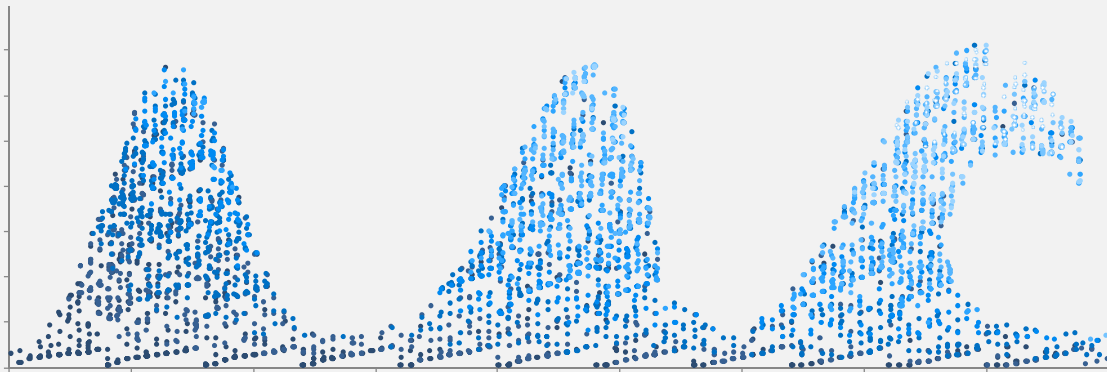


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**Probabilistic modelling of extreme beach erosion using XBeach.**

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## Abstract

The long series (>30 year) of measurement data of erosion events at Narrabeen beach (NWS, Australia) provides insight in erosion volumes and their return periods in this area. The aim of this study was to replicate these data using XBeach in order to assess the validity of both the Joint Probability Model (JPM) and XBeach on beaches such as Narrabeen.

In this study, a large number of different storms were simulated using XBeach. The probability and thus return period of the resulting erosion volumes were determined using the JPM.

XBeach was calibrated against two individual erosion events, one at Narrabeen beach and one at Hasaki beach (Japan). The best fit for the Narrabeen beach, obtained using a stationary mode, led to an overestimation of erosion volumes at lower return periods (< 3 year) but fell within the boundaries implied by a 95% confidence interval of the measurement data for higher return periods.

When calibrated against the erosion volumes with low return periods (<2 year), XBeach slightly underpredicted the erosion volumes at higher return periods. Depending on the method of determining confidence levels, the results were outside or well within the confidence interval of the measurements. This could suggest that this method is a valid way to predict erosion volumes and their return periods, in cases where long term erosion volumes measurements are absent.

## 1 Introduction

*“Long-term prediction of sediment transport and morphological behaviour in the coastal zone is an increasingly important issue, now that we are becoming aware of the need for sustainable development and are facing threats such as sea level rise.”* wrote de Vriend in 1993 (de Vriend et al., 1993). In the 20 years since, climate change has become an even bigger issue and subsequently, the demand for reliable and accurate predictions of beach erosion.

The reason for his growth in demand of accurate predictions of beach erosion is caused by the ongoing increasing usage of the coastal zone. More people than ever live close to the shore, and monetary value of the coastal zone has increased subsequently. Especially in the lower coastal areas that are based on erodible materials such as sand, sea level rise (SLR) as well as increased storminess, could lead to more erosion, threatening lives and infrastructure. Understanding the behaviour of the coast would lead to more safety in the short term, but would also allow further development without taking unknown risks.

Many different methods have been applied, and are still in use, to determine erosion volumes at erosion events, and to quantify the risk of such an erosion event. Some of the most commonly used methods are described in more detail in Chapter 2.

Two approaches in determining coastal safety can be distinguished: a deterministic approach and a probabilistic approach. In general, a deterministic approach determines values, such as beach erosion, from known or assumed parameters, whereas a probabilistic approach assigns probabilities to these values. The increasing use of risk-based coastal zone management fuels the demand for probabilities of erosion events. Probabilities of erosion events can be determined in roughly two ways (i) a large (and long term) dataset of erosion

volumes and their occurrence by measurements (ii) (numerical) modelling of the coastal zone to obtain erosion volumes, combined with the statistical distribution of the forcing. In the later case, measurements remain needed to validate the results from the model.

Few long term datasets of beach erosion measurements exists worldwide, Narrabeen Beach, New South Wales, Australia being a notable example. For over 30 year, monthly surveys have been carried out (A. Short), generating a dataset which can be used to calibrate and validate model results.

In recent years, Callaghan et al. (2008a,b) have introduced the Joint Probability Model (JPM) which combines erosion volume models such as Kriebel and Dean (Kriebel and Dean, 1985, 1993) and SBEACH (Larson and Kraus, 1989) with a statistical framework, giving probabilities to erosion events.

K&D is an extension of the Bruun rule of erosion (Bruun, 1962) calculating erosion as a function of the difference between the current beach shape and the equilibrium beach profile. The Bruun rule, however, has many drawbacks such as the limited applicability on beaches worldwide. SBEACH, a numerical profile model based on field measurements as well as model measurements, excludes many processes, such as infra-gravity waves.

XBeach, a new numerical beach erosion model (Roelvink et al. 2009) is used in this study in combination with the JPM. This state of the art, process based, numerical model includes a novel non-stationary wave driver with directional spreading to account for wave-group generated surf and swash motions. Therefore, XBeach is expected to simulate single beach erosion events more accurately than K&D and SBEACH. XBeach is described in more detail in chapter 2.

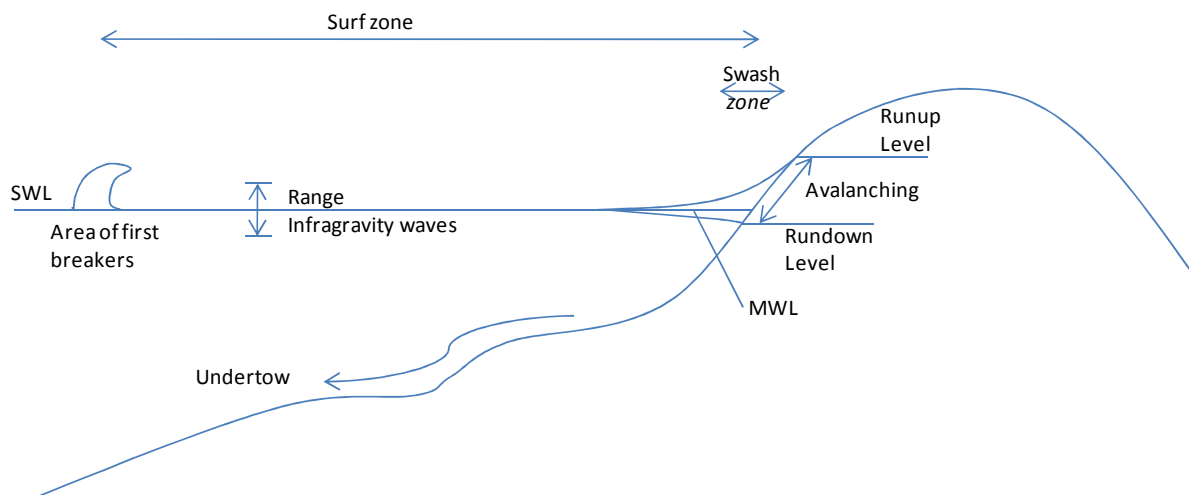


Figure 1-1; Graph of processes in the surf zone and swash zone included in XBeach.

### 1.1 Setup and Goal of this research

In this study, XBeach will be calibrated on two individual erosion events, at the Australian and Japanese coast. In these calibrations, the focus is on the shape of the post-storm profile.

In a second series of calibration the predicted return period of erosion volumes, as determined by XBeach in combination with the JPM, will be compared with the return

period of measured erosion volumes using the complete Narrabeen dataset. In these cases, erosion volumes are compared.

After the calibration of XBeach, many different storm scenarios will be simulated and erosion volumes will be determined. Combining these storm-simulations with the probability of their occurrence, erosion volumes and their return period are calculated. The confidence intervals of these erosion volumes will be determined with Monte Carlo analyses.

The goal of this research is to assess the applicability of XBeach as structural function in the JPM in order to determine the return period of erosion volumes.

This leads to the main question of this research: *Are the predictions made by the JPM and XBeach more accurate and reliable, compared to existing research using K&D and SBEACH as structural function in the JPM?*

If predictions made by the JPM in combinations with XBeach are comparable to the measurements at Narrabeen, more confidence can be placed in predictions for other beaches where long term erosion measurements are absent, but wave data is available.

## **1.2 Overview of this research**

Chapter 2 starts with an overview of methods used to calculate coastal erosion. It shows the possibilities and drawbacks of some of the widely used methods. It continues with a brief description of the JPM that was used to calculate beach erosion. It also provides a description of the numerical program XBeach. Chapter 3 describes the calibration of XBeach on two beaches in case of an individual erosion event, as well as the fitting of erosion volume-return periods to the long term measurements of Narrabeen beach.

In Chapter 4 the long term erosion calculation using the JPM is provided. As the models of Kriebel and Dean (1993) and SBEACH are orders of magnitude faster than XBeach, XBeach can be described as computationally expensive. Consequently, the necessity of a high density input matrix was implemented and investigated for optimal density (trade-off between accuracy and computational cost).

Conclusions and recommendations for future research are provided in Chapter 5 and 6.

## 2 Method

### 2.1 Determining coastal safety

Historically, two approaches in determining coastal safety can be distinguished: a deterministic approach and a probabilistic approach.

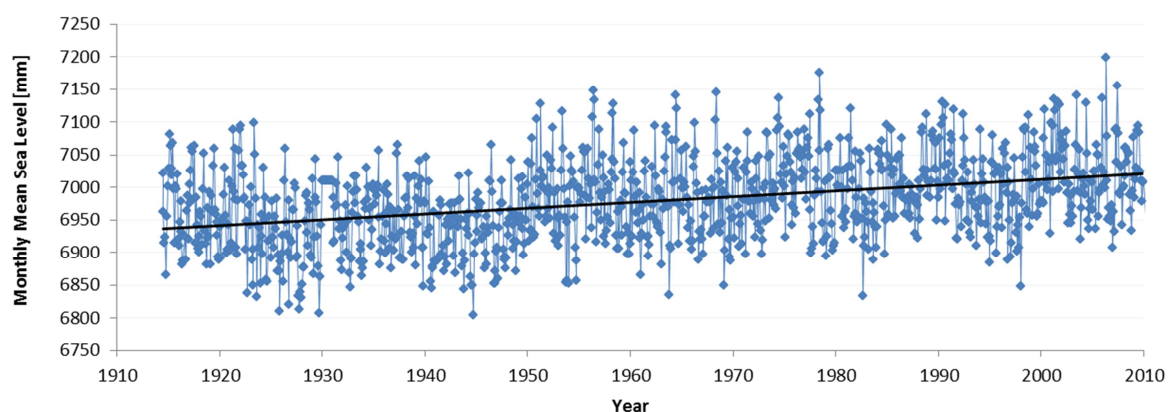
#### 2.1.1 Deterministic approach

The Dutch government was one of the first to use a probabilistic approach to determine coastal safety, in response to the floods of 1953. However, in many places a deterministic approach remained in use to calculate the load on the coast or to determine erosion volumes, due to the simplicity of the approach. This deterministic approach leads to coastal defenses being designed to withstand the highest known storms, or to survive the biggest measured erosion. Although this approach works well cases where track records of coastal events are available, it is not generic and therefore does not answer the more fundamental question of coastal safety.

Another drawback in setting safety standards using measured historical events is that temporal changes are not considered. This poses a problem for the long term prediction of extreme beach erosion. Wave and water level records are usually in the scale of years or decades, virtually excluding variations having a longer period. For instance, Nott et al. (2007) shows that the number of tropical cyclones making landfall in Queensland, Australia, has a centennial variation, where a peak number of cyclones can be found in the period AD 1600-1800. This peak is excluded from most historical records, leading to an underestimation of extreme beach erosion.

Climate change, as discussed extensively in the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), is excluded from the deterministic approach as well. The coast is affected by climate change in two ways, described here briefly:

First, the long term impact of sea level rise (SLR) generally causes beach recession. Near Sydney, SLR has been about 9 cm/century over the period 1914-2010, which is less than the predictions for the next century.



Figuur 2-1; Sea Level Measurements at Fort Denilson (Sydney, NWS, Australia). Data from <http://www.psmsl.org/data/obtaining/stations/196.php>

The latest IPCC projections (2007) indicate an SLR range from 0.18 m to 0.79 m by 2090–2099 relative to the period 1980–1999, including an allowance of 0.2 m for uncertainty

associated with ice sheet flow, while Rahmstorf et al. (2007) suggests that SLR could even exceed this value.

Second, it is expected that the wave climate will change (Bindoff et al., 2007), e.g., a change in storm intensity, and storm frequency. This trend has already been observed. A downward trend in tropical cyclone occurrences in the northern Australian regions exists since the late 1960s, partly caused by more El Niño years occurring. (Nicholls et al., 1998). Knutson (2001) and Walsh (2000) predict a maximum potential intensity increase of tropical cyclones in Australia of up to 5-10%, however with a large margin of uncertainty.

For the south eastern Australian coast, the change in wave climate is partly due to the change in the distribution of El Niño and La Niña years. The relationship between storm frequency and the El Niño-Southern Oscillation (ENSO) was examined by Ranasinghe et al. (2004) and You and Lord (2008). Both studies reported a correlation between average yearly storm intensity and Southern Oscillation Index, implying more severe storm events during La Niña years. Ranasinghe et al. (2004) observed a beach rotation related to the ENSO, with the northern part of some beaches accreting during El Niño phases, while the southern part erodes. The opposite occurs during La Niña phases, resulting in a net anti-clockwise rotation of the beach. This is mainly due to the change in predominant direction of the swell and a changing distribution in wave steepness. Apart from beach rotations, does the New South Wales coast resides in La Niña years, and recovers in El Niño years.

The future distribution of El Niño and La Niña years is still however under great uncertainty. Vecchi et al. (2008) argue that no conclusive evidence exists for a change in either direction, whereas DiNezio et al. (2010) suggest that the changes are likely to be location dependent. I.e., regions with mostly El Niño influenced climate will have more El Niño type weather in the future, and vice versa.

The fact that sea levels are generally rising worldwide (e.g., Meehl et al., 2007), in combination with the big and yet unknown influence of the El Niño-Southern Oscillation change on Australian coast, makes designing coastal defense on the basis of historic measurements perilous public policy. Including extra safety by using a thereto unknown margin does not solve the problem either, as an extensive margin would in all likelihood lead to sufficient safety, albeit with excessive recourses usage.

### 2.1.2 Probabilistic approach

To avoid this ad-hoc approach, one could derive a return period distribution by fitting the erosion distribution directly on the measurements. This method does require measurements stretching for a long period e.g., decades. The maximum return period for which erosion volume can be determined is equal to the length of the measurement period (however with high uncertainty), making this method only applicable to a few beaches worldwide, e.g., Narrabeen beach (New South Wales, Australia). Future temporal changes, such as described previously, are still excluded from this method.

When wave parameters are available from measurements, but insufficient beach erosion data is available, erosion volume can be simulated. An empirical probability can be assigned based on the probability of the wave parameters. These calculated values are then extrapolated using extreme value distributions. As before, a problem of this method is the fact that temporal changes, such as SLR, are limited to the measurement period. Storm grouping, i.e., the fact that two small storms can create more erosion due to the fact that the beach has not recovered yet, is excluded as well.



## **2.2 Methods in literature used to determine beach erosion**

To be able to predict return periods of several decades and to avoid the practical limitations of calculations based solely on measurements, many alternative methods have been suggested.

### **2.2.1 Bruun rule of erosion**

One of the first widely used methods to calculate coastline retreat due to SLR is the Bruun Rule of erosion (Bruun, 1962). This rule is based on the assumption that the coast will maintain the same amount of material, and that it will maintain the same bottom profile.

While this method shows good results given the right boundary conditions (Bruun, 1983) such as a sufficiently “2D” profile, Zhang et al. (2004) concluded in a large scale study that almost 70% of the US coast was excluded from application of the Bruun rule due to inlets and engineering structures. Since the Bruun rule is based on a beach in its equilibrium following the SLR, the rule would be less accurate if this equilibrium shape changes, e.g., due to change in wave climate. The assumption of uniform sediment size and the exclusion non-equilibrium profile shapes e.g., profiles with a bar, are further limitations of the Bruun rule. Furthermore, Ranasinghe et al. (2009) showed that large uncertainty is included in the equation due to the definition of the ‘Depth of Closure’ (DoC), the depth at which no net sediment transport occurs due to erosion or accretion. Using four accepted DoC calculation methods, Ranasinghe et al. showed that the variation in recession predicted by the Bruun rule is as much as 500%. Apart from the wide level of uncertainty, Ranasinghe et al. (2009) argued that the Bruun rule appears to be highly conservative. Therefore they proposed that the Bruun rule can best be used for broad indicative estimates, suggesting that comprehensive numerical models are needed for coastal planning and management.

### **2.2.2 Kriebel and Dean**

An improvement over the Bruun rule, with respect to the development of erosion during a storm, was proposed by Kriebel and Dean (K&D) (Kriebel and Dean, 1985, Kriebel and Dean, 1993). The Bruun rule assumes instantaneous response of the beach to changing wave parameters and sea level, a clear deviation from reality. K&D proposed the idea that beaches reshape to their instantaneous equilibrium profile in an approximately exponential manner. In other words, the rate of profile change is proportional to the difference of the instantaneous beach shape to the equilibrium beach shape. The amount of erosion is thus a function of the difference between the present shape and the equilibrium shape, and the timescale of the forcing.

This idea can be applied in short term on the development of the beach during a storm, or on the long term, in response to variations caused by SLR and El Niño/La Niña.

## **2.3 Beach erosion modules in statistical framework**

Including K&D approach in a statistical framework, Callaghan et al. (2008b) presented a Joint Probability Distribution Method (JPM) using K&D as structural function. While this method accounts for storm grouping, temporal variations, such as increased storm intensity, are still excluded.

Callaghan et al. (2008a) were able to include temporal changes in wave climate by replacing K&D for the SBEACH model (Larson and Kraus, 1989). SBEACH is a numerical profile model

based on field measurements as well as model measurements. It assumes that a beach profile will reach an equilibrium shape if exposed to constant wave conditions for a sufficiently long time. The sediment transport rate is a function of the difference between the actual wave energy dissipation and the equilibrium wave energy dissipation.

SBEACH does not include the influence of long-period waves, such as partially standing waves and infra-gravity waves, nor does it allow for the formation of bars. Partly because of the lack of measurement data, berm processes are not properly predicted. This was shown by Komar et al. (2002) who pointed out that SBEACH did not match their dune recession measurements. Callaghan et al. (2008b) did include a swash model and dune erosion model.

Ranasinghe et al. (2009) extended on Callaghan's (Callaghan et al., 2008a, Callaghan et al., 2008b, Callaghan et al., 2009) work by proposing the Probabilistic Coastline Recession model, which is capable of including temporal variations such as SLR. This means that virtually all statistical parameters, if known, can be included in the probabilistic modelling of coastline recession.

#### **2.4 Future of numerical modelling**

As knowledge about the probabilistic description of extreme erosion advances, future improvements can be distinguished on two fields; wave parameters and their probabilities, and beach response.

Numerical simulation of ocean climate caused by weather systems would be beneficial in regions where wave data is scarce, as well in time as in detail. At present, some fully numerical models exist (e.g., Alves, 2006, Zhou et al., 2008), these models simulate a part of the wave spectrum, (e.g., swell) under some circumstances (e.g., hurricanes) within reasonable accuracy. Others, (e.g., Jain et al., 2011) combine a numerical model with measurements to predict the sea-state. A full scale model able to provide accurate wave parameters under any circumstance, and thus providing accurate return periods for these conditions, has yet to be developed.

In recent years, many different parametric or empirical numerical erosion models have been developed (e.g., TELEMAC-SISYPHE, SBEACH, TUFLOW, DELFT3-D, MIKE21, XBeach etc.) which simulate sediment transport to various extent. To date, no fully process based model exists. While, under most conditions, reasonable accuracy can be achieved with empirical approaches, the applicability of the model will remain limited. A fully process based 3D model is however still infeasible due to (i) lack of computational resources and (ii) the present level of understanding of processes involved in motions of waves and transport of sediment.

#### **2.5 XBeach**

Recently, Roelvink et al. (2009) presented XBeach, a nearshore numerical model used to calculate coastal response during time-varying storm and hurricane conditions, including dune erosion and overwash. It includes a non-stationary wave driver with directional spreading to account for wave-group generated surf and swash motions and an avalanching mechanism providing a smooth and robust solution for slumping of sand during dune erosion. XBeach does not include a swash zone erosion model; it therefore makes use of an avalanching module. This avalanching module limits the steepness of the bed profile, with different values for the wet and dry parts of the profile. XBeach uses Soulsby – Van Rijn transport formulations to solve the 2DH advection-diffusion equation to produce transport

vectors, which, in turn, update the bathymetry. Hydraulic forcing in the swash zone is generated by hydrostatic oscillations of short waves of different period, generating wave grouping. Their time-averaged forcing is combined with an avalanche module to create erosion. XBeach is described in more detail in paragraph 2.8.

### 2.5.1 JPM and XBeach

In this report, XBeach replaces K&D and SBEACH in the JPM (Callaghan et al., 2008a, 2008b) as the structural function converting nearshore forcing in cross-shore beach erosion. This means the JPM draws wave input for XBeach from statistical distributions; where XBeach calculates the beach erosion. These erosion volumes are grouped according to the probability of the forcing, and thus a probability of the erosion volume is determined. This process is described in more detail in paragraph 2.7.

## 2.6 Joint probability

The JPM used in this study is based on the joint probability of input variables, such as wave parameters. A correct assessment of joint probability is essential to be able to determine the return period of quantities such as erosion volume.

As long as the distributions of two or more uncorrelated variables are known, determining their joint probability is relatively straightforward. In coastal hydraulics, however, variables such as water level, wave height, wave period, and storm duration are often not independent. Although the astronomical tide is independent of weather systems, storm surge is directly influenced by one or more meteorological systems, which, in turn, might not be independent. Similar dependency is observed between wave height and storm duration, both usually being largely influenced by the same meteorological system. Moreover, the correlation between water levels and wave heights can be both negative and positive (Hawkes et al., 2002). While these correlations might be unknown, and thus not explicitly considered in the statistical analysis of the JPM, these correlations will affect the collected data, and are thus included implicitly.

To calculate the return period of a certain amount of erosion, one starts with short term erosion Volume ( $EV_t$ ).  $EV_t$ , at any given time ( $t$ ), is related to sea conditions ( $X_1, X_2, \dots, X_n$ ) via a structural variable  $\Delta$ .

$$EV_t = \Delta(\mathbf{X}_t) = \Delta(X_1, X_2, \dots, X_n) \quad (1)$$

The probability of exceeding a specific value ( $a$ ) is calculated by integrating the joint density over the region ( $A > a$ ):

$$\Pr(EV_t > a) = \int_{A > a} f(\mathbf{x}) d\mathbf{x} \quad (2)$$

The return period,  $RP$ , is then defined as the expected interval between two events.

$$RP = \frac{1}{\{\Pr(A > a)\}} \quad (3)$$

Calculating the  $RP$  analytically is possible, but gets very complicated as soon as more than 2 variables are included. To solve this problem, numerical solutions such as Monte Carlo analysis can be used.

## 2.7 Joint probability model (JPM)

In the present study, the Full Temporal Simulation (e.g Hawkes et al., 2002, Callaghan et al., 2008b) is applied. This simulation consists of the following eight steps:

1. Identify meteorologically independent storm events.
2. Fit extreme value distributions to wave height and storm duration (marginal distributions).
3. Fit the dependency distribution between wave height and storm duration.
4. Fit the wave period and peak tidal anomaly conditional distributions.
5. Determine the empirical distribution for wave direction.
6. Fit a non-homogenous Poisson distribution to the spacing between storms.
7. Simulate the wave climate using the fitted distributions including storm spacing.
8. Estimate extreme values of beach erosion from the simulated wave climate.

Using the generalized Pareto distribution together with the logistics model, the model creates a long record of storms which have similar dependency between storm parameters, such as the peak wave height ( $H_{s,max}$ ), storm duration ( $D$ ), and storm surge ( $SS$ ) as observed. The wave period was conditionally dependant on  $H_{s,max}$ , following the wave steepness distribution. The  $H_{s,max}$  created by the model was limited by the local maximum wave steepness according to  $T_{s,min} \approx 3.9\sqrt{H_{s,max}}$ , limiting the wave height of less than 5% of the waves. Both significant wave period and the storm surge were correlated to the maximum significant wave height. Storm occurrence was modelled using the spacing between events and assuming a non-homogeneous Poisson process with a seasonally varied annual value in the occurrence intensity. No event clustering caused by event dependency was observed, in other words, the occurrence of one event did not influence the probability of occurrence of another (storm) event. For values of the parameters see Callaghan et al.(Callaghan et al., 2008b)<sup>1</sup>

The time series of storm erosion volumes was simulated with the first event at time  $t$ , using the Monte Carlo simulation and the fitted distributions by repeating the following process;

- A. Generate random realizations of  $H_{s,max}$ ,  $D$ ,  $T$ ,  $\theta$ ,  $SS$ ;
- B. Transfer the offshore wave climate to nearshore (using SWAN);
- C. Estimate beach erosion using a storm erosion model (using XBeach);
- D. Generate time to next storm;
- E. Determine erosion volume [ $m^3/m$ ] recovery till next storm using exponential function;

This process was repeated for the entire length of the simulation, each storm was simulated using the same initial beach profile, which resembled the Narrabeen beach profile in average state (not accreted or eroded). For practical reasons, a matrix of erosion volumes was created using parameters for  $H_{s,max}$ ,  $D$ ,  $T$ ,  $\theta$ ,  $SS$  shown in Table 4-2. In step C, the erosion volume was read from this transfer matrix. Intermediate values generated in step A were

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<sup>1</sup> The 95% confidence interval shown for  $\xi$  for the GPD of the maximum significant storm duration in Callaghan et al. (2008) [-0.11 ; -0.24], is incorrect and should be [-0.13 ; +0.15].

determined from the transfer matrix using linear inter- or extrapolation (see Callaghan et al. (2008b) for more details on the JPM).

## 2.8 Brief overview of XBeach's formulations

A new 2DH numerical model, XBeach (Roelvink et al., 2009), developed to model nearshore responses to hurricanes, was used as the beach erosion structural function. XBeach requires, amongst others, bathymetry and bed, time series of offshore wave height, period, and sea water level (SWL) as input. During this research, XBeach version 17 (mid 2010) has been used.

During this research, erosion volumes determined by XBeach are compared to erosion volumes determined by K&D and SBEACH. Below, a small part of the formula's in the XBeach program are shown. The selection is based on main functions of XBeach to transform wave energy into sediment transport; formulae lacking in K&D and SBEACH.

In XBeach, Equation (4) (Roelvink, 1993) is used to model the directionally integrated total wave energy dissipation that is caused by wave braking,  $\bar{D}_w$ . Equation (4) can be seen as the multiplication of the energy of waves before breaking and the probability of breaking.<sup>2</sup>

$$\bar{D}_w = 2 \frac{\alpha}{T_{rep}} Q_b E_w \quad (4)$$

$$Q_b = 1 - \exp\left(-\left(\frac{H_{rms}}{H_{max}}\right)^n\right), \quad H = \sqrt{\frac{8E_w}{\rho g}}, \quad H_{max} = \frac{\gamma \tanh kh}{k}$$

where  $\gamma$  represents the breaker parameter defined by  $(H/h)$ ,  $T_{rep}$  the representative wave period, and  $H_{rms}$  the root mean square wave height.  $E_w$  represents the directional wave energy over one wave period and is given by eq. (5).

$$E_w(x, y, t) = \int_0^{2\pi} S_w(x, y, t, \theta) d\theta \quad (5)$$

Choosing *break* = 3 instead of *break* = 1 changes the equation for  $\bar{D}_w$  given in eq. (4) into

$$\bar{D}_w = 2 \frac{\alpha}{T_{rep}} Q_b E_w \frac{H_{rms}}{h} \quad (6)$$

This leads to the wave dissipation being proportional to  $H^3/h$  instead of  $H^2$ .

XBeach assumes that intra-wave sediment transport due to wave asymmetry is small compared to transport caused by long-waves and mean current. Consequently, the Soulsby-Van Rijn (Soulsby, 1997) short wave averaged and wave group resolving model was used:

$$C_{eq} = \frac{A_{sb} + A_{ss}}{h} \left( \left( |u^E|^2 + 0.018 \frac{u_{rms}^2}{C_d} \right)^{0.5} - u_{cr} \right)^{2.4} (1 - \alpha_b m) \quad (7)$$

where  $C_{eq}$  represents the equilibrium sediment concentration,  $A_{sb}$  and  $A_{ss}$  the bed load coefficients as defined by Soulsby (1997),  $u^E$  the Eulerian mean velocity,  $u_{rms}$  the near bed

<sup>2</sup> The use of equation (4) (Roelvink, 1993) is specified by selection option *break*=1 in the XBeach input file *params.txt*.

short-wave orbital velocity,  $C_d$  the drag coefficient due to flow velocity.  $u_{cr}$  the minimum water velocity at which sediment sets in motion, and  $m$  the bed slope with calibration factor  $\alpha_b$ .

The sediment transport is modelled using a depth average advection diffusion equation (8) (Galappatti and Vreugdenhil, 1985), which basically shows the transport as a function of the equilibrium sediment concentration  $C_{eq}$  minus the instantaneous concentration  $C$ , divided by an adaption time scaling factor  $T_s$ :

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial hCv^E}{\partial y} + \frac{\partial}{\partial x} \left( D_h h \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_h h \frac{\partial C}{\partial y} \right) = \frac{hC_{eq} - hC}{T_s} \quad (8)$$

with the adaption time defined by equation (9).

$$T_s = \max \left( 0.05 \frac{h}{w_s}, 0.2 \right) s \quad (9)$$

where  $h$  represents the local water depth,  $w_s$  the sediment fall velocity, and  $s$  the specific weight  $\rho_{sed}/\rho_{wat}$ . Unrealistic profile slopes  $m$  are prevented by an avalanching module, according to equation (10),

$$\left| \frac{\partial z_b}{\partial x} \right| > m_{cr} \quad (10)$$

with  $m_{cr,wet} = 0.3$  and  $m_{cr,dry} = 1.0$  as standard settings.

XBeach includes a nonstationary wave driver to account for wave-group generated surf and swash motions. This means that the envelope of the wave group is modelled by XBeach, individual waves are not. See figure Figure 2-2

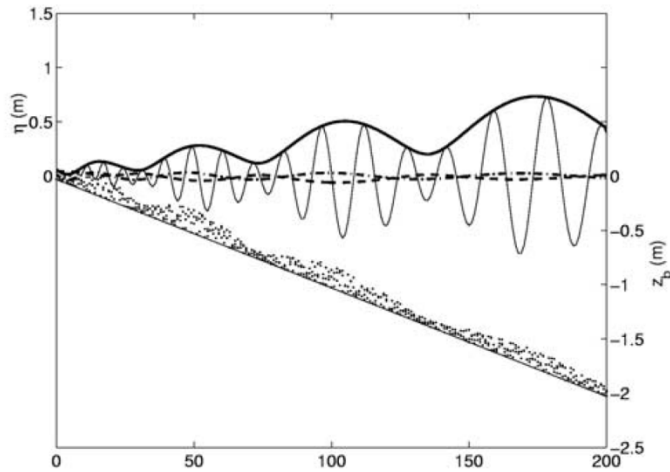


Figure 2-2; Wave groups and corresponding wave envelope (thick solid line), bound infragravity waves (dashed line) and free returning infragravity waves (dash-dotted line). After Reniers et al. (2004).

Swash motion transport caused by standing infragravity waves is dominant over incident band swash since the latter is saturated during storm conditions (Raubenheimer et al., 1996). Yet, Baldock et al. (1997) found no evidence of correlation between the low frequency motion of the swash zone and cross-shore standing long waves on steep beaches without fully saturated surf zone. Consequently, they argue that these low frequency motions are caused by wave grouping. The effect of the wave groups is depicted in Figure

2-. The offshore wave period is 12.8s, the period of the sediment transport is about 3 times larger.

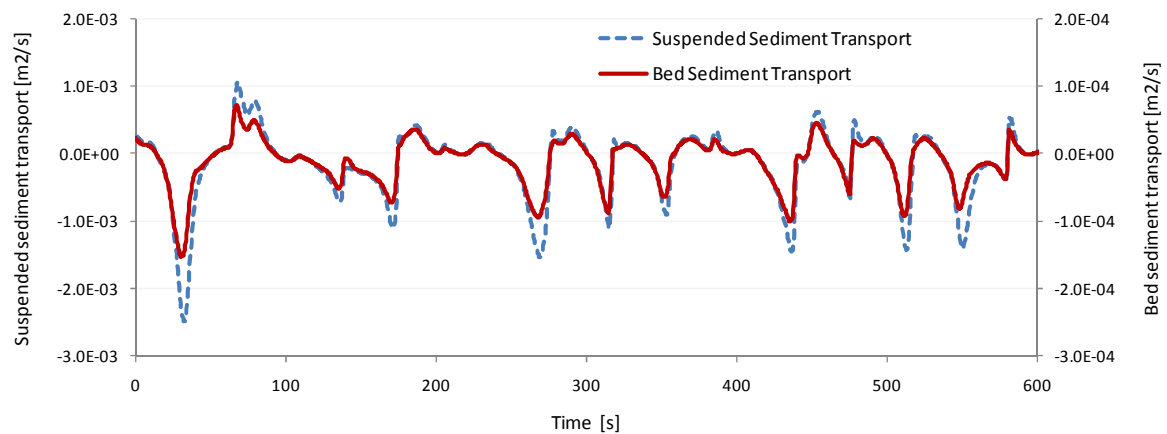


Figure 2-3; Suspended sediment transport (red line) and bed sediment transport (blue dashed line) in the surf zone (depth 1 m) with  $H_s$  equal to 5.1 m and  $T=12.8$  s.

Erosion in the swash zone modelled by XBeach is mainly a result of wave setup caused by infragravity waves combined with the avalanche module. Both factors are essential for modelling of the beach face, i.e., part of the profile above MSL+Setup (Roelvink et al., 2009).



### 3 XBeach model calibration

#### 3.1 Narrabeen beach field description

For single erosion events as well as for long term coastline retreat predictions, field measurements are rare. One of the longest ongoing beach surveys in the world is in Narrabeen making this beach ideal for validating the long term prediction of erosion events.

The 3.6 km long beach is located on the northern Sydney Coast and faces the Tasman Sea to the east. It is bounded by Narrabeen Head in the north and by Collaroy and Long Reef point in the south. The beach is composed of medium to fine quartz sand ( $d_{50} = 0.3$  mm), with approximately 30% carbonate fragments (shells and algae detritus). The spring tide range is 1.6 m (2 m maximum) and average wave height is 1.6 m, with 20% of the waves exceeding 2 m, 5% exceeding 3 m, 1% exceeding 4 m and very few may reach 8 m (Short and Trenaman, 1992).

In a 25.7 years period, five beach profiles have been surveyed 284 times, giving an average of one survey per 33 days [range 2-127 days]. An inverse relation between beach width of the northern and the southern part exists, effectively rotating around profile 4 (see figure 3-1), making this the ideal profile for long term erosion modelling (Short and Trenaman, 1992).

The offshore wave measurements were obtained from Botany Bay (Lawson and Abernethy, 1975, Youll, 1981, Trindade et al., 1993) and Long Reef (Kulmar et al., 2005), both located near Sydney (see Figure 1b for a topographical map).

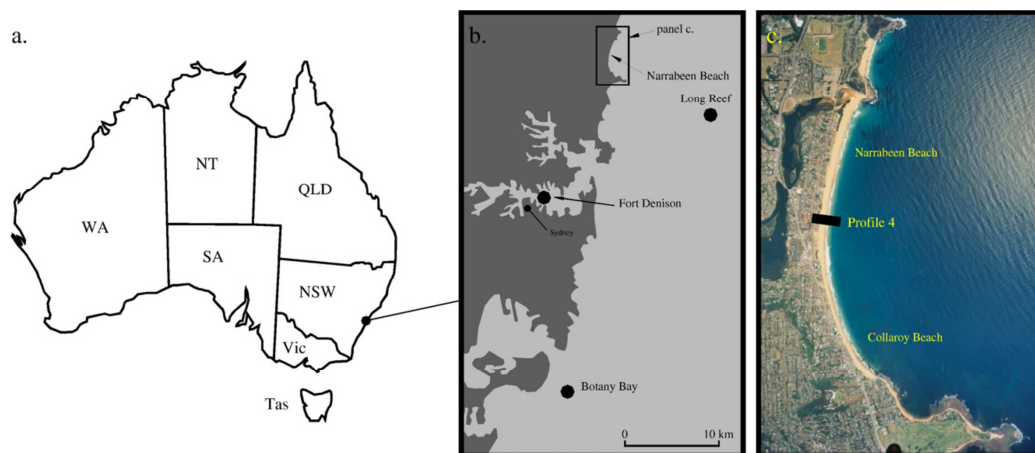


Figure 3-1; Location map for field measurements. a. Location of Sydney within Australia; b. The Botany Bay and Long Reef wave buoy locations and the Fort Denison tidal recording station; and c. The location of long term beach profile surveys at Narrabeen Beach (profile 4) (after Callaghan et al, 2008).



The bathymetry of Narrabeen beach profile 4 is shown in Figure 3-2; numerical data can be found in Appendix I. The post-storm profile has been measured at 10m. intervals to a depth of 0.85 below MSL, four days after the end of the storm (14<sup>th</sup> May 1997). In this period between the end of the storm and measurement, is the profile expected to change towards a new equilibrium profile. Ranasinghe et al. (2011) found the period for a beach to return to the pre-storm profile to be about 11 days, however with a large range and variability in location. For Narrabeen beach, Callaghan et al. (2008) assumed a period of 400 hours for beach recovery. Dunes, as eroded in this 1997 storm are expected to recover as fast as the beach, or slower. The measured profile, therefore, can be used to calibrate the XBeach model.

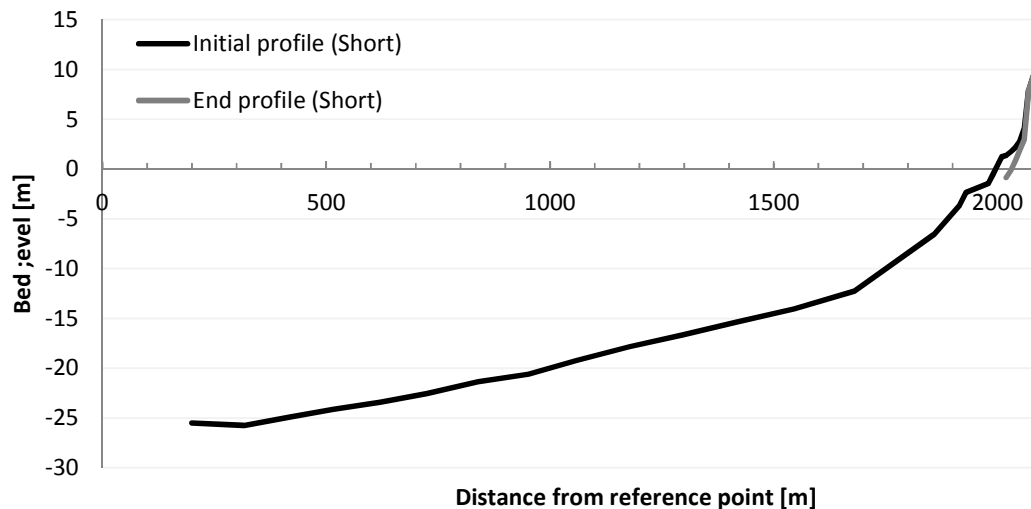


Figure 3-2; Bathymetry of Narrabeen beach before and after May 1997 storm. (A. Short)

### 3.2 Calibration 1; Narrabeen, Storm 1997

The model was calibrated on the first of two storms in the winter of 1997. The storm started on the 7<sup>th</sup> of May in 1997 and lasted for about 4 days. Wave height, wave period and water level during the storm are depicted in Figure 3-3.

Detailed wave and tidal data from Narrabeen beach are provided in Appendix I.

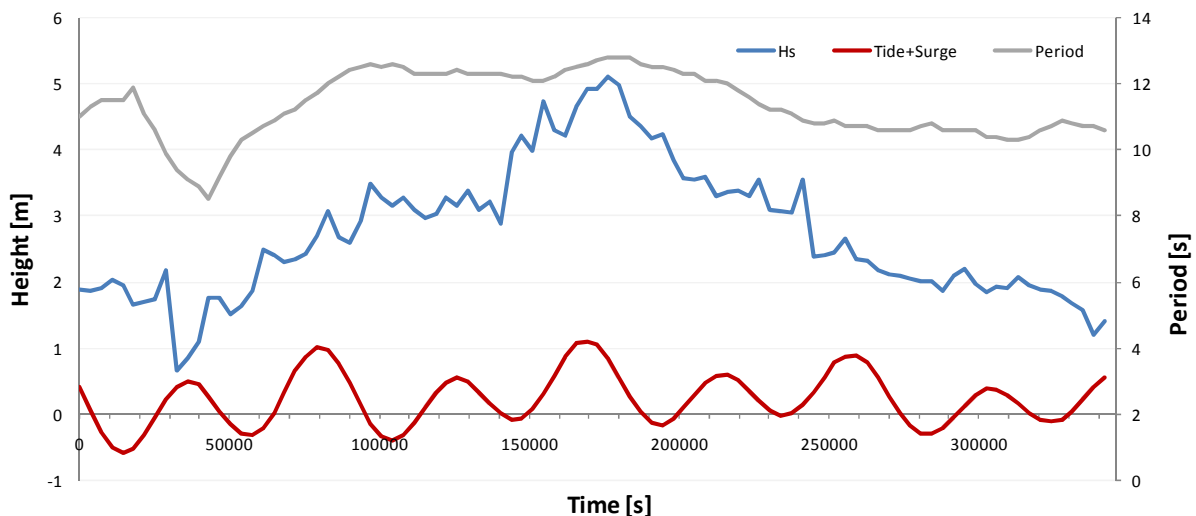


Figure 3-3; Significant Wave height, wave period and Tide plus Storm Surge during the may 1997 storm at Narrabeen Beach

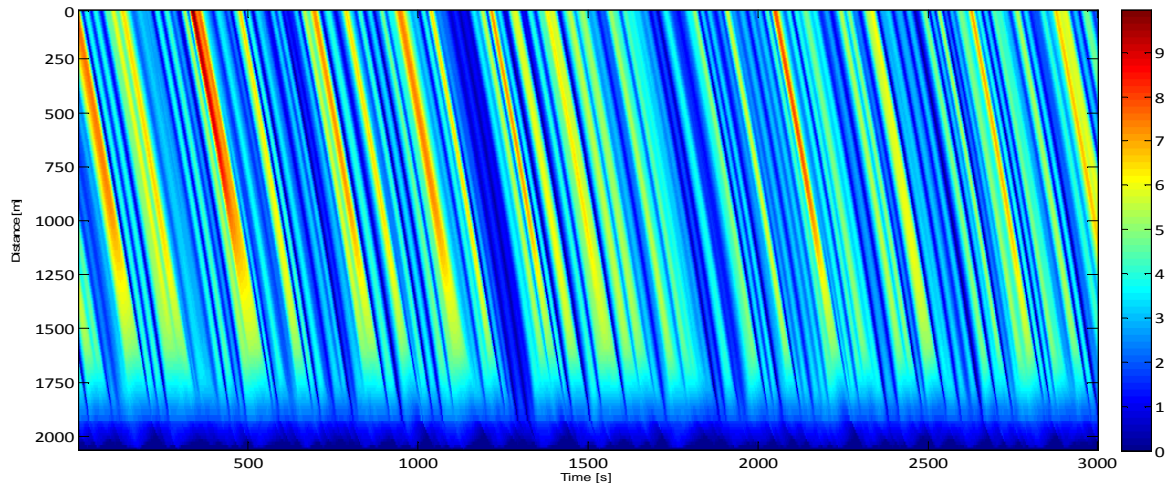


Figure 3-4; Height of envelope of wavegroups entering the computational domain over period of 3000s real time during peak of the storm, generated by XBeach (start at  $t=175000s$ ). Colour indicates height [m].

The pre-storm profile was measured just before the storm in April 1997 (Short) and post storm on the 15<sup>th</sup> of May 1997 (Short).

### 3.2.1 Results

XBeach calculates sediment transport and thus bed level change over the whole domain (see Figure 3-5). For the storm of 1997, only post-storm measurement till -0.85m. MSL exists. This research focus' is mainly on this area, as it the part of the beach which has been measured the most (Short) and is of the most importance when calculating erosion above the 2m+ contour.

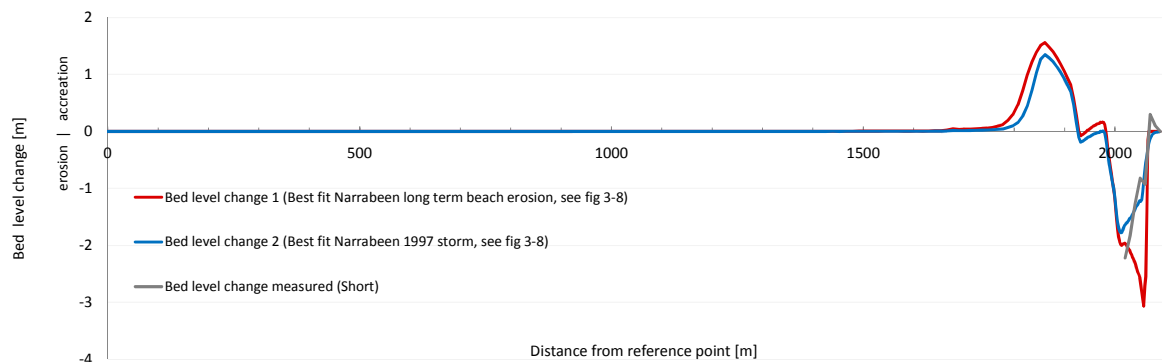


Figure 3-5; Beach accretion and erosion over the whole computational domain. Initial bed compared to end profile of simulations. Red line: simulated bed level change after 1997 storm (using setting leading to best fit in ong term beach erosion, see fig 3-8). Blue line: simulated bed level change after 1997 storm (using setting leading to best fit in 1997 storm, see fig 3-8). Grey line: Measured bed level change (Short) No post-storm data is available below -0.85m MSL.

The XBeach default settings led to a relative flat beach and low dune toe and a steep dune front, compared to Short's measurements. Varying values for  $\gamma$ ,  $\beta$ ,  $h_{min}$ , and the dryslip and wet slip for the avalanching module greatly changed the amount of erosion, but hardly changed the profile shape, see Figure 3-6 for results using  $break=1$ , and Figure 3-7 for results using  $break=3$ .

With a maximum still water level of about 1m+ MSL, most of the erosion measured by Short et al. (Short and Trembanis, 2004) is due to the swash. The absence of a swash model in XBeach might be a part of the problem in generating erosion above the 2 m contour.

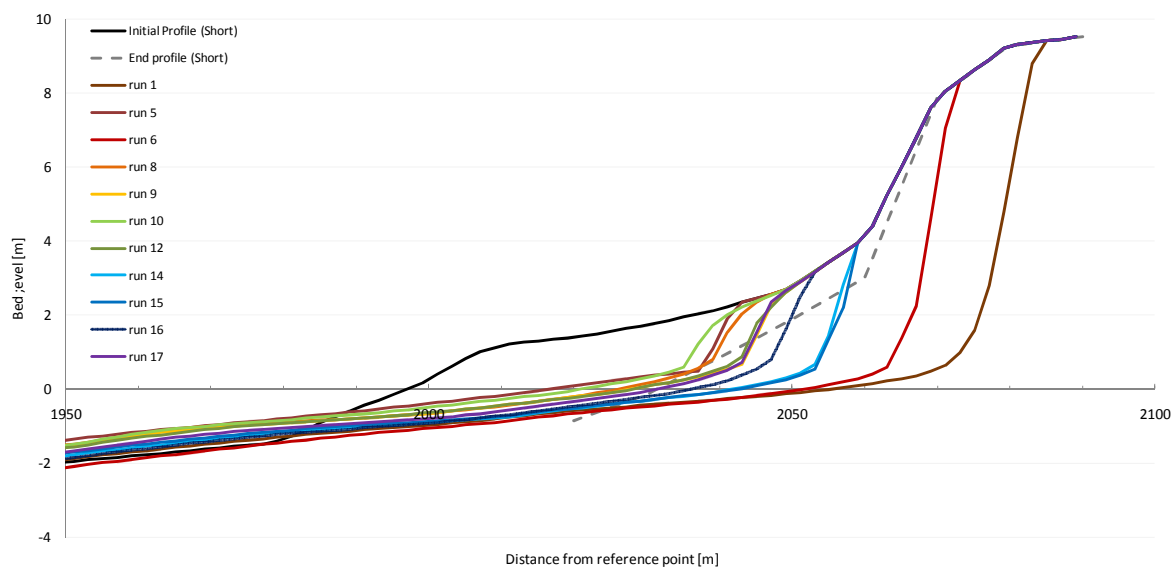


Figure 3-6; Measured profiles before and after the May 1997 storm and eleven results from different XBeach simulations with break=1. See Appendix I for input values.

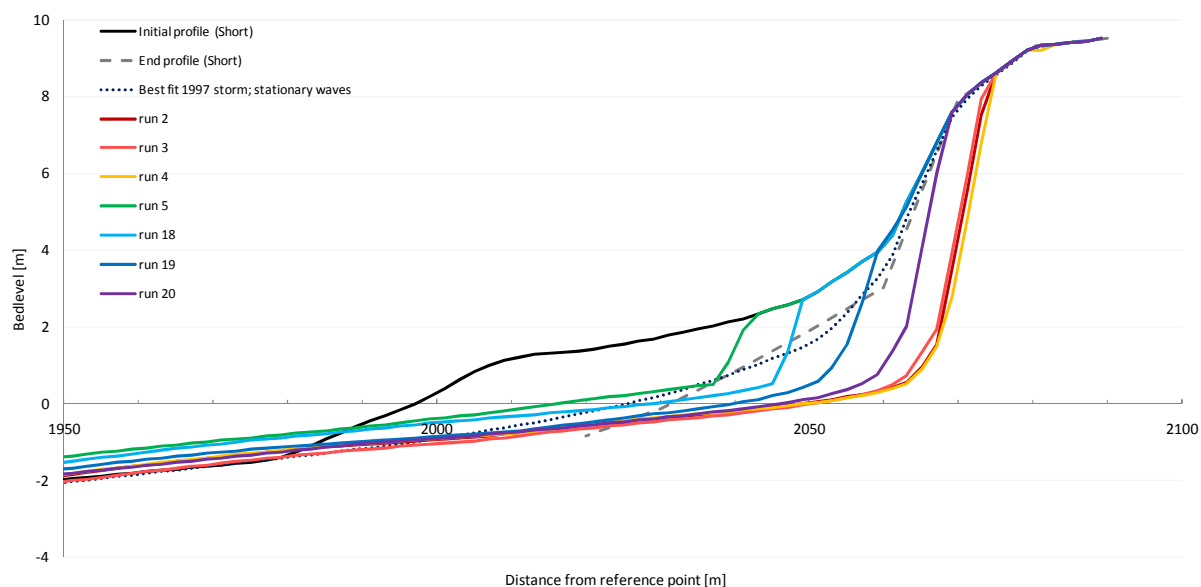


Figure 3-7; Measured profiles before and after the May 1997 storm and eight results from different XBeach simulations with break=3. See Appendix I for input values.

The best resemblance of the 1997 storm was simulated using the stationary<sup>3</sup> function in XBeach. Running XBeach with nonstationary<sup>4</sup> wave input and default values led to a too horizontal beach, a too steep dune face and overall too much erosion above the two metre contour.

In paragraph 3.4, XBeach was calibrated using the erosion measurements of the period 1971-2006 and the resulting erosion return period. The setup of XBeach leading to the best results when fitting to this whole dataset, led to the red line shown in Figure 3-8.

<sup>3</sup> Using *instat=40*, XBeach generates a sequence of stationary conditions (sea states).

<sup>4</sup> Using *instat=41*, XBeach generates a sequence of time-varying wave groups

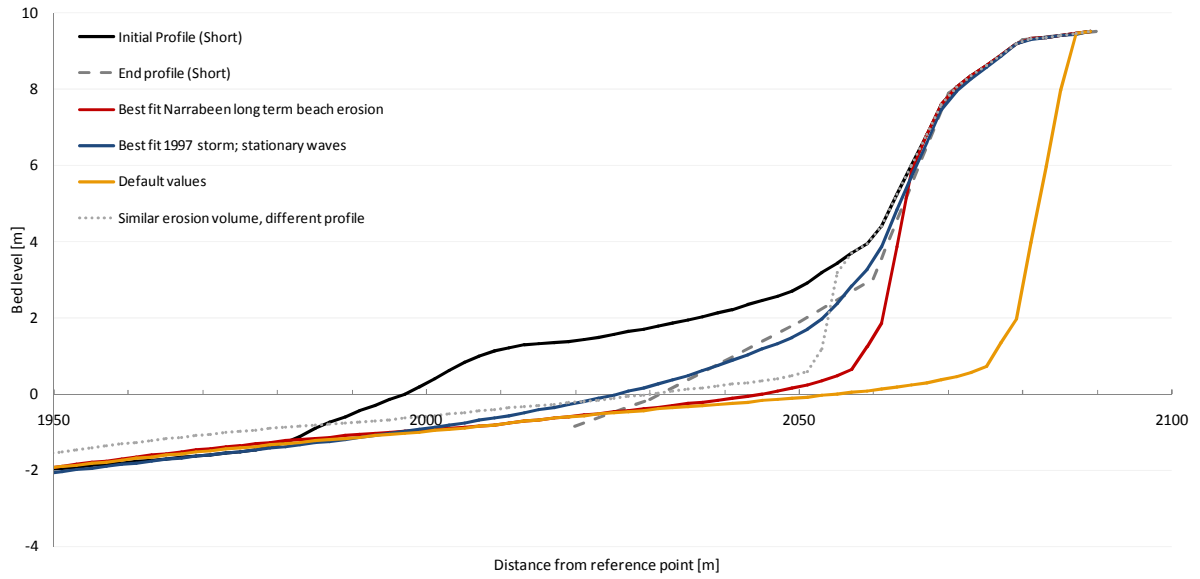


Figure 3-8; Measured profiles before and after the May 1997 storm and three results from different XBeach simulations; the blue profile is the best fit, achieved by using a stationary wave model (no wave groups), the red line is the result of the single run with parameters described in paragraph 3.4, the yellow line is the result of the default values of XBeach. The gray dotted line represents the result of an XBeach simulation leading to an equal amount of erosion (+2%) above the 2m+ contour line, however showing an different profile shape.

### 3.2.2 Detailed swash zone analysis

A more detailed analysis was done on the processes performed by XBeach in the swash zone. The analysis was done on a 1000 s. run at the most intense part of the storm, using a 2Hz sampling rate. Apart from the long wave height, which was determined using low and high pass filtering, all outputs were taken directly from XBeach. Since the volume concentration  $c$  of sediment is defined as  $\frac{\text{sediment}}{\text{water volume}}$ , transport is the rate of change of the concentration,  $\frac{\partial c}{\partial x}$ . The erosion or accretion is  $\frac{\frac{\partial c}{\partial x_{in}} - \frac{\partial c}{\partial x_{out}}}{\partial x}$ , and equals the change in rate of transport,  $\frac{\partial^2 c}{\partial x^2}$ .

This implies that the sign of the gradient of the transport is directly related to the erosion and accretion of the beach. This can be seen in Figure 3-9, where the resulting bed change is the inverse of the average sediment transport rate.

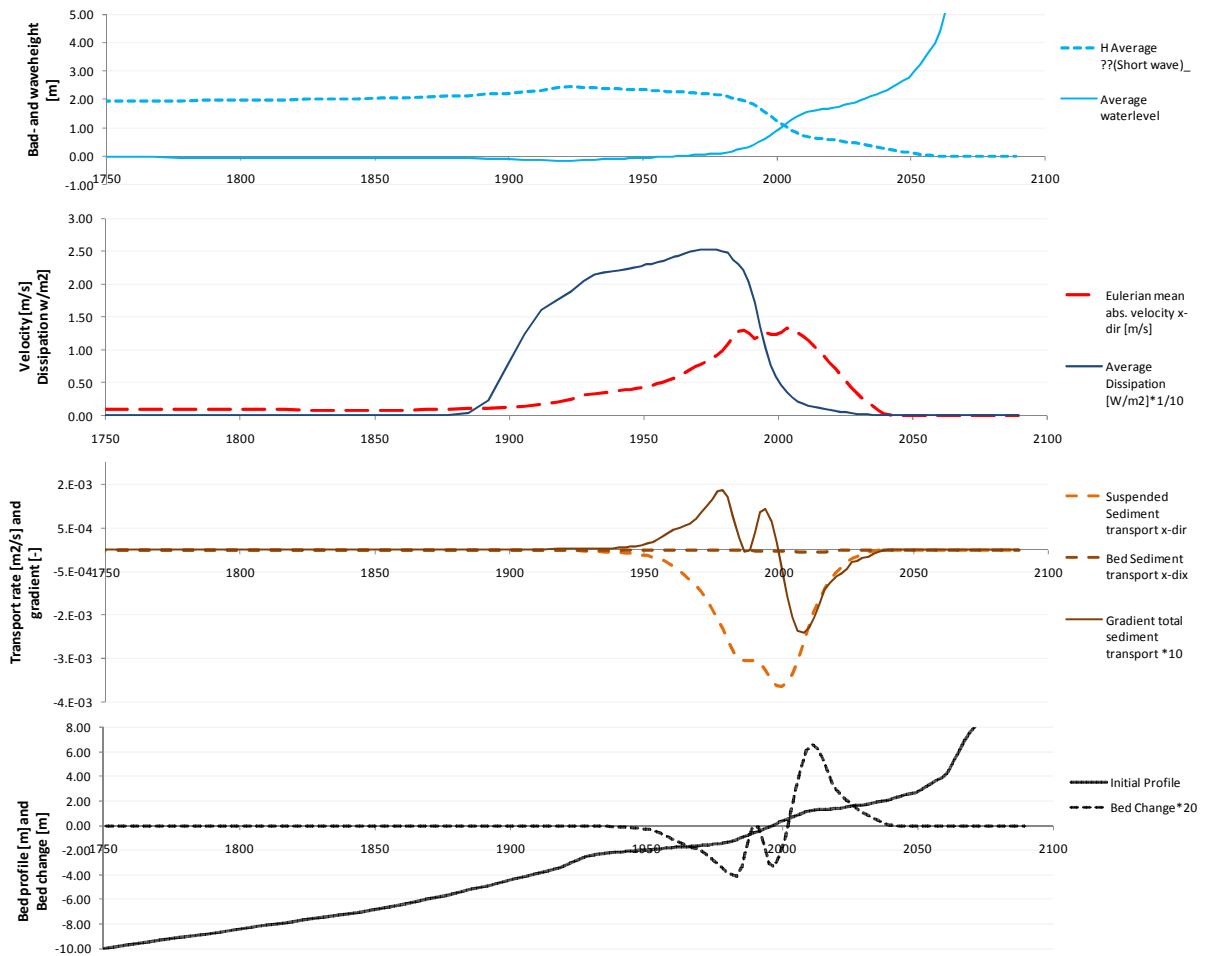


Figure 3-9; Detailed analysis of XBeach-output in the surf zone, Narrabeen, over period of 1000sec real time (sampling rate 2Hz) during peak of th storm ( $t_{start}=175000$  s).

### 3.2.3 Erosion development during storm

As Kriebel and Dean (1993), argued, the occurring erosion approaches the equilibrium response in an exponential manner. In other words, in a finite storm, the maximum erosion is less than the equilibrium response and has a phase lag.

A similar result is observed during the development of erosion of the XBeach model of Narrabeen, as is shown in Figure 3-10. (see Appendix III for method of calculating the amount of erosion during a storm)

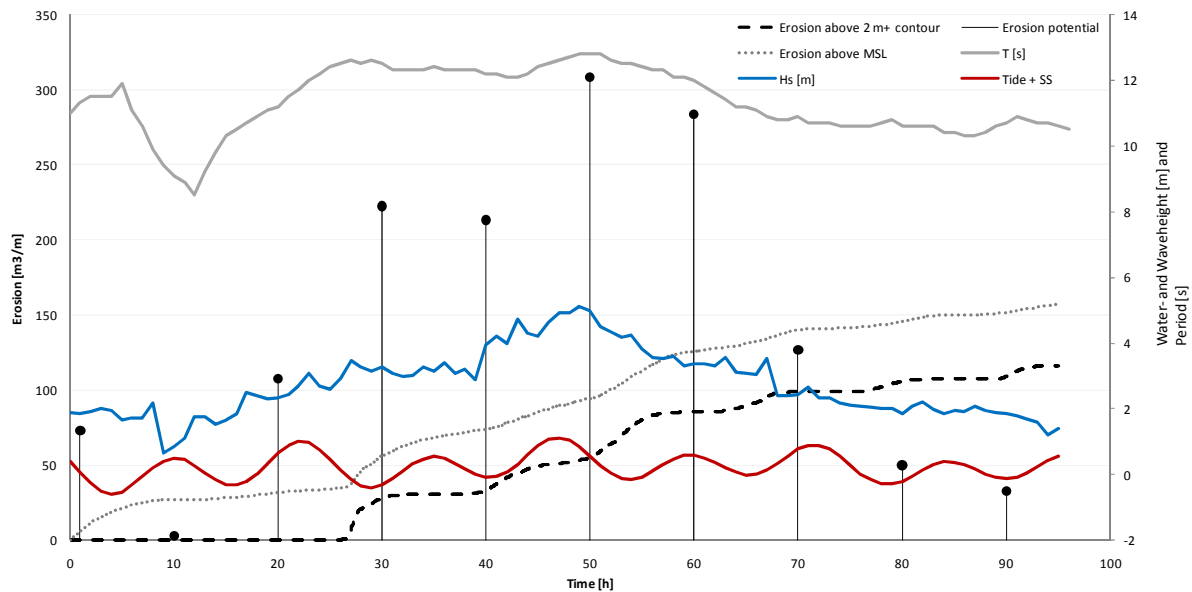


Figure 3-10; Erosion development above 2 m contour (Hoffman and Hibbert, 1987) and above MSL. The black dots represent instantaneous erosion potential, i.e., erosion after 10 days of storm with constant conditions.

The dashed line in Figure 3-10 represents the erosion ( $\text{m}^3/\text{m}$ ) above the 2 m contour, as defined by Hoffman and Hibbert (1987) (see Figure 4-4 on page 34). Kriebel and Dean (1993) defined the maximum potential retreat, or in this case, erosion potential, as the occurring erosion volume if the beach were to reach a new equilibrium relative to the water level and wave conditions.

Using Kriebel and Dean (1985), a practical limit of 240 hours was chosen as time to reach this equilibrium state. The validity of this limit was confirmed by exposing the beach to the wave parameters of the 1997 storm after 20 hours, for a 480 hour period. This 100% increase in storm duration yielded and 14% increase in erosion volume, which confirms the validity of the 240 hours limit.

In Figure 3-10, the black dots (•) represent the amount of erosion ( $\text{m}^3/\text{m}$ ) after a 10 day run with the instantaneous conditions held constant. The erosion potential was calculated using the initial bed profile.

While the storm is not idealized in any sense, as is the case in Kriebel and Dean (1985, 1993), a pattern similar to their predictions can be seen. The rate of erosion is at its maximum close to the moment at which the erosion potential is at its peak. While the erosion potential showed in Figure 3-10 is likely to be an overestimation due to the fact that the initial profile was used, instead of the current profile, the rate of erosion decreases to almost zero as the erosion potential approaches the observed erosion, or is bigger than the observed erosion.

A result of the XBeach model is the apparent step-profile of the growth of erosion, in which a relation with the tide can be seen.

Figure 3-10 shows a correlation between water level and rate of erosion. At water levels above MSL, the average rate of erosion [ $\text{m}^3/\text{m}/\text{s}$ ] is 3.3 times higher than during water levels below MSL. With a tidal range of 1.7m during this storm, the erosion is much more likely to reach the 2m contour during high tide, thus leading to more erosion.

Erosion above the MSL contour is shown as a comparison to the erosion development of the beach above the 2 m contour. The beach started to erode immediately after the run

commenced, as there is no sand to be removed first before the sand above the MSL contour can erode.

### 3.3 Calibration 2; Hasaki, 1997

In order to get a better understanding of results of the Narrabeen modelling of XBeach, a different beach with different grain size was modelled. Data was taken from the field experiments performed in the period 1990-1997 by Kubota et al. (Kubota et al., 1994, Kubota et al., 1997, Larson et al., 2004).

Kubota et al. (1994, 1997) artificially steepened the foreshore on Hasaki Beach (see Figure 3-11) and measured the change in topography as the beach returned to equilibrium profile. Prior to the experiment, measurements on the natural beach slope were carried out yielding close to zero net transport, indicating a beach in its equilibrium profile (Larson et al., 2004).

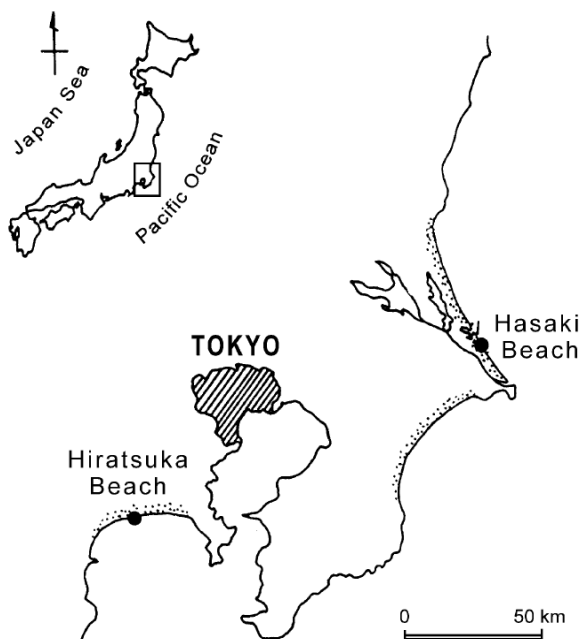


Figure 3-11; Hasaki Beach, located about 80 km east of location faces the Pacific ocean to the North-East (after Larson et al. 2004)

The relatively gentle foreshore of the beach is composed of fine sand with a median grain size of about 0.18 mm, the tidal range has a typical value of about 1.5 m. In the experiments, the waves with a significant wave height of 0.55 m and period of 13 s. were approximately normally incident to the shore and the measured longshore current was less than 0.2 m/s in the area immediately seaward of the swash zone (Larson et al., 2004).

In this case two different models were run using non-stationary mode in XBeach. First, the original equilibrium beach profile without artificial beach slope change was modelled and tested under the equilibrium sea state. Second, the changed profile was modelled, and the XBeach results have been run and compared with Kubota's measurements.

As the beach prior to adjustment was almost in equilibrium, the model was calibrated to a small difference in profile after a period of 2 tidal cycles. The default value of gamma, the breaker parameter, led to a too flat beach profile (not shown). With an initial beach slope of 0.05, the value for gamma was lowered to a 0.35 (Raubenheimer et al., 1996). This led to energy dissipation further from the coastline, and thus, to a slightly steeper beach with a slope of 0.04.

As the adjusted beach profile with a steepness of 0.13 was out of equilibrium with the wave conditions at the time, the beach eroded. The slope gradually dropped to 0.10 and sediment was transported down the beach.

As shown in Figure 3-12, the XBeach model narrowly follows the slope of the measurements. Similar to the calibration at Narrabeen, the erosion did not reach high enough up to the beach, resulting in a considerable smaller amount of erosion than defined by Hoffman and Hibbert's (1987).

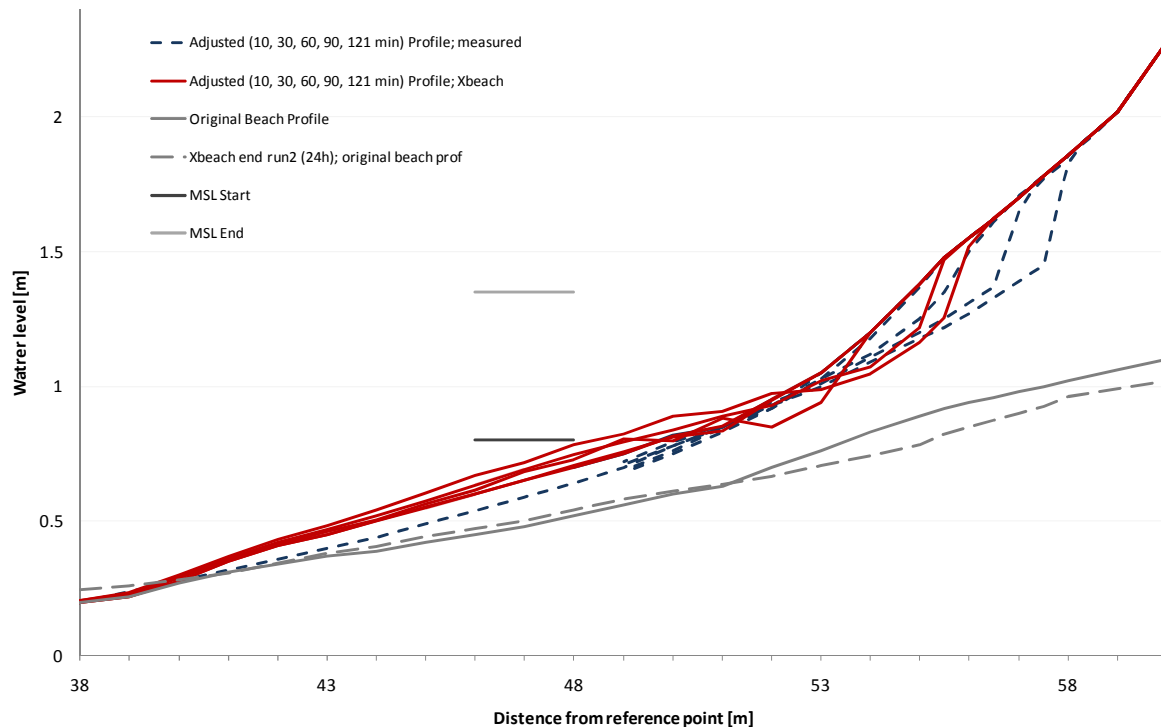


Figure 3-12; Comparison between measured (Larson et al. 2004) and calculated (break=1) beach profile, for adjusted and original beach profile. Note the sea water level at the start (+0.80m) and end (+1.35) of the measurement period.

A closer look at the processes in the surf zone is presented in Figure 3-13, in which especially the absence of bed-sediment transport is remarkable.



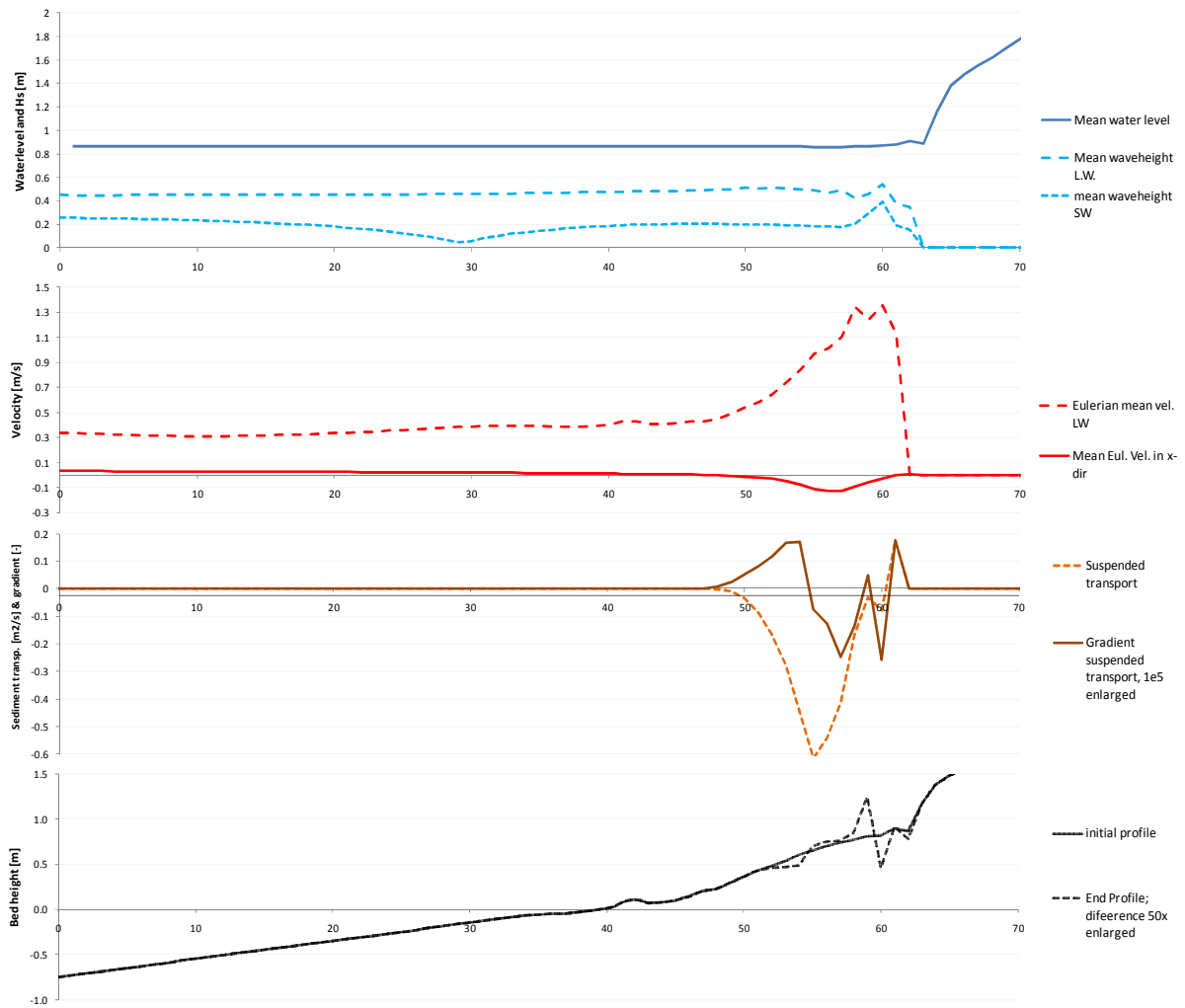


Figure 3-13; Detailed analysis of XBeach-output in the surf zone, Narrabeen.

### Adjusted to erosion

One reason for the difference in model results and the measurements can be the looseness of the sand, causing much faster sand erosion. Under the assumption that after one hour of wave impact some of the new sand is more compact, the period of one to two hours after the start of the run should resemble the model better. However, taking the one hour measured profile as a starting point, hardly improved the agreement between the model and the measurements.

Another difference in the XBeach model results compared to the experiment at Hasaki beach, was the shape in longshore direction. As the model assumed a uniform shape in longshore direction, no net longshore transport eroded material was placed in front of the swash zone where it decreases wave height and further erosion. In reality, material would spread out in longshore direction and higher erosion volumes in the measurements are thus expected. To adjust for this effect, the shape of the beach below sea level was manually set to the measured beach at half hours interval. The result after 2 hours was however still below the measured beach profile, excluding this effect as a significant factor in reducing the erosion.

Using *break* = 3 instead of *break* = 1 in the input file of XBeach, led to very good similarity with the measurements for the adjusted profile, as shown in Figure 3-14. The natural beach slope eroded slightly more than with the use of *break* = 1 (gray dashed line), but comparison remained reasonable.

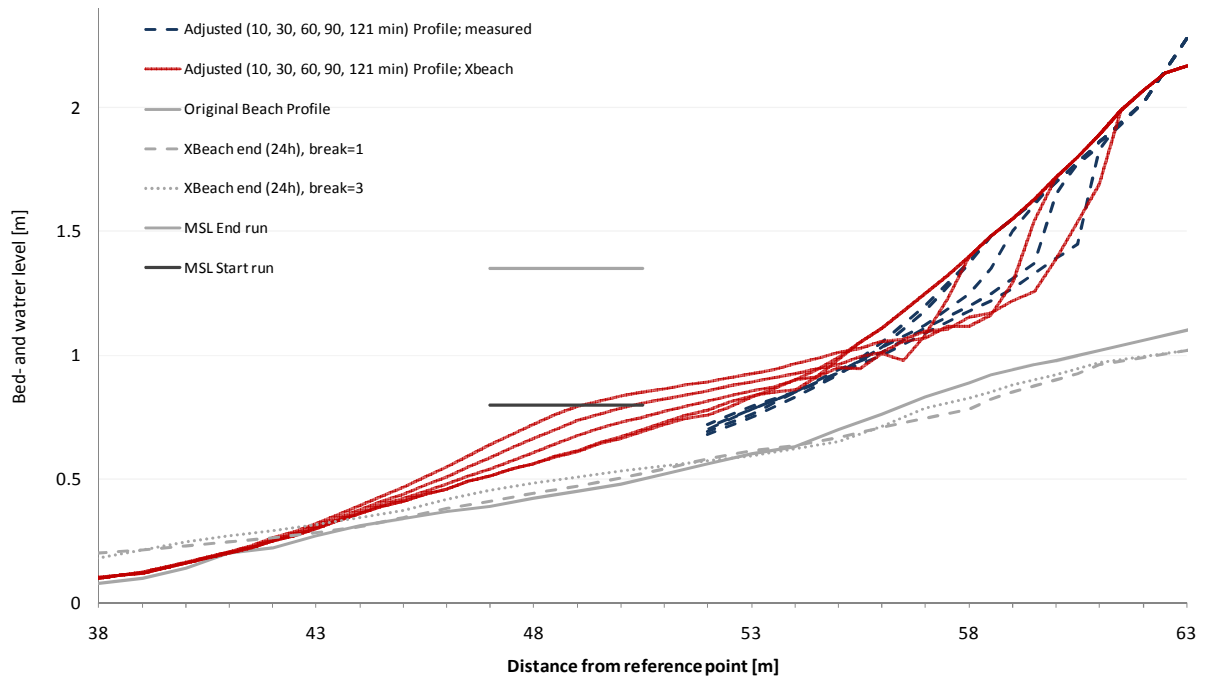
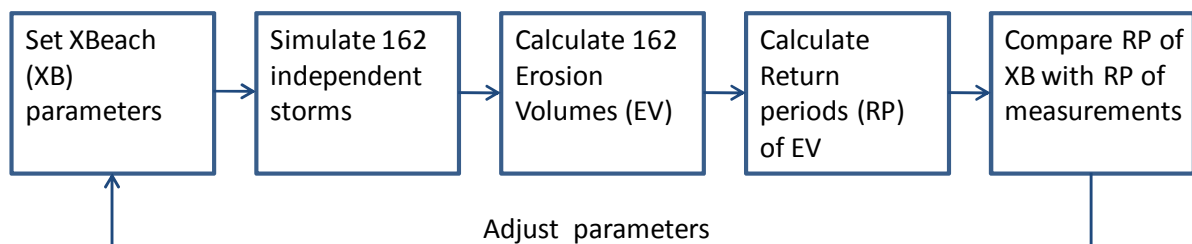


Figure 3-14; Comparison between measured (Larson et al. 2004) and calculated (*break* = 3) beach profile, for adjusted and original beach profile. Note the sea water level at the start (+0.80m) and end (+1.35) of the measurement period.

### 3.4 Calibration 3; Narrabeen 1971-2006

A different method of calibrating XBeach is fitting the resulting return periods, calculated with the JPM. In this case, 162 different and independent storms are simulated, and erosion volumes calculated. Of these 162 storms, probabilities are determined using the JPM, thus assigning return periods to the erosion volumes.



The return periods of erosion volumes is calculated using the Monte Carlo simulation described in Callaghan et al (2008b). This has been done for 22 different sets of parameters. The input parameters of each set of 162 simulations and the resulting erosion return periods are presented in Appendix V. The results of four of these sets of simulations are plotted in Figure 3-8.

First, the default values for XBeach were used, leading to a significant overestimations of the erosion volumes (yellow line). Second, the parameter set leading to the best results during the calibration at Narrabeen 1997 are used. This led to an slight underestimation of

the erosion volumes for the best fit for Narrabeen, but values remain with the confidence interval of the data for the smaller (<2 yr.) and bigger (>20 yr.) return periods.

The best fit of the erosion volume-return period to the measured return periods of erosion volume can be defined in three ways: (i) best fit on lower return periods, (ii) best overall fit (iii) best fit to high return periods. While from a safety perspective the biggest storms and erosion volumes are the most important, are they based on a relative few number of measurements, i.e. one new storm can change the tail. As the measurements with a lower return period (<2 year) are the most numerous and thus most robust, was XBeach calibrated on this part of the dataset.

The best fit of the 20 simulation-sets is shown in red; it predicts slightly lower erosion volumes for the higher return periods compared to the measurements. The line does show a downward curve near the higher return periods, as does the measurements, indicating a bounded erosion volume for the biggest storms.

The predictions of the JPM using XBeach, when calibrated on the storms with a low return period (<2 yr) remain within the confidence interval of the measurement data.

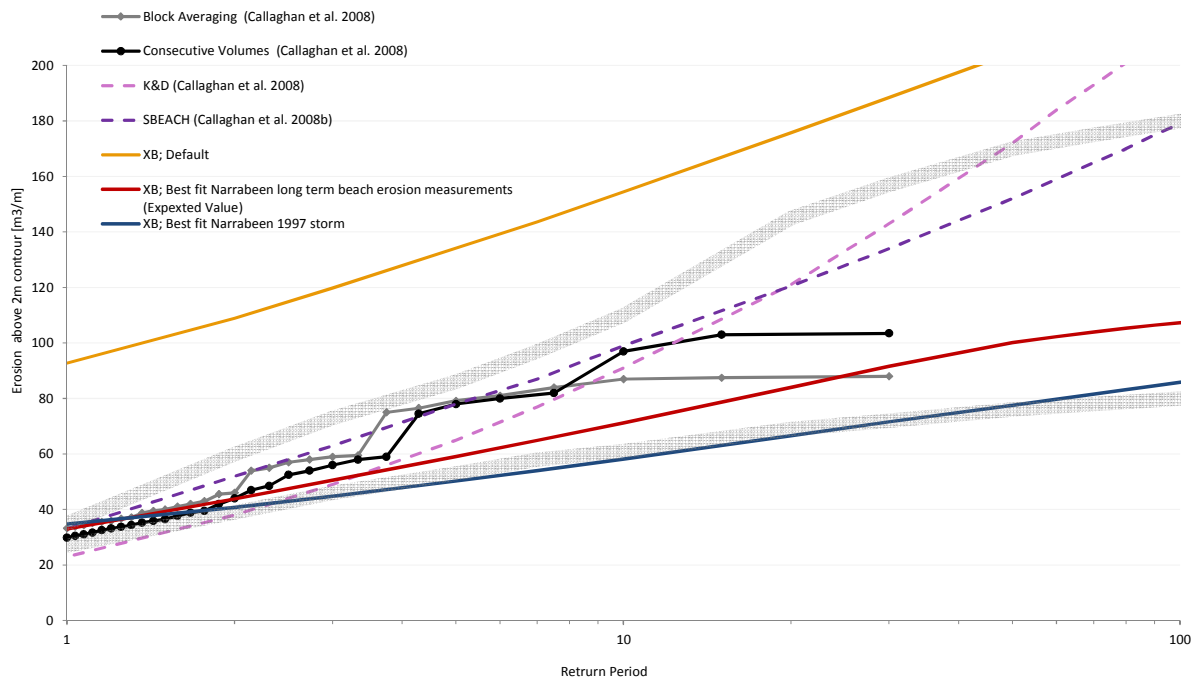


Figure 3-15; Erosion return period for Narrabeen beach. The gray and black lines represent the calculated Return Periods based on measurements. The red line resembles the best approximation to these measurements from the 20 simulations using  $Instat = 41$ ,  $Break = 1$ ,  $Roller = 1$ ,  $Beta = 0.18$ ,  $Gamma = 0.42$ ,  $Dryslp = 1$ ,  $Wetslp = 0.3$  (see Appendix V). The blue line is the approximation using the setup giving the best result on the single 1997 Narrabeen storm, using stationary waves. The yellow line is the result of the simulation using XBeach' default settings. The thick gray lines are the 95% confidence intervals of the data.

### 3.5 Conclusion and discussion

According to the Hasaki Beach calibration (paragraph 3.3), XBeach is able to model processes in the coastal zone well. The erosion, both quantitatively and qualitatively, of the adjusted beach profile is replicated to very good extent.

Even with erosion volumes and beach profile at Hasaki very close to the measurements, one still needs to be careful in concluding that XBeach is perfectly calibrated. One could argue, for instance, that the erosion modelled by XBeach at Hasaki, was probably too high. The reason being the lower compactness of the adjusted beach profile, leading to higher erosion than a natural beach under similar slope. Since XBeach did not take this effect into account, could a perfect match with the measurements be considered as a small overestimation of erosion by XBeach.

While XBeach performed well on the Hasaki 1997 beach, some discrepancies between measurements at Narrabeen and estimates from XBeach remain unresolved. The best fit to the 1997 measurements were obtained using stationary wave input, excluding one of XBeach's main innovations; the wave groups.

Using the nonstationary wave input led to either an over- or underestimation of erosion, depending on the chosen parameters. Virtually all runs ended with a beach being slightly too horizontal and dune face being too steep. As grain size differs considerably between Hasaki Beach and Narrabeen beach (0.18mm and 0.3 mm, respectively), is it unlikely to have caused most of the difference between measurement and simulation. Moreover, the program is tested and calibrated on, among others, the Dutch coast (Deltares, 2011), which has a similar grain size to Narrabeen.

The Narrabeen coast and simulated storm does differ from some of the beaches on which the program has been calibrated with respect to the storm surge and tidal range. The relatively small storm surge (maximum about 0.75 m.) at Narrabeen beach means most erosion above MSL is generated by wave impact, which is not directly included in XBeach (Ranasinghe R., 2011).

An overestimation of the berm erosion, and unlikely scarp formation by XBeach, was observed earlier by Voudoukas et al. (2011) at Faro Beach, Portugal. As in the case of Narrabeen, best results were obtained when excluding long waves.

These two cases could imply that the avalanching module, which works well in cases with considerable storm surge, is less effective on swell dominated beaches such as Narrabeen and Faro Beach.

In order to rely on XBeach to determine erosion volume – return periods, needs the eroded volume, as well as the resulting beach shape, to be consistent with measurement. The latter is especially of importance with longer storms, where a beach tends to shape to an equilibrium with the forcing, leading to a reduced rate of erosion.

To obtain this shape for steep, narrow beaches with little storm setup, a more detailed modelling of the swash zone could perhaps be beneficial. In the next paragraph, some literature describing the swash zone is reviewed.

Calibrating XBeach's erosion volumes and their probabilities on the measurements of Narrabeen lower return period erosion events (<2yr.), results in good resemblance to the measurement data, suggesting this method as a valid way to predict erosion volumes and their return periods in cases where long term measurement are absent.

### 3.5.1 Processes in the swash zone

XBeach can predict erosion in the swash zone to good extent, using the relatively simple avalanching module (Roelvink et al., 2009). However, it is shown that differences between

model and measurement remain in specific cases. Sediment transport in the swash zone is subject to many physical mechanisms, which are excluded from XBeach due to its use of a relative simple but efficient avalanching module. Here, some processes in the swash zone are described which are excluded in the XBeach version used in this research, and suggestions are made how to add processes to the modelling of the swash zone. Note; newer versions of XBeach include a groundwater module, as well as direct modelling of the swash zone. These versions of XBeach have not been tested here.

Firstly, a big difference in hydrodynamic conditions can be seen during run up, with decelerating flow, and run down, with accelerating flow. Infiltration leads to sediment being deposited on the beach slope, mainly caused by a smaller and shorter backwash, causing lower shear forces on particles and a higher effective weight, in turn leading to higher resistance against shear stress. However, inflow makes boundary layer thinner, increasing shear stress, in turn leading to more erosion (Nielsen, 2008). Exfiltration basically causes the reverse effects of infiltration, in a severe scenario leading to fluidization, which enhances the sediment transport rate even more (Elfrink and Baldock, 2002, Nielsen, 2008).

Bed load is affected by shear stress, a non-linear function of velocity, which implies that near bed skewness and asymmetry influence the bed load transport (Elfrink and Baldock, 2002). As the vertical velocity gradients in the bottom boundary layer are steeper during run-up than during the backwash, the shear stresses and bed load transport rates are higher during the run-up (Guard and Baldock, 2007). This is partially counteracted by the fact that the backwash takes longer, however, Baldock and Holmes (1997) reported a net sediment transport increased by a factor 4 for head gradients of -0.2m as a combined result of these effects.

Second, XBeach generates forcing in the swash zone by hydrostatic oscillations of short waves of different period, generating wave grouping. Their time-averaged forcing is then combined with an avalanche module to create erosion. Time-averaging of the swash itself generates an error that cannot be accounted for by choosing the right parameters. A representative monochromatic wave could simulate the wave energy and sediment stirring to good extent, but will under-estimate the maximum run-up under random wave conditions. Furthermore, the smoothing effect of the random wave run-up is ignored (Baldock et al., 2007).

Sediment transport in the swash zone can be calculated using a steady flow transport equation (Meyer-Peter and Müller, 1948). This equation is based on the difference between the critical Shields parameter and the actual Shields parameter. As the equation is based on steady flow, inertia forces are not included. One of the problems with oscillating flow is to find the instantaneous Shields parameter. Nielsen (2002) proposes eq. (11) for calculating the instantaneous skin friction Shields parameter,  $\theta_{2.5}$ , numerically.

$$\theta_{2.5}(t) = \frac{1}{2} \frac{f_{2.5}}{(s-1)gd_{50}} (A_{rms})^n \cdot \left( \cos \varphi_t u_{\infty}(t) \sin \varphi_t \frac{u_{\infty}((t + \delta_t) - u_{\infty}(t - \delta_t))}{2\omega_p \delta_t} \right)^{2-n} \cdot \frac{u_*(t)}{|u_*(t)|} \quad (11)$$

with a bed roughness of  $2.5d_{50}$ . The value of  $n$  is  $\in [0;1]$  with a fully harmonic free flow velocity  $u_{\infty}(t)$  if  $n=1$  (Nielsen, 1992) and  $u_{\infty}(t)$  with a steeper front face if  $n>0$ .  $\omega_p = \frac{2\pi}{T_s}$  is the peak angular frequency,  $\delta_t$  is time step, and  $\varphi_t$  is the phase lead of the bed shear stress

over the friction velocity. Equation (12) is used to calculate the corresponding instantaneous friction velocity,  $u_*(t)$ .

$$u_*(t) = \sqrt{\frac{1}{2} f_{2.5}} \left( \cos \varphi_t u_*(t) + \sin(\varphi_t) \frac{u_\infty(t + \varphi_t) - u_\infty(t - \varphi_t)}{2\omega_p \varphi_t} \right) \quad (12)$$

The representative near-bed semi-excursion,  $A_{rms}$ , is based on the variance of the overall free flow velocity  $u_\infty$ , and is given in equation (13)

$$A_{rms} = \frac{\sqrt{2}}{\omega_p} \sqrt{Var(u_\infty(t))} \quad (13)$$

Applying equation (11), (12) and (13) to the swash zone, Nielsen (2002) reported the following pickup function,

$$\Phi(t) = \begin{cases} 0 & \text{for } \theta_{2.5} < 0.05 \\ C(\theta_{2.5} - 0.05) \sqrt{\theta_{2.5}} \frac{u_*(t)}{|u_*(t)|} & \text{for } \theta_{2.5} > 0.05 \end{cases} \quad (14)$$

And suggested the following C values for uprush and downrush.

$$C_{uprush} = 19.9 \pm 4.1$$

$$C_{downrush} = 8.9 \pm 1.7$$

Nielsen's analysis is based on a dataset in which the flow in the swash zone accelerates for a significant part of the swash cycle (Masselink and Hughes, 1998). During the experiment, the current was measured using spinning current meters in the swash zone. Part of the acceleration might thus be caused by the initial acceleration of the instruments. Baldock and Huges (2006) measured surface slope in the surf zone using a set of horizontal wires. They reported, apart from the zone up to 0.5m from the front bore, a virtually always sloping seaward surface level of the swash zone was, which makes acceleration in the swash uprush highly unlikely. The seaward averaged swash profile causes problems in generation of accretion using Soulsby-van Rijn. This problem can be solved by defining the sediment transport direction based on the difference between the gradient of the instantaneous profile and the gradient of the equilibrium profile (Baldock et al., 2007). A great disadvantage of Baldock's (2007) method, however, is the uncertainty in the assumed equilibrium profile.

While accretion in the swash zone is negligible during storm conditions, it might be relevant during calm conditions. Infiltration, as described before, is essential for accretion in the swash zone. Baldock et al. (2007) showed the need for variable run-up using a probabilistic-deterministic approach with Rayleigh distributed bore heights and net transport. This method showed little difference between a monochromatic and probabilistic approach in case of erosion however showed significant difference in case of accretion. Alsina et al. (2009) showed the importance of advection in the swash zone, measuring 25% of the pre-suspended sediment reaching the mid-swash zone.

A model including more processes in the swash zone might improve the results on the beaches named before, and will, in any case, lead to a better understanding of the complex mechanisms involved in sediment transport in the swash zone.

## 4 Long term erosion prediction

### 4.1 Introduction

Optimally, the model is calibrated to replicate field measurements and subsequently used for a long term prediction; it was however decided to proceed with XBeach as it stands.

To avoid the risk of losing the relationship with reality, it was decided to continue the long-term (return period of about 100 year) erosion prediction using standard XBeach values.

Joint probability refers to two or more partially related environmental variables occurring simultaneously to produce a response of interest (Hawkes et al., 2002). In this study, five different variables were considered, and the response of interest, beach erosion, was calculated using XBeach.

Optimally, the different input parameters were taken randomly from a fitting distribution, and ran in the XBeach model. Due to the large numbers of simulations in this study, this would have led to practical problems in switching between the statistics program and the XBeach module at the High Performance Computer (HPC). Therefore, a high density transfer matrix, instead of random input parameters, was used. This transfer matrix is a six (five parameters and erosion volume) by  $n$  matrix, where  $n$  is the total simulated storm events. Erosion volumes caused by storms which are not transfer matrix are determined using linear inter- or extrapolation. Using a high density transfer matrix (large  $n$ ) reduces the error caused by this inter- and extrapolation, but requires more computational effort.

For the initial run, an average beach profile of Narrabeen beach, as described in paragraph 3.1, was selected. As a minimum threshold for a storm simulation, an offshore significant wave height of 3 m was taken. This threshold with an exceedance probability of about 4% for the South-Eastern Australian coast (Lord and Kulmar, 2000) allows for a sufficient amount of events to be defined to calculate extreme probability density, with most of the events being unrelated. This threshold value of 3 m would be caused by a slightly higher offshore wave height, resulting in 3.1 m as a minimum significant wave height. Wave heights of more than 15 m are rare (<1,5%, (Lord and Kulmar, 2000) and therefore unlikely to significantly impact the long term prediction.

The wave height during a storm was simulated from  $H_{s,Base}$  and  $H_{s,Peak}$ , using a  $\sin^2$  function, (see Figure 4-1). A filter was implemented to avoid unrealistic combinations of large waves and short wave periods and to limit the wave height according to equation  $T_{s,min} \approx 3.9\sqrt{H_s}$  (Callaghan et al., 2008b) Both  $H_{s,Base}$  and  $H_{s,Peak}$  have been determined using SWAN, transforming wave characteristics from the measurement site to the edge of the computational domain of XBeach at the Narrabeen beach.

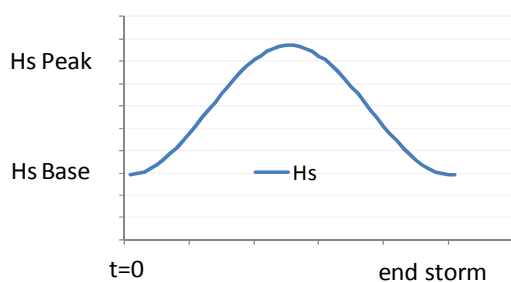


Figure 4-1; Significant wave height during storm

A range of zero crossing periods of 6-12 s have been selected, covering about 85% of the wave periods that were observed in the field. The higher prevalence of the region 8-11 seconds during storms in the simulations reflects the higher density observed in the field (about 50%) (Short and Trenaman, 1992).

Waves in this region (latitude 33° 42') are generated by five meteorological systems: tropical cyclones, east-coast cyclones, mid-latitude cyclones, zonal anticyclones heights, and local summer sea breezes. The east-coast cyclones usually last the longest, about 4-5 days (Short and Trenaman, 1992), hence a maximum duration of 5 days (432000 s.) has been modelled.

The wave angle was transformed to nearshore wave angle using a SWAN model, in which the angle is defined in respect to the shore normal. A maximum Storm Surge of 0.7 m was modelled, in which  $SS = \text{measured MSL} - \text{Predicted MSL}$ . The storm surge was held constant during the storm. Due to relatively small wave heights at the start and of the storm, does the overestimation of the surge at the beginning and end of the storm cause a likely, but small overestimation of the erosion. The tide at Narrabeen is predominantly a M2 tide, the amplitude was set at 1m, close to the local maximum.

## 4.2 Tidal phase

A check was performed to verify possible influences of phase of the tide on the amount of erosion. Three scenarios were compared, (a) high tide at the peak of the storm, (b) low tide at the peak of the storm, and (c) mid-tide (MSL+SS) during the peak of the storm.

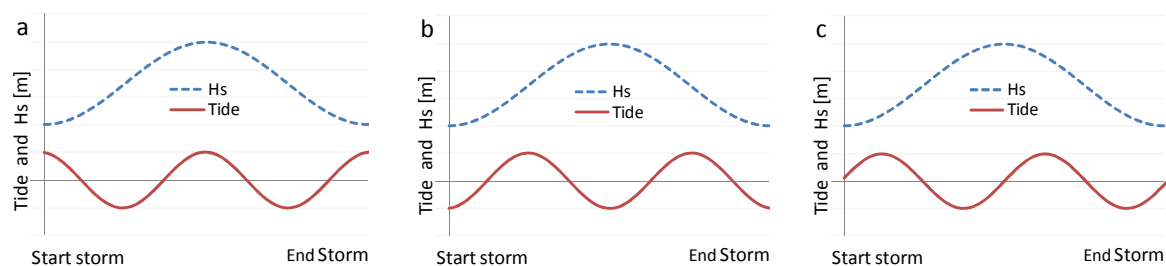


Figure 4-2; tide during a one day (24h) storm.

In 3 x 108 model trial runs, the variables shown in Table 4-1 were combined with the tidal phase as explained above.

	1	2	3
Hs [m]	3.1	10	15
T [s]	6	9	12
D [s]	86400	432000	
Angle [°]	10	60	90
S [m]	0.25	0.7	

Table 4-1; Offshore variables used in 3·3·2·3·2=108 trail runs in XBeach

Using model runs with identical wave forcing, i.e., no random wave generation, for scenario a, b and c, a return period as calculated.

As shown in Figure 4-3, compared to scenario c, scenario a and b led to higher and lower return periods, respectively, therefore a tidal phase was chosen for the full calculation in which MSL+SS coincides with the middle of the storm period. This is in accordance with the average value of the tide during the peak of the storm; MSL.



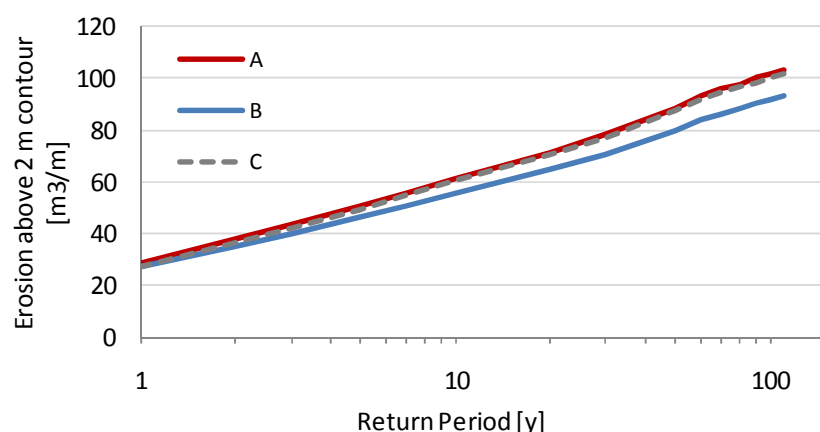


Figure 4-3; Return interval of erosion volume with three different tidal phases, taken from 108 different storms.

### 4.3 Transfer matrix

The transfer matrix consists of 8800 discrete possible combinations of 5 different variables, as shown in Table 4-2. The input values used in the matrix represent a wide range of possible parameter values, with a slightly higher density at the most common or interesting values.

	1	2	3	4	5	6	7	8	9	10	11
Hs [m]	<b>3.1</b>	3.5	4.5	6	7	<b>8</b>	9	10	11.5	13	<b>15</b>
T [s]	<b>6</b>	7	8	8.5	<b>9</b>	9.5	10	10.5	11	<b>12</b>	
D [s]	<b>86400</b>	172800	259200	345600	<b>432000</b>						
θ [°]	<b>10</b>	<b>30</b>	60	<b>90</b>							
SS [m]	<b>0</b>	0.25	<b>0.5</b>	<b>0.7</b>							

Table 4-2; Offshore variables used in  $11 \cdot 10 \cdot 5 \cdot 4 \cdot 4 = 8800$  XBeach runs. Using just the variables printed in bold leads to a reduction of more than 98% in computational time, still providing more than 95% accuracy (see paragraph 4.7 for further discussion)

For each scenario, individual input files were written in FORTRAN 90, and saved into separate directories. The directories were copied to the HPC at The University of Queensland, and ran independently, minimising risk of interference with a possible error. The simulations started with the same, average, beach profile.

Using MATLAB (2010B), the erosion volume per scenario was calculated using the Hoffman and Hibbert's (1987) method (see Figure 4-4) and was written into the (8800 \* 6) Transfer Matrix.

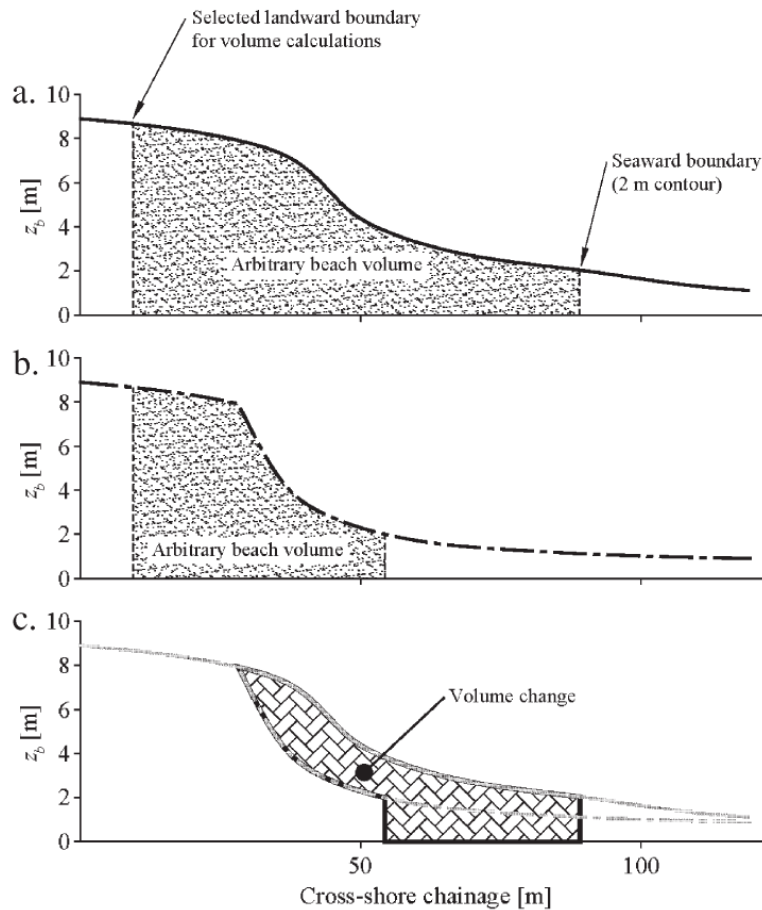


Figure 4-4; Beach volume change definition sketch after Callaghan et al. 2008 for a. Pre-storm, b. Post-storm, c. Beach volume change.

XBeach showed a considerable failure rate at the higher end of the storms simulations, i.e., high significant waves and long wave periods (see Figure 4-5).

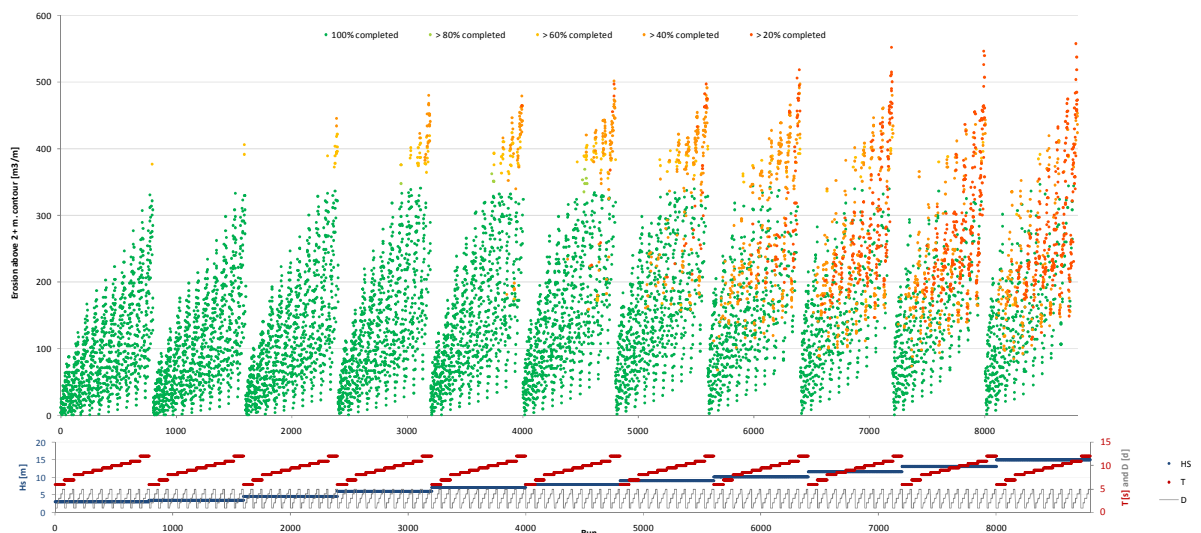


Figure 4-5; Erosion volume for 8800 modelled storm scenarios. Colour of the dots in upper panel represents the degree of completion before XBeach aborted the run. Erosion volumes for incomplete runs have been extrapolated. The lower panel indicates the input for the runs (wave angle and storm surge excluded from lower panel) showing a higher crash rate for higher wave heights and longer wave periods.

## 4.4 Model results

### 4.4.1 Results XBeach

As too many of the 8800 runs failed to compare results of individual runs, a new set of 1080 simulations has been run to completion, to compare erosion volumes generated at different wave parameters.

1080	1	2	3	4	5	6
Hs [m]	3.1	4.5	7	9	11.5	15
T [s]	6	8	9	10	11	
D [s]	86400	259200	432000			
Θ [°]	10	30	60	90		
SS [m]	0.25	0.5	0.7			

Table 4-3; Offshore variables used in  $6 \cdot 5 \cdot 3 \cdot 4 \cdot 3 = 1080$  XBeach runs, used in paragraph 4.4, 4.5 and 4.6.

As shown in Figure 4-6, Figure 4-7 and Figure 4-8, in many situations the development of erosion above the 2m+ contour is almost linear with time. It should be noted that the results in the graphs are obtained from separate XBeach runs, e.g., the erosion after two days (with given parameters) was determined with an independent run from the erosion after three days, using the same parameters. Given the randomness in the wave generation module in XBeach, it is in theory possible to get lower amounts of erosion after three, than after two days. However, a re-simulation of 613 storm scenarios revealed an average erosion volume difference of only 2.5%, with a standard variation of 2.9%. This means that the random wave generation has little influence on the final erosion volume, which is also resembled by the monotonic behaviour of the figures.

Only during intense storms with Hs offshore of over 10 m and/or wave periods of over 10s. a clear decrease in erosion rate can be seen, suggesting a beach close(r) to it's equilibrium. This contrasts the findings of Kriebel and Dean (1993), who suggested equation (15) to calculate the characteristic timescale  $T_s$  of the erosive and accretive exponential response.

$$T_s = C_1 \frac{H_b^{3/2}}{g^{1/2} A^3} \left( 1 + \frac{h_b}{B+D} + \frac{mx_b}{h_b} \right)^{-1} \quad (15)$$

in which  $H_b = 0.78h_b$ , based on Miche's breaking criterion,  $h_b$  represents the breaking depth,  $m$  the linear beach-face slope, and  $x_0$  the distance from the still-water shoreline to the virtual origin of the concave equilibrium profile form, given by  $x_0$  is  $hT/3m$ , where  $hT$  is the depth at which the linear slope is tangent to the concave profile,  $B+D$  is berm + dune height,  $A$  a parameter that varies primarily with fall velocity, and  $C_1$  a dimensionless constant with a value of 320.

With a greater wave height, and all else being equal, the breaking depth will increase, therefore the characteristic timescale  $T_s$  of erosion will increase.

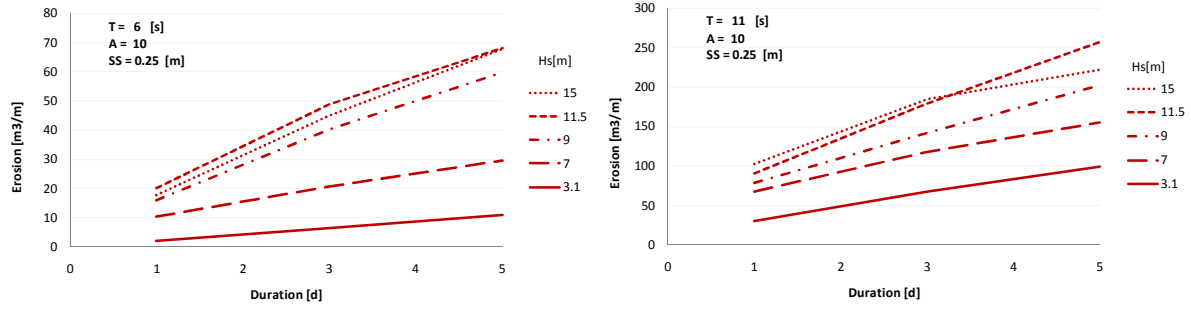


Figure 4-6; Erosion occurring at storms of variable duration, shown for 5 different offshore significant wave heights. Period 6s. (Left panel) and 11s. (Right panel). Results are from independent, separate model runs.  $T$  stands for the peak period [s],  $A$  for the angle to the shore-normal [°] and  $SS$  for the storm surge or tidal anomaly [m].

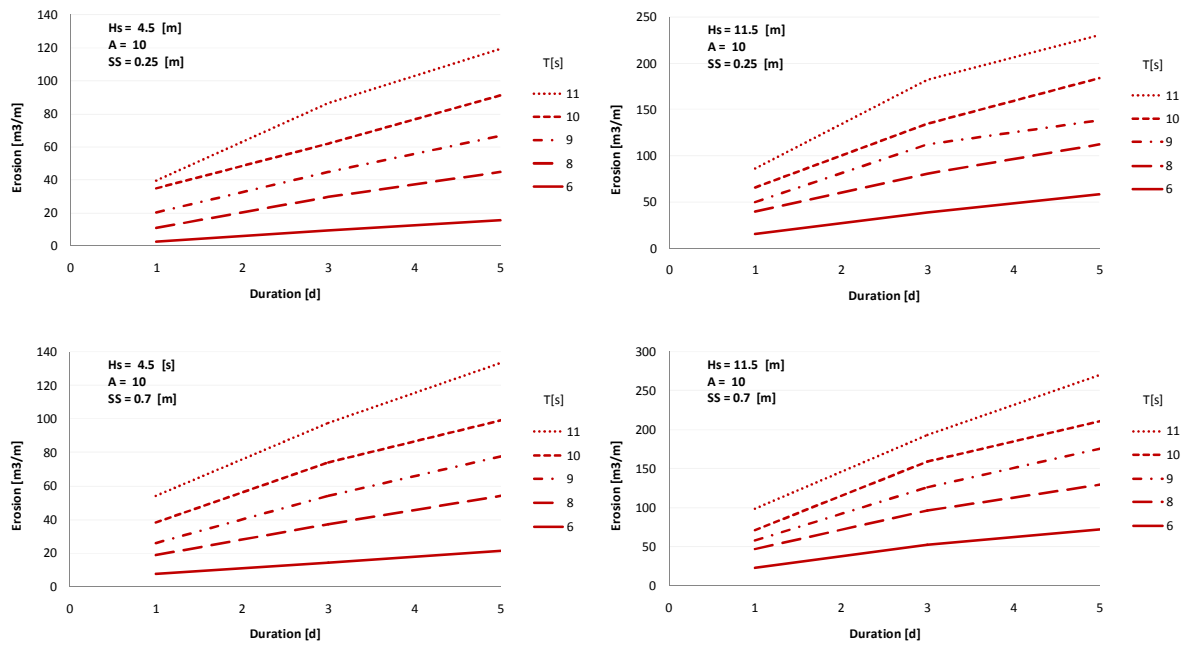


Figure 4-7; Erosion occurring at storms of variable duration, shown for 5 different offshore wave periods. Offshore significant wave height 4.5m, Storm Surge =0.25 m (Upper left panel) and 11.5 m (Upper right panel). The upper two panels have a storm surge of 0.25m; the two lower panels have a storm surge of 0.25 m. Results are from independent, separate model runs.  $H_s$  represent the offshore significant wave height.

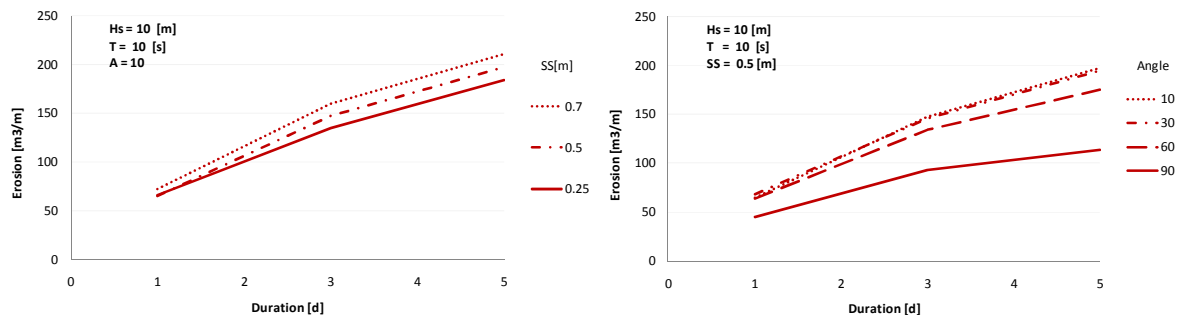


Figure 4-8; Erosion occurring at storms of variable duration, shown for 3 different storm surges (Left panel) and erosion with waves under 4 different wave angles (in respect to shore-normal) (Right panel). Results are from independent, separate model runs.

#### 4.5 El Niño/La Niña long term effect

As discussed earlier, part of the effects of climate change will be the change in the distribution of years dominated by La Niña and years dominated by El Niño. The possible effects of this changing distribution were determined by different distributions in wave height and storm duration, during a La Niña year opposed to an El Niño year. Also, a distinction is made in the number of storms.

The number of storms affecting the Central Coast of New South Wales, Australia, have been counted over the period 1880-1980. Using a negative yearly average ENSO as an indication of a El Niño year, and a positive yearly average ENSO as indication for a La Niña year, the average number of storms ( $H_s > 2.5$  m) per La Niña and El Niño were determined. Determining the number of storms per La Niña year and El Niño year when for each storm the *monthly* ENSO was used, instead of the yearly average, yielded very similar results.

58 La Niña years showed an average of 5.2 storms per year whereas 42 El Niño years showed an average of 5.4 storms per year implying 3% more storm events in El Niño years. As the majority of the data was obtained from observations onshore, the number of storm events were compared to data obtained from a wave buoy at Botany Bay, using  $H_s > 3$  m as threshold.

Analysis of 36 years (1971-2006) at Botany Bay showed a similar pattern; with more storm events during El Niño years. This is in contrast with Ranasinghe et al. (2004) who reported twice as many storms during La Niña compared to El Niño years, however with a slightly different definition of a storm ( $H_s > 2.5$  m, opposed to  $H_s > 3.0$  m. in this study).

The duration and maximum significant wave height was higher during the La Niña years, see Table 4-4.

	Measurement years [y] (%)			Number of storms [-] ( <i>average</i> )		
	All	El Niño	La Niña	All	El Niño	La Niña
1880-1980	100	42 (42%)	58 (58%)	526 (5.26/y)	225 (5.36/y)	301 (5.19/y)
1971-2006	35	22.3 (72%)	12.7 (36%)	703 (20.1/y)	471 (21.1/y)	232 (18.3/y)

	Storm Duration [h] and ( <i>stdev</i> )			Offshore $H_s$ [m] and ( <i>stdev</i> )		
	All	El Niño	La Niña	All	El Niño	La Niña
1880-1980	-	-	-	-	-	-
1971-2006	21.1 (22.4)	19.5 (21.1)	23.7 (24.6)	4.09 (0.92)	4.07 (0.88)	4.13 (1.02)

Table 4-4; Comparison of number of storms, storm duration and significant wave height in El Niño and La Niña years. Data on storm duration and offshore significant wave height in the period 1880-1970 was either not available or not reliable.

To simulate the effect of a change in distribution of El Niño and La Niña years, the statistical distribution of storm duration ( $D$ ) and offshore significant wave height ( $H_s$ ) is required.

Both,  $D$  and offshore significant wave height are assumed to be modeled by a Generalized Pareto distribution (GDP), given by

$$Pr\{X > x | X > u\} = \int_u^x \left[ 1 + \xi \left( \frac{x-u}{\sigma} \right) \right]^{-\frac{1}{\xi}} \quad (16)$$

where  $\sigma$  and  $\xi$  represent the GP scale and shape parameters,  $u$  the value above which the distribution is assumed to be exponential, and  $\xi \neq 0$  (Coles, 2001).

To fit the parameters, the log-likelihood  $l$ , given by eq. (17) for  $\xi \neq 0$ , was maximized.

$$l(\sigma, \xi) = -N \ln(\sigma) - \left(1 + \frac{1}{\xi}\right) + \sum_{i=1}^N \ln \left\{1 + \frac{\xi}{\sigma} (x - u)\right\} \quad (17)$$

Due to the uncertainty in determining  $u$ ,  $u$  was fixed as a constant, equaling values used by Callaghan et al (2008b).

	Storm Duration			Offshore Hs		
	All	El Niño	La Niña	All	El Niño	La Niña
$u$	40	40	40	4.5	4.5	4.5
$\xi$	-0.029	-0.183	0.040	0.032	0.078	-0.119
95% conf. int.	[-0.17; 0.11]	[-0.39; 0.02]	[-0.17; 0.24]	[-0.14; 0.21]	[-0.13; 0.29]	[-0.38; 0.85]
$\sigma$	24.03	28.45	21.52	0.86	0.73	1.23
95% conf. int.	[19.1; 30.3]	[20.7; 39.1]	[15.1; 30.6]	[0.68; 1.08]	[0.55; 0.96]	[0.14; 1.79]

Table 4-5; Values for GP scale parameter  $\sigma$  and shape parameter  $\xi$  for the whole dataset (1971-2006) and El Niño and La Niña years separate. 95% confidence interval was determined using a maximum log likelihood, and is given between square brackets.

The measurement data of storm duration and wave height, as well as the fitted model, are plotted in Figure 4-9 and Figure 4-10. It shows clearly higher wave heights and storm durations for La Niña years, consistent with the generally retreating beaches during these years.

The measurement data over the period 1971-2006 show more resemblance to the El Niño years, consistent with the fact that about 2/3 of this period consisted of El Niño years.

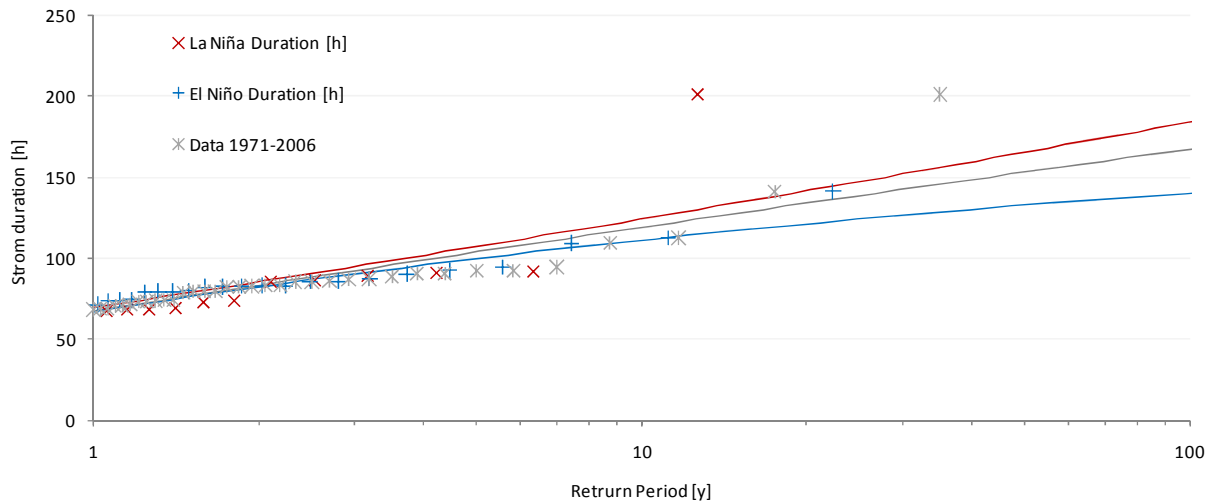


Figure 4-9; Return level plot of the distribution of storm duration for the whole dataset (1971-2006) and El Niño and La Niña years separately. The constant lines show the fitted model.

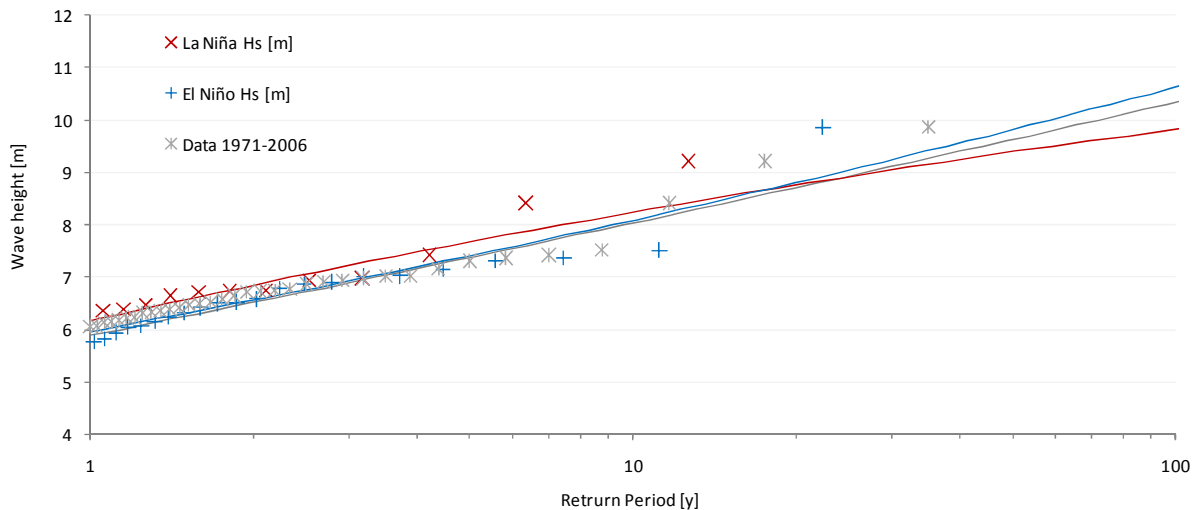


Figure 4-10; Return level plot of the distribution of offshore wave height for the whole dataset (1971-2006) and El Niño and La Niña years separately. The constant lines show the fitted model.

The influence of La Niña / El Niño on the return periods of erosion volumes is small. Erosion volumes and their return periods were calculated using the expected storm duration, storm frequency, and offshore  $H_s$  for a perfect La Niña and a perfect El Niño climate. This was done by using the statistical parameters taken from the La Niña years or the La Nina return periods, and the statistical parameters taken from the El Niño years for the El Niño return periods.

On average, the erosion volumes for a given return period with a perfect La Niña climate, are 2% higher compared to the climate in the period 1971-2006. The erosion volumes for a given return period with a perfect El Niño climate are on average 3% lower compared to the climate in the period 1971-2006 (see Figure 4-11).

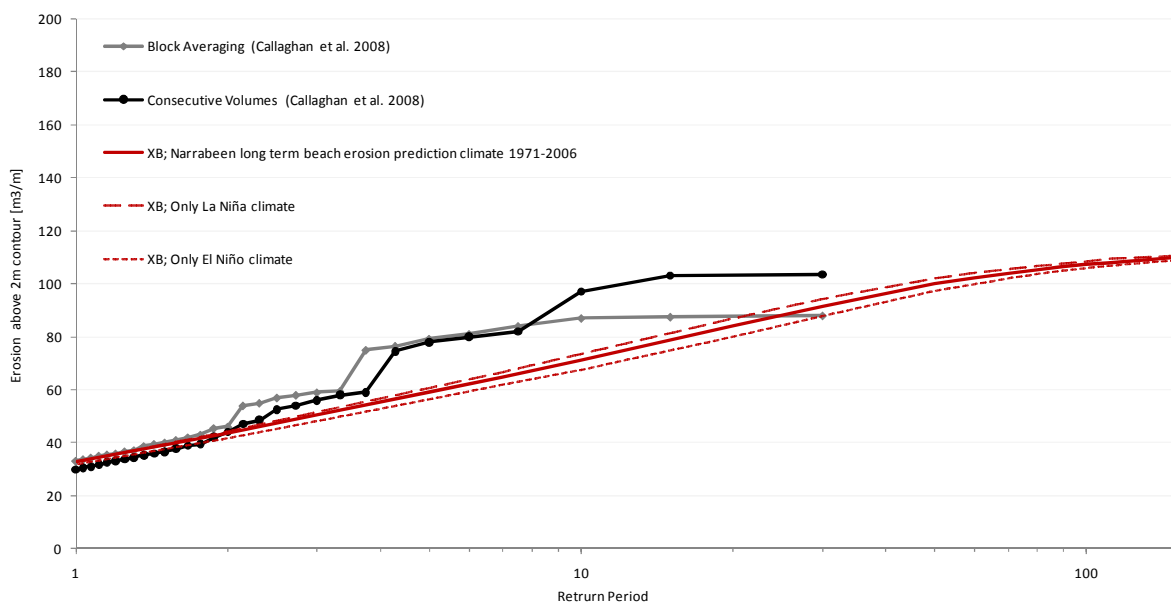


Figure 4-11; Return interval erosion using XBeach. Analysis done with measured storm-frequency of period 1976-2006, and in case of only El Niño and La Niña storm-frequency. Compared to measurements (Callaghan et al. 2008)

As discussed earlier, the exact distribution of El Niño/La Niña years for the future is not clear yet. Moreover, the exact influence of El Niño/La Niña on wave parameters is not without uncertainty. For the east coast of Australia a decrease in  $H_s$  in the range of 0.04 – 0.15 m. (about 2 -10%) was predicted for the period 2080-2010, as well as a shift in wave direction up to 5° clockwise, depending on the method of calculation (Hemer et al, 2010).

The uncertainty in these wave characteristics and the unknown development of characteristics as storm surge leads to extra uncertainty in the erosion volumes – return periods. Therefore, a sensitivity analysis on the erosion volumes has been done by varying parameters such as storm occurrence, storm duration, wave height, storm surge, and wave angle. The average erosion volumes for the 1-, 2-, 3-, 5-, 7-, 10-, 20-, 30-, 50-, 60-, 70-, 80-, 90-, 100-year return periods were calculated.

Changing the expected number of storms, the significant wave height during a storm, the storm surge and the offshore wave direction led to different averaged erosion volumes, over the 1- 100 year return period (see Figure 4-12).

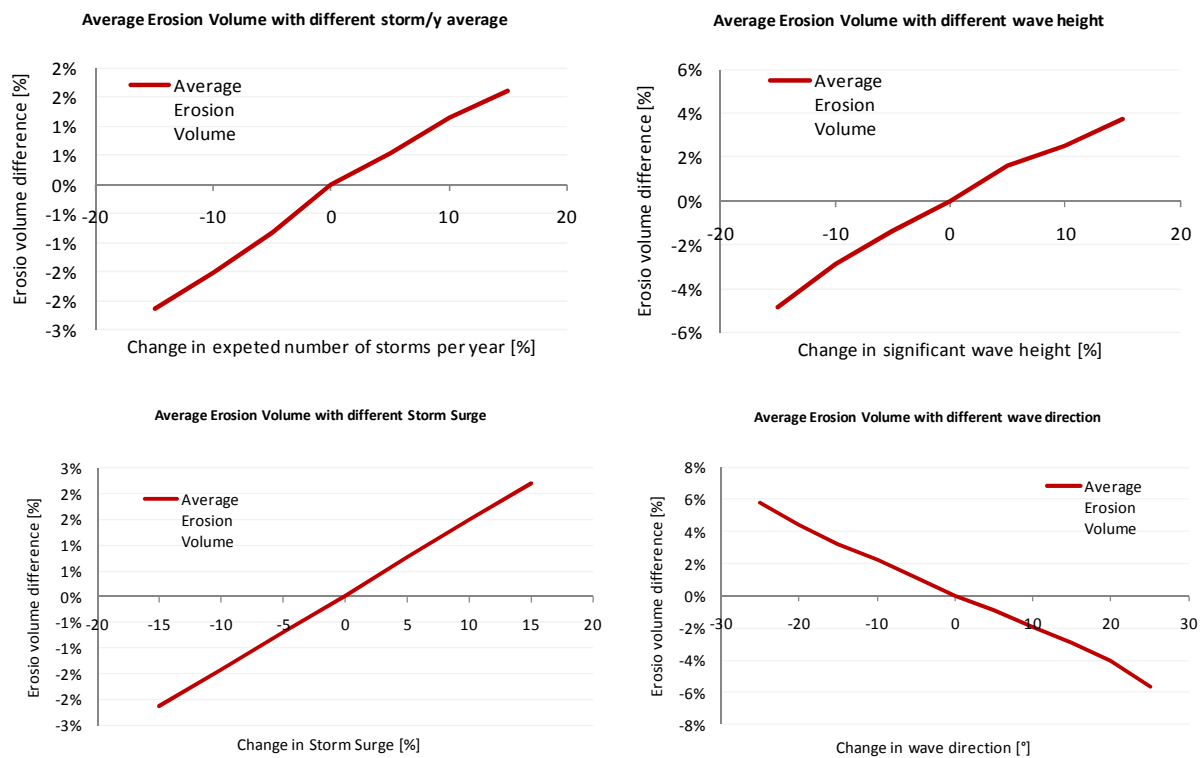


Figure 4-12; Sensitivity of the average erosion volumes-return periods due to changes in wave input. A positive value in wave direction represents a clockwise change in direction.

#### 4.6 Joint Probability Method; erosion volume - return period

The return period of erosion volumes is determined using the data obtained from 162 simulations with XBeach. Convergence was found after approximately  $10^3$  cycles, in figure 4-13,  $10^5$  cycles have been used. The 95% confidence intervals are shown with gray lines. The small confidence interval, especially at the lower return periods, indicates small changes in erosion volumes determined by XBeach in respect to small changes in storm parameters.

The uncertainty is distributed close to normal around the expected value or skewed towards smaller erosion volumes, especially at greater return periods. The skewedness at greater



return periods implies a relatively stable maximum erosion volume, despite changes in wave input.

The calculated erosion volume plotted against the return period does show a concave shape on the log scale implying bounded erosion volumes at higher return periods. This is in accordance to the measurement data.

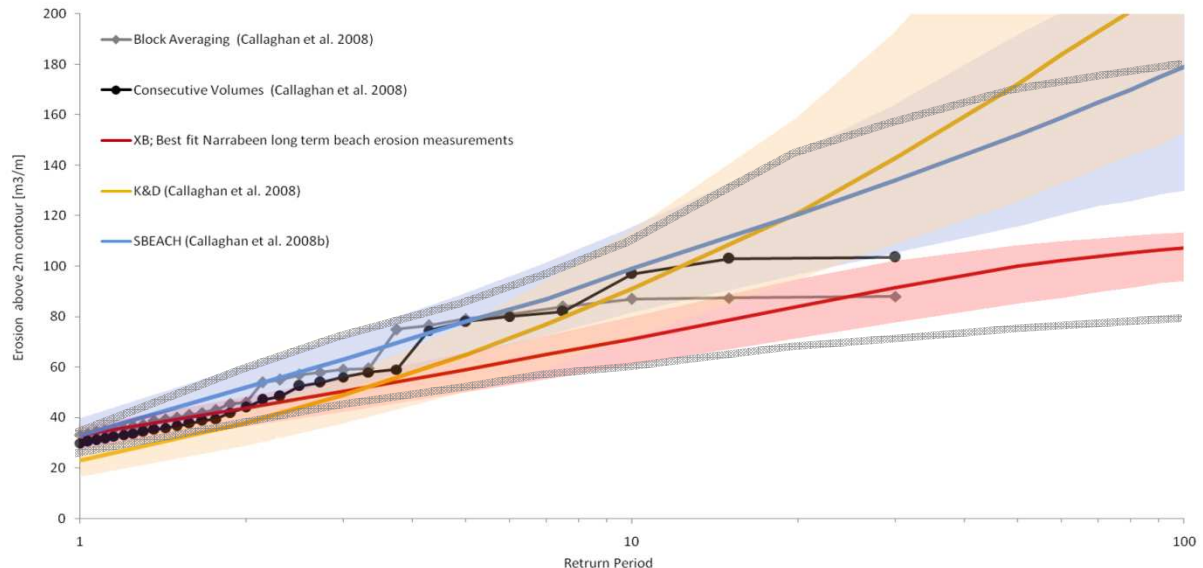


Figure 4-13; Return interval erosion using XBeach and 95% confidence interval based on  $1000 \times 10^4$  simulations (red line and red shaded area). Analysis done with measured storm-frequency of period 1976-2006. Compared to JPM method using K&D (orange line) with 95% confidence interval indicated by the orange shaded area, and SBEACH (blue line) with 95% confidence interval indicated by the blue shaded area (after Callaghan et al. 2008a and 2008b). The gray lines represent the 95% confidence interval of the data (Consecutive volumes method).

#### 4.6.1 Measurement – simulation comparison

To assess whether the measurement data fits the calculated erosion volumes, two methods are distinguished; using the confidence intervals of the simulated values, or using the confidence intervals of the measurements.

In the first case, 95% of the data needs to lie within the 95% confidence intervals of the simulations. For the Narrabeen measurements determined using consecutive volumes, 23 out of 30 (77%) data points are within the Xbeach confidence interval. Of the Narrabeen measurements determined using block averaging, 18 out of 30 (60%) data points are within the XBeach confidence interval. Based on these numbers, one could argue that the JPM with XBeach as structural function deviates to far from measurement.

In the second case, a 95% confidence interval is placed around the measurement, shown by the grey lines in figure 4-13. In this case falls the expected value of the erosion volumes well within the confidence interval of the measured data.

The difference in result of these two methods leads to a recommendation for more statistical effort to determine if confidence that can be placed on this set of simulations.

Overall can be concluded that XBeach as a structural function for the JPM generates better results than using the JPM in combination with K&D and SBEACH. This is especially clear at the higher return periods, where both other methods deviate further from measurement, however only K&D significantly. The XBeach-JPM combination is the only method showing a roll-off in erosion volumes, as does the data.

#### 4.7 Sensitivity analysis

While a high density transfer matrix leads to a higher accuracy due to the smaller error in interpolation between the calculated values, computational costs increase accordingly. In this paragraph the loss of accuracy is provided, given a decrease in number of simulations with XBeach.

To be able to make a comparison, the erosion volume - return period, calculated with all 8800 scenarios, was taken as a 100% resemblance, or skill score. As 23% of the simulations did not finish, extrapolated values were used.

The extrapolated erosion volume,  $EV_{ep}$ , is determined using

$$EV_{ep} = \frac{EV_0}{c^{1/n}} \quad (18)$$

where  $EV_0$  is the erosion volume generated by XBeach at the end of the run,  $c$  is the rate of completion of the run.  $N$  is taken 1.42 (see Appendix VII for calculation of  $n$ ).

Using MATLAB, parameters from Table 4-2 were randomly deleted, effectively creating new transfer matrices (see MATLAB script in Appendix VIII). New erosion volume return periods were calculated, using these transfer matrices in Monte Carlo simulations,. This step was repeated 1410 times.

The erosion volume was calculated for 16 return periods, i.e., 1, 2, 3, 5, 7, 10, 20, 30, 50, 60, 70, 80, 90, 100, 110, and 150 year, hence for the total skill score, the root mean squared error was taken, using

$$\text{Skill score} = 1 - \sum_1^{16} \frac{\sqrt{(RI_{8800} - RI_x)^2}}{16 \cdot RI_{8800}}. \quad (19)$$

Since the 1410 newly made transfer matrices had generally different lengths (e.g., exclusion of one value of  $H_s$  would lead to 8000 scenarios while exclusion of one value of  $T$  would lead to 7920 scenarios) the Skill scores were sorted in 22 bins. Appendix VIII provides an overview of the results of this sorting. The average skill score per bin, plotted against the number of scenarios, can be seen as the average resemblance of the return period calculated using 8800 scenarios.

##### 4.7.1 Confidence interval.

The distribution per bin was analysed, and while most fitted a normal distribution according to the Kolmogorov-Smirnov test of normality (Figure 4-14 left panel), some did not (Figure 4-14 right panel).

The spread of the data was therefore shown using the 10<sup>th</sup> and 90<sup>th</sup> percentile. The maximum observed resemblance per bin is shown as a gray dotted line in Figure 4-15.

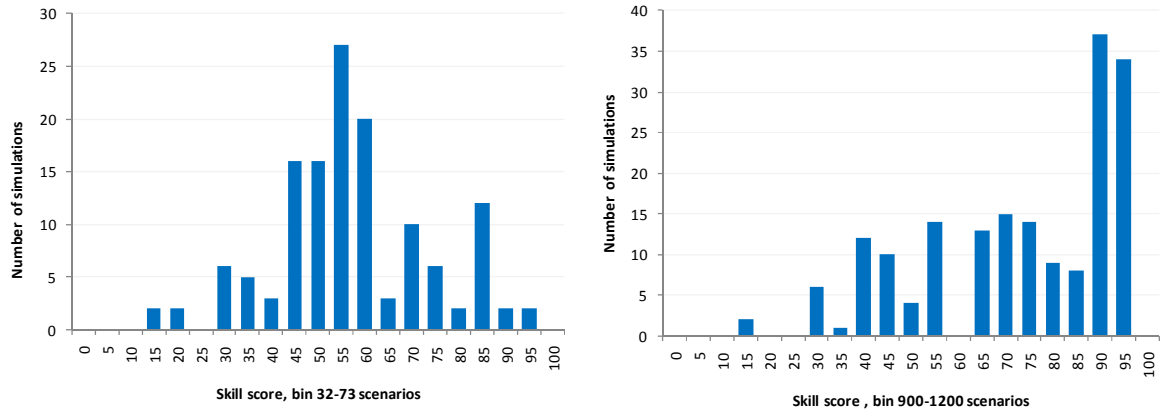


Figure 4-14; Skill score distribution. Bin 2 (32-74 simulations)) (left) and bin 15 (900-1200 simulations) (right)(see Appendix VIII for more information)

It must be noted, however, that these skill scores and confidence intervals are based on random sets of scenarios. These sets could thus include simulations with only short wave periods, leading to big extrapolation errors for the erosion volumes at high wave periods.

When a well spread set of parameters is chosen, i.e. including a high and low value, an one near the middle of the set, a much higher skill score can be obtained. As erosion volume for the Narrabeen beach turns out to be highly linear in time with  $H_s$ ,  $T_p$ ,  $\theta$ ,  $D$ , and  $SS$ , a considerable reduction in computational cost can be achieved by decreasing the density of the transfer matrix. Using only the values of  $H_s$ ,  $T$ ,  $D$ ,  $\theta$ ,  $SS$  printed in bold in Table 4-2 on page 33, would lead to  $3 \cdot 3 \cdot 2 \cdot 3 \cdot 3 = 162$  simulations, or a reduction of 98.8% in computational time.

This reduction of 98.8% of the number of simulations leads to a minor 5% difference in return periods, compared to the return periods calculated using all 8800 simulations. This error is well below the uncertainty of the model, and this finding could lead to significant reduction in modelling time in future research.

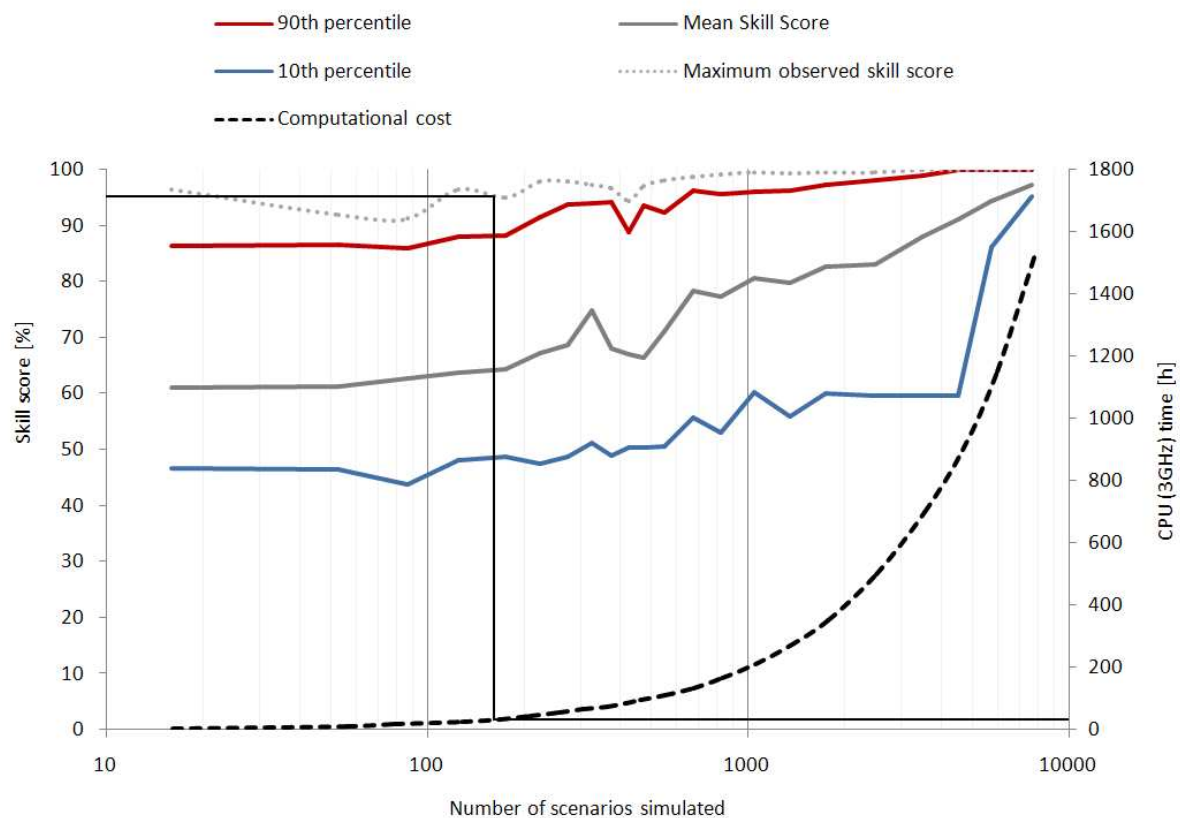


Figure 4-15; Skill score of return period of erosion volumes, with different amount of scenarios run. 10<sup>th</sup> and 90<sup>th</sup> percentile values show the spread of the data. Use of only 162 well chosen simulations (requiring a run time of about 30 hour) leads to a resemblance in erosion volume-return periods of 95%, compared to erosion volume – return periods calculated using 8800 simulations. Computational cost as a reference only, real value depends on many factors as bathymetry and wave input, requested XBeach output, hardware and software computer properties.

## 5 Conclusions

As coastal management is gradually shifting to a probabilistic approach, return periods of erosion events are of more importance than ever. Combining a method of determining erosion with a statistical model to calculate the return period was done previously by Callaghan et al (Callaghan et al., 2007, Callaghan et al., 2008a, Callaghan et al., 2008b) using Kriebel and Dean (1993), and SBEACH (Larson and Kraus, 1989) as a method to determine beach erosion. Using XBeach (Roelvink et al., 2009), a new 2DH model, this study aimed to refine the calculated return periods. In this research, XBeach is only used in 1D mode.

Using a novel non-stationary wave driver, XBeach generally produced a flat beach, and steep dune face. As these XBeach results has been observed before at similar beaches with little storm setup, some additions for the modelling of the swash zone are suggested. XBeach was however able to recreate the post-storm profile that was measured at Narrabeen beach after the 1997 storm to good extent, using stationary wave forcing.

It has to be noted, however, that uncertainty in the pre-storm profile as well as in the post-storm profile is unavoidable. Submerged bars can be expected at beaches such as Narrabeen, but did not appear in any measurements. Additional simulations with a barred profile have been run, these led however to no significant different post-storm profiles. Erosion of the beach was delayed by the presence of the bar, suggesting influence of the bars at shorter storms.

As the post-storm profile was measured 4 days after the storm, had some recovery of the beach already taken place. As full recovery is assumed to take about 400 hours, was the measured profile used to calibrate XBeach.

The setup for XBeach leading to the best match in the 1997 storm led to a slight underprediction in erosion volumes – return periods, when comparing it to the 30 year Narrabeen measurement. Values remained within the confidence interval of the data for the smaller (<2 yr.) and bigger (>20 yr.) return periods.

Fitting erosion volumes – return periods directly to the return periods of measurements has been carried out as a second method of calibration. A large number of erosion volumes-return period plots were created using varying wave breaking, energy dissipation, and sediments transport parameters. The programs' sensitivity to differences in parameter settings led to a wide range of erosion volume-return periods. The best approximation was chosen to be the best fit at lower return periods, since most data are available for the lower return periods.

For the best fit, the value of erosion volumes modelled by XBeach were slightly lower compared to the measurements at the higher return periods. The fact that in the present study each event was forced on the same beach profile, effectively excluding storm grouping, leads to an underestimation of erosion volume prediction, partly explaining the difference. The shape of the return period function created by XBeach is convex on a log scale, which implies bounded erosion volumes at higher return periods. This behaviour is similar to measurements at Narrabeen (Callaghan et al., 2008b). The confidence interval for the erosion volumes-return periods were narrow at lower return periods, and skewed toward lower erosion volumes for the higher return periods.

Depending on the method of determining the 95% confidence intervals, i.e. the XBeach data or the measurement data, one could argue the results fit or do not fit the measurements.

This discrepancy needs to be solved in order to conclude if simulations fit to the measurements within sufficient limits.

Overall can be concluded that the JPM in combination XBeach, when calibrated against the lower return periods, replicates the data within the confidence intervals. XBeach performs better as structural function in the JPM than K&D and SBEACH for the higher return periods. It generates erosion volumes closer to the measurements, and shows qualitatively better behaviour, with a rolling off of the erosion volumes in a logarithmic plot.

This leads to increased confidence in the capability of XBeach in combination with the JPM to predict extreme beach erosion on beaches similar to Narrabeen.

As future distribution of El Niño and La Niña years is fairly uncertain, two limiting scenarios were covered; an erosion volume return period with a constant El Niño wave climate, and an erosion volume return period with a La Niña wave climate. Wave statistics were extracted from a 36 year dataset (23 El Niño and 13 La Niña years) and were used in Monte Carlo simulations. While the erosion volumes themselves might have little predictive value, the relative difference between erosion volumes expected in an El Niño and La Niña climate could be used as an indication of expected beach erosion change caused by climate change. The difference in erosion volumes during El Niño and La Niña years were determined, yielding on average 3% higher erosion volumes at the calculated return periods during La Niña years.

Finally, this study shows that a considerable reduction in computational cost can be achieved with respect to the amount of different storm scenarios modelled. A low density transfer matrix with 162 different storm scenarios used to calculate erosion volumes, led to return periods for beach erosion within 5% rms-error of return periods compared to a high density transfer matrix with 8800 different scenarios. The use of this low density transfer matrix yielded a reduction of about 99% in computational cost.

## 6 Recommendations

One of the main foundations of this research is the measurements at Narrabeen beach. However, even with such a frequent set of measurements, uncertainty in the data remains, as is the case when the profile is surveyed several days after the storm. To account for the change in bathymetry, more research is required on the recovery of Narrabeen beach after a storm.

Numerical modelling of beach erosion has variable results, even when the model is calibrated optimally for a given beach and storm. Calibrating against multiple storms avoids discarding setups that would lead to the best results on slightly different circumstances.

This research shows that the post-storm profile as generated by XBeach deviates from measurements, depending on the setup of the program. Similar behaviour of XBeach has been shown before. An extension of XBeach' modelling of the swash zone might improve the erosion of narrow beaches with little wave setup.

In this research, each storm started with the same initial profile, introducing an error even before the start of the XBeach simulation. When two storms occur in a relative short period of time, this led, to e.g., smaller erosion volumes than measured. It overestimated the effect of a storm, however, when a relative calm period preceded the storm and the real profile was accreted. As long as XBeach did not include accretion during calm periods, a full implementation in the JPM was not possible. The JPM does allow events to start with different profiles. Several initial profiles could be determined (e.g., very accreted, accreted, neutral, eroded, very eroded) thus effectively modelling a storm event forcing on an accreted or eroded beach. This improvement, however, does not take into account the various shapes a 'very eroded' beach can have due to different types of storms.

## 7 References

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## Appendix I;Input files Narrabeen beach

Jonswap.txt						
Hm0	Tp	Angle	Gamma	Spreading	Duration	Timestep
1.89	11	21	3.3	10	3600	0.25
1.87	11.3	6	3.3	10	3600	0.25
1.91	11.5	18	3.3	10	3600	0.25
2.03	11.5	8	3.3	10	3600	0.25
1.95	11.5	14	3.3	10	3600	0.25
1.66	11.9	24	3.3	10	3600	0.25
1.71	11.1	17	3.3	10	3600	0.25
1.74	10.6	12	3.3	10	3600	0.25
2.18	9.9	21	3.3	10	3600	0.25
0.66	9.4	32	3.3	10	3600	0.25
0.86	9.1	32	3.3	10	3600	0.25
1.1	8.9	32	3.3	10	3600	0.25
1.76	8.5	32	3.3	10	3600	0.25
1.76	9.2	29	3.3	10	3600	0.25
1.52	9.8	29	3.3	10	3600	0.25
1.65	10.3	28	3.3	10	3600	0.25
1.87	10.5	28	3.3	10	3600	0.25
2.49	10.7	25	3.3	10	3600	0.25
2.41	10.9	26	3.3	10	3600	0.25
2.31	11.1	26	3.3	10	3600	0.25
2.35	11.2	26	3.3	10	3600	0.25
2.43	11.5	25	3.3	10	3600	0.25
2.7	11.7	25	3.3	10	3600	0.25
3.08	12	23	3.3	10	3600	0.25
2.68	12.2	24	3.3	10	3600	0.25
2.6	12.4	23	3.3	10	3600	0.25
2.92	12.5	23	3.3	10	3600	0.25
3.48	12.6	19	3.3	10	3600	0.25
3.29	12.5	22	3.3	10	3600	0.25
3.16	12.6	20	3.3	10	3600	0.25
3.28	12.5	21	3.3	10	3600	0.25
3.09	12.3	21	3.3	10	3600	0.25
2.97	12.3	20	3.3	10	3600	0.25
3.03	12.3	22	3.3	10	3600	0.25
3.28	12.3	20	3.3	10	3600	0.25
3.16	12.4	22	3.3	10	3600	0.25
3.39	12.3	21	3.3	10	3600	0.25
3.09	12.3	21	3.3	10	3600	0.25
3.21	12.3	19	3.3	10	3600	0.25
2.88	12.3	20	3.3	10	3600	0.25
3.96	12.2	18	3.3	10	3600	0.25
4.21	12.2	20	3.3	10	3600	0.25
3.98	12.1	20	3.3	10	3600	0.25
4.73	12.1	13	3.3	10	3600	0.25
4.3	12.2	16	3.3	10	3600	0.25
4.22	12.4	19	3.3	10	3600	0.25
4.64	12.5	15	3.3	10	3600	0.25
4.91	12.6	19	3.3	10	3600	0.25

4.92	12.7	19	3.3	10	3600	0.25
5.1	12.8	15	3.3	10	3600	0.25
4.98	12.8	19	3.3	10	3600	0.25
4.51	12.8	19	3.3	10	3600	0.25
4.35	12.6	19	3.3	10	3600	0.25
4.18	12.5	19	3.3	10	3600	0.25
4.23	12.5	19	3.3	10	3600	0.25
3.83	12.4	19	3.3	10	3600	0.25
3.57	12.3	16	3.3	10	3600	0.25
3.54	12.3	19	3.3	10	3600	0.25
3.6	12.1	19	3.3	10	3600	0.25
3.31	12.1	19	3.3	10	3600	0.25
3.36	12	17	3.3	10	3600	0.25
3.38	11.8	19	3.3	10	3600	0.25
3.3	11.6	19	3.3	10	3600	0.25
3.55	11.4	14	3.3	10	3600	0.25
3.1	11.2	20	3.3	10	3600	0.25
3.08	11.2	20	3.3	10	3600	0.25
3.05	11.1	18	3.3	10	3600	0.25
3.54	10.9	21	3.3	10	3600	0.25
2.39	10.8	21	3.3	10	3600	0.25
2.41	10.8	22	3.3	10	3600	0.25
2.44	10.9	22	3.3	10	3600	0.25
2.65	10.7	19	3.3	10	3600	0.25
2.35	10.7	21	3.3	10	3600	0.25
2.33	10.7	21	3.3	10	3600	0.25
2.19	10.6	21	3.3	10	3600	0.25
2.11	10.6	22	3.3	10	3600	0.25
2.09	10.6	24	3.3	10	3600	0.25
2.05	10.6	22	3.3	10	3600	0.25
2.02	10.7	21	3.3	10	3600	0.25
2.02	10.8	21	3.3	10	3600	0.25
1.87	10.6	24	3.3	10	3600	0.25
2.09	10.6	22	3.3	10	3600	0.25
2.2	10.6	18	3.3	10	3600	0.25
1.97	10.6	21	3.3	10	3600	0.25
1.85	10.4	23	3.3	10	3600	0.25
1.94	10.4	21	3.3	10	3600	0.25
1.91	10.3	22	3.3	10	3600	0.25
2.07	10.3	20	3.3	10	3600	0.25
1.96	10.4	18	3.3	10	3600	0.25
1.89	10.6	19	3.3	10	3600	0.25
1.87	10.7	20	3.3	10	3600	0.25
1.79	10.9	17	3.3	10	3600	0.25
1.69	10.8	17	3.3	10	3600	0.25
1.58	10.7	20	3.3	10	3600	0.25
1.2	10.7	26	3.3	10	3600	0.25
1.41	10.6	22	3.3	10	3600	0.25

Surge	
Time[s]	MSL [m]
0	0.41
3600	0.07
7200	-0.26
10800	-0.5
14400	-0.59
18000	-0.52
21600	-0.32
25200	-0.05
28800	0.22
32400	0.41
36000	0.5
39600	0.46
43200	0.28
46800	0.04
50400	-0.15
54000	-0.3
57600	-0.31
61200	-0.21
64800	0.03
68400	0.34
72000	0.66
75600	0.88
79200	1.02
82800	0.97
86400	0.77
90000	0.47
93600	0.15
97200	-0.14
100800	-0.33
104400	-0.39
108000	-0.32
111600	-0.13
115200	0.11
118800	0.33
122400	0.48
126000	0.56
129600	0.5
133200	0.34
136800	0.17
140400	0.02
144000	-0.08
147600	-0.06
151200	0.09
154800	0.32
158400	0.59
162000	0.88
165600	1.07
169200	1.11

172800	1.06
176400	0.86
180000	0.56
183600	0.28
187200	0.05
190800	-0.12
194400	-0.16
198000	-0.07
201600	0.1
205200	0.3
208800	0.48
212400	0.59
216000	0.6
219600	0.51
223200	0.36
226800	0.21
230400	0.07
234000	-0.01
237600	0.02
241200	0.14
244800	0.34
248400	0.57
252000	0.78
255600	0.88
259200	0.89
262800	0.78
266400	0.56
270000	0.28
273600	0.02
277200	-0.16
280800	-0.29
284400	-0.29
288000	-0.21
291600	-0.05
295200	0.13
298800	0.29
302400	0.39
306000	0.38
309600	0.29
313200	0.16
316800	0.03
320400	-0.08
324000	-0.11
327600	-0.08
331200	0.04
334800	0.23
338400	0.42
342000	0.57
345600	0.67

X-grid [m]	Bathymetry [m]	
	April 1995	15th May 1995
0	9.52	9.52
10	9.3	9.3
20	7.9	7.9
30	4.06	3.02
40	2.76	1.88
50	2.16	0.85
60	1.73	-0.14
70	1.38	-0.85
80	1.25	
90	0.36	
100	-0.58	
110	-1.42	
160	-2.34	
175	-3.66	
232	-6.58	
410	-12.26	
544	-14.05	
671	-15.33	
794	-16.65	
912	-17.84	
1030	-19.23	
1138	-20.62	
1251	-21.33	
1365	-22.54	
1469	-23.4	
1573	-24.1	
1670	-24.88	
1774	-25.76	
1890	-25.49	

## Params.txt Default

### ----- Grid input

nx = 216  
ny = 2

alfa = 0.  
thetamin = -60.  
thetamax = 60.  
dtheta = 120.  
depfile = 0ln\_z.dep

vardx = 1  
xfile = 0ln\_x.grd  
yfile = 0ln\_y.grd

-----  
Numerics input  
CFL = 0.7

### ----- Time input

tstop = 345600  
taper = 1000.

-----  
General constants  
rho = 1025.

### ----- Water level boundary conditions

tideloc=1  
tidelen=192  
zs0file=0ln\_surge.txt

### ----- Boundary wave conditions absorbing

front = 1  
left = 0  
right = 0  
back = 2

### ----- Boundary wave conditions generating

instat = 41  
bcfile = 0ln\_jonswap.txt

### ----- Wave calculation options

break = 3  
roller = 1  
beta = 0.15  
gamma = 0.55  
n = 10.

### ----- Flow calculation options

hmin = 0.05  
C = 65.

### ----- Sediment transport calculation options

D50 = 0.0003  
D90 = 0.0005  
rhos = 2650

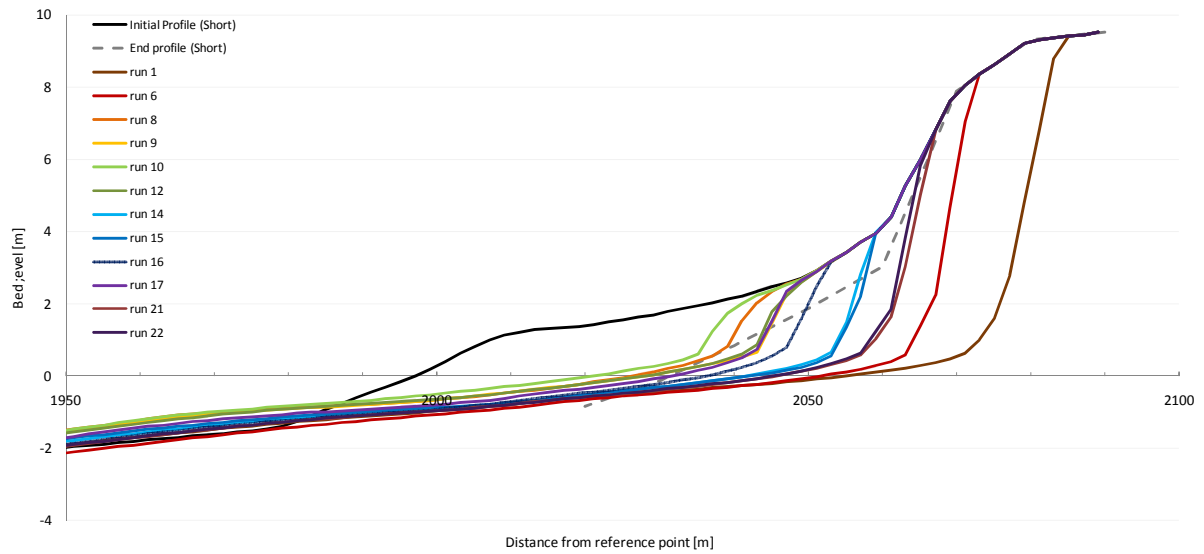
### ----- Morphological calculation options

morfac = 0  
morstart = 120.  
por = 0.4  
dryslp = 1.0  
wetslp = 0.3  
hswitch = 0.1

-----  
tstart = 1000.  
tintg = 100  
nglobalvar = -1

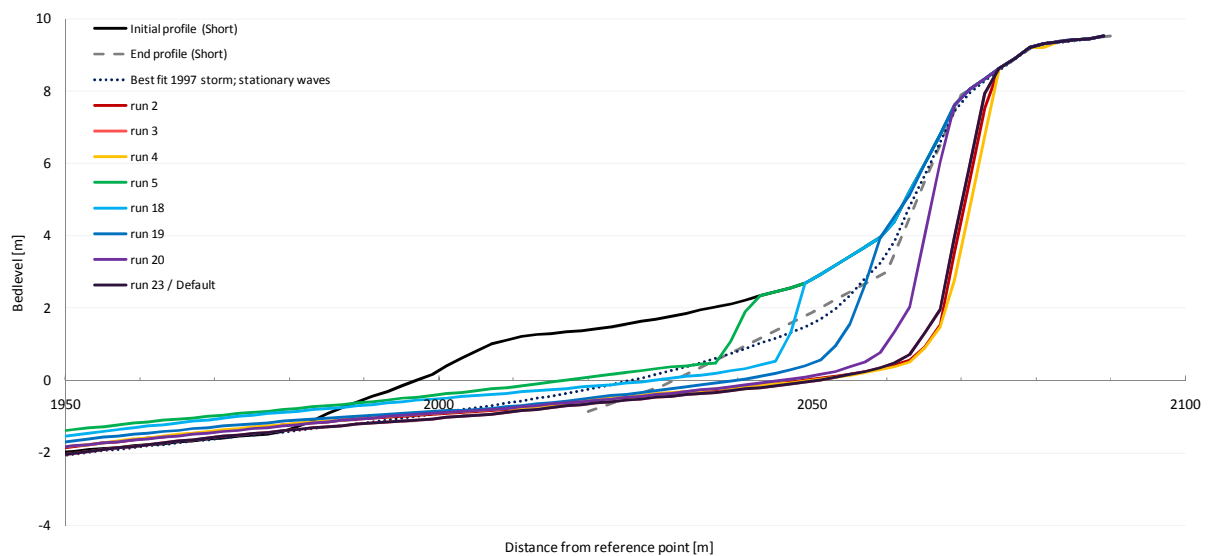
tintm = 7200  
nmeanvar = 1  
H

Profiles Storm 1997 Narrabeen\_CA\_break=1



CA	run 1	run 6	run 8	run 9	run 10	run 12	run 14	run 15	run 16	run 17	run 21	run 22
Wave calculation options												
break	1	1	1	1	1	1	1	1	1	1	1	1
roller	1	1	0	1	1	1	1	1	1	1	1	1
beta	0.15	0.15	0.1	0.3	0.25	0.3	0.22	0.22	0.22	0.25	0.18	0.19
gamma	0.5	0.5	0.3	0.3	0.25	0.3	0.4	0.4	0.4	0.35	0.45	0.45
n	10	10	10	10	10	10	10	10	10	10	10	10
Flow calculation options												
hmin	0.1	0.1	0.1	0.1	0.05	0.1	0.1	0.1	0.08	0.08	0.15	0.15
C	65	65	65	65	65	65	65	65	65	65	65	65
Morphological calculation options												
dryslp	1	1.2	1.1	1.2	1.1	0.9	0.7	1.4	0.6	0.7	1	1
wetslp	0.3	0.4	0.36	0.36	0.33	0.45	0.4	0.4	0.4	0.4	0.3	0.3
hswitch	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Profiles Storm 1997 Narrabeen\_CA\_break=3



CA	run 2	run 3	run 4	run 5	run 18	run 19	run 20	run 23 / Def
Wave calculation options								
break	3	3	3	3	3	3	3	3
roller	1	1	1	1	1	1	1	1
beta	0.15	0.15	0.15	0.1	0.15	0.25	0.35	0.15
gamma	0.35	0.5	0.35	0.4	0.15	0.4	0.5	0.55
n	10	10	10	10	10	10	10	10
Flow calculation options								
hmin	0.1	0.1	0.05	0.1	0.1	0.1	0.8	0.05
C	65	65	65	65	65	65	65	65
Morphological calculation options								
dryslp	1	1	1	1	1	1	1	1
wetslp	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
hswitch	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1



## Appendix II; Inputfiles Hasaki beach

Surge	
time [s]	waterlevel [m]
0	0.80
600	0.85
1200	0.89
1800	0.94
2400	0.98
3000	1.03
3600	1.08
4200	1.12
4800	1.17
5400	1.21
6000	1.26
6600	1.30
7200	1.35
7800	1.40

Jonswap						
Hm0	Tp	Angle	Gamma	Spreading	Duration	Timestep
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25
0.55	13	0	3.3	10	900	0.25

Bathymetry Hasaki beach					
X-grid	Bed [m]	X-grid	Bed [m]	X-grid	Bed [m]
0	3.00	40.5	1.78	79	-0.13
1	2.95	41	1.70	80	-0.15
2	2.90	41.5	1.62	81	-0.17
3	2.85	42	1.55	82	-0.19
4	2.80	42.5	1.48	83	-0.21
5	2.75	43	1.38	84	-0.23
6	2.70	44	1.20	85	-0.25
7	2.65	45	1.05	86	-0.27
8	2.60	46	0.95	87	-0.29
9	2.55	47	0.85	88	-0.31
10	2.50	48	0.82	89	-0.33
11	2.45	49	0.75	90	-0.35
12	2.40	50	0.70	91	-0.37
13	2.35	51	0.65	92	-0.39
14	2.30	52	0.60	93	-0.41
15	2.25	53	0.55	94	-0.43
16	2.20	54	0.50	95	-0.45
17	2.15	55	0.45	96	-0.47
18	2.10	56	0.41	97	-0.49
19	2.05	57	0.35	98	-0.51
20	2.00	58	0.28	99	-0.53
21	1.80	59	0.22	100	-0.55
22	1.66	60	0.20	101	-0.57
23	1.63	61	0.14	102	-0.59
24	1.61	62	0.10	103	-0.61
25	1.58	63	0.08	104	-0.63
26	1.55	64	0.07	105	-0.65
27	1.53	65	0.10	106	-0.67
28	1.50	66	0.11	107	-0.69
29	1.48	67	0.10	108	-0.71
30	1.45	68	0.07	109	-0.73
31	1.42	69	0.03	110	-0.75
32	1.40	70	0.01		
33	1.44	71	-0.01		
34	1.48	72	-0.03		
35	1.60	73	-0.05		
36	2.00	74	-0.05		
37	2.42	75	-0.06		
38	2.28	76	-0.07		
39	2.02	77	-0.09		
40	1.86	78	-0.11		

## Params.txt (Hasaki Beach)

-----  
Numerics input  
CFL = 0.8  
-----

Time input  
tstop = 7760  
taper = 500.  
-----

General constants  
rho = 1025.  
-----

Water level boundary conditions  
tideloc=1  
tidelen=192  
zs0file=0In\_surge.txt  
-----

Boundary wave conditions  
absorbing  
front = abs\_1d  
left = wall  
right = wall  
back = abs\_1d  
-----

-----  
Boundary wave conditions  
generating  
instat = 41  
bcfile = 0In\_jonswap.txt  
-----

Wave calculation options  
break = 1  
roller = 1  
beta = 0.3  
gamma = 0.5  
n = 10.  
-----

Flow calculation options  
hmin = 0.2  
C = 65.  
-----

Sediment transport calculation  
options  
D50 = 0.00018  
D90 = 0.0005  
rhos = 2650  
-----

-----  
Morphological calculation options  
morfac = 10  
morstart = 1000.  
por = 0.4  
dryslp = 1.0  
wetslp = 0.3  
hswitch = 0.1  
-----

tstart = 500.  
  
tintg = 1  
nglobalvar = 3  
zs  
zb  
H  
  
tintm = 500  
nmeanvar = 1  
H

## Appendix III; MATLAB script - erosion during storm

```

ErosionVol_DuringStorm.m
%% Erosion Volume by MJRiesenkamp at UQ
% according to method Hoffmann and Hibbert 1987
% Calculates development of beach erosion (output XBeach) during a run.

% Checked

clear
clc

Cont=2;           % contour line
BL=0;             % Bottom line of arbitrary beach volume
Vol=0;            % Initial value

%% create Vardata_zb 2 dimensionaal with Xgrid in array
XBdims=getdimensions;
Xgrid(:,1)=XBdims.x(:,1) ;
Vardata_zb=readvar('zb.dat',XBdims);
[A B C]=size (Vardata_zb);
Profiles = zeros (A,5);    %pre-allocation
steps=1724;
ErosionDevelop=zeros(steps+1,1);
tel=0;

for q=1:floor(C/steps):C
    tel=tel+1;
    q

    Profiles(:,1)=Vardata_zb(:,2,1);    % Y value at start run (1)
    Profiles(:,2)=Vardata_zb(:,2,q);    % Y value at end run (2)
    Profiles(:,3)=Xgrid(:,1);           % X value grid point
    Profiles(:,4)=Profiles(:,1)<Cont;    % gives 1 when Y value1 is under contour
    Profiles(:,5)=Profiles(:,2)<Cont;    % gives 1 when Y value2 is under contour

    n = sum(Profiles(:,4)); % number grid point
    m = sum(Profiles(:,5));

    XOIn=(Profiles(n,3));
    XOEnd=(Profiles(m,3));

    SlopeIn=(Profiles(n,1)-Profiles((n+1),1))/(Profiles(n,3)-Profiles((n+1),3)); % Slope at
    interval of contour crossing
    XlIn=((Cont-Profiles((n+1),1))/SlopeIn)+Profiles((n+1),3); % X value of contour crossing
    VollIn=0.5*((Profiles(n+1,1)-BL)+(Cont-BL))*(Profiles((n+1),3)-XlIn); % volume first interval
    nn=(n+1):(A-1); % (from first xgrid above contour(n+1))
    Heights=(0.5*((Profiles(nn,1)-BL)+(Profiles((nn+1),1))-BL));
    Withs=(Profiles((nn+1),3)-(Profiles(nn,3)));

    VolIn=(sum(Heights.*Withs))+VollIn; %initial volume beachward of contour line

    SlopeEnd=(Profiles(m,2)-Profiles((m+1),2))/(Profiles(m,3)-Profiles((m+1),3)); % Slope at
    interval of contour crossing
    XlEnd=((Cont-Profiles((m+1),2))/SlopeEnd)+Profiles((m+1),3); % X value of contour crossing
    VollEnd=0.5*((Profiles(m+1,2)-BL)+(Cont-BL))*(Profiles((m+1),3)-XlEnd); % volume first interval
    mm=(m+1):(A-1);
    Heights=(0.5*((Profiles(mm,2)-BL)+(Profiles((mm+1),2))-BL));
    Withs=(Profiles((mm+1),3)-(Profiles(mm,3)));

    VolEnd=(sum(Heights.*Withs))+VollEnd;
    VolErosion=VolIn-VolEnd
    ErosionDevelop(tel,1)=VolErosion;

end

```

## Appendix IV; MATLAB script – Read HPCU output

```
ErosionVol_HPC_Output.m

%% file to read output from HPC; each run at HPCU is stored in separate dir, sit filename
%% "Shhttdas" where hh is index for wave height (e.g. Hs = 3.1 -> HH=01), tt is index for
%% period, d is index for storm duration, a is index for wave angle and s is index for Storm
%% Surge.
%% by M.J.Riesenkamp at UQ, Brisbane

% Checked.

clear; clc
pause on
SearchForFile='XBerror.txt'; %search for this file (extension required)

%% Create list of sub-directories.
%% latest version

List=dir;
[pl,ql]=size(List);
NrDirs=-2; %Matlab always returns two 'dirs' named '.' and '..'
for i=1:size(List)
    ReadDirTemp{i,1}=List(i,1).name;
    NrDirs=NrDirs+isdir(ReadDirTemp{i,1});
end
j=0;
for i=(3):size(List);
    if isdir(ReadDirTemp{i,1})==1
        j=j+1;
        ReadDir{j,1}=List(i,1).name;
    end
end
%%
Erosion_Vols=zeros(7,length(ReadDir));
CurrentDir=cd;

for run=1:length(ReadDir)
S=char(ReadDir(run,1));
stopBar= progressbar(run/length(ReadDir),0);

%% read input Hs, T, D, Alfa, S from filename for good bookkeeping
nrHs = [S(1,2),S(1,3)]; %reads Hs from filename
eval(nrHs); %needs eval to combine the two
nrT = [S(1,4),S(1,5)]; %reads T from filename
eval(nrT); %needs eval to combine the two
nrD = S(1,6); %reads D from filename (only one, no eval needed)
nrAlfa = S(1,7); %reads Alfa from filename (only one, no eval needed)
nrS = S(1,8); %reads S from filename (only one, no eval needed)

S=char(ReadDir(run,1));
eval(['cd '' CurrentDir '\ S ''']);
pause(1); % opening folder can take a while (wait for 1 sec)

%% start erosion volume calculation
Cont=2; % contour line
BL=0; % Bottomline of arbitrary beach volume
Vol=0; % initial value
%VolSE=zeros(B,1); % Start and end Volume in array
C=((str2double(nrD))*860);

%% create Vardata_zb 2 dimensionaal met Xgrid in array
XBdims=getdimensions;
Xgrid(:,1)=XBdims.x(:,1);
Vardata_zb=readvar('zb.dat',XBdims);
[A B C]=size(Vardata_zb);
%end

Profiles(:,1)=Vardata_zb(:,2,1); % Y value at start run (1)
Profiles(:,2)=Vardata_zb(:,2,C); % Y value at end run (2)
Profiles(:,3)=Xgrid(:,1); % X value gridpoint
Profiles(:,4)=Profiles(:,1)<Cont; % gives 1 when Y value1 is under contour
Profiles(:,5)=Profiles(:,2)<Cont; % gives 1 when Y value2 is under contour

n = sum(Profiles(:,4)); % number gridpoint
m = sum(Profiles(:,5));
```

```

XOIn=(Profiles(n,3));
XOEnd=(Profiles(m,3));
SlopeIn=(Profiles(n,1)-Profiles((n+1),1))/(Profiles(n,3)-Profiles((n+1),3)); % Slope at
interval of contour crossing
XlIn=((Cont-Profiles((n+1),1))/SlopeIn)+Profiles((n+1),3); % X value of contour crossing
VollIn=0.5*((Profiles(n+1,1)-BL)+(Cont-BL))*(Profiles((n+1),3)-XlIn); % volume first interval
nn=(n+1):(A-1); % (from first xgrid above contour(n+1)
Heights=(0.5*((Profiles(nn,1)-BL)+(Profiles((nn+1),1))-BL));
Withs=(Profiles((nn+1),3)-(Profiles(nn,3)));

VolIn=(sum(Heights.*Withs))+VollIn; %initial volume beachward of contour line

SlopeEnd=(Profiles(m,2)-Profiles((m+1),2))/(Profiles(m,3)-Profiles((m+1),3)); % Slope at
interval of contour crossing
XlEnd=((Cont-Profiles((m+1),2))/SlopeEnd)+Profiles((m+1),3); % X value of contour crossing
VollEnd=0.5*((Profiles(m+1,2)-BL)+(Cont-BL))*(Profiles((m+1),3)-XlEnd); % volume first interval
mm=(m+1):(A-1);
Heights=(0.5*((Profiles(mm,2)-BL)+(Profiles((mm+1),2))-BL));
Withs=(Profiles((mm+1),3)-(Profiles(mm,3)));

VolEnd=(sum(Heights.*Withs))+VollEnd;
VolErosion =VolIn-VolEnd;

InputVal=[3.1, 3.5, 4.5, 6, 7, 8, 9, 10, 11.5, 13, 15; ...
6.0, 7, 8, 8.5, 9, 9.5, 10, 10.5, 10, 11, 12; ...
1, 2, 3, 4, 5 ,0,0,0,0,0,0;...
10, 30, 60, 90, 0,0,0,0,0,0;...
0, 0.25, 0.5, 0.7, 0 ,0,0,0,0,0];

%% output results in one array
Erosion_Vols(1,run)=InputVal(1,(str2num(nrHs)));
Erosion_Vols(2,run)=InputVal(2,(str2num(nrT)));
Erosion_Vols(3,run)=InputVal(3,(str2num(nrD)));
Erosion_Vols(4,run)=InputVal(4,(str2num(nrAlfa)));
Erosion_Vols(5,run)=InputVal(5,(str2num(nrS)));
Erosion_Vols(6,run)=VolErosion;
if exist('XError.txt')>=1 %check if run is completed
Erosion_Vols(7,run)=-123;
end
Erosion_Vols(8,run) =C/((str2double(nrD))*860); % approx measurement of completion (+/- 2%)
% should be about 860 (+/- 6)*nr_Days
end

TM=Erosion_Vols'; % Transfer Matrix

```

## Appendix V; XBeach fitting to long term measurement

Fitting of the XBeach model was based on the return period of measured erosion events, as described in paragraph 3.4. The measurements are represented by the black and gray line in Figure 7-1.

Input parameters are presented in Table 7-1.

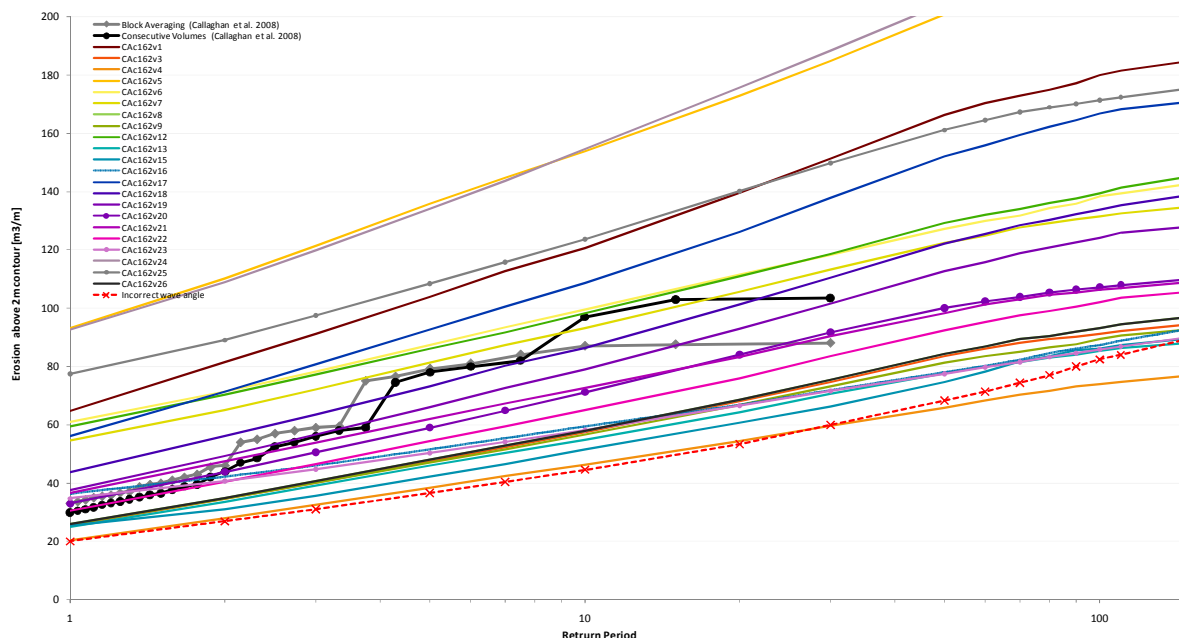


Figure 7-1; Return periods for erosion volumes resulting from 23 sets of 162 storm simulation. The dotted red line indicates the return period resulting from a set of storm simulations with wave direction slightly (20°-30°) offshore.

CA 162	1	3	4	5	6	7	8	9	12	13	15	16
Instat	41	41	41	41	41	41	41	41	41	41	41	40
Break	1	1	1	3	3	3	1	1	3	1	1	1
Roller	1	1	0	1	1	1	1	1	1	1	1	1
Beta	0.15	0.25	0.25	0.15	0.25	0.3	0.25	0.25	0.3	0.35	0.25	0.15
Gamma	0.55	0.4	0.4	0.5	0.4	0.35	0.4	0.4	0.4	0.4	0.4	0.5
Hmin	0.15	0.1	0.1	0.15	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.1
Dryslp	1	1.3	1.1	1	1.1	1.2	1.2	1.1	1.2	0.9	0.8	1
Wetslp	0.3	0.39	0.33	0.3	0.33	0.36	0.36	0.33	0.3	0.27	0.25	0.3
Hswitch	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.05	0.05	0.1	0.1

CA 162	17	18	19	20	21	22	23	24	25	26	I.W.A.
Instat	41	41	41	41	41	41	41	41	41	41	41
Break	1	1	1	1	1	1	3	3	3	1	1
Roller	1	1	1	1	1	1	1	1	1	1	1
Beta	0.16	0.17	0.18	0.18	0.19	0.18	0.15	0.15	0.1	0.3	0.1
Gamma	0.52	0.48	0.45	0.42	0.45	0.45	0.5	0.55	0.35	0.4	0.52
Hmin	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.05	0.2	0.1	0.05
Dryslp	1	1	1	1	1	1	1	1	1	1	1
Wetslp	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Hswitch	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 7-1; Input parameters (part of params.txt) varied to fit the calculated return period to measurements. I.W.A.= Incorrect wave angle, i.e. slightly (20°-30°) offshore moving wave groups.

## Appendix VI; Transfer Matrix

The full transfer matrix , or the result of 8800 runs is presented in the pages below, in which  
column 1,4,7,... is the number of the run,  
column 2,5,8,... is the erosion volume [m<sup>3</sup>/m] above the 2m. contour  
column 3,6,9,... is the percentage of completion by XBeach before the end of the run.  
The five columns with wave input can be generated using the following MATLAB code.

```
Create_input_var_list.m

%% Transfer Matrix column 1-5
% by MJR at UQ, Brisbane.

% Checked

clear
clc

TM=zeros(8800,5);
row=1;

Hs=[3.1, 3.5, 4.5, 6, 7, 8, 9, 10, 11.5, 13, 15]; % Offshore significant waveheight
T =[6.0, 7, 8, 8.5, 9, 9.5, 10, 10.5, 11, 12]; % Wave period
D =[1, 2, 3, 4, 5]; % Duration Storm in Days
Angle=[10, 30, 60, 90]; % Wave Angle; 0 is perpendicular to coast.
SS=[0, 0.25, 0.5, 0.7]; % Storm Surge in respect to MSL

for i1=1:11
    Tmp1(i1,1)=Hs(1,i1);
    for i2=1:10
        Tmp2(i2,1)=T(1,i2);
        for i3=1:5
            Tmp3(i3,1)=D(1,i3);
            for i4=1:4
                Tmp4(i4,1)=Angle(1,i4);
                for i5=1:4
                    Tmp5(i5,1)=SS(1,i5);
                    TM(row,:)= [Tmp1(i1,1),Tmp2(i2,1),Tmp3(i3,1),Tmp4(i4,1),Tmp5(i5,1),];
                    row=row+1;
                end
            end
        end
    end
end
end
end
end
```



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	4.04	6.01	8.01	10.01	12.01	14.01	16.01	18.01	20.01	22.01	24.01	26.01	28.01	30.01	32.01	34.01	36.01	38.01	40.01	42.01	44.01	46.01	48.01	50.01	52.01	54.01	56.01	58.01	60.01	62.01	64.01	66.01	68.01	70.01	72.01	74.01	76.01	78.01	80.01	82.01	84.01	86.01	88.01	90.01	92.01	94.01	96.01	98.01	100.01	102.01	104.01	106.01	108.01	110.01	112.01	114.01	116.01	118.01	120.01	122.01	124.01	126.01	128.01	130.01	132.01	134.01	136.01	138.01	140.01	142.01	144.01	146.01	148.01	150.01	152.01	154.01	156.01	158.01	160.01	162.01	164.01	166.01	168.01	170.01	172.01	174.01	176.01	178.01	180.01	182.01	184.01	186.01	188.01	190.01	192.01	194.01	196.01	198.01	200.01	
2	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00	28.00	29.00	30.00	31.00	32.00	33.00	34.00	35.00	36.00	37.00	38.00	39.00	40.00	41.00	42.00	43.00	44.00	45.00	46.00	47.00	48.00	49.00	50.00	51.00	52.00	53.00	54.00	55.00	56.00	57.00	58.00	59.00	60.00	61.00	62.00	63.00	64.00	65.00	66.00	67.00	68.00	69.00	70.00	71.00	72.00	73.00	74.00	75.00	76.00	77.00	78.00	79.00	80.00	81.00	82.00	83.00	84.00	85.00	86.00	87.00	88.00	89.00	90.00	91.00	92.00	93.00	94.00	95.00	96.00	97.00	98.00	99.00	100.00																	
3	3.07	3.17	3.27	3.37	3.47	3.57	3.67	3.77	3.87	3.97	4.07	4.17	4.27	4.37	4.47	4.57	4.67	4.77	4.87	4.97	5.07	5.17	5.27	5.37	5.47	5.57	5.67	5.77	5.87	5.97	6.07	6.17	6.27	6.37	6.47	6.57	6.67	6.77	6.87	6.97	7.07	7.17	7.27	7.37	7.47	7.57	7.67	7.77	7.87	7.97	8.07	8.17	8.27	8.37	8.47	8.57	8.67	8.77	8.87	8.97	9.07	9.17	9.27	9.37	9.47	9.57	9.67	9.77	9.87	9.97	10.07																													
4	18.02	18.07	18.12	18.17	18.22	18.27	18.32	18.37	18.42	18.47	18.52	18.57	18.62	18.67	18.72	18.77	18.82	18.87	18.92	18.97	19.02	19.07	19.12	19.17	19.22	19.27	19.32	19.37	19.42	19.47	19.52	19.57	19.62	19.67	19.72	19.77	19.82	19.87	19.92	19.97	20.02	20.07	20.12	20.17	20.22	20.27	20.32	20.37	20.42	20.47	20.52	20.57	20.62	20.67	20.72	20.77	20.82	20.87	20.92	20.97	21.02	21.07	21.12	21.17	21.22	21.27	21.32	21.37	21.42	21.47	21.52	21.57	21.62	21.67	21.72	21.77	21.82	21.87	21.92	21.97	22.02	22.07	22.12	22.17	22.22															
5	18.03	18.08	18.13	18.18	18.23	18.28	18.33	18.38	18.43	18.48	18.53	18.58	18.63	18.68	18.73	18.78	18.83	18.88	18.93	18.98	19.03	19.08	19.13	19.18	19.23	19.28	19.33	19.38	19.43	19.48	19.53	19.58	19.63	19.68	19.73	19.78	19.83	19.88	19.93	19.98	20.03	20.08	20.13	20.18	20.23	20.28	20.33	20.38	20.43	20.48	20.53	20.58	20.63	20.68	20.73	20.78	20.83	20.88	20.93	20.98	21.03	21.08	21.13	21.18	21.23	21.28	21.33	21.38	21.43	21.48	21.53	21.58	21.63	21.68	21.73	21.78	21.83	21.88	21.93	21.98	22.03	22.08	22.13	22.18	22.23															
6	18.04	18.09	18.14	18.19	18.24	18.29	18.34	18.39	18.44	18.49	18.54	18.59	18.64	18.69	18.74	18.79	18.84	18.89	18.94	18.99	19.04	19.09	19.14	19.19	19.24	19.29	19.34	19.39	19.44	19.49	19.54	19.59	19.64	19.69	19.74	19.79	19.84	19.89	19.94	19.99	20.04	20.09	20.14	20.19	20.24	20.29	20.34	20.39	20.44	20.49	20.54	20.59	20.64	20.69	20.74	20.79	20.84	20.89	20.94	20.99	21.04	21.09	21.14	21.19	21.24	21.29	21.34	21.39	21.44	21.49	21.54	21.59	21.64	21.69	21.74	21.79	21.84	21.89	21.94	21.99	22.04	22.09	22.14	22.19	22.24															
7	18.05	18.10	18.15	18.20	18.25	18.30	18.35	18.40	18.45	18.50	18.55	18.60	18.65	18.70	18.75	18.80	18.85	18.90	18.95	19.00	19.05	19.10	19.15	19.20	19.25	19.30	19.35	19.40	19.45	19.50	19.55	19.60	19.65	19.70	19.75	19.80	19.85	19.90	19.95	20.00	20.05	20.10	20.15	20.20	20.25	20.30	20.35	20.40	20.45	20.50	20.55	20.60	20.65	20.70	20.75	20.80	20.85	20.90	20.95	21.00	21.05	21.10	21.15	21.20	21.25	21.30	21.35	21.40	21.45	21.50	21.55	21.60	21.65	21.70	21.75	21.80	21.85	21.90	21.95	22.00	22.05	22.10	22.15	22.20																
8	18.06	18.11	18.16	18.21	18.26	18.31	18.36	18.41	18.46	18.51	18.56	18.61	18.66	18.71	18.76	18.81	18.86	18.91	18.96	19.01	19.06	19.11	19.16	19.21	19.26	19.31	19.36	19.41	19.46	19.51	19.56	19.61	19.66	19.71	19.76	19.81	19.86	19.91	19.96	20.01	20.06	20.11	20.16	20.21	20.26	20.31	20.36	20.41	20.46	20.51	20.56	20.61	20.66	20.71	20.76	20.81	20.86	20.91	20.96	21.01	21.06	21.11	21.16	21.21	21.26	21.31	21.36	21.41	21.46	21.51	21.56	21.61	21.66	21.71	21.76	21.81	21.86	21.91	21.96	22.01	22.06	22.11	22.16	22.21																
9	18.07	18.12	18.17	18.22	18.27	18.32	18.37	18.42	18.47	18.52	18.57	18.62	18.67	18.72	18.77	18.82	18.87	18.92	18.97	19.02	19.07	19.12	19.17	19.22	19.27	19.32	19.37	19.42	19.47	19.52	19.57	19.62	19.67	19.72	19.77	19.82	19.87	19.92	19.97	20.02	20.07	20.12	20.17	20.22	20.27	20.32	20.37	20.42	20.47	20.52	20.57	20.62	20.67	20.72	20.77	20.82	20.87	20.92	20.97	21.02	21.07	21.12	21.17	21.22	21.27	21.32	21.37	21.42	21.47	21.52	21.57	21.62	21.67	21.72	21.77	21.82	21.87	21.92	21.97	22.02	22.07	22.12	22.17	22.22																
10	18.08	18.13	18.18	18.23	18.28	18.33	18.38	18.43	18.48	18.53	18.58	18.63	18.68	18.73	18.78	18.83	18.88	18.93	18.98	19.03	19.08	19.13	19.18	19.23	19.28	19.33	19.38	19.43	19.48	19.53	19.58	19.63	19.68	19.73	19.78	19.83	19.88	19.93	19.98	20.03	20.08	20.13	20.18	20.23	20.28	20.33	20.38	20.43	20.48	20.53	20.58	20.63	20.68	20.73	20.78	20.83	20.88	20.93	20.98	21.03	21.08	21.13	21.18	21.23	21.28	21.33	21.38	21.43	21.48	21.53	21.58	21.63	21.68	21.73	21.78	21.83	21.88	21.93	21.98	22.03	22.08	22.13	22.18	22.23																
11	18.09	18.14	18.19	18.24	18.29	18.34	18.39	18.44	18.49	18.54	18.59	18.64	18.69	18.74	18.79	18.84	18.89	18.94	18.99	19.04	19.09	19.14	19.19	19.24	19.29	19.34	19.39	19.44	19.49	19.54	19.59	19.64	19.69	19.74	19.79	19.84	19.89	19.94	19.99	20.04	20.09	20.14	20.19	20.24	20.29	20.34	20.39	20.44	20.49	20.54	20.59	20.64	20.69	20.74	20.79	20.84	20.89	20.94	20.99	21.04	21.09	21.14	21.19	21.24	21.29	21.34	21.39	21.44	21.49	21.54	21.59	21.64	21.69	21.74	21.79	21.84	21.89	21.94	21.99	22.04	22.09	22.14	22.19	22.24																
12	18.10	18.15	18.20	18.25	18.30	18.35	18.40	18.45	18.50	18.55	18.60	18.65	18.70	18.75	18.80	18.85	18.90	18.95	19.00	19.05	19.10	19.15	19.20	19.25	19.30	19.35	19.40	19.45	19.50	19.55	19.60	19.65	19.70	19.75	19.80	19.85	19.90	19.95	20.00	20.05	20.10	20.15	20.20	20.25	20.30	20.35	20.40	20.45	20.50	20.55	20.60	20.65	20.70	20.75	20.80	20.85	20.90	20.95	21.00	21.05	21.10	21.15	21.20	21.25	21.30	21.35	21.40	21.45	21.50	21.55	21.60	21.65	21.70	21.75	21.80	21.85	21.90	21.95	22.00	22.05	22.10	22.15	22.20																	
13	18.11	18.16	18.21	18.26	18.31	18.36	18.41	18.46	18.51	18.56	18.61	18.66	18.71	18.76	18.81	18.86	18.91	18.96	19.01	19.06	19.11	19.16	19.21	19.26	19.31	19.36	19.41	19.46	19.51	19.56	19.61	19.66	19.71	19.76	19.81	19.86	19.91	19.96	20.01	20.06	20.11	20.16	20.21	20.26	20.31	20.36	20.41	20.46	20.51	20.56	20.61	20.66	20.71	20.76	20.81	20.86	20.91	20.96	21.01	21.06	21.11	21.16	21.21	21.26	21.31	21.36	21.41	21.46	21.51	21.56	21.61	21.66	21.71	21.76	21.81	21.86	21.91	21.96	22.01	22.06	22.11	22.16	22.21																	
14	18.12	18.17	18.22	18.27	18.32	18.37	18.42	18.47	18.52	18.57	18.62	18.67	18.72	18.77	18.82	18.87	18.92	18.97	19.02	19.07	19.12	19.17	19.22	19.27	19.32	19.37	19.42	19.47	19.52	19.57	19.62	19.67	19.72	19.77	19.82	19.87	19.92	19.97	20.02	20.07	20.12	20.17	20.22	20.27	20.32	20.37	20.42	20.47	20.52	20.57	20.62	20.67	20.72	20.77	20.82	20.87	20.92	20.97	21.02	21.07	21.12	21.17																																						



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8901	113.02	36%	8901	148.39	39%	8901	259.85	100%
8902	186.85	10%	8902	254.93	60%	8902	291.78	100%
8903	111.89	33%	8903	214.27	47%	8903	302.80	100%
8904	190.72	36%	8904	266.64	37%	8904	346.89	54%
8905	150.51	19%	8905	174.91	100%	8905	260.90	34%
8906	134.31	31%	8906	194.89	100%	8906	147.45	12%
8907	144.12	53%	8907	211.66	100%	8907	236.11	32%
8908	140.74	49%	8908	230.81	100%	8908	246.11	31%
8909	156.48	100%	8909	160.04	29%	8909	270.46	38%
8910	119.25	100%	8910	154.28	29%	8910	248.05	30%
8911	145.74	100%	8911	137.93	30%	8911	270.87	33%
8912	150.15	100%	8912	185.22	30%	8912	252.14	32%
8913	142.18	36%	8913	233.89	47%	8913	272.16	42%
8914	150.52	36%	8914	201.40	30%	8914	267.35	36%
8915	142.95	30%	8915	130.13	27%	8915	250.15	43%
8916	144.56	33%	8916	252.51	40%	8916	276.88	33%
8917	157.27	36%	8917	172.03	40%	8917	312.03	100%
8918	120.12	30%	8918	158.75	47%	8918	344.46	100%
8919	123.31	34%	8919	125.87	29%	8919	337.22	74%
8920	124.98	30%	8920	237.53	41%	8920	370.23	100%
8921	142.39	41%	8921	222.74	100%	8921	35.16	33%
8922	151.79	100%	8922	230.95	100%	8922	126.43	12%
8923	127.62	31%	8923	261.25	100%	8923	117.48	30%
8924	153.89	39%	8924	282.43	100%	8924	115.46	30%
8925	143.44	100%	8925	227.26	28%	8925	96.03	10%
8926	161.16	100%	8926	140.55	23%	8926	86.32	30%
8927	118.28	100%	8927	242.37	34%	8927	176.16	34%
8928	191.41	100%	8928	240.31	33%	8928	127.83	37%
8929	143.29	31%	8929	240.10	41%	8929	174.36	44%
8930	151.05	30%	8930	255.95	33%	8930	116.27	42%
8931	150.89	36%	8931	177.01	31%	8931	138.86	40%
8932	200.50	31%	8932	188.84	37%	8932	178.54	37%
8933	146.75	31%	8933	274.59	44%	8933	165.85	100%
8934	167.55	36%	8934	236.59	47%	8934	171.26	30%
8935	239.22	44%	8935	260.52	42%	8935	116.86	83%
8936	191.52	36%	8936	261.22	47%	8936	246.76	30%
8937	151.46	41%	8937	256.17	100%	8937	152.08	38%
8938	260.84	50%	8938	289.33	100%	8938	130.44	28%
8939	269.00	10%	8939	304.52	37%	8939	135.14	30%
8940	284.23	53%	8940	324.51	100%	8940	133.71	28%
8941	112.35	100%	8941	93.15	49%	8941	113.25	30%
8942	195.99	100%	8942	95.98	30%	8942	117.08	28%
8943	217.88	100%	8943	158.38	36%	8943	136.14	30%
8944	238.24	100%	8944	111.74	40%	8944	136.81	28%
8945	219.15	31%	8945	102.07	40%	8945	139.60	12%
8946	158.80	31%	8946	152.34	42%	8946	117.21	29%
8947	175.81	31%	8947	95.90	40%	8947	138.82	31%
8948	262.80	33%	8948	150.04	47%	8948	176.83	28%
8949	153.15	31%	8949	102.48	50%	8949	251.12	100%
8950	207.70	43%	8950	158.63	47%	8950	264.90	100%
8951	148.38	30%	8951	124.21	51%	8951	307.89	100%
8952	201.21	30%	8952	134.15	51%	8952	307.26	30%
8953	273.25	54%	8953	105.88	100%	8953	154.46	28%
8954	303.54	55%	8954	137.07	100%	8954	155.22	28%
8955	273.70	10%	8955	136.27	100%	8955	270.11	32%
8956	254.51	49%	8956	130.78	100%	8956	170.58	24%
8957	252.45	100%	8957	132.12	32%	8957	159.36	30%
8958	225.36	100%	8958	112.05	29%	8958	171.34	28%
8959	253.12	100%	8959	158.82	36%	8959	210.02	33%
8960	272.76	100%	8960	122.29	28%	8960	220.04	30%
8961	85.16	42%	8961	122.60	23%	8961	133.96	28%
8962	131.03	41%	8962	86.15	29%	8962	220.30	31%
8963	94.65	41%	8963	122.32	31%	8963	219.45	30%
8964	85.45	29%	8964	120.28	30%	8964	227.16	30%
8965	113.21	53%	8965	133.87	44%	8965	242.91	100%
8966	113.07	10%	8966	149.90	30%	8966	136.51	38%
8967	156.51	42%	8967	158.43	41%	8967	274.76	58%
8968	58.26	42%	8968	135.88	24%	8968	278.16	100%
8969	120.87	61%	8969	170.61	100%	8969	207.08	28%
8970	113.17	56%	8970	174.16	100%	8970	197.38	27%
8971	139.76	56%	8971	158.86	100%	8971	238.80	28%
8972	119.62	54%	8972	223.34	100%	8972	219.03	28%
8973	86.18	100%	8973	144.25	36%	8973	186.17	28%
8974	92.74	100%	8974	161.14	33%	8974	171.57	28%
8975	166.22	100%	8975	162.26	36%	8975	245.36	30%
8976	118.32	100%	8976	212.35	36%	8976	232.38	28%
8977	120.09	32%	8977	133.47	30%	8977	242.85	38%
8978	120.87	34%	8978	148.07	33%	8978	174.87	28%
8979	120.50	32%	8979	161.34	34%	8979	185.33	28%
8980	123.43	33%	8980	188.86	34%	8980	273.15	34%
8981	123.98	34%	8981	163.19	36%	8981	289.88	55%
8982	132.01	34%	8982	147.21	33%	8982	236.39	50%
8983	126.16	31%	8983	148.72	33%	8983	236.10	54%
8984	167.56	30%	8984	238.11	42%	8984	271.62	100%
8985	159.16	52%	8985	224.73	100%	8985	237.80	36%
8986	150.17	51%	8986	238.19	100%	8986	174.05	22%
8987	139.89	41%	8987	250.86	100%	8987	264.07	27%
8988	204.44	59%	8988	272.98	100%	8988	237.34	24%
8989	127.12	100%	8989	142.86	36%	8989	235.45	32%
8990	153.52	100%	8990	209.54	32%	8990	252.76	31%
8991	164.46	100%	8991	222.72	37%	8991	236.88	31%
8992	173.80	100%	8992	179.33	28%	8992	260.74	31%
8993	128.07	33%	8993	171.59	31%	8993	272.14	30%
8994	121.35	33%	8994	233.72	39%	8994	255.05	32%
8995	159.84	34%	8995	263.89	39%	8995	298.73	32%
8996	173.89	35%	8996	248.89	39%	8996	258.08	32%
8997	119.87	35%	8997	186.01	40%	8997	314.33	54%
8998	124.44	33%	8998	192.39	41%	8998	321.80	52%
8999	145.11	34%	8999	140.41	28%	8999	300.34	47%
9000	154.42	35%	9000	251.70	38%	9000	272.25	49%



## Appendix VII; Extrapolation aborted simulations

To account for the unfinished XBeach runs, extrapolation was used to be able to calculate the skill score for a coarser transfer matrix.

Two possible methods of extrapolation were compared; linear extrapolation and extrapolation using the following equation,

$$EV_{ep} = \frac{EV_0}{c^{1/n}} \quad (20)$$

where  $EV_{ep}$  is the extrapolated erosion volume,  $EV_0$  is the erosion volume generated by XBeach at the end of the run,  $c$  is the rate of completion of the run.  $n$  is equal to one for linear extrapolation.

A set of 28 simulations which failed at, on average, 0.60 (sd=0.16, range: 0.35-0.96) of the run, was re-run till all simulations reached 100% completion. The calculated values were compared to the extrapolated values, using iteration of  $n$  to find the highest  $R^2$  value. A maximum  $R^2$  value of 0.57, was obtained at  $n=1.47$ , which was subsequently used in further analysis.

The influence of extrapolation of failed runs with different values for  $n$  on the calculated return period of erosion volumes was verified. For 5 different values for  $n$  (see Table 7-2), the return periods of erosion volumes were determined.

As XBeach mainly crashed during the simulation of extreme storms, storms with a low return period are virtually unaffected.

The difference between the two extreme possibilities; linear extrapolation and using a root function ( $n=2$ ) is about 20% for the higher return periods (>20yr.), and less for the whole domain.

	$n=0$ (XB results)	$n=1$	$n=1.42$	$n=1.5$	$n=2$
110	181.89	245.37	217.54	213.81	198.16
100	181.06	242.69	216.13	212.16	197.13
90	179.53	239.65	214.15	210.58	195.90
80	178.32	236.33	211.47	208.38	194.48
70	176.79	231.72	208.27	205.39	192.72
60	174.45	225.94	204.97	201.99	190.58
50	172.47	219.37	200.89	198.24	187.41
30	164.65	194.24	184.96	183.77	179.38
20	157.89	174.55	171.56	171.11	169.01
10	143.07	145.99	145.74	145.71	145.49
7	132.89	133.48	133.48	133.48	133.48
5	121.72	121.85	121.85	121.85	121.85
3	106.95	106.94	106.94	106.94	106.95
2	95.72	95.71	95.71	95.71	95.72
1	80.61	80.60	80.60	80.60	80.60

Table 7-2; Table calculated return periods as result of extrapolating failed XBeach runs. Calculation of return periods was based on a transfer matrix containing 8800 (extrapolated) storm simulations, of which 76% were completed. The average completion rate was 87%. The uncompleted runs reached on average 47% (sd 14%).

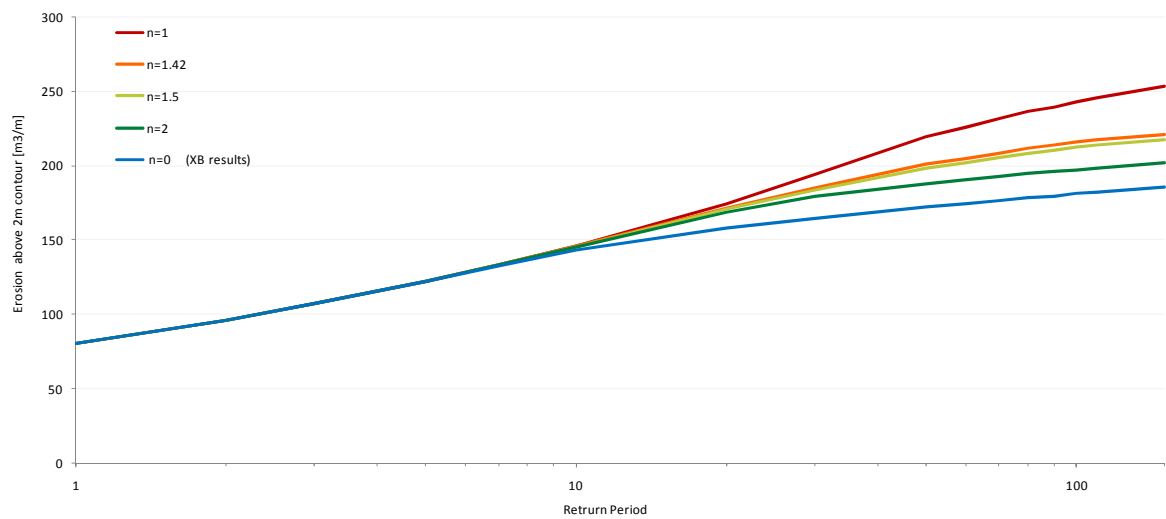


Figure 7-2; Figure of calculated return periods resulting from extrapolating of failed XBeach runs using different values for  $n$ .

## Appendix VIII; Skill score Mean and Confidence Interval

MATLAB code used to generate random (and smaller) transfer matrices, to determine loss of accuracy using courser transfer matrix.

```
SkillScore_RandTransMatCreatorForConfInt.m
%% 21-03-2011 by M.J.Riesenkamp, script for Expected Value and Confidence Interval of
% Skill Score.

% Uses RunThis.bat (batch code to start SimEBE (by D.P.Callaghan) to calculate return interval
% erosion by linear interpolation of a transfer matrix (made in thisscript))
% Source of these here-made transfer matrices are the results
% of 8800 runs at the HPC at UQ, which are stored in Erosion_All_8800_CA.m.

% Checked.
clear;clc

load Erosion_All_8800_CA %contains full (8800) TM, and first(=original) R.P. calculation
[P,Q] = size (Erosion_all_8800);
loops=1410; %any number, the more the better (but takes longer)
EVolAll=zeros(8800,1); %only on first run
Resemblance=zeros(loops,2);
ii=0;
serie=1

%%      leave this one (=source)
%      1      2      3      4      5      6      7      8      9      10      11
AHs = {3.1, 3.5, 4.5, 6, 7, 8, 9, 10, 11.5, 13, 15};
AT = {6.0, 7, 8, 8.5, 9, 9.5, 10, 10.5, 11, 12};
AD = {86400, 172800, 259200, 345600, 432000 }; % Time in s.
AAngle = {10, 30, 60, 90 }; % 0 = perpendicular to beach
AS = {0, 0.25, 0.5, 0.7 };

for loop=1:loops
progressbar; % Create figure and set starting time
progressbar(loop/loops); % Update figure

%%      start loop, set values for Hs T D Angle and S
%      This program starts with all values for the vars., and takes at random one
%      var. out in each loop.
%      If one of the vars. is completely empty or the multiply of the lengths of the
%      remaining vars <32, it starts over again.
clearvars -except EVolAll P Q AHs AT AD AAngle AS Erosion_all_8800 ReturnInt8800 loop...
Resemblance Hs T D Angle S loops Deleted ii serie
tel=0;
if length(EVolAll)==8800
Hs = AHs;
T = AT;
D = AD;
Angle = AAngle;
S = AS;
Deleted=zeros(34,1);
ii=0;
end
if length(EVolAll)<=32
Hs = AHs;
T = AT;
D = AD;
Angle = AAngle;
S = AS;
Deleted=zeros(34,1);
ii=0;
serie=serie+1 % show how many times it started with fresh (full) transfer matrix.
end
EVolAll=zeros(1,1); % reset EVolAll, but don't delete; in case a whole var (Hs, T,...) is
empty...
%      it won't crash in line 146. and in the next loop
%      it will start with the complete array, since 1<=32
(line 46)
A=rand();
Del=floor((A*33))+1; %var to be deleted
ii=ii+1;
while any(Del==Deleted)==1; %determine if var is already deleted, if yes, choose another
A=rand();
Del=floor((A*33))+1;
```

```

end
Deleted(ii,1)=Del; % update list of deleted vars

if Del <= 11
    Hs{1,Del}= -123;
else if Del <= 21
    T{1,Del-11}= -123;
else if Del <= 26
    D{1,Del-21}= -123;
else if Del <= 30
    Angle{1,Del-26}= -123;
else if Del <= 34
    S{1,Del-30}= -123;
end
end
end
end

%%
for wHs = Hs
    for wT = T;
        for wD = D;
            for wAngle = Angle;
                for wS = S;
                    for i=1:P
                        if (wHs{1,1}==Erosion_all_8800(i,1)) && wT{1,1}
==Erosion_all_8800(i,2) && ...
(wD{1,1} ==Erosion_all_8800(i,3)) && wAngle{1,1}
==Erosion_all_8800(i,4) &&...
(wS{1,1} ==Erosion_all_8800(i,5)) ,i;
EVol=Erosion_all_8800(i,6);
tel=tel+1;
EVolAll(tel,1)=EVol;
end
end
end
end
end
end

%% write new transfer matrix file based on less input parameters
fid =
fopen('H:\backup_usb\ProfAndMC\ZTest\TestANarrabeenProfile4\XBeachNarrabeen\TransferMatrix_Pro
file4Erosion.dat','w');
fprintf(fid,'5 1\n');

for telH=1:11
    if Hs{1,telH}>=0
        fprintf(fid,'%6.1f',Hs{1,telH});
    end
end
fprintf(fid,'\n');
for telT=1:10
    if T{1,telT}>=0
        fprintf(fid,'%6.1f',T{1,telT});
    end
end
fprintf(fid,'\n');
for telD=1:5
    if D{1,telD}>=0
        fprintf(fid,'%10.1f',D{1,telD});
    end
end
fprintf(fid,'\n');
for telAngle=1:4
    if Angle{1,telAngle}>=0
        fprintf(fid,'%6.1f',Angle{1,telAngle});
    end
end
fprintf(fid,'\n');
for telS=1:4
    if S{1,telS}>=0
        fprintf(fid,'%6.2f',S{1,telS});
    end
end

```



```

end
fprintf(fid, '\n');
fprintf(fid, '%6.4f\n', EVolAll);
fclose(fid);
%pause (1)

% run RunThis (starts SimEBE.exe to calculate return period, based on parameters taken
from XBeach.Montecarlo)
try
    !RunThis.bat &
catch exception
    disp 'RunThis.bat does not work, check location bat file'
end
pause (30) % It takes RunThis (=SimEBE) about 20 sec; MATLAB will read results after 30
sec.

% read result from file rof4_10000.res
fidd=fopen('H:\backup_usb\ProfAndMC\ZTest\TestANarrabeenProfile4\Prof4_10000.res');
ReturnIntX = textscan(fidd, '%f %f');
AA=zeros(16,3);
AA(:,1)=ReturnIntX(:,2);
fclose(fidd);
AA(:,2)=ReturnInt8800(:,2);
for i=1:16
    AA(i,3)=(((AA(i,1)-AA(i,2))^2)^0.5)/(max(AA(i,1),AA(i,2)))*100;
End

% save result in array
Resemblance(loop,1) = length(EVolAll);
Resemblance(loop,2) = 100-(mean(AA(:,3)));
%return
save('H:\Thesis\Narrabeen\Model\CA\OUT_HPC\Resemblance_CA.mat', 'Resemblance')
end

```

Table including results of SkillSort.m; ordering of skill score per number of simulations (bounded by upper and under bin)

bin	under	upper	n	u	sd	Kolmogorov-Smirnov		
						Statistic	df	Sig.
1	0	32	97	55.19	20.36	0.093	15	.200*
2	32	74	159	54.46	16.40	0.229	15	0.034
3	74	100	47	50.87	18.45	0.237	15	0.024
4	100	150	109	54.64	16.85	0.14	15	.200*
5	150	200	62	53.39	20.68	0.111	15	.200*
6	200	250	62	59.99	21.18	0.142	15	.200*
7	250	300	72	63.64	21.03	0.133	15	.200*
8	300	350	37	63.27	22.41	0.13	15	.200*
9	350	400	63	59.71	21.05	0.112	15	.200*
10	400	450	46	69.73	21.39	0.232	15	0.029
11	450	500	21	71.57	22.35	0.284	15	0.002
12	500	600	84	66.83	21.96	0.144	15	.200*
13	600	750	57	74.09	18.24	0.113	15	.200*
14	750	900	95	77.07	19.06	0.207	15	0.082
15	900	1200	121	74.19	21.35	0.122	15	.200*
16	1200	1500	88	75.08	19.66	0.149	15	.200*
17	1500	2000	147	74.03	20.17	0.187	15	0.165
18	2000	3000	159	79.53	19.60	0.256	15	0.009
19	3000	4000	157	84.47	18.54	0.366	15	0
20	4000	5000	132	86.80	17.58	0.371	15	0
21	5000	6500	159	93.51	13.89	0.434	15	0
22	6500	8800	146	96.68	9.90	0.332	15	0