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LONG-TERM MODELLING OF AEOLIAN TRANSPORT AND BEACH-DUNE EVOLUTION

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Abstract

A model to simulate long-term beach-dune evolution due to interacting longshore and cross-shore sediment transport processes is developed and tested. The work builds on a cross-shore model (CSM) previously developed at Lund University and includes changes to the equations describing aeolian transport and morphological evolution. The modifications are mainly based on existing conceptual geomorphological models which are translated into a numerical model, dealing with aeolian transport rates, transport limiting factors, and dune evolution under positive, negative, or stable beach sediment budgets. CSM is tested against a seven year data set of morphological evolution and sediment grain-size samples from Ängelholm Beach, Sweden. Results show a satisfactory fit between the simulated and observed evolution, although not all processes could be validated due to the limited temporal extent of the data set.

Key words: aeolian transport, dunes, long-term modelling, sea level rise, beach-dune interaction, cross-shore processes

1. Introduction

Simulation of long-term coastal evolution requires robust, reliable, and computationally efficient models. For simulations at large temporal and spatial scales, shoreline evolution models based on the one-line theory, such as GENESIS (Lund University/USACE) and Unibest CL+ (Deltares) are presently the most commonly used models. In one-line models, cross-shore (CS) processes are typically not described and if included, only very schematically. The active profile has a fixed shape and morphological changes due to, *e.g.*, seasonal variations, storm erosion, dune build-up from aeolian transport, and sea level rise, are neglected. However, variations in storage volumes of dunes and bars may have large impact on shoreline position and accurate modelling of dune dynamics is crucial when predicting long-term erosion and flood risk.

To better account for CS processes in long-term modelling, a CS model (CSM) to simulate profile evolution was developed (Larson *et al.*, 2016). The different components of CSM were derived, calibrated, and validated against a wide range of data from both the laboratory and the field, and tested in three different case studies (Palalane *et al.*, 2016). The aim is to later incorporate CSM into Unibest CL+ in order to account for the impact of CS processes on long-term shoreline evolution.

The objectives of this study are to develop the aeolian transport equations and the associated morphologic evolution of the dune in CSM and to validate the approach against data from Ängelholm Beach in South Sweden from 2010 - 2016.

1.1 *The CS-model (CSM)*

CSM is designed to be used in combination with longshore sediment transport models to improve predictability of shoreline location, taking into account changes in the cross-shore profile due to storms and seasonal effects, but also to simulate the long-term evolution of the beach-dune system (Larson *et al.*, 2016). Compared to the previous version of CSM (Larson *et al.*, 2016), the model presented here include changes to dune and beach schematization, aeolian transport equations, and morphological dune evolution. It also includes sediment transport processes to account for effects of sea level rise and nominal longshore

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sediment transport gradients, here estimated from the observed evolution of the vegetation line.

CSM is robust and computationally efficient which makes it suitable for long-term simulations, decades up to years. Required input is wind (speed and direction), deep water waves (root-mean-square wave height, peak period, and direction), and still water level (including tide and surge). Simulations are typically carried out with hourly time steps. The computational efficiency is due to a simple schematization of the beach profile (Figure 1 and 2), which is divided into a beach volume $V_{beach,tot}$ (including subvolume V_{beach}), a dune volume V_{dune} (including subvolume V_{ramp}), and a bar volume V_{bar}. The beach geometry is resolved through height and length coordinates of the seaward and landward dune foot (y_L and y_S), dune crest (y'_L and y'_S) and shoreline at mean sea level (y_G), assuming fixed angles of the dune slopes (β_L and β_S) and a fixed dune foot height (D_F). The subaqueous part of the beach profile is assumed to follow an equilibrium profile shape, out to depth of closure D_C (Hallermeier, 1981). The storage volume V_{beach} is limited by a maximum foreshore slope angle (β_F).

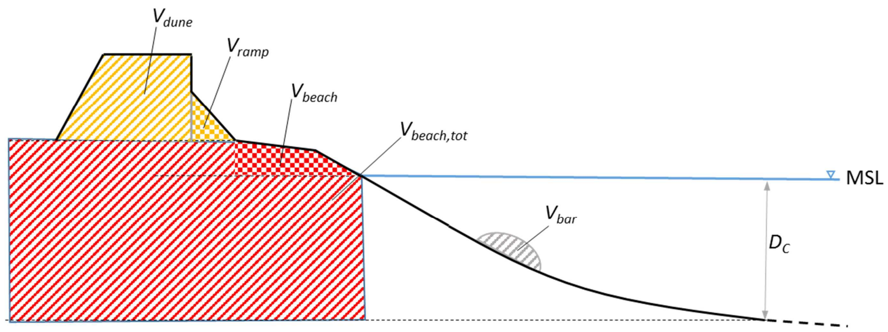

Figure 1. Schematization of beach profile volumes and depth of closure (D_C), in relation to mean sea level (MSL).

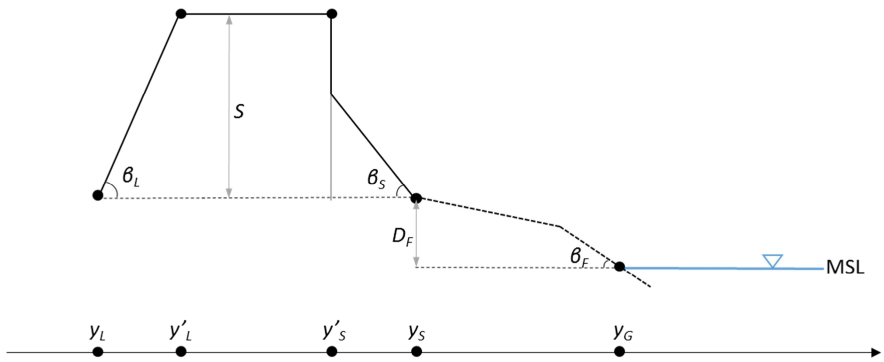

Figure 2. Characteristic heights, length coordinates and angles, describing beach and dune geometry.

Sediment is shifted between the volume entities due to cross-shore sediment transport, fulfilling conservation of mass. Included cross-shore processes are dune erosion and overwash, dune build up by wind, and berm-bar exchange (Larson *et al.*, 2016). Nourishments or sand extractions are included in the model by simply increasing or decreasing the concerned volume entity. Longshore processes are here included as constant transport rates based on observed long-term evolution of the vegetation line. Sea level rise is described in CSM as a continuous sink calculated using the Bruun model (Bruun, 1962; 1954). The sediment needed to compensate for sea level rise in the equilibrium profile is subtracted from the beach volume. The dune foot height is kept constant so that the dune foot elevation is shifted upwards with rising mean sea levels. In this particular application, however, sea level rise is not included, because postglacial land uplift compensate sea level rise in the study area during the simulation period.

In previous applications (Palalane *et al.*, 2016), aeolian transport has been included as a constant rate and the dune height regarded as constant. In this paper, a method to include a physics based aeolian transport and wind-blown sediment distribution scheme over the dune, is developed based on a literature study and tested with the field data. Model developments also included changes to the profile schematization to allow for a more dynamic morphological evolution.

1.2 *Aeolian transport and dune evolution*

The mechanics of sediment transport by wind and the associated morphological evolution of coastal dune systems have been studied extensively (*e.g*. Bagnold, 1937; Hesp, 1988). Still, few models manage to predict transport rates at time scales of months to years. Commonly used formulas for wind transport, *e.g*., the equilibrium transport formulas by Bagnold (1937), Hsu (1971), Kawamura (1951), and Lettau and Lettau (1978) tend to overestimate the transport rate when compared to field observations (Barchyn *et al*., 2014; Sherman *et al*., 1998). These equations typically relate the aeolian transport rate to grain size, wind shear velocity (*i.e*., a measure of shear stress on the sediment grains), and a critical wind shear velocity for initiation of motion. In a natural beach environment, the equilibrium transport for fully developed saltation is frequently not reached, due to limiting factors such as beach slope, beach width, sediment availability, soil moisture, and snow and ice-cover.

In long-term modelling of the beach-dune system, not only the rate of aeolian transport between the beach and dune is of interest, but also the sediment distribution over the dune. Several conceptual models have been put forward to describe long-term dune evolution under influence of aeolian transport (*e.g*. Davidson-Arnott, 2005; Psuty, 1988; Sherman and Bauer, 1990) of which a few are translated into numerical models (*e.g*. Duran and Moore, 2013; Hoonhout and de Vries, 2016; Sauermann *et al*., 2001; Van Dijk *et al*., 1999).

Here we aim to develop an aeolian submodule to CSM, which estimates aeolian transport rates and foredune evolution based on the local wind climate and parameters that can be calculated by CSM. For this purpose the conceptual model by Psuty (1988), relating morphological evolution of dune to the sediment budget, and the concept of dune ramps, described by Christiansen and Davidson-Arnott (2004), is translated into a numerical model and incorporated in CSM. In the two following paragraphs we summarize our interpretation of long-term dune evolution based on the results of Psuty (1988) and Christiansen and Davidson-Arnott (2004).

At an accreting beach, dunes will grow fast and create a prograding beach ridge topography where a new foredune is formed in front of the other, creating low dunes with mild slopes. The dunes are low because there is not enough time for them to grow in height, before a new foredune is built in front of them. At a stable beach, the dune stays in place and grow higher due to scarping and recovery. Eroding beaches may develop in two different ways; if they are slightly eroding, the dune will maintain or even increase its volume, grow higher and be displaced inland through scarping in combination with aeolian transport or overwash. If the beach is eroding fast, and overwash processes are dominant, the dune will be flattened out and move landwards.

The explaining mechanism between the different morphological dune evolution schemes is the impact of the sediment budget on vegetation and formation of dune ramps. Accreting beaches are less often overwashed, enabling establishment of new vegetation on the upper part of the beach around which an embryonal foredune may form. On stable or eroding beaches, dune ramps form from collapsing erosion scarps, or wind-blown sand being piled up against the dune, as there is not enough vegetation on the beach to trap the sand in front of the dune. These ramps then acts as a bridge, bypassing aeolian transported sediment to the crest or landward slope of the dune.

We base our model on the following assumptions:

1. On a decadal time scale, the most important limiting factor for aeolian sediment transport is the supply of material of appropriate grain size. Sediment availability can be estimated by book-keeping transport of this sand, to and from the beach, due to gradients in longshore sediment transport, transport to the subaqueous part of the active profile to compensate for sea level rise, aeolian transport, dune erosion, and nourishments.
2. If sediment of appropriate grain size is abundant, the aeolian transport rate can be estimated by using the equilibrium transport equation by Lettau and Lettau (1978) corrected for the fetch effect. If not, aeolian transport can be neglected.
3. The beach-dune sediment budget (positive, negative, or stable) can be used as a proxy to control morphological dune evolution, instead of explicitly including vegetation in the model.

2. Model development

This paper describes the development of the profile schematization, aeolian transport formulations, and the morphological evolution schemes. For explanations of the other included processes in CSM (dune erosion, overwash, and beach-bar exchange), we refer to Larson *et al*. (2016).

2.1. *Profile schematization*

The main principles of the profile schematization is described in section 1.1, Figure 1 and Figure 2. Changes from the previous version (Larson *et al*., 2016) include the introduction of a dune ramp volume as an integrated part of the dune volume. The ramp volume will be eroded first and if eroded away completely, the main part of the dune (behind the seaward dune crest, y'_S) will start to erode. Aeolian transport will first be deposited in the dune ramp, until it reaches its maximum volume. Then, additional sediment will be distributed over the dune according to a morphological dune evolution scheme. In reality, the sediment in the ramp could originate from dune scarp avalanching instead of aeolian transport, which would affect the morphological evolution, although the dune volume would still be represented correctly.

The schematization of the beach is changed by defining a beach volume, V_{beach}, as the sediment volume above mean sea level, *MSL*, between y_G and y_S. V_{beach} is an integrated part of the total volume, $V_{beach,tot}$. The beach width, y_G-y_S, is defined as a function of V_{beach} based on site specific data, to define the shoreline location and runup height. If V_{beach} is smaller than its minimum value with respect to maximum foreshore slope angle, β_F, the dune will erode.

Runup height, *R*, is estimated using the formula (Larson *et al*., 2004),

$$R = 0.158\sqrt{H_0 L_0} \tag{1}$$

where H_0 and L_0 are deep-water root-mean-square wave height and mean wave length, respectively. If exceeding the dune foot, D_F, *R* is corrected for friction over the beach according to (Hanson *et al*., 2010),

$$R' = \exp(-2c_f x) + (D_F - SWL)(1 - \exp(-2c_f x)) \tag{2}$$

where *R'* is the adjusted runup height, c_f is an empirical friction coefficient, *SWL* is the still water level, and *x* is the horizontal travel distance of the wave front, here defined as,

$$x = \frac{2V_{beach}}{D_F}\left(1 - \frac{SWL}{D_F}\right) \tag{3}$$

The runup length coordinate, y_R, for runup not exceeding the dune foot, is defined as,

$$y_R = y_S + \left(1 - \frac{R + SWL}{D_F}\right)(y_G - y_S) \tag{4}$$

2.2. *Aeolian transport formulations*

The volume of sediment available for aeolian transport, V_W, during time step $t=i$ is calculated as:

$$V_{W,i} = V_{W,i-1} + (q_{S,i-1} - q_{W,net,i-1} - A(q_{SLR,i-1} + q_{LS,i-1}))\Delta t + A'V_{nour,i-1} \qquad Vw \geq 0 \tag{5}$$

where q_S is the transport rate of eroded sediment from the dune to the beach, $q_{W,net}$ is the aeolian transport rate from the beach to the dune, q_{SLR} is the transport rate of sediment to compensate for sea level rise, q_{LS} is the net transport rate of sediment alongshore, Δt is length of time step, and V_{nour} volume of added artificial nourishments to the beach or to the subaqeous profile (dune nourishments are not included). *A* and *A'* are coefficients describing the fraction of transport rate and nourished volume respectively which is within the proper range for aeolian transport. Volumes and transport rates are given per meter of beach width. If $V_{W,i} > 0$, aeolian transport will take place during timestep $t=i$. If $V_{W,i} \leq 0$, the aeolian transport will be turned off and $V_{w,i}$ is set to zero.

q_S is calculated by the dune erosion formula (Larson *et al.*, 2016),

$$q_S = 4C_S \frac{(R' - D_F - SWL)^2}{T_H} \tag{6}$$

where C_S is an impact coefficient and T_H average wave period.

The potential aeolian sediment transport rate (m_{WE}), is calculated with an equilibrium transport formula and corrected for limited fetch length. Here the formula proposed by Lettau and Lettau (1977) is used:

$$m_{WE} = K_W \sqrt{\frac{D_{50}}{D_{50}^{ref}}} \rho_a \frac{u_*^2}{g} \left(u_* - u_{*c} \right) \tag{7}$$

where D_{50}^{ref} is the median reference grain size (0.25 mm), ρ_a the density of air, g the standard acceleration due to gravity, u_* the shear velocity at the bed, u_{*c} the critical shear velocity at the bed, and K_w an empirical coefficient set equal to 1.2 (Sherman *et al.*, 2013). The median grain size, D_{50}, should be chosen as a representative grain size found in the dunes. If $u_* < u_{*c}$, $m_{WE} = 0$.

The mass flux m_{WE} is converted to a volumetric equilibrium transport rate (q_{WE}) of sand to the dunes by:

$$q_{WE} = \frac{m_{WE}}{\rho_s}(1 - P) \tag{8}$$

where ρ_s is the density of sand (approximately 2650 kg/m^3) and P the porosity (approximately 40%).

The critical shear velocity is calculated from (Bagnold, 1937),

$$u_{*c} = A_W \sqrt{\frac{(\rho_s - \rho_a)}{\rho_a} g D_{50}} \tag{9}$$

where A_W is a coefficient (about 0.1).

The shear velocity, u_*, is calculated using the law of the wall,

$$\frac{u_z}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0} \right) \tag{10}$$

where u_z is the wind velocity at z meter above ground, z_0 is the aerodynamic roughness height and κ is von Karman's constant ($\approx$ 0.41), z_0 is here, as a rule of thumb, parameterized as $D_{50}/30$ (see e.g. Zhang *et al.*, 2015).

The fetch length depends on the wind angle against shore normal, θ, and the dry beach width, B_{dry},

$$F = \frac{B_{dry}}{\cos(\theta)} \quad \text{for } 0° \le \theta \le 80° \tag{11}$$

The dry beach width, B_{dry}, is calculated as the horizontal distance from the runup limit to the seaward dune foot, $y_R - y_S$. If $y_R \ge y_S$ the whole beach is assumed to be wet and there will be no aeolian transport. Aeolian transport due to offshore directed winds is neglected.

A simplified equation for the corrected potential transport rate, q_W, for limited fetch has been developed (Larson *et al.*, 2016) based on the work by (Sauermann *et al.*, 2001),

$$q_W = q_{WE}\left(1 - \exp(-\delta F)\right) \tag{12}$$

where δ an empirical coefficient assumed to be about 0.1. Theoretically, the constant is expected to vary with wind speed, but for simplicity a constant value is considered here. The constant should be representative for the wind conditions under which most aeolian sediment transport occurs and may be determined from field measurements.

Oblique wind angles have longer fetch and may therefore generate higher aeolian transport rates. This effect is counteracted by the cosine effect, implying that only the onshore component, $q_{W,net}$, adds to the dune volume,

$$q_{W,net} = q_W \cos(\theta) \tag{13}$$

2.3. *Morphological evolution scheme*

The sediment budget is calculated as the change of volume in the beach-dune system (ΔV_T) over a significant time scale (T_{bud}), referring to the required time for vegetation establishment, and can either be negative ($\Delta V_T < 0$), stable ($\Delta V_T \approx 0$; the range is site specific), or positive ($\Delta V_T > 0$):

$$\Delta V_T = \frac{1}{T_{bud}} \sum_{t=i-T}^{t=i} \left((-q_{SLR,t} + q_{LS,t}) \Delta t + V_{nour,t} \right) \tag{14}$$

Here all nourishments are considered in V_{nour}, also dune nourishments. The significant time scale, T_{bud}, is in the order of years and should be long enough to represent long-term trends and not seasonal variations. If the beach sediment budget is altered, for example nourishments are added to an eroding beach, the morphologic evolution will change. However, this change will be gradual due to the significant time scale, taking into account the time required for vegetation to establish or disappear when the sediment budget is changing.

In the case of a positive sediment budget, $\Delta V_T > 0$, the ramp is filled until the ramp height is equal to the dune height, S. After the ramp has filled up, if $S < S_{max}$, for a trapezoidal shape, the sediment will be deposited on the crest, and for a triangular dune shape, on the seaward side. If $S \geq S_{max}$, all sediment is deposited on the seaward side of the dune and the dune grows seaward in a trapezoidal shape.

In the case of stable sediment budget, $\Delta V_T \approx 0$, the ramp is also filled until the ramp height is equal to the dune height, S. Thereafter, in the case of a trapezoidal dune shape, a fraction of the sediment, A_{stable}, is deposited on the crest and the remaining fraction 1 - A_{stable} is deposited on the seaward side of the dune. If the dune has a triangular shape, the dune grows vertically in its place, maintaining a constant dune crest coordinate, $y'_L = y'_S =$ constant.

In the case of a negative sediment budget, $\Delta V_T < 0$, the ramp is filled until 1 m below dune crest level (Christiansen and Davidson-Arnott, 2004). Thereafter, in the case of a trapezoidal dune shape, a fraction of the sediment, A_{erod}, is deposited on the crest and the remaining fraction 1 – A_{erod} is deposited on the landward side of the dune. If the dune has a triangular shape, $y'_L = y'_S$, the dune grows on its landward side.

3. Application in Ängelholm, Sweden

CSM is applied to Ängelholm beach, located in Skälderviken bay, south Sweden (Figure 3). The model is calibrated for the period 12/04/2010 – 21/04/2016 and then validated for the period 22/04/2016 – 17/01/2017 for three different profiles within the study area, profiles A, B, and C.

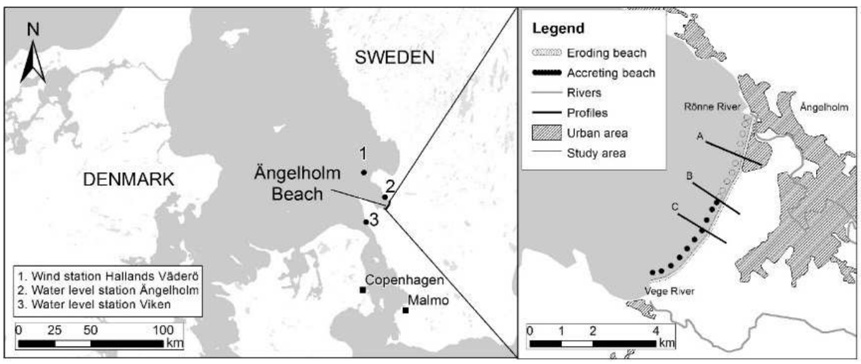

Figure 3. Map over the study area and measurement stations.

3.1. *Wind, waves and water levels*

Wind data was collected from station 1 (Figure 3), operated by the Swedish Meteorological and Hydrological Institute (SMHI), as hourly observations of 10 minute average wind speeds and directions, 10 m above ground. Deep water wave conditions, energy based significant wave height, H_{m0}, and peak period, T_m, at the mouth of Skälderviken bay are hindcasted from the wind data using the CERC-formulations (USACE, 1984). The wave calculations are modified with a memory function (Hanson and Larson, 2008a) to simulate wave growth and decay, and converted to root-mean-square wave height, H_{rms} and average period, T_H.

The runup height and cross-shore sediment exchange processes are assumed to depend on the wave energy (Hanson and Larson, 2008b). Therefore the input wave height is adjusted so that only the onshore component of wave energy is accounted for in the runup and transport equations according to,

$$H'_{rms} = H_{rms}\sqrt{\cos\varphi} \tag{15}$$

where H'_{rms} is the wave height representing the onshore energy flux and ϕ is the offshore incident wave angle from the shore normal.

Water levels are collected from station 3 (Figure 3) operated by SMHI. To account for wind setup, Δh, in Skälderviken Bay, the observations are corrected according to (USACE, 1984),

$$\Delta h = \frac{\rho_a}{\rho_w}\frac{C_D u_X^2 L_B}{gd} \tag{16}$$

where ρ_w is water density, ρ_a air density, C_D drag coefficient, u_x onshore wind speed component, L_B bay length, and d average depth.

C_D was calibrated against data from the SMHI station 2 (Figure 3) from 2011 to 2014. The drag coefficient, C_D, was determined to 2.3×10^{-3}, with a weak correlation coefficient between the calculated and observed wind setup (r^2=0.17), indicating a complex relationship between the water level at the two stations. However validation against a local measurement station in the harbor at Rönne river mouth showed good performance of peak values which are the most important for dune erosion calculations.

Astronomical tidal variation in the study area is small, < 20 cm, and the wave climate is normally calm due to the sheltering effects of the bay. During storms from west to northwest, storm surges and large waves occur. During 2010 – 2016 there has been five major storm events impacting the dunes with water levels exceeding 150 cm above normal, in November 2011, December 2013, January and November 2015, and December 2016. The highest observed water level, adjusted for wind setup, is 185 cm above MSL in November 2011 and the largest computed wave with H_{m0} = 5.3 m and T_m = 9.3 s occurred in December 2013.

3.2. *Morphology and sediment*

The beach morphology is varying along the coastline, from higher dunes and a narrower beach in the north, to lower dunes and a wider beach in the south. The observed long-term beach evolution is erosion in the north and accretion in the south. The studied profiles, A, B and C, have been selected to represent stretches of the beach with different long-term evolution. Analysis of aerial photos since the 1940's suggests that the vegetation line has been retreating about 0.3 m/year in profile A, stable in profile B, and accreting about 0.3 m/year in profile C (Palalane *et al*., 2016). This rate is converted to an average transport, q_{LS}, and included in the model. In profile A, to repair storm damages, the dune has been nourished with sediment taken from just below the water line within the same profile in April 2012, April 2014, and March 2015. The nourishment volumes are uncertain as no topographic surveys were carried out before and after the operations. They are included in the model and are used as a calibration parameter rather than input, due to lack of data.

The morphological evolution is based on 9 observations of the beach profiles from 12/04/2010 to 17/01/2017, of which five are derived from digital elevation models (DEMs) with resolution 1×1 m provided by Ängelholm municipality, two based on LiDAR data, and three on topographic data constructed by photogrammetry. The other four are based on profile surveys completed using a Topcon GR-3 GPS in Network-RTK mode using the SWEPOS real-time network, with a nominal uncertainty of measurement of ±1-2 cm (95%) in horizontal and 2-3 cm (95%) in vertical. Figure 4 displays the initial profiles and their schematizations used in CSM. The beach width function has been derived from measured profiles extending from the dune foot to the intersection with MSL (Figure 5).

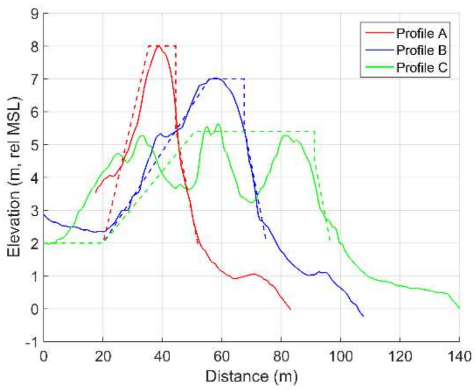

Figure 4. Initial beach profiles and dune schematizations.

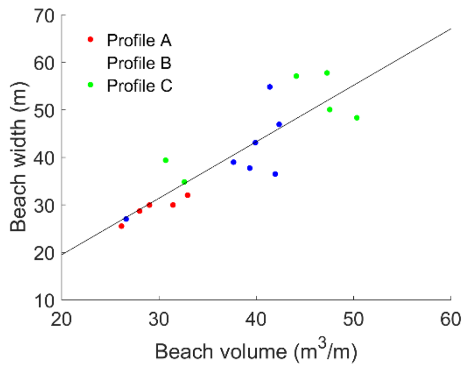

Figure 5. Linear relation between beach width and beach volume.

The relation between the beach width, y_G - y_S, and the beach volume, V_{beach}, is described by the linear function,

$$y_G - y_S = 1.2V_{beach} - 4.3 \quad (17)$$

with a coefficient of determination of $R^2 = 0.76$.

Sediment samples have been collected from 7 different locations within the subaerial part of profiles A, B, and C at four different occasions during 2015 and 2016. Sample points are indicated in a schematic sketch in Figure 6. In profile A, sample 6 was taken from windblown sand and not from the artificial fill in the dune front. The samples were sieved for 15 minutes using a vibratory sieve shaker of type Retsch AS200 Basic with the vibration amplitude set to 0.7 mm, and sieve sizes (in mm) of 2, 1.4, 1, 0.71, 0.5, 0.355, 0.25, 0.18, 0.125, 0.09, and 0.063. The median grain size, $D_{50,}$ of each sample are presented in Figure 7, note that all sampling points were not represented at all sampling occasions. All samples had a homogenous grading with an average D_{84}/D_{16} of 1.84 with a standard deviation of 0.35.

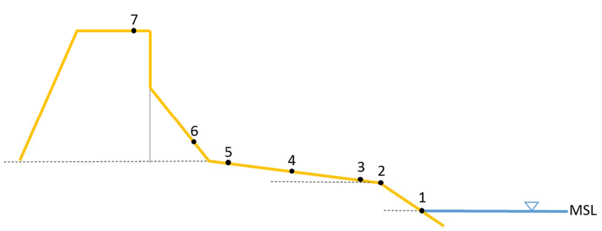

Figure 6. Sampling locations on the beach and dune.

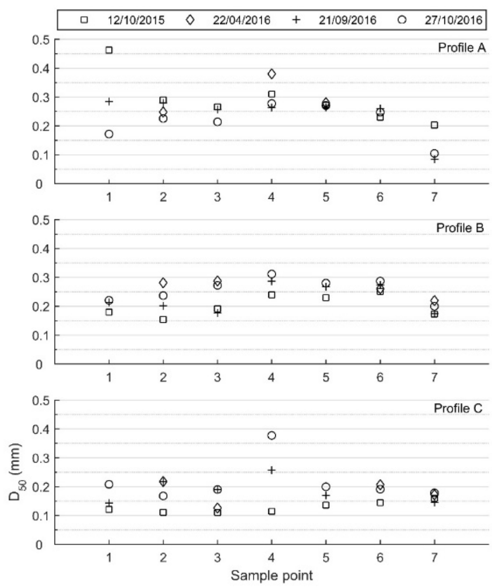

Figure 7. Median grain size, $D_{50,}$ in sediment samples.

The result of the grain size analysis indicate that the appropriate sediment grain size for dune building aeolian transport is about 0.15 – 0.25 mm, corresponding to the grain size found in the dune (sample point 7). In profile A, samples 7 from 21/09/2016 and 27/10/2016 have a D_{50} about 0.1 mm and probably originate from the artificial dune fill, which has an observed D_{50} of 0.08 mm.

4. Results

In the calibration, standard values given in section 2.2 were used for parameters in the aeolian transport formula, D_{50} was set to 0.2 mm for all profiles, *A* and *A'* were set to 1, and A_{stable} and A_{erod} were both set to 0.5. For this study, there was no information on the morphological evolution of the subaqueous part of the profile. The initial bar volume, which represent subaqueous deposits interacting with the beach deposits, were calibrated to 20 m^3 for profile A, 70 m^3 for profile B, and 50 m^3 for profile C to reproduce the evolution of the beach volume. For the validation, the bar volume at the end of the calibration period was used as initial value.

Dune erosion was calibrated by adjusting the impact coefficient, C_S, describing the resistance of the dunes to wave erosion, which depends on, *e.g.*, shape, grain size, vegetation, and sediment compaction. For profile B and C, which are both natural dunes built up by aeolian transport with similar vegetation, C_S was calibrated to a common value of 7.5×10^{-5}. In profile A, the dune had initially naturally transported sand, but has after April 2012 partly been filled out with fine, silty material. The impact coefficient, C_S, was here calibrated to a larger value of 5×10^{-4}. Results of calibration and validation are shown in Figures 8 – 11. The sudden increases of dune volume in profile A are due to the dune nourishments to repair the dune after storm damages. Since there were no reliable data of nourishment volumes, their values were estimated to fit the observations.

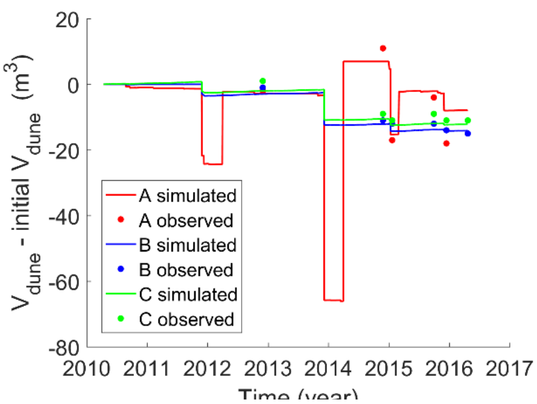

Figure 8. Result of dune volume evolution, calibration.

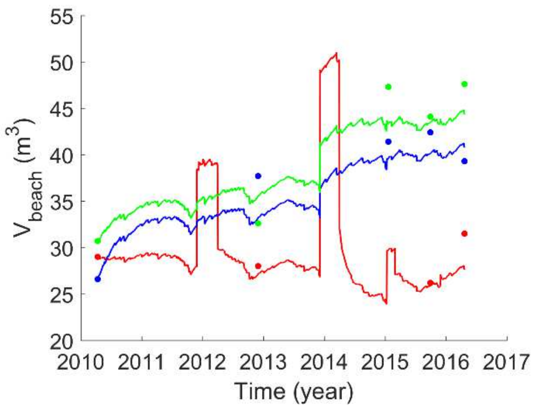

Figure 9. Result of beach volume evolution, calibration.

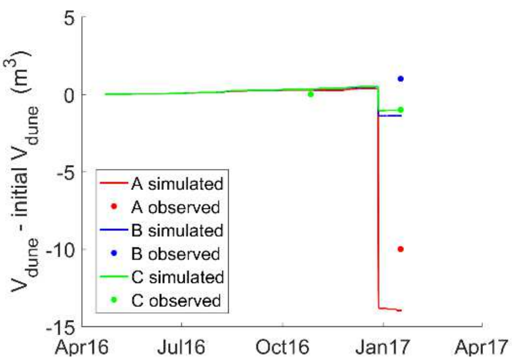

Figure 10. Result of dune volume evolution, validation.

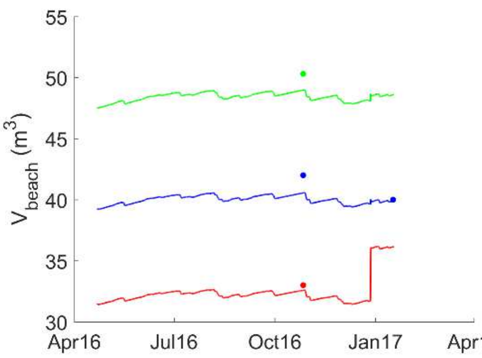

Figure 11. Result of beach volume evolution, validation.

Initial available sediment for aeolian transport was set to 0 m^3/m in the calibration phase. Figure 12 displays the available sediment for aeolian transport and Figure 13 the accumulated sediment transport over time. The simulated yearly average aeolian transport amounts to 0.3 m^3/year in profile A, 0.5 m^3/year in profile B and 0.6 m^3/year in profile C.

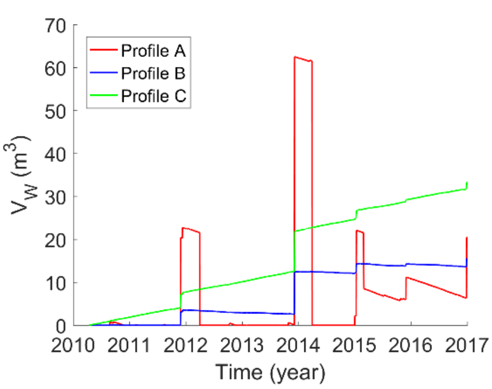

Figure 12. Available sediment volume for aeolian transport.

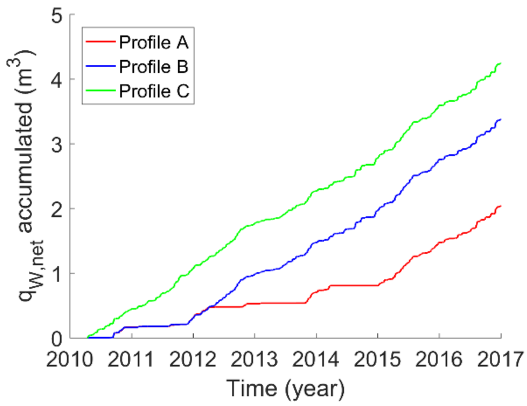

Figure 13. Aeolian transport, accumulated.

5. Discussion

The result of the calibration and validation indicates that CSM has the capability to represent long-term evolution of the beach and dune. The fit of the simulation results with the observed data is satisfactory. However, in this case study there are large uncertainties associated with the observed data and model input. The beach profiles are derived from DEMs with resolution of 1×1 m based on both LiDAR data and photogrammetry, and topographic surveys with GPS are carried out by both the municipality and by researchers within this study. Therefore, it is uncertain whether some of the minor observed topographic developments are due to actual morphologic changes or artefacts of different data acquisition methods. The lack of data on the subaqueous part of the profile, and lack of exact information about nourishment volumes in profile A is another weakness of the data set. The bar volume, V_{bar}, and the dune nourishment volumes, V_{nour}, are here used as calibration parameters instead of being actual input to the model.

The eroded volumes under storms are on some occasions overestimated, and on other occasions underestimated. This can both be due to uncertainties in the topographic data and in the forcing. In the dune erosion equation, water level and wave data both have large impact on the eroded volume. The lack of *in situ* water level gage data, creates uncertainty when the water levels within the bay are corrected for local wind setup. The coarse wave model with a simple correction for refraction, is also a source of error. It is possible that local variation in the wave climate occurs within the study area, which is not considered here, and could partly explain the large variation when calibrating the dune erosion impact coefficient; thus, Profile A has a much higher impact coefficient than profiles B and C. It was also difficult to perform the calibration since the observed response to different storms showed larger variations. One explanation for this can be the mix of sediment in the dune, where the main part of the dune consists of sand with D_{50} around 0.15 – 0.25 mm and the front part consists of finer, silty material from dune nourishment.

In this application, the gradient in longshore sediment transport was included as an average constant increase or decrease in the total beach volume based on an observed evolution since the 1940's. Temporal variations during the simulation time are thus not accounted for and may contribute to longshore variations, especially in the beach volume. Temporal variations in the longshore sediment transport gradients can be properly accounted for by coupling CSM to a longshore sediment transport model.

The aeolian transport scheme was implemented with default values, without calibration. Compared to previous CSM applications, where a constant transport rate was applied, the results here are more realistic. The simulation results with the highest aeolian transport in profile C and lower transport in profile A are in line with field observations. The simulated differences in average annual transport rates are due to variations in sediment supply between the different profiles as well as the variation in beach width.

The four sets of sediment samples taken from October 2015 to October 2016 display variations both in space and time (Figure 7). D_{50} is the median grain size, so there will be sediment with both finer and coarser grain size on the beach. However, beach material typically has a fairly uniform distribution, so it is assumed that D_{50} can be used to assess if the material on the beach is of the right grain size to build dunes. The dunes in Ängelholm beach are built up by sand with D_{50} in the range 0.15 - 0.25 mm. Consequently, dunes will only form if that sediment is available on the beach. Sample points 1 – 5 represent sediment available for aeolian transport, sample point 6 wind-blown sand deposited at the foot of the dune, and point 7 sediment on the dune crest. In profile C, dune building sediment was available at all sampling occasions, except for the first in October 2015 when it was finer with D_{50} below 0.15 mm. Fine sediment may be transported to the dune, but could stay in motion instead of being deposited in the dune. In fact during a field visit in October 2015, the beach was wet, which could be explained by capillary forces within the fine sediment, beach height, and water level; unfortunately no topographic survey was carried out during that visit. In Profile A, sediment of appropriate grain size was only available on the last sampling occasion in October 2016. Profile B had only a complete sample from three of the occasions and then showed availability in some of the sampling points, but not all. This pattern is reflected in the simulated available sediment (Figure 12), where profile C has the most available sediment, profile B less, and profile A intermittent availability throughout the simulation period 2010 - 2016. However, the simulation results show that there should be sediment available for aeolian transport within all three profiles during the actual sampling period, which was not supported by the sediment grain size data. An explanation for this could be that the material eroded from the dune in profile A before the sampling period was finer than the appropriate grain size for dune build up and thus should not have been accounted for in the available sediment bookkeeping, V_W.

6. Conclusion

Despite the uncertainties in the data, the model simulation results are satisfactory. Also, the new version of CSM has proven to be fast and robust, which makes it suitable for long-term simulations of beach and dune evolution over large spatial scales. The included processes of aeolian transport and dune evolution are based on previous studies of aeolian and geomorphological processes that have been translated into a numerical model for which CSM provided a good framework. The new components in CSM need further testing, especially the long-term processes of sea level rise and morphological evolution, for which there was no signal in the dataset employed. Further studies are also needed to estimate the site-specific proportion of sediment available for aeolian transport in the volumes accumulating and eroding due to nourishments, gradients in longshore sediment transport, and transport to the subaqueous part of the profile, to compensate for sea level rise.

Combined with a longshore sediment transport model, CSM has the capacity to improve predictions of shoreline location but also to simulate the dune evolution, which is of major importance to assess flood safety along sandy coastlines, and to test the effect of nourishments in different parts of the beach profile. To validate CSM's capacity to predict long-term morphological evolution, tests with long-term data sets, including the simulated morphological changes and reliable data of the forcing mechanisms, are required.

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