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2DH Morphodynamic Time-Dependent Hindcast Modelling of a Groyne System in Ghana

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ABSTRACT: A groyne system was constructed west of the Volta river mouth at Ada (Ghana) to mitigate the local beach retreat of up to 6 m/year. During and after these coastal protection works, surprisingly severe erosion was observed downstream from the first groyne. An in-depth analysis was done to identify the causes by performing a hindcast over one year with the 2D depth-averaged time-dependent morphological model XBeach. The model appears to qualitatively reproduce the same morphological evolutions of the groyne system as measured in situ. The main causes of the severe erosion are a 2D bathymetrical feature (longshore sediment transport gradient) and differences in beach crest height east and west of the first groyne (difference in overwash occurrence). A parallel hindcast, without introducing groynes into the model, was also performed. This shows that the groynes, while contributing to the severe erosion, are not the main cause of it. The beach west of the first groyne has clearly benefitted from the construction of the groynes, since the beach erosion to the west of the groynes was less with groynes than without.

Keywords: XBeach, Groyne, Numerical modelling, Hindcast, Morphodynamics, Swell waves

1 INTRODUCTION

1.1 *Project site*

Coastal erosion is a major threat to the whole of the West-African coast. Along the northwest coast of Africa 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. In total, a stretch of about 16 km is to be defended with a combination of a groyne system and a beach nourishment. The project is split into two phases (cf. Figure 1): first the groynes in the most critical stretch near the Volta river mouth are built (phase 1, finished in the summer of 2013), then the remaining groynes and the beach nourishment are executed in the second phase (phase 2, currently ongoing).

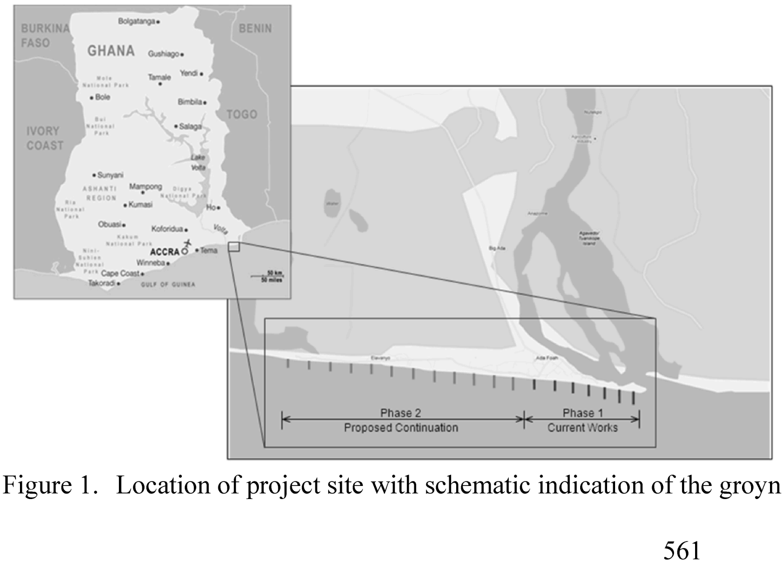

Figure 1. Location of project site with schematic indication of the groyne system in construction.

1.2 *Scope and purpose of the morphological modelling*

During and after the construction works of the groynes of phase 1, severe erosion was observed east from the very first and most eastern groyne (cf. Figure 2, groyne A): approximately 150 m of beach retreat was observed over almost one year. Erosion was expected because of the net wave-induced longshore current directed to the east along the Ada coast. However, the observed erosion east of groyne A occurred faster than predicted during the design of phase 1 (IMDC, 2011). This warranted further investigation into what the main causes of this local severe erosion are. Because of the complexity and variety of the physical processes involved, a 2DH morphological time-dependant numerical model XBeach is used for this purpose.

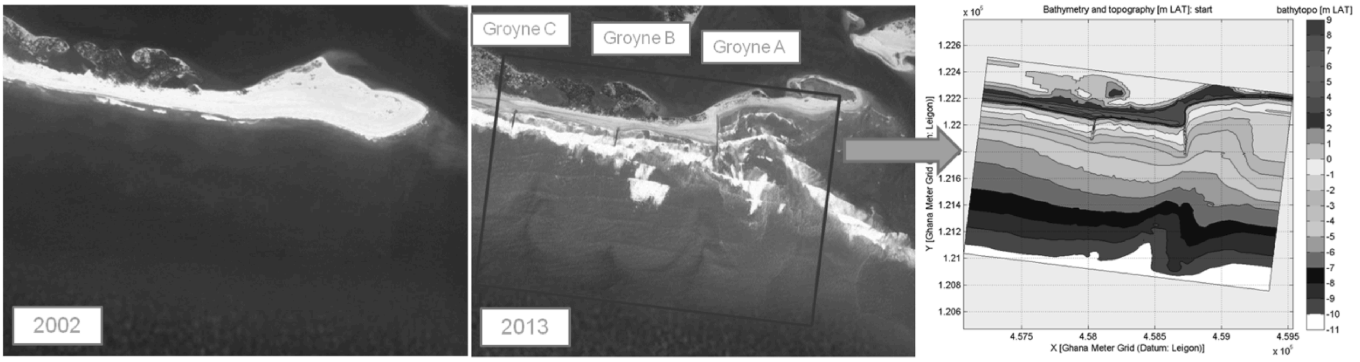

Figure 2. Left: sand spit west of the Volta river mouth (©Google Earth, 2002). Middle: hindcast model area (red rectangle) on background of ©Google Earth (2013). Right: interpolated measured bathymetry of March 2013.

The investigation is done by performing a hindcast over a period of one year between two topographical and bathymetric surveys (in March 2012 and March 2013). The hindcast is done to:

1. Try to reproduce the main morphological changes observed around the first two groynes of phase 1 (i.e. groynes A & B, cf. Figure 2);
2. Identify and understand better the main governing processes which drive the (observed) local morphological changes;
3. Do a parallel hindcast simulation where no groynes are introduced. This allows to compare the hindcast model with the situation if no groynes were built and to demonstrate the benefit of the groynes regarding the stability of the coastline and assess their contribution to the severe erosion east of groyne A.

2 XBEACH MODEL

2.1 *Description*

XBeach is a two-dimensional depth-averaged (i.e. 2DH) time-dependent numerical model for nearshore processes such as wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms. It is primarily 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). XBeach 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 XBeach model was originally designed to simulate storm impact on dunes and barrier islands. It combines a wave action balance with the nonlinear shallow water equations (NLSW equations) to solve high and low frequency wave motions, respectively. This modelling concept is known as the surf beat approach. For a detailed description of the XBeach model and its equations, reference is made to the works of Roelvink et al. (2009) and Roelvink et al. (2010).

The model also includes an avalanching routine 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 model has been validated with a series of analytical, laboratory and field test cases. It 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).

2.2 *Model settings and calibration*

The default parameter settings in XBeach are primarily intended for the North Sea wave conditions off the Dutch coast (Roelvink et al., 2009). The wave climate off Ghana differs significantly from the wave climate in the North Sea, since the wave climate off the West-African coast is swell dominated (IMDC, 2013b).

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 be very accurate. Indeed, during calm and moderate wave conditions the beach erosion 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 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 behaviour in the shoaling, wave breaking, surf and swash zones. The factors applied to skewness (*facSk*) and asymmetry (*facAs*) determines the magnitude and direction of the cross-shore 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 (Roelvink, 2013): 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 dune 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.

Splinter and Palmsten (2012) found that the wave dissipation model is also very 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 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.

To make the XBeach model applicable to the specific conditions of the area of this study, calibration of these parameters is necessary. The calibration was performed with a 1DH cross-shore profile model of a beach cross-section in the project area. The calibration was mainly based on the wave asymmetry/skewness parameters (i.e. *facAs* and *facSk*), the wave breaking module (i.e. parameter *break*) and dune avalanching trigger parameter *wetslp* until a more or less stable beach profile was obtained under the wave action over a year (Verheyen et al., 2014). The parameters were calibrated such that the beach retains as much as possible the original (measured) shape of the cross-shore profile. An overview of the calibrated parameters is given in Table 1.

Table 1. Main calibrated parameters of the XBeach model.

Parameter	Default	Calibrated
facSk [-]	0.10	0.10
facAs [-]	0.10	0.30
break [-]	Roelvink2	Roelvink1
wetslp [-]	0.30	0.30

2.3 *Model domain and bathymetry*

The hindcast model domain is centred around the location of groynes A and B indicated in Figure 2. Both seabed and land topography measurements are needed for the initial bathymetry of the hindcast model.

Measurements are also needed for the end bathymetry to be able to validate the hindcast model results. These topographical and bathymetrical surveys are available for March 2012 (cf. Figure 3) and March 2013 (cf. Figure 2).

The initial bathymetry of the model was interpolated from the March 212 survey to the model grid. That was before the start of the construction of the groynes and the initial bathymetry therefore does not yet include them. During the course of the hindcast modelling, the simulation was halted to introduce (parts of) the groyne constructions. These introductions were done at the same point in time as they were finished in reality. They were introduced as a non-erodible hard layer. Because the groynes were built gradually, it was decided to include the groynes after 50% and 100% of their length was finished.

To implement the groynes in the bathymetry, the as-built groyne survey datasets after construction were used. However, the top rock armour layer height of the groynes was decreased by 30% to take the permeability of 30% into account. To take wave dissipation and flow restriction across the groynes into account, the friction on the groynes was increased to a Chézy coefficient of 25 $m^{0.5}/s$.

The grid of the model has variable cell widths and lengths to optimise the calculation time (cross-shore resolution = ~25 m offshore to 5 m nearshore; longshore resolution = 60 m at the side boundaries to 5 m around the groynes and 20 m in between).

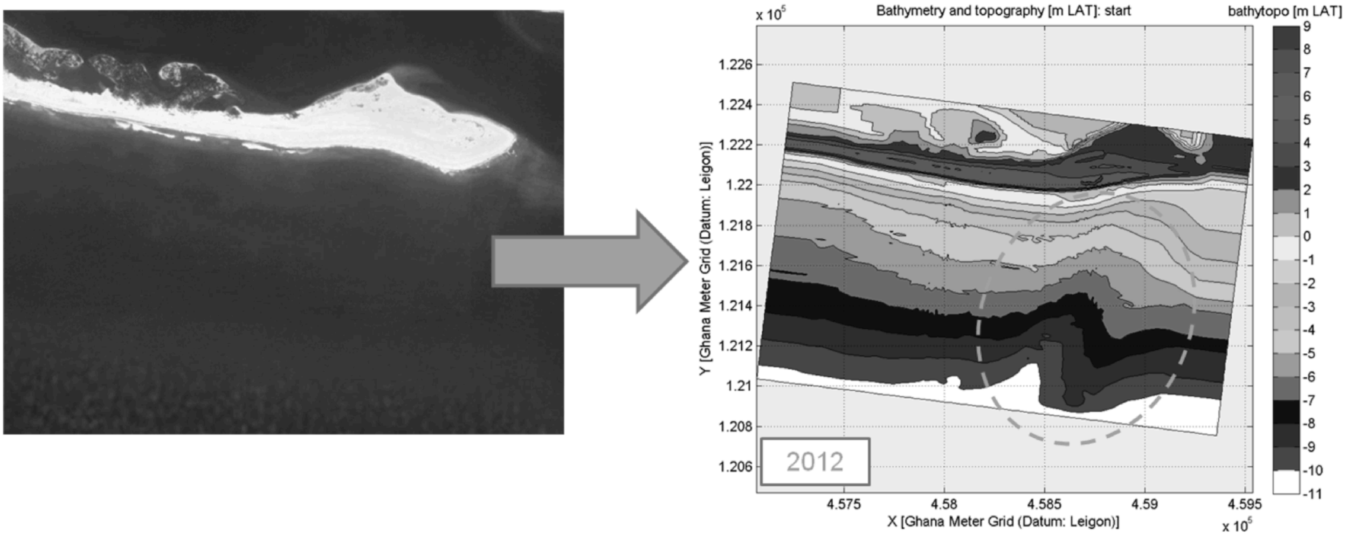

Figure 3. Left: Volta river mouth (©Google Earth, 2002), rectangle indicates model domain. Right: measured bathymetry and topography of March 2012 interpolated to the model grid, with indication of the offshore trough feature (gray dash).

Based on sand samples taken in the area of the model domain, a grain size of D_{50} = 520 µm and D_{90} = 1000 µm was defined in the model.

3 ENVIRONMENTAL CONDITIONS

3.1 *Water levels, waves and currents*

The tidal range along the coast of Ghana is limited. At Ada the average tidal range is about 1.0 m (cf. Table 2). There is also almost no wind induced (storm) surge, which makes the still water level almost completely determined by the astronomical tide.

Table 2. Overview of the typical water levels at Ada, Ghana.

Type	Water Level [m LAT*]
Mean High Water	1.66
Mean Sea Level	1.15
Mean Low Water	0.66

* Reference level: Lowest Astronomical Tide

The wave climate off the coast of Ghana is swell dominated with occasionally a minor wind sea component. No long local wind storms occur along the coast of Ghana. Severe wave conditions along the coast of Ghana (and most of Western Africa) are therefore completely determined by severe swell waves and not by severe wind waves (IMDC, 2013b).

Two to three swell systems are almost continuously present each with their own peak wave direction between 170°N – 210°N. Due to the orientation of the Ada coast relative to the dominant wave directions, a net wave-induced longshore current is directed to the east along the Ada coast. The nearshore significant wave height (at -10 m LAT, along the offshore boundary of the XBeach model) 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 longshore ocean-, wind- and tidal currents are relatively weak (IMDC, 2013a) compared to the wave-induced longshore currents. They are of minor importance to the longshore sediment transport, which is mostly wave-driven as was shown by a sensitivity analysis of Verheyen et al. (2014).

3.2 *Model boundary conditions*

The water level is varied in time along the offshore boundary of the model according to the predicted astronomical tide. So no longshore currents (tidal or otherwise) are imposed at the boundaries. Longshore currents are therefore only generated in the model by oblique incidence of the waves.

Waves along the XBeach model boundary are forced by the hindcasted wave modelling output (IMDC, 2013b) in a point along the offshore XBeach model boundary. More specifically, 2D wave spectra from the SWAN wave model are imposed at the boundary. This is important because the more detailed directional information of the 2D spectra delivers a much more accurate wave climate compared to a standard JONSWAP spectrum centred around one main wave direction. Accurate wave directions are essential for the wave induced longshore transport.

Figure 4 shows part of the time series of hydrodynamic conditions imposed at the offshore model boundary.

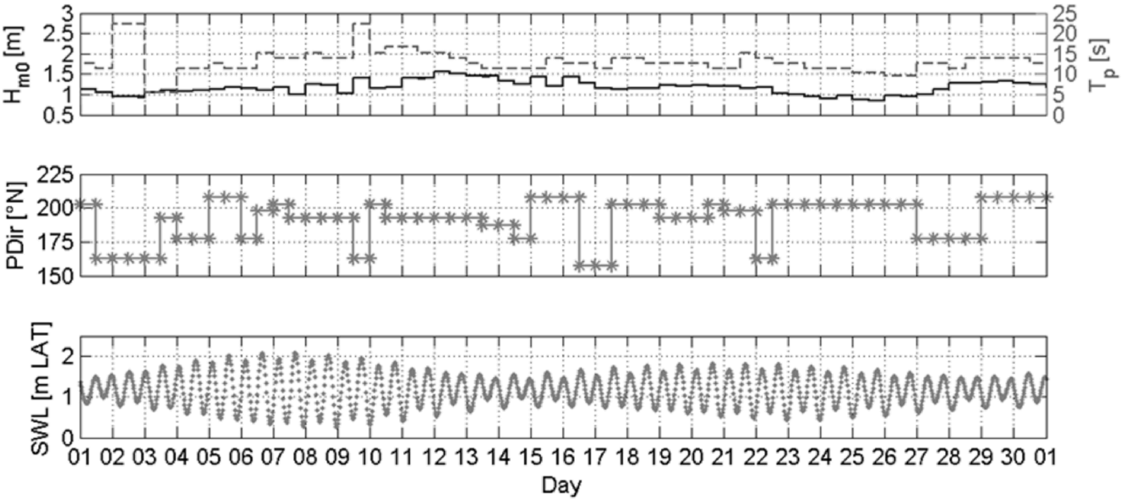

Figure 4. Example of boundary conditions for the XBeach model. Top: wave conditions (H_{m0} (bold line) and T_p (dashed line)). Middle: peak wave direction. Bottom: astronomical tide (still water level).

4 RESULTS

4.1 *Comparison model end result - measurement*

With the model calibrated and boundary conditions prepared, the morphological evolution around groynes A and B was hindcasted with the 2DH XBeach model during the period of almost one year (i.e. 01/04/2012 – 01/03/2013) starting from a measured bathymetry and topography in March 2012 (cf. Figure 3). The simulation was halted to include each construction phase relevant to the morphological evolution. The end result of the hindcast model is shown together with the measured bathymetry in Figure 5.

Comparing these figures, the following observations can be made:

- The severe erosion east of groyne A has been reproduced by the model. However, it is somewhat underestimated, especially the beach retreat just east of groyne A.
- The erosion and deposition patterns west of groyne A correspond quite well, at least qualitatively. The erosion and beach retreat is overestimated however.
- The realignment of the beach between the groynes in the hindcast model is comparable with the measured bathymetry.
- The hindcast model overestimates accretion of the foreshore west of groyne B.

The differences are primarily a result of model limitations (i.e. model uncertainties, underestimation of overwash and onshore transport during mild wave conditions) and boundary effects (i.e. Volta river mouth not included, higher longshore resolution near the boundaries). So the model is capable of reproducing the important morphological changes in mostly a qualitative way and less quantitatively, but very satisfactory nonetheless given these limitations.

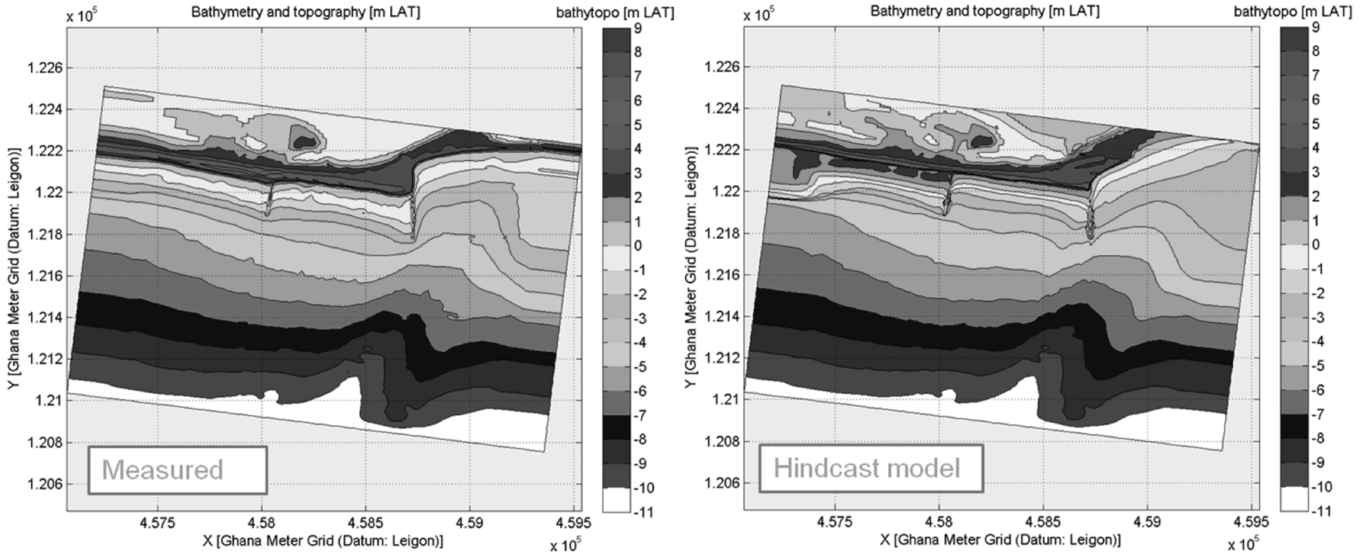

Figure 5. Comparison of measured bathymetry and hindcast model result. Left: measured bathymetry. Right: end result of hindcast model.

4.2 *Main physical processes*

Analysis of the significant wave height, longshore currents, sediment transport and water levels shows that the main causes of the severe beach erosion east of the first groyne are:

- A 2D bathymetric feature (i.e. a trough or bottom depression, cf. right in Figure 3): it greatly influences the swell waves (wave refraction, divergence/convergence, cf. Figure 6, left) and causes a longshore current gradient (cf. Figure 6, right) accompanied by a sediment transport gradient. This gradient leads to a local erosion hotspot.
- Topographical features (i.e. differences in beach crest height west and east of the first groyne): this allows overwash to occur east more than west, causing the beach to retreat more east.

The longshore gradient in sediment transport and overwash are two phenomena which were already present before groyne construction because it is dependent on the already present bathymetry and topography. The construction of the groynes also contributed to the eastern erosion, but probably less so (which will be further investigated in §4.3). The contribution of the groynes is that they partially blocked the longshore sediment transport. This decreased the supply of incoming longshore sediment in the east and as such also contributed to the erosion just east from groyne A.

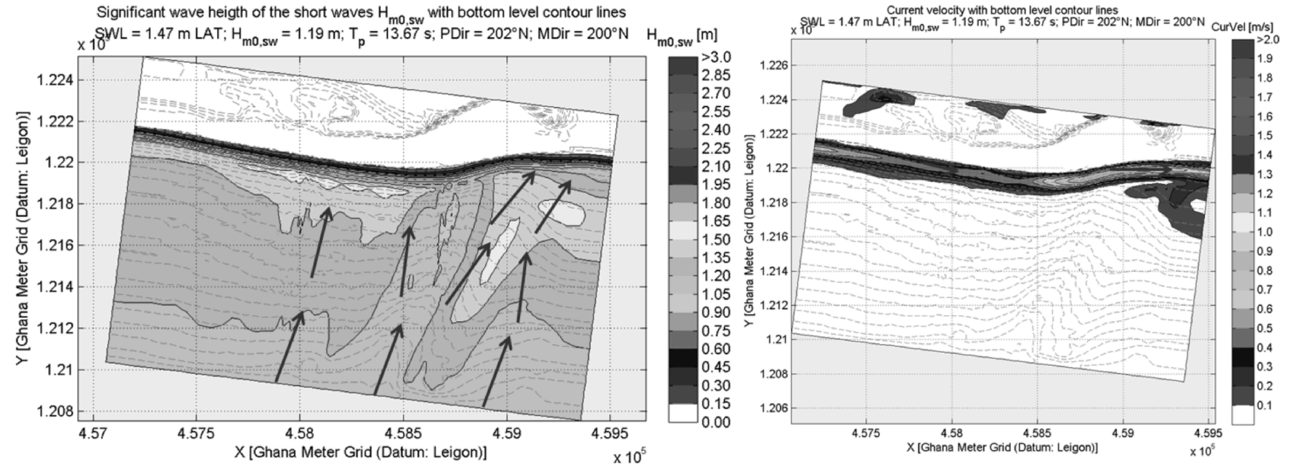

Figure 6. Left: significant wave height H_{m0} [m] of the short waves for typical wave conditions on background of bottom contour lines (gray dashes, 0.5 m increment). Schematic indication of the wave direction (black arrows). Right: wave-induced longshore current velocities. Schematic indication of the longshore direction and gradient (black arrows).

4.3 *Comparison hindcast model with and without groynes*

Most of the main physical processes (e.g. the longshore sediment transport gradient, overwash) responsible for the severe erosion east of groyne A were already present before the construction of the groynes began. It is therefore plausible that even when no groynes would have been built, severe erosion in that area would have occurred. This hypothesis is further investigated here by comparing the two hindcast models with and without implementation of the groynes.

In Figure 7 the end bathymetries of both hindcast models are compared. Based on these figures several observations can be made:

- Severe erosion east from the groyne A location would also have occurred if no groynes were built, although it would have been less severe (about 50 m less beach retreat). The construction of groyne A (and B) has therefore contributed to the erosion east of groyne A, but it is not the sole cause.
- After the construction of groyne A was finished, sedimentation or beach protection did occur in the area west of groyne A, which is of course not present in the model without groynes (up to 15 m difference).
- The same can be observed after construction of groyne B in the area west of it. However, the area just east from groyne B has benefitted less from the groynes due to the coastline reorientation between groynes A and B.

From these observations it is clear that the groynes have caused sediment from the longshore transport to be trapped in between them. The beaches west from groyne A are therefore better protected than when no groynes would have been built. In the east from groyne A however, the groynes have exacerbated the erosion already present in this area, but it is however not the main cause.

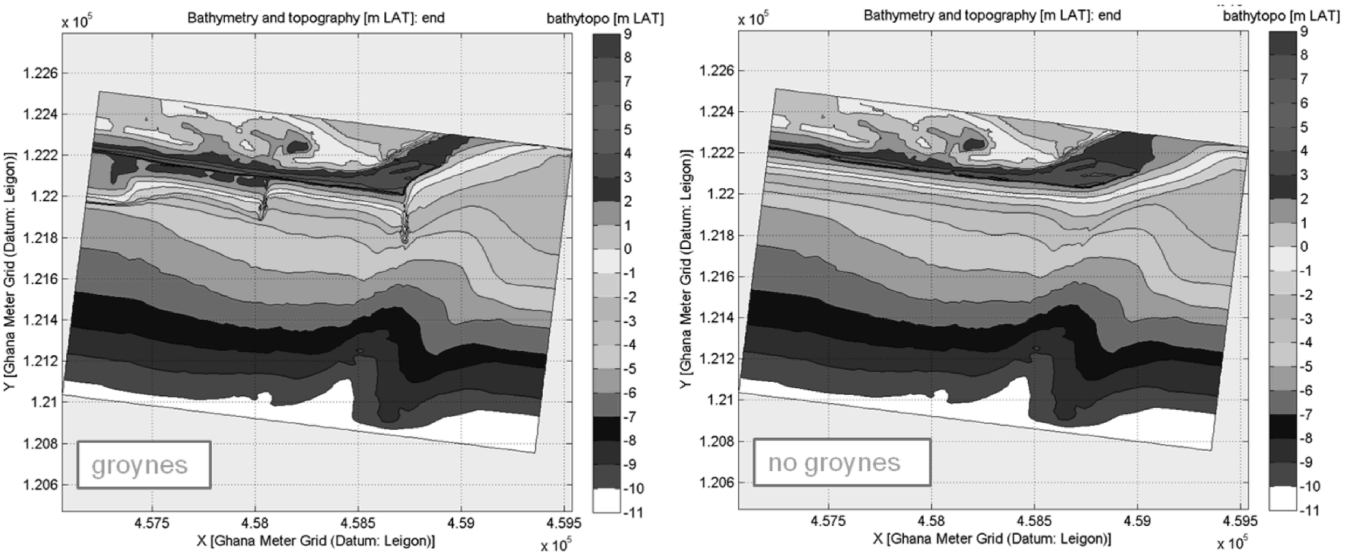

Figure 7. Comparison of the end bathymetries of the hindcast models with and without groynes. Left: with groynes. Right: no groynes.

5 CONCLUSIONS

During and after the coastal protection works at Ada (Ghana), severe erosion was observed downstream from the first groyne. Because this erosion was much larger than initially predicted, a more in-depth analysis was done by performing a hindcast with the 2DH time-dependent morphological model XBeach.

The start bathymetry of the hindcast model was set up based on measurements in March 2012. After a detailed calibration of the model, the morphological evolution around groynes A and B was hindcasted during the period of one year. During this period the consecutive construction phases of the groynes were taken into account. The model was driven by a hindcasted wave climate and the water levels of the predicted tide. Validation of the hindcast model end result with bathymetric and topographic measurements has shown that the model is capable of reproducing important morphological changes in mostly a qualitative way, but less quantitatively. The model seems to somewhat overestimate erosion between the groynes, primarily as a result of an underestimation of onshore sediment transport during mild wave conditions.

The most important physical processes which caused the main morphological changes observed during this period in the area around groynes A and B were identified by analysis of the numerical model results. Analysis of the significant wave height, longshore currents, sediment transport and water levels shows that important causes of the severe beach erosion east of the first groyne were found to be:

- A 2D bathymetric feature (i.e. a trough or bottom depression): it greatly influences the swell waves (wave refraction, divergence/convergence) and causes a longshore sediment transport gradient leading to a local erosion hotspot.
- 2D topographical features (i.e. differences in beach crest height west and east from the first groyne): this allows overwash to occur east more than west, causing the beach to retreat more in the east.

Finally, a big advantage of a numerical model was exploited by modelling in parallel a second hindcast model wherein no groynes were introduced. This showed that the beach west of groyne A has clearly benefitted from the construction of the groynes, since the beach erosion was less with groynes than without for this area. It also showed that while the groynes have contributed to the severe erosion east of groyne A, they are not the main cause of it.

NOTATION

D_{50}	Median grain size (diameter) [μm]
D_{90}	90-percentile grain size (diameter) [μm]
h	Water depth [m]
H	Wave height [m]
H_{m0}	Spectral significant wave height [m]
LAT	Lowest Astronomical Tide [m]
T_p	Peak wave period [s]

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