Conference Paper, Published Version

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ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

Medium Term Time-Dependent Morphodynamic Modelling of Beach Profile Evolution in Ada, Ghana

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ABSTRACT: In coastal engineering, assessment of the longer term cross-shore morphological evolution is an important aspect in coastal management, but modelling this is still a challenge. A time-dependent process based model has been applied to evaluate medium term (one year) profile evolution near Ada, Ghana, supporting the design of a coastal defense system. The coastal section near Ada is characterized by severe erosion, of which cross-shore losses are estimated to be important. To better understand the coastal system, morphological model studies are performed, one of which includes an XBeach cross-shore profile model. This model has been used in conditions different for which it has been originally designed. A representation of the average profile evolution was possible by calibrating parameter settings, such as wave asymmetry, skewness, dune avalanching triggers and the wave breaking module. The calibrated model still overestimates the erosion and underestimates accretion under mild wave conditions and does not explain the expected cross-shore losses. An improvement of the representation of the profile was found by applying the groundwater module.

Keywords: XBeach, Numerical modelling, Profile model, Morphodynamics, Cross-shore erosion, Ghana

1 INTRODUCTION

Ada Foah and other surrounding villages located at the east coast of Ghana have been suffering from ongoing erosion for a very long period of time. The Ghanaian government decided to protect the coast in Ada with a combination of groynes and beach and dune nourishments (Figure 1).

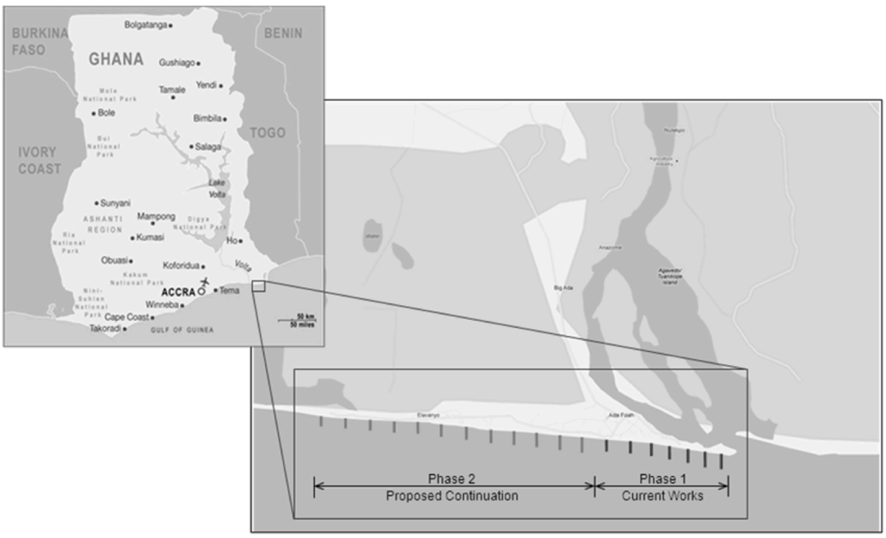

Figure 1. Overview of project site location and foreseen groynes as coastal defense system.

Hydrodynamic and morphological modelling have been undertaken to obtain better insight in the governing coastal processes and to support the design of the coastal protection system consisting of groynes and beach nourishments. Because of the complexity and variety of the physical processes involved at the site, a process based time-dependent morphodynamic model XBeach is used to evaluate the longer term morphological evolution.

Due to the environmental conditions at the site, the profile behavior in the XBeach model did initially not correspond well with observations. A 1DH XBeach model has been set up to evaluate cross-shore profile evolution. A common observation is that the nearshore part of a profile adapts very quickly to changes in the sediment balance and stays close to a dynamic equilibrium (Roelvink and Reniers, 2012). Based on this observation, the parameter settings of the 1DH model have been calibrated to represent the equilibrium profile on a medium term (one year) analysis. Such a longer term assessment of beach dynamics has also been tested by Pender et al. (2012) and goes beyond the normal short timescales for these kind of applications. To incorporate a full range of forcing conditions, a full year climate including normal to lower extreme waves has been used in the 1DH model.

Furthermore, cross shore losses have been estimated to be important in the coastal area near Ghana, but at this stage the profile model is not able to evaluate these processes

The results of this study have supported a more complex 2D hindcast analysis of the present groyne system (Phase 1 in Figure 1) in Gruwez et al. (2014) and supported a forecast of the designed groyne system in the Phase 2 area (Figure 1).

2 MORPHOLOGICAL SYSTEM

2.1 *Environmental conditions*

The wave climate off the coast of Ghana is swell dominated with occasionally a minor wind sea component. Extreme wave conditions along the coast of Ghana (and most of Western Africa) are completely determined by extreme swell waves and not by extreme wind waves, since no long local wind storms occur along the coast of Ghana (IMDC, 2013b). Peak wave directions of the present swell systems near the Ada coast are between 170°N -210°N and induce locally a net West to East longshore sediment transport. The nearshore significant wave height (at -10 m LAT) is between 1.0 m and 2.0 m for 75% of the time with wave periods higher than 10.0 s for 80% of the time (IMDC, 2013b).

The water level variation along the coast of Ghana is dominated by the astronomical tide, since no long local wind storms occur and wind induced (storm) surge is limited. At Ada the average tidal range is about 1.0 m, mean sea level is about 1.15 m LAT.

Tidal and wind-induced currents are small compared to the ocean currents (Guinea current & countercurrent). Offshore Ada (-10 m LAT) currents are mainly oriented to the East and vary between 0.15 m/s and 0.60 m/s (IMDC, 2013b). Nearshore the wave-induced longshore currents are dominant.

2.2 *Sediment dynamics*

Coastal erosion is a major threat to the whole of the West-African coast. Along the gulf of Ghana average rates of coastal retreat are between one and two meters per year (UNESCO, 2012). In 2010, the Ghanaian government decided to protect the coast in Ada, where the average rate of coastal retreat is locally, close to the Volta river mouth, more than 6 m/year.

The net longshore transport on the coast of Ghana is mostly directed from West to East. Estimations in IMDC (2010), based on the growth of the Volta and Keta sand spits, suggest net longshore transport rates near Ada in the order of 0.4 to 0.8 Mm^3/year. A transport gradient of 0.7 Mm^3 over the project area is also needed to explain the local erosion rates.

There is a large uncertainty about the fate of the sediment eroded by longshore transport. The evaluation and quantification of the causes of coastal erosion near Ada is hindered by the lack of reliable and quantified data. But the sediment budget based on longshore transport rates does not account for the fact that erosion is observed almost on the entire coast of Ghana and sediment is likely to be lost out of the system by other sources. The most likely sources are (IMDC, 2013b):

- While the beach profiles mainly consist of coarse sand, occasional silt or clay layers are present. Once eroded, these sediments are too fine to stay in the active profile and are lost seaward.
- The combination of fine sediments and very long swell waves, and consequently a very large closure depth. The closure depth has been estimated in IMDC (2010) with the classical formula of Hallermeier between 6 and 8 m. Including the beach berm height of around 4m yields a profile height of 10 to 12m. Based on the wave model results (IMDC, 2013b), closure depths up to 30 m

seem possible when large swell waves and fine sediments are present. A large closure depth gives accommodation space for large profile variation due to sea level rise.

- Overwash losses over beach berms or in lagoons, resulting in cross-shore losses landward. Also wind transports beach material landwards.
- Beach mining activities, in particular extraction of coarser material (pebbles, beach sand). The extraction of the material can undermine the system sustainability. Beside the net resource extraction, it may also weaken the cross-shore profile which will tend to develop a less steep slope.

The first three processes are related to cross-shore sediment dynamics, the last one is human-induced, but all can be referred to as sediment losses since the sediment cannot contribute to beach accretion.

3 XBEACH MODEL

3.1 *Description*

XBeach is a two-dimensional numerical model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms (Roelvink et al., 2009). It is intended as a tool to assess the natural coastal response during time-varying storm and hurricane conditions, including dune erosion, overwash and breaching (Roelvink et al., 2010). It is a public-domain model that has been developed with funding and support by the US Army Corps of Engineers, by a consortium of UNESCO-IHE, Deltares (Delft Hydraulics), Delft University of Technology and the University of Miami.

The (depth-averaged) XBeach model combines a wave action balance with the nonlinear shallow water equations (NLSW equations) to solve high and low frequency wave motions, respectively. This modeling concept is known as the surf beat approach.

The model consists of formulations for short wave envelope propagation, nonstationary shallow water equations, sediment transport and bed update. Innovations include a newly developed time-dependent wave action balance solver, which solves the wave refraction and allows variation of wave action in x, y, time and over the directional space, and can be used to simulate the propagation and dissipation of wave groups. An added advantage to this setup, compared to the existing surf beat (infragravity wave) model, is that a separate wave model is not needed to predict the mean wave direction, and it allows different wave groups to travel in different directions. Full wave-current interaction in the short wave group propagation is included. A wave dissipation model is implemented for use in the nonstationary wave energy balance (in other words, when the wave energy varies on the wave group timescale).

The Generalised Lagrangean Mean (GLM) approach was implemented to represent the depth-averaged undertow and its effect on bed shear stresses and sediment transport, cf. Reniers et al. (2004). Quasi 3D formulations are included as well as ground water flow through a porous medium.

Both Soulsby – Van Rijn and Van Thiel – Van Rijn sediment transport formulations have been included, which solve the 2DH advection-diffusion equation and produce total transport vectors, which can be used to update the bathymetry. The pickup function following Reniers et al. (2004) was implemented. An avalanching routine was implemented with separate criteria for critical slope at wet or dry points providing a smooth and robust solution for slumping of sand during dune erosion. The velocity used to compute sediment transport includes a correction for onshore transport based on wave form parameters (asymmetry and skewness), effectively stabilizing the long term profile evolution.

Infiltration and exfiltration of water in the swash zone during the uprush and downrush can also be modelled thanks to the inclusion of a groundwater model based on the Darcy law.

The model has been validated with a series of analytical, laboratory and field test cases. The model performs well in different situations including dune erosion, overwash and breaching and these cases are all modelled using a standard set of parameter settings (Roelvink et al., 2009).

3.2 *Model setup*

The 1DH profile model is built with a measured cross-shore profile at the phase 2 area (Figure 1) of Ada beach from a survey in March 2012 (IMDC, 2013b). Figure 2 shows that the selected profile is representative for the Phase 2 area (Figure 1). And a sensitivity analysis indicated that the selected profile corresponds with an average longshore transport rate. The profile extends offshore to a depth of -15 m LAT, the berm has a height of 5.7 m LAT. Based on sand samples taken on the beach, a grain size of D_{50} = 540 μm and D_{90} = 1200 μm have been applied.

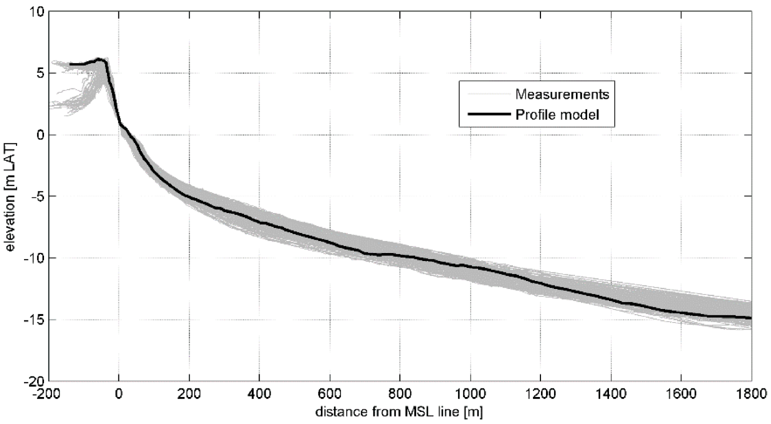

Figure 2. Range of measured beach profiles in the Phase 2 area, and the selected profile applied in the model.

The 1DH profile model grid is built in three parallel rows of the selected profile (Figure 3 Left). A longshore resolution of 100m was necessary to allow a steady longshore current of 30 cm/s to be formed, based upon a head difference in the tide, which represented the ocean current. Wave-induced currents were calculated by the model. The cross-shore resolution varies from 2m nearshore to 30m offshore. As focus was on medium term modelling, the model setup was chosen such as to reduce calculation time, nonetheless aiming to allow accurate modelling. Therefore as an alternative, a “superfast” model was tested in which only one row with one single profile is applied. In such an XBeach model setup, no currents can be imposed and wave refraction is calculated based on Snellius’ law.

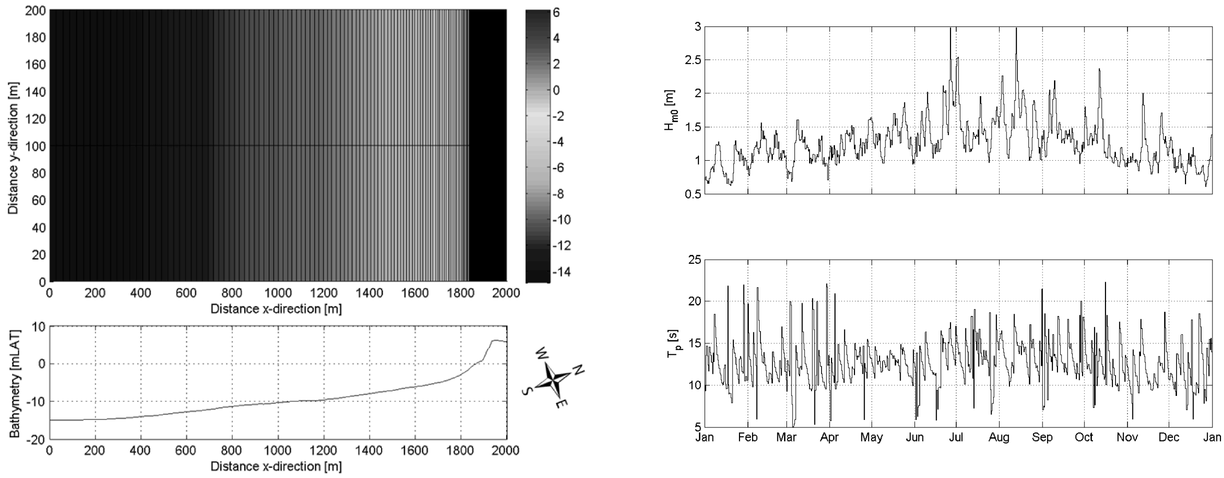

Figure 3. Left:Top: 1DH XBeach model, waves originating from a range of 170°N – 210°N. Left: Cross shore profile of the bed. Right: Offshore imposed wave conditions.

Instead of calculating an entire time series of offshore wave boundary conditions, a common approach is to discretize the wave time series in a set of characteristic wave conditions. But this introduces the limitation that the successive series of wave conditions are artificially imposed and the impact of successive erosive and accretive waves is not modelled. Pender and Karunarathna (2013) have recently applied in their medium term modelling a statistical approach to combine erosive and accretive wave conditions in random time series. In this model is chosen to impose an entire time series of measured wave conditions for one year.

The offshore boundary conditions includes a 12 hourly time series of wave conditions for the year 2007 from a SWAN wave model (IMDC 2013a), including normal to lower extreme waves (with two conditions similar to yearly storm) (Figure 3, right). An average tidal fluctuation is imposed over the entire year.

To speed up calculations, a morphological acceleration factor (morfac) has been applied (Roelvink et al., 2010). A morfac of 30 is applied, using the XBeach option (morfacopt=1), which implies that for every prescribed hour, the model actually calculates 2 minutes during which the bottom changes are multiplied by a factor 30. This means that the water level changes are accelerated. Based on sensitivity testing, the morfac has been limited to 30, larger values eroded the whole upper beach.

3.3 *Model settings*

The standard set of parameter settings in XBeach are primarily intended for environments similar to the Dutch coast. In areas where the wave climate and beach properties (grain size, slopes, etc.) significantly deviate from typical Dutch values, a calibration of some of these parameters is necessary, as is the case in this study. The wave climate along the Ghanaian coast is swell dominated (IMDC, 2013b) and therefore differs significantly from the wind sea dominated Dutch coasts. Also beach slopes are significantly steeper in Ghana (~1:10) compared to the Dutch coast (~1:60).

Moreover, since the XBeach model was initially designed for relatively short simulations (hours, days) during storm conditions, simulations over longer periods (weeks, months) may not (yet) be very accurate. Indeed, during calm and moderate wave conditions the beach erosion (retreat) is overestimated by XBeach due to the offshore sediment transport associated with long waves (van Thiel de Vries, 2009). Van Thiel de Vries (2009) hypothesizes that inner surf and swash zone sediment transports associated with long waves are not properly simulated since the model misses some relevant physics in this case (e.g. long wave breaking, interactions with short waves in the swash zone). It was shown by A. Van Rooijen (2011) that modelling the short waves with the NLSW equations together with the long waves and using the combined intra-wave Nielsen and Bagnold type transport model, onshore transport during calm or moderate wave conditions is better represented. However, doing this greatly increases the calculation time and therefore decreases the usability of the model in 2DH over longer periods. Although not a full alternative, onshore sediment transport can be promoted in some areas of the beach by increasing the onshore transport associated with non-linear short waves without influencing the calculation time too much. This is controlled by the parameters *facAs* and *facSk*, which represent calibration factors for the time averaged flows due to wave asymmetry and skewness. These flows are a result of non-linear wave behavior in the shoaling, wave breaking, surf and swash zones. The factors applied to skewness (*facSk*) and asymmetry (*facAs*) determine the magnitude and direction of net sediment transport. Varying these factors therefore determines the predominant sediment transport direction (Pender and Karunarathna, 2013).

The parameter *facSk* influences the profile shape most in the shoaling and breaker zone: increasing *facSk* increases the wave skewness which leads to mostly offshore sediment fluxes. On the other hand, *facAs* shapes the cross-shore profile more nearshore in the surf and swash zone; increasing *facAs* increases the wave asymmetry which leads to an increase of the onshore transport.

Another parameter which has influence on the beach profile is *wetslp* or the critical slope for which the avalanching algorithm is triggered in the model when the beach is wet (saturated). A lower (higher) value will cause a gentler (steeper) equilibrium slope of the bed in the swash zone and along the wet intertidal beach.

Table 2. Parameter settings of reported simulations with the XBeach model.

Parameter	Default	Calibrated	Calibrated (Superfast)	GW01	GW02
facSk [-]	0.10	0.10	0.10	0.10	0.10
facAs [-]	0.10	0.30	0.30	0.30	0.30
break [-]	Roelvink2	Roelvink1	Roelvink1	Roelvink1	Roelvink1
wetslp [-]	0.30	0.30	0.30	0.30	0.30
Groundwater [-]	no	no	no	yes	yes
kx [m/s]	-	-	-	0.01	0.005
Superfast [-]	no	no	yes	yes	yes

Splinter and Palmsten (2012) found that the wave dissipation model is also important for the modelling of erosion in XBeach. Two main wave dissipation models at the scale of wave groups exist within XBeach, both formulated by Roelvink (1993). The wave dissipation is by default proportional to H^3/h rather than H^2/h in the alternative wave breaking model. The default is therefore a more intense dissipative wave breaking model in the nearshore zone.

Finally, infiltration and exfiltration during the wave runup and rundown on the beach can also have an important effect on the morphodynamics in the swash zone, more so on coarse sand, as is the case in Ada, and (especially) on gravel beaches. The infiltration during swash uprush causes weaker backwash flows. It also has an influence on the overwash/runup level. The hydraulic conductivity *K* determines the permeability of the beach and is therefore dependent on the grain size D_{50}. A value of 0.0031 m/s has been used by Pender and Karunarathna (2013), for a D_{50} range of 250 µm – 500 µm.

Different parameter settings and model setups have been tested. Final model settings are presented below (Table 2).

4 RESULTS

4.1 *Profile evolution over the medium term*

On a time scale of a year or more, the cross-shore profile of a beach is generally assumed to be in average in equilibrium (Dean 1991), but constantly being reworked by the combination of a given water level and wave conditions. As XBeach tends to overestimate erosion and underestimate accretion, especially for mild wave conditions (Van Rooijen, 2011), the morphological calculations are not intended to reproduce exact erosive and accretive conditions during the one year cycle but rather reproduce the overall beach shape and slopes evolution. Results are compared with the measured equilibrium beach.

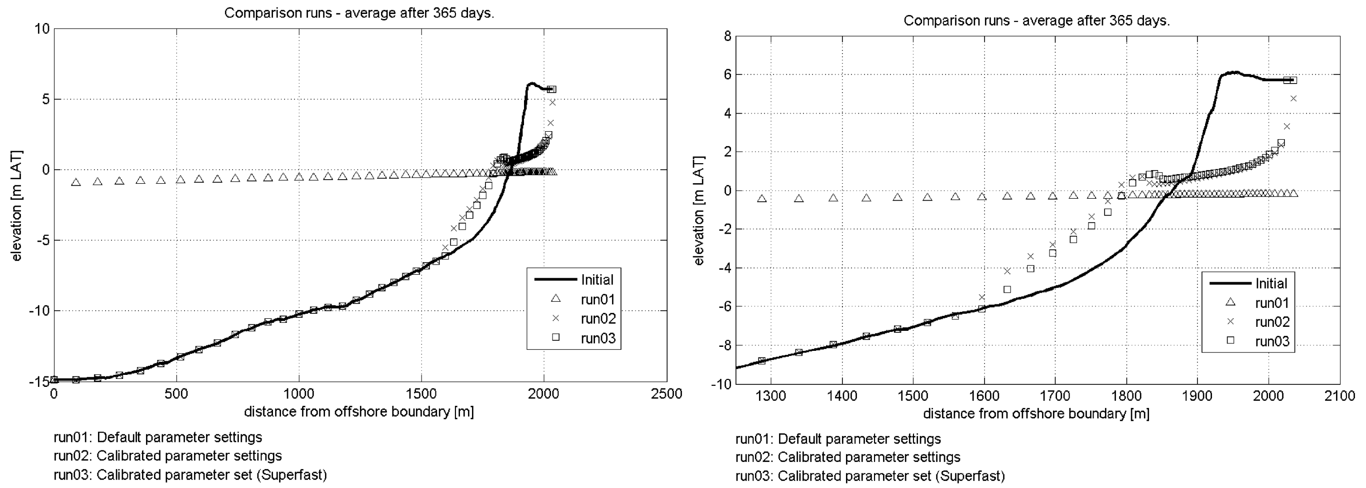

Figure 4: Measured profile and XBeach model results for default parameter settings and calibrated settings in normal 1DH and superfast mode. Left: entire cross-shore profile, Right: zoom in the morphological active zone.

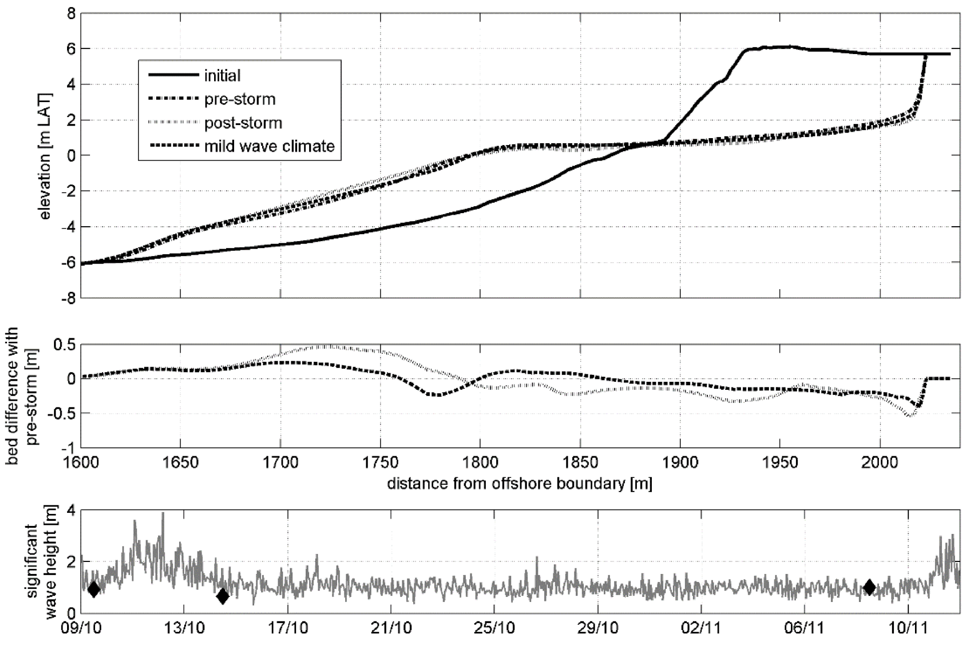

Figure 5: Cross shore profiles before and after a storm event and after milder wave conditions (Top). Comparison of the bed level change of the post-storm profile and profile after the mild wave conditions with the pre-storm profile (Middle), and the offshore wave conditions (Bottom).

Beach profile evolutions after one year based on different parameter settings for wave asymmetry and wet slope are presented in Figure 4. This figure shows that the default parameter settings in XBeach lead to an overestimation of erosion to the point where it is unrecognizable from the initial profile. Changing the key parameters leads to a better simulation of the profile variability with more realistic foreshore slopes and berm developments. The use of the Superfast model approach seems justified based on the resulting similar profile to the normal setup. In the model, the dune is eroded to create a large intertidal area with mild slope which dissipates the incoming wave energy and results in a more stable profile. The eroded material is deposited in the lower part of the profile (below 0 m LAT) and create a more offshore located foreshore berm, with slopes similar to the equilibrium profile. The resulting profile is varying around the equilibrium profile, but results indicate as stated above that the XBeach model is overestimating the erosion and is not capable in rebuilding the upper beach. The berm has eroded over 100m. Below -7m LAT no morphological changes are observed, which corresponds to the closure depth according to the XBeach results.

The shorter term response of the profile is presented in Figure 5. The typical profile, with the large intertidal area has been developed and the variation over the profile during a time series including erosive and accretive conditions is presented. After a storm event, the upper part of the beach profile has eroded and deposited the sediment at the lower part (grey line in Middle Figure 5). After more than 3 weeks of mild wave conditions, part of the foreshore material has been transported away and accretion has occurred in the upper part, yet compared to the pre-storm profile XBeach calculates a net erosion.

4.2 *Impact of modelling groundwater*

The calibrated model has been further applied by implementing the groundwater module. Values for the hydraulic conductivity of 0.005 m/s and 0.01 m/s have been tested. The model results are presented in Figure 5. Results indicate that the profile is more stable when the groundwater module is activated (run03 and run04). Erosion of the upper beach is reduced and a smaller berm is formed. Increasing the hydraulic conductivity leads to a more stable profile but the foreshore slope is less steep.

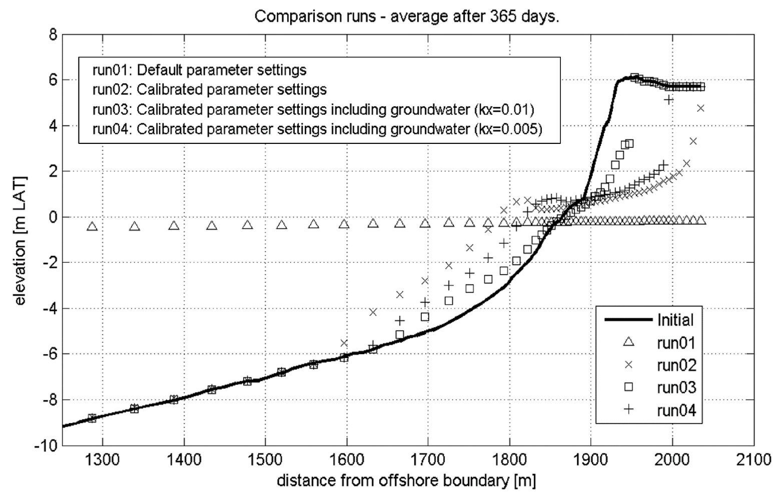

Figure 6: Measured profile and XBeach model results for default parameter settings, calibrated settings in superfast mode, and the model results including groundwater modelling with different conductivity parameters.

5 DISCUSSION

The calibrated model settings show promising results in simulating cross-shore profile behaviour over medium term. A new equilibrium profile is generated which represents the measured beach slopes. To this end wave asymmetry had to be increased (*facAs*) and a larger wet beach slope (0.3) compared to the actual beach slope (~0.2) had to be chosen to compensate for the erosive trend in XBeach. Wave skewness (*facSk*) equals the default value, increasing it would promote offshore directed transport. Also the less intensely dissipative wave breaking model of Roelvink (1993) appeared to give better results.

All calibrated parameter settings tended to reduce erosion in XBeach compared to the default settings. But only a small accretion is calculated and large erosion is present in the upper part of the profile. This might be related to not including the impact of build up by wind in the upper part of the beach profile, although this is not estimated as a major transport process in Ghana. Or might be related to the underestimation of runup. Although the general profile behaviour can be captured by calibrating the parameter settings, the entire evolution of beach profiles does not seem to be modelled.

In the XBeach model, a more stable profile has been observed when applying the groundwater module. A better profile was obtained with a K = 0.01 m/s, compared to a K = 0.005 m/s, which is significantly larger than the findings of Pender and Palmsten (2013) for similar sediment types. The benefit of the groundwater module on the profile stability is related to the increased infiltration and reduced backwash, yet it is unclear whether this is a justified physical process or introduces artificial damping.

Further improvements in medium term modelling could be found in applying the groundwater module, the Nielsen and Bagnold type transport model to stimulate the onshore transport, include sediment variation in the profile and include the wind impact on the upper part of the profile.

6 CONCLUSION

In coastal engineering, the longer term morphological evolution is an important aspect in coastal management, but modelling this is still a challenge. XBeach has been applied to evaluate medium term (one year) profile evolution near Ada, Ghana. Using default settings is a valid option for conditions similar to those for which the software is validated. In different environmental conditions the behavior might deviate significantly.

The coastal system in Ghana is characterized by large swell wave conditions and estimated to have important cross-shore losses. Parameters known to impact the cross-shore transport that are examined are wave asymmetry/skewness, dune avalanching triggers, the applied wave breaking module and groundwater modelling. Using the superfast model and applying a large morfac allow for feasible medium term calculation times.

It is demonstrated that by calibrating relevant parameters a reasonable profile evolution can be captured. Improvements are observed by using the groundwater module. Yet the profile model is not accurate enough to study cross shore profile losses accurately, but a first step in this process has been made by demonstrating the applicability of modelling medium term. The final calibrated parameter settings have been used by other studies in the project.

The results presented in this paper support research in coastal sustainability by presenting the use of a process based morphological model on a longer time scale and the governing parameters to apply it under different conditions.

NOTATION

D_{50}	Median grain size (diameter) [µm]
D_{90}	90-percentile grain size (diameter) [µm]
H_{m0}	Spectral significant wave height [m]
K	Hydraulic conductivity [m/s]
LAT	Lowest Astronomical Tide [m]
T_p	Peak wave period [s]

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