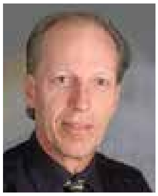
EXTREME VALUE ANALYSIS OF WAVE RUNUP AND DUNE EROSION AT ÄNGELHOLM BEACH, SOUTH SWEDEN

EXTREMVÄRDESANALYS AV VÅGUPPSPOLNING OCH DYNEROSION VID ÄNGELHOLMS STRAND

By Caroline Hallin[1], Nader Tajvidi[2], Björn Almström[1], Magnus Larson[1], and Hans Hanson[1]

[1] *Water Resources Engineering, Lund University, Box 118, 221 00 Lund, Sweden e-mail: caroline.hallin@tvrl.lth.se*
[2] *Mathematical Statistics, Lund University, Box 118, 221 00 Lund, Sweden*

Abstract
This study employs extreme value analysis to estimate 10-, 50-, and 100-year return levels of wave run-up and annual dune erosion on the basis of 40 years simulated data from Ängelholm Beach, Sweden. The offshore wave climate is computed with the SMB-formulations and propagated nearshore with the SWAN wave model. The runup is computed with a Hunt-type equation and the erosion with an impact formula. The results show that the dune crest elevation is in general higher than the most extreme runup. The volume of sediment in the dunes is sufficient to protect the developed hinterland in the short-term perspective; however, long-term effects due to sea level rise and gradients in longshore sediment transport are not considered and may change this conclusion.

Key words: Runup, dune erosion, GEV, GPD, Ängelholm Beach

Sammanfattning
I den här studien används extremvärdesanalys för att beräkna våguppspolning och årlig dynerosion med 10, 50, och 100 års återkomsttid. Frekvensanalysen baseras på en 40 år lång tidsserie med simulerad dynerosion och våguppspolning från Ängelholms strand i Skälderviken. Med SMB-metoden beräknas vågor ute till havs som sedan transformeras till kustnära vågor i vågmodellen SWAN. Våguppspolningen beräknas med en formel av Hunt-typ och dynerosionen med en semi-empirisk formel som relaterar erosionsvolymen till vågornas kraft mot dynen. Resultatet visar att dynhöjden längs den största delen av stranden är högre än den mest extrema beräknade våguppspolningen. Dynerna längs stranden skyddar ett bakomliggande bostadsområde mot översvämning och erosion. Beräkningarna visar att dynvolymen idag skyddar mot skador som kan uppkomma vid extrema stormar. Emellertid har inga långtidsförändringar av dynvolymen till följd av stigande havsnivåer eller gradienter i den kustparallella sedimenttransporten beaktats i denna studie.

Introduction

Nature-based coastal protection, such as dunes, has in the recent decades been gaining ground over more conventional methods, *e.g.*, grass-covered dikes, and rock and concrete structures (Borsje *et al.*, 2011; de Vriend *et al.*, 2015; Hanson *et al.*, 2002). Along vast stretches of sandy coastlines, dunes provide a multifunctional protection against flooding and erosion (Doody *et al.*, 2004; Louisse and Van Der Meulen, 1991; Nordstrom, 2000; van Vessem and Stolk, 1990). During storms, dunes protect the hinterland through preventing or mitigating inundation and wave overtopping, while supplying sediment to the berm and bar where wave energy is being dissipated (Sallenger, 2000). From a risk management perspective, the dune height in relation to the wave runup level and the dune volume to the eroded dune volume are of interest. In this study, we explore the extreme value distributions of wave runup and annual dune erosion at a study site in south Sweden, Ängelholm Beach (Figure 1). The aim is to estimate 10-, 50-, and 100-year return levels of wave runup and annual dune erosion to assess coastal safety.

Study site

Ängelholm Beach is located in Skälderviken Bay between Rönne River and Vege River. The beach is micro-tidal, and the semidiurnal tide has an average amplitude of about 5 cm and a spring tide amplitude of up to 20 cm (SMHI, 2013). The wind climate is dominated by winds from SW to W. The beach has a sheltered location in the bay but is impacted almost yearly by storm surges and large waves from the NW, causing beach and dune erosion (Palalane *et al.*, 2016). During onshore winds, a significant local wind setup can occur in the bay and storm surges typically occur in combination with large waves. The dune height and volumes are varying alongshore. The dune crest height is decreasing from north to south and in the northern part of the beach, the dunes protect the developed hinterland from flooding and erosion (Almström, 2010). In this part, the front dune is the primary defence against flooding and damage to buildings behind the beach.

Wave runup

Wave runup can be defined as the time-varying location of the shoreline water level about the still

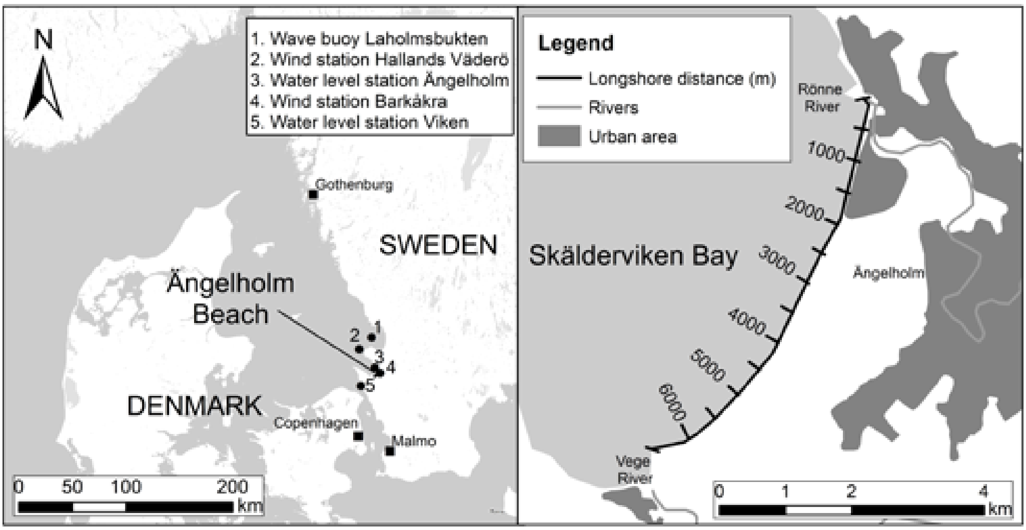


Figure 1. *Overview maps with observation stations (left) and longshore distance from Rönne River mouth (right) (Hallin* et al*, 2019).*

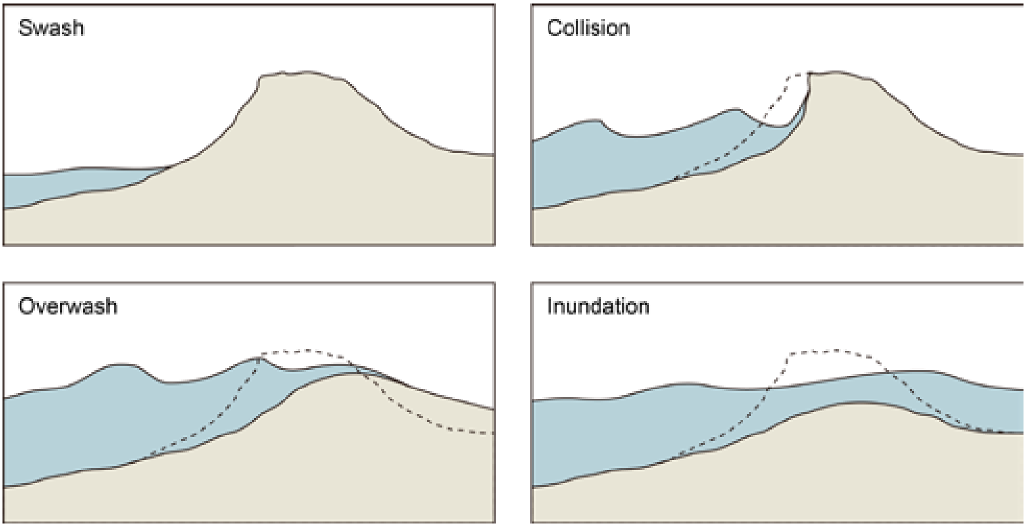


Figure 2. *The storm impact scale for barrier islands by Sallenger (2000).*

water level, where the still water level is the level that would have occurred without the presence of waves (Holman and Sallenger, 1985). Runup is an important parameter when assessing coastal safety and the vulnerability of dunes. The impact of waves on dunes can be divided into four different types according to the storm impact scale (Sallenger, 2000); swash, collision, overwash, and inundation. The storm impact scale is governed by the wave runup level in relation to the beach and dune morphology (Figure 2).

In the swash regime, the waves only reach and erode the foreshore and do not impact the dune. In the collision regime, wave run-up collides with the base of the dune; sediment is eroded from the dune and deposited on the beach or transported offshore. During overwash, the waves reach over the foredunes and wash sand landwards at the same time as sediment is eroded from the dune as for the collision regime. Inundation means that the entire front dune ridge is inundated with water; the dune is then impacted by surf-zone like processes (Sallenger, 2000).

The total runup is a combination of swash and wave setup (Hedges and Mase, 2004; Holman and Sallenger, 1985; Stockdon *et al.*, 2006). Wave setup implies an increase of the water level at the shoreline and a decrease – set-down – at wave breaking in the surf-zone. The theoretical explanation for wave setup is that a gradient of excess momentum flux associated with wave breaking must be balanced by a slope of the sea level (Longuet-Higgins and Stewart, 1964). Swash can be described as the motion of breaking, non-breaking, or broken waves washing up on the beach. The setup and swash motions, both from infragravity (long waves) and incident band waves, are commonly described as a function of deep-water wave height, deep-water wave period, and a representative slope (Stockdon *et al.*, 2006).

When designing coastal structures, wave runup is an important design parameter; therefore, large efforts have been put into the development of methods to compute runup on structures (EurOtop, 2018; Hunt, 1959). Runup equations for natural beaches have not been as widely developed and used (Holman and Sallenger, 1985; Stockdon *et al.*, 2006). A problem when working in natural systems is the definition of a representative slope. Much of the data used to develop runup equations have been produced in laboratory experiments with uniform bottom slopes, or two uniform composite bottom slopes (Hunt, 1959; Mayer and Kriebel, 1994; Saville, 1958).

On natural beaches, it is more difficult to define a representative slope. Mayer and Kriebel (1994) developed a method to calculate wave runup on composite-slope and concave beaches, where a representative slope was defined between the incipient breakpoint and the runup limit according to the definition by Saville (1958). Stockdon *et al.* (2006) defined the representative slope as the average slope over a region +/- two times the standard deviation of a continuous water level record. However, for practical applications, continuous water level records are not always available and the bathymetry is changing, especially during storms. Thus, it is not always feasible to compute a representative slope for every wave and water level condition. Holman and Sallenger (1985) found that the foreshore slope was a proper estimate for incident and infragravity swash, while the offshore bar system had some influence on wave setup at low tide.

Dune erosion

Dune erosion is a threat to the coastal safety, and thus, many analytical and numerical methods have been developed to quantify dune erosion due to the impact of waves and water levels (Larson *et al.*, 2004). The analytical models are based on the equilibrium profile (Kriebel and Dean, 1993; Steetzel, 1993; Vellinga, 1986) or wave impact approach (Larson *et al.*, 2004; Nishi and Kraus, 1996; Overton, Fisher, and Young, 1988). The equilibrium approach assumes that the beach adjusts towards an equilibrium state with the wave and water level conditions (Bruun, 1954; Dean, 1977). The new equilibrium is approached through erosion of sediment from the beach and the dune, and deposition in the subaqueous part of the profile (Vellinga, 1986). In real situations, storm surges and wave conditions are time-varying, and the storm durations typically are too short to reach a storm equilibrium profile (Larson *et al.*, 2004).

The wave impact approach is a more physics-based method, assuming that the dune erosion is a function of the frequency and intensity of wave impact. The eroded weight – or volume – of sediment is assumed to be proportional to the force acting on the dune, where the force equals the change of momentum flux of the bores impacting the dune (Overton, Fisher, and Young, 1988). Based on this concept, Larson *et al.* (2004) derived an analytical model where the dune erosion is proportional to the square of the runup level above the dune toe. The impact equation is combined with a Hunt-type runup equation so that the dune erosion can be computed from deep-water wave conditions in combination with still water levels (*SWL*), which is practical for engineering applications. Following a site-specific calibration of the empirical coefficient in the formula, the model showed good agreement with both field data and laboratory data (Larson *et al.*, 2004).

The advantage of analytical models is that they are easy to use and fast to apply with a small amount of required input data, making them suitable for approximate estimations over large spatial scales. In more detailed studies, numerical methods such as SBeach (Larson and Kraus, 1989) or XBeach (Roelvink *et al.*, 2009) are commonly used.

The numerical models typically require more computational effort and user skill than the analytical models. Following the objectives, and relevant time and spatial scales of this study, a reduced complexity analytical model is preferred. The analytical dune erosion model by Larson *et al.* (2004) was therefore selected. It offers a physics-based, yet simple schematization of a complicated process.

Extreme value analysis

Extreme value theory is used to analyse data and to predict events with low probability. Typically, extreme value analysis is used to determine the return period, T_r, for a specific event, or the return level, X_p, corresponding to a specific return period (*e.g.*, 100 years). The return period is the inverse of the probability of exceedance, p, $T_r=1/p$.

By extrapolation, return levels can be predicted for return periods that are longer than the data series. The theory is based on the assumption that the tail of an arbitrary distribution can be approximated by an extreme value distribution. Hourly or daily measurements of *e.g.* wave runup are generally normal or Rayleigh distributed (Hughes, Moseley, and Baldock, 2010), whereas the tail with the highest values, follows an extreme value distribution.

The highest observations are selected either as block maxima (*e.g.*, the highest observations during each year) or as exceedances over a high threshold. The modelled observations should be independent and identically distributed. Block maxima are assumed to follow a Generalized Extreme Value distribution (GEV) and peaks over thresholds to follow the Generalized Pareto Distribution (GPD).

When assessing coastal vulnerability, runup and coastal erosion are typically computed for a design storm. The design storm conditions are a combination of wave and water level conditions, with a specific duration. The design conditions can be determined by multivariate extreme value analysis or taken as the most extreme observation.

In this study, instead of calculating a design storm, return values of runup and dune erosion are determined by extreme value analyses of simulated data based on a 40-year long data set of simultaneous wind and water levels.

Method

Hourly values of wave characteristics, runup, and dune erosion were calculated in 59 points distributed with approximately 100 m distance alongshore. The calculations are based on wind and water level observations from the measurement stations indicated in Figure 1 during the period 01/07/1976 – 30/06/2016.

Wave climate

Energy-based significant wave height, spectral peak period, and wave direction were calculated at the outer bay using the SMB formulations for wave hindcasting (USACE, 1984). The formulations were modified with a memory function, as used by Hanson and Larson (2008), so that antecedent wave conditions were taken into account, both for wave growth and decay. Wind data was collected from the SMHI station Hallands Väderö (Figure 1) and the bathymetry from EMODnet Bathymetry portal (http://www.emodnet-bathymetry.eu).

The waves were transformed nearshore using the SWAN model (Booij, Ris, and Holthuijsen, 1999) for Skälderviken Bay (Figure 3). A nested modelling approach was used to simulate the nearshore wave propagation, using a 500-m grid size for the bay model and 100 m for the nearshore model (<10 m depth). Since no wave measurements from the bay were available for calibration, default model parameter settings were applied.

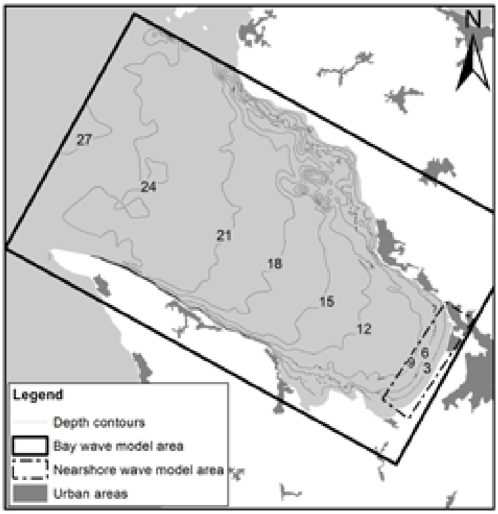


Figure 3. *Extent of the bay and nearshore wave model together with the bathymetry of Skälderviken.*

Energy-based significant wave height, H_{m0}, mean wave period, T_{m0}, and wave direction were extracted from the SWAN model at 5 m depth before breaking. H_{m0} is approximately equal to the significant wave height, H_S, at this depth. The mean wave period is transformed to significant period, T_S, following the relation described by Kitano *et al.* (2002), with the peak enhancement parameter of the JONSWAP spectrum set to 3.3, which is default in SWAN,

$$T_s = 1.15T_{m0} \tag{1}$$

The extracted waves were transformed to breaking depth using an explicit formula (Larson, Hoan, and Hanson, 2010). The explicit formula computes wave height, H_{sb}, and wave angle towards the shore normal, α_b, at incipient breaking based on a simplified solution of the wave energy flux conservation equation combined with Snell's law. H_{sb} is computed for a depth induced breaking with a breaker depth ratio, γ_b=0.78,

$$\gamma_b = \frac{H_{sb}}{d_b} \tag{2}$$

where d_b is the breaking depth.

The wave transformation using SWAN and

the explicit formula account for wave refraction and wave shoaling. The runup and dune erosion equations employ the equivalent deep-water wave height, H'_{s0} and H'_{rms0}, respectively. Only the onshore component of the incoming wave energy is accounted for in the run-up and transport equations according to,

$$H_{sby} = H_{sb}\sqrt{\cos\alpha_b} \qquad (3)$$

where H_{sby} is the wave height representing the onshore energy flux (Hanson and Larson, 2008).

The equivalent deep water significant wave height, H'_{s0}, is computed through a reversed shoaling (see *e.g.* USACE, 1984),

$$H'_{s0} = \frac{H_{sby}}{K_S} \qquad (4)$$

where K_S is the shoaling coefficient defined as,

$$K_S = \sqrt{\frac{C_{g0}}{C_g}} \qquad (5)$$

The wave group velocity in deep water, C_{g0}, and the wave group velocity at breaking, C_g, assuming shallow water wave theory, is defined as,

$$C_{g0} = \frac{gT_s}{4\pi} \qquad (6)$$

$$C_g = \sqrt{gd_b} \qquad (7)$$

where g is the acceleration due to gravity.

The significant wave height is transformed to root-mean-square wave height by,

$$H'_{rms0} = \frac{H'_{s0}}{1.414} \qquad (8)$$

Wave runup

For this study, Stockdon's runup equation (Stockdon *et al.*, 2006) was first tested but gave unrealistically low values. Instead, the maximum runup, $R_{2\%}$, here defined as the runup height of the 2 % largest waves, is computed following the method described by Hedges and Mase (2004), which includes swash and wave setup,

$$R_{2\%} = H'_{s0}\left(0.34 + 1.49\zeta_0\right) \qquad (9)$$

where ζ_0 is the Irribaren number defined as,

$$\zeta_0 = \frac{\tan\beta_F}{\sqrt{H'_{s0}/L_{s0}}} \qquad (10)$$

with $\tan\beta_F$ taken as the foreshore slope and L_{s0} is the deep-water wavelength. The foreshore slope was defined as the average slope between -1 and 0.8 m relative to *MSL* based on the profile shape within the study area. The slope within this depth range was fairly uniform across-shore, but has a significant longshore variation (Figure 4).

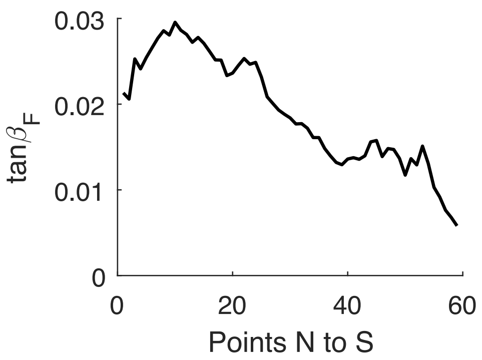


Figure 4. *Longshore variation of foreshore slope,* $\tan\beta_F$*.*

The deep water wavelength is computed by,

$$L_{s0} = \frac{gT_s^2}{2\pi} \qquad (11)$$

The runup level relative to the mean sea level, *MSL*, is computed as the sum of the runup height and the still water level, *SWL*, at any given time,

$$R_{tot} = R_{2\%} + SWL \qquad (12)$$

The *SWL* is collected from the Swedish Meteorological and Hydrological Institute's (SMHI) measurement station Viken located outside the Skälderviken Bay. *MSL* in 2018 was 7.9 cm relative to the Swedish height reference system RH 2000. The SMHI station Ängelholm is closer to the study area, but has only been operating between 22/03/2011 and 07/05/2014 with several gaps in the time series. During onshore winds, the water level at the study area is higher than at the

SMHI-station in Viken, due to local wind setup in the bay. Assuming a rectangular shaped bay, negligible bottom friction and stationary conditions, wind setup, Δh, was calculated according to (USACE, 1984),

$$\Delta h = \frac{\rho_{air}}{\rho_{water}} \frac{C_D W_x^2 L_B}{gd} \qquad (13)$$

where ρ_{water} is the water density, ρ_{air} the air density, C_D the drag coefficient, W_x the onshore wind speed component, L_B the bay length, and d the average depth in the bay. In a previous study (Palalane *et al.*, 2016), C_D was calibrated to $2.3 \cdot 10^{-3}$ by fitting equation 13 to the observed difference between water level in Ängelholm and Viken during onshore winds.

Dune erosion

The dune erosion is calculated using the impact formula (Larson *et al.*, 2004). The runup equation associated with the impact formula does not account for longshore variation of foreshore slope. A foreshore slope factor was introduced in the runup equation to account for the foreshore slope variability within the study area,

$$R = \frac{\tan \beta_F}{\overline{\tan \beta_F}} 0.158 \sqrt{H'_{rms0} L_{m0}} \qquad (14)$$

where $\overline{\tan \beta_F}$ is the mean foreshore slope within the study area and L_{m0} is the mean deep water wavelength, calculated according to equation 11, but with T_{m0} instead of T_S.

If the total runup level exceeds the dune foot height D_F $(R+SWL > D_F)$ dune erosion will occur. The transport of sediment from the dune face, q_D, is then computed by (Larson *et al.*, 2004),

$$q_D = 4 C_S \frac{(R + SWL - D_F)^2}{T_{m0}} \qquad (15)$$

where C_S is an empirical coefficient. On the basis of the observations of storm erosion in 2011 and 2013 (Fredriksson, 2011; Schönström, 2013) C_S was calibrated to $7 \cdot 10^{-3}$, which is in the middle of the range $1.7 \cdot 10^{-4}$ –$1.4 \cdot 10^{-3}$ given in the literature (Larson *et al.*, 2004). The total eroded volume during each year is obtained through integrating the computed hourly transport rates.

Extreme value analysis

The method description is based on extreme value theory as presented in Coles (2001). The extreme value analysis is performed in the R software (R Core Team, 2016) using the packages extRemes (Gilleland and Katz, 2011) and in2extRemes.

Generalized Extreme Value distribution

The simulated runup levels are analysed with a GEV distribution. A GEV-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, simulated wave runup data are hourly so the year maxima is determined for $n=365 \times 24$. Block maxima are selected from July to June each year to avoid dependence between consecutive observations, as extreme runup levels are rarely occurring during the summer months.

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

$$G(x) = \exp\left\{ -\left[1 + \xi \left(\frac{x-\mu}{\sigma} \right) \right]_+^{-1/\xi} \right\} \qquad (16)$$

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 equation, also called double exponential, has the form:

$$G(x) = \exp\left[-\exp\left\{ -\left(\frac{x-\mu}{\sigma} \right) \right\} \right] \qquad (17)$$

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

$$x_p = \mu - \frac{\sigma}{\xi}\left[1 - \left\{-\ln\left(1-p\right)\right\}^{-\xi}\right] \quad \text{for } \xi \neq 0 \text{ and,} \quad (18)$$

$$x_p = \mu - \sigma \ln\left\{-\ln\left(1-p\right)\right\} \quad \text{for } \xi = 0 \quad (19)$$

An important difference between the various types of GEV-distributions is that the support of the Gumbel distribution is the whole real number line, whereas Weibull and Frechet distributions have supports with finite end-points on the right and left, respectively.

Generalized Pareto Distribution

Dune erosion does not occur every year; instead a GPD distribution is used to analyse the return levels of the total yearly eroded volume. The GPD describes the cumulative distribution of the excesses, $y=x-u$, over a certain threshold, u, under the condition that $x > u$:

$$H(y) = 1 - \left(1 + \frac{\xi(y)}{\sigma}\right)^{-1/\xi} \quad (20)$$

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

In the special case of $\xi = 0$, equation 20 reduces to:

$$H(y) = 1 - \exp\left(-\frac{y}{\sigma}\right) \quad (21)$$

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

$$x_m = u + \frac{\sigma}{\xi}\left[\left(m\zeta_u\right)^{\xi} - 1\right] \quad \text{for } \xi \neq 0 \text{ and,} \quad (22)$$

$$x_m = u + \sigma \ln\left(m\zeta_u\right) \quad \text{for } \xi = 0 \quad (23)$$

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, for a 100-year return level from yearly measurements, then $m=100$.

The behaviour of the upper and lower limits is depending on the shape-parameter in the same way as for GEV; for $\xi >= 0$, the upper end point is infinite, whereas for $\xi < 0$, there is a finite upper end point.

The threshold is selected based on a mean residual life plot, where 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. The threshold was selected individually for all computation points alongshore.

Confidence intervals

For the return levels of runup and yearly eroded volume, 95 % confidence intervals were estimated using the profile likelihood method. Profile likelihood functions are obtained through re-parameterization of the GEV and GPD models, so that the return level estimates x_p and x_m, become model parameters. Then the profile log-likelihood is obtained by maximization with respect to the remaining parameters. This is a more accurate method to estimate the limits of a confidence interval compared to the commonly used – and simpler – normal approximation. For a more detailed description of the profile likelihood method we refer to Coles (2001).

Dune height and volume

The computed runup levels and eroded dune volume are compared to the observed dune crest height and dune volume at the study site. The dune dimensions are obtained from a digital elevation model from 2017 with 0.1×0.1 m resolution that was provided by Ängelholm Municipality.

The total runup level is compared to the maximum dune height above *MSL*. The protective dune volume was obtained through integrating the volume of sand over the part of the dune that is protecting the houses and infrastructure from flooding and erosion. The protective dune volume is vertically limited by the dune foot elevation (2 m above the *MSL*; Palalane *et al.* (2016)) and the dune crest. The horizontal limit on the seaward

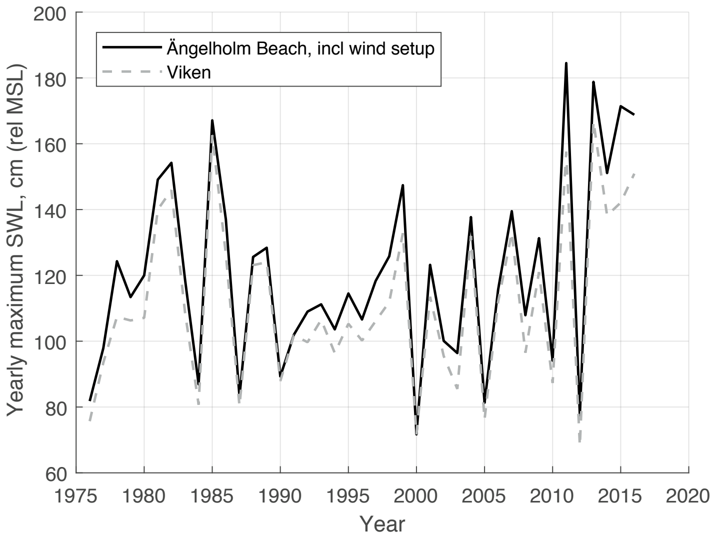


Figure 5. *Yearly maximum water levels observed at the SMHI station in Viken (dashed line) and computed for Ängelholm Beach (solid line) with addition of wind setup.*

side is the dune foot. On the landward side, the horizontal limit is the most landward elevation contour of the runup level with 100-years return period (approximately 2.8 m above *MSL*). If buildings and infrastructure are located within the protective dune area, their most seaward extent is then horizontally limiting the protective dune volume.

Results

Water levels

Wind setup in Skälderviken Bay cause higher storm surge levels compared to the SMHI measurement station in Viken (Figure 5). The last decade has seen several extreme events compared to the previous decades, which resulted in erosion of large sand volumes from the dunes (Fredriksson, 2011; Schönström, 2013).

Wave climate

The SMB-model that was used to compute the waves at the bay mouth was validated against wave data from a buoy in the adjacent Laholm Bay. The buoy was operated by SMHI between 19/03/1984 – 05/10/1985. The wave height was better predicted than the wave period with an R^2 value of 0.64 compared to 0 (Figure 7). The SMB-model underestimated the low wave periods and overestimated the high wave periods, which may impact the accuracy of the calculated runup during energetic wave conditions.

The simulated waves at the bay mouth were used as input on the seaward boundary of the SWAN model grid. The SWAN model simulated the nearshore wave climate from 01/07/1976 – 30/06/2016. Figure 8 displays the simulation results from the time steps during the storms in 2011 and 2013, when the largest computed erosion occurred. Dune erosion is a function of both *SWL* and waves; thus, the time steps with the largest computed erosion are not necessarily coinciding with the largest waves. The black line indicated the *MSL* contour. In the time steps with the largest erosion during the storms in 2011 and 2013, the *SWL* was 185 cm and 139 cm, respectively. The higher *SWL* in 2011 can be seen as a larger blue area on the landward side of the *MSL*-contour. During the storm in 2013, the nearshore wave heights were on the other hand larger.

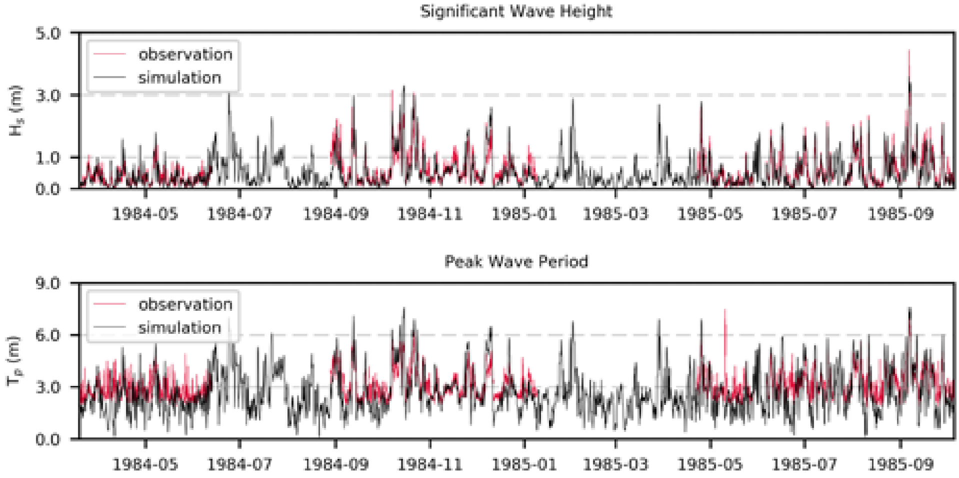


Figure 6. *Simulated and observed significant wave height (H_S) and wave period (T_p) at the wave buoy in Laholm Bay.*

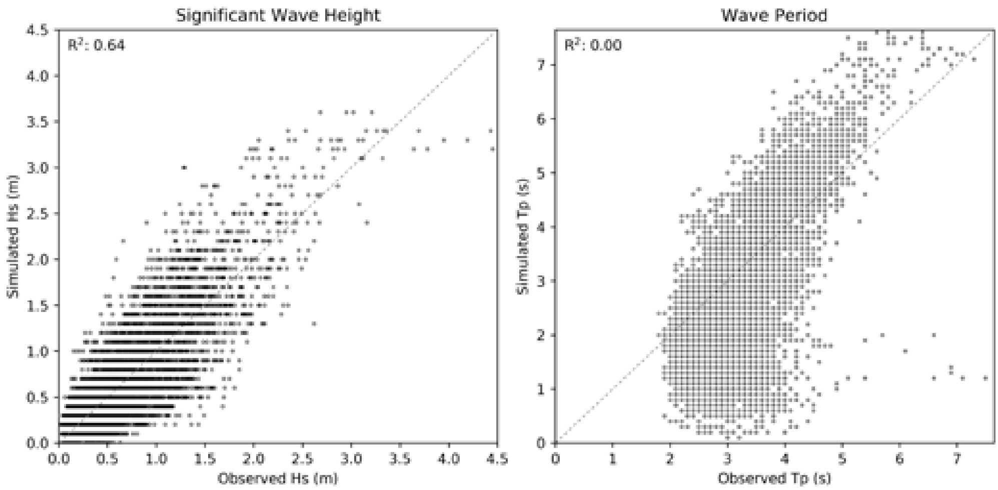


Figure 7. *Scatter plots of simulated and observed data.*

Runup

The computed waves and water levels were used to calculate wave runup at every time step. The yearly maximum runup levels were analysed with a GEV-model to estimate return levels for 10-, 50-, and 100-years return periods. In Figure 9 the estimated total runup levels together with the upper and lower limits of their 95% profile likelihood confidence intervals are presented. The runup level and also the upper limits of the confidence intervals are well below the dune crest elevation in the part of the beach where the dunes protect the developed hinterland from flooding (Almström, 2010).

Dune erosion

The result of the simulated return levels of dune erosion indicate higher erosion rates in the northern part of the beach than in the southern part of the beach (Figure 10) in accordance with previous

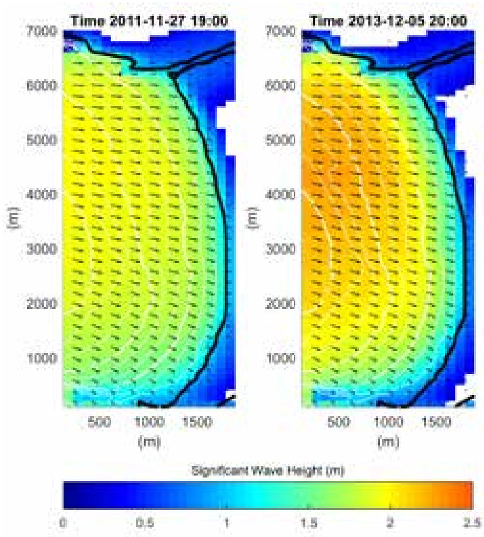


Figure 8. *Significant wave height and direction for particular time steps during the 2011 and 2013 storms with the largest computed dune erosion.*

observations (Fredriksson, 2011; Schönström, 2013). South of x=3700 m, there were too few years with observed erosion in the 40-year simulation period to estimate parameter values of the GPD model. This is due to wave energy dissipation over the shallower foreshore in that area, reducing the number of dune erosion events.

Overall, the dune volume between the sea and the buildings and infrastructure is sufficient to protect against the yearly erosion that can be expected with a return period of 100 years (Figure 11). Also when comparing to a very extreme erosion volume of two times the upper limit of the 95 % confidence interval for a 100-year return period, the dune volume is mostly sufficient. In the most northern part, at about *x*=300, the dune volume is smaller than the 100-year erosion volume. However, in this part of the beach, the dune is constructed with a gabion core and the dune does not function as flood protection for the hinterland. Further south, there are some stretches of the beach where the protective dune volume is significantly lower than in the surrounding areas, *e.g.*, *x*=600-700 m, *x*=1000 m, and *x*=1400-1600 m. In these areas, the protective dune volume is limited by houses and infrastructure located within the dunes. Then the risk of damage from erosion only concerns sin-

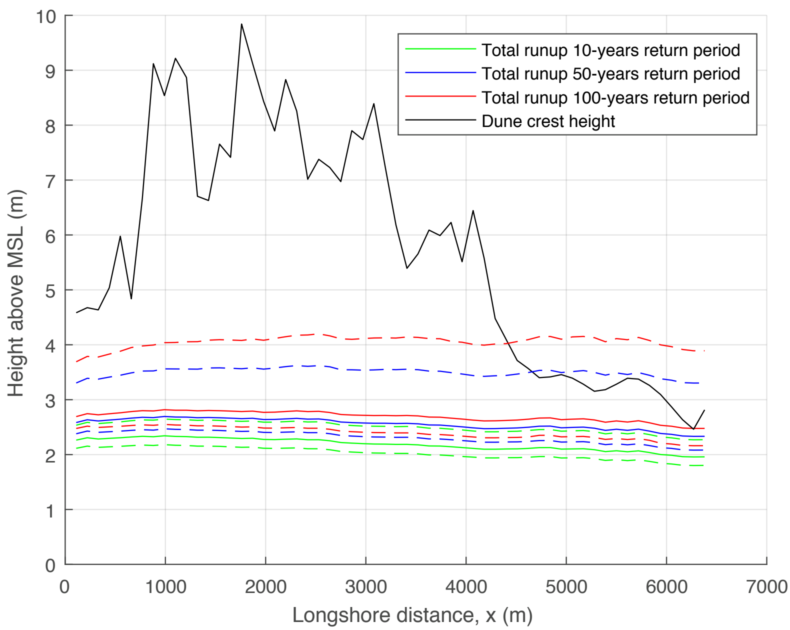


Figure 9. *Estimated total runup with 10-, 50-, and 100-year return intervals (solid colour lines). The dashed lines in the same colour coding indicate the 95 % confidence intervals derived with the profile likelihood method. The black line shows the dune crest elevation.*

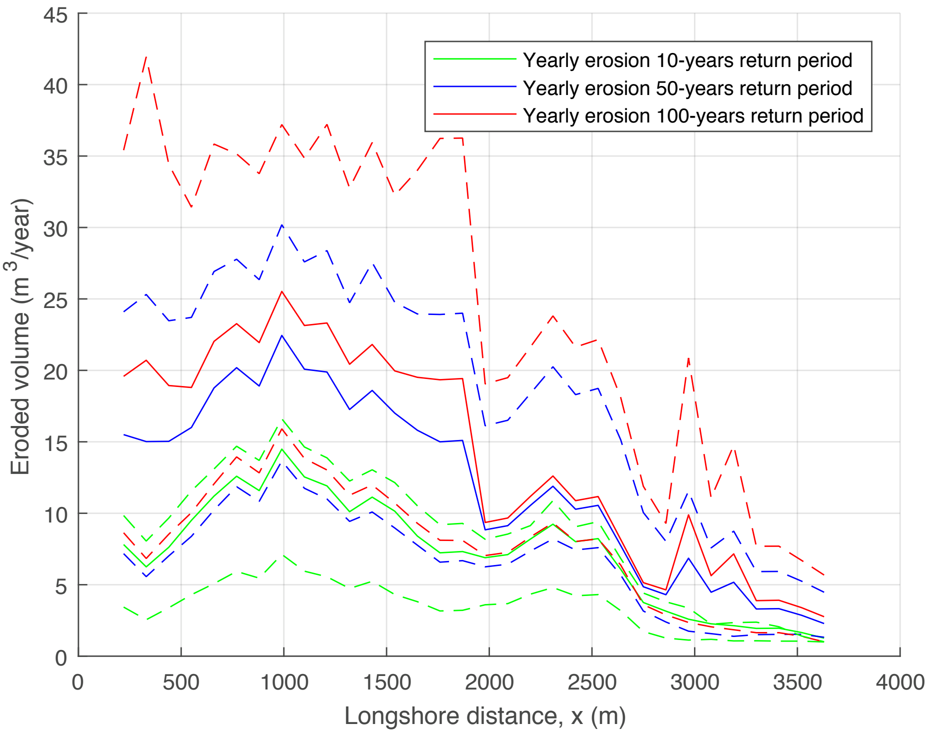


Figure 10. *Estimated eroded volume (solid lines) together with the upper and lower limit of the 95% confidence intervals derived with profile likelihood method.*

gle objects and is not a threat to the entire area as would be the case of a dune breach.

Discussion and concluding remarks

The results show that that the simulated runup levels and dune erosion volumes are largest at *x*=500-2000 m and decreasing in the southward directions. This longshore variability is consistent with observations (Fredriksson, 2011; Schönström, 2013), and explained by a longshore variability in the wave climate (Figure 8) and foreshore slope (Figure 4). Comparing the computed runup and dune erosion to the dune height and the protective dune volume, respectively, for specific return levels showed that there is no immediate risk of breaching and overtopping at this beach. However, this analysis does not take into account the effects of long-term changes due to, *e.g.*, sea level rise, gradients in longshore sediment transport or repeated years of dune erosion without sufficient recovery from aeolian transport. Gradients in longshore sediment transport are known to cause erosion in the northern part of the beach at about *x*=0-3000 m (Hallin *et al.*, 2019). This process is expected to deplete the protective dune volume with time.

In this study, the computed return levels were only compared to the most recent available DEM from 2017. From a management perspective, it is interesting to see how the protective dune volume changes over time. A trend implying decreasing protective dune volumes could be a motivation for intervention measures based on a chosen management strategy.

It is important to emphasize that the confidence intervals presented for the estimated return levels only account for uncertainties in the statistical

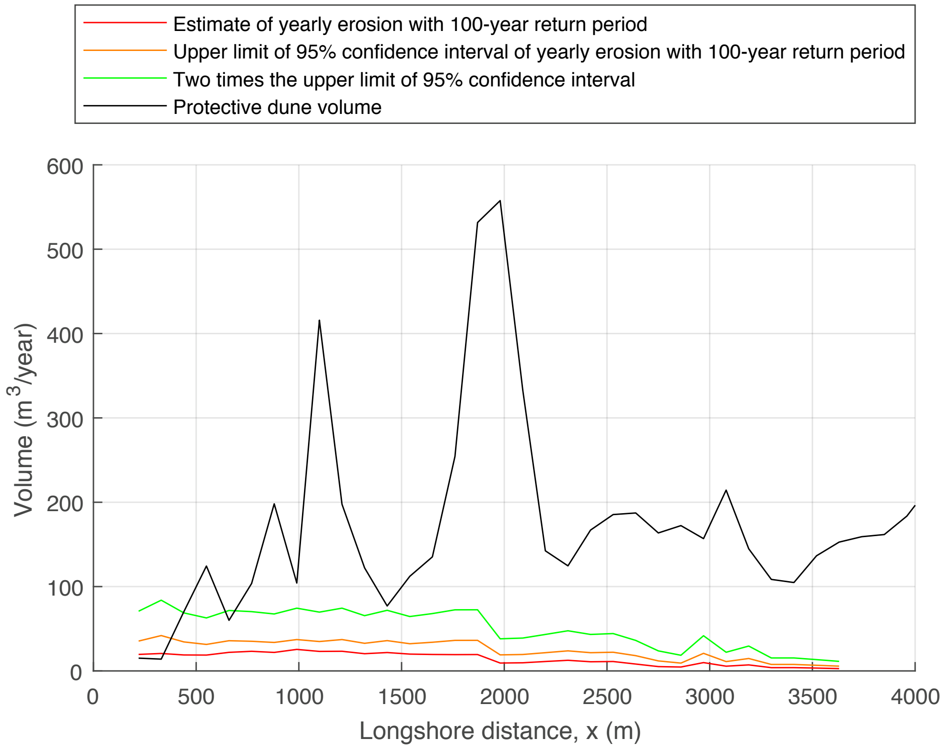


Figure 11. *The protective dune volume together with the 100-year erosion volume as well as one and two times the upper limit of the 95 % confidence interval.*

models and do not take into account measurement errors and uncertainty related to the wave models, runup calculations, and erosion model. The uncertainty can be decreased by collecting more data. Yearly topographic and bathymetric surveys, together with measurements before and after storms, indicate the long-term evolution and improve the calibration and validation of the dune erosion model. The local *SWL* has a large impact on runup levels and dune erosion rates; a local water level gauge would significantly have decreased the uncertainties in this study.

In conclusion, the applied method provided a simple and robust estimate of extreme runup levels and eroded dune volume during storms for a coastal area with data scarcity.

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