantage with the GEV-method is that plenty of data is discarded when the distribution is based only on the highest value within each block. An alternative approach based on exceedances of observations over a high threshold overcomes this drawback in block maxima method. This is generally known as Peaks Over Thresholds (POT) model and it leads to the so called GPD distribution as described below.

The GPD describes the conditional cumulative distribution of the excesses, $y = x - u$, over a certain threshold, u, under the condition that $x > u$:

$$H(y) = 1 - \left(1 + \xi\frac{y}{\sigma}\right)^{-1/\xi}$$

where σ is a scale parameter and ξ is a shape parameter, as for GEV.

When parameters have been estimated, a level x_m which is exceeded on average once every m observations can be determined:

$$x_m = u + \frac{\sigma}{\xi}\left[(m\zeta_u)^{\xi} - 1\right] \quad \text{for } \xi \neq 0 \text{ and,}$$

$$x_m = u + \sigma\, 1\text{n}(m\zeta_u) \quad \text{for } \xi = 0$$

where the parameter ζ_u is estimated from the data as the proportion of values exceeding the threshold u in the full data set. If k is the number of exceedances and n_{tot} is the number of measurements, $\zeta_u = k/n_{tot}$.

To estimate the N-year return level, m is chosen as the number of observations during N years. For example if you wish to calculate the 100-year return level from hourly measurements, m is the product of the return period, the number of days in a year and the number of hours per day, $m=100\times365.25\times24$.

The behaviour of the upper and lower limits is depending on the shape-parameter in a similar way as for GEV, if $\xi >= 0$, the exceedances have no finite right end point, while for $\xi < 0$ it is possible to estimate an endpoint for the upper end of the exceedances.

The threshold is selected based on a mean residual life plot, where the mean of the exceedance above a threshold is plotted against threshold level, choosing a point from which the mean excesses show a linear increase with increasing threshold value and by comparing diagnostic plots for different thresholds. We refer to Coles (2001) for further details.

Water level observations are time dependent data and exceedances will therefore appear in clusters from which we are only interested in the highest observation. However, during a storm surge event water levels may fluctuate around the threshold value, and to avoid dependent peaks, we define a number of observations that needs to be below the threshold before a new event can be considered to be independent of the previous. Storm surge peaks are normally occurring from a couple of hours up to maximum a couple of days. Here we choose 48 hours with values below the threshold as the limit for declustering of extreme events.

4.3 Accumulated probability

When return levels are calculated with GEV or GPD, the associated return period represents the probability of exceedance during any given year. However, when designing structures with a specified design life, the accumulated probability over the life time is an important factor. Temporary constructions and constructions with

Table 2. *Result of correlation analysis between the different stations.*

	Observations	Correlation coefficient, r_{xy}
Skanör-Klagshamn	1992-02-17–2016-05-23	0.95
	Year max 1992–2015	0.97
Ystad-Klagshamn	1961-01-01–1987-01-05	0.95
	Year max 1961–1986	0.92

short design life should be designed for events with shorter return periods, T, than structures with long design lives as the accumulated probability of exceedance, P, increases with time where n is number of years e. g. corresponding to the life span of a structure:

$$P = 1 - \left(1 - \frac{1}{T}\right)^n$$

4.4 Correlation analysis

To be able to compare the different time series without influence from sea level rise and differences in mean still water level between the different stations, the water levels are presented relative to the local mean sea level. Sea level rise is here assumed to be a constant linear process which is fitted to a linear equation and subtracted from each data set. Sea level rise is in fact not linear but the associated error is estimated to be negligible in these relatively short time scales.

Correlations between different data sets are estimated by comparing hourly values, and GEV-models estimated for overlapping time periods.

The correlation coefficient, r_{xy}, is estimated according to:

$$r_{xy} = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2}}$$

where x and y are the correlated parameters with average values $\overline{x}$ and $\overline{y}$.

5 Results

5.1 Correlation between data series

Correlation analysis was performed for periods where the stations have overlapping data. In Table 2 the result is presented for the correlation between Skanör – Klagshamn and Ystad – Klagshamn, both for all values and for yearly maxima. The correlation coefficient, r_{xy}, ranges from –1 to 1, where a higher absolute value indicates stronger correlation.

The correlation analysis indicates a strong correlation between all three stations, both between hourly data and yearly maxima. Figure 7 and Figure 8 display scatter

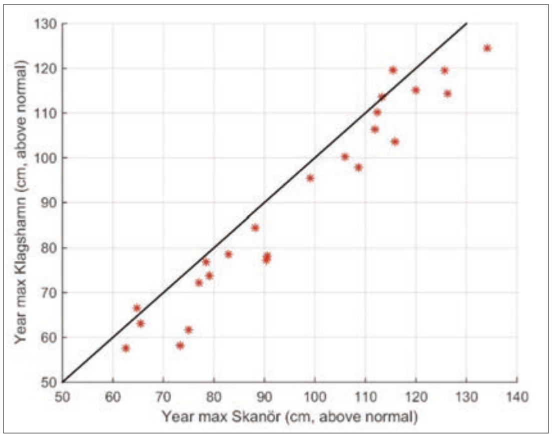

Figure 7. *Yearly maxima in Klagshamn plotted against yearly maxima in Skanör. The line represents a 1:1-relation.*

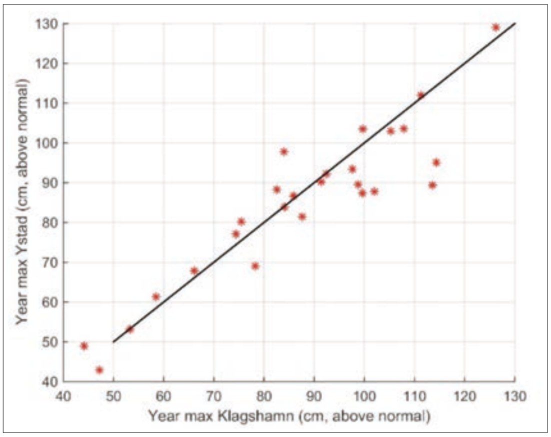

Figure 8. *Yearly maxima in Ystad plotted against yearly maxima in Klagshamn. The line represents a 1:1-relation.*

Table 3. *Maximum likelihood estimates of parameters in the GEV model for the different data sets. 95 % confidence intervals estimated with normal approximation are presented within brackets.*

Period	Data series	Location, μ	Scale, σ	Shape, ξ
1992–2015	Skanör	90.4 *(80.2 – 100.6)*	22.1 *(13.9 – 30.4)*	–0.41 *(–0.81 – –0.02)*
	Klagshamn	85.6 *(74.6 – 96.7)*	23.8 *(13.9 – 33.7)*	–0.55 *(–1.0 – –0.09)*
1961–1986	Klagshamn	82.0 *(72.6 – 91.3)*	22.3 *(15.4 – 29.3)*	–0.45 *(–0.68 – –0.02)*
	Ystad	78.7 *(70.4 – 87.0)*	19.8 *(14.2 – 25.4)*	–0.32 *(–0.50 – –0.14)*

plots of yearly maxima, Skanör compared to Klagshamn and Klagshamn compared to Ystad, respectively. In Skanör the yearly maximum values are on average 6.1 cm higher than in Klagshamn with a standard deviation of 5.1 cm. In Klagshamn the yearly maximum values are on average 2.6 cm higher than in Ystad with a standard deviation of 8.3 cm.

To test if extreme value analysis can be performed on a combined series with data from all three stations, GEV-models were fitted to compare the distribution of yearly maxima in the overlapping time series. The results are presented in Table 3. The GEV distributions fitted to the Skanör and Klagshamn series are very similar, while the Ystad distribution is slightly different, with lower values on all parameters. The location parameter can be adjusted by adding the observed mean difference between the data series, but the difference in scale and shape parameter will remain. This difference, and the asymmetry in the scatter plot (Figure 7), indicate that the observations from Ystad may have a different distribution than the other stations and that the condition of identically distributed data can not be fulfilled if the three data sets would be combined into one.

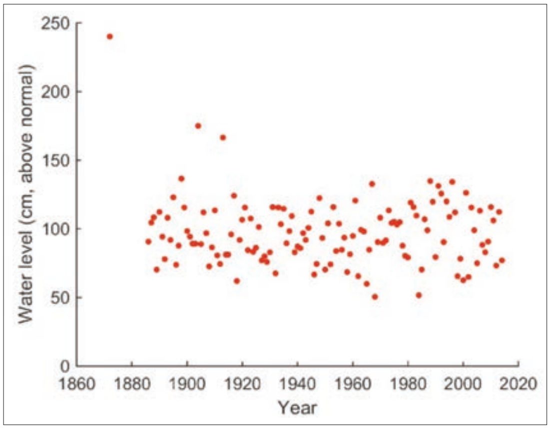

Figure 9. *Yearly maxima from 1886 – 2015 in a combined data set with observations from Skanör, Ystad and Klagshamn, including the 1872 storm surge level.*

GEV and GPD analysis is performed on the separate data sets, but to give a picture of the variations of yearly maxima during the entire period Figure 9 displays observations from Ystad 1886–1960, Klagshamn 1961–1992, Skanör 1992–2015, and the estimated level of the 1872 storm surge at the Falsterbo Peninsula. The data series are transformed so that sea levels are given relative to mean sea level and adjusted to represent the yearly maximum sea levels in Skanör by adding 6.1 cm to the Klagshamn series and 7.7 cm to the Ystad series, although differences in yearly maxima between the series are not significant.

The estimated level of the 1872 storm stands out, being 1.4 m higher than the average of 97 cm. The second and third largest observations occurred during early 20th century and are thus only included in the Ystad data set.

5.2 Block maxima analysis

GEV and Gumbel models were fitted to the data from Skanör, Klagshamn, and Ystad. Parameters were estimated with the maximum likelihood method. The models were tested with likelihood ratio test with a significance level of 95 %. If GEV was significantly better, the Gumbel model was rejected. Otherwise the Gumbel model was kept for the advantage of being a simpler model.

The estimated parameters are presented in Table 4 together with point estimates of the 100-year return level and the return period for the 1872 storm. The three data

Table 4. *Maximum likelihood estimation of parameters for the GEV and Gumbel (ξ=0) model (with standard error within brackets), estimated 100-years return level relative mean sea level (with 95 % confidence interval within brackets), and estimated return period for the 1872 storm.*

	Location, μ	Scale, σ	Shape, ξ	Estimated water level 100 years return period	Estimated return period 1872-storm
Skanör 1992–2015	85.9 *(4.1)*	19.1 *(3.0)*	0	174 *(143–204)*	3200 years
Klagshamn 1961–2015	85.3 *(3.5)*	23.3 *(2.7)*	–0.47 *(0.1)*	129 *(125–144)*	Exceeds the upper limit of distribution (135 cm)
Ystad 1886–1987	77.9 *(1.8)*	17.4 *(1.3)*	0	158 *(144–171)*	7000 years

sets give varying results. The Skanör time series is too short to estimate the 100-year return level with precision. There is a rather large difference in the estimates of 100-year return levels between the data series from Klagshamn and from Ystad. This is probably mainly due to climate variability between the different measurement periods, with the highest measured water levels included in the Ystad series but not in the Klagshamn series. The Klagshamn data follow a Weibull-type distribution, with an upper limit of 135 cm. This is unrealistic considering the 1872 storm and the estimation in literature that the storm in 1904 reached 185 cm above normal in Klagshamn (Hellström, 1941).

5.3 Peaks over thresholds

GPD models were fitted to daily maxima from Skanör, Klagshamn, and Ystad. The thresholds were estimated based on mean residual life plots and fit diagnostics. The results are presented in Table 5. For Ystad and Klagshamn estimated 100-year return levels are similar compared to the estimates based on the GEV-distributions, which indicate stability in the models. The estimate for Skanör is considerably lower, probably due to the fact that the data series is too short to make estimations for 100-year return periods.

5.4 Estimation of return levels for the Falsterbo Peninsula and probability of the 1872 storm

For estimation of return levels for the Falsterbo Peninsula, the data series from Ystad is assumed to give the most reliable results, as the data from Klagshamn represent an unusually calm period and the data series from Skanör is too short. The choice between GEV and GPD model is based on diagnostics plots (Figure 10–Figure 13) comprising density and QQ-plots. In the density plots, the fitted distribution density functions are plotted together with the density of calculated probabilities for different water levels from the empirical observations. QQ-plots are scatter plots of the empirical and modelled quantiles, which are the corresponding water levels to each probability assigned to the observations. Points falling on the 1:1 line in the QQ-plot indicate a perfect fit.

Table 5. *Threshold value, number of exceedances, maximum likelihood estimates of GPD parameters (with standard error within brackets), estimated 100-years return level relative mean sea level (with 95 % confidence interval within brackets), and estimated return period for the 1872 storm.*

	Threshold, u	Number of clusters exceeding u	Scale, σ	Shape, ξ	Estimated water level 100 years return period	Estimated return period 1872-storm
Skanör 1992–2015	90 cm	21	31.2 *(7.9)*	–0.69 *(0.2)*	134 *(133 –152)*	Exceeds the upper limit of distribution (226 cm)
Klagshamn 1961–2015	90 cm	47	24.6 *(4.29)*	–0.60 *(0.13)*	128 *(127–137)*	Exceeds the upper limit of distribution (147 cm)
Ystad 1886–1987	90 cm	58	15.4 *(2.7)*	0 *(0.12)*	153 *(134–184)*	16 000 years

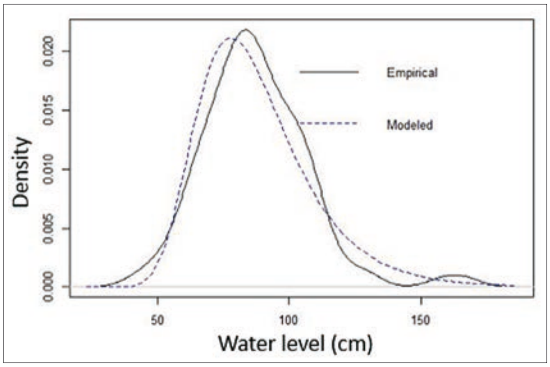

Figure 10. *Density plot for GEV-model based on the Ystad data.*

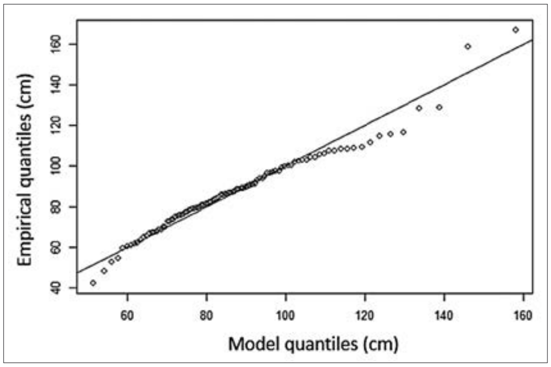

Figure 11. *QQ-plot for the GEV-model based on the Ystad data.*

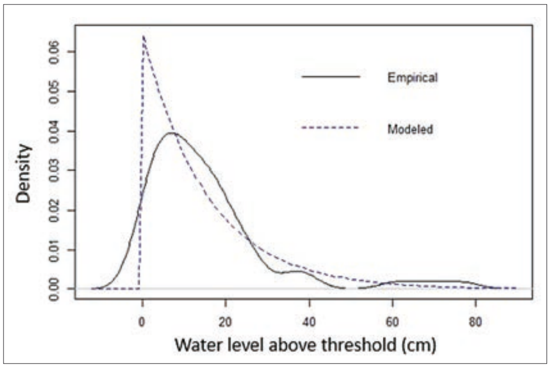

Figure 12. *Density plot for GPD-model based on the Ystad data with a threshold of 90 cm.*

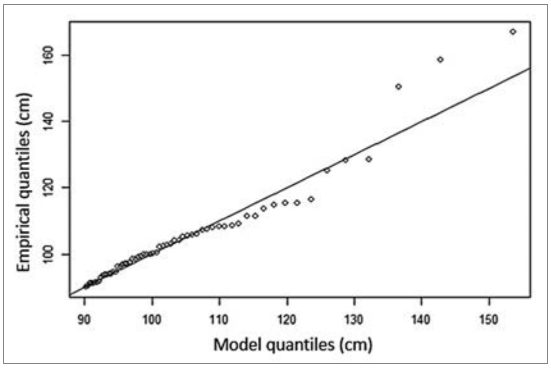

Figure 13. *QQ-plot for the GPD-model based on the Ystad data with a threshold of 90 cm.*

The diagnostics plots indicate acceptable fits for both models, with similar representation of the highest values. Note that the scales are different on the y-axis in the QQ-plots (Figure 11 and Figure 13). The GEV model is chosen for further analysis because it has a narrower confidence interval as it is based on more observations, and the estimation of return levels are higher, rendering the more conservative estimations of design still water levels among the two.

In Table 6 return levels for 100, 200, 300, and 500 years return periods are calculated for the fitted GEV model. The results are presented both relative to the normal sea level and the elevation reference system RH 2000. As the values are calculated based on the Ystad data, according to the correlation analysis, 7.7 cm have been added to the result to adjust the levels to conditions at the Falsterbo Peninsula. The table also includes a column with the accumulated probability over a period of 50, 100 and 200 years which are examples of design periods considered in coastal protection and coastal

Table 6. *Estimated return levels and their probability of exceedance during time intervals of 50, 100 and 200 years. 95 % confidence intervals are given within brackets.*

Return period	Water level at the Falsterbo Peninsula		Probabiliity of exceedance during:		
	cm rel MSL	cm rel RH 2000	50 years	100 years	200 years
100	165 *(152–179)*	181 *(168–194)*	39 %	63 %	87 %
200	177 *(163–192)*	193 *(178–207)*	22 %	39 %	63 %
300	183 *(168–200)*	199 *(184–216)*	15 %	28 %	49 %
500	193 *(177–213)*	209 *(192–229)*	10 %	18 %	33 %

planning. For long return periods the confidence intervals become very broad, indicating that the range of applicability of the model has been exceeded.

The Ystad models generate return periods for the 1872 storm of 7 000 years with the GEV model and 16 000 years with the GPD model. These return periods correspond to an accumulated probability of occurrence during the last 150 years of 2 % and 0.9 % respectively. This is a very low probability which indicates that the 1872 storm surge is another type of event than the observations in the here analysed data and may follow a different distribution.

6 Discussion and conclusions

In this paper we have, based on a literature study, estimated the peak still water level during the 1872 storm to 240 cm above normal at the Falsterbo Peninsula. We tried to use extreme value analysis to determine the return period of the event, but the estimated return periods do not seem reasonable. The 1872 storm appears to belong to a different distribution than the observations in the studied data sets.

The historical records indicate that the 1872 storm is an extreme but not unique event. For estimation of the return period of the 1872 storm, a more detailed study of historical records and geological studies of storm surge traces could provide valuable information. In further studies, other statistical methods can be tested, for example classifying different types of events with regard to wind patterns (speed, direction and duration) and atmospheric pressure variations in consideration of the shape of the Baltic Sea basin. It would also be interesting to perform a deeper analysis of the relation between the different measurement stations. The joint probability that a certain water level is exceeded in all or some of the stations can be modelled with multivariate analysis.

This study confirms that estimations of return levels are sensitive to choice of method and measurement periods of data series. Missing data points is a potential source of error when estimating extreme values. Sea level measurements from Klagshamn had many values missing during wintertime from 1929–1960 and this period should therefore not be used in extreme value analysis. Further, the plot of the combined data set with observations from all stations indicate that the period from 1960 onwards could have been a period with unusually few extreme events, which may not be representative for future conditions. Instead data from Ystad was used to estimate extreme return levels for the Falsterbo Peninsula. When choosing a measurement station further away from the study area, uncertainties related to the correlation between extreme water levels in the different locations are introduced. Safety margins are recommended to account for uncertainties related to method and data quality.

When designing coastal protection it can be hazardous to rely on short data records, which may not be representative for the design period. The confidence intervals become very broad for long return periods and the method is then no longer useful for practical purposes. When determining design return period in the order of 500 years, study of historical events or modelling of different weather scenarios is probably a more accurate method unless sufficiently long data records are provided. Some more advanced statistical methods such as those discussed in Tajvidi (2004) might also be used in this context.

Furthermore, our estimates of return levels are likely more accurate for the next year than a year 50 or 100 years from now due to climate variability and climate change. When designing for such long periods, sea level rise has to be considered and added to the design level. The uncertainty about future wind and weather conditions can be dealt with by safety margins on the estimated levels but also by selecting flexible solutions that may be altered in response to changing conditions.

However, the risk has to be in balance with costs and environmental considerations. In the design phase, it is likely that safety considerations in some areas needs to stand back for economical, practical, or aesthetic reasons. However, it is important to be aware of the risk and the consequences if an event would occur that exceeds the design level.

Black and grey swans is a popular concept within risk management. The term black swan was stated by economist Nassim Nicholas Taleb to symbolize an extremely unlikely, unpredictable event with major impact. A grey swan is an event with major impact, but which possibly could be predicted. The 1872 storm is a grey swan. If it has happened before it can happen again, and we need to remind ourselves about that once in a while, even though we do not necessarily have to design for it.

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