# 10

# Modeling the Morphological Impacts of Coastal Storms

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## 10.1 Introduction

This chapter discusses the modeling of morphodynamical storm impacts on coasts. We will give an overview of classes of models, the physical processes that each class resolves, and the model class applicability on the different coastal environments discussed in the previous chapters. We discuss recent advances in coastal storm impact modeling, with examples of applications, and an outlook of modeling challenges and opportunities ahead.

Any model is a schematized representation of reality. The real world is usually too complex to represent with a model, and the challenge is thus to capture reality at a level such that a model is still useful (i.e. still resolves the essential processes) but is not too complex and cumbersome to use. This is true in general but also for coasts, which have many time and spatial scales and details. For every coastal environment we need to ask the questions: what are the relevant and dominant processes that control storm impacts? And: do we need to simulate these processes directly, or can we represent them in some way, or even can we neglect them altogether? Thus there is a triage of 'direct simulation', 'representation' or 'elimination'.

The approach taken in this chapter is somewhat biased towards sandy coasts. This is for good reason, as processes on these types of coasts have been studied most intensively in the past. The reason for this is that sandy coasts at the mid-latitudes protect high-investment coastal zones (Europe, USA mid-Atlantic) and have therefore received the most attention. However, as has been shown in the previous chapters, more and more attention is being paid to other types of coasts as economic development is increasing, climate-change effects are being felt and the eco-system services that these coastal types provide are being appreciated more. These coastal types are discussed in this chapter as well.

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With respect to coastal impact modeling, and specifically impacts on sandy coasts, two general types of model classes can be identified: empirical models and process-based models. We will find that there are 'pure' empirical models, but there are no practical 'pure' process-based models. To date, every process-based model includes some representation of processes by empirical closure. We note that besides these two processes, Roelvink and Brøker (1993) also name descriptive or conceptual models (such as Sallenger, 2000), but as this type does not provide quantitative response information, it is not included here.

### 10.1.1 Empirical models

Empirical models typically use observations to relate the response of a coast to the forcing. Purely empirical models are thus 'black box' models that do not consider or incorporate the underlying physical processes. Examples of this type of model are Dean (1977), Van de Graaff (1977), Vellinga (1986) and Van Gent *et al*. (2008), which relate the post-storm profile shape to stationary wave properties and sediment properties, independent of the pre-storm state.

This type of model relies on observations taken in the field or the laboratory. Field observations are typically sparse and may not include all forcing parameters, which necessitates a simplification of the response model and thus limits the predictive value. Laboratory data is usually more controlled, that is, more quantitative data of more forcing and response parameters are taken under known conditions. However, laboratory experiments are performed with explicit (and implicit) assumptions and limitations. Typically, laboratory data is taken in a flume, which assumes longshore uniformity in the wave and water level forcing, the initial state of the coast and its response. This means that the coastal response process is considered to be a 1D process. Moreover, empirical models are only valid for the range of data obtained; hence empirical models are strictly limited to the coastal profile, sediment characteristics and the range of forcing parameters (wave heights and water levels). Furthermore, the sediment transport does not scale according to the hydrodynamical Froude Scale, which results in so-called vertically-distorted scale models. For a discussion on this aspect we refer to Vellinga (1986) and Van Thiel de Vries (2009) The benefit of these models is that they are computationally fast, but the drawback is that their applicability strictly is limited.

Another type of empirical model is the convolution model that describes the time evolution of the profile (Kriebel, 1982; Kriebel & Dean, 1993; Madsen & Plant, 2001). This model is based on simple analytical solutions to predict the longshore uniform, time-dependent beach and dune profile response to storm scale variations in water level and breaking wave height. The underlying assumption is that the coastal profile will exponentially tend to an equilibrium shape for a given wave condition and characteristic erosion time scale. Yates *et al*. (2009) presented a model to predict the shoreline position on the US Pacific coasts, where the predicted shoreline change is a function of the previous state (shoreline location) and the equilibrium energy state. They did not include the entire profile, however. Yates *et al*. (2011) extended the model to storm conditions, and showed that it was applicable to other sites as well. Davidson *et al*. (2013) concurrently developed a similar model for the Australian East Coast. These models are also discussed in Chapter 10.

### 10.1.2 Process-based models

Process-based models rely on the principle that the coastal response is governed by known physical processes of wave dynamics and sediment transport dynamics. This type of model requires that the coastal system and its governing processes are known well enough such that the relevant and dominant processes can be included in the model. This also means that they are usually far more complex and computationally more intensive than empirical models. However, since they are based on universal physical principles, these are more generally applicable. For instance, various regimes in coastal forcing (e.g. Sallenger, 2000) can be then be simulated seamlessly: alongshore non-uniformity in the coastal shape, forcing and response can be taken into account; different coastal environments can be modeled; and aspects such as buildings in the coastal impact zone can be modeled.

In reality and in practicality, 'pure' process-based models, that is, models that are fully-dependent on physical process formulation are not feasible. In our case of coastal storm impact, this would require Direct Numerical Simulations of the Navier-Stokes equations, including sediment transport in three dimensions over a range of time scales (from the time-scale of turbulence to the time-scale of the storm event). Thus, only part of the physical processes is simulated directly, whereas the rest is represented or neglected. The model developer's trade is to analyze the processes and determine which are the essential processes to be modeled directly and which can or must be modeled by representation. The reason for the latter may be that either the processes are unknown or are too computationally expensive.

Even with the most computationally-expensive processes parameterized, the simulations of even the essential processes may be demanding. In practice this has led to two versions of process-based models: profile (1D) models and area (2D) models. Similarly to empirical models, profile models implicitly assume alongshore uniformity in the coastal properties, forcing and response. However, they are more generally applicable and can include various Sallenger regimes, wave directional spreading, the presence of seawalls, cross-shore variability in coastal properties and shape, and time-dependent forcing and response. Two-dimensional models are required in the case of strong coastal curvature, alongshore variation in forcing by surge or water levels, transitions from one coastal type to another. Examples of 1D and 2D models are detailed in the following sections. A more thorough discussion can be found in Ciavola *et al.* (2015).

**10.1.2.1 1D (profile) models** Many 1DV semi-empirical models are used throughout the world. For the purpose of this discussion, we will look at models that include the calculation of the eroded volume in the submerged profile as well as in subaerial profile. Therefore, profile models such as UNIBEST-TC (Reniers *et al.*, 1995), LITPROF (Brøker-Hedegaard *et al.*, 1991) and COSMOS (Nairn & Southgate, 1993), which only simulate the submerged profile are of limited use in this respect. Here, we will discuss the internationally well-known models SBEACH, DUROSTA and CSHORE, which do include the subaerial part.

SBEACH (Larson & Kraus (1989), Larson *et al.* (1990) and Larson *et al.* (2004a)) is a 1DV semi-empirical time-dependent dune erosion model which uses time-averaged process-based wave transformation and empirical-based sediment transports. It thus couples a stationary hydrodynamic approach to a non-stationary morphodynamic one, on the assumption that the morphodynamic time scale is slower that the hydrodynamic one so that the waves have ample time to adjust. The dry dune supplies sediment through an empirical relation between wave impact and the weight of the sand which is eroding (Overton & Fisher, 1988), with innovations by Nishi & Kraus (1996), Larson *et al.* (2004b) and Palmsten & Holman (2011). While it is technically a process-based model, it is for a large part based on empirical formulations.

A different type of model in this class is represented by DUROSTA (Steetzel, 1993), also known as UNIBEST-DE. It solves the processes of wave transformation (refraction, wave breaking), cross-shore and alongshore wave-induced currents, sediment transport and morphological change for time-varying hydraulic conditions. While strictly a 1D model, it does allow for the parameterized effects of wave obliquity, alongshore current gradients and coastal curvature. Dune erosion is represented by extrapolating near dune sediment transports over the dry dune face using an estimate for the wave runup.

Finally, a third type of model is CSHORE (Kobayashi *et al.*, 2009) which was developed for use by the US Corps of Engineers for ocean and great lake coasts for cases with long straight coasts where gradients in longshore directed transport are negligible and waves constitute the principal generation mechanism for sediment suspension. In CSHORE waves, currents and sediment transport are computed simultaneously through an iterative landward-marching procedure. The model development has focussed on process-based sediment transport formulations for a nearshore breaking wave environment. The model has since been extended to two horizontal dimensions; see below.

The above models assume along-shore uniform conditions, both in the hydrodynamic forcing and in the coastal response, and have been applied successfully along relatively undisturbed coasts. However, as stated above, there are a number of limiting conditions for its general applicability, which is where 2DH area models are fit for purpose.

**10.1.2.2 2D (area) models** In complex coastal environments, empirical models and process-based 1D profile models do not suffice. This complexity can take a number of forms. The coast may:

- Have an alongshore-varying topography, for instance if the dune elevation displays a spatial variation in natural dune system
- Have an alongshore-varying bathymetry, for instance it may be fronted by deep channels, or be associated with a nearby tidal inlet
- Be strongly curved, for instance in the case of barrier island heads
- Be forced by alongshore-varying wave and water level conditions
- Show a transition between coastal types, for instance a rocky headland with a sheltered pocket beach
- Be partly vegetated
- Include a transition of hard (engineered) coastal protection to a sandy (softer) environment
- Include discrete buildings

**Figure 10.1** Areas (marked in red) along the Dutch coast where the assumption of alongshore uniformity is violated (courtesy of Dr M. Boers, Deltares).

An analysis for the (mostly sandy) Dutch coast revealed that an estimated 40% of its alongshore length violates the assumption of alongshore uniformity for a number of the above reasons, see Figure 10.1.

These situations call for a 2D-process-based model, which includes hydrodynamics and morphodynamics on the storm time-scale. We will discuss two 2DH models of this type.

One model is C2Shore Johnson & Grzegorzewski (2011); Sleath-Grzegorzewski *et al*., 2013). This model is an extension of the CShore model and is coupled with a spectral wave model STWAVE (Smith *et al*., 2001) and a circulation model (Westerink *et al*., 1994), which computes currents and (tidal and surge) water levels. Johnson & Grzegorzewski (2011) present the model formulations and an application to Ship Island, Mississippi, USA for the case of Hurricane Katrina. They find that beach erosion and shoreline retreat were well predicted, but the deposition on the lee of the island was severely overestimated. They note substantial uncertainty in hydraulic boundary conditions and a lack of conservation of sand in the observations. Sleath-Grzegorzewski *et al*. (2013) applied the model to study the effect of Ship Island restoration.

Another, and more widely-used, model is XBeach (Roelvink *et al*., 2009), which was developed to simulate the seamless hydrodynamic and morphological impact of storms and hurricanes on complex coasts. The model has two modes: a hydrostatic or 'surfbeat' mode and a non-hydrostatic mode. In the hydrostatic model, the hydrodynamic processes are separated into motions at the time scale of the short waves and motions at longer time scales, such as currents and long (infragravity) waves. A principle sketch is given in Figure 10.2. The short-wave motion is solved using the wave action equation, which solves the variation of short-waves envelope (wave amplitude) on the scale of wave groups (dark blue line), rather than the time trace of the individual short waves themselves (black line). It employs a dissipation model for use with wave groups (Roelvink, 1993; Daly *et al*., 2012) and a roller model (Svendsen, 1984; Nairn *et al*., 1990; Stive & de Vriend, 1994) to represent momentum stored at the surface after breaking. These variations, through radiation stress gradients (Longuet-Higgins & Stewart 1962, 1964) exert a force on the water column and drive longer period waves (infragravity waves) and unsteady currents, which are solved by the nonlinear shallow water equations (e.g. Phillips, 1977; Svendsen, 2003). The infragravity wave motions typically consist of incoming waves that propagate with (and are bound to) the wave groups (light blue line), as well as free components, which typically propagate offshore (red line).

The hydrodynamics drive sediment transports under wave and flow conditions, following Van Rijn *et al*. (2007a,b) and Van Thiel-Van Rijn (Van Thiel de Vries, 2009)

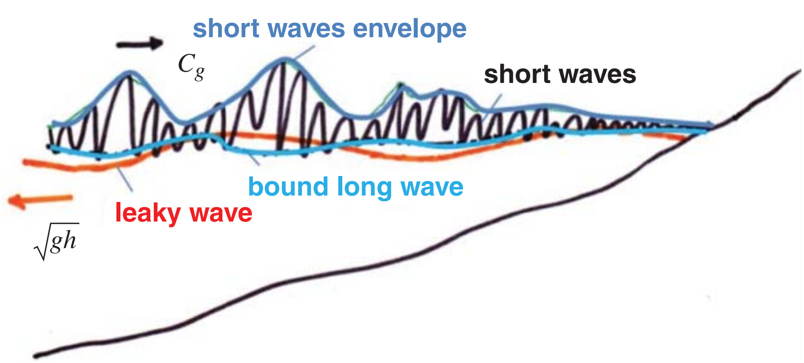


**Figure 10.2** A principle sketch of short wave motions (black), the short wave envelope (dark blue), the incoming bound long wave (light blue) and the reflected free long wave (red) (courtesy of Dr Ad Reniers).

transport equations. The sediment transport includes an empirical formulation for avalanching (slumping) of dune front. On the basis of transport gradients the bathymetric update is computed. We refer to Roelvink *et al*. (2009) for a full description of the model.

The model is applicable on spatial scales of order $10 \times 10$ kilometers, which includes the wave shoaling and surfzone, barrier islands and the back-barrier lagoon system, if present. It allows for the modeling of 'hard' structures such as seawalls and buildings. The model is boundary curve fitting (curvilinear) and can be driven with measured or modeled boundary conditions, obtained from larger area models. The model has been validated with a series of analytical, laboratory and field test cases (Roelvink, *et al*., 2009; van Thiel de Vries, 2009; Van Dongeren *et al*., 2009), and applied in a number of coastal environments, which will be addressed below.

In the non-hydrostatic mode, the depth-averaged flow due to waves and currents is computed using the non-linear shallow water equations, but includes a non-hydrostatic pressure term, so that the dispersive short wave motion (black line in Figure 10.2) is resolved. The depth-averaged normalized dynamic pressure is derived in a method similar to a one-layer version of the SWASH model (Zijlema *et al*., 2011). The depth averaged dynamic pressure is computed from the mean of the dynamic pressure at the surface and at the bed by assuming the dynamic pressure at the surface to be zero and a linear change over depth. The main advantages of the non-hydrostatic mode are that the incident-band (short wave) runup and associated overwash are included, which is especially important on steep slopes such as gravel beaches. Another advantage is that the wave asymmetry and skewness are resolved by the model and no approximate local model or empirical formulation is required for these terms. Finally, in cases where diffraction is a dominant process, wave-resolving modeling is needed as it is neglected in the short wave averaged mode. When using the non-hydrostatic model, a much higher spatial resolution is needed to resolve the short waves. In an explicit numerical scheme, this results in smaller time steps, making this mode much more computationally expensive.

### 10.1.3 Process-model applications

In this section, we will discuss the applicability of process-based models (for which we took XBeach as the example) in various coastal environments: sandy, gravel, coral reef, vegetated and urbanized coasts. We will show not only the model's merits but also its drawbacks and the need for further development of process-based models in general.

**10.1.3.1 Sandy coasts** XBeach has been extensively applied and tested on various sandy coasts. One of the first applications of XBeach was on Hurricane Ivan impact on Santa Rosa Island, Florida. This barrier island is part of the Gulf Coast National Seashore, which is sparsely vegetated and not urbanized. Hurricane Ivan made landfall on 16 September 2004 just to the west of the island, with maximum onshore winds, waves and surge occurring to the east of the hurricane eye. McCall *et al*. (2010) showed that the island was subject to a sequence of collision, overwash and inundation regimes, which caused dune erosion and deposition in the nearshore at first, followed

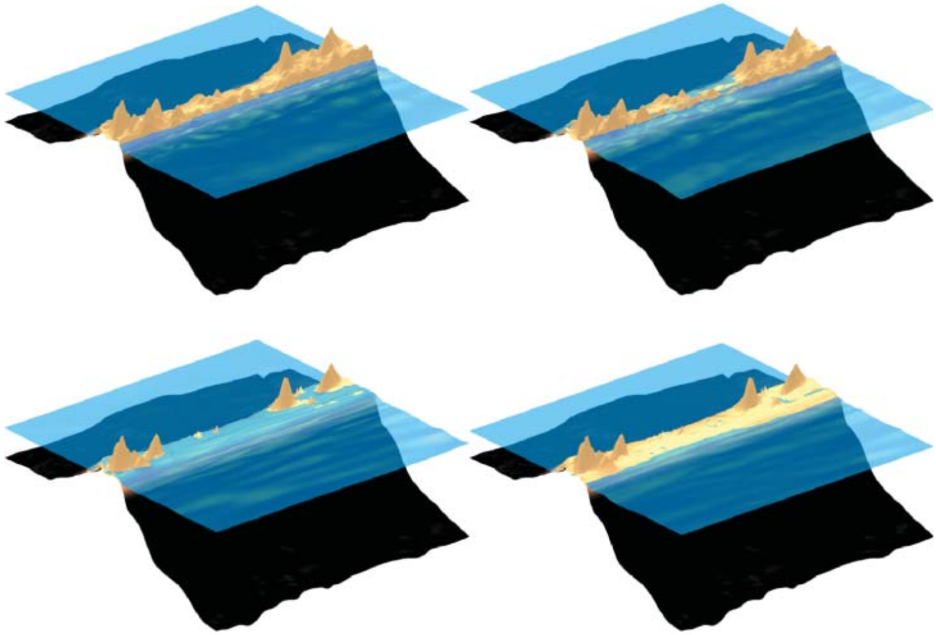

**Figure 10.3** Four stages of the morphodynamical impact of Hurricane Ivan on Santa Rosa Island, Florida. The Gulf of Mexico is in the front and the Santa Rosa Sound is at the back. Top left: collision regime, top right: overwash regime, bottom left: inundation regime, bottom right: topography after recession of the flood. Reprinted from McCall *et al.*, 2010, *Coastal Engineering*, with permission from Elsevier.

by overwash erosion and deposits on and behind the island in typical overwash fans, see Figure 10.3.

The little infrastructure on this section of the island, mostly consisting of roads and parking lots was destroyed. The model, driven by wave and surge time series based on field data and large-scale numerical model results, was capable of predicting the morphological changes. The skill of the model was high (66% of variance explained, maximum bias –0.21 m), albeit these results were obtained using a sheet flow sediment transport limiter, which maximizes sediment transport in the case of extreme high flows (Froude numbers) that are outside the calibration range of the Van Thiel-Van Rijn sediment transport formulation. To overcome this incomplete formulation, De Vet *et al.* (2015) removed the sheet flow limiter, and used a more physics-based approach of a better approximation of the bed roughness and wave skewness and asymmetry in the case of overwash and breaching on a Long Island barrier island under Hurricane Sandy conditions.

Lindemer *et al.* (2010) applied the model to the Chandeleur Islands (Louisiana, USA), which is a detached (almost relic) barrier island off the coast of the Mississippi River birdfoot, and was completely inundated during the storm. The authors show that qualitatively the patterns of erosion and channel formation were predicted well, but the magnitude of the erosion was underpredicted. Specifically, XBeach correctly predicted erosion of the sandy berm and regions that became subaqueous, but areas that remained subaerial were not well predicted. They cite as causes, uncertainties in pre-storm topography (derived from older data), as well as incomplete sediment transport formulations due to sediment diameter variations and the existence of vegetation. Uncertainties in the hydrodynamic forcing were found to have a small effect on the inundation regime.

Splinter & Palmsten (2012) evaluated XBeach and two parametric models for the case of storm impact on the East coast of Australia. They found that XBeach could reproduce both the dune toe retreat and dry beach volume change, but only after careful calibration of its parameters. Without calibration, the empirical model proposed by Palmsten & Holman (2012) performed best on dune toe retreat, but underestimated the dry beach volume change.

Van Dongeren *et al.* (2009) presented an overview of beach profile changes due to storms on eight European beaches, including a comparison of model results obtained with off-the-shelf models. The results showed that the XBeach has skill in predicting the coastal profile, albeit that in most cases the erosion around the mean water line is over predicted and the depositions at the lower beach face are over predicted. In follow-up papers on beaches included in that study, Vousdoukas *et al.* (2012) extensively calibrated the model to predict morphological response to storm events along a meso-tidal, steeply sloping beach near Faro (Portugal). They found that in the case of steeper sloped beaches, the default parameter set derived for dissipative beaches over predicts the morphological change, with resulting Brier Skill Scores (Van Rijn *et al.*, 2003) from 0.2 to 0.72. Values below zero are labelled 'bad'; in the range of 0–0.3, 'poor'; 0.3–0.6, 'reasonable'; 0.6–0.8, 'good'; and 0.8–1.0, 'excellent'. Thus, the computed values in this case range between poor and good. Armaroli *et al.* (2013) applied the model to a sandy Adriatic beach, which is protected with offshore breakwaters. They found that the erosion of the upper beach and dune toe was reasonably well predicted, but the model did not reproduce the slope of the dune, as it does not account for biotic factors (e.g. plant roots), which explains the steeper observed dune slopes. Dissanayake *et al.* (2014) applied the model to evaluate the storm impact on the Sefton coast in north-west UK. Nested with a larger area model, XBeach predicted the beach change quite accurately, with BSS scores of 0.8 and above.

Callaghan *et al.* (2013) considered the use of XBeach in a probabilistic approach to estimate storm erosion volumes. Compared with alternative (and computationally-cheaper) storm erosion models such as the convolution model by Kriebel & Dean (1993) and the semi-empirical SBEACH model, the XBeach model performed well for a case study in Australia, provided that the entire erosion volume data set is used to calibrate XBeach. The advantage that XBeach predicts physically more realistic behavior offsets the relatively high computational demand.

Splinter *et al.* (2014) hindcasted the cumulative impact of a series of relatively small storms that impacted the Gold Coast of Australia. In this case, four clustered storms caused more erosion than a single normative (1/100 per year annual probability) event. XBeach could reproduce the observed dry beach erosion volume to about 20% and shoreline retreat by about 10%. They show that artificial changes in the sequence of storms did not affect the total erosion volume. Karunarathna *et al.* (2014) concurrently analysed the impact of sequences of storms on a beach in New South Wales, Australia. They used XBeach to estimate the post-storm profile, as profile observations are often taken too long after the occurrence of an event and thus include part of the beach recovery phase. Thus, the model was used to fill data gaps, which made the analysis more precise. They also found that erosion due to a sequence of storms is consistently higher than for a comparable single event (in terms of wave power), but also that the time between storms and the rate of recovery in the intermediate periods play a role.

The above shows that the storm impact model performed adequately but that some physical processes need attention, such as the erosion in the presence of vegetation, wave-driven onshore transport of sediment, sediment transport under sheet flow conditions and the effect of topographic roughness.

**10.1.3.2 Gravel coasts** Despite their wide-ranging use as cost-effective and sustainable forms of coastal defence, relatively little research has been directed at understanding the morphodynamics of gravel beaches in comparison to their sandy counterparts (Mason & Coates, 2001), and in particular their morphodynamic response to energetic wave conditions (Poate *et al*., 2013). Due to this lack of understanding of fundamental processes, few process-based models have been developed that are able to simulate the morphodynamics of gravel beaches, and even fewer have been applied and validated for storm impacts.

Gravel beaches differ from sandy beaches during storms in three important aspects. First, gravel beaches are generally steep ($\beta = 0.05$–$0.20$), reflective and have a very narrow surfzone, leading to dominant forcing at the incident wave band over the infragravity band. Second, gravel beaches are relatively permeable, leading to substantial infiltration losses in the swash and subsequent asymmetry in the uprush and backwash volume. Finally, sediment transport on gravel beaches is dominated by bed load and sheet flow transport in the swash, due to the relatively high fall velocity of gravel and the absence of a dissipative surfzone leading to highly energetic conditions in the swash (Buscombe & Masselink, 2006).

Van Gent (1995a, 1995b, 1996) presented the first promising numerical process-based model for the morphodynamic simulation of storm impacts on gravel beaches. The model simulates intra-wave motions of shallow water waves and groundwater inside the porous beach, and uses a critical threshold of motion to displace particles on the bed in an upslope or downslope direction. The model was validated using data from physical model experiments and one berm breakwater in the USA, in conditions that ranged from low to high energy.

Pedrozo-Acuña *et al.* (2006, 2007) applied a modification of an existing Boussinesq wave model (COULWAVE; Lynett *et al*., 2002) to gravel beaches under mildly energetic forcing conditions. Although the model did not include groundwater processes, the model was found to reproduce the berm-building conditions observed in physical model experiment relatively well if the sediment friction factor in the uprush was increased with respect to that of the backwash. Groundwater processes, as well as the effects of acceleration in the swash and sediment fluidization under plunging breakers were hypothesized to cause the apparent difference in the sediment friction factor.

Williams *et al*. (2012) and Jamal *et al*. (2014) applied a modified version of XBeach to simulate the morphodynamic response of gravel beaches during overwash and berm-building conditions, respectively. Both studies found the permeability of the gravel beach to be important in the simulation of morphological change. While neither XBeach model used in the study explicitly computed the incident swash, Jamal *et al.*

(2014) found that an additional parameterization of the bed return flow was required to reduce the dominantly offshore-directed transport of the surf-beat type approach.

The latest process-based model to be applied successfully to model storm impacts on gravel beaches is XBeach-G (McCall *et al.*, 2014). The model is a derivative of XBeach that includes the non-hydrostatic computation of the incident and infragravity wave band (Smit *et al.*, 2010) and a groundwater model to account for swash infiltration losses (McCall *et al.*, 2012). Through comparison with data collected during physical model experiments, as well as data collected at six natural gravel beaches, the model has been shown to simulate storm hydrodynamics, including wave runup and overtopping well (Masselink *et al.*, 2015). Furthermore, the model has been shown to have considerable skill in predicting the morphodynamic response of gravel barriers across a wide range of forcing conditions and barrier response types (Figure 10.4), from berm building to barrier rollover, with minimal calibration (McCall *et al.*, 2015).

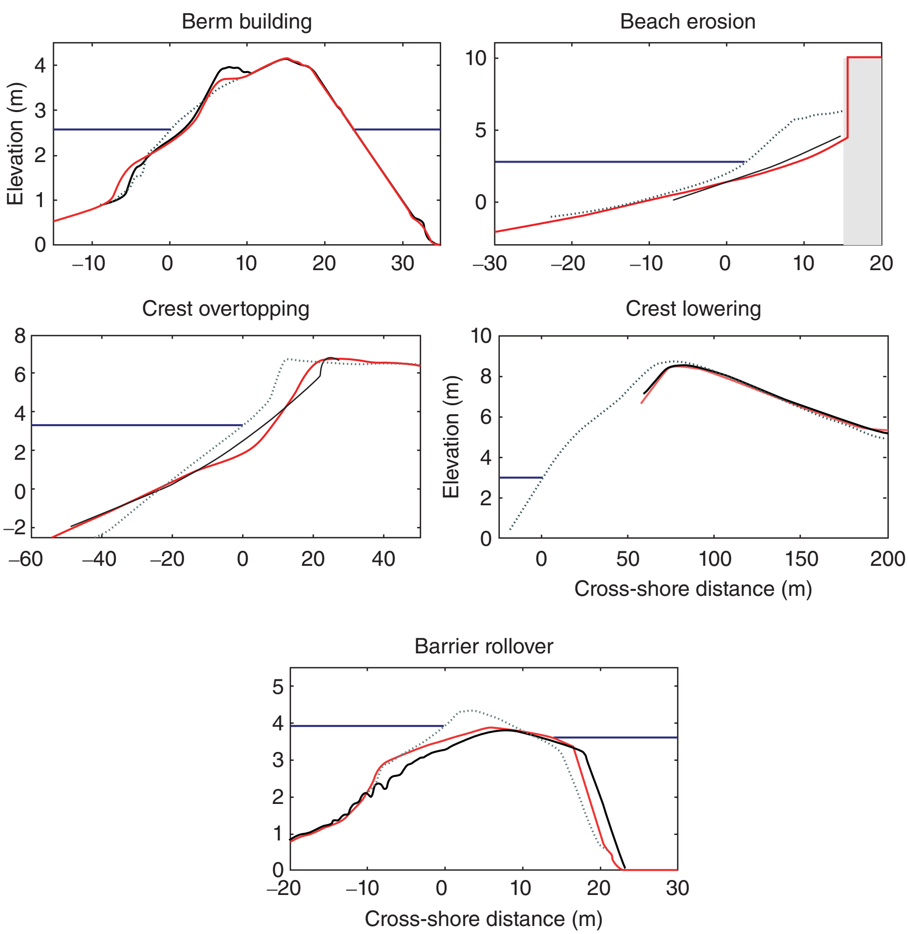


**Figure 10.4** Example of measured (black) and modeled (red) post-storm beach profiles for five separate events and locations. The pre-storm profiles are shown in grey, whereas the maximum still water levels are represented by the blue lines. Modified from McCall *et al.* (2015) under Creative Commons Attribution License (CC BY).

**10.1.3.3 Coral and rocky platform coasts** Even though a large proportion of the world's coastlines, perhaps as high as 80% (Emery & Kuhn, 1982), contain a broad class of submerged reef structures, including tropical coral reefs, very little work (compared to sandy beaches) has addressed the range of nearshore hydrodynamic processes in reef environments. Field and modeling reef studies (see Van Dongeren *et al.*, 2013 for a review) show that reefs exhibit similar processes as seen on sandy beaches, with two important differences: the slope of a coral reef is generally much steeper and rougher, followed by a relatively flat-sloped reef top and lagoon. Therefore, the surfzone is much further away from the shoreline than on sandy beaches, which allows for a clear distinction between zones of wave generation, propagation and decay. Also, due to the presence of the lagoon momentum, separation between wave-induced circulation currents and setup takes place. The XBeach model had to be extended by introducing a dissipation term due to bottom friction in the wave action equation, following Jonsson (1966). This introduces a free parameter $f_w$ which can be constrained using field data by Lowe *et al.* (2007).

Storm impacts are important on reef-lined coasts. Especially on small (atoll) islands, (swell) wave-induced runup, overtopping and inundation causes not only flooding hazards, but also salinization of the aquifer. Damlamian *et al.* (2013) used XBeach to create inundation risk maps for five atolls in French Polynesia, after careful calibration of short wave and long wave propagation and dissipation over a reef flat and accompanied by an extensive sensitivity study. Quataert *et al.* (2015) modeled runup using XBeach on Roi Namur (Kwajalein, Republic of Marshall Islands). While the wave transformation and mean water levels (due to setup) were predicted correctly, the most extreme runup events were under predicted. A likely cause for this is the fact that in the hydrostatic surfbeat model short waves are not taken into account, which means that in these cases a non-hydrostatic model should be used.

**10.1.3.4 Vegetated coasts** Coastlines, especially those between the tropics, may be fronted by different types of vegetation such as kelp, sea grass and mangrove forests. This vegetation has an effect on the impact of waves, currents and water levels on the hinterland and may help to reduce hydraulic loads and thus flood risk. The mechanism by which vegetation reduces the wave height is well known (Dalrymple *et al.*, 1984; Løvås, 2000; Løvås & Tørum, 2001; Mendez & Losada, 2004). However, the effect of vegetation on the mean water level (or wave induced setup) is less well known, with just a few theoretical (Dean & Bender, 2006) and experimental studies (Wu *et al.*, 2011) showing that, under certain hydrodynamic conditions, the presence of vegetation results in a lower mean water level near the coast. The effect of mangrove vegetation during storms has been documented by Mazda *et al.* (2006), Quartel *et al.* (2007), Bao (2011) and Phan *et al.* (2015), and the effect of salt marsh vegetation by Moller *et al.* (1999, 2014), among other references.

A reduction through vegetation thus reduces wave runup, overtopping and morphological impact. Van Rooijen *et al.* (2015) implemented a more complete vegetation dissipation formulation in XBeach. The model was tested using data from different physical experiments. Figure 10.5 shows the wave height transformation and the wave-induced setup for the conventional case of no vegetation (black lines represent the model results and circles the observations), where waves decay due to depth-induced breaking, which causes radiation stress gradients and a balancing wave-induced setup. In the case of

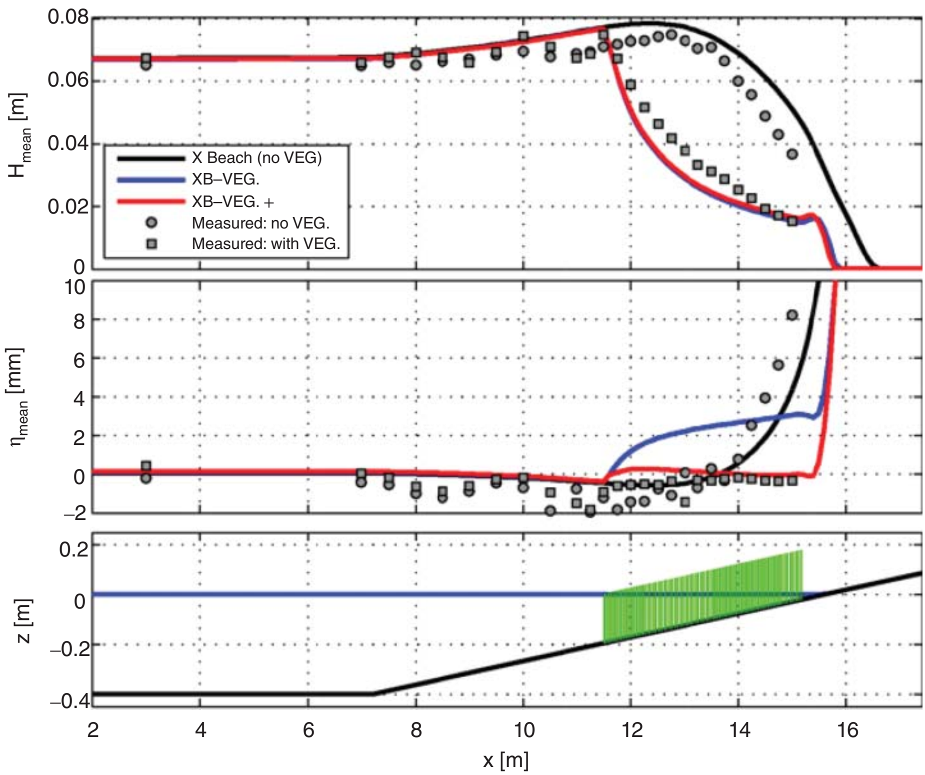


**Figure 10.5** Example result of measured (squares and circles) and modeled wave height (top panel) and mean water level (middle panel). The effect on the mean water level is indicated by the difference between the red and blue line. Figure, courtesy of Arnold van Rooijen, Deltares.

emerged vegetation, the short-wave height decays not only through breaking but also through dissipation in the canopy (blue line and squares), which is quite accurately modeled using the formulation by Mendez & Losada (2004); this is widely used and implemented in numerical models. By itself, the change in short wave height transformation has an effect in the spatial distribution of the radiation stress gradients, and thus on the setup profile, as evidenced by the blue line in the middle panel. However, there is still a mismatch between this result and the observations (see blue line), which is due to the effect of wave skewness that causes an onshore-directed net forcing on the vegetation field, thus reducing the setup. Incorporating these effects in the momentum equations yields a prediction, which shows that vegetation can dramatically reduce or even eliminate setup (red line in the middle panel).

**10.1.3.5 Urbanized/hard structure coasts** In the previous sections, natural coastal systems were discussed. However, in urbanized environments, the coast may contain hard elements such as dune foot revetments, seawalls, groins and buildings. In the presence of a structure and for the specific case of sandy coasts, dune erosion and overwash are strongly affected both in cross-shore and in longshore direction, as visualized in Figure 10.6.

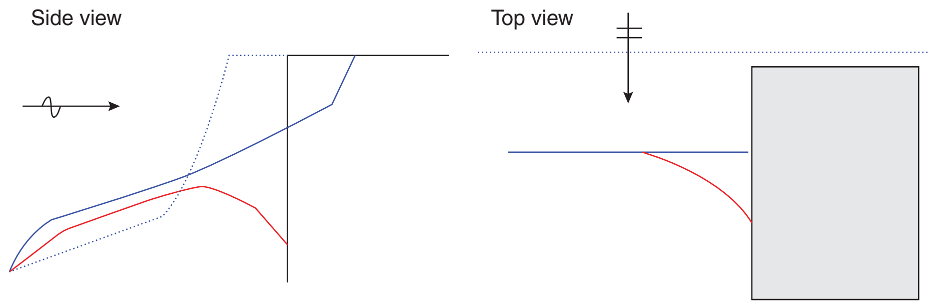


**Figure 10.6** The impact of hard elements – both in cross-shore (left) and in the longshore direction(right). The blue line indicates the response of a coast without the structure, while the red line indicates the response in the presence of a structure. Figure, courtesy of Kees Nederhoff.

In the case of a sandy coast, during storm conditions sand is eroded from the dune and deposited in the nearshore area, which helps to reduce the wave impact on and erosion of the remaining dune. When in the cross-shore direction the dune face is intersected with a hard element, part of the sediment supply from the dune to the nearshore is blocked, while the initial offshore transport capacity caused by the attacking waves in front of the structure remains. As a result, a scour hole can develop (WL Delft Hydraulics, 1987). The amount of erosion (scour) can vary considerably and depends on (amongst other factors) on whether the waves reflect, overtop or break at the structure, and on sediment characteristics (Sumer & Fredsoe, 2002). A positive effect of the cut-off of sediment is that on the whole less erosion by volume in the cross-shore direction will occur. Irish *et al.* (2013) showed, using a Bousssinesq-type model without morphological change, that during Hurricane Sandy a seawall near Bay Head, NJ, reduced the momentum flux at the longshore transect by at least 50%. XBeach is used in a subsequent numerical study, which does include morphological change (Smallegan *et al.*, 2015).

Besides the effect of hard structures in the cross-shore direction, an alongshore interaction is also expected. Hard structures can increase the erosion volume of the adjacent coasts (WL Delft Hydraulics, 1993). There are two drivers for this effect:

1. An alongshore exchange of sediment from the 'sandy' towards the 'hard' cross-section that is driven by setup differences. Hard-structure cross-sections are less dissipative due to the cut-off of sediment supply and therefore waves break right in front of a structure rather than at a distance offshore in the case of a soft cross-section. This initiates an alongshore setup difference and thus alongshore sediment transport (Van Geer *et al.*, 2012).
2. Locally higher waves will impact the soft cross-section that will result in more erosion. These waves are more energetic, due to the weaker soft cross-section (due to driver 1) and diffraction around the construction, which increases the offshore sediment transport (Nederhoff *et al.*, 2015).

The alongshore effect of constructions have both been reproduced in laboratory experiments and in hindcasts of Hurricane Sandy. Boers *et al.* (2011) showed in the

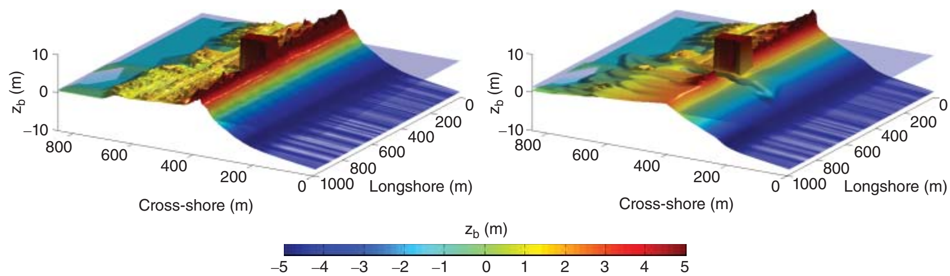


**Figure 10.7** Pre (left) and post-Sandy (right) in a three dimensional plot with both bed and water levels as simulated by XBeach (Courtesy Kees Nederhoff).

laboratory that a dune-dike transition resulted in 27% more erosion at the adjacent coast and that this percentage can increase up to 88% for a breach in a dike. Nederhoff *et al*. (2015) made a hindcast of the impact of Hurricane Sandy on a condominium building at Camp Osborne, Brick, NJ (USA), see Figure 10.7. The presence of the building resulted in an increase of the erosion volume of the adjacent coast with a maximum of +32% (52 $m^3$/m) over a length of 266 m. Remarkable is the fact that this pattern of increase in erosion only occurred at one side, which was found to be related to the obliqueness of the incoming waves.

### 10.1.4 Operational models

While storm impact morphological simulations are still computationally expensive, the incorporation of such models in operational models comes into view. Haerens *et al*. (2012) showed results from the EU-funded MICORE project of the construction of a number of operational storm early warning systems in Europe. Vousdoukas *et al*. (2012) demonstrated the result of the Faro (Portugal) case study site from the same project where nested XBeach models were forced by an existing operational wave-forecast model to generate daily forecasts of storm impacts, whereas Harley *et al*. (2011) demonstrated a system for the Italian Emilia-Romagna Coast. In Van Dongeren *et al*. (2014) and Van Verseveld *et al*. (2015), this approach is furthered to include damage due to inundation, wave impact and morphological change, for a number of case study sites. On an even larger scale, Barnard *et al*. (2014) incorporated hundreds of XBeach transect models in an operational morphodynamic forecast system for the southern California coast, with the objective to predict cliff failure. The model system identified coastal sections that are vulnerable to a range of current and future oceanographic coastal hazards.

## 10.2 Outlook

This chapter gives an overview of model classes with the physical processes that each class resolves, and the model class applicability on the different coastal environments, such as sandy, gravel and coral/rock coasts, as well as coasts with hard structures and vegetation. It is clear that storm impact processes on each of these coasts are complex and are composed of many sub-processes, such as wave dissipation, dune avalanching, offshore/alongshore and onshore transports, to name just a few. This implies careful understanding of each process in isolation, which is best done in controlled laboratory environments. With this data and understanding, process formulations can be calibrated. Many experimental results have already been collected but more are needed in order to further test coastal impact models. Field data of storm events, with well-documented pre-existing conditions, hydrodynamic boundary conditions of waves, wind and surge, and the storm impact measured directly after the storm, are needed to validate models on the prototype scale. We foresee that in the future many more physical processes which act at the storm time scale will be implemented in models. One can think of the effect of vegetation on morphological change, the effect of buildings on coastal change, sediment transports on beaches composed of gravel and sand, but also the inundation of the hinterland, the infiltration of seawater in aquifers and the damage of infrastructure. In addition, the recovery processes after a storm will also become important, to answer the question what the long-term behavior of the coast, which is hit successively by storms, will be.

More complex models need good calibration of subprocesses and validation on field data, but also need to be manageable in terms of computational expense. Here, besides an expected increase in raw computational power, smart techniques such as multi-processor implementation, code optimization and cloud computing will bring the simulation of coastal storm impacts closer to engineering and forecasting practice.

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