AN ANALYTICAL TOOL FOR LONG-TERM DUNE MANAGEMENT – CASE STUDY: YSTAD SANDSKOG BEACH, SWEDEN

Sofia Westergren[1], Magnus Larson[1] and Hans Hanson[1]

Climate change calls for coastal management to consider longer time scales. The main objective of this study is to develop an analytical tool for long-term dune management to help evaluate the risk associated with high water levels, high waves, and their joint probability, as well as the probability of dune erosion, overwash, and breaching to occur. The tool also aims to identify vulnerable dune sections. A case study was made in Ystad Sandskog beach located on the south coast of Sweden. Data covering 20 years were used to investigate probabilities and consequences resulting from extreme waves and water levels. The data were also manipulated in order to indicate future implications in the context of climate change. The analytical tool turns out to be easy to implement and to interpret. The case study shows that Ystad Sandskog beach is subject to dune erosion and that many houses and infrastructure located behind the dunes may be exposed to more frequent flooding in the future.

Keywords: Baltic Sea, dune erosion, extreme events, overwash, run-up level, breaching

INTRODUCTION

Climate change, causing sea-level rise and changing wave conditions, calls for coastal management to consider longer time scales. In order to draw conclusions about the socio-economic impacts, threats to ecosystems, and to face other challenges, tools to evaluate the natural flood and erosion protection provided by dunes are needed.

The main objective of this study is to develop an analytical tool for long-term dune management to help evaluate the risk associated with high water levels, high waves, and their joint probability, as well as the probability of dune erosion, overwash, and breaching to occur.

A case study was made in Ystad Sandskog beach located in the south of Sweden, see Figure 1. The area is characterized by dry and relatively narrow subaerial beaches and has low dunes running along the shore. It is a popular area for tourism and recreation, but the sandy beach has been subject to gradual erosion for more than 150 years (Larson and Hanson 1992). Ever since the 1950's, measures have been taken to stabilize the beach, by means of, e.g., groins and beach nourishment.

In order to consider the impacts of future climate change, existing data were manipulated in accordance with the IPCC scenario known as A2. This scenario implies an increase of the global mean temperature by 3.7 °C by year 2100 relative to year 2000 plus an increase in wind speed during December-January due to increased greenhouse gas emissions. EA2 is the corresponding Scandinavian climate scenario derived by SWECLIM from several different global and regional scenarios (Meier *et al*. 2004; Karoly *et al*. 2003; Hudson and Jones 2002).

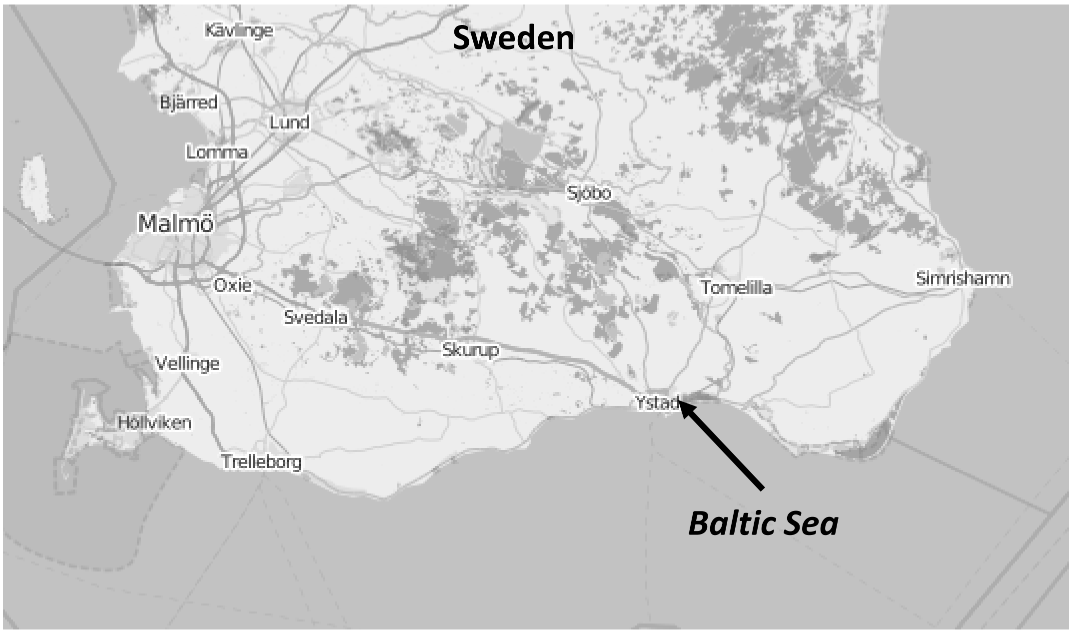

Figure 1. Ystad, the site of interest in this study, is situated in the south of Sweden (marked with arrow).

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[1] Department of Water Resources Engineering, Lund University, P.O. Box 118, Lund, 221 00, Sweden

DATA

Run-up levels, the number of overwash events as well as dune erosion volumes were calculated based on simultaneous water level and wave data in combination with measured beach profiles.

Since 1997, annual beach profile measurements have been made at Ystad Sandskog beach along 25 survey lines. In this study, each of the profiles were schematized by means of a fixed seaward slope, dune foot elevation and location, and crest elevation.

Since neither a consistent time series of water level data, nor a long-term wave data set from Ystad is available, water level data from Simrishamn monitoring station were applied (Figure 1), and waves were hindcasted from 3-hourly wind data. Both data sets, stretching from 1993 to 2011, were provided by the Swedish Meteorological and Hydrological Institute (SMHI). The hindcasted wave climate represents a location at latitude 55.4 deg and longitude 13.9 deg, which is around 4 km from the shoreline at an approximate water depth of 24 m.

Severe storms in the study area mainly occur during fall and winter (Larson and Hanson 2008); therefore the data was divided into 19 so-called climatic years, extending from July 1 to June 30. Consequently, related storm events at the turn of the year were prevented from being split into two different statistical years. Using calendar years has shown to result in an overestimation of extreme water levels for a specific return period in the study area (Hanson and Larson 2008).

The data were also manipulated in accordance with the EA2 scenario in order to simulate future conditions, i.e., water levels were increased and the wind speed was magnified with 20 percent during December-February.

METHOD

This analytical tool is based on wind and water level data combined with beach profile measurements. Waves and beach profiles were used to calculate the run-up height, which is a crucial quantity for further calculations of run-up level, overtopping, dune erosion, and breaching.

Water Levels

Based on the time series of water level data, an empirical estimation of the return period of the annual mean and maximum water levels were made using Gringorten's plotting position formula,

$$T_r = \frac{N+0.12}{r-0.44} \tag{1}$$

where T_r is the return period (years), N is the number of values, and r is the ranking number. A Gumbel distribution was fitted to the data and the water level was plotted against the reduced value given by:

$$y = -ln\left(-ln\left(1-\frac{1}{T_r}\right)\right) \tag{2}$$

If the plotted data follow a straight line, the Gumbel distribution is considered a good description of the statistical properties of the data.

Wave Climate

The wave climate was hindcasted from wind data using the WAM wave prediction model (Komen *et al*. 1994). The fundamental equation used in WAM is the energy balance equation, also known as the transport equation. In order to run the WAM model it requires at least two input data files: the bathymetry of the modelled area and the wind field acting over the same area. The model output is the significant wave height, the direction of wave propagation, and the spectral wave peak period, as well as the entire frequency-direction spectrum.

The wave climate, together with the water level, constitutes the basis for further calculations. Similar to the analysis of the water level data, the return periods for the annual maximum significant wave height was empirically estimated using Gringorten's plotting position formula and compared with the Gumbel distribution.

Run-up Levels

The run-up is a crucial quantity in storm impact assessments, since it controls the probability of dune erosion, over-topping, breaching, and flooding. The run-up height is defined as the highest elevation of wave effect on the beach relative to the still water level (SWL), and includes the wave setup. The total run-up level is defined as the run-up height added to the corresponding SWL, implying the elevation above mean sea level (MSL). Hunt (1959) developed the first formula for wave run-up height, which was used in this study,

$$\frac{R}{H_0} = \frac{\tan\beta}{\sqrt{H_0/L_0}} \tag{3}$$

where R is run-up height (m), H_0 is the deep-water wave height (m), β is the beach slope, and L_0 the deep-water wavelength (m). In order to take into account the incident wave angle, the wave height used in Hunt's formula is estimated from (Hanson and Larson 2008),

$$H_0' = H_0\sqrt{\cos\theta_0} \tag{4}$$

where θ_0 is the deep water incident wave angle with respect to the shoreline.

The underwater profile can be represented by a simplified equilibrium profile formula (Dean 1977),

$$h = Ay^{2/3} \tag{5}$$

where h is the water depth (m), y is the distance from the shoreline (m), and A is a shape parameter ($m^{1/3}$) primarily dependent on the sediment fall speed ω (m/s) (Dean 1977, Bruun 1954). According to Kriebel *et al.* (1991), the shape parameter can be approximated by,

$$A = 2.25\left(\frac{\omega^2}{g}\right)^{1/3} \tag{6}$$

where g is the acceleration due to gravity (m/s^2).

Based on evaluation against representative measured beach slopes, it was found that $A = 0.16\ m^{1/3}$ can be used for Ystad Sandskog beach. It corresponds to a grain size of 0.40 - 0.45 mm. A generalized beach slope for the study area can be represented by a straight line with an 11.3° inclination, i.e., $m = 0.20$.

Overtopping

Overtopping occurs when the run-up level exceeds the dune crest level. The frequency of overtopping was calculated using Hunt's formula for the run-up height and the recorded mean water level. The result indicates where the probability of overtopping events is the greatest.

In the case study, the individual beach slope for each profile line was used, and dune heights were taken as the arithmetical averages from measurements 1997-2012.

Dune Erosion

The erosion from the dune face of a schematized section of the beach can be calculated using a simplified solution to the analytical model developed by Larson *et al.* (2004). The model is based on the assumption that there is a linear relation between the weight of the eroded volume and the force resulting from the change in momentum that occurs when the wave packet collides with the dune face. Accordingly, the change in dune volume (V) ($m^3/m/s$) can be written,

$$\frac{dV}{dt} = -4C_S\frac{(R_d - z_0)^2}{T} \tag{7}$$

where C_S is a transport coefficient, $R_d = 0.158(H_0L_0)^{1/2}$ is a runup height that represents the total hydrodynamic effect on the dune (Larson *et al.* 2004), T is the period (sec), and z_0 the dune foot elevation (m), which is considered to be a function of the mean water level variation only. For constant wave and water level input conditions, the eroded volume (ΔV) is given by,

$$\Delta V = 4C_S(R_d - z_0)^2\frac{\Delta t}{T} \tag{8}$$

where Δt (sec) is the time step during which the forcing conditions are constant. When the run-up level reaches the dune foot elevation, i.e., $R_d > z_0$, erosion will occur. Instant removal of the sand in front of the dune is assumed, even though this sand in reality offers a sheltering effect to the dunes before being removed.

For Ystad, a dune foot elevation of z_0 = 1.7 m (with reference to MSL), and a transport coefficient of $C_S = 3.3 \cdot 10^{-4}$ was used. The latter was empirically determined by Dahlerus and Egermayer (2005) by comparison between model calculations and measured dune retreat. Again, Gringorten's plotting position formula and the Gumbel distribution were used to find return periods for eroded dune volume.

Breaching

Breaching was defined by the cumulative eroded volume corresponding to the total available dune volume. The time required for breaching (TRB) was defined as the number of events of a certain magnitude required to cause this erosion.

RESULTS

Water Levels

A linear trend line fitted to the annual mean water level measured 1993 - 2011showed an increase of 0.29 cm/yr in the study area, see Figure 2. The corresponding trend line fitted to the annual maximum water level indicates a decrease of 0.36 cm/yr, see Figure 3. In both cases, the coefficient of determination (r^2) is very low. Aslo, if looking at a longer time span (1887-2012) the corresponding numbers are 0.074 cm/yr and -0.023 cm/yr, indicating significantly lower values. Annual fluctuations are much larger than the trend line, making it difficult to establish whether an acceleration in sea level rise is occurring in Ystad during recent years.

The annual maximum water level with a 100-year return period is estimated to be 135 cm above MSL, see Figure 4. However, the Gumble fit seems to overestimate water levels with high return periods.

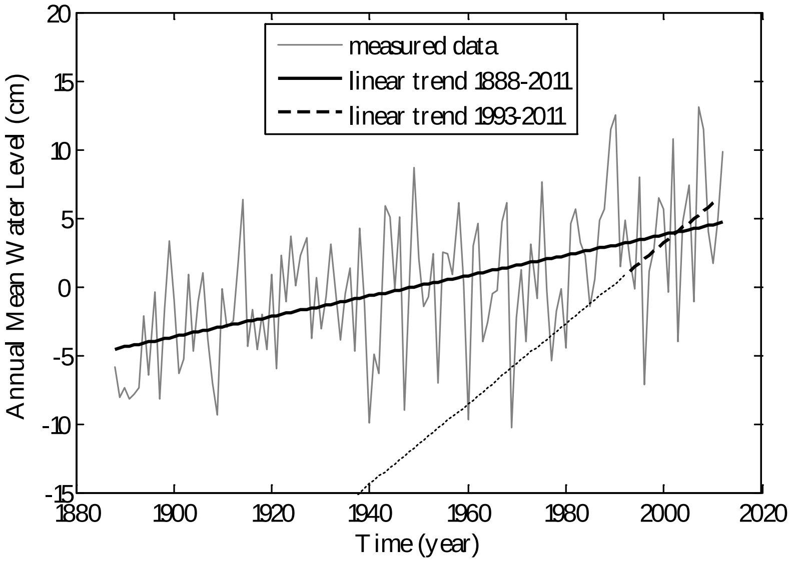

Figure 2. Annual mean water level in Ystad 1888-2011. The trend line for 1993-2011 indicates an annual increase of 0.29 cm/yr, whereas a trend line for 1888-2011 indicates an annual increase of 0.074 cm/yr.

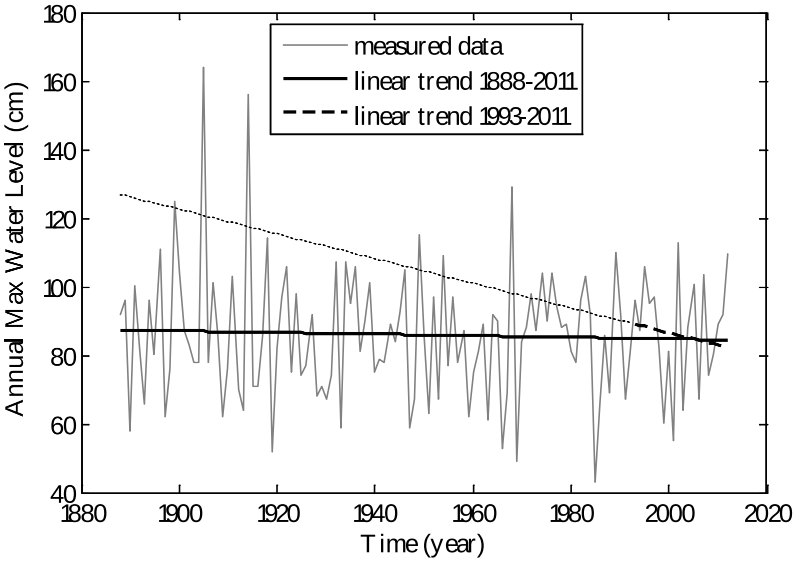

Figure 3. Annual maximum water level in Ystad 1888-2011. The trend line for 1993-2011 indicates a decrease of 0.36 cm/yr, whereas a trend line for 1888-2011 indicates a decrease of 0.023 cm/yr.

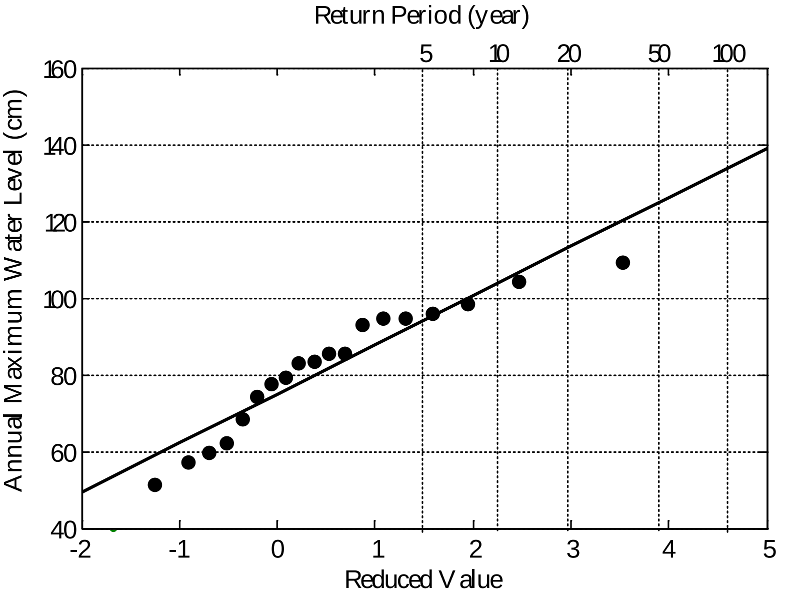

Figure 4. Extrapolated linear fit based on a Gumbel distribution for return periods of annual maximum water level relative to MSL, 1993-2011. Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

Wave Climate

The waves hindcasted with WAM gave a mean significant wave height of 0.80 m and a largest calculated deep-water significant wave height of 4.4 m for the period 1993-2011. The annual maximum wave height with a 100-year return period is approximately 5.1 m, see Figure 5. The Gumbel distribution shows an overall good fit for the annual maximum wave height.

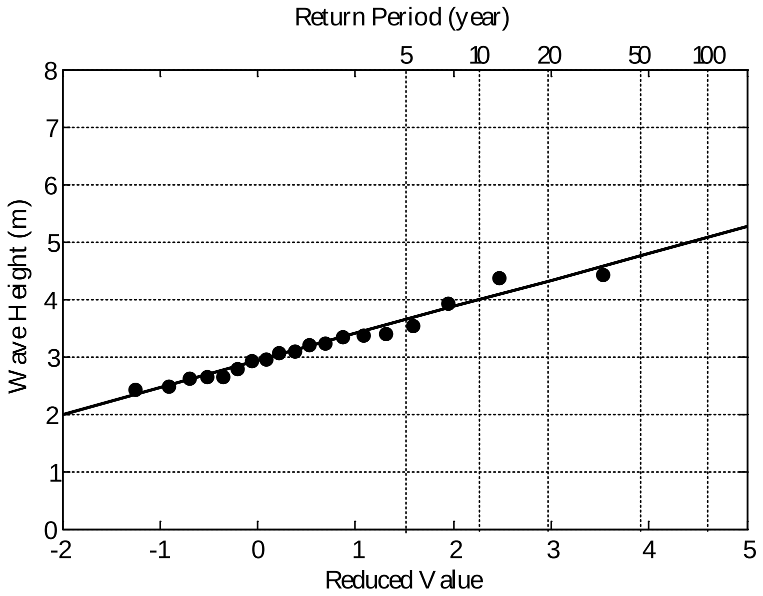

Figure 5. Extrapolated linear fit based on a Gumbel distribution for return periods of annual maximum wave height, 1993-2011. Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

Run-up Levels

The annual maximum run-up for the studied 19-year period was 4.3 m, and the annual maximum run-up level with a 100-year return period is approximately 4.5 m, see Figure 6. The Gumbel distribution yields a good fit to the data points.

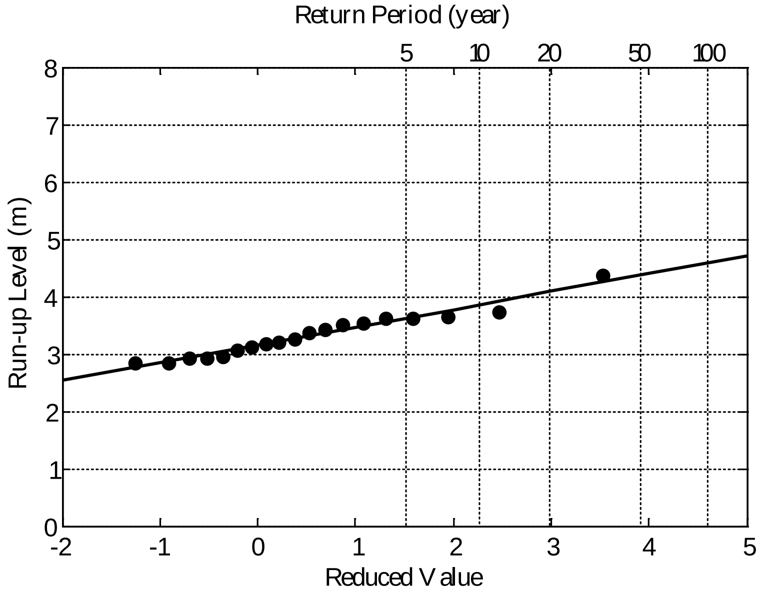

Figure 6. Extrapolated linear fit based on a Gumbel distribution for return periods of annual maximum runup level, 1993-2011. Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

Overtopping, Dune Erosion and Breaching

Three profiles showed risk of being overwashed. All were characterized by steep beach slopes and low dune height (distance from dune foot to crest). Interestingly, profiles with the lowest dune crest elevation did not show any risk of overtopping, probably because the beach slope was milder and the runup heights smaller.

The annual maximum dune erosion for the 19-year period is 27 m^3/m, see Figure 7. The simulation showed severe dune erosion in 2007 and 2008, which may be explained by the extreme January storm in 2007, and a number of summer storms in 2008 (SMHI 2009). According to the Gumbel fit to the Gringorten plot, the annual maximum dune erosion with a 100-year return period is

31 m^3/m, i.e., corresponding to the major part of a typical dune. The schematized profile of Ystad Sandskog beach together with three profiles with different characteristics was further studied regarding dune erosion. Large erosion was observed for profiles with relatively steep beach slopes, whereas profiles with mild beach slopes seemed to experience no or small erosion. The same was valid for the risk of breaching. The schematized profile of Ystad Sandskog beach can be classified as relatively steep.

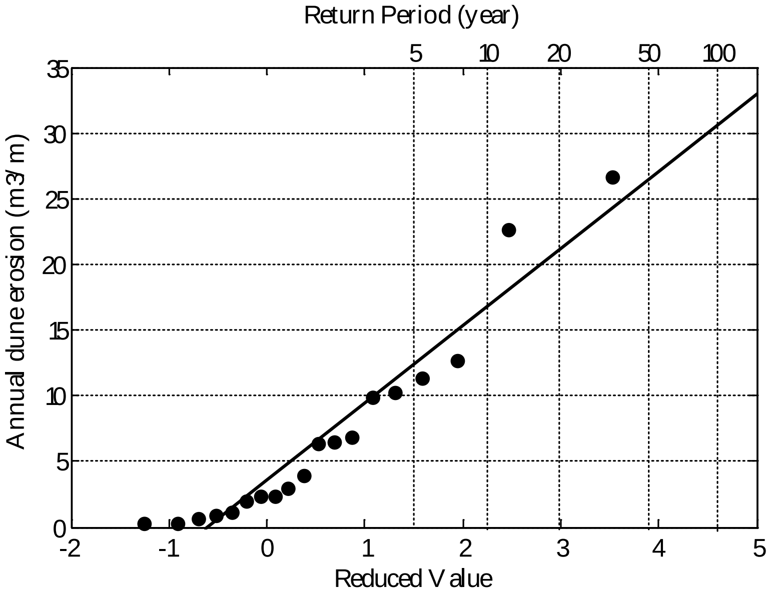

Figure 7. Extrapolated linear fit based on a Gumbel distribution for return periods of annual maximum dune erosion, 1993-2011. Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

Extreme Events

The largest calculated deep-water significant wave height during the 19-year period was 4.4 m and appeared in connection with a water level of -0.66 cm. Dahlerus and Egermayer (2005) as well as Hanson and Larson (2008) concluded that large waves do not appear in combination with high water levels in Ystad. This phenomenon can be explained by the Baltic Sea being more or less an enclosed basin, where the water body is dependent on the wind and air pressure conditions. Winds from SW to W tend to generate high waves in Ystad bay, but at the same time these winds push the water northwards resulting in a temporary water level decrease in the southern parts of the Baltic Sea (Hanson and Larson 2008). The typical annual erosion pattern of the 19-year period shows that a limited number of storm events per year (between 1 and 8) are responsible for most of the erosion, rather than the erosion being a continuous process at the site.

Future Scenarios

The future climate change scenario EA2 was used to forecast the situation up to year 2100. The EA2 scenario indicates that the annual maximum wave height with a 100-year return period possibly can be more than 7 m by year 2100, see Figure 8. The corresponding number today, 5.1 m, may have a return period of 6-7 years by the same year. Furthermore, the EA2 scenario indicates that the annual maximum run-up level with a 100-year return period possibly can be about 7 m by year 2100, see Figure 9. The corresponding number today, 4.5 m, may have a return period of less than a year by 2100.

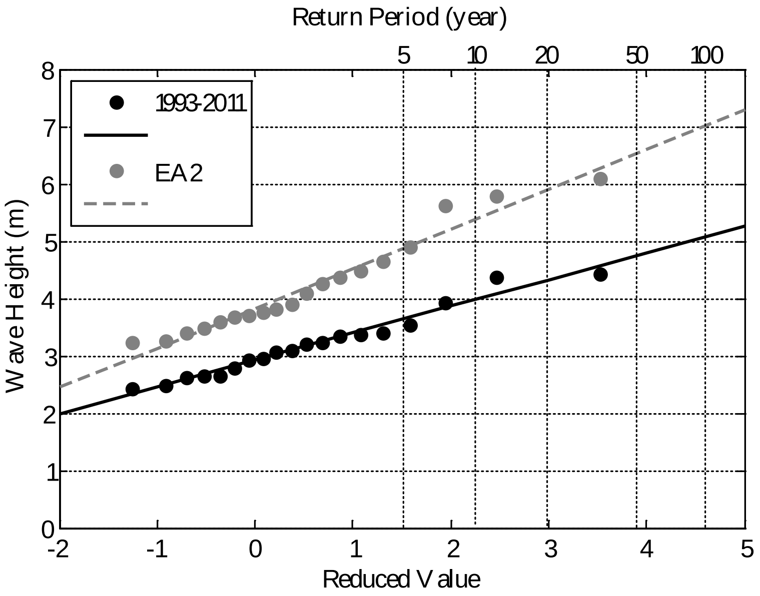

Figure 8. Extrapolated linear fit based on a Gumbel distribution for return periods of annual maximum wave height, 1993-2011 (black) and EA2 (grey). Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

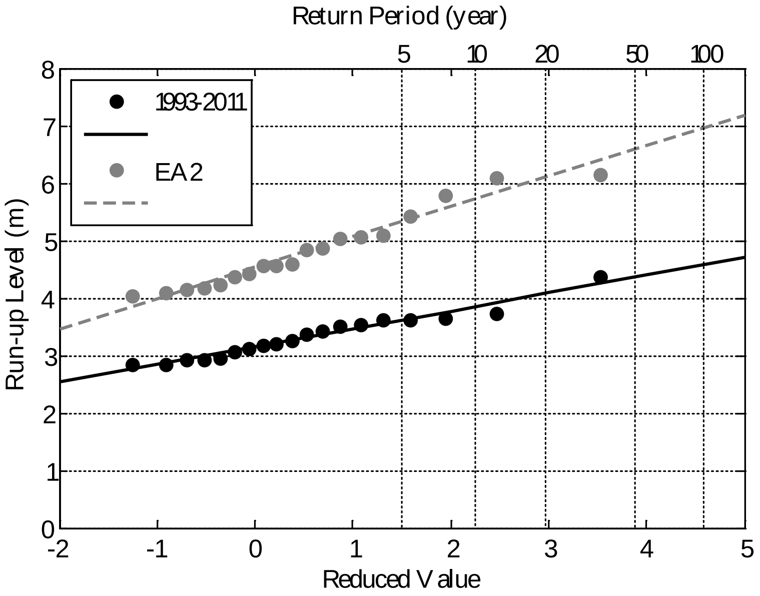

Figure 9. Extrapolated linear fit based on a Gumbel distribution for return periods of annual runup level, 1993-2011 (black) and EA2 (grey). Empirical distribution function (black dots) estimated with the Gringorten plotting position formula.

DISCUSSION

The analysis of the present conditions at Ystad Sandskog beach shows that the dunes are eroding, and that some sections are more at risk than others. Low dune foot elevation and/or steep beach slope means that a section is more critically exposed to overtopping, erosion, and breaching; thus, it should be considered a target section when carrying out beach and dune management.

The analysis of the future conditions at Ystad Sandskog beach shows that the dunes may be at great risk of being damaged, or even disappear, if the EA2 scenario is realized. According to Dahlerus and Egermayer (2005), the EA2 scenario would mean a 75% increase of the annual dune erosion by the year 2100.The new IPCC scenarios, Representative Concentration Pathways (RCP) scenarios, derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) model, says that the global mean surface temperature for 2081-2100 (relative to 1986-2005) will likely increase with 0.3-4.8 °C. As a consequence, the sea level will likely rise by 0.26-0.82 m (IPCC, 2013).

CONCLUSIONS

This analytical tool for long-term beach and dune management has been shown to be easy to implement and to interpret. It can preferably be used for a first assessment when evaluating the risk of high water levels, large waves, and their joint probability, as well as when performing risk assessment associated with dune erosion, overwash, and breaching. The tool is also tenable to identify vulnerable sections of the beach.

This study shows that Ystad Sandskog beach is subject to dune erosion over time. Sections at risk are characterized by low dune foot elevation and/or steep beach slopes. Even a small change in beach slope can cause significant changes in the vulnerability. The annual maximum dune erosion with a return period of 100 years corresponds to the major part of dune volume at many sections of the beach.

The analysis of future conditions and implications at Ystad Sandskog beach shows that wave heights that currently has a return period of 100 years may have a return period of 6-7 years by 2100. Also, run-up levels that currently has a return period of 100 year may occur even more often than once every year due to the risk of a considerable sea level rise. Thus, many houses and infrastructure located behind the dunes may be subject to more frequent flooding and damage in the future.

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