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COASTAL AND MARINE ENGINEERING AND MANAGEMENT
COMEM

ANALYSIS OF MODEL PERFORMANCE RELATED TO UNCERTAINTY IN THE MODEL BEACHPLAN FOR THE SIMULATION OF SHORELINE EVOLUTION

University of Southampton
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UNIVERSITY OF SOUTAMPTON

FACULTY OF CIVIL ENGINEERING AND THE ENVIRONMENT

ANALYSIS OF MODEL PERFORMANCE RELATED TO UNCERTAINTY IN THE MODEL BEACHPLAN FOR THE SIMULATION OF SHORELINE EVOLUTION

LIJIE QIU

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ABSTRACT

As a useful tool in understanding the coastal behaviours, one-line models , which are designed to simulate the long-term shoreline evolution in response to imposed wave conditions, coastal structures, and other engineering activities such as beach nourishment, have been developed and applied to a wide range of projects in coastal engineering and management. However, most of them are deterministic and not probabilistic, the model performance is associated with presumed uncertainty due to the high quality input data required and the large number of processes involved in reality but which are simplified in the one-line theory. In the past, the assessment of model performance has usually been a subjective judgement of goodness of fit, which depends on researchers' expertise and experience by comparing prediction with observation.

This dissertation study aims to find a method of evaluating the performance of one-line models such as BEACHPLAN, so as to qualify the model accuracy in an objective way. To measure the skill of a model, uncertainty, optimization and sensitivity modelling of beach behaviour related parameters, such as shoreline orientation, wave climates, etc., are investigated, which provide acknowledge of shoreline response to variable input data. Four error analysis methods: correlation, shoreline movement, probabilistic and distortion length, are employed to quantify the model errors. Applied to a set of proposed criteria-Model Performance Rating System (MPRS), error indicators of these four approaches are ranked so that the best-fit input parameter/model performance can be identified. The adapted assessment method is tested on a ''log-spiral'' shaped shoreline of Poole Bay, UK. Additionally, shoreline orientation is addressed in this dissertation study, which is critical in shoreline evolution analysis. The results show that the methods are able to evaluate the model performance and select the best match.

The significance of the method adapted in this research is quantifying and reducing the model uncertainty and establishing model reliability. In the future, more validations with other numerical models are needed before it can be recognized as a sophisticated assessment method.

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LIST OF SYMBOLS

b	subscript, denotes breaking conditions
c	wave phase velocity [m/s]
D_B	berm elevation, landward limit [m]
D_C	closure depth [m]
E	wave energy [J/m^2]
g	gravitational acceleration [m/s^2]
h	water depth [m]
H	significant wave height [m]
I	The underwater weight of sediment transported [kg/s]
K	calibration coefficient in CERC formula [-]
K_1 , K_2	scaling coefficient [-]
n	ration between group and phase velocity [-]
M	number of transects
N	computational steps in the model
p	porosity of bed material [-]
q	Volume of material brought onshore [m^3/s/m]
Q	longshore sediment transport rate [m^3/s]
Q_0	amplitude of longshore sediment transport rate [m^3/s]
r	correlation coefficient [-]
s	relative density of the sediment [-]
t	time [s]
x	distance alongshore [m]
y	shoreline position [m]
α	angle between wave crests and shoreline [^{o}]
α'	shoreline angle relative to the north [^{o}]
β	slope of beach face [-]
γ_s	submerged weight of beach material in place [kg]
σ	standard deviation
ρ	density of water [kg/m^3]
ρ_s	density of sediment [kg/m^3]
ε	diffusion coefficient [-]
φ	wave angle of incidence [^{o}]
ϕ	grain size

LIST OF GLOSSARY & ABBREVIATIONS

BEACHPLAN	One-line model, HR Wallingford, UK
BIS	Beach Improvement Scheme
BSS	Brier Skill Scores
CCO	Coastal Channel Observation
CCRA	Climate Change Rise Assessment
CDF	Cumulative Distribution Function
CERC	Coastal Engineering Research Centre, USA
CIRIA	Construction Industry Research and Information Association
CPI	Confidence Performance Index
DHI	Danish Hydraulic Institute, Demark
DL	Distortion Length
GENESIS	Generalized Model for Simulation Shoreline Change, one-line model, Sweden
GIS	Geographic Information System
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
LITPACK	One-line model, DHI
LST	Longshore Sediment Transport
NMSE	Normalised Mean Square Error
MAE	Mean Absolute Error
MHW	Mean High Water Level
MHWN/MHWS	Mean High Neap/Spring Water Level
MLWN/MLWS	Mean Low Neap/Spring Water Level
MPI	Model Performance Index
MPRS	Model Performance Rating System
MSE	Mean Square Error
MSL	Mean Sea Level
ODN	Ordnance Datum Newlyn, UK
RMSE	Root Mean Square Error
SPI	Skill Performance Index
TELURAY	Wave model
UNIBEST-CL	One-line model, HL/ Delft Hydraulic

1. General Introduction

This chapter firstly provides a brief description of the background and scope as well as the purpose of this dissertation study. Next, the aims and objectives are introduced considering the potential problems that may occur. The structure of this dissertation is outlined at the end of the chapter.

1.1 Introduction

Humans take advantages from a wide variety of oceanic resources and vast space in the coastal zone. According to investigations, there are approximately three billion people who live or work within hundreds of kilometres of a shoreline, notwithstanding some areas that are vulnerable of flooding or erosion (Bosbom and Stive, 2011). Natural processes, such as geologic activities, wind, wave, tide and storm surges, are important driving forces that determine the characteristics of a coast. Meanwhile, human activities such as fishing, shipping, water treatment, and recreation etc., have inevitable influences on the coastal area, changing or reshaping the coastlines.

In coastal regions, due to the variation of wave climate and/or construction of coastal structures which act as barriers to wave propagation and longshore sediment transport, beach erosion or accretion happens from time to time. Coastal erosion, in particular, has been a world-wide problem for decades. An estimate of 70% of world's sandy beaches are retreating (Bird, 1985), while in the UK, approximately 3,000 km (17%) of coastline are experiencing erosion (CCRA, 2012). At the same time, some areas in the world such as the low-lying country the Netherlands, a lot of emphasis have been put on flood protection.

Considering the high population densities and extensive infrastructures and property development along the coast, the forecast of shoreline evolution for both short and long time-scales plays an essential role in coastal engineering and management. One-contour-line theory (one-line theory), as a simple and easy method, has been used for the prediction of shoreline changes for more than 50 years. Based on this theory, some one-line models such as GENESIS, LITPACK, UNIBEST-CL and BEACHPLAN have been developed in different research institutions. They are widely used in coastal projects especially forecasting shoreline changes, and they are a great advancement for the study of coastal processes. However, most one-line models are deterministic and not probabilistic, with restriction on predictive reliability depending on the quality of input data.

One-line models have been designed as a first-stage tool in understanding the behaviour of a coast and the impact of engineering works upon it. There are various constraints with one-line theory, e.g. straight shore baseline, no source or sink, etc. As well as this, extremely complex and absolutely arbitrary coastal processes create more problems for models to consider all the factors and simplifications are needed. In some cases, the assumptions used in the model fail to be met or are oversimplified so that the model's effectiveness as a predictive tool is limited at best.

One-line models such as BEACHPLAN have been developed with a lot of progresses, e.g. involving more beach behaviour model parameters, as well as different coastal structures (seawall, groyne, breakwater, etc.). Even though, one-line models still have insufficiencies, further efforts also need to focus on accuracy and predictive capability.

In terms of the great variability of the coastal activities, it is clear that a single answer obtained from a deterministic model must be assessed with some methods to determine its accuracy, so as to be viewed as a representative result. In the past, most modellers only used a subjective analysis to identify the performance of one-line numerical model, which relied on their own technical expertise and judgement. A set of standardized, objective model evaluation criteria is therefore required to evaluate the prediction skill of a model.

1.2 Aim and Objectives

The aim of this dissertation is to find a method of comparing quantified indicators for assessing model performance, so as to estimate the quality between predictions in a more objective sense.

To achieve this aim, three objectives are set out:

1. Investigate the principles of one-line models;
2. Gain an understanding of the model settings in BEACHPLAN and test the model with a simple straight beach as well as the case of Poole Bay in terms of its unique log-spiral plan shape (see Figure 1-1);
3. Error analysis against field measurement data, in order to determine the best-fit parameters and predict the longshore drift as well as shoreline responses in a more realistic way.

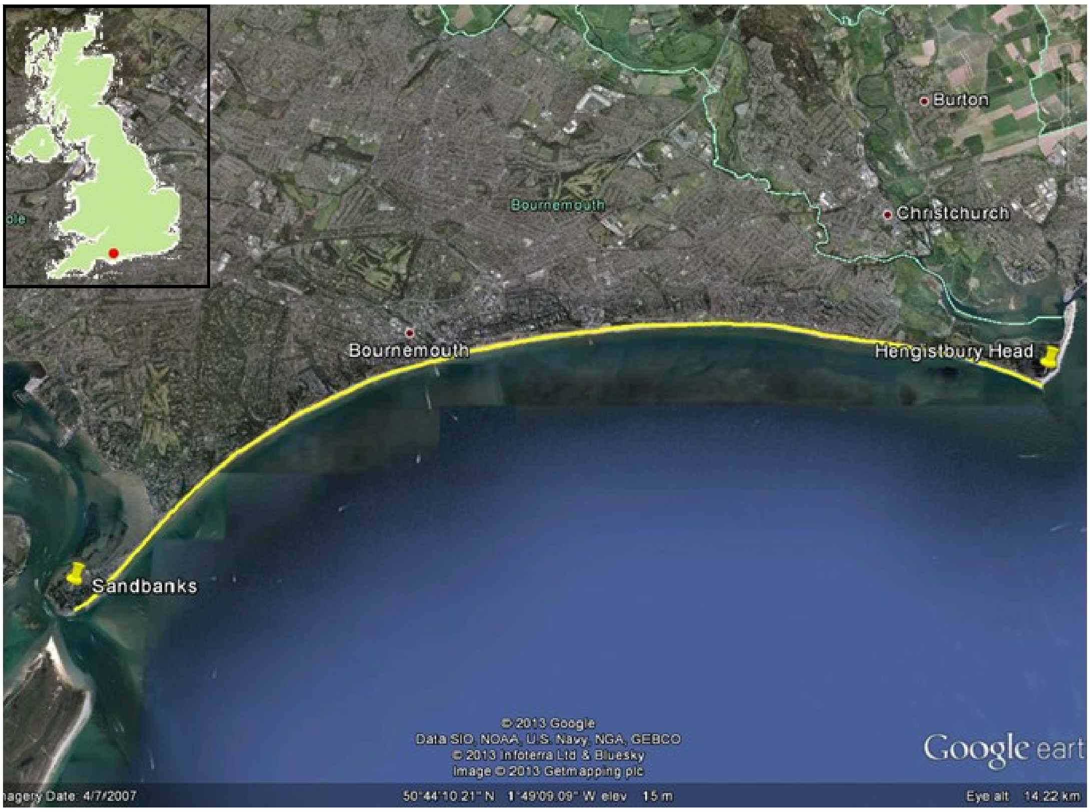


Figure 1-1 Location of Study Area - Poole Bay

1.3 Structure of Dissertation

In this dissertation, one-line shoreline theory and models, tests of model BEACHPLAN and assessment methods of model performance are presented. This dissertation is organized in six chapters:

Chapter 1 introduces the research background, aim and objectives, as well as the structure of this dissertation.

Chapter 2 provides a literature review related to this study, a detailed description of numerical shoreline change models, one-line theory and one-line models. Several methods used for model evaluation are summarized. The background information of tested case Poole Bay is investigated in the last section.

Chapter 3 gives a brief introduction of the one-line model BEACHPLAN and Monte Carlo toolbox, as well as the model set-up for the studied case Poole Bay; then explains the chosen methods to assess model performance from three aspects: uncertainty, optimization and sensitivity.

Chapter 4 provides a succinct summary of results from the model and model performance aspects.

Chapter 5 discusses the assessment methods of model performance in more detail.

Chapter 6 summarizes the conclusions reached by the study and give some possible recommendations for the further work on model performance.

References and appendices are listed at the end of the dissertation.

2. Literature review

In this chapter, numerical models and one-line theory are studied in detail. Main features of four frequently used one-line models with respect to shoreline evolution are summarized. The last section illustrates several methods that are commonly used for evaluating the performance of numerical models.

2.1 Numerical Models for Shoreline Evolution

Shoreline changes, including erosion and accretion, are not only controlled by natural factors, e.g. wind, waves, currents and sediments, but are also influenced by engineering activities, which alter or block sediment movement along and/or across the shore. Considering the complexity between coastal processes and responses, it is not easy to predict the beach evolution in a precise way. With the increase in computational technology, numerical models have been developed and used in industries to solve the problems such as forecasting of coastal processes.

Shore protection and beach stabilization are major responsibilities in the field of coastal engineering and management. Over the last decades, a lot of numerical models have been developed and applied on a variety of coastal research projects. There is an increasing reliance on numerical models especially to forecast shoreline changes. These models are referred to as shoreline change or shoreline response models because they simulate changes in position of the beach in response to wave action and boundary conditions (Hanson and Krause, 1989). Most of the numerical shoreline models are designed for simulating the beach plan shape for particular situations which is usually caused by a significant perturbation, for example, construction of a breakwater, or sand nourishment near a coastal area.

Shoreline change models can predict beach position changes over a period from several months to years, with a spatial extent of simulated region ranging from small scale (hundreds of meters) to large scale (hundreds of kilometres). According to Lakhan (2003), numerical models of beach change can be classified into three broad types:

1). Profile evolution models, which only simulate cross-shore processes, but ignoring the longshore processes;

2). Contour line models, e.g. one-line models, which simulate the shoreline evolution caused by gradients in the longshore sediment transport rate (more introductions are described in Section 2.2 and Section 2.3);

3). Three-dimensional (3-D) models, which involve both cross-shore and longshore processes.

A modified classification of beach change models is developed by Hanson and Kraus (1989) for comparing the capabilities of beach evolution models by their applicability in spatial and temporal scales, as shown in Figure 2-1. Ranges of model domains were estimated by considering computation costs and model accuracy. As the knowledge of coastal processes and modelling experience are building up, data becomes available and numerical schemes are optimized, accordingly computer costs will decrease.

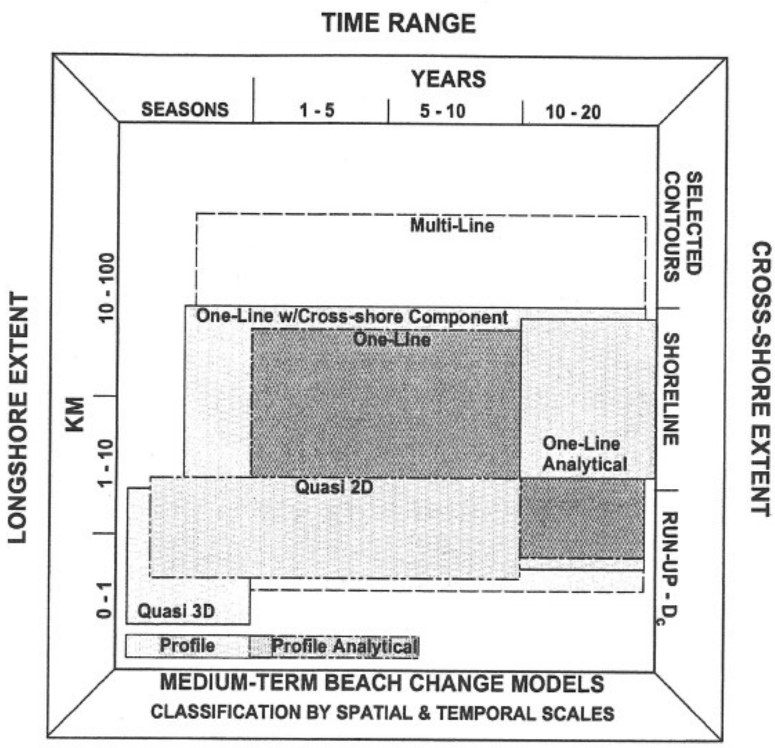


Figure 2-1 Classification of Shoreline Change Models by Spatial and Temporal Scales

(Source: Modified from Hanson and Kraus (1989))

In coastal engineering there is an increasing reliance on numerical models to predict the beach behaviour. However, some coastal researchers, such as Pilkey (1993) and Thieler et al. (2000), argued that there’s a great discrepancy between the predicted beach behaviour produced by models and the reality. They suggested that many assumptions and/or simplifications used in these models are not valid in the context of modern oceanographic and geologic principles. In one-line models, for example, the concept of closure depth is brought into question by theory and field investigation, in which closure depth means that there is no sediment transport assumed beyond this boundary. But many studies, e.g.

Snedden et al. (1988), Loughran and Campbell (1995), have discovered that larger volumes of nearshore sediment were found to have been moved out on the continental shelf as a result of storm driven currents. Coastal engineers and researchers should understand these weaknesses and limitations before they apply modelling results for decision-making, e.g. designs of coastal structure.

In practice, a simulation model often has enough parameters to reproduce the coast behaviours of a particular location, and greater accuracy can be obtained through model calibration (Figure 2-2).

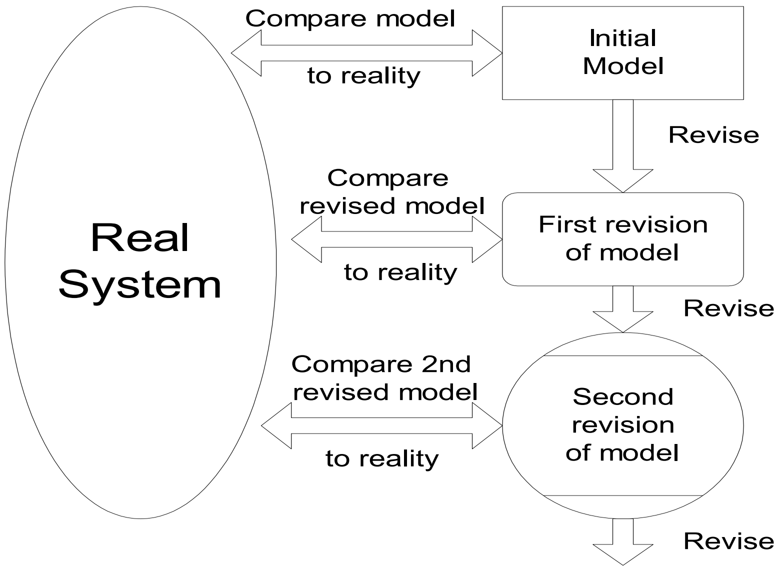


Figure 2-2 Calibration Process of Numerical Models

2.2 One-line Theory

Before introducing one-line models, the fundamental principles and constitutive laws of material behaviour need to be investigated, which is known as one-line theory.

Over a long period of time it is observed that the beach profile of a particular coast does not change much but maintains an average shape that is characteristic, ignoring extreme changes due to storm events. Ever since Pelnard-Considère (1956) first introduced the one-line theory in beach evolution modelling, it has been adopted by many researchers worldwide. One-line theory works under some assumptions that the beach profile moves parallel to itself (Figure 2-3), and wave breaking is the main reason of sediment transporting alongshore within the closure depth. This provides a simple way to calculate changes of beach position and sand volume.

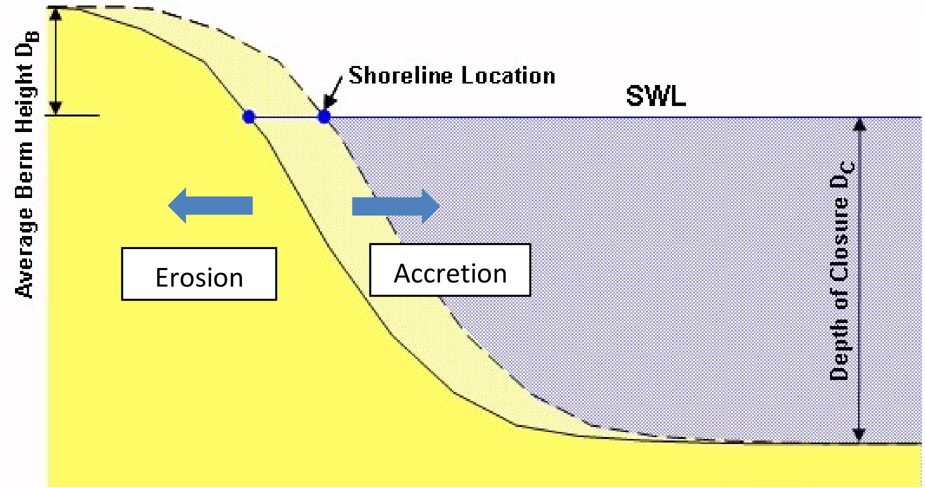


Figure 2-3 Assumption of Shoreline Movement Parallel to Itself in One-Line Theory

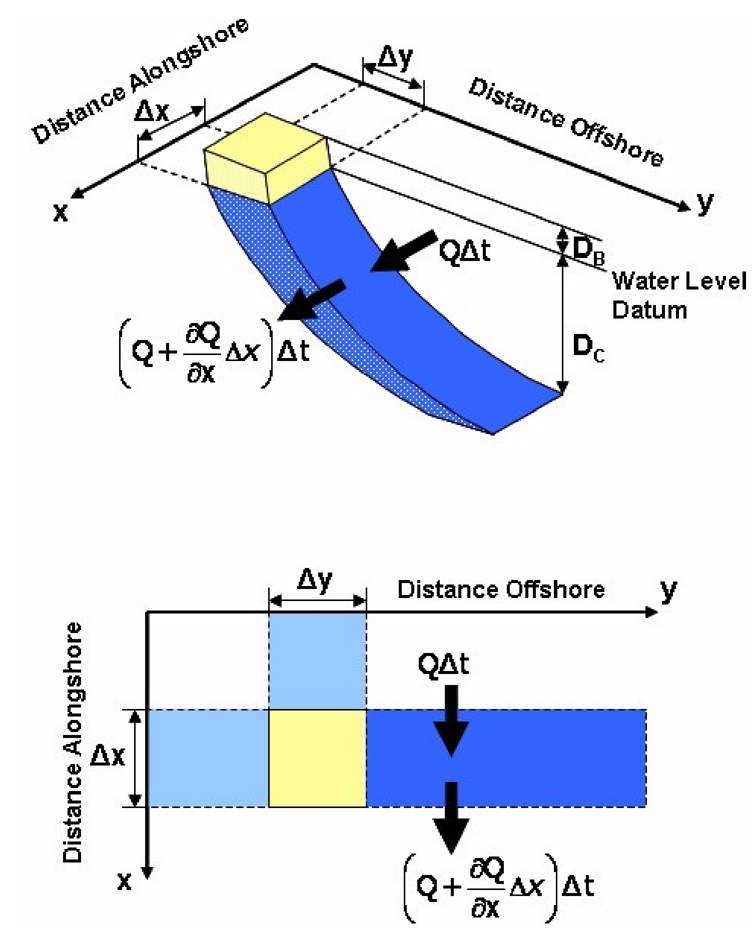


Figure 2-4 Definition Sketch for Shoreline Change Calculation

(Sources: http://www.vliz.be/wiki/Long-term_modelling_using_1-line_models_GENESIS_and_new_extensions)

Based on the equation of mass conservation, longshore variation in the sand transport rate is balanced by changes in the shoreline position, the governing equation is written as

$$\frac{\partial y}{\partial t} + \frac{1}{D_B + D_C}\left(\frac{\partial Q}{\partial X} - q\right) = 0 \qquad (2.1)$$

Where

D_B: berm elevation, landward limit [m],

D_C: closure depth, seaward limit [m],

Q: longshore sediment transport rate [m^3/s],

q: volume of material brought onshore [$m^3/s/m$],

x: distance alongshore [m],

y: shoreline position [m],

t: time [s].

If there is no onshore input (q=0), erosion will occur in case of a positive gradient in the transport direction ($\frac{\partial Q}{\partial x} > 0$), while accretion occurs in case of a negative gradient in the drift direction ($\frac{\partial Q}{\partial x} < 0$). A uniform sediment transport along the shore ($\frac{\partial Q}{\partial x} = 0$) does not change the plan shape of coastline.

To solve Equation (2.1), a general expression for longshore sand transport rate is specified:

$$Q = Q_0 sin2\alpha_b \qquad (2.2)$$

Where

Q_0: amplitude of longshore sediment transport rate [m^3/s],

α: angle between wave crests and shoreline [º], subscript ''b'' denotes breaking conditions. This angle may be expressed as

$$\alpha_b = \alpha_0 - \arctan(\frac{\partial y}{\partial x}) \qquad (2.3)$$

in which α_0 is the angle of breaking wave rests relative to an axis set parallel to the trend of the shoreline, and $\frac{\partial y}{\partial x}$ is local shoreline orientation (Figure 2-5).

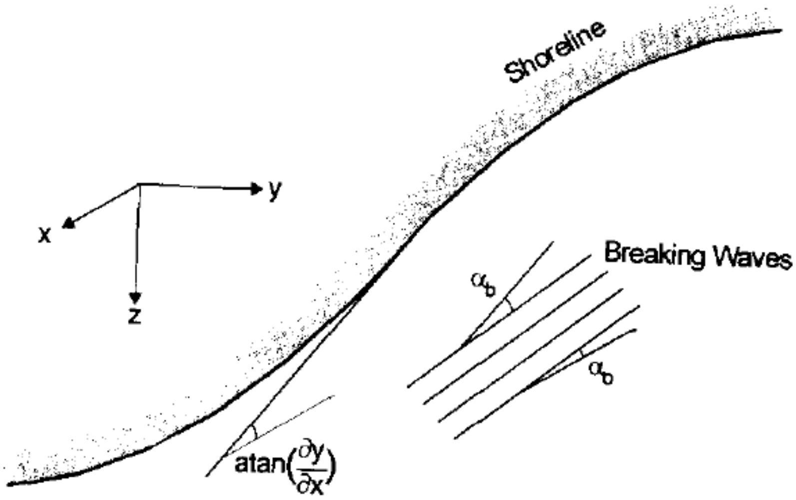


Figure 2-5 Plan View of Shoreline Evolution at Specific Location

(Source: Adapted from Larson et al. (1997))

Longshore sediment transport (LST) plays a large role in the evolution of a shoreline. In the last decades, numerous formulas for computing the LST by waves and currents have been proposed and used in different one-line models, e.g. CERC formula (further explained as following) in the model GENESIS and BEACHPLAN. However, there is no well-established transport formula that takes into account all the factors that control LST in the surf zone. Bayram et al. (2001) evaluated the skill of six well-known formulas by analysing the cross-shore distribution of LST, which were proposed by Bijker (1967), Engelund-Hansen (1967), Ackers-White (1973), Bailard-Inman (1981), van Rijn (1984), and Watanabe (1992) respectively (Figure 2-6), and compared the calculation results against detailed, high quality data on hydrodynamics and sediment transport from Duck, NC. They found that the Van Rijn formula gave the most reliable predictions for all wave conditions (including swell and storm, one comparison is shown in Figure 2-7).

Formula	Longshore sediment transport formula	Coefficients	Verification data		
			D (mm)	$\tan\beta$	Exp. condition
Bijker	$q_{b,B} = Ad_{50}\frac{V}{C}\sqrt{g}\,exp\left[\frac{-0.27(s-1)d_{50}\rho g}{\mu\tau_{b,wc}}\right]$	$A=1-5$	0.23	0.07	$H_0=1.6$ m;
	$q_{s,B} = 1.83q_{b,B}\left[I_1\ln\left(\frac{33h}{r}\right)+I_2\right]$	(non-breaking–breaking)			$T=12.0$ s;
					$\alpha=13°$
Engelund–Hansen	$q_{t,EH} = V\frac{0.05C\tau_{b,wc}^2}{(s-1)^2 d_{50}\rho^2 g^{5/2}}$	–	0.19–0.93	–	–
Watanabe	$q_{t,W} = A\left[\frac{(\tau_{b,wc}-\tau_{b,cr})V}{\rho g}\right]$	$A=0.5-2$	0.2–2.0	0.2–0.01	$H_0=0.02-2.4$ m;
		(regular–irregular)			$T=1.0-18.0$ s; $\alpha=15-45°$
Ackers–White	$q_{t,AW} = V\frac{1}{1-p}d_{35}\left(\frac{V}{V_*}\right)^n\frac{C_{d,gr}}{A^m}(F_C-A)^m$	$A, m, n, C_{d,gr}, F_C$	0.2–0.61	–	$h=0.18-7.17$ m
(not modified)					
Van Rijn	$q_{b,VR} = 0.25\gamma\rho_s d_{50}D_*^{-0.3}\sqrt{\frac{\tau'_{b,wc}}{\rho}}\left[\frac{\tau'_{b,wc}-\tau_{b,cr}}{\tau_{b,cr}}\right]^{1.5}$		0.1–0.2	–	$H_0=0.07-0.2$ m;
					$T=1.0-2.0$ s;
	$q_{s,VR} = c_a Vh\frac{1}{h}\int_a^h \frac{v}{V}\frac{c}{c_a}dz = c_a VhF$				$\alpha=90°$
Bailard–Inman	$q_{t,BI} = 0.5\rho f_w u_0^3\frac{e_b}{(\rho_s-\rho)g\tan\gamma}\left(\frac{\delta_v}{2}+\delta_v^3\right)$	$e_b=0.1$; $e_s=0.02$	0.175–0.6	0.034–0.138	$H_0=0.05-1.44$ m;
	$+0.5\rho f_w u_0^4\frac{e_s}{(\rho_s-\rho)gw_s}(\delta_v u_3^*)$				$T=1.0-11.0$ s;
					$\alpha=2.8-18.9°$

Figure 2-6 Formulae of Longshore Sediment Transport (LST)

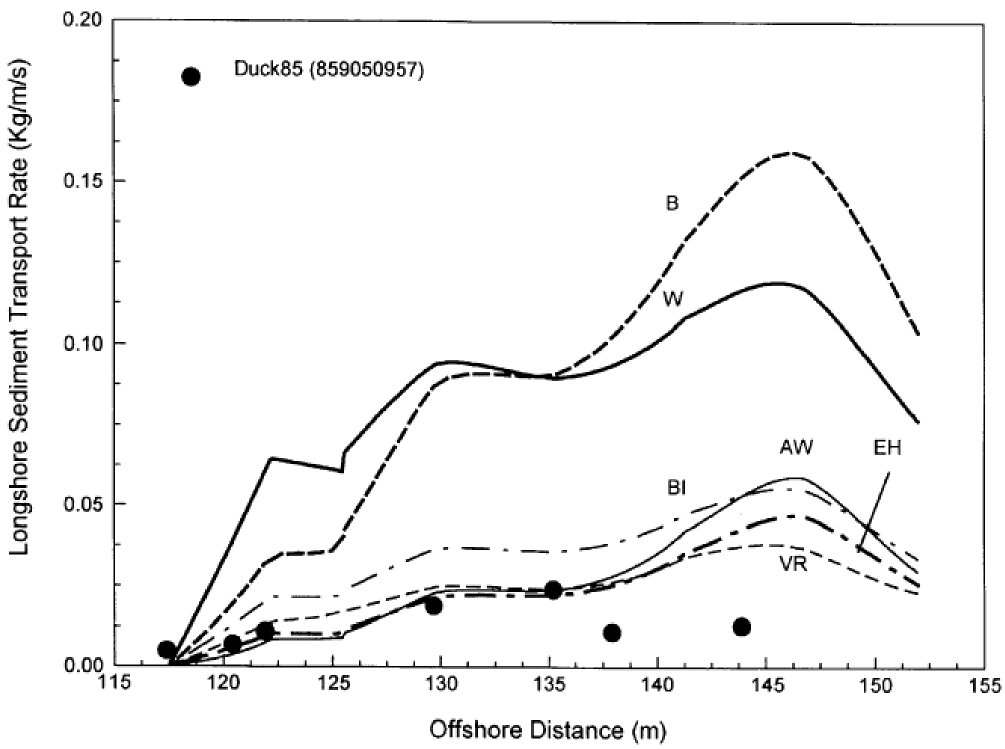


Figure 2-7 Comparison between Calculated and Measured Cross-Shore Distribution of Longshore Sediment Transport Rate from the DUCK85 Experiment

(Source: Adapted from Bayram et al. (2001))

At present the most frequently used formula however for model computations are CERC (Komar and Inman, 1970) and Kamphuis formula (1991) as below:

CERC: $$Q = \frac{I}{\rho g(s-1)(1-p)} = \frac{K}{\rho g(s-1)(1-p)}(Enc)_b cos\varphi_b sin\varphi_b \quad (2.4)$$

Kamphuis: $$Q = 6.4 \times 10^4 H_{sb}^2 T_p^{1.5} m^{0.75} d_{50}^{-0.25} sin^{0.6}(2\varphi_b) \quad (2.5)$$

Where

I: the underwater weight of sediment transported [kg/s],

ρ: density of water [kg/m^3],

s: relative density of the sediment [-],

p: porosity of bed material [-],

g: gravitational acceleration [m/s^2],

K: calibration coefficient [-], estimated as 0.77 by Komar and Inman (1970),

E: wave energy [J/m^2],

c: wave phase velocity [m/s],

n: the ratio between group and phase velocity [-],

φ: wave angle of incidence [^{o}],

H_{sb}: significant wave height at breaking [m],

T_p: peak wave period [s],

m: beach slope from the breaker line to the shoreline [-],

d_{50}: median grain size [m],

Other variables are the same as previously defined.

The CERC formula (Equation (2.4)) is a simple way to calculate LST (including both suspended and bed load), which is assumed to be proportional to the energy flux. However, the CERC formula only considers wave height, wave angle and water depth to determine the wave energy flux, where sand properties and the beach slope are ignored. Equation (2.5) was developed by Kamphuis (1991) based on physical model experiments, which includes influences of the beach slope, sediment grain size and wave period. The predictive ability of these two formulas is compared by Wang et al. (1998) and they found that the Kamphuis (1991) formula predicted consistently lower total LST than that predicted by the CERC formula for those low-wave conditions. Additional field and laboratory data and research are needed to develop more accurate and robust predictors for the magnitude of LST as well as its cross-shore distribution pattern (Wang et al., 2002).

2.3 One-line Models in Practice

Considering that available computational technology and techniques can provide engineers with the option of exploring complex but relatively accurate solutions, numerical models are more widely used to solve practical problems, such as one-line models.

Nowadays, one-line models have demonstrated their practical capability in predicting shoreline changes for a long-term period, and greatly help to understand the physical processes and solve practical problems stipulated by coastal zone management. One-line models such as GENESIS, LITPACK, BEACHPLAN, etc., have been widely used by coastal researchers for longshore sediment transport quantification and shoreline response analysis. The general structure of one-line models is shown in Figure 2-8.

One-line models have been proven to be a powerful tool for prediction of beach evolution, however, according to Murray (2003) there’s no one universal model that can be applied in any spatial and temporal scale, most of one-line models are deterministic in nature. The model BEACHPLAN, developed by HR Wallingford, is a useful one-line theory based tool for coast protection and management (more introduction of the model BEACHPLAN is given in Section 3.1.1).

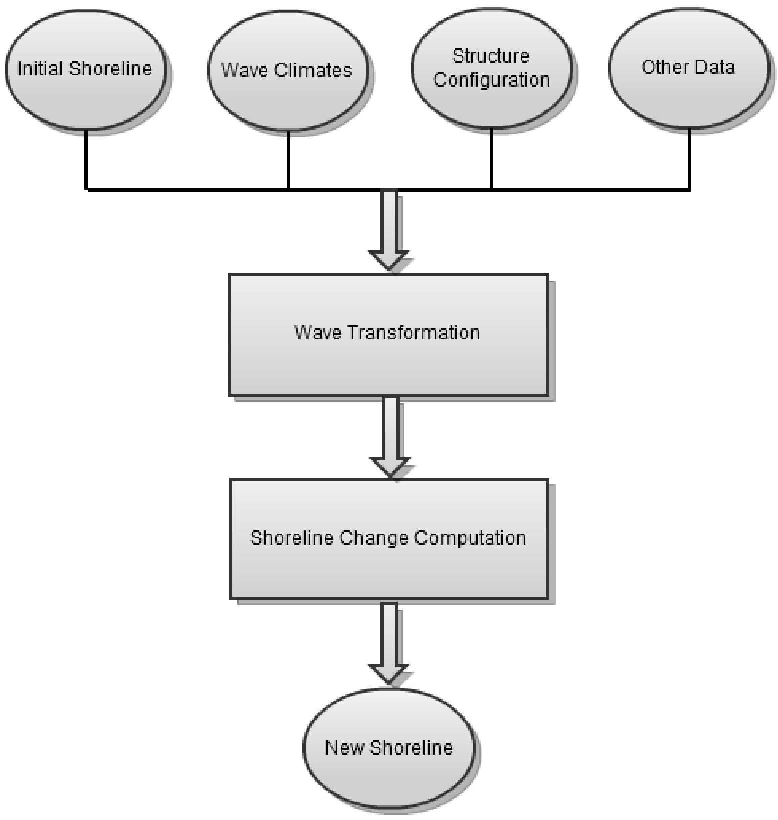


Figure 2-8 Flowchart of One-line Model

Szmytkiewicz et al. (2000) tested four one-line models and summarized some main features with respect to the computations of shoreline evolution. Comparing the model BEACHPLAN with three other well-known one-line models: GENESIS, LITPACK and UNIBEST, the main features are shown in Table 2-1 (Szmytkiewicz et al., 2000). Each model has its own strengths and deficiencies, it is therefore not feasible to conclude which one is better overall.

Additionally, recent improvements have boosted the practical applicability of one-line models by extending them towards two-directional modelling, e.g. ONELINE (Queen's University), and BEACHPLAN (HR Wallingford) coupled with COSMOS, which calculate shoreline variation due to longshore sediment differentials as well as cross-shore sediment movements. Model tests by Dabees and Kamphuis (1998) at two locations of Sea Isle City beach, New Jersey, and the Nile Delta Coast in Egypt indicate that the predictions of sediment transport and shoreline response to various combinations of coastal structures are reasonable against field data.

Table 2-1 Main Features of Four One-Line Models

Feature	GENESIS	LITPACK	UNIBEST	BEACHPLAN
2D Bathymetry	Necessary in full run; not used in simplified run	Required only for determination of representative profiles	Required only for determination of representative profiles	Required only for determination of representative profiles
Variability of seabed properties along shore profile	Not taken into account	Taken into account	Not taken into account	Taken into account
Wave input parameters	Significant	Root-mean-square	Significant	Significant
Wave chronology	Taken into account	Taken into account	Not taken into account	Taken into account
Wave transformation	''Mild slope'' equation type in full run; linear refraction/ shoaling in simplified run	Battjes-Janssen	Battjes-Janssen	Linear theory
Diffraction around structures	Taken into account	Taken into account	Not taken into account	Taken into account, under improvement
Longshore current	Not modelled	Longuet-Higgins type	Longuet-Higgins type	Longuet-Higgins type
Longshore sediment transport	CERC type formula	DHI model	Engelund-Hansen, Bijker, van Rijn, Bailard, CERC	CERC type formula
Beach nourishment	Taken into account	Taken into account	Taken into account	Taken into account, under improvement
Groins, jetties	Taken into account	Taken into account	Taken into account	Taken into account
Offshore breakwaters	Taken into account	Taken into account	Not taken into account	Taken into account
Seawalls, revetments	Taken into account	Taken into account	Taken into account	Taken into account

(Source: Modified from Szmytkiewicz et al. (2000))

2.4 Assessment of Model Performance

It is desirable to include as much detail about the observations and model predictions as possible in the assessment of model performance.

During the past decades, the theoretical knowledge of coastal processes and the models to reproduce these have been improved considerably. Although remarkable progress has been achieved in the performance of numerical models, model evaluation remains a controversial problem, and is an essential part of establishing models' credibility. In the past, researchers usually compared predicted results with observed behaviour, and judged the goodness of fit in a subjective way. Studies about model performance are hard to find in the literature, despite the variety of numerical models.

As an important tool for investigating coastal processes and engineering designs, numerical models require an objective assessment for their modelling performance, which is desired to include as much detail as possible. While Miller (2004) implied in his PhD dissertation that it is impossible to evaluate a model in a completely objective sense, it is the objective measures that actually provide quantified data and criteria for subjective analysis that help to evaluate a model.

Model evaluation has so far been seen to consist of quantitative comparisons between predicted variables and corresponding measured data in the field or laboratory. In theory, modelers aim to see that the model results are the same as field data so as to validate the performance of the model. In practice, however, there's no such perfect fit between a model and real data, as the model cannot take into account all the processes that affect the quantitative accuracy of the model.

As Young et al. (1995) proposed, computer models should output probabilistic results together with indications of the level of error expected as a function of the quality of the input data. However, most modellers focus on the accuracy of computed results judging by their expertise, a few researchers have been working on probabilistic modelling, such as Ruggiero et al. (2006), Wang and Reeve (2010), Wegen and Jaffe (2013), etc.

2.4.1 Uncertainties with Numerical Models

Corresponding to natural and human-induced forces, the coastline is always adjusting itself towards an ''equilibrium state''. For simplification, the movement of shoreline position can be divided into three categories: erosion, no change and accretion. One-line models provide simple solutions for predicting these changes, which are significantly helpful for coastal engineering design and management.

However, numerical models are being disputed for their physical accuracy and reliability as a predictive tool for practical application (Young et al., 1995). Many faulty assumptions, model imperfections and averaged values contained in these models all contribute to the uncertainty of the results in ways that are hard to quantify or predict.

It is worthwhile to explore uncertainties in model inputs as well as outputs. Loucks and van Beek (2005) classified uncertainty types by investigating some models of water resources system, referring to Figure 2-9.

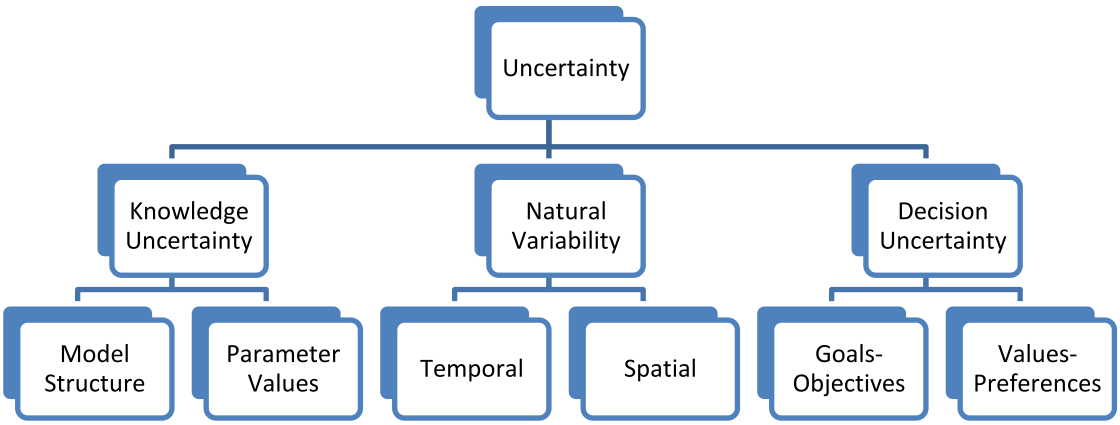


Figure 2-9 Classification of Model Uncertainties

The main source of model output uncertainty is the natural variability of input parameters. Natural variability includes both temporal variability and spatial variability, to which model input values may be subject. Considering the limitations of measuring or recording the complex natural variability, in numerical models, however, much of the input data is averaged by smoothing over an unquantified variability. For example:

a). Wave data is the most important data in this category. The longshore drift is assumed to be solely driven by waves, and the wave data input into the model (e.g. wave period) is averaged to some extent- statistical summaries are used, monochromatic wave trains are assumed; during long runs, wave datasets are often repeated.

b). Shoreline curvature is neglected in model computation, which actually is important since shoreline curvature is one of the factors that result in increase or decrease of coastal erosion (Murray and Ashton, 2002).

c). Profile shape, berm height, and closure depth are all assumed to remain constant along the entire model length and through time; and thus, an average for each must be chosen from the alongshore variation of the model reach.

d). Average nearshore slope is estimated and used in the longshore transport equation.

e). Coastline changes due to short-term variations such as storm events cannot be predicted in numerical models. Extreme events are considered as ''noise'' and assumed to be smoothed out over the long term.

Knowledge uncertainty includes parameter value and model structure uncertainties. Improve the numerical models by increasing model complexity may add the cost of data collection, as well as more potential sources of uncertainty in model output. The main reason is a lack of knowledge, e.g. conflicting evidence, ignorance, effects of scale, etc., which can be reduced through further measurement and/or research.

Decision uncertainty is simply an acknowledgement that people cannot predict what decisions individuals and organizations will make in the future, or even just what particular set of goals or concerns will be considered and the relative importance of each. An example is that people wanted the swampy region protected from floods and urban development some half a century ago, but now for ecological restoration reasons they want more wetlands and unobstructed flows. Complex and changing social and economic processes influence human activities and their demands for coastal utilization over time.

2.4.2 Uncertainty Modelling

Considering that traditional one-line models are deterministic in nature and accuracy of their predictions relies on the uncertainties associated with input parameters, Ruggiero et al. (2006) studied the shoreline changes along the Long Beach Peninsula with the quasi-2D numerical one-line model UNIBEST-CL (WL/Delft Hydraulic, 1994) and suggested a probabilistic manner for predicting shoreline evolution (Figure 2-10), which would be more meaningful than that with a single deterministic outcome, since future coastal changes are determined by environmental conditions (e.g. wave climates and sediment supply) which can only be forecast in a statistical sense. Even though the magnitude of shoreline changes is not precisely known by this approach, the tendency of beach evolution (erosion or accretion) can be predicted with relatively high confidence (Figure 2-11). By applying a deterministic shoreline change model in a probabilistic way, the influence of variability in environmental conditions is therefore transferred to a range of predicted shoreline positions. Additionally, the probability distribution functions of shoreline change prediction at specific alongshore locations can be generated and then used for further analysis.

By studying the computations of shoreline position, Vrijling and Meijer (1992) concluded that ‘’the probabilistic methods provide a qualitative insight in uncertainties of coastal structures and an overview of the contributions of the stochastic coastal variables and model factors to the total uncertainty of the predicted coastline position’’. According to CIRIA (1977), the mean value approach is the simplest probabilistic method, and is very suitable to explain the philosophy even the accuracy is limited.

These probabilistic manners provide an idea that the uncertainty of model performance can be quantified by producing an envelope of beach movement under different scenarios, which will be illustrated in Section 3.3.1.

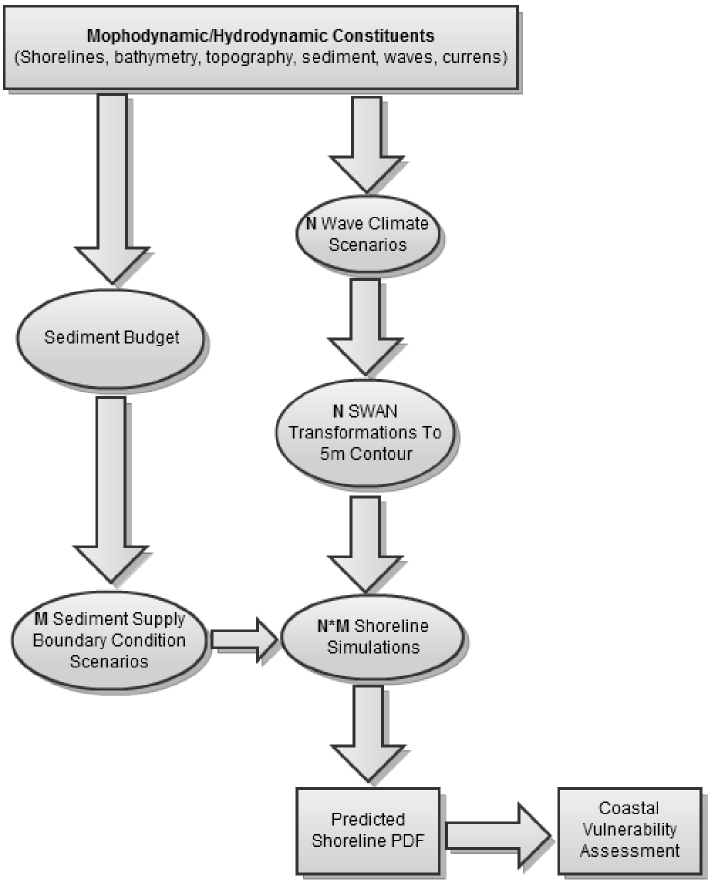


Figure 2-10 Methodology for Constructing Predicted Shoreline Probability Density Functions (PDFs)

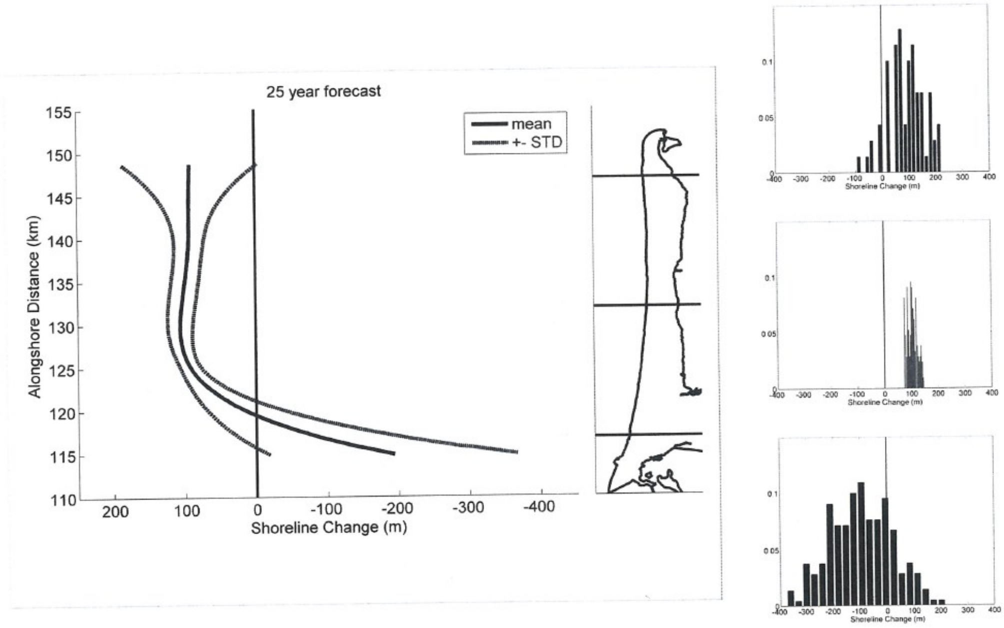


Figure 2-11 Mean and Standard Deviation of Shoreline Forecasts in Probabilistic Manner (Left)

Shoreline Prediction Probability Density Functions at Three Alongshore Locations (Right)

(Source: Adapted from Ruggiero et al. (2006))

2.4.3 Optimization

Uncertainty modelling provides some alternatives for input parameters, while optimization is the selection of a best one with regard to some criteria from these available alternatives. The procedure of optimization is often interpreted by comparisons between the model results and the measurement in field or laboratory. Quantified indicators or criteria are needed to assess the goodness of fit.

Correlation is one of the most used methods when deciding which model simulation has the highest accuracy, e.g. Szmykiewicz et al. (2000), Sutherland et al. (2004). The value of correlation coefficient r=1 denotes a perfect agreement, while smaller than 1 means that computational result has errors to a certain degree. If the correlation coefficient r was negative, a model would produce accretion instead of erosion and vice versa. Szmykiewicz et al. (2000) pointed out in their shoreline modelling study that the correlation method for assessing models’ performance, in terms of accuracy, sometimes produced low score for the results that look good visually, and vice versa.

Error analysis is another widely employed approach for optimization modelling by many researchers, including mean absolute error (MAE), mean square error (MSE)/root mean square error (RMSE), normalized mean square error (NMSE), etc. A perfect model in which the predictions exactly match the observations is characterized by all these error indicators of zero. Another error measuring method proposed by some researchers, such as Carter and Guy (1983), Carter et al. (1986), is computing the shoreline movement of the defined transects between model prediction and observation, which is quite straightforward.

Ramirez (2000) developed four metrics for the positional quality assessment of the linear features, which can be used for analysis of shoreline changes. The four quality metrics are distortion factor, generalization factor, bias factor and fuzziness factor, an overview of them and calculations are shown in Figure 2-12. Ali (2003) and Srivastava et al. (2005) employed these four metrics for error analysis as well as the positional quality assessment of the linear features. In their studies, the results show that the four factors describe independently different characteristics of a linear feature, and distortion factor is proved to be more important due as the calculation is carried out in smaller segments, which are meaningful for comparison under the measure of closeness (Srivastava et al., 2005).

In a probabilistic approach, Wegen and Jaffe (2013) proposed to evaluate the model performance by both ‘’a skill criterion’’(how well does the model reproduce observed patterns?) and ‘’a confident criterion’’ (how sensitive are model results to uncertain input?) by considering the outcome of a batch of model runs including variations of input parameters and forcing schematizations. This idea also helps to determine which input parameters cause largest uncertainty in the model output.

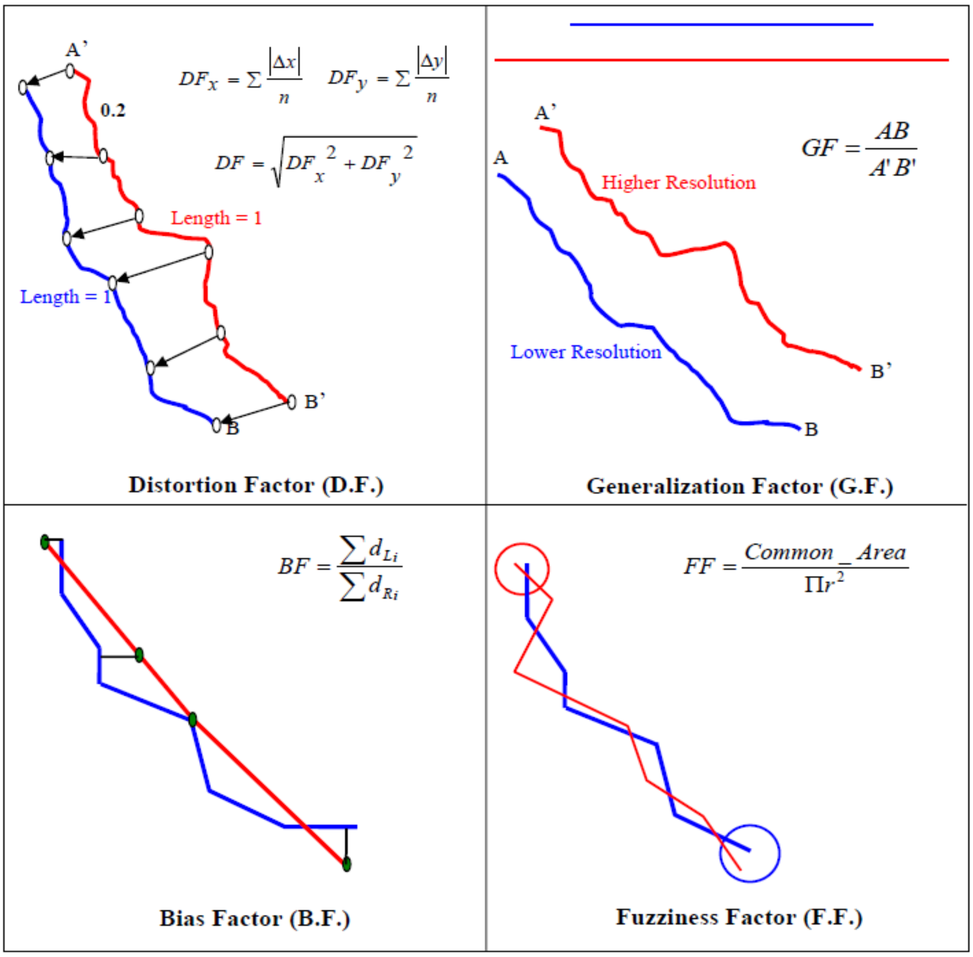


Figure 2-12 Quality Metrics for Comparison of Two Blufflines

(Source: Adapted from Ali (2003))

2.4.4 Sensitivity modelling

The uncertainties associated with parameters in models can be reduced by sensitivity modelling, which helps to build confidence in the model. In addition, identifying which render the shoreline most vulnerable to erosion is the main concern that many coastal researchers and managers are trying to figure out when predicting future shoreline changes with numerical models. Hanson et al. (1991) pointed out that it is necessary to examine the sensitivity of shoreline response to variations in key input parameters before using the model prediction of shoreline changes for alternative designs or management strategies.

Sensitivity tests aim to show how the model behaviour responds to different sources of uncertainty in its input. Many parameters in numerical models represent quantities that are very difficult or even impossible to measure to a great deal of accuracy in the real world (Breierova and Choudhari, 1996). For example, wave climate, including wave height, wave period and wave direction, is an essential factor that determines the development of a coastline. Some model simulations revealed that in some coastal areas , for example, the sandy shore of Rio Grande do Sul in Brazil (Esteves et al., 2006, see Figure 2-13), even subtle changes in the annual wave climate can reverse the local shoreline displacement from erosion to accretion and vice-versa.

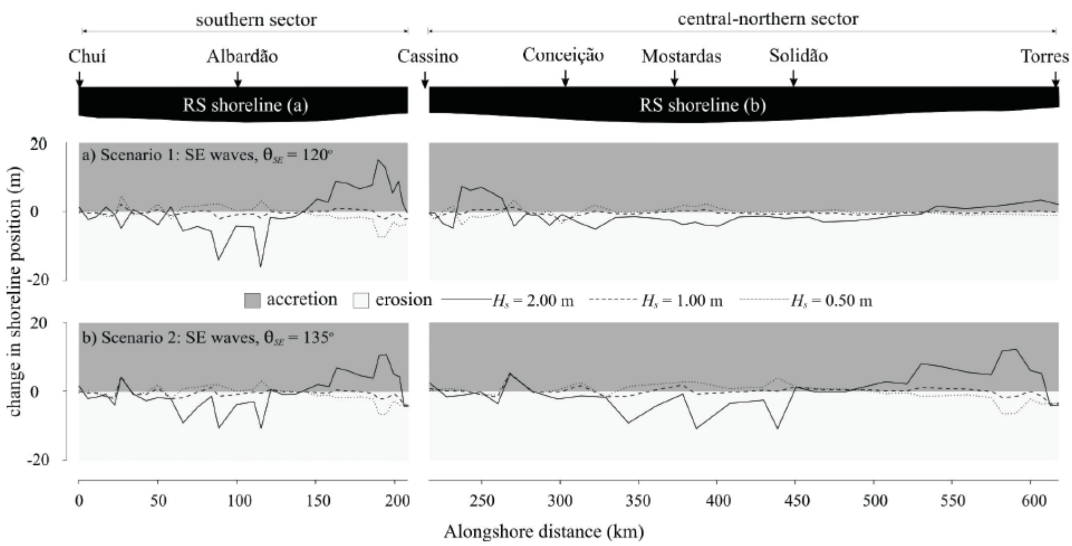


Figure 2-13 Sensitivity Model Tests of Wave Climate

(Source: Adapted from Esteves et al. (2006))

Model tests with a wide range of parameter values not only help modellers to understand dynamics of a shoreline, but also offer insights into beach behaviour under different situations. A study of shoreline response to sea level rise by Murray et al. (2007) indicates that even with the worst-case scenario of sea level rise, the shoreline variation could be an order of magnitude smaller than that wave climate related shoreline changes. When addressing the effects of sea level rise on a sandy beach, researchers usually refer to Brunn Rule and consider cross-shore transport processes (Brunn, 1962; Cowell et al., 1995; Zhang et al., 2004), which assumes that sea level rise will tend to produce uniform retreat along the shoreline. However, the shoreline responses to sea level rise are found to be alongshore-heterogeneous through numerical modelling, and might be difficult to detect on many shorelines because the wave-climate shifts produce alongshore variations in shoreline change that will likely overwhelm sea level rise related shoreline changes (Ashton et al., 2001; Valvo et al., 2006; Murray et al., 2007).

2.5 Background of Poole Bay Test Case

Poole Bay is located on the southern coast of England, extending from the Sandbanks peninsula in the southwest to Hengistbury Head in the east. It is a popular destination of tourists, the seafront affords opportunities for a range of activities, such as sailing, surfing, boating, and beach volleyball. Tourism is vital to the local economy with beaches one of the most important assets. There are a number of large hotels, restaurants and beach huts built along the bay, providing a comfortable holiday environment for both local and foreign tourists.

2.5.1 Shoreline

Poole Bay has a very gentle log spiral form approximately 16 km long, curving slightly more in the west than to the east, also called ‘‘crenulate shaped bays’’(Wright, 1981), which are most common along exposed coasts and are formed by the long-term combined effects of refraction and diffraction around headlands.

The shoreline is dynamic and, constantly changing in response to forces acting upon it. Short –term fluctuations due to storm surges are smoothed out by coastal processes as time going on. Generally speaking, Poole Bay has a quasi-stable condition due to the ‘’anchoring’’ effect of Hengistbury Head (Figure 2-14). However, Wright (1981) indicated that with increased human intervention, in the long term, probably within the next 1000 years, the narrow neck of land which currently separates Christchurch Harbour from Poole Bay would be breached and shortly thereafter Hengistbury Head would retreat and diminish, which would result in a new phase of severe coastal instability for both of the bays.

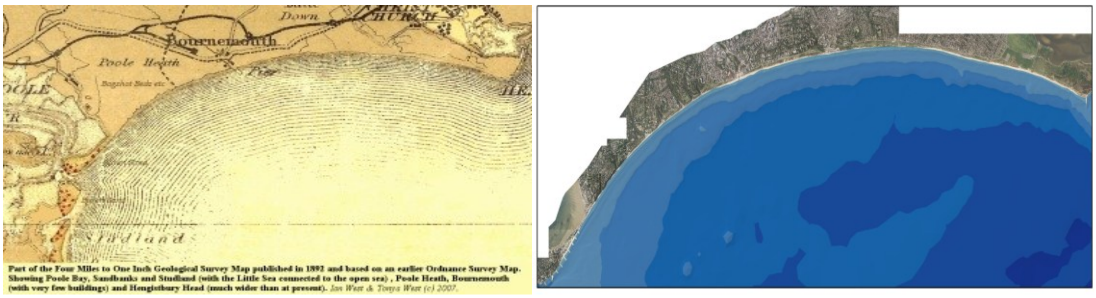


Figure 2-14 Shoreline Evolution of Poole Bay over Centuries

(Source: Left-West (2012), Right-Aerials from CCO (2008))

The central parts of Poole Bay are characterised by cliffs between 10-35m in height (see Figure 2-15). Much of the shoreline has suffered severe erosion due to the feature of soft Tertiary sand and clay cliffs, but has been protected by seawalls and esplanade built progressively eastwards ever since 1890’s. However, there are still 2 km of cliffs which have no protection covered at the easternmost side of Poole Bay, and thus supply of sand and gravel to the beach. Despite cliff stabilization and vegetation of grasses and shrubs, sub-aerial processes of weathering and mass movement continue (Bournemouth Borough Council, 1991). An estimated cliff top retreat rate was approximately 1 cm/year as a result of wind erosion, surface wash and gullying (due to groundwater seepage) by Harlow (2001).

Figure 2-15 Cliffs and the Protection of Seawalls Along Poole Bay

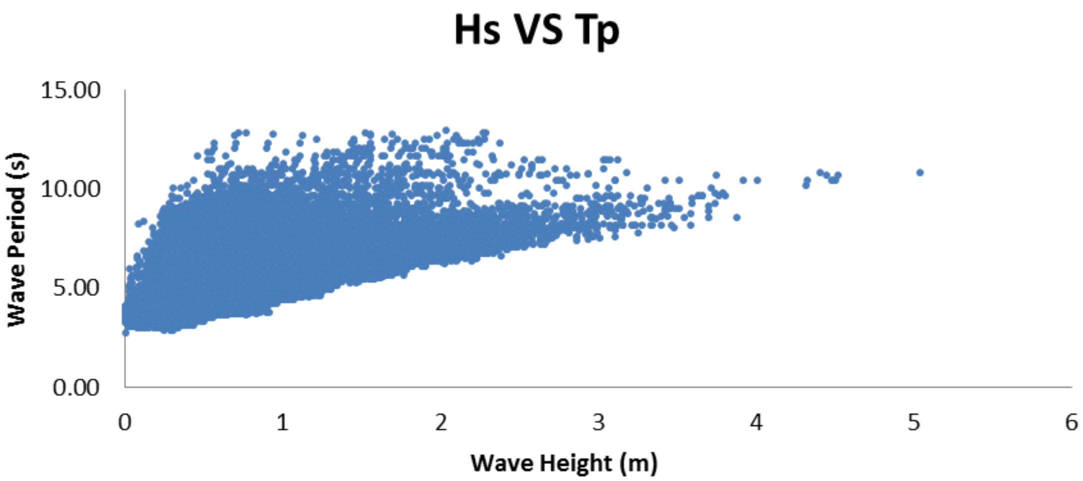
2.5.2 Wave Climate

Poole Bays lies within the storm wave environments of the middle latitudes. Along the great majority of the coastline, sediment transport and hence changes in the plan-shapes and profiles of its beaches, is dominated by wave action (HR Wallingford, 2009). Studies by HR Wallingford (1999) demonstrate that the prevailing wave conditions offshore and the largest waves come from the directions of south-west to west-south (210°N-250°N), either as locally generated storm waves or as swells which have been generated in the English Channel. The highest waves are predicted to be 4.88m approaching Southbourne from 245°. Waves from this sector cannot directly enter Poole Bay, but are refracted and diffracted. Near shore wave climate is characterised by transformed swell waves and waves generated by local fetches to the south and south-east.

Near shore waves and their variability are one of the most significant factors for driving sediment transport and coastal evolution. Several studies were undertaken to investigate the link of wave climate and the formation of Poole Bay, it is suggested by HALCROW (1999) that the historical alignment of Poole Bay is strongly related to the swell waves from the south west. The transformed waves from offshore will be dominant at positions on the open coast.

HR Wallingford (2005) reported that the largest inshore waves along the shoreline of Poole Bay are predicted around 5 or 6 metres and the directions of these waves are clustered in a fairly narrow band around the beach normal at each predicted point. However, the mean direction of the waves at the shoreline changes along the coastline, from approximately south-east in Studland Bay to near to south-west near Hengstbury Head.

Figure 2-16 shows the wave data from Cefas Wavenet, more information will be given in the model setup Section 3.2.



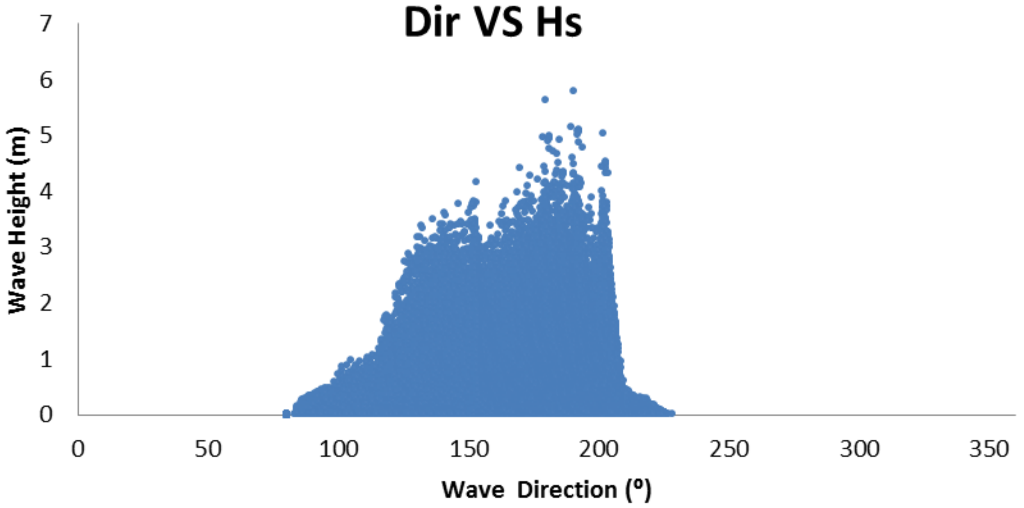


Figure 2-16 Wave Climates in the Near Shore of Poole Bay

(Data source: Cefas Wavenet)

2.5.3 Tide

At Poole, the tidal range is low, approximately 2.0m during spring cycles and 1.0m during neap. The tidal curve is strongly distorted, having a double high water and only a short ‘‘stand’’ at low water. Tidal levels at the entrance to Poole Harbour are shown in Table 2-2 (HR Wallingford, 2005).

Table 2-2 Tidal Levels at Poole Harbour Entrance

HAT	MHWS	MHWN	MWL	MLWN	MLWS	LAT
2.6m	2.2m	1.7m	1.6m	1.2m	0.6m	0.0m

(Chart datum & Ordnance datum difference at Poole Bay: -1.40m)

Waves are the dominant force of sediment transport for inner Poole Bay, which makes Poole Bay a good example to apply one-line model BEACHPLAN to. It was concluded that tidal current velocities alone are below sediment entrainment thresholds, and that stresses imparted by shoaling and breaking waves are a necessary auxiliary to tidal currents to affect significant sand transport.

2.5.4 Coastal Structures

Poole Bay is continually eroding, even though various of hard and soft protection measures have been implemented for a long time. A number of timber/rock groynes have been built to stabilize the beach profiles (Figure 2-17), however, some of them have lost their functions.

At the easternmost end of Poole Bay, Hengistbury Head is an important historic feature and nature reserve for many species, this area of shoreline is protected and monitored by coastal management issues. The Long Groyne, which was constructed in 1938, has been working as a barrier intercepting drift on the intertidal beach.

Rock groynes were built to preserve the beach at Sandbanks in 1995 and Branksome Chine in winter 2008/2009 (Poole Beach & Harbour Projects, 2013), serving to retain sands on the beach for benefits both of local residence and recreation and protect the seawall behind the beach. Two pier constructions, remnants of Victoriana, still stand at Bournemouth and Boscombe, which are very popular tourist destinations. As coastal structures, the two piers also play the role of intercepting longshore sediment transport, but the difference with groynes is that the piers are transmissible for sediment drift (Figure 2-18).

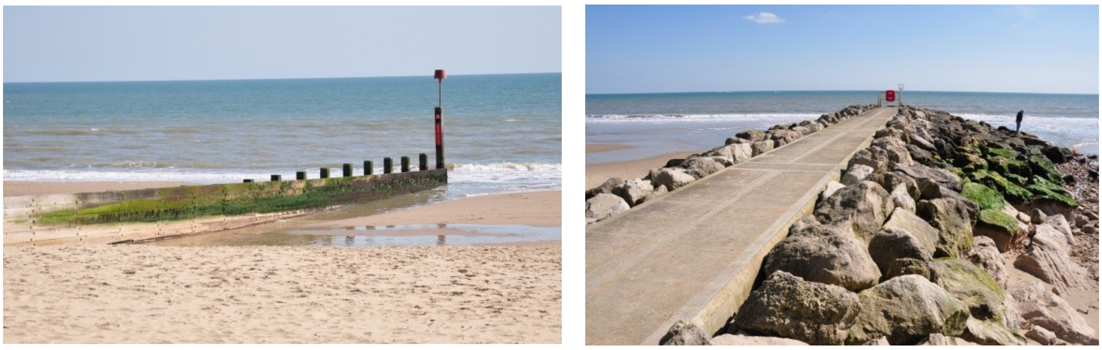


Figure 2-17 Timber Groyne at Bournemouth (left) and Rock Groyne at Poole Bay (right)

Figure 2-18 Bournemouth Pier (upper) and Boscombe Pier (lower)

2.5.5 Replenishment

Beaches along Poole Bay are predominantly composed of sands (CCO, Bournemouth Sediment Sampling 2009 and 2010), and become sandier nearer the mouth of the inlet (very fine sand with grain size of ϕ4).

To keep the beach in a stable position, intensive beach management has been practiced since 1970s (Lelliott, 1989; Harlow, 2001). A recent big beach replenishment was carried out from 2005 to 2007 with 1.1 million m^3 of sand dumped to Swanage, Poole and Bournemouth Bay (Beach Replenishment, BIS 4.1 & 4.2). The replenished materials were dredged from Poole Harbour Channels and Approaches, where dredging is necessary to deepen and widen the navigation channel. The total volume dredged was 2 million m^3, of which about 1.1 million m^3 was suitable for beach replenishment, the remainder (silts and clays) were disposed to a licenced location off Swanage. In Poole beaches, 450,000 m^3 of sands was replenished between Shore Road and Branksome Dene Chine, whereas 600,000 m^3 between Boscombe Pier and Double Dykes in Bournemouth beaches in the winter of 2005/2006 (Poole Bay Coastal Management, BIS 4.1, Figure 2-19).

The nourishment project continued at Bournemouth beach between Boscombe and Alum Chine during the winter of 2006/2007, using a further of 700,000 m^3 of sand from a Licensed Dredging Area off the Isle of Wight (Poole Bay Coastal Management, BIS 4.2).

Table 2-3 Beach Improvement Scheme in Poole Bay

Replenishment	Year	Net Volume [m^3]
BIS 1	1970	84,500
BIS 2	1974-1975	760,500
BIS 3	1988-1990	1,147,362
BIS 4.1	2006	615,705
BIS 4.2	2006-2007	897,722
BIS 4.3	2008	81,209
BIS 4.4	2009	74,192

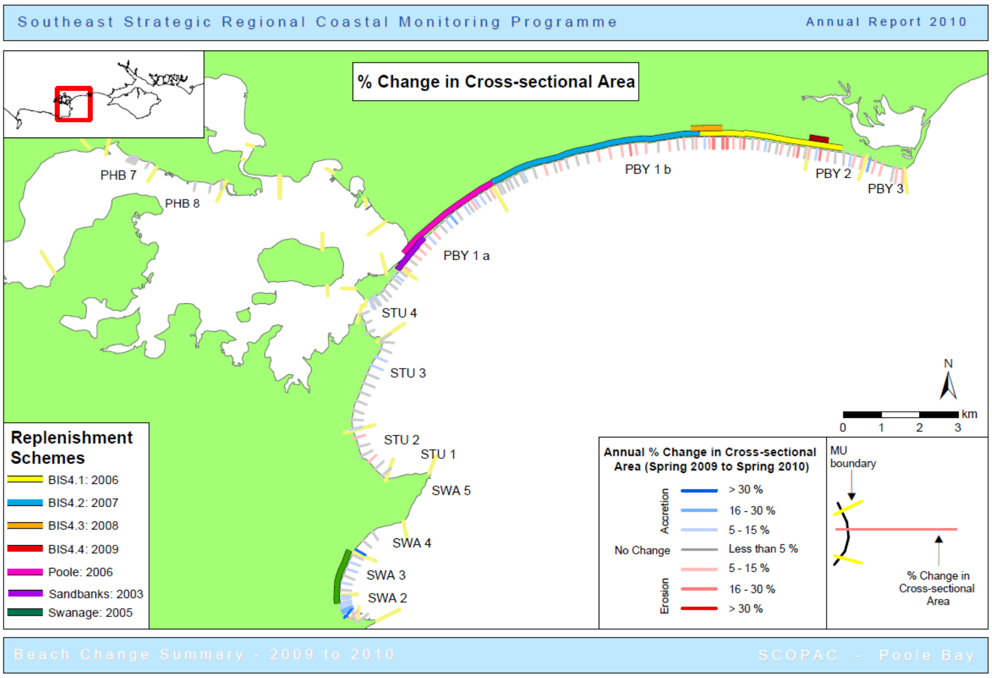


Figure 2-19 Beach Replenishment Schemes in Poole Bay

(Source: SCOPAC, Annual Report 2010)

After the beach replenishment projects, coast profiles are under monitoring and beach volume is calculated and recorded by researchers. Some critical comparative analysis of sediment recharge schemes was undertaken by Cooper (1997, 1998), Harlow and Cooper (1994, 1996), Harlow (2000, 2001), Cooper and Harlow (1998). It is observed that beach profile adjustment and volume losses slow down after a peak up to four years following nourishment, as material placed off-/near shore is moved into the inter-tidal zone (see Figure 2-20).

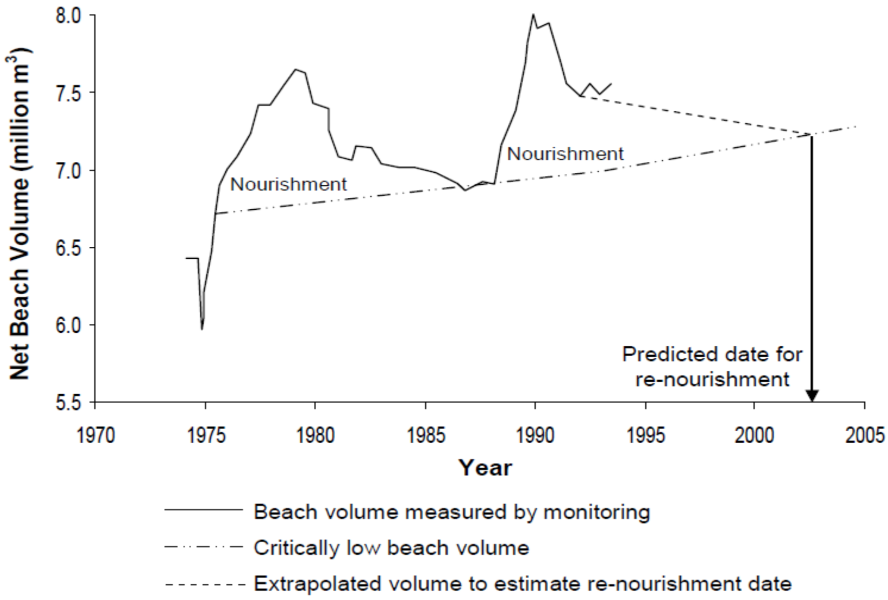


Figure 2-20 Data Illustrating Beach Volume at Bournemouth

(Source: Adapted from Harlow and Cooper (1996))

2.5.6 Longshore Drift

In the eastern part of Poole Bay, the coast is exposed to waves approaching from the south-west travelling up the English Channel from the Atlantic. This produces a net eastwards drift of sediment along the beaches along most of the coastline of Poole Bay. However, the further the drift progresses westwards from Bournemouth towards Studland, the greater is the shelter provided by the Isle of Purbeck and Handfast Point, which refract and diffract waves from south-west directions, and diminish their height and energy. Thus the wave height gradient leads to a general accumulation of sediment in the western part of Poole Bay (HR Wallingford, 2005). Numerous researchers have attempted to model and predict drift within the bay and a wide range of estimates is available for different locations, e.g. Harlow (1995, 2001) and Cooper (1997). It is generally revealed that net littoral drift has a route moving from west to east along much of the frontage, although reversals are an important feature especially in western parts (SCOPAC, 2003, see Figure 2-21). This divergent point of longshore drift was found between two piers by a field investigation at Poole Bay in April 2013 (Figure 2-22).

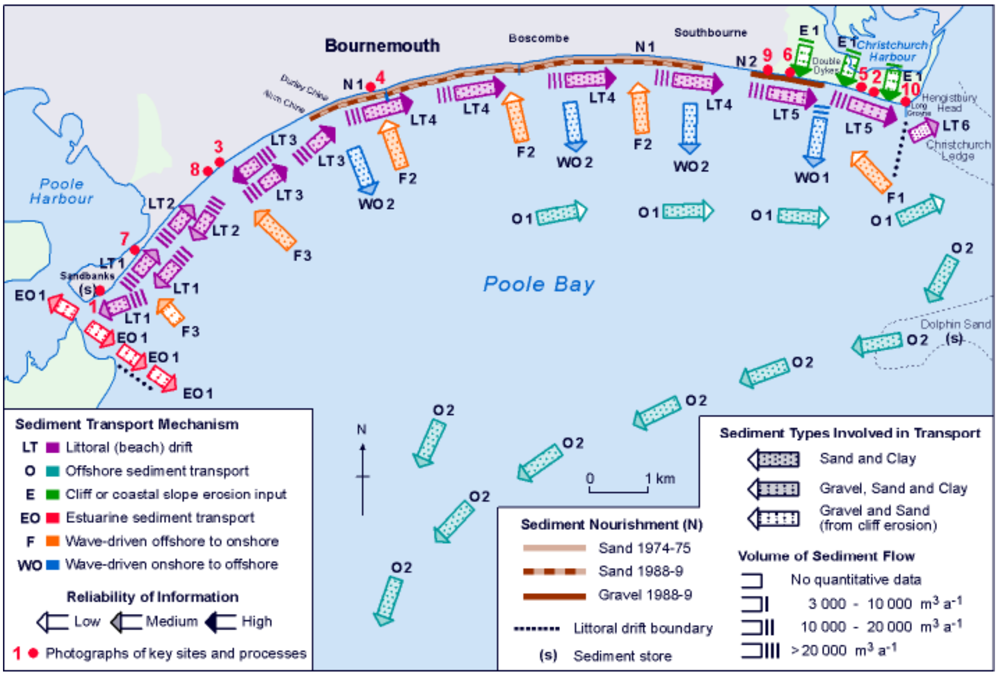


Figure 2-21 Sediment Transport Pattern of Poole Bay: Poole Harbour Entrance to Hengistbury Head

(Source: http://www.scopac.org.uk/scopac_sedimentdb/pbay/index.htm)

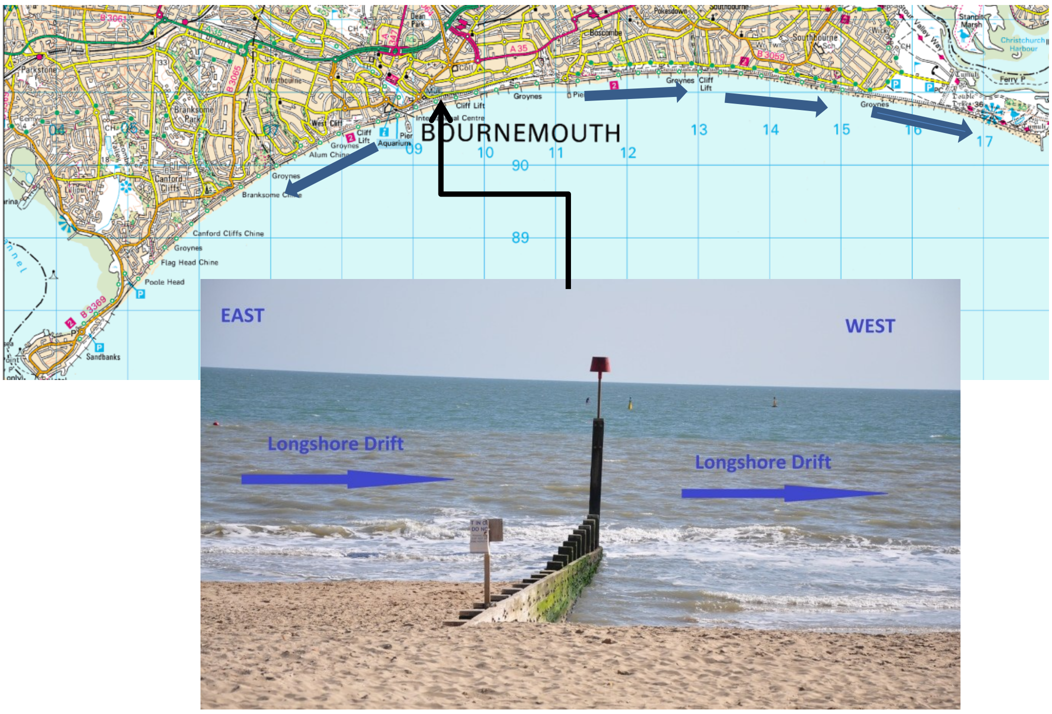


Figure 2-22 Longshore Drift Reversal Discovered in Field

To better understand processes occurring throughout the whole bay, a systematic measurement programme of beach profiles (from 1974) and of beach levels against groynes (from 1993) was undertaken by Bournemouth Borough Council. Major trends and patterns in drift and beach accretion/erosion are analysed from the datasets. Harlow (1995, 2001) pointed out that survey frequency was sufficient to identify alongshore variations in net drift direction due to spatial variation in response to changes of incident winds. Drift reversals appear to commence at the most exposed and energetic section of the beach, and then progress westwards. It is not clear if this is linked, either directly or indirectly, to the fact that groyne spacing reduces from west to east in response to this wave energy gradient (SCOPAC, 2003).

3. Assessment of Model Performance

This chapter describes the method used in this study to judge the best-fit from a series of numerical model runs compared to measured data due to different sources of uncertainty. To start with, an introduction of the model BEACHPLAN and Monte Carlo toolbox is presented. Then through uncertainty modelling, the response of model outputs to shoreline orientation is investigated. Based on the error analysis from four commonly use methods, the uncertainty and sensitivity in model performance can be quantified. A rating method is introduced to find an optimum parameterization for shoreline modelling.

3.1 Model Description

To investigate the uncertainty in model performance, one-line theory based model BEACHPLAN is used for the simulation of shoreline evolution.

3.1.1 BEACHPLAN Model

BEACHPLAN is a state-of-the-art model based on one-line theory, developed by HR Wallingford for simulating the evolution of a beach in plan shape (Rivaton, 1997). It is used for predicting shoreline change as a response to spatial and temporal gradients in longshore sediment transport associated with coastal engineering projects like groynes and breakwaters. After more than 30 years testing and improvement, BEACHPLAN has been applied in many projects and is proved to be a reliable model for long-term simulation of the beach plan shape in response to wave attack alone.

In BEACHPLAN, by working through the model interface pyxis (Figure 3-1), users can specify a number of external variables specific to that particular stretch of shoreline and may add a variety of nearshore coastal engineering structures to be tested, without having to alter the program code or a detailed knowledge of the internal structure of the program.

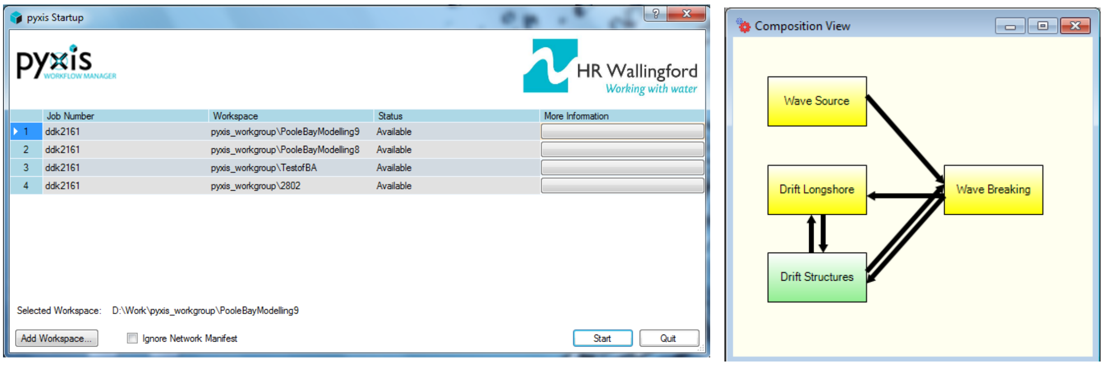


Figure 3-1 Interface of Model BEACHPLAN

Like other one-line models, the plan shape of a beach in BEACHPLAN is represented by a contour line, e.g. mean water level or mean high water level. Based on the linear wave theory, waves are refracted up to breaking points and then the breaking waves are used for calculation of longshore sediment transport in the model. The new beach position is computed by the longshore gradients of sediment transport. The model uses a formulation of the total longshore sediment transport rate modified from the CERC formula (Equation (2.4)) introduced in Section 2.2 One-line Theory, it is written as:

$$Q = K_1(\gamma_s)^{-1}E_b(nc)_b(sin2\alpha_b - 2K_2\frac{\partial H_b}{\partial x}cot\beta cos\alpha_b) \qquad (3.1)$$

Where

Q: longshore sediment transport rate [m^3/s],

K_1: scaling coefficient, 0.32 for sand and 0.02 for shingle,

K_2: scaling coefficient (0.7-1.4), used to scale the effect of wave height gradients to the rate of littoral drift,

γ_s: submerged weight of beach material in place [kg],

E: the wave energy density [J/m^2],

n: the ratio between group and phase velocity [-],

c: wave phase velocity [m/s],

H: significant wave height [m],

x: distance alongshore [m],

α: angle between wave crests and local depth contours [°],

β: slope of beach face [º],

b: subscript denotes breaking wave conditions.

When diffracting structures are included in the model, Beachplan initially calculates the effect the diffracting structure has on the wave climate, considering diffraction alone, into the breaking point. This new wave field is then transferred back out to the wave point and subjected to the sequence above, this time only the effect of refraction and shoaling is considered.

In BEACHPLAN, the following processes are involved:

1). Wave transformation (diffraction, refraction and shoaling);

2). Sediment transport (longshore drift due to alongshore variation of breaking wave height, cross-shore distribution of the longshore drift);

3). Effects of coastal structures (seawall, groynes, breakwaters, etc.);

4). Active beach management techniques (sediment replenishment, beach mining, etc.).

However, shoreline changes produced by cross-shore sediment transport, such as that accompanied with storm events, is not taken into account in BEACHPLAN. In addition, like most one-line models, it only quantifies changes in shoreline plan view and does not include offshore areas beyond the closure depth, as it assumes that sediment is transported alongshore between two defined (and constant) limited elevations of the profile: top of the active berm and depth of closure. Other assumptions, similar to those of other one-line models (as described in Section 2.3 One-line Models in Practice) are summarized as below:

1). The bathymetry is locally parallel to the longshore axis (x-axis) i.e. shore-parallel contours within the model.

2). The beach profile moves landward / seaward while retaining the same cross-shore shape.

3). The beach sections are represented mathematically as rectangles.

4). The more the true beach diverges from these assumptions, the worse this representation and the greater the computational errors are.

5). The model requires a predictive expression for the net longshore transport rate, where, for open beaches, this transport is a function of the wave height and direction at breaking. Detailed structure of the near shore circulation is ignored .

6). For a time representation the model must be applied where there is a long-term trend in shoreline behaviour.

As a simulation model, there are several limitations of BEACHPLAN (and other one-line models) that users need to bear in mind, e.g. some physical processes that are not included within the model, such as tidal currents, different sediment sizes, 3-D complicated circulation patterns.

Model set-up of BEACHPLAN is described in Section 3.2.

3.1.2 Monte Carlo Toolbox

The Monte Carlo technique is a method of uncertainty simulation used for generating different scenarios of shoreline, which has been adopted frequently by researchers to evaluate uncertainty in spatial and non-spatial data (Ali, 2003). Monte Carlo simulations allow modellers to account for a complexity in quantitative analysis and decision making. A Monte Carlo toolbox has been developed so that it can be used in combination with BEACHPLAN.

The Monte Carlo toolbox allows the users to specify the variable for each model run in the batch or randomly sample from a specified probability distributions. The variables can also be modified using a Python script (Figure 3-2).

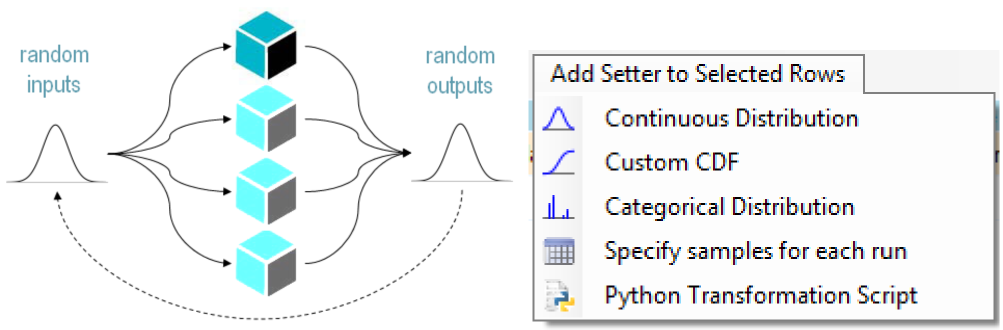
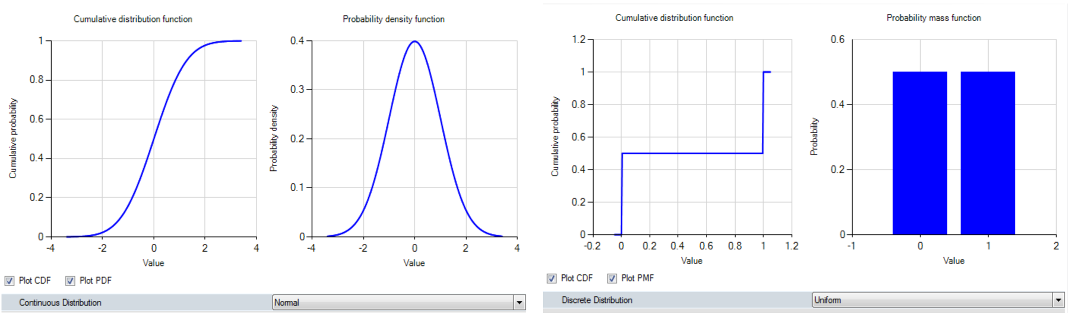


Figure 3-2 Options for Variable Setting in Monte Carlo Toolbox

(Source: pyxis Monte Carlo toolbox)

The types of probability distributions available for random sampling depend upon the type of variable. For example, a real-valued scalar may be sampled from a continuous distribution (such as the Normal distribution, Figure 3-3 (a)) while an integer-valued scalar may be sampled from a discrete distribution (Figure 3-3 (b)).



(a) (b)

Figure 3-3 Probability Distribution for Random Sampling in Monte Carlo Toolbox

(a) Continuous distribution of normal for real-valued scalar

(b) Discrete distribution of uniform for integer-valued scalar

(Source: pyxis Monte Carlo toolbox)

Due to the uncertainties in the model performance, Monte Carlo simulations provide a number of advantages over a single model run, such as probabilistic results, scenario analysis, etc.

3.2 Model Setup

In the model BEACHPLAN, the basic data required include the following parameters:

1) Shoreline position
2) Beach cross-section profile
3) Wave characteristics (wave height, wave period, wave direction)
4) Coastal engineering structures (groynes, seawalls, breakwaters, etc.)
5) Boundary conditions
6) Physical parameters (water density, sediment density and porosity, etc.)

A straight shoreline (L=3000m, 90^0 respect to the North) with one groyne (location x=980m) is set up for modelling before investigating the more complicated case of Poole Bay. Some main input parameters in the simple case are shown in Table 3-1.

Table 3-1 Model Setup of Simple Case in BEACHPLAN

Wave Height/Period	1.5m/7s
Wave Direction	10^0
Cross-Shore Slope	20^0
Running Period	500 hrs
Water Density	1027 kg/m^3
Sediment Density	2650 kg/m^3
Porosity	0.6
Wave Breaking Coefficient	0.55

Figure 3-4 Sketch of Shoreline in the Simple Case

More information about model setup of Poole Bay is described in the followings sections:

3.2.1 Shoreline

1). Model coordinate system

The first step in preparing to run model BEACHPLAN is the establishment of a shoreline coordinate system (Figure 3-5). The x-axis is parallel to the regional trend in the shoreline with the y-axis oriented offshore, setting up a right-hand coordinate system. The longshore axis (model x-axis) should follow the general trend of the shoreline, running more or less parallel to the beach contours. As shorelines usually curve, this will not always be possible. Poole Bay is a log-spiral shaped shoreline, the curvature varies between two headlands – Sandbanks and Hengistbury Head. But in model BEACHPLAN, the shoreline angle is constrained by one input value, raising a problem for modellers when simulating nonstraight coast such as Poole Bay. For this case, both uncertainty and sensitivity modelling are required to determine an optimum shoreline angle. In addition, there may also be situations in which it is preferred to artificially extend the shoreline boundaries in the model so that the boundary influence can be minimised in the study area.

In the real situation of Poole Bay, however, in the geographical coordinate system of British-National-Grid, the y-axis is landward, completely opposite to the model coordinate system (

Figure 3-6). In this case, a transformation between two coordinate systems is required.

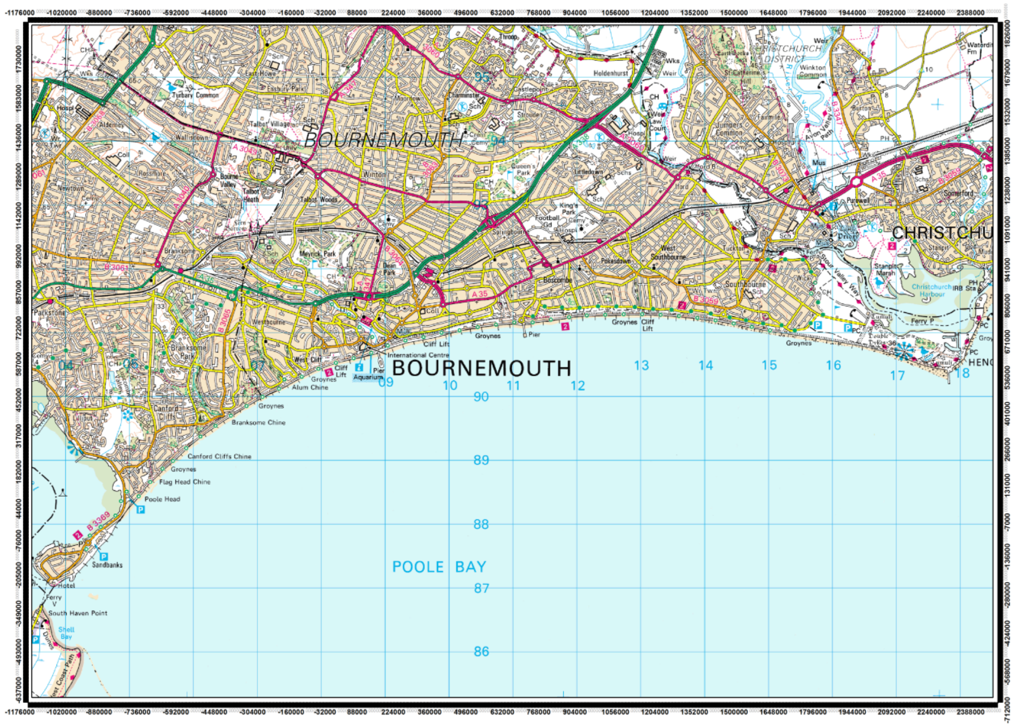


Figure 3-5 Plan View of Poole Bay in the Geographical Coordinate System

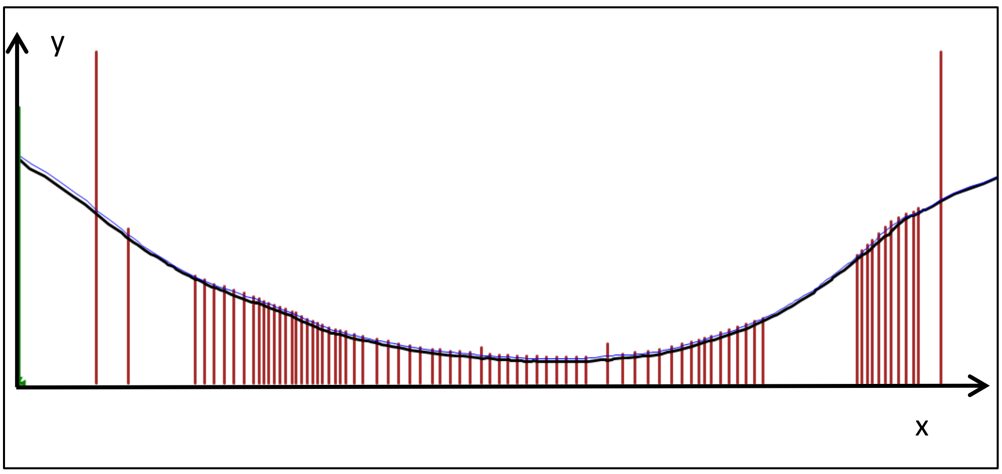


Figure 3-6 Plan View of Poole Bay in the Model Coordinate System

2). Representative shoreline position

BEACHPLAN is a one-line model, which means the beach, cross-shore profile shape is assumed to remain constant as it moves landward or seaward, thus a contour line may be chosen to represent the change in profile positions. It can be obtained from direct shoreline surveys or aerial image from Channel Coastal Observatory (CCO). With field observation data, beach positions at mean high water level (MHW), that is 0.5m ODN are extracted as referenced point and transformed to the modelled XY-coordinate system and used for modelling.

In the case study of Poole Bay, the years of 2009 is selected as initial time for model simulation. Before 2009, several beach replenishment schemes were carried out in different locations along Poole Bay. Additionally, six new rock groynes were built near Branksome Chine in 2008. After these coastal works have been done, the beach position adjusts itself with changes. Considering the time-series wave data ends in January 2012, the modelling period is defined as two years from 2009 to 2011. An analysis of shoreline evolution from observation of CCO is given in Appendix 1 Shoreline Evolution from 2009 to 2012 in Poole Bay.

3). Computational grid size

The model grid setup in BEACHPLAN does not have to be uniform along the full model domain. By splitting the shoreline into sections the grid can be varied. The section division is normally based on the desired detail, computation time, and the quality or availability of the input data. Within a section, however, the spacing has to be uniform (Figure 3-7). In BEACHPLAN, a typical grid spacing of 25 or 50m is used for the calculation of shoreline position. For open beach it can be increased and more common is to use 50m, 100m, 200m. As mentioned, it is also desirable to include a section of greater cell spacing to extend the model artificially at an open boundary. The orientation of the extension should be such as to provide enough material to maintain the stability of the actual open boundary to mirror the real life scenario.

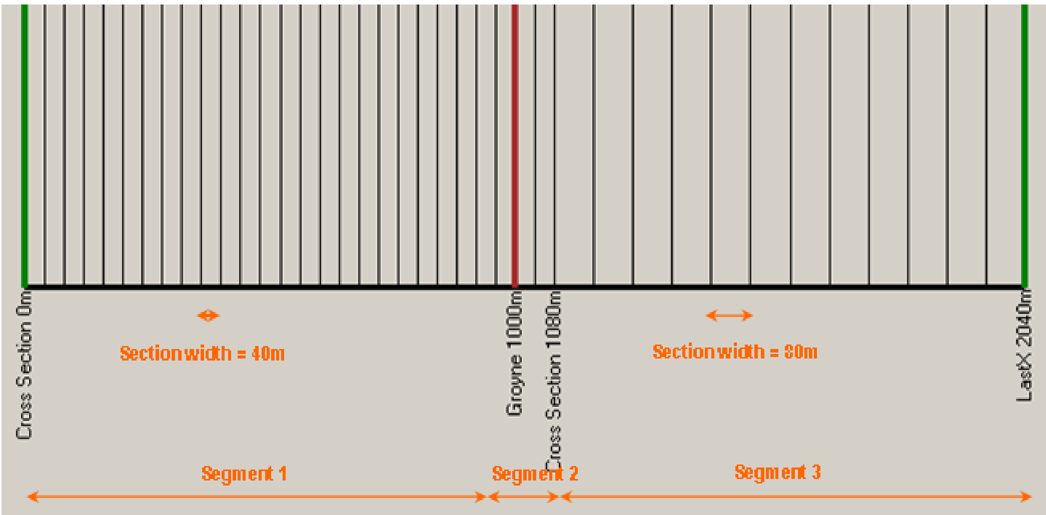


Figure 3-7 Sketch of Computational Grid in Model BEACHPLAN

4). Cross-shore profile

The beach profile information is determined by topographic data from CCO (Figure 3-8). In reality, the gradient of beach profile is not constant alongshore. For Poole Bay the profile is relatively steep in the east but gentler on the other side for the case of Poole Bay. The model does not consider the actual profile shape when calculating shoreline changes, because the profile, down to closure depth, is assumed to move back and forth without changing shape. A representative profile gradient is therefore chosen which is assumed to move parallel to itself when accreting or eroding. Heterogeneous composition of beach sediment along Poole Bay results in a non-uniform shoreface profile. To the west, the profile is milder because of the alluvial sedimentation, while the east is relatively steep. By comparison, seven representative beach profiles (e.g. two end boundaries, water depth changes dramatically, etc.) are chosen as inputs in the model. More information of cross-shore section is given in Table 3-2.

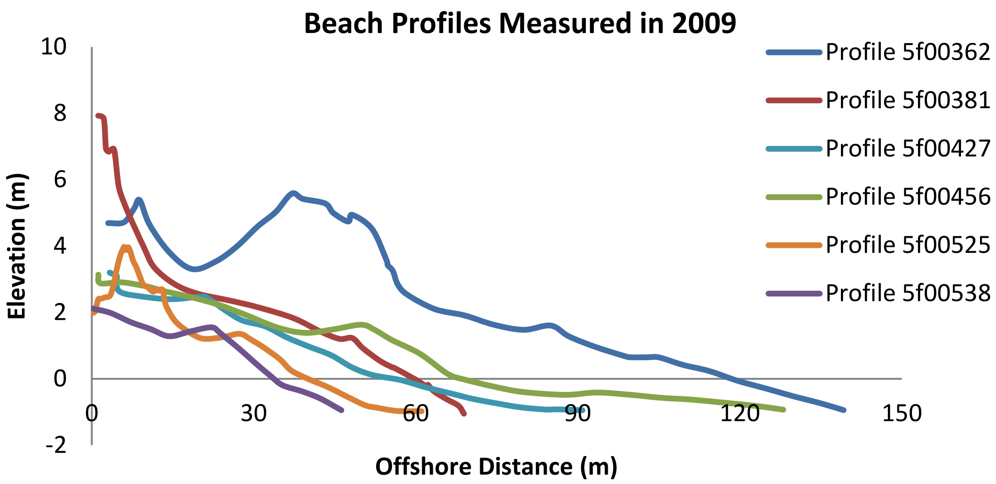


Figure 3-8 Beach Profiles along Poole Bay

(Data source: CCO, 2013)

Table 3-2 Model Setup of Beach Profile in BEACHPLAN

Cross-Section	Slope	Swash level	Closure depth	Rock level
1	20°	2.80m	-4.0m	-100.0m
2	17°			
3	17°			
4	20°			
5	20°			
6	19°			
7	20°			

5). Physical parameters

Sediment properties are important input data for model simulation, including grain size (related to K1), density and porosity. According to the field survey, beach sediments on the east part of Poole Bay are mainly shingle and sand, coarser than those in the updrift direction. Report of Bournemouth Sediment Sampling 2009 & 2010 pointed out that the grain size in Poole Bay range from ϕ4 (very fine sand) to ϕ-3 (pebble/coarse sand).
In BEACHPLAN, some default values are proposed in Table 3-3.

Table 3-3 Default Values of Physical Parameter in Model BEACHPLAN

Physical Parameter	Water Density	Sediment Density	Porosity	Wave Breaking Coefficient
Default Value	1027 kg/m^3	2650 kg/m^3	0.6	0.55

3.2.2 Waves

It is rare to have adequate wave gage data for a modelling effort, but for this dissertation study, more than six years of time-series with a half-hour interval accurate wave data from Poole Bay were collected (Table 3-4) and transformed to near shore by a backtracking ray model – TELURAY, which uses Snell's law to represent refraction and shoaling over all components of the offshore waves spectrum. 13 wave points at -5m contour are chosen along the Poole Bay for modelling, as shown in Figure 3-9, and wave roses are given in Appendix 2 Wave Roses in the Near Shore of Poole Bay.

Based on the linear wave theory, BEACHPLAN then refracts the waves up to the point of breaking and the breaking wave conditions are then used to calculate the longshore drift at specified sections of the model. The movement of the shoreline position is then calculated from differences in the wave induced longshore transport.

Table 3-4 Offshore Wave Information

Location	Latitude	Longitude	Depth	Parameters	Sampling intercal	Date range	Source
Poole Bay	50.63389	-1.719	26m	Hm0, Tp, Tz, SST, Dir, Spread	30 min	October 2004 to January 2011	Cefas Wavenet

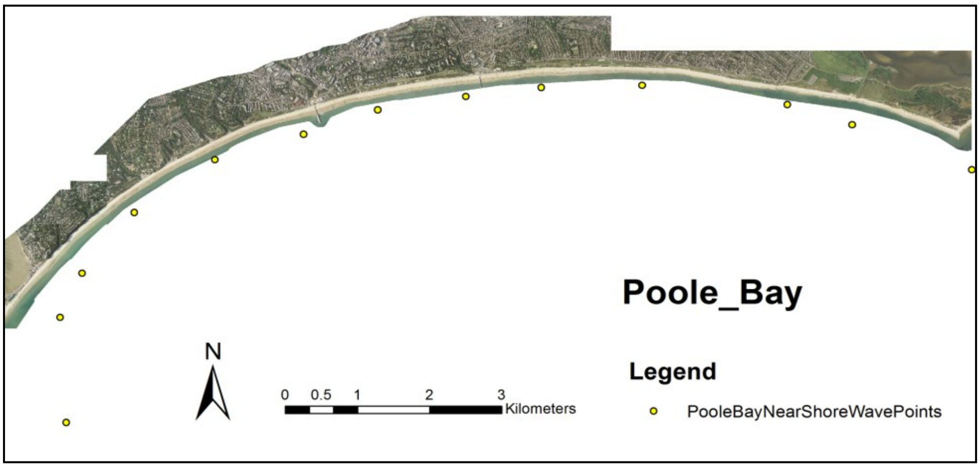


Figure 3-9 Modelled Wave Points along Poole Bay

3.2.3 Coastal Structures

Seawalls and 78 groynes (the two piers are represented as groynes) were built up to stabilize the beach position in Poole Bay. In the model BEACHPLAN, the specific shape of structures is not taken into consideration for computation but the central axis.

The locations of seawalls and groynes were collected from aerial images and information report from Poole & Bournemouth Councils, and then transformed into the model coordinate system. The physical characters are shown in Table 3-5.

Table 3-5 Model Setup of Coastal Structures in BEACHPLAN

Structure	Height	Slope	Foundation depth
Seawall	5.0m	84	-4.0m

Structure	Top Level	End Level	Transmission
Groyne	1.0m	-2.0m	0
Pier	5.0m	-5.0m	0.5

3.2.4 Replenishment

As discussed in Section 2.6.4, replenishment work has been carried out in Poole Bay since 1970s. All but one replenishment were conducted prior to the time period used for modelling, and the one that was done in 2009 was comparatively small to all other recharges, therefore it is not been taken into consideration in this study. If the aim is to fully calibrate the model for use of future predicts the beach plan-shape then the renourishment episode in 2009 would have to be included in the model setup.

3.3 Methodology

Uncertainty, optimization and sensitivity analysis are important to consider for the evaluation of model performance. By incorporate what is known about the uncertainty and optimization of input parameters, and also sensitivity of model outputs to variable inputs, the model performance can be improved and thereby the predictions as well. In this study, the shoreline orientation is addressed in the analysis of uncertainty and optimization modelling.

3.3.1 Uncertainty Modelling

To identify the uncertainty associated with shoreline evolution, all the model outputs of the final shoreline position from the Monte Carlo toolbox are analysed. The mean final shoreline position y_{mean}, as well as maximum/minimum/standard deviation can produce an envelope of beach movement, which is used to quantify the uncertainty.

$$y_{mean} = \frac{1}{N}\sum y_i \quad (3.2)$$

$$y_{max} = MAX\{y_i\} \quad (3.3)$$

$$y_{min} = MIN\{y_i\} \quad (3.4)$$

where:

y_{mean}, y_{max}, y_{min}: mean/maximum/minimum shoreline position,

N: computational steps, depend on model grid spacing setting,

y_i: shoreline position.

A simple case with a straight shoreline is set up for uncertainty modelling prior to the complex case of Poole Bay. For the simple case, 20 model runs with the beach orientation varying from 81° to 100° (the interval is 1°) was carried out.

In Poole Bay, considering the shoreline is curved between two headlands, the baseline of which differs from 230° to 280°, the uncertainty modelling of Poole Bay was done with 51 runs with a shoreline angle interval of 1°.

For both test cases, the final shoreline positions are calculated with Equation (3.2), Equation (3.3), Equation (3.4), and then shoreline envelopes are plotted for further analysis.

3.3.2 Optimization

Before the analysis of optimization, it is worthwhile to mention that when analysing model prediction of large spatial-scale coastline (magnitude of km), it is proposed to use segments of shoreline. It helps to better analyse shoreline change patterns by dividing the full domain into a number of sections, for example, an area with or without coastal structures, an area with relatively straight shoreline, etc. In the case of Poole Bay, the shoreline is 16 km long with a large curvature, five sub-cells are defined by taking into account the slope of the bay and structures such as groynes/piers (Figure 3-10, Table 3-6). In each segment, the same analysis approach can be applied as in the full bay.

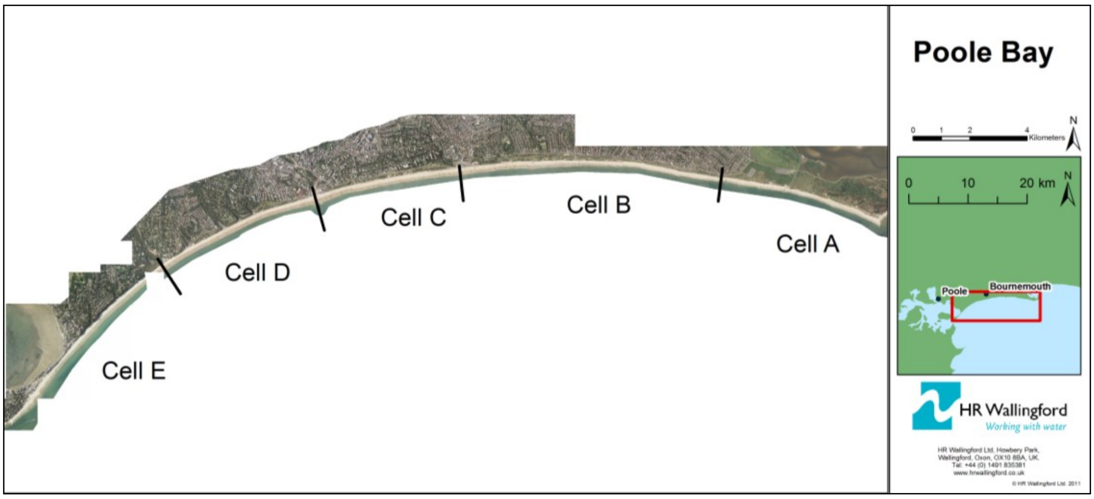


Figure 3-10 Shoreline Segments of Poole Bay

Table 3-6 Information of Shoreline Segments in Poole Bay

Segment	Cell A	Cell B	Cell C	Cell D	Cell E
Begin	HHLong Groyne	HH1	Boscombe Pier	Bournemouth Pier	Poole1
End	HH1	Boscombe Pier	Bournemouth Pier	Poole1	Sandbanks Head
Length	2369m	4019m	2300m	2808m	2877m

The uncertainty modelling introduced in the previous section aims to show how the shoreline develops under various scenarios. An optimum model performance based on best-fit input parameters can be determined by the following steps:

(1). Choose one or more parameters for Monte Carlo simulations;

(2). Error analysis in the full domain and/or each shoreline segment respectively;

(3). Ranking the quantified errors and give ‘’reasonable’’ scores;

(4). Then the goodness of fit is judged by the total scores.

Applying the above steps, Poole Bay is tested in this dissertation study:

Step 1. Choose one or more parameters for Monte Carlo simulations:

The chosen parameter to vary in the Monte Carlo toolbox is the shoreline angle between 250° to 270°.

Step 2. Error analysis in the full domain and/or each shoreline segment respectively :

Error analysis is done on the 21 model runs from Step 1 using the methods introduced as below:

A. Correlation Method

This is a measure of the correlation (linear dependence) between two series y1 and y2, giving a value called correlation coefficient r= [-1, +1]. r=1 denotes a perfect agreement, r=0 means that two series of data are completely uncorrelated, while r=-1 shows the variables are ideal but inversely correlated.

$$r(y_1, y_2) = \frac{cov(y_1, y_2)}{\sigma_{y_1}\sigma_{y_2}} \quad (3.5)$$

where

r: correlation coefficient,

y1, y2: variables to be correlated,

cov(): covariance function,

σ: standard deviation of a variable.

This correlation method has been applied in two ways: absolute variables and relative variables.

(a). Absolute variables

One correlated series is the final shoreline relative to the baseline x-axis in the local BEACHPLAN coordinate system (predicted shoreline 2011), and the other series is the observed shoreline 2011 from field measurement, which need to be transferred to the model coordinates along the x-axis. The correlation coefficient calculated by Equation (3.5) is expected to approach 1 for the best-fit modelling.

$$r(y_{pr}, y_{ob}) = \frac{cov(y_{pr}, y_{ob})}{\sigma_{y_{pr}}\sigma_{y_{ob}}} \quad (3.6)$$

where

y: shoreline position [m], if no specified differently, this is compared against the final shoreline 2011.

Subscript ''ob''/''pr'' denote field observed/model predicted, other symbols are the same as defined previously.

(b). Relative variables

The correlated variables are the anomalies Δy measured by the coastline position changes during the time being modelled. The correlation coefficient is calculated by Equation (3.7), similar to Equation (3.5) and Equation (3.6), but the correlation is between the final shoreline position relative to the initial modelled beach position.

$$r(\Delta y_{pr}, \Delta y_{ob}) = \frac{cov(\Delta y_{pr}, \Delta y_{ob})}{\sigma_{\Delta y_{pr}} \sigma_{\Delta y_{ob}}} \quad (3.7)$$

Where

Δy: changes of shoreline position during the simulation period [m],

Other symbols are the same as previously defined.

B. Shoreline Movement Method

This approach is to compare the model errors in terms of shoreline movement, the smallest error represents the best-fit. Two ways are employed for error measurement using **Transects** and **Mean Absolute Error**.

(a). Transects

A number of profiles along the modelled shore are chosen as transects. In this study, survey profiles from Channel Coastal Observatory in the UK are used. Along these digitized transects, intersection points of transects and shorelines represent the beach variation. The distance of transects between model predicted shoreline and observed shoreline is measured with tools, such as Spatial Analyst in Arc GIS. Then the average errors are derived by dividing the sum of those distances by the number of transects. This is a direct error measuring approach, the accuracy of error analysis depends on the number of transects taken into account.

$$Error = \frac{1}{M} \sum \Delta y \quad (3.8)$$

where

M: number of transects, for Poole Bay, M=86, Δy: changes of shoreline position along transects during the simulation period [m].

An overview of transects along Poole Bay is given in Appendix 3 Transects in the Sub-Divided Cells of Poole Bay

(b). Mean Absolut Error (MAE)

MAEs are calculated at each computational grid defined in the model setting, similar to the method of transects, but may not be influenced by external selection of calculation points. Nevertheless, the interpolation of observed data to model computational steps is needed for MAE calculation with Equation (3.9).

$$MAE = \frac{1}{N}\sum\left|y_{ob} - y_{pr}\right| \tag{3.9}$$

Where

N: computational steps in the model, depends on the model setup.

Other symbols are the same as previously defined.

C. Probabilistic method:

In this probabilistic method, the performance of the model is assessed by using the following three sub-methods: **Bias, Accuracy and Skill.**

(a). Bias

Bias reveals the tendency towards under- or over-prediction, for an absolutely accurate prediction, the bias is zero. A negative bias indicates that the model over-predicts, and vice versa.

$$Bias = \frac{1}{N}\sum(y_{ob} - y_{pr}) \tag{3.10}$$

where all symbols have the same definition as described above.

(b). Accuracy

Accuracy is a measure of the average error between values predicted by a model and the value actually observed, which can be represented in two ways: dimensional, e.g. mean square error, non-dimensional (relative accuracy), e.g. normalized mean square error. Normally, smaller errors imply better model performance.

The accuracy is tested in four ways: **Mean Square Error**, **Root Mean Square Error**, **Normalized Mean Square Error** and **L2-error norm**.

i. **Mean Square Error (MSE)/Root Mean Square Error (RMSE)**

MSE/RMSE is one of the most common measures of accuracy, and RMSE is the root square of MSE, defined as Equation (3.11) and Equation (3.12). The error indicator gives a direct answer of whether model results are better or not, simple and efficient for model evaluation.

$$MSE = \frac{1}{N}\sum(y_{ob} - y_{pr})^2 \tag{3.11}$$

$$RMSE = \left\{\frac{1}{N}\sum(y_{ob} - y_{pr})^2\right\}^{1/2} \tag{3.12}$$

where symbols are the same as previously defined.

ii. **Normalized Mean Square Error (NMSE)/L2-error norm**

The NMSE is an estimator of the overall deviations between predicted and measured values. It is defined as:

$$\mathrm{NMSE} = \frac{\sum\left(\mathrm{y_{ob}}-\mathrm{y_{pr}}\right)^2}{\sum(\mathrm{y_{base}}-\mathrm{y_{ob}})^2} \tag{3.13}$$

where variables are the same as previously defined.

The error function of L2-error norm is the root square of NMSE (Equation (3.13)). It is expected that L2-error norms will show a convergence as the input parameter varying, in this case, the input data corresponding to the lowest L2-error norm is the optimum parameter value.

$$Err^{L2} = \left\{\frac{\sum(y_{ob}-y_{pr})^2}{\sum(y_{base}-y_{ob})^2}\right\}^{1/2} = \{NMSE\}^{1/2} \tag{3.14}$$

where all the symbols are the same as in Equation (3.13).

(c). Brier Skill Scores (BSS)

BSS is commonly used in meteorology and has already been applied to the modelling of coastal morphodynamics by some researchers. It offers an objective indicator when comparing the performance of different runs and not focusing too much on actual values. BSS can be derived from NMSE as shown in Equation (3.15). Skill scores have a range of -∞

to 1, negative values indicate that the forecast is less accurate. If the error associated with a perfect prediction, NMSE is taken to be zero, where BSS gives a perfect value of 1.

$$BSS = 1 - \frac{\Sigma(y_{ob}-y_{pr})^2}{\Sigma(y_{base}-y_{ob})^2} = 1 - NMSE \qquad (3.15)$$

where all symbols have the same definition as described above.

D. Distortion Length

This method is based on the metrics developed by Ramirez (2000) for the positional quality assessment of the linear features. For the error analysis of shoreline change modelling, the distortion factor seems to be more meaningful under the measure of closeness than the other factors.

Distortion length is a modified indicator from the distortion factor. The algorithm is described below:

(a). Decide the number of the points N to be created on the compared two shorelines, which will be used to establish the correspondence between them. In this study, N=5;

(b). Calculate the distance L1 and L2 that will be used to create the new points on the shorelines respectively by dividing their lengths by (N+1);

(c). Create N new points on the two shorelines;

(d). Computer the distance between corresponding points on the two shorelines. The average distance is then used as a measure of distortion.

$$DL_i = \sqrt{\Delta x_i^2 + \Delta y_i^2}, \qquad (3.16)$$

$$DL = \frac{1}{n}\sum_{i=1}^{n} DL_i \qquad (3.17)$$

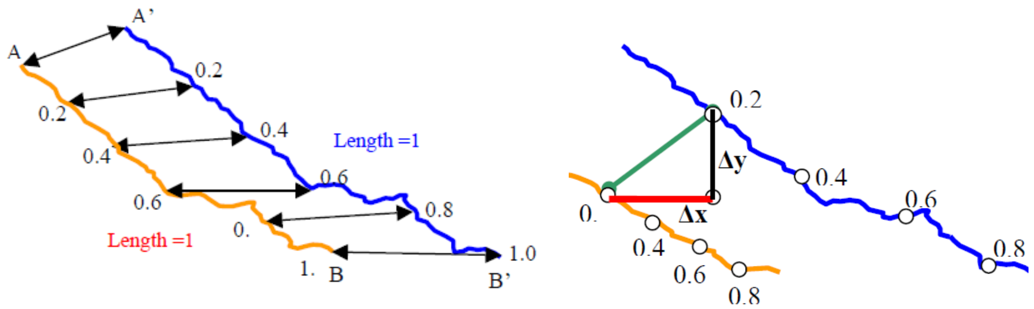


Figure 3-11 Sketch Definition of Distortion Length

Step 3. Ranking the quantified errors and give ''reasonable'' scores and

Step 4. The goodness of fit is judged by the total scores are applied as described below:

The aforementioned measures of model errors are not capable to evaluate the performance of model prediction, due to a lack of systematic criteria for distinguishing the accuracy of model prediction. To solve this problem, the Model Performance Rating System (MPRS, see Table 3-7), inspired from Skill/Confidence/Model Performance Index (SPI/CPI/MPI, Wegen and Jaffe, 2013), is adapted and applied in assessing model performance. MPRS provides a holistic evaluation of model performance by incorporating the objective measurement with a subjective analysis. A score from zero to five is assigned to each range relative to the error indicator. Based on the MPRS, error statistics are transformed to relatively simple scores. The goodness of model fit is then determined by the total score by adding up the individual score from the full shoreline and/or shoreline segments.

Table 3-7 Model Performance Rating System (MPRS) for Error Indicators

Score	5	4	3	2	1	0
Correlation Coefficient	>0.8	0.6-0.8	0.3-0.6	0.1-0.3	0-0.1	<0
Transect/ MAE	0-10	10-20	20-30	30-35	35-40	>40
RMSE	0-10	10-20	20-30	30-40	40-50	>50
NMSE	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	>1.0
BSS	>0.9	0.7-0.9	0.5-0.7	0.3-0.5	0-0.3	<0
Distortion Length	0-10	10-20	20-30	30-35	35-40	>40

3.3.3 Sensitivity Modelling

Sensitivity modelling is often carried out after the calibration phase and the user should get a feeling for the changes the different parameters may make in order to have an idea of the possible envelope of variation of the shoreline position. In this section, the input parameter of shoreline angle is investigated to explore its sensitivity to the shoreline evolution alone, as well as combining together with wave direction/cross-shore slope.

A sensitivity analysis is different from an uncertainty analysis, which measures the change due to specific changes to the input. Any error indicators described in previous section can be used for quantify the sensitivity of the variability of model inputs to shoreline changes, and L2-error norm is employed for sensitivity analysis in this study.

As introduced in Section 2.4.1, natural variability is the main source of the model uncertainty. Based on this classification, the following beach behaviour related parameters are chosen for sensitivity modelling:

1). Shoreline Angle

The studied case Poole Bay is highly curved from Sandbanks to Hengistbury Head, and the shoreline orientation varies between approximately 230^{o} and 280^{o}, therefore 51 model runs with an interval of 1^{0} were conducted to determine an optimum angle of baseline.

2). Wave Climates

In one-line models, waves are the main driving force responsible for longshore sediment transport, therefore the order of magnitude of shoreline variations responding to changes in the wave climate are necessary to be examined. Wave directions at 13 points along Poole Bay (Figure 3-9) are tested separately by taking into account the local effects at each wave point that may not have been considered in the wave modelling. Additionally, the sensitivity of wave directions is tested together with the shoreline angle in the Monte Carlo toolbox, and Table 3-8 shows the tested values of each parameter.

Table 3-8 Sensitivity Modelling of Wave Climates

Wave Point	Changes of Wave Direction	Shoreline Angle
151 to 163	-5^{o}, +5^{o}	250^{o} to 270^{o}

3). Cross-Shore Profile

For most shoreline change models, it is assumed that in the long term, the cross-shore beach profile retains a consistent time-averaged shape in the near shore region. Considering the different responses of beach behaviour to mild or steep profile, a sensitivity analysis is necessary to tell the effects of the beach slope on the coastline change. A constant slope and varied beach slope are chosen for model testing (Table 3-9). This series of sensitivity modelling is also conducted with the shoreline orientation varying from 250^{o} to 270^{o}, so 2*21 model runs in total.

Table 3-9 Slopes of Cross Profile for Sensitivity Modelling

Cross Section	Uniform Profile	Varied Profile						
		NO. 1	NO. 2	NO. 3	NO. 4	NO. 5	NO. 6	NO. 7
Slope	20°	20°	17°	17°	20°	20°	19°	15°

4). Grain Size

In BEACHPLAN, there is no grain size input. However, its influence to the longshore sediment transport is not ignored but reflected in the parameter K1. This coefficient should be calibrated by comparing predicted plan shape changes against historic plan shapes. It can also be calibrated against littoral drift. According to the model manual, "first guess" value of K1 = 0.32 is often used for sandy beaches, and a value of K1 = 0.02 is used for shingle beaches. In this study, the two limits are tested in two model runs to show the sensitivity of shoreline evolution to grain size.

5). Closure Depth

The closure depth is the seaward boundary for the zone of bottom changes, which means beyond this water depth limit no longshore sediment transport is assumed. It is a time-and space-scale dependent water depth, the longer of time scales, the deeper of the significant depth will be. Unfortunately, it is difficult to assess in the field the quantitative value, but there are a number of methods to estimate this depth, such as the formula proposed by Hallermeier (1981):

$$Dc = 2.28H_e - 68.5(\frac{H_e^2}{gT_e^2}) \tag{3.18}$$

Where

D_c: closure depth [m],

He: the effective significant wave height exceeded for 12 hours per year [m],

g: gravity acceleration [m/s^2],

Te: the associated wave period [s].

To investigate the sensitivity of closure depth to shoreline movement, nine modelling tests with closure depth varying from 2m to 10m are carried out.

6). Physical parameters

In most one-line models, physical parameters, such as water/sediment density, sand porosity, etc., are usually regarded as constant values ignoring some little changes due to environmental reasons (e.g. temperature). Wave breaking coefficient, as a function of local wave steepness and bottom slope, is not easy to be determined. The model default value 0.55 donates irregular waves, 0.4 and 0.8 are selected as lower and higher limit for sensitivity modelling.

In this study, the sensitivity of physical parameters is tested with 3*4 model runs, and their values are shown in Table 3-10.

Table 3-10 Physical Parameters for Sensitivity Modelling

Physical Parameter	Value		
	Lower Limit	Default	Higher Limit
Water Density	1000 kg/m^3	1027 kg/m^3	1050 kg/m^3
Sediment Density	2000 kg/m^3	2650 kg/m^3	3000 kg/m^3
Porosity	0.4	0.6	0.7
Wave Breaking Coefficient	0.4	0.55	0.8

4. Model Results

In this chapter, uncertainty, optimization and sensitivity are analysed respectively to investigate the goodness of fit of model performance by applying the method introduced in Chapter 3. A summary of best-fit shoreline angles derived from the assessment method is provided.

4.1 Uncertainty

As shown in Figure 4-1, the envelope of shoreline variations in the simple case is plotted by the maximum and minimum final beach position from 20 model runs. The shoreline movements indicate that the beach advances a lot on the right side of the groyne (location x=980m), and erosion occurs on the lee side.

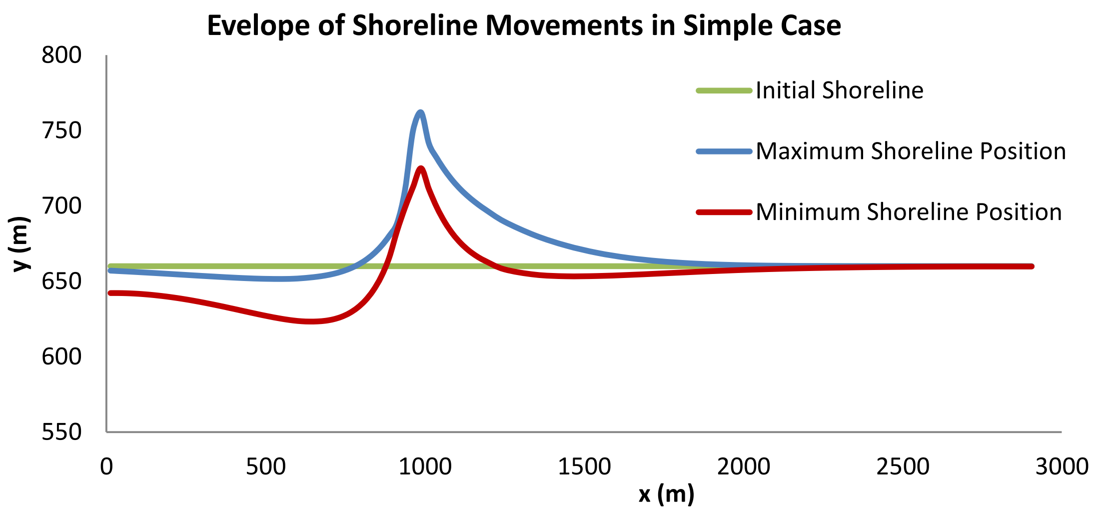


Figure 4-1 Uncertainty of Shoreline Evolution in the Simple Case

Back to the case of Poole Bay, due to the uncertainty of the shoreline angle in BEACHPLAN as explained in Section 3.2.2, Figure 4-2 shows the maximum and minimum final shoreline positions derived from 50 batch runs (model failed when $\alpha'=230^{o}$). As seen instabilities have been experienced, particularly for either end of the range of angles tested and explain the extreme peak.

A detail of shoreline positions calculated from Equation (3.3) and Equation (3.4) are given in Appendix 4 Uncertainty Modelling of Shoreline Angle.

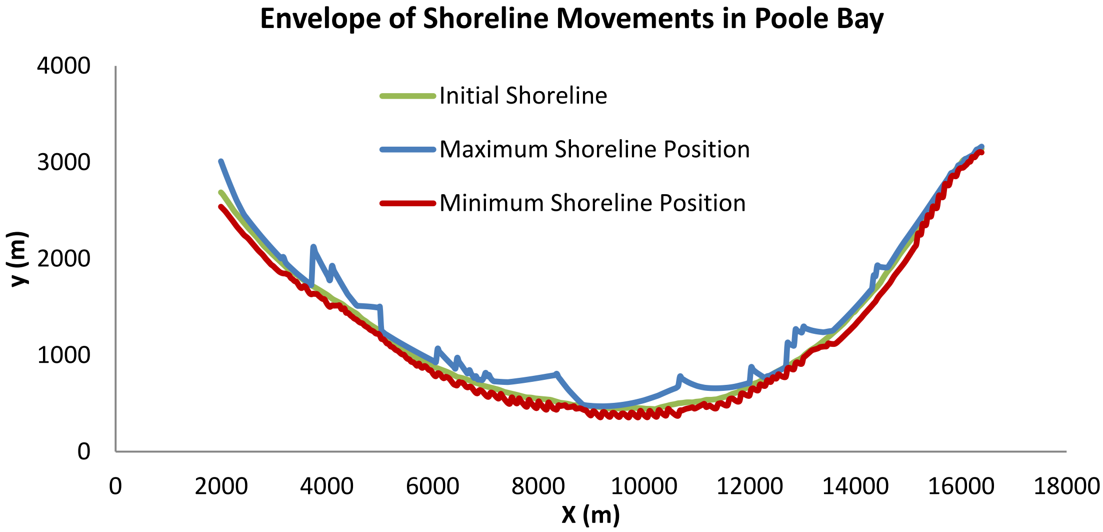


Figure 4-2 Uncertainty of Shoreline Evolution in Poole Bay

4.2 Optimization

Based on four methods of error analysis, error indicators are quantified accordingly in the whole bay as well as in five sub-divided cells. The full statistics of the calculated values are given in Appendix 5 Statistics of Error Analysis in this section, only the best three results are listed. The optimum parameter is then determined by applying the Model Performance Rating System (MPRS) introduced in Section 3.2.3 (Appendix 6 Scores of Model Assessment from MPRS). In this study, the input parameter of shoreline orientation is addressed, which is critical in shoreline evolution analysis because it considers the direction of the incident waves propagating to the shore.

1). Correlation Method

As shown in Table 4-1, the correlations of shoreline position relative to the baseline x-axis in the model coordinates indicate perfect match between the observed shoreline 2011 and all the predicted shoreline 2011, excluding the shoreline segment in Cell C. Corresponding the coefficients in Table 4-1 to the MPRS, the highest sum score is 14 for ''absolute'' correlation coefficients and 8 for ''relative'' correlation coefficients among the 21 model runs (see Table 4-2).

Table 4-1 Correlation Coefficients

Correlation coefficients for absolute shoreline positions (relative to baseline x-axis)						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
262°	0.999132	0.999068	0.996678	0.746646	0.998371	0.997814
263°	0.999119	0.999484	0.996746	0.60517	0.997987	0.998045
264°	0.999122	0.999612	0.996975	0.531851	0.997473	0.998389
Correlation coefficients for absolute shoreline positions (relative to seawall)						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
262°	0.186	0.358	0.138	0.235	0.070	0.511
263°	0.186	0.444	0.056	0.303	0.055	0.526
264°	0.165	0.464	-0.118	0.329	0.033	0.549
Correlation coefficients for shoreline variation (relative to initial shoreline)						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
268°	0.262	-0.185	0.504	-0.025	-0.316	0.322
269°	0.273	-0.174	0.525	-0.027	-0.307	0.434
270°	0.277	-0.160	0.528	-0.028	-0.310	0.531

Table 4-2 Scores of Model Performance from Correlation Method

Correlation Coefficient for shoreline position (relative to the position of seawall)							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
262°	2	3	2	2	1	4	14
263°	2	3	1	3	1	4	14
264°	2	3	0	3	1	4	13
Correlation Coefficient for shoreline variation (relative to shoreline observation in 2009)							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
268°	2	0	3	0	0	3	8
269°	2	0	3	0	0	3	8
270°	2	0	3	0	0	3	8

2). Shoreline Movement Method

The shoreline movements along the transects and the computational positions are given in Table 4-3. For the approach of transects, the maximum score 20 is found in the model run with the shoreline angle α'=260°, different from the result analysed from MAE, which is α'=259° as shown in Table 4-4.

Table 4-3 Shoreline Movements

Transects						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
258°	26.86	16.78	26.50	19.69	24.73	38.59
259°	25.89	21.87	27.14	12.76	21.78	35.65
260°	26.16	28.83	29.40	9.02	18.85	33.13
MAE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
258°	28.07	16.15	28.18	18.82	30.56	44.67
259°	26.33	18.89	28.73	12.57	26.94	42.21
260°	25.88	23.97	30.63	9.18	23.45	40.06

Table 4-4 Scores of Model Performance from Shoreline Movement Method

Transects							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
258°	3	4	3	4	3	1	18
259°	3	3	3	4	3	1	17
260°	3	3	3	5	4	2	20
MAE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
258°	3	4	3	4	2	0	16
259°	3	4	3	4	3	0	17
260°	3	3	2	5	3	0	16

3). Probabilistic Method

The error indicators (bias is not included) in the probabilistic method (Table 4-5) show a good agreement with each other that the model performance is the best when the shoreline orientation is set to 260^o, see Table 4-6.

Table 4-5 Error Indicators from Probabilistic Method

Bias						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
258^o	-4.47	8.45	-19.41	5.29	-28.04	38.99
259^o	-4.92	15.25	-21.65	0.22	-24.61	35.86
260^o	-5.22	23.48	-25.54	-2.04	-21.27	32.89
RMSE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
259^o	37.15	30.44	35.42	18.62	34.30	59.05
260^o	36.62	39.84	36.62	12.76	29.59	56.09
261^o	37.59	49.59	39.34	11.07	25.35	53.27
NMSE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
258^o	0.489	0.183	0.454	0.230	0.512	0.833
259^o	0.450	0.327	0.459	0.135	0.388	0.762
260^o	0.437	0.561	0.491	0.064	0.289	0.687
BSS						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
259^o	0.55	0.673	0.541	0.865	0.612	0.238
260^o	0.563	0.439	0.509	0.936	0.711	0.313
261^o	0.539	0.131	0.434	0.952	0.788	0.38

Table 4-6 Scores of Model Performance from Probabilistic Method

RMSE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
258^o	2	2	2	4	2	0	12
259^o	2	2	2	4	3	0	13
260^o	2	1	2	4	3	0	12
NMSE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
258^o	4	5	4	5	4	2	24
259^o	4	4	4	5	4	3	24
260^o	4	4	4	5	5	3	25
BSS							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
259^o	3	3	3	4	3	1	17
260^o	3	2	3	5	4	2	19
261^o	3	1	2	5	4	2	17

4). Distortion Method

The maximum score 15 analysed from the distortion length is found in two model runs, where the shoreline angle is 260^o and 261^{o}respectively (Table 4-7 and

Table 4-8).

Table 4-7 Distortion Length

Shoreline Angle	FULL	CELL A	CELL B	CELL C	CELL D	CELL E
260^o	27.43	27.18	33.08	18.42	31.11	39.87
261^o	27.32	32.56	34.83	15.73	27.01	37.32
262^o	27.51	39.62	35.87	15.09	22.97	34.71

Table 4-8 Scores of Model Performance from the Distortion Method

Shoreline Angle	FULL	CELL A	CELL B	CELL C	CELL D	CELL E	TOTAL
260^o	3	3	2	4	2	1	15
261^o	3	2	2	4	3	1	15
262^o	3	1	1	4	3	2	14

In summary, the best-fit shoreline angles analysed from four methods illustrated above are shown in Table 4-9.

Table 4-9 Summary of Best-Fit Shoreline Angle for Optimum Model Performance

NO.	Method	Error Indicator	Best-fit Shoreline Angle
1	Correlation	r (Absolute Variables)	262^o, 263^o
		r' (Relative Variables)	268^o, 269^o, 270^o
2	Shoreline Movement	Transect	260^o
		MAE	259^o
3	Probabilistic	RMSE	260^o
		NMSE/BSS	260^o
4	Distortion	DL	260^o, 261^o

4.3 Sensitivity

As introduced in Section 3.3.2, in this study the error function of L2-error norm is employed as the error indicator to measure the model sensitivity to variable input parameters.

1). Shoreline Angle

Figure 4-3 gives the L2-error norms of 51 model runs (α'=230º-280º) by comparing against the shoreline data measured in autumn 2011. It shows a convergence as the angle increasing, and the smallest error (Err^{L2}=3.54%) is the model run with shoreline angle of 260º.

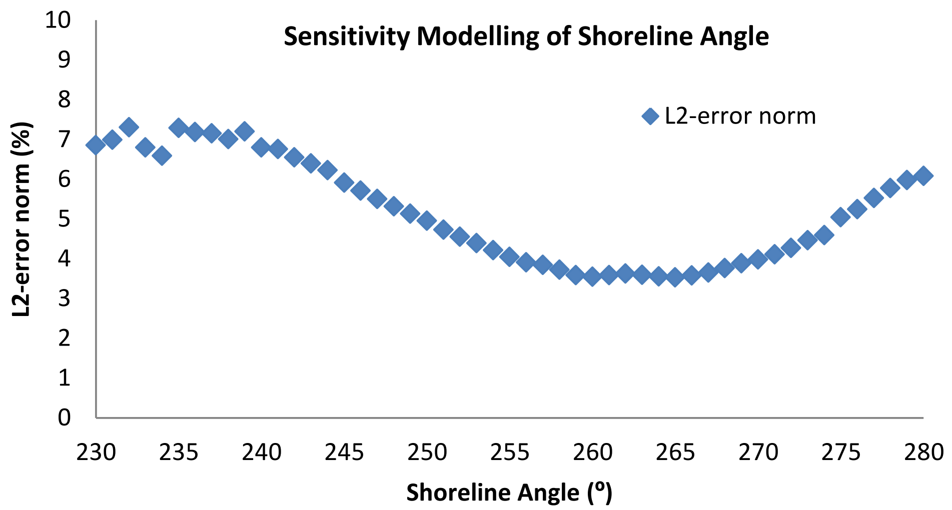


Figure 4-3 Sensitivity Analysis of Shoreline Angle

2). Wave Climate

As described in Section 3.3.3, the sensitivity modelling of wave climate put emphasis on wave directions. For Poole Bay, wave directions at 13 points are tested respectively by taking into account the local effects at each wave point that may not have been considered in the wave modelling. The trend of model errors from 21 simulations shows a convergence as shoreline angle varies from 250º to 270º, but the influence of wave direction changes at a single wave point to the model accuracy is not noticeable in the analysis of the full domain (vertical comparison in Figure 4-4), while in the adjacent shoreline cell of tested wave point the effect is more significant (see Figure 4-5). The model errors analysed in shoreline segment Cell C vary from 2% to 13%, the range of which are larger than in full scale (Err^{L2}=2.5% - 4%).

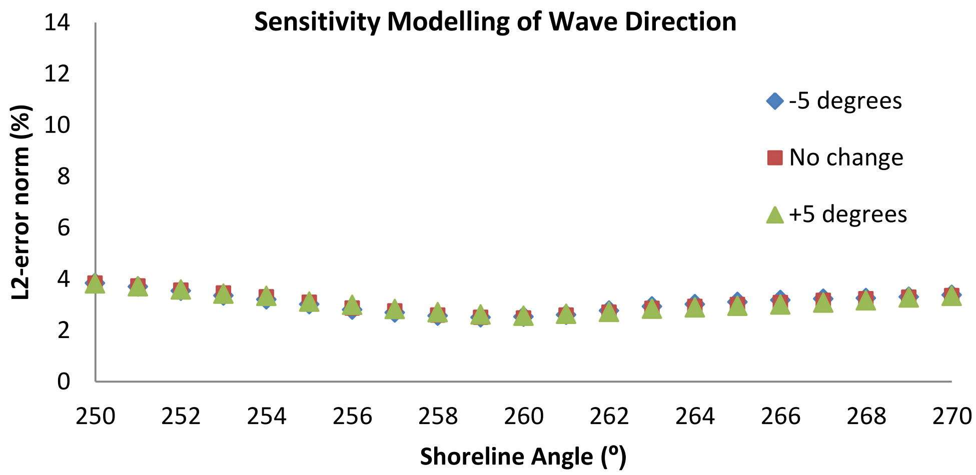


Figure 4-4 Sensitivity Analysis of Wave Direction (at Wave Point 158) in the Full Bay

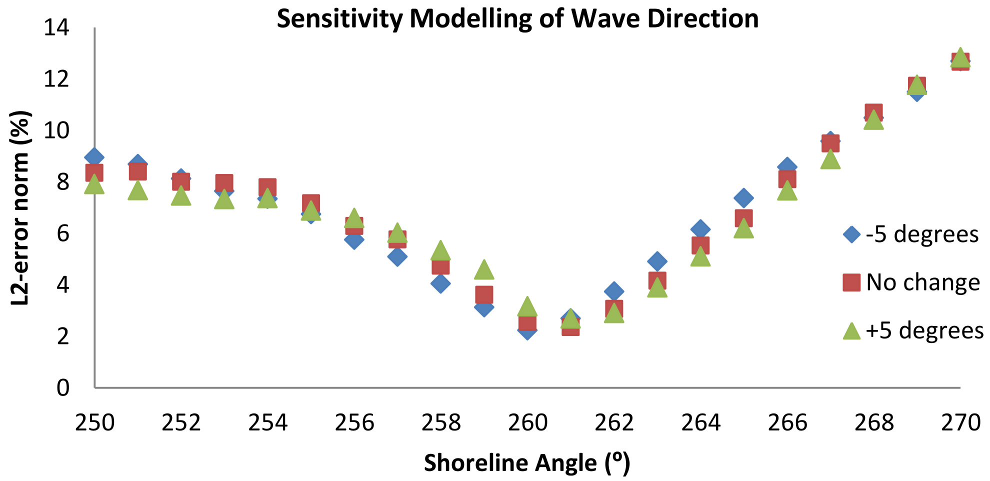


Figure 4-5 Sensitivity Analysis of Wave Direction (at Wave Point 158) in the Cell C

3). Cross-Shore Profile

The sensitivity of beach profile to model performance is focus on the constant slope and varied slope along the shoreline. As shown in Figure 4-6, the errors calculated from two types of cross-section show a convergence as the shoreline angle increasing. The varied slope indicates a better model accuracy than that of the uniform profile when shoreline angle is over 260°, and the best-fit shoreline angle is 265° with the smallest L2-error norm of 3.3%.

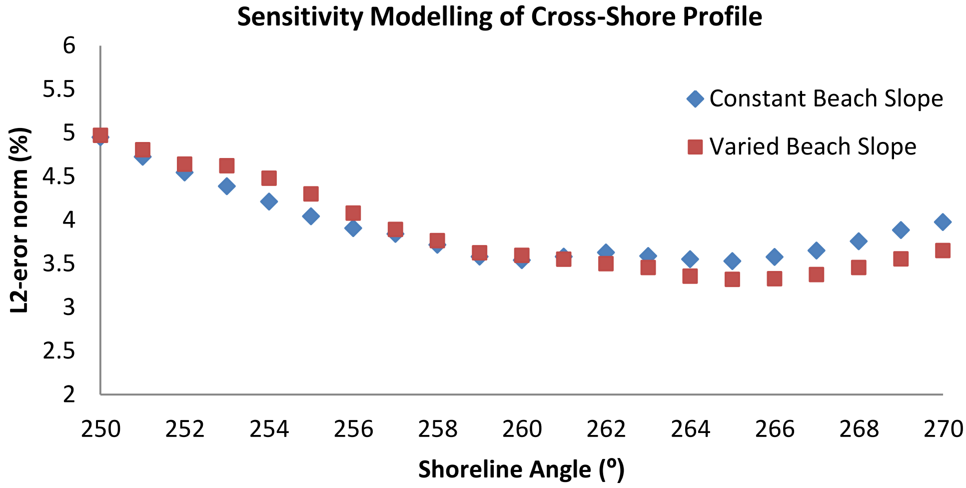


Figure 4-6 Sensitivity Analysis of Cross-Shore Profile

4). Grain Size

The sensitivity of grain size is based on the model tests of coefficient K1 in the CERC formula. The results in Table 4-10 show that coarse sediment is better for accuracy modelling, and the lowest L2-error norm is only 0.91%. As grain size becomes finer, however, the model errors grow subsequently.

Table 4-10 Sensitivity Analysis of Grain Size

K1	0.02 (Shingle)	0.3 (Sand)
Err^{L2}	0.91%	4.29%

5). Closure Depth

The closure depth for Poole Bay is approximately 4m calculated by Equation (3.18), nevertheless, a series of closure depth ranging from 2m to 10m are tested for sensitivity analysis of shoreline changes with respect to different closure depths. The results from error function L2-error norm are given in Table 4-11. As the closure depth moves towards deeper water such as 10m, the model prediction shows better match with field observation and the model error 1.8% is half of that in 2m closure depth. More discussions are in Section 5.3.

Table 4-11 Sensitivity Analysis of Closure Depth

Dc	-2m	-3m	-4m	-5m	-6m	-7m	-8m	-9m	-10m
Err^{L2}	3.05%	2.81%	2.61%	2.36%	2.21%	2.07%	1.97%	1.88%	1.80%

6). Physical Parameters

Physical parameters, such as water and sand density, are tested with some extreme values (Table 4-12). It shows that the model is not so sensitive to physical parameters, where model errors have minor changes even with extreme inputs.

Table 4-12 Sensitivity Analysis of Physical Parameters

Water Density	**1000 kg/m^3**	**1027 kg/m^3**	**1050 kg/m^3**
Err^{L2}	2.44%	2.47%	2.58%

Sediment Density	**2000 kg/m^3**	**2650 kg/m^3**	**3000 kg/m^3**
Err^{L2}	3.40%	2.47%	2.23%

Porosity	**0.4**	**0.6**	**0.7**
Err^{L2}	2.47%	3.23%	3.81%

Wave Breaking Coefficient	**0.4**	**0.55**	**0.8**
Err^{L2}	2.69%	2.47%	2.28%

5. Model Performance Analysis and Discussion

This chapter analyses the model errors from uncertainty and sensitivity modelling, and discusses in more detail about the optimization of model performance with respect to methods of error analysis as well as the rating system.

5.1 Uncertainty

While variability of the model output is a direct result of variability of the model input, the extent of the variability, and its lower and upper limits, may also be affected by the values of parameters. In this dissertation study, the shoreline angle is addressed for the uncertainty analysis. In the simple case, among the 11 model runs (initial shoreline position y=660m) erosion occurs on the lee side of the groyne, where the most retreating beach position y_{min} is 623m. Updrift of the groyne, shoreline accretes to the maximum beach position y_{max} =762m. For the Poole Bay case, the shoreline advances the most near the two piers, ignoring the model instabilities. Due to the log-spiral shape, the mean shoreline position is not suitable to quantify the uncertainty of Poole Bay development.

The movement of the envelope of the shoreline position allows the modeller to quickly assess the model uncertainty associated with the input parameters such as shoreline angle at a first estimate. However, there is a bias when analysing shoreline position from all the modelling, where model instability happens at times. Besides, the accuracy of this assessment relies on the number of model runs, more uncertainty modelling is therefore required before a precise judgement of shoreline accretion or erosion is made.

5.2 Optimization

1). Correlation Method

As an objective measure of correlation between variables, however, correlation coefficient only indicates the strength and direction of a linear relationship between two variables, but not how significant the correlation is. There are two concerns that need to be remembered when applying this method to model evaluation.

Firstly, if the shoreline position y is defined too far from the baseline x-axis in the model coordinate system, the large value of y may overwhelm the effect of shoreline variation on the correlation (Figure 5-1 (a)). This happened in the case of Poole Bay, as the mean shoreline position of the initial condition is 1487m, while the maximum beach movement is observed to be approximately 150m. If correlated the two shorelines with absolute values in the model coordinate system, the correlation coefficient might indicate a near perfect agreement, for example, r_1 =0.998465 as shown in in Table 5-1. To solve the problem, a ''new baseline'' is used in which the distances are relative to the changes observed. As the seawall is kept the same in every model run, it can be used as a new baseline for the correlation analysis. As a result, the correlation coefficient becomes much smaller r_2 = 0.186.

The second concern relates to when the movements of beach position within the simulated time period are greater than that measured in field investigation, but the plan shape of predicted shoreline is similar to the observation (Figure 5-1 (b)). In this situation, correlation does not consider the magnitude of variations but their distribution along the shoreline, therefore, a good model performance will be tagged incorrectly judging from the correlation coefficient value ($r \approx 1$). Due to this problem, shoreline changes within the model period, which indicate coastline positions relative to the initial condition, are correlated instead of the absolute shoreline position. Even in a ''calm'' beach where the retreat/advancing is not easy to detect from maps, this correlation method is able to assess where the modelling is good and where it is bad. For the same example as mentioned above, the correlation coefficient r_3 is reduced to 0.049 due to the error in predicting the position of erosion and deposition.

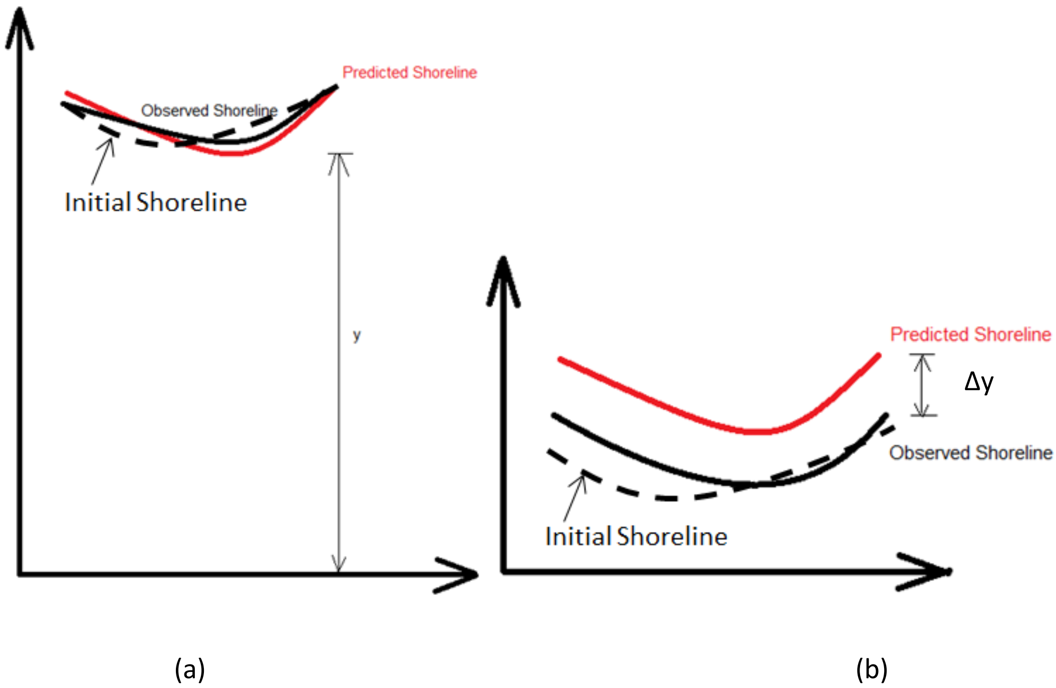


Figure 5-1 Correlation of Predicted and Observed Shoreline

Table 5-1 Correlation Coefficients of Shoreline in Poole Bay

Shoreline Angle	Correlation Coefficient		
α'	r_1	r_2	r_3
260°	0.998465	0.186	0.049

It is also noticed that the correlation of shoreline positions (relative to the seawalls) is quite diverse in each shoreline segment. For the whole bay, the correlation coefficient shows a convergence as the shoreline angle increases from 250° to 270 °; in Cell A and Cell C, the correlation becomes stronger with larger beach orientation, while the opposite trend is found in Cell B, and no significant changes in Cell E (Table 5-2). Different from other shoreline segments, the correlation coefficients analysed in Cell D have no significant tendency.

Rather different results are analysed from the shoreline variations correlation coefficients (relative to the initial shoreline 2009). In the full bay as well as in Cell B and Cell E, the correlations get better when increasing the shoreline angle, yet in Cell A and Cell D the changing trends are going down. As seen in Cell C, a convergence is found, so that the best-fit shoreline angle can be determined from the testing values.

A comparison between two sub-methods of correlation is shown in Table 5-2.

Table 5-2 Analysis of Correlation Results in Poole Bay

Trend of Correlation as Shoreline Angle Increasing	Correlation Coefficient for Shoreline Positions (relative to seawall)	Correlation Coefficient for Shoreline Variations (relative to initial shoreline)
Better	Cell A, Cell C	Full, Cell B, Cell E
Worse	Cell B	Cell A, Cell D
Convergence	Full	Cell C
No Change	Cell E	-

2). Shoreline Movement

For the assessment of model performance, only the mean errors from transects method are considered. In the six analysed sections, mean errors show a good convergence as the shoreline angle varies from 250° to 270°, where the minimum value 8.01 is found in Cell (Table 5-3).

This approach can approximately estimate the accuracy of the simulated shorelines as compared to the measured shoreline without interpolating the data to the same x-axis for error calculation, so there will be no further inaccuracies introduced. However, the accuracy of this method depends on the number of transects taken into consideration. The more transects are chosen, the more accurate the result will be. However, a denser network of transects will ensure a more exhaustive comparison between the shorelines.

MAE is one of the most common measures of model accuracy. This indicator interprets the average errors between the predicted shoreline and field observation. The smallest value of MAE is observed in the same model run as the approach of transects in Cell C. Additionally, the same best-fit shoreline angles are analysed in Cell A and Cell E. This confirms the possibility of increasing model accuracy by deducing the uncertainty of input parameters, for example, in the small-scale such as sub-divided cells, the curvature of shoreline is less than in the full bay, so the shoreline angle is easier to define for modelling.

Generally, the two sub-approaches show that the Cell A and Cell B more favourable towards lower shoreline angles. In the shoreline segment of Cell C and Cell E, higher angles as can be expected with the baseline moving round. The full bay seems similar to the Cell C centralized.

Table 5-3 Analysis of Shoreline Movement Method

Transect						
Segment	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
Minimum Mean Error	25.89	11.75	24.68	8.01	8.79	17.94
Best-Fit Shoreline Angle	259°	256°	250°	261°	270°	269°

MAE						
Segment	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
Minimum MAE	25.88	13.59	27.27	8.47	13.15	26.34
Best-Fit Shoreline Angle	260°	256°	256°	261°	264°	269°

3). Probabilistic Method

The error indicators in the probabilistic method (excluding bias) show that the best-fit shoreline angle is 260° for the overall analysis, which agrees with the segment shoreline orientation in Cell C (see Table 5-4).

Table 5-4 Analysis of Probabilistic Method

Indicator	Bias	RMSE	NMSE/BSS
Minimum Value	0.22	11.05	0.048/0.952
Segment	Cell C	Cell C	Cell C
Best-Fit Shoreline Angle	259°	260°	261°

Bias is not an indicator for quantifying the errors, but is sometimes referred to whether a model necessarily accurate or not, as shoreline movements may counteract between accretion and erosion. Therefore, even if there is no bias in a model (Bias=0), the accuracy may still be unknown.

Sutherland (2004) pointed out that the difference between MAE and RMSE depends largely on the error outliers. The presence of a few outliers will have greater influence on RMSE than on MAE as RMSE squares the differences. Therefore, RMSE is greater than or equal to the MAE, as shown in Table 5-5, so RMSE is a more conservative error predictor.

NMSE is an extremely effective measure of model performance, however, since the difference term in the numerator is squared (Equation (3.13)), it has the unfortunate property of being oversensitive to large deviations, such as NMSEs in the Cell A and Cell E, which are larger than that in the Cell C (Table 5-5).

Table 5-5 Comparison between MAE and RMSE

Poole Bay: Shoreline Angle α'=260°						
Segment	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
MAE	25.88	23.97	30.63	9.18	23.45	40.06
RMSE	36.62	39.84	36.62	12.76	29.59	56.09
NMSE	0.437	0.561	0.491	0.064	0.289	0.687

Contrary to the Bias, in the NMSE the deviations (absolute values) are summed instead of the differences. For this reason, the NMSE generally shows the most striking differences among models. If a model has a very low NMSE, then it is well performing both in space and time. On the other hand, high NMSE values do not necessarily mean that a model is completely wrong. That case could be due to time and/or space shifting. Moreover, it must be pointed out that differences on peaks have a higher weight on NMSE than differences on other values.

4). Distortion Method

The distortion length between model output and measured data indicates the resolution of shoreline positions. For the modelling in Poole Bay, the minimum distortion length is 15.09m in Cell C, which agrees with the analysis of shoreline movement and probabilistic methods, however, the optimum shoreline angle here is $\alpha' = 262^0$.

Distortion length is computed using standardized parameterization of the two shorelines under comparison, as indicated by Schmidley (1996), ''other measures reduces the difference between lines to a single number or result in unwieldy functions that are at best difficult to work with and at worst obscure the nature of the difference between lines''. In the distortion method, the shoreline positions acquired from the linear sample approach by generating a set of individual point discrepancies, ''can be analysed in accordance with the stochastic model used to summarized the accuracy of point objects''.

The four methods of error analysis applied this this study are summarized in Table 5-6.

Table 5-6 Comparisons of Analysis Methods for Optimization

NO.	Method	Error Indicator	Perfect Model Performance Value	Advantages	Disadvantage
1	Correlation	r	1	quick, easy and well tested in literature in other fields	1. effect of baseline 2. model accuracy is not quantified 3. data interpolation
		r’	1	1. quick, easy and well tested in literature in other fields 2. no effect of baseline 3. give tendency of shoreline evolution	1. model accuracy is not quantified 2. data interpolation
2	Shoreline Movement	Transects	0	1. quantify model accuracy 2. no data interpolation	accuracy relies on the number and distribution of transects
		MAE	0	1. easy to calculate with formula 2. quantify model accuracy	data interpolation
3	Probabilistic	RMSE	0		
		NMSE/BSS	0/1		
4	Distortion	DL	0		

The judgement of a model performance through the methods introduced in Section 3.3.2 depends on subjective threshold criteria MPRS. Either boundary vales and/or assigned score in each range are changed, the analysis result will probably change consequently. For example, Sutherland (2004) proposed a classification for BSS as given in Table 5-7.

Applying to this rating criteria, the ranking of 21 model performance (modelling of shoreline angle) will change as shown in Table 5-8, and the best-fit shoreline angle is 259^0 not 260^0 with the MPRS in the previous analysis.

Table 5-7 Classification of BSS

Rating	BSS
Excellent	1.0-0.5
Good	0.5-0.2
Reasonable	0.2-0.1
Poor	0.1-0
Bad	<0

Table 5-8 Assessment Metrics from Error Indicator BSS

	BSS						
Shoreline Angle	FULL	CELL A	CELL B	CELL C	CELL D	CELL E	TOTAL
250°	2	5	5	4	1	1	18
251°	3	5	5	4	1	1	19
252°	3	5	5	4	1	1	19
253°	4	5	5	4	1	1	20
254°	4	5	5	4	1	1	20
255°	4	5	5	5	2	1	22
256°	4	5	5	5	3	1	23
257°	4	5	5	5	4	2	25
258°	5	5	5	5	4	3	27
259°	5	5	5	5	5	4	29
260°	5	4	5	5	5	4	28
261°	5	3	4	5	5	4	26
262°	5	1	4	5	5	4	24
263°	4	1	4	5	5	5	24
264°	4	1	4	5	5	5	24
265°	4	1	4	5	5	5	24
266°	4	1	4	4	5	5	23
267°	4	1	4	2	5	5	21
268°	4	1	4	1	5	5	20
269°	4	1	4	1	5	5	20
270°	4	1	4	1	5	5	20

In addition, it is difficult to judge the model performance of an ensemble of model runs if the summed scores of error indicator have the same value. It happens if the band width of the distribution of errors is too small so that they fall to the same index range. For example, 11 simulations with incident wave angles at wave point 158 varying -5° to +5° were carried out in model BEACHPLAN, which aims to find out the local effects at each wave point that may not have been considered in the wave transformation modelling. The statistics of calculated indicator BSS are shown in Table 5-9. If they are ranked them with the same criteria as the previous analysis adopted (Table 3-7), there will be no difference between scores in some segments such as Cell B, where the maximum BSS is 0.611, and minimum is 0.596, as a result, all the BSS values are in the range 0.5-0.7 with a score of 3. In this case, the rating system is not applicable to evaluate the model performance any more, therefore, it is better to analyse indicator values instead of the scores they get from the rating system. Table 5-9 shows that the model performs best in Cell C as the BSSs are more close to the perfect value 1, especially when the wave direction decreases 4° (BSS=0.958, 1.448% of increasing, see Table 5-10), but the shoreline in other cells are not responded to this change in the same way. It confirms the influence of wave climate on local shoreline.

Table 5-9 Statistics of BSS from modelling of wave directions

BSS											
Changes	**-5°**	**-4°**	**-3°**	**-2°**	**-1°**	**0**	**1°**	**2°**	**3°**	**4°**	**5°**
FULL	0.563	0.568	0.572	0.571	0.571	0.579	0.565	0.566	0.557	0.551	0.550
CELL A	0.182	0.185	0.196	0.184	0.178	0.232	0.191	0.182	0.178	0.185	0.180
CELL B	0.598	0.606	0.605	0.605	0.608	0.611	0.596	0.603	0.598	0.599	0.604
CELL C	0.957	0.958	0.957	0.954	0.947	0.944	0.934	0.937	0.919	0.912	0.915
CELL D	0.756	0.773	0.787	0.794	0.797	0.795	0.785	0.775	0.754	0.728	0.710
CELL E	0.380	0.378	0.379	0.378	0.379	0.383	0.379	0.383	0.383	0.377	0.384

Table 5-10 Optimization Analysis of BSS

% changes of BSS based on NO wave direction altering											
Changes	**-5°**	**-4°**	**-3°**	**-2°**	**-1°**	**0**	**1°**	**2°**	**3°**	**4°**	**5°**
FULL	-2.90	-1.98	-1.32	-1.4	-1.42	0	-2.41	-2.40	-3.83	-4.93	-5.07
CELL A	-21.4	-20.3	-15.5	-20.6	-23.2	0	-17.7	-21.7	-23.1	-20.3	-22.2
CELL B	-2.11	-0.86	-1.10	-0.95	-0.61	0	-2.55	-1.40	-2.16	-1.97	-1.26
CELL C	1.37	1.45	1.38	1.03	0.33	0	-1.11	-0.73	-2.73	-3.42	-3.14
CELL D	-4.91	-2.75	-1.06	-0.12	0.29	0	-1.27	-2.55	-5.17	-8.37	-10.6
CELL E	-0.78	-1.27	-1.15	-1.34	-1.01	0	-1.03	-0.09	-0.07	-1.56	0.28

5.3 Sensitivity

In general, the sensitivity analysis shows that the model performance is most influenced by the input parameter of the shoreline orientation and grain size, which L2-error norms vary 3.76% and 3.96% respectively. Figure 5-2 Variation of Model Errors in Sensitivity Modelling shows the sensitivity of shoreline changes to the input parameters tested in this research. It is necessary to point out that the results here are biased as the sensitivity analysis only involves nine parameters, which were not tested with equal number of runs. More beach behaviour related parameters (see Table 5-11) need to be tested before a comprehensive conclusion can be reached.

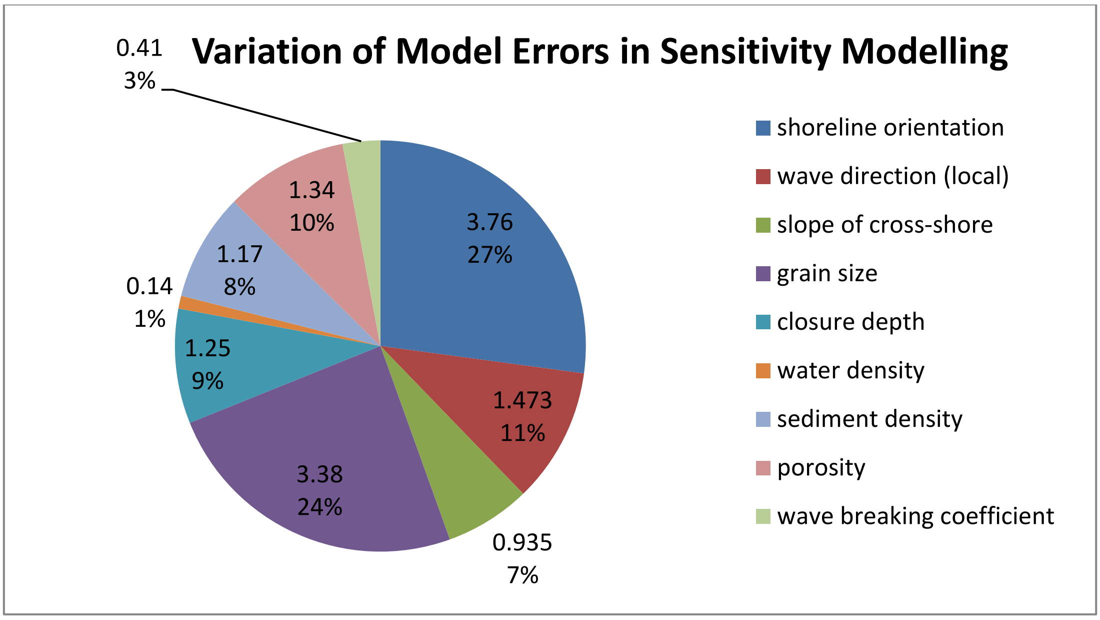


Figure 5-2 Variation of Model Errors in Sensitivity Modelling

Table 5-11 Beach Behaviour Model Parameters

Systems	wave height, wave angle, storms, morphologic feedback, shoreface morphology, underly geology	sensitive to shoreline evolution
Subsystems	offshore bar configuration, wave current interactions, coastal type, grain size, sediment supply, engineering structures, beach rock, near shore winds	sensitive to shoreline evolution
Components	external factors (wind), bed liquefaction, bed forms, bed roughness, beach state, bottom currents, storm surge, tidal range, tidal currents, coastal currents	not taken into account
Factors	water temperature (density), sediment sorting (lags – armouring), hydraulic conductivity, ground water (pore pressure), organic mats, aeolian loss or gain, over-wash loss, gravity currents, infragravity waves, storm surge ebb currents	not sensitive to shoreline evolution

(Source: Modified from Pilkey and Cooper, (2002)) More shoreline responses to tested parameters are discussed as followings:

1). Shoreline Angle

In one-line theory, only one contour line is necessary to describe the evolution of the beach plan shape, as individual profiles are assumed to move horizontally over the entire active profile height as a result of erosion or accretion (Figure 2-3). As the depth contour lines are assumed to be parallel to the shoreline, the angle relative to the north of the contour line will affect the approaching direction of incident waves, which is significantly important for coastline development.

With global warming changing wind patterns/directions and thereby wave climates may be varied, as well as a rise in sea levels. Changing the angle of the baseline can therefore explore the implications of changing weather/wave patterns. Sea level rise has not been considered in this study.

As introduced in Section 3.3.2, sensitivity modelling is not only done to examine shoreline response to variation of a single input parameter, but can also include more variables, e.g. shoreline angle and wave direction, wave direction and grain size, etc. In order to find the best-fit shoreline angle, its sensitivity to the coast variation, as well as together with other parameters, such as wave direction, beach profile gradient, are tested. As shown in Figure 4-3, Figure 4-4, Figure 4-5, Figure 4-6 in Section 4.3, error indicator L2-error norm in each model set shows a convergence as the shoreline angle increases, and the concave points are found near $\alpha'=260^{o}$.

2). Wave Climate

In one-line models, waves are the main driving force responsible for longshore sediment transport. Some modelling studies have suggested that wave climate shifts could cause alongshore variations in shoreline change that will likely overwhelm other reasons related shoreline changes, such as sea-level rise(Slott et al., 2006; Murray et al., 2007). Therefore the order of magnitude of shoreline variations responding to changes in the wave climate is necessary to be examined. In this study, the sensitivity modelling put the emphasis on wave direction, as the relative angle between shoreline angle and incident wave crest determines the magnitude of longshore drift. In addition, wave climate has both regional and local impacts for shoreline development, which should be taken into account for sensitivity analysis as well.

In addition, wave climate has both regional and local impacts for shoreline development, which should be taken into account for sensitivity analysis as well. Based on the sensitivity tests of shoreline angle, results from wave directions show that some parts of the simulated shoreline agree with the observation quite well, but the rests still need further modification. Take the pronounced accretion found on the west side of the Bournemouth Pier from one model result for example, this large amount of sand blockage is not expected in reality. To diminish the local sedimentation, the local effect of the wave point nearest the pier is considered. In this case, wave point 158 was chosen for adjustment.

Figure 4-4 and Figure 4-5 show the response of the full bay and Cell C (from Bournemouth Pier to Boscombe Pier) to the change of wave direction at wave point 158 (nearest to Bournemouth Pier). It is concluded that the local impact is more obvious (Err^{L2}=2% - 13%) than the regional (Err^{L2}=2.5% - 4%), because the longshore sediment flux Qs is a nonlinear function of the local shoreline angle θ relative to the wave crests ϕ_0 (Figure 5-3). The beach orientation in each shoreline segment varies, as a result, the shoreline response to incident waves differently.

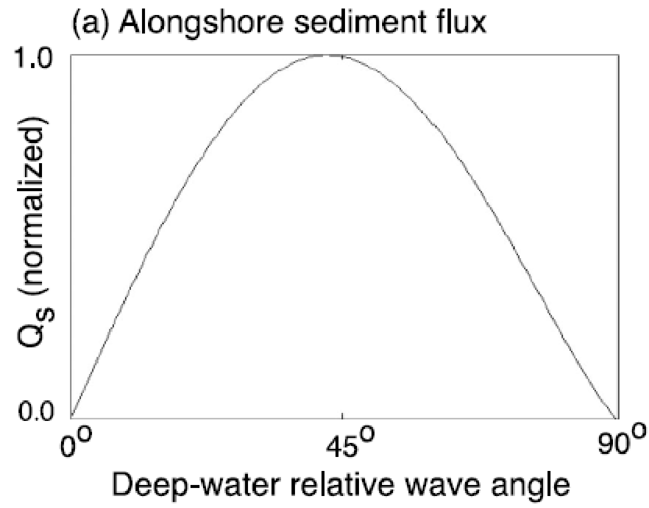


Figure 5-3 Schematic Relationship between Longshore Transport and the Relative Angles

(Source: Adapted from Bosbom and Stive (2011))

3). Cross-Shore Profile

The sensitivity analysis of beach profile indicates little difference between uniform and varied gradient, especially when the shoreline angle α'< 260^0. Considering the beach profile in reality is not homogenous, the varied slope of cross-shore is more reasonable.

4). Grain Size

According to Wright (1981), both directly and indirectly the variations in beach sediment size further contribute to the shoreline plan geometry. Model errors show that the coefficient K1, which is related to the grain size, promotes the model performance with smaller values (donate coarser materials, such as shingle). The dominant sediments in Poole Bay are sands, therefore, the calibrated K1 should be approximately 0.3 as defined in the model.

5). Closure Depth

In the sensitivity tests of closure depth, it is found that if the depth of closure D_c is deeper than the calculated value 4m from Equation (3.18), the model prediction shows a better agreement with the measured shoreline. However, the width of surf zone increases with larger closure depth, thus the existing groynes are relatively shortened and will lose their functions of stabilizing beach positions. The majority of longshore transport (due to the cross-shore distribution of longshore sediment transport rate as shown in Figure 5-4) would pass through these coastal structures and not reshape the shoreline in the designated area.

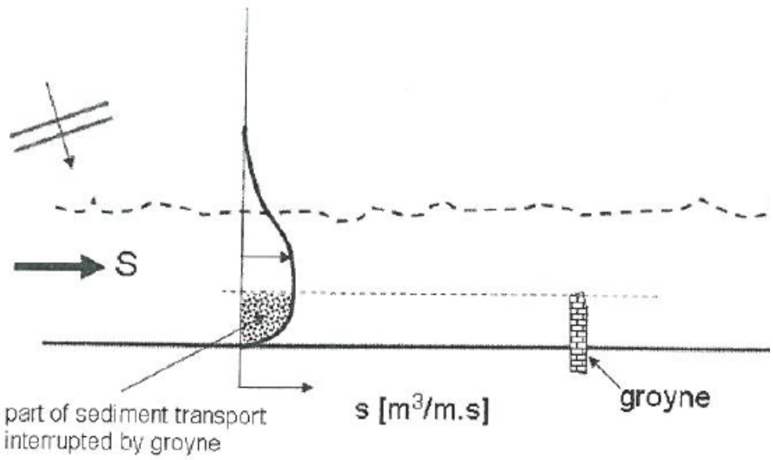


Figure 5-4 Sketch of Rate of Interruption of Sediment Transport by a Groyne

(Source: Adapted from Bosbom and Stive (2011))

6). Physical Parameters

Physical parameters are influenced by coastal environment, e.g. temperature, location, etc. The sensitivity modelling indicates that the shoreline response is slightly influenced by these physical parameters, although some extreme values were adopted. Therefore it can be concluded that the shoreline evolution is not sensitive to physical parameters.

6. Conclusions and Recommendations for Future Research

6.1 Conclusions

An assessment method of model performance is developed based on the error analysis and a rating system, and it was validated in the shoreline simulation with one-line model BEACHPLAN at Poole Bay, UK. Model performance was evaluated in terms of segment shoreline orientation, where both objective measurements and subjective criteria were used. Overall, the goodness of fit can be ranked by the score corresponding between the error indicator and a rating system.

-Uncertainty

Considering numerical models are imperfect abstractions of reality, and precise input data are rarely if ever available, therefore, model outputs are inevitably subject to uncertainty. Developing models by involving more processes in the complex coastal system, however, will not always reduce uncertainty in model predictions. For one-line models, it is possible to quantify the uncertainty of shoreline responses to variable environmental conditions by producing an envelope of shoreline movements. In addition, uncertainty analysis with the average or maximum/minimum/standard deviation of beach positions is often used to make general interpretations, such as describing the likelihood of different potential shoreline movements and estimating the relative impacts of input variable uncertainties.

-Optimization

Based on the error analysis as well as MPRS, the best-fit parameters are able to be selected from several alternatives, thus are used to forecast shoreline evolution with higher accuracies. Analysing with different error indicators, the optimized parameters are confirmed with confidence. But sometimes the results may not agree with each other, e.g. correlation coefficient and distortion length. In this study, the best-fit shoreline angle for Poole Bay is determined: $\alpha'=260^o$. Moreover, the definition of MPRS needs to rely on model results and modellers' technical expertise, which are argued by the subjective values in the rating system for judging model prediction better or not.

-Sensitivity

When predicting future shoreline movements with numerical models, the sensitivity of beach responses to variable input parameters is of significantly important to investigate the accuracy of model prediction. The case study in this dissertation shows that the shoreline orientation and wave climates are more sensitive to the shoreline change modelling than other input parameters, ignoring the grain size sensitivity because the tested value are unrealistic as in Poole Bay.

6.2 Recommendations for Future Research

Due to the limitations of tested cases and research time, the adapted method for the assessment of model performance is not perfect. Future work is needed to improve the approach, including the following aspects:

1). Model testing with more input parameters other than shoreline orientation for uncertainty and optimization analysis, as well as sensitivity analysis;

2). Apply the method to other one-line models in different cases for validation, making it a robust method;

3). Improve the assessment method to be more objective rather than subjective.

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Appendices

Appendix 1 Shoreline Evolution from 2009 to 2012 in Poole Bay

Segment	2009-2010	2010-2011	2009-2011
CELL A	Net erosion to the east, natural adjustments after BIS 4.4 at Southbourne in March 2009 to the west.	No major changes except a noticeable increase in the central section.	Erosion to the east and relatively stable to the west.
CELL B	Significant erosion in the central further to west.	The eastern end showed erosion, whilst the central area hadnet accretion of up to 36%, immediately east of Boscombe Pier experienced considerable net erosion.	A variety of changes occurred over two years, comparatively stable overall, some sections gained slight accretion.
CELL C	Noticeable decrease in beach volume overall.	Relatively stable to the west, but both erosion and accretion occurred to the east section.	Erosion dominant the whole cell.
CELL D	Relatively stable except a negative net balance less than 15% in the central section.	Middle area showed no major change, whilst two ends especially the western end had significant accretion.	Net loss of sediment to the east and accretion to the west.
CELL E	Both erosion and accretion occurred, eastern part showed slight increase in beach volume while the opposite to the west.	Little change overall.	Relatively stable, but noticeable accretion near rock groynes.

Aerial image courtesy of Channel Coastal Observatory

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Poole Bay

Cell A

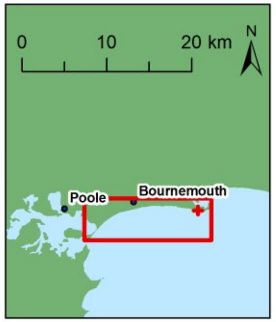
HH1- HHLong Groyne

Legend

Surveyed Data (tip-Autumn, tb-Spring)

- 0.5mShoreline2012_tip
- 0.5mShoreline2011_tip
- 0.5mShoreline2010_tip
- 0.5mShoreline2009_tip
- 0.5mShoreline2012_tb
- 0.5mShoreline2011_tb
- 0.5mShoreline2010_tb
- 0.5mShoreline2009_tb
- Transections

0 0.1 0.2 0.4 Kilometers N



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Poole Bay

Cell B

Boscombe Pier - HH1

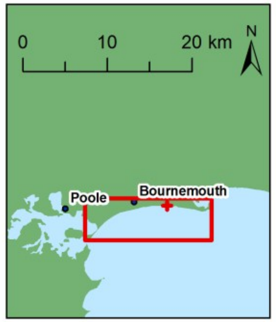
Legend

Surveryed Data (tip-Autumn, tb-Spring)

- 0.5mShoreline2012_tip
- 0.5mShoreline2011_tip
- 0.5mShoreline2010_tip
- 0.5mShoreline2009_tip
- 0.5mShoreline2012_tb
- 0.5mShoreline2011_tb
- 0.5mShoreline2010_tb
- 0.5mShoreline2009_tb
- Transections

0 0.125 0.25 0.5 Kilometers

N



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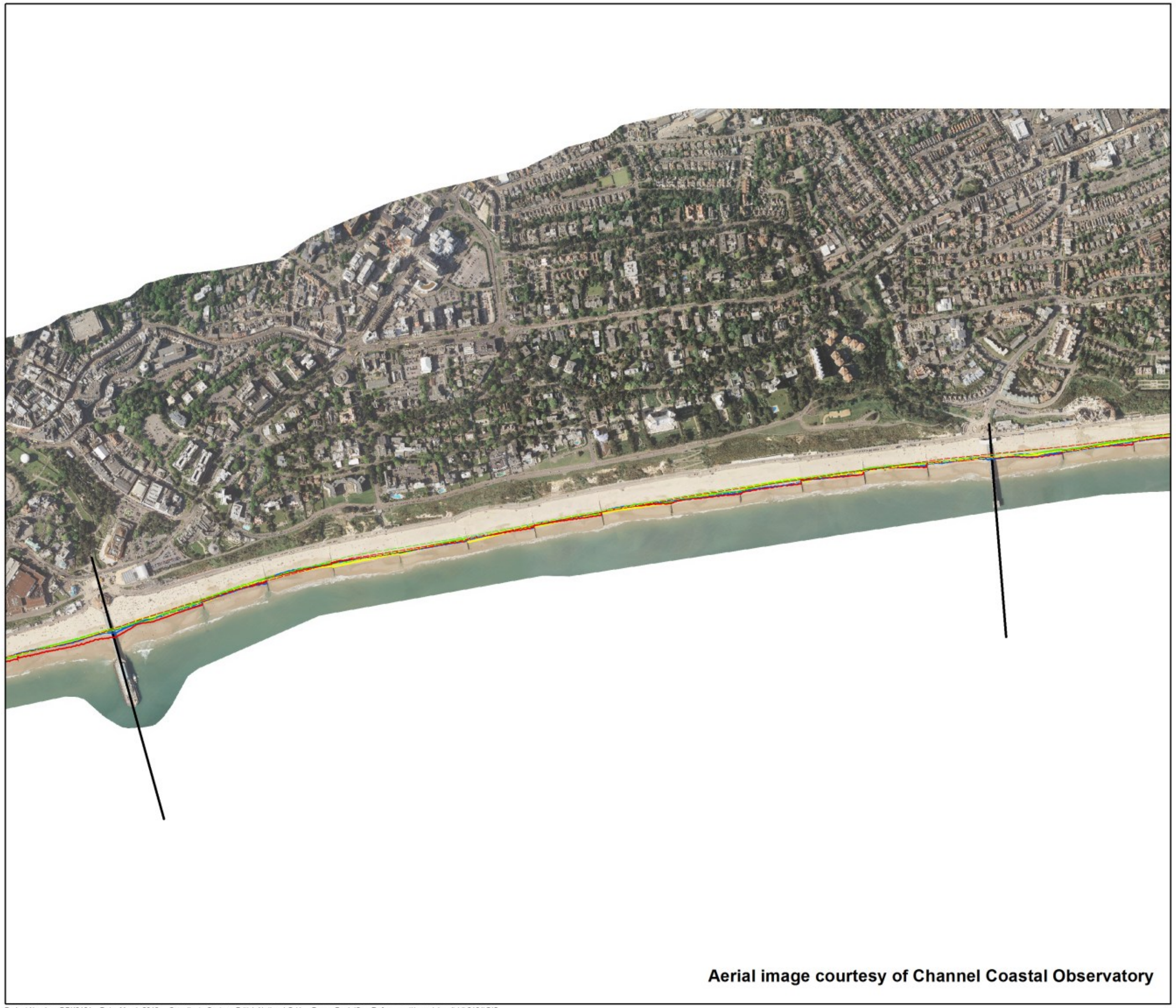
Poole Bay

Cell C

Bournemouth Pier - Boscombe Pier

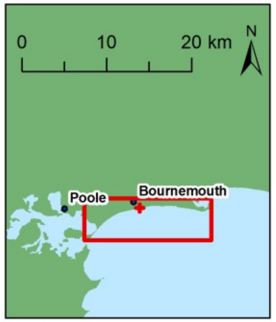


Legend

Surveryed Data (tip-Autumn, tb-Spring)

- 0.5mShoreline2012_tip
- 0.5mShoreline2011_tip
- 0.5mShoreline2010_tip
- 0.5mShoreline2009_tip
- 0.5mShoreline2012_tb
- 0.5mShoreline2011_tb
- 0.5mShoreline2010_tb
- 0.5mShoreline2009_tb
- Transections

0 0.1 0.2 0.4 Kilometers N



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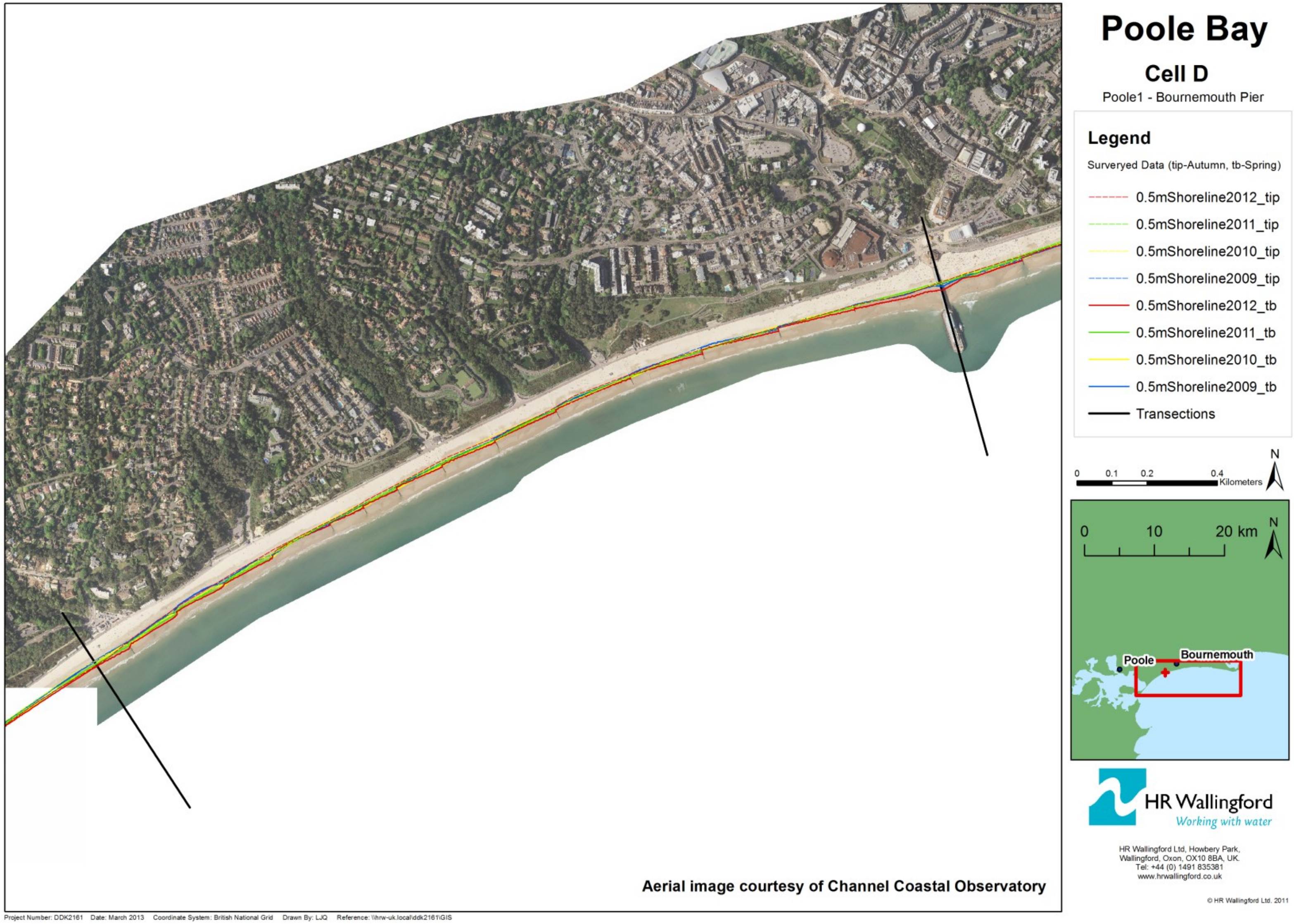
Poole Bay
Cell D
Poole1 - Bournemouth Pier
Legend
Surveryed Data (tip-Autumn, tb-Spring)
0.5mShoreline2012_tip
0.5mShoreline2011_tip
0.5mShoreline2010_tip
0.5mShoreline2009_tip
0.5mShoreline2012_tb
0.5mShoreline2011_tb
0.5mShoreline2010_tb
0.5mShoreline2009_tb
Transections
N
0 0.1 0.2 0.4 Kilometers
0 10 20 km
Poole
Bournemouth
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Poole Bay
Cell E
Sandbanks Head - Poole1
Legend
Surveryed Data (tip-Autumn, tb-Spring)
0.5mShoreline2012_tip
0.5mShoreline2011_tip
0.5mShoreline2010_tip
0.5mShoreline2009_tip
0.5mShoreline2012_tb
0.5mShoreline2011_tb
0.5mShoreline2010_tb
0.5mShoreline2009_tb
Transections
0 0.1 0.2 0.4 Kilometers
N
0 10 20 km
N
Poole
Bournemouth
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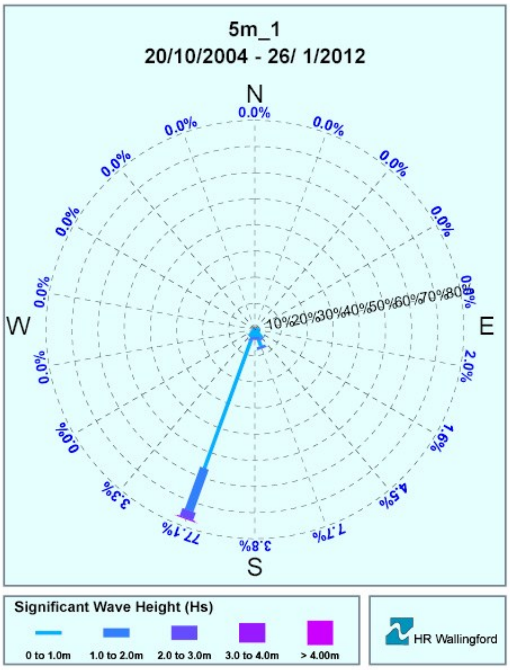
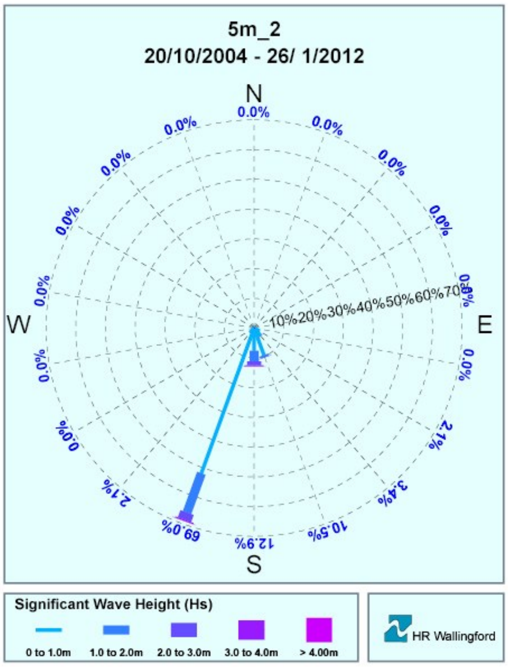
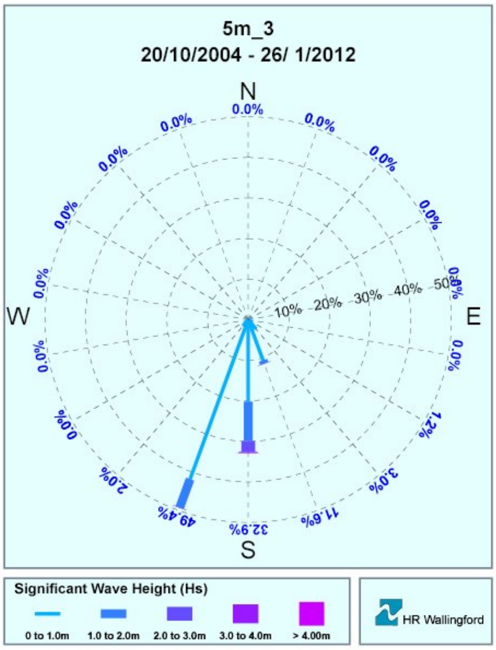
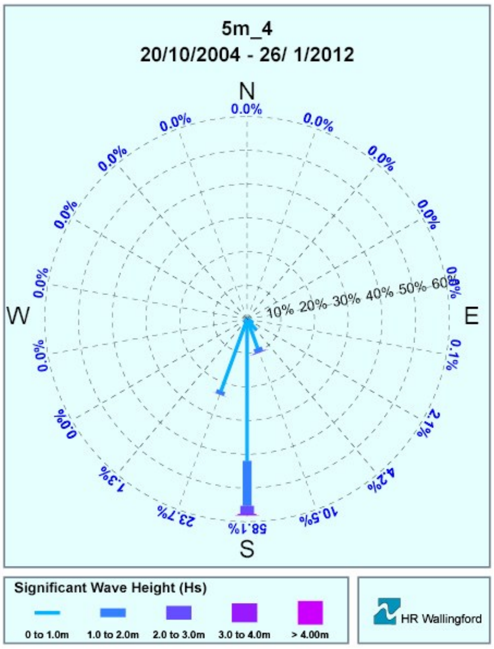
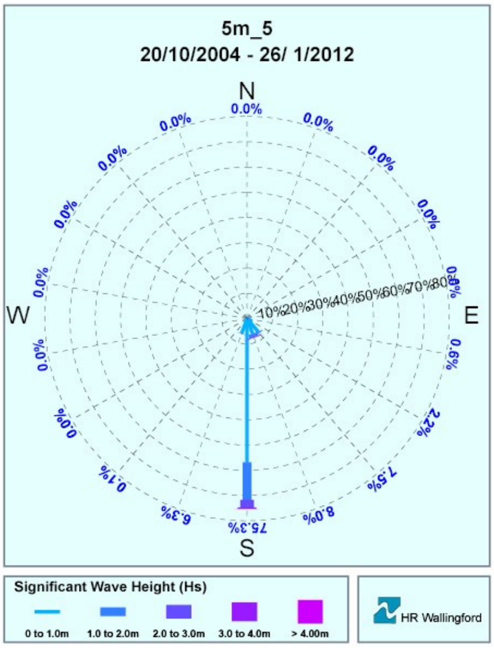
Appendix 2 Wave Roses in the Near Shore of Poole Bay










5m_5
20/10/2004 - 26/ 1/2012
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
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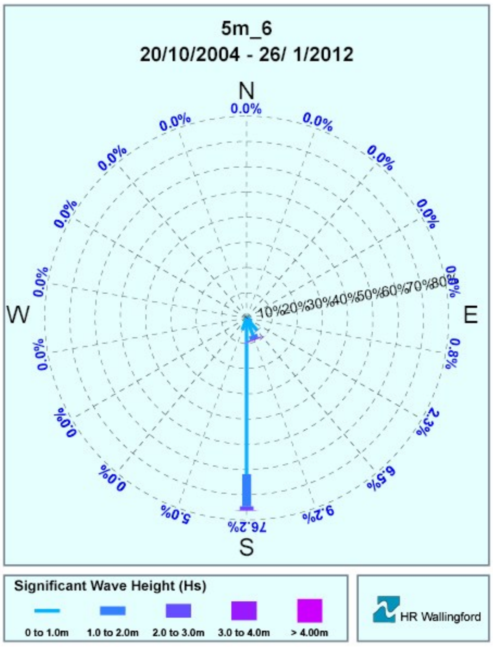
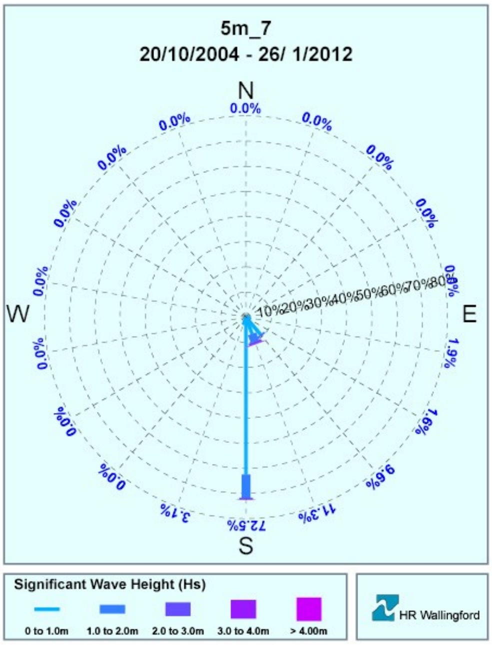
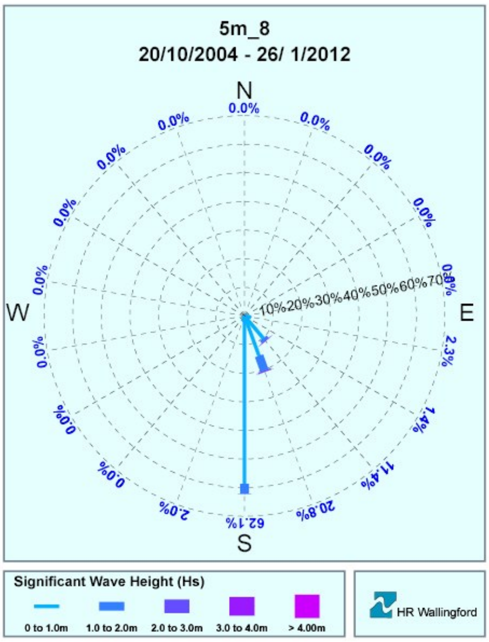
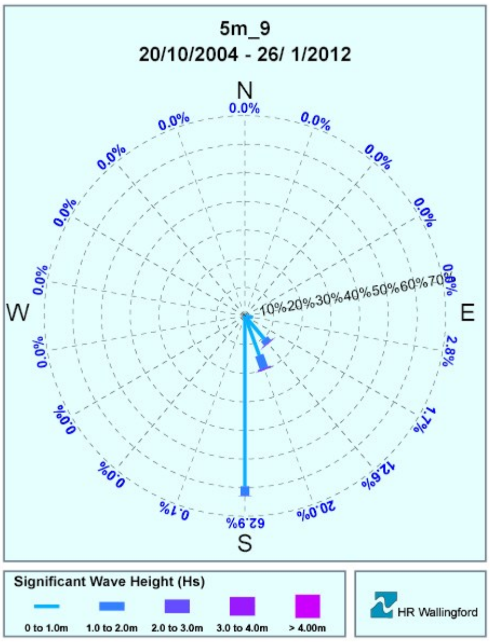
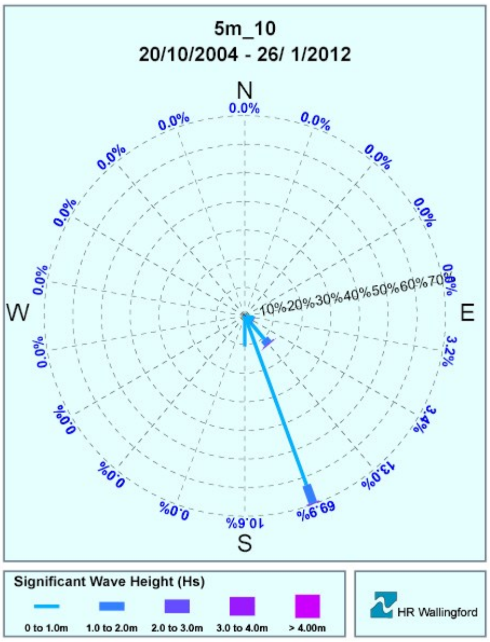
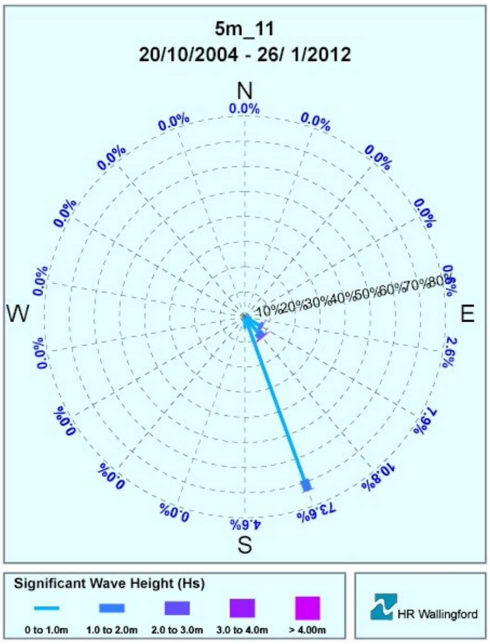

5m_6
20/10/2004 - 26/ 1/2012
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford

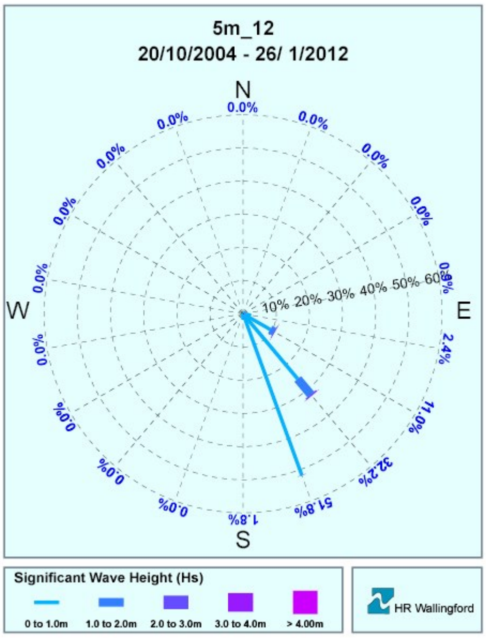

5m_7
20/10/2004 - 26/ 1/2012
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford

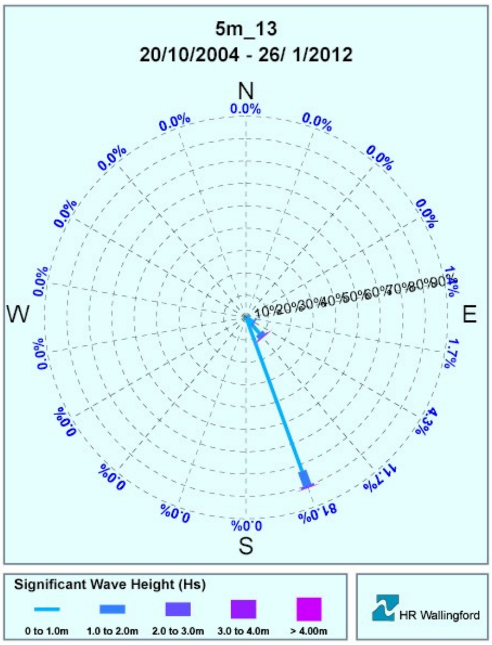

5m_8
20/10/2004 - 26/ 1/2012
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford


5m_9
20/10/2004 - 26/ 1/2012
N
E
S
W
10% 20% 30% 40% 50% 60% 70%
2.8%
1.7%
12.6%
20.0%
62.9%
0.1%
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford


5m_10
20/10/2004 - 26/ 1/2012
N
E
S
W
10% 20% 30% 40% 50% 60% 70%
3.2%
3.4%
13.0%
69.9%
10.6%
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford


5m_11
20/10/2004 - 26/ 1/2012
N
E
S
W
10% 20% 30% 40% 50% 60% 70% 80%
2.6%
7.9%
10.8%
73.6%
4.6%
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford


5m_12
20/10/2004 - 26/ 1/2012
N
E
S
W
10% 20% 30% 40% 50% 60%
2.4%
11.0%
32.2%
51.8%
1.8%
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
HR Wallingford


5m_13
20/10/2004 - 26/ 1/2012
N
E
S
W
0.0%
1.4%
1.7%
4.3%
11.7%
81.0%
10%20%30%40%50%60%70%80%90%
Significant Wave Height (Hs)
0 to 1.0m
1.0 to 2.0m
2.0 to 3.0m
3.0 to 4.0m
> 4.00m
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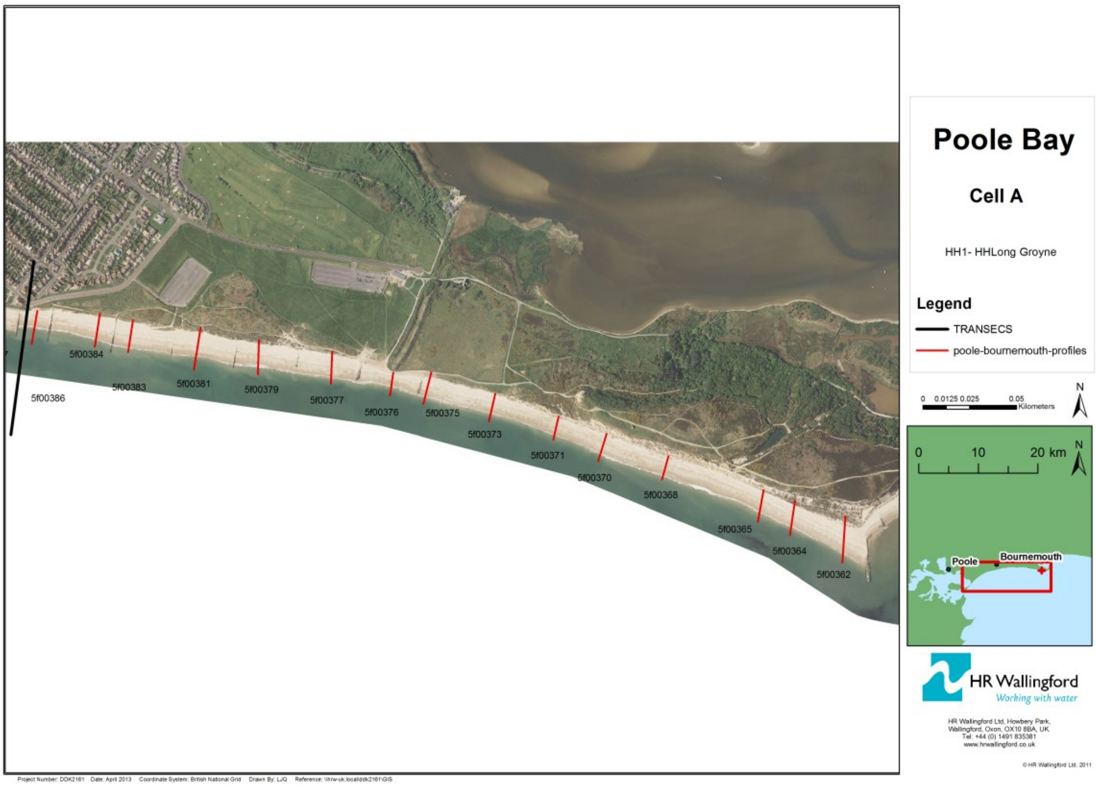
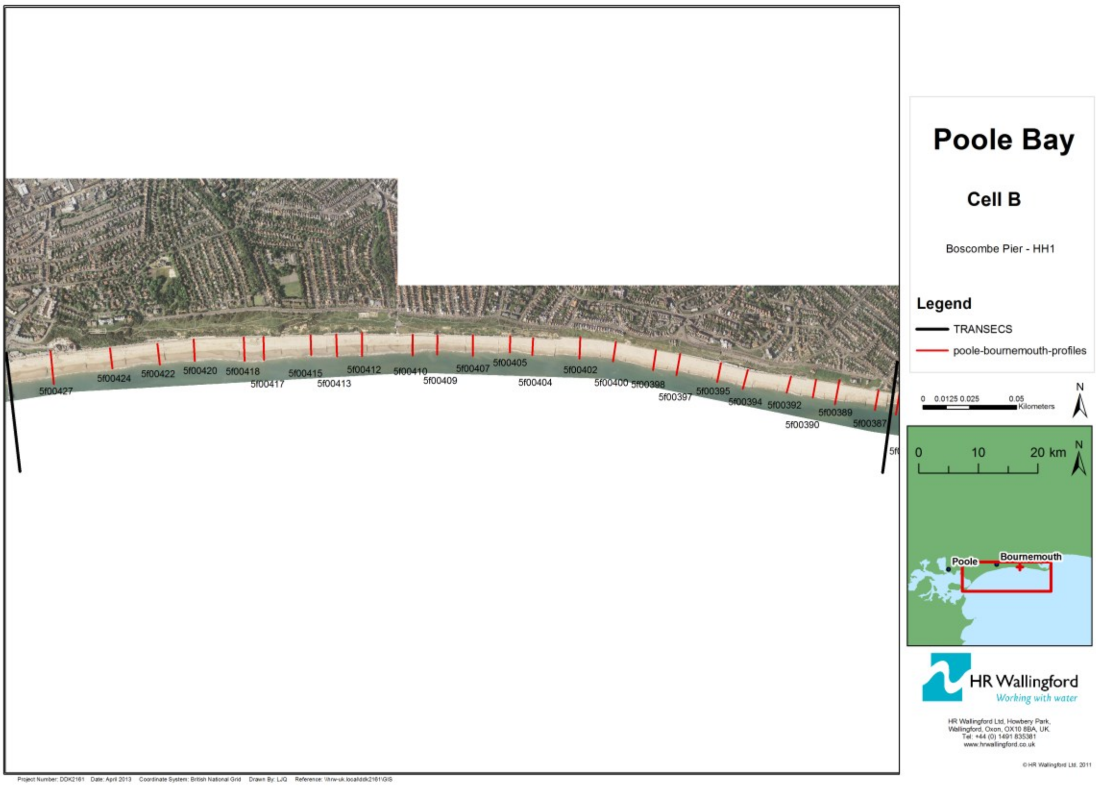
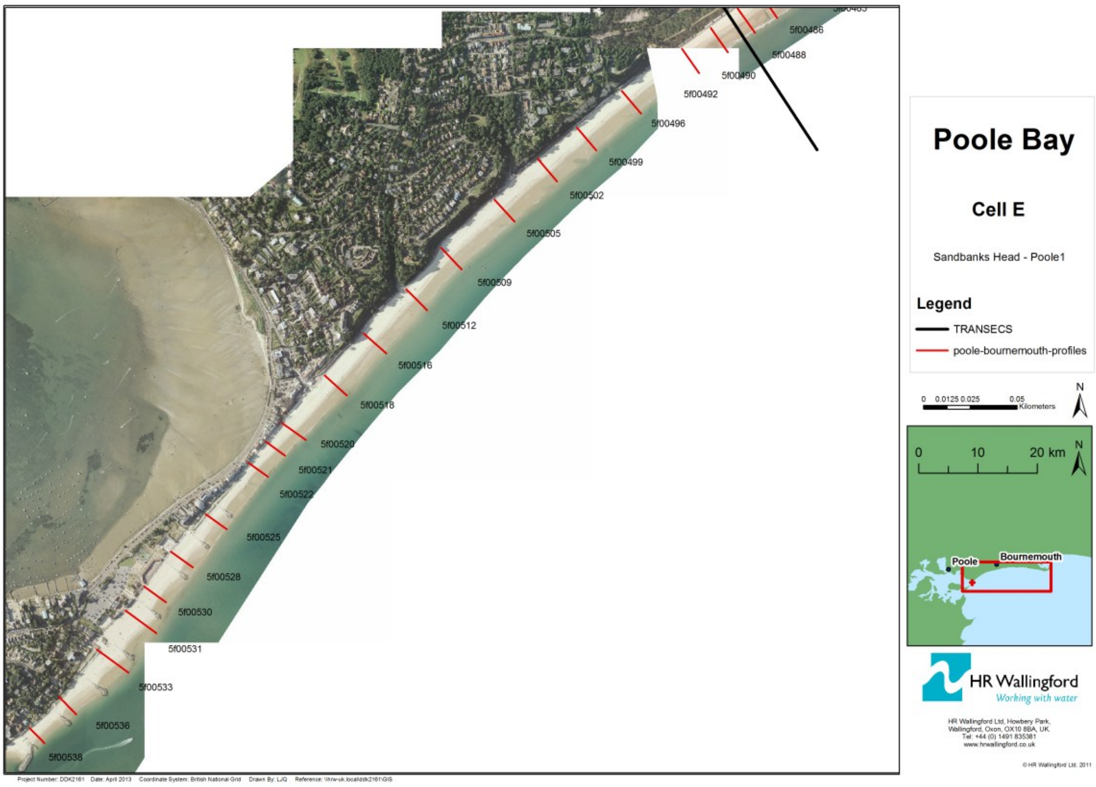
Appendix 3 Transects in the Sub-Divided Cells of Poole Bay






Poole Bay
Cell C
Bournemouth Pier - Boscombe Pier
Legend
TRANSECS
poole-bournemouth-profiles
5f00431
5f00434
5f00436
5f00438
5f00441
5f00444
5f00447
5f00450
5f00453
5f00456
0 10 20 km
Poole
Bournemouth
HR Wallingford
Working with water


Poole Bay
Cell D
Poole1 - Bournemouth Pier
Legend
TRANSECS
poole-bournemouth-profiles
5f00453
5f00456
5f00458
5f00461
5f00464
5f00467
5f00468
5f00470
5f00472
5f00473
5f00475
5f00476
5f00478
5f00480
5f00483
5f00486
5f00488
5f00490
0 10 20 km
Poole
Bournemouth
HR Wallingford
Working with water



5f00486
5f00488
5f00490
5f00492
5f00496
5f00499
5f00502
5f00505
5f00509
5f00512
5f00516
5f00518
5f00520
5f00521
5f00522
5f00525
5f00528
5f00530
5f00531
5f00533
5f00536
5f00538
Poole Bay
Cell E
Sandbanks Head - Poole1
Legend
TRANSECS
poole-bournemouth-profiles
0 0.0125 0.025 0.05 Kilometers
N
0 10 20 km
Poole
Bournemouth
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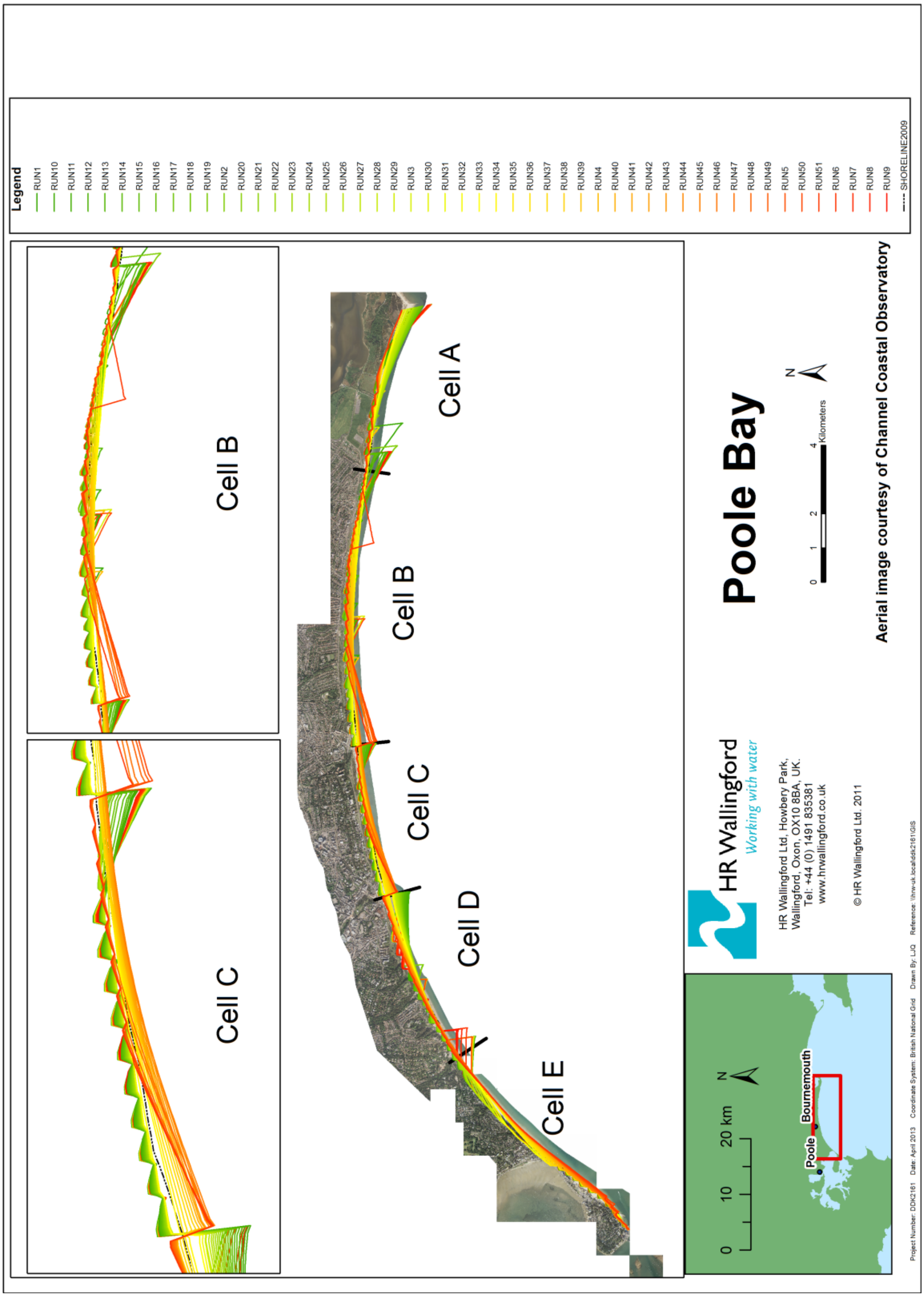
Appendix 4 Uncertainty Modelling of Shoreline Angle

Simple Case						
x [m]	y_{Min} [m]	y_{Max} [m]		x [m]	y_{Min} [m]	y_{Max} [m]
12.5	657.04	642.17		837.5	668.01	643.91
37.5	656.77	642.17		862.5	673.29	653.01
62.5	656.5	642.06		887.5	680.04	665.58
87.5	656.21	641.83		912.5	688.6	683.53
112.5	655.92	641.49		937.5	710.79	699.01
137.5	655.62	641.05		962.5	749.91	712.5
162.5	655.31	640.5		987.5	762.07	725
187.5	654.99	639.88		1012.5	741.29	711.04
212.5	654.67	639.16		1037.5	731.6	698.9
237.5	654.35	638.36		1062.5	723.49	689.13
262.5	654.04	637.49		1087.5	716.6	681.36
287.5	653.72	636.54		1112.5	710.8	675.23
312.5	653.41	635.53		1137.5	705.9	670.41
337.5	653.11	634.47		1162.5	701.64	666.62
362.5	652.81	633.37		1187.5	697.88	663.66
387.5	652.53	632.23		1248.72	689.62	657.94
412.5	652.27	631.07		1346.15	680.37	654.37
437.5	652.04	629.9		1443.59	673.65	653.31
462.5	651.83	628.75		1541.03	668.83	653.49
487.5	651.67	627.63		1638.46	665.5	654.19
512.5	651.57	626.56		1735.9	663.29	655.11
537.5	651.52	625.57		1833.33	661.9	656.08
562.5	651.55	624.69		1930.77	661.03	656.96
587.5	651.68	623.97		2028.21	660.53	657.71
612.5	652	623.46		2125.64	660.26	658.32
637.5	652.47	623.27		2223.08	660.12	658.79
662.5	653.05	623.37		2320.51	660.05	659.14
687.5	653.85	623.81		2417.95	660.02	659.4
712.5	654.93	624.77		2515.38	660.01	659.57
737.5	656.37	626.39		2612.82	660	659.69
762.5	658.26	628.84		2710.26	660	659.77
787.5	660.71	632.36		2807.69	659.99	659.8
812.5	663.9	637.24		2905.13	659.97	659.79



Legend
RUN1
RUN10
RUN11
RUN12
RUN13
RUN14
RUN15
RUN16
RUN17
RUN18
RUN19
RUN2
RUN20
RUN21
RUN22
RUN23
RUN24
RUN25
RUN26
RUN27
RUN28
RUN29
RUN3
RUN30
RUN31
RUN32
RUN33
RUN34
RUN35
RUN36
RUN37
RUN38
RUN39
RUN4
RUN40
RUN41
RUN42
RUN43
RUN44
RUN45
RUN46
RUN47
RUN48
RUN49
RUN5
RUN50
RUN51
RUN6
RUN7
RUN8
RUN9
SHORELINE2009
Cell B
Cell C
Cell A
Cell B
Cell C
Cell D
Cell E
Poole Bay
0 1 2 4 Kilometers
N
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0 10 20 km
N
Poole
Bournemouth
Project Number: DDK2161 Date: April 2013 Coordinate System: British National Grid Drawn By: LJQ

Poole Bay						
x [m]	y_{Min} [m]	y_{Max} [m]		x [m]	y_{Min} [m]	y_{Max} [m]
1995.65	3012.07	2540.76		3669.96	1744.74	1645.07
2029.39	2962.51	2521.6		3706.63	1729.61	1632.01
2063.13	2913.57	2502.44		3742.57	2120.68	1640.04
2097.04	2865.51	2480.47		3777.78	2070.49	1636.12
2131.11	2818.27	2455.99		3812.99	2033.13	1635.71
2165.19	2771.96	2431.7		3848.2	1995.67	1615.64
2199.26	2726.42	2407.6		3883.41	1958.75	1599.58
2233.33	2681.5	2382.84		3918.73	1922.4	1584.77
2267.41	2637.08	2356.64		3954.15	1886.49	1581.49
2301.48	2596.17	2332.06		3989.57	1851.01	1547.44
2335.56	2559.1	2309.66		4024.99	1815.86	1516.63
2369.63	2522.86	2288.59		4060.41	1780.98	1502.08
2403.7	2486.9	2266.01		4096.23	1926.47	1518.03
2437.78	2454.82	2244.65		4132.46	1879.45	1515.09
2471.85	2430.24	2230.17		4168.69	1844.06	1515.43
2505.93	2405.94	2214.25		4204.92	1808.74	1515.89
2540	2381.9	2193.45		4241.15	1774.07	1518.1
2574.07	2358.13	2171.21		4274.05	1743.04	1480.63
2608.15	2334.61	2148.98		4303.6	1715.5	1480.74
2642.22	2311.33	2127.37		4333.16	1688.21	1485.83
2676.3	2288.29	2104.36		4363.22	1660.65	1441.94
2710.37	2265.48	2083.35		4393.77	1632.78	1441.25
2744.44	2242.9	2064.76		4424.33	1611.11	1427.75
2778.52	2221	2046.65		4454.47	1590.26	1410.03
2812.59	2199.34	2024.29		4484.19	1569.87	1399.06
2846.67	2177.91	2000.85		4513.91	1549.65	1382.95
2880.74	2156.69	1980.01		4544.62	1528.91	1374.65
2914.81	2135.69	1959.44		4576.32	1513.17	1363.1
2948.89	2114.91	1939.16		4608.03	1512.36	1346.54
2982.96	2094.33	1926.61		4641.36	1511.44	1336.65
3019.59	2072.43	1906.6		4676.31	1510.4	1330.67
3058.78	2049.27	1886.8		4711.26	1509.26	1309.35
3097.97	2026.38	1867.6		4746.32	1508	1296.65
3137.15	2003.77	1855.45		4781.49	1506.59	1284.9
3176.34	2020.54	1848.98		4816.66	1504.99	1266.09
3213.41	1968.74	1847.76		4852.38	1503.09	1255.88
3248.35	1942.81	1840.16		4888.65	1500.78	1245.5
3283.3	1924.46	1831.16		4924.93	1498.14	1226.82
3318.25	1906.4	1802.53		4955.14	1496.12	1223.28
3353.2	1888.61	1788.52		4979.31	1495.44	1221.98
3387.77	1871.21	1769.77		5003.48	1504.2	1204.9
3421.96	1854.28	1763.48		5032.88	1258.89	1170.23
3456.14	1838.39	1736.91		5067.52	1239.98	1167.3
3490.33	1823.19	1707.81		5102.17	1224.03	1148.03
3524.52	1808	1697		5136.86	1212.15	1122.78
3559.95	1792.29	1717.1		5171.6	1200.31	1119.22
3596.62	1776.06	1711.45		5206.34	1188.55	1092.87
3633.29	1760.17	1676.47		5239.29	1177.45	1086.04

x [m]	y_{Min} [m]	y_{Max} [m]
5270.44	1167.04	1072.71
5301.6	1156.78	1056.19
5333.88	1146.29	1048.88
5367.28	1135.73	1035.04
5400.69	1125.22	1017.66
5431.82	1115.48	1008.07
5460.67	1106.49	1006.19
5489.53	1097.55	984.53
5522.53	1087.36	964.77
5559.69	1075.97	957.66
5596.84	1064.65	933.17
5633.94	1053.42	927.72
5670.98	1042.28	910.17
5708.02	1031.21	891.34
5743	1020.83	914.95
5775.93	1011.12	882.31
5808.87	1001.48	869.97
5840.49	992.27	888.24
5870.81	983.5	885.56
5901.13	974.79	866.82
5932.71	965.77	847.29
5965.55	956.46	845.51
5998.4	947.22	817.81
6031.24	938.05	792.67
6064.09	928.98	783.12
6095.65	1068.32	813.28
6125.91	1039.39	812.27
6156.18	1021.37	796.46
6186.44	1003.35	771.99
6216.71	985.35	762.12
6247.47	967.31	776.97
6278.72	949.35	773.52
6309.97	931.7	762.14
6341.22	914.3	742.75
6372.47	897.12	719.81
6403.72	880.12	699
6434.97	863.26	690.83
6466.22	974.35	688.27
6498.55	936.13	722.19
6531.97	909.96	717.12
6565.39	883.57	716
6598.81	857.16	699.26
6632.23	832.18	675.75
6665.65	811.58	667.44
6697.83	848.26	675.45
6728.77	812.42	672.56
6759.71	788.64	652.86
6790.65	764.32	630.02
6821.59	785.4	610.61

x [m]	y_{Min} [m]	y_{Max} [m]
6852.53	751.09	606.56
6883.18	748.37	637.79
6913.54	746.27	636.24
6943.89	744.19	625.44
6974.25	776.25	605.42
7004.61	819.53	587.12
7034.96	782.67	572.38
7065.32	798.96	571.8
7096.52	765.58	611.33
7128.56	743.99	611.3
7160.59	730.92	596.55
7192.63	729.34	576.61
7224.67	727.88	558.34
7256.71	726.57	553.7
7290.11	725.35	600.42
7324.87	724.27	572.84
7359.62	723.37	547.24
7394.38	722.68	523.31
7429.14	722.41	503.16
7463.9	724.36	499.19
7498.74	726.4	563.86
7533.67	728.6	533.88
7568.6	731.03	510.47
7603.53	733.51	503.38
7636.42	735.85	554.16
7667.26	738.09	527.99
7698.11	740.38	508.31
7728.95	742.72	488.82
7759.8	745.12	471.25
7790.65	747.57	468.95
7821.41	750.06	538.19
7852.09	752.59	512.91
7882.77	755.17	495.03
7913.45	757.78	475.58
7944.12	760.44	457.83
7974.8	763.13	454.91
8005.67	765.87	521.87
8036.74	768.67	499.26
8067.8	771.51	480.96
8098.86	774.38	460.3
8129.92	777.29	442.19
8160.98	780.21	438.8
8192.43	783.17	510.55
8224.25	786.14	490.06
8256.08	789.02	469.4
8287.9	791.82	448.23
8319.73	795.07	441.15
8351.56	809.51	438.3
8383.59	774.92	482.15

x [m]	y_{Min} [m]	y_{Max} [m]
8415.83	751.74	474.48
8448.07	728.4	476.98
8480.31	705.29	479.35
8512.56	682.59	483.21
8545.12	659.99	462.46
8578.01	638.21	462.48
8610.89	618.6	464.69
8643.78	599.11	467.34
8676.67	579.86	472.45
8709.21	561	448.24
8741.4	542.81	448.24
8773.59	525.6	451.09
8805.79	508.57	448.94
8837.98	491.39	440.69
8870.56	484.91	432.68
8903.51	481.29	429.31
8936.46	479.35	407.04
8969.41	477.81	385.57
9002.36	476.47	377.77
9033.97	474.81	416.96
9064.23	473.91	417.36
9094.49	473.22	399.69
9124.75	472.73	380.32
9155.01	472.4	362.89
9185.27	472.25	359.1
9218.18	471.94	407.37
9253.73	472.21	410.98
9289.28	472.75	390.6
9324.84	473.54	369.55
9360.39	474.56	362.64
9396.01	475.74	398.62
9431.69	477.26	403.48
9467.38	479.03	388.09
9503.06	481.05	367.42
9538.75	483.31	360.86
9574.58	485.82	392.27
9610.56	488.59	397.48
9646.55	491.6	384.61
9682.53	494.86	364.2
9718.51	498.37	357.77
9754.22	502.08	403.34
9789.64	505.98	401.93
9825.06	510.08	382.04
9860.48	514.51	363.51
9895.89	519.18	359.06
9931.26	523.98	424.46
9966.58	528.92	401.43
10001.9	534.12	382.61
10037.22	540.27	364.62

x [m]	y_{Min} [m]	y_{Max} [m]
10072.54	546.5	360.27
10107.51	552.76	423.85
10142.13	559.04	403.32
10176.75	565.38	385.83
10211.37	571.78	368.87
10246	578.22	365.2
10281.03	585.52	431.8
10316.47	594.2	413.84
10351.91	602.81	397
10387.35	611.36	380.35
10422.8	619.82	376.92
10456.69	627.79	443.37
10489.03	635.27	429.41
10521.38	642.56	414.7
10553.72	649.6	399.54
10586.07	656.3	385.93
10618.41	665.06	374.65
10650.76	684.65	375.29
10683.56	781.33	427.87
10716.83	760.23	426.82
10750.1	748.48	434.62
10783.37	737.24	442.24
10817.35	726.72	447.81
10852.06	716.98	451.81
10886.77	708.14	456.51
10921.47	700.06	461.9
10954.72	692.87	447.26
10986.51	686.41	452.62
11018.29	680.65	462.41
11050.08	676.28	471.61
11081.87	672.31	480.62
11113.65	668.71	489.61
11145.44	665.43	496.25
11177.56	663.23	464.04
11210.01	661.64	469.31
11242.46	660.4	480.08
11274.9	659.5	469.38
11307.35	658.92	457.79
11339.8	658.64	448.74
11372.25	658.65	452.12
11403.6	658.94	495.26
11433.85	659.44	502.17
11464.1	660.18	504.34
11494.35	661.13	494.18
11524.61	662.3	485.45
11554.86	663.68	478.77
11585.11	665.27	482.83
11616.32	667.12	541.6
11648.49	669.45	552.09

x [m]	y_{Min} [m]	y_{Max} [m]	x [m]	y_{Min} [m]	y_{Max} [m]
11680.66	672.07	551.37	13269.3	1248.23	1067.5
11712.83	675.2	538.23	13300.96	1245.58	1073.79
11745	678.69	526.82	13332.58	1243.3	1084.5
11777.17	682.74	519.13	13364.17	1241.31	1087.97
11809.35	686.95	525.93	13395.76	1239.53	1090.27
11841.16	691.25	600.99	13427.35	1241.67	1091.71
11872.62	695.65	605.73	13458.94	1244.88	1093.9
11904.09	700.17	596.41	13490.39	1248.01	1123.95
11935.55	704.83	587.71	13521.71	1250.84	1120.29
11967.01	709.61	580.69	13553.02	1253.23	1118.2
11998.48	714.64	582.67	13584.34	1260.29	1117.11
12030.76	877.48	646.86	13616.67	1277.26	1119.49
12063.88	852.06	658.08	13650	1294.95	1130.86
12097	836.6	647.78	13683.33	1312.8	1148.04
12130.11	822.01	637.26	13716.67	1330.87	1164.34
12163.23	809.74	638.32	13750	1349.14	1182.14
12196.85	797.69	697.01	13783.33	1367.6	1199.87
12230.99	785.74	693.62	13816.67	1386.24	1218.15
12265.12	774.19	683.84	13850	1405.05	1236.27
12299.26	771.08	685.75	13883.33	1424.06	1253.09
12334.11	783.88	741.27	13916.67	1443.27	1271.67
12369.68	787.73	728.61	13950	1462.69	1290.1
12405.26	796.52	725.57	13983.33	1482.32	1308.2
12440.29	806.66	771.83	14016.67	1502.18	1328.97
12474.77	815.7	762.8	14050	1522.27	1350.61
12509.25	825.24	760.16	14083.33	1542.6	1370.48
12544.22	836.07	802.93	14116.67	1563.18	1390.16
12579.69	846.23	791.96	14150	1584.01	1413.23
12615.15	856.67	781.49	14183.33	1605.1	1434.69
12650.62	867.51	773.47	14216.67	1626.45	1453.99
12686.09	878.9	778.2	14250	1648.05	1475.36
12719.01	1131.61	864.28	14283.33	1669.92	1495.25
12749.37	1115.74	871.11	14316.67	1692.02	1516.14
12779.74	1110.06	864.04	14350	1830.84	1537.63
12810.1	1105.02	854.44	14383.33	1819.09	1557.91
12840.47	1100.86	856.49	14416.67	1931.28	1588.58
12870.67	1270.6	918.06	14450	1918.83	1615.02
12900.7	1254.36	928.47	14483.33	1915.72	1637.3
12930.74	1248.19	919.71	14516.67	1913.16	1657.66
12960.77	1242.55	911.19	14550	1911.46	1679.51
12990.81	1237.66	914.55	14583.33	1910.57	1701.15
13021.09	1299.06	975.43	14616.67	1913.71	1724.02
13051.63	1282.06	990.38	14650	1941.2	1746.33
13082.17	1275.6	1005.38	14683.33	1969.23	1774.51
13112.7	1269.5	1020.15	14716.67	1997.82	1805.97
13143.24	1263.99	1035.24	14750	2026.98	1833.01
13174.34	1259.14	1049.55	14783.33	2056.43	1856.23
13205.99	1254.92	1057.05	14816.67	2085.14	1879.43
13237.65	1251.32	1062.18	14850	2113.35	1901.93

x [m]	y_{Min} [m]	y_{Max} [m]
14883.33	2140.91	1925.45
14916.67	2167.78	1949.27
14950	2193.82	1974.79
14983.33	2219.02	2002.73
15017.23	2245.25	2031.26
15051.68	2271.96	2060.59
15086.13	2298.75	2089.86
15120.58	2325.64	2119.12
15155.03	2352.62	2148.38
15186.87	2377.66	2263.29
15216.1	2400.71	2250.12
15245.32	2423.86	2254.87
15276.07	2448.29	2362.48
15308.33	2474.06	2349
15340.59	2499.94	2352.57
15372.47	2525.64	2452
15403.96	2551.14	2438.45
15435.45	2576.72	2441.35
15470.17	2604.99	2542.16
15508.11	2635.92	2527.05
15546.06	2666.81	2529.44
15584.38	2698.14	2656.86
15623.09	2729.44	2640.83
15661.79	2760.34	2642.68
15699.71	2789.61	2776.18
15736.86	2818.73	2763.99
15774	2850.2	2765.65
15809.93	2887.34	2841.51
15844.64	2895.89	2864.04
15879.36	2908.45	2857.57
15914.08	2921.37	2859.97
15947.19	2968.28	2915.67
15978.69	2975.53	2937.95
16010.19	2985.13	2942.98
16041.69	2995.54	2945.69
16074.64	3033.19	2962.41
16109.05	3041.59	2979.19
16143.46	3052.42	3005.15
16177.88	3063.22	3009.16
16208.82	3072.8	3054.4
16236.29	3083.85	3053.15
16263.77	3105.22	3054.79
16293.76	3132.29	3080.07
16326.25	3139.58	3098.98
16358.75	3151.75	3108.33
16391.25	3164.86	3103.64

Appendix 5 Statistics of Error Analysis

Correlation coefficients for absolute shoreline positions (relative to baseline x-axis)						
Shoreline Angle	FULL	CELL A	CELL B	CELL C	CELL D	CELL E
250°	0.997405	0.999053	0.996785	0.769964	0.991777	0.998005
251°	0.99753	0.999046	0.996141	0.778887	0.992668	0.997763
252°	0.9977	0.999152	0.995683	0.792297	0.993579	0.997584
253°	0.997866	0.99924	0.995477	0.803473	0.994471	0.9974
254°	0.998054	0.999257	0.995286	0.802256	0.995179	0.997313
255°	0.998246	0.999094	0.995182	0.792529	0.996089	0.997154
256°	0.99845	0.998885	0.995392	0.782114	0.996866	0.997022
257°	0.998668	0.998656	0.9953	0.776276	0.99765	0.997112
258°	0.998851	0.998426	0.995266	0.761647	0.998235	0.997211
259°	0.999022	0.998245	0.995528	0.778531	0.998576	0.997294
260°	0.999131	0.998238	0.995986	0.83445	0.998689	0.997446
261°	0.999139	0.998577	0.996367	0.846401	0.998613	0.997631
262°	0.999132	0.999068	0.996678	0.746646	0.998371	0.997814
263°	0.999119	0.999484	0.996746	0.60517	0.997987	0.998045
264°	0.999122	0.999612	0.996975	0.531851	0.997473	0.998389
265°	0.99909	0.999574	0.997217	0.457648	0.996845	0.998759
266°	0.999016	0.99951	0.997551	0.372389	0.996052	0.999017
267°	0.998931	0.999436	0.99811	0.338118	0.995687	0.999239
268°	0.998836	0.999351	0.998356	0.294034	0.996248	0.99935
269°	0.998737	0.999336	0.998418	0.26524	0.997047	0.999397
270°	0.998589	0.999335	0.998017	0.25188	0.997811	0.999395

Correlation coefficients for absolute shoreline positions (relative to seawall)						
Shoreline Angle	FULL	CELL A	CELL B	CELL C	CELL D	CELL E
250°	0.166	-0.304	0.626	-0.291	0.049	0.531
251°	0.164	-0.311	0.561	-0.289	0.054	0.523
252°	0.166	-0.274	0.521	-0.302	0.060	0.519
253°	0.169	-0.225	0.499	-0.324	0.065	0.515
254°	0.171	-0.160	0.478	-0.353	0.073	0.512
255°	0.174	-0.140	0.467	-0.373	0.081	0.506
256°	0.177	-0.053	0.470	-0.382	0.092	0.500
257°	0.183	0.023	0.453	-0.351	0.096	0.500
258°	0.186	0.082	0.424	-0.371	0.094	0.502
259°	0.186	0.133	0.382	-0.432	0.093	0.497
260°	0.186	0.203	0.302	-0.334	0.088	0.495
261°	0.187	0.276	0.239	-0.003	0.081	0.500
262°	0.186	0.358	0.138	0.235	0.070	0.511
263°	0.186	0.444	0.056	0.303	0.055	0.526
264°	0.165	0.464	-0.118	0.329	0.033	0.549
265°	0.144	0.473	-0.262	0.352	0.007	0.576
266°	0.123	0.471	-0.374	0.363	-0.043	0.591
267°	0.097	0.464	-0.514	0.373	-0.028	0.599
268°	0.085	0.457	-0.584	0.381	0.062	0.589
269°	0.082	0.458	-0.601	0.381	0.162	0.564
270°	0.078	0.466	-0.587	0.380	0.254	0.523

Correlation coefficients for shoreline variation (relative to initial shoreline)						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250°	-0.063	0.119	-0.386	0.084	0.426	-0.421
251°	-0.060	0.104	-0.378	0.100	0.421	-0.414
252°	-0.054	0.102	-0.377	0.130	0.417	-0.404
253°	-0.045	0.091	-0.371	0.161	0.415	-0.396
254°	-0.035	0.069	-0.368	0.188	0.415	-0.392
255°	-0.026	-0.015	-0.360	0.204	0.414	-0.390
256°	-0.015	-0.151	-0.350	0.218	0.411	-0.389
257°	-0.006	-0.247	-0.334	0.208	0.404	-0.384
258°	0.004	-0.297	-0.311	0.154	0.391	-0.373
259°	0.021	-0.302	-0.271	0.122	0.370	-0.355
260°	0.049	-0.294	-0.187	0.092	0.336	-0.334
261°	0.078	-0.247	-0.115	0.050	0.284	-0.309
262°	0.109	-0.201	-0.027	-0.018	0.196	-0.269
263°	0.141	-0.161	0.068	-0.036	0.082	-0.212
264°	0.178	-0.158	0.202	-0.022	-0.050	-0.134
265°	0.206	-0.177	0.296	-0.020	-0.169	-0.032
266°	0.225	-0.182	0.376	-0.024	-0.247	0.066
267°	0.247	-0.182	0.462	-0.021	-0.307	0.203
268°	0.262	-0.185	0.504	-0.025	-0.316	0.322
269°	0.273	-0.174	0.525	-0.027	-0.307	0.434
270°	0.277	-0.160	0.528	-0.028	-0.310	0.531

	Transects														
	FULL			Cell A			Cell B			Cell C			Cell D			Cell E		
Shoreline Angle (^{0})	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
250	39.59	138.1	0	33.17	57.1	1.9	24.68	53.2	0	32.38	74.1	18.6	43.59	138.1	1.7	60.29	118.2	3.6
251	38.45	131	0.5	31.49	53.8	0.7	25.18	50.7	0.5	32.16	71.4	18.5	41.78	131	1.3	57.81	120.7	3.5
252	36.65	122	0	28.53	47.8	0.8	25.69	53	0	31.14	68.7	13.9	39.61	122	0.7	54.25	111.9	3
253	34.99	114.2	0.2	25.24	42.4	0.6	25.78	56	0.4	30.23	67.7	6.8	37.47	113.5	0.2	51.84	114.2	2.5
254	32.77	112.3	0	20.13	36.3	2.2	25.56	58.1	0.2	30	69.1	4.6	35.52	106.9	0	48.37	112.3	1.9
255	30.63	115.3	0	14.24	31	2.9	25.47	58.9	0	28.84	70.6	7	33.23	97.9	0.3	46.26	115.3	0
256	28.94	115.6	0.5	11.75	26	1	24.84	59.3	1.1	26.51	70.6	2.3	30.58	87.1	0.5	44.92	115.6	1
257	27.68	116.2	0	13.44	35.5	2.7	25.37	59.7	0	23.79	65.4	2.9	27.63	74.5	0.6	41.56	116.2	0
258	26.86	115.9	0	16.78	56.7	1.7	26.5	60.6	0.6	19.69	60.7	0	24.73	60.2	0	38.59	115.9	0.7
259	25.89	115.9	0	21.87	79.6	3.6	27.14	60.5	0	12.76	48.3	0	21.78	54.6	0	35.65	115.9	0
260	26.16	105.4	0	28.83	102.2	0	29.4	60.6	1.5	9.02	31.1	1	18.85	49.8	0	33.13	105.4	0
261	27.58	119.6	0	39.24	119.6	6.8	32.52	62.6	2	8.01	19.2	0.5	16.03	45	0.5	30.63	102.5	0
262	28.97	121.3	0	48.13	121.3	11.1	35.76	62.2	5.1	8.54	31.7	0	12.98	39.8	0.9	28.5	102.5	1.9
263	30.16	121.7	0	54.21	121.7	15.2	37.7	62.1	5.8	13.26	44	0	10.62	34.9	0	26.67	99.8	1.7
264	30.83	122.7	0	57.47	122.7	16.5	38.53	61.1	9.9	17.61	55.7	0.8	10.76	31.4	1.3	24.28	93	0
265	31.3	122.9	0	59.41	122.9	18.4	39.05	58.6	4.8	22.57	67.4	0	11.06	32.1	0.8	21.99	78.7	0.7
266	31.56	124.2	0	60.54	124.2	19.8	38.69	55	2.6	27.72	78.8	1.2	11.78	46.8	0	19.98	63.1	0
267	32.19	124.2	0	61.66	124.2	21.7	38.34	52.3	8.4	35.14	89.5	6.8	12.18	59	0	18.73	44.1	2.3
268	32.42	124.2	0	62.47	124.2	23.2	37.45	53.9	9.1	40.8	98.3	10.4	11.44	55.7	0	18.26	42.5	1.9
269	32.55	124.2	0	63.23	124.2	23.4	36.98	56.3	6.7	45.48	106.5	12.2	9.975	48.3	0	17.94	41.4	1.3
270	33.1	124.2	0	63.98	124.2	23.9	36.24	57.4	1.9	51.36	115.3	16.2	8.788	44.1	0	18.85	40	1

MAE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250°	40.22	30.06	28.14	33.42	53.88	61.73
251°	39.33	28.83	28.69	33.41	51.42	59.45
252°	38.02	26.54	28.77	33.20	48.70	56.85
253°	36.63	23.87	28.58	32.82	46.08	54.66
254°	34.99	19.79	28.30	32.52	43.57	51.97
255°	33.14	15.06	28.11	30.74	40.62	50.57
256°	31.30	13.59	27.27	27.74	37.51	49.50
257°	29.56	14.27	27.45	23.73	33.99	46.90
258°	28.07	16.15	28.18	18.82	30.56	44.67
259°	26.33	18.89	28.73	12.57	26.94	42.21
260°	25.88	23.97	30.63	9.18	23.45	40.06
261°	26.83	32.52	33.79	8.47	20.07	38.22
262°	28.12	40.65	37.08	10.06	16.41	36.46
263°	29.67	47.83	39.39	14.74	13.46	34.70
264°	30.97	51.86	40.45	19.64	13.15	32.48
265°	32.14	53.91	41.20	24.77	13.52	30.48
266°	33.10	54.95	41.31	29.89	14.24	28.78
267°	34.09	56.06	40.60	37.21	14.37	27.25
268°	34.86	56.79	40.00	43.09	14.12	26.64
269°	35.35	57.56	39.33	47.80	13.33	26.34
270°	36.32	58.35	38.82	54.07	12.81	26.73

Bias						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250°	3.29	-21.91	8.65	25.54	-45.66	58.87
251°	1.70	-21.29	4.05	25.49	-44.84	56.46
252°	0.29	-19.25	-0.40	24.64	-43.38	53.72
253°	-0.83	-17.06	-4.14	23.28	-41.62	51.40
254°	-1.88	-12.39	-8.07	21.13	-39.74	48.58
255°	-2.51	-7.04	-11.41	18.24	-37.27	46.71
256°	-3.13	-2.48	-14.38	14.66	-34.51	45.11
257°	-3.85	2.39	-16.52	9.54	-31.24	41.85
258°	-4.47	8.45	-19.41	5.29	-28.04	38.99
259°	-4.92	15.25	-21.65	0.22	-24.61	35.86
260°	-5.22	23.48	-25.54	-2.04	-21.27	32.89
261°	-5.24	32.52	-29.82	-2.98	-18.00	30.41
262°	-5.06	40.65	-32.16	-6.07	-14.45	28.09
263°	-4.70	47.83	-32.39	-11.21	-11.05	25.81
264°	-4.50	51.86	-30.85	-17.80	-7.56	22.94
265°	-4.27	53.91	-28.55	-24.26	-3.89	19.91
266°	-3.99	54.95	-26.15	-29.57	-0.74	17.32
267°	-3.66	56.06	-22.40	-37.21	2.76	14.35
268°	-3.39	56.79	-19.15	-43.09	5.16	11.91
269°	-3.02	57.56	-15.85	-47.80	6.87	9.62
270°	-2.68	58.35	-11.80	-54.07	8.97	6.83

RMSE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250^{o}	53.16	37.62	32.58	36.87	71.28	77.91
251^{o}	51.84	35.89	33.25	36.69	68.31	76.17
252^{o}	50.11	32.74	33.69	36.37	64.87	73.93
253^{o}	48.42	29.11	33.75	35.95	61.40	72.31
254^{o}	46.57	23.35	33.95	35.96	58.09	69.87
255^{o}	44.72	17.82	34.23	34.46	53.94	68.75
256^{o}	42.75	15.70	33.66	31.85	49.53	67.87
257^{o}	40.48	17.39	34.26	28.47	44.42	64.61
258^{o}	38.73	22.75	35.23	24.27	39.40	61.76
259^{o}	37.15	30.44	35.42	18.62	34.30	59.05
260^{o}	36.62	39.84	36.62	12.76	29.59	56.09
261^{o}	37.59	49.59	39.34	11.07	25.35	53.27
262^{o}	38.67	56.49	41.55	14.57	21.33	50.63
263^{o}	39.67	61.27	42.86	20.94	18.44	47.76
264^{o}	40.19	63.71	43.39	27.73	16.88	43.68
265^{o}	40.80	65.15	43.46	34.93	17.13	39.27
266^{o}	41.73	65.95	43.06	42.04	19.21	35.94
267^{o}	42.79	66.73	42.08	49.41	21.37	32.80
268^{o}	43.93	67.28	41.63	55.76	21.39	31.26
269^{o}	45.05	67.86	41.39	61.06	20.54	30.79
270^{o}	46.60	68.50	41.26	67.15	20.21	30.90
NMSE						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250^{o}	0.922	0.500	0.388	0.531	1.675	1.326
251^{o}	0.876	0.455	0.405	0.525	1.538	1.267
252^{o}	0.819	0.379	0.415	0.516	1.387	1.194
253^{o}	0.765	0.299	0.417	0.504	1.243	1.142
254^{o}	0.707	0.193	0.422	0.505	1.112	1.066
255^{o}	0.652	0.112	0.429	0.464	0.959	1.032
256^{o}	0.596	0.087	0.415	0.396	0.808	1.006
257^{o}	0.534	0.107	0.430	0.317	0.650	0.912
258^{o}	0.489	0.183	0.454	0.230	0.512	0.833
259^{o}	0.450	0.327	0.459	0.135	0.388	0.762
260^{o}	0.437	0.561	0.491	0.064	0.289	0.687
261^{o}	0.461	0.869	0.566	0.048	0.212	0.620
262^{o}	0.488	1.128	0.632	0.083	0.150	0.560
263^{o}	0.513	1.327	0.672	0.171	0.112	0.498
264^{o}	0.527	1.434	0.689	0.300	0.094	0.417
265^{o}	0.543	1.500	0.691	0.476	0.097	0.337
266^{o}	0.568	1.537	0.678	0.690	0.122	0.282
267^{o}	0.597	1.573	0.648	0.953	0.150	0.235
268^{o}	0.629	1.599	0.634	1.214	0.151	0.213
269^{o}	0.662	1.627	0.627	1.456	0.139	0.207
270^{o}	0.708	1.658	0.623	1.760	0.135	0.209

BSS						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250°	0.078	0.5	0.612	0.469	-0.675	-0.326
251°	0.124	0.545	0.595	0.475	-0.538	-0.267
252°	0.181	0.621	0.585	0.484	-0.387	-0.194
253°	0.235	0.701	0.583	0.496	-0.243	-0.142
254°	0.293	0.807	0.578	0.495	-0.112	-0.066
255°	0.348	0.888	0.571	0.536	0.041	-0.032
256°	0.404	0.913	0.585	0.604	0.192	-0.006
257°	0.466	0.893	0.57	0.683	0.35	0.088
258°	0.511	0.817	0.546	0.77	0.488	0.167
259°	0.55	0.673	0.541	0.865	0.612	0.238
260°	0.563	0.439	0.509	0.936	0.711	0.313
261°	0.539	0.131	0.434	0.952	0.788	0.38
262°	0.512	-0.128	0.368	0.917	0.85	0.44
263°	0.487	-0.327	0.328	0.829	0.888	0.502
264°	0.473	-0.434	0.311	0.7	0.906	0.583
265°	0.457	-0.5	0.309	0.524	0.903	0.663
266°	0.432	-0.537	0.322	0.31	0.878	0.718
267°	0.403	-0.573	0.352	0.047	0.85	0.765
268°	0.371	-0.599	0.366	-0.214	0.849	0.787
269°	0.338	-0.627	0.373	-0.456	0.861	0.793
270°	0.292	-0.658	0.377	-0.76	0.865	0.791

Distortion Length						
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**
250°	45.44	47.81	32.96	45.22	68.45	71.6
251°	39.33	42.93	33.34	44.44	64.78	71.11
252°	34.68	37.67	32.28	43.28	61.06	66.79
253°	31.76	33.36	29.67	41.47	57.66	61.83
254°	30.71	28.51	30.4	39.73	54.73	58.97
255°	31.18	24.96	31.47	37.76	51.41	57.18
256°	31.39	22.22	30.78	35.88	48.22	56.02
257°	30.58	20.58	29.66	32.4	44.11	53.7
258°	29.49	21.11	29.25	26.93	39.94	48.16
259°	28.42	23.42	31.2	22.41	35.46	43.39
260°	27.43	27.18	33.08	18.42	31.11	39.87
261°	27.32	32.56	34.83	15.73	27.01	37.32
262°	27.51	39.62	35.87	15.09	22.97	34.71
263°	31.12	44.59	37.19	18.27	20.57	32.25
264°	36.52	48.35	39.08	23.88	20.15	29.99
265°	40.46	50.79	42.15	30.19	21.06	28.04
266°	44.51	52.25	45.69	36.11	22.97	26.35
267°	47.78	53.77	45.98	43.18	24.34	27.44
268°	50.9	54.83	45.64	49.13	24.09	29.41
269°	53.96	55.64	44.22	54.07	23.15	31.01
270°	56.57	56.54	42.09	60.37	23.23	31.78

Appendix 6 Scores of Model Assessment from MPRS

Correlation Coefficient for shoreline position (relative to the position of seawall)							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	2	0	4	0	1	4	11
251°	2	0	3	0	1	4	10
252°	2	0	3	0	1	4	10
253°	2	0	3	0	1	4	10
254°	2	0	3	0	1	4	10
255°	2	0	3	0	1	4	10
256°	2	0	3	0	1	4	10
257°	2	1	3	0	1	4	11
258°	2	1	3	0	1	4	11
259°	2	2	3	0	1	4	12
260°	2	2	3	0	1	4	12
261°	2	2	2	0	1	4	11
262°	2	3	2	2	1	4	14
263°	2	3	1	3	1	4	14
264°	2	3	0	3	1	4	13
265°	2	3	0	3	1	4	13
266°	2	3	0	3	0	4	12
267°	1	3	0	3	0	4	11
268°	1	3	0	3	1	4	12
269°	1	3	0	3	2	4	13
270°	1	3	0	3	2	4	13
Correlation Coefficient for shoreline variation (relative to shoreline observation in 2009)							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	0	2	0	1	3	0	6
251°	0	2	0	1	3	0	6
252°	0	2	0	2	3	0	7
253°	0	1	0	2	3	0	6
254°	0	1	0	2	3	0	6
255°	0	0	0	2	3	0	5
256°	0	0	0	2	3	0	5
257°	0	0	0	2	3	0	5
258°	1	0	0	2	3	0	6
259°	1	0	0	2	3	0	6
260°	1	0	0	1	3	0	5
261°	1	0	0	1	2	0	4
262°	2	0	0	0	2	0	4
263°	2	0	1	0	1	0	4
264°	2	0	2	0	0	0	4
265°	2	0	2	0	0	0	4
266°	2	0	3	0	0	1	6
267°	2	0	3	0	0	2	7
268°	2	0	3	0	0	3	8
269°	2	0	3	0	0	3	8
270°	2	0	3	0	0	3	8

Transects							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	1	2	3	2	0	0	8
251°	1	2	3	2	0	0	8
252°	1	3	3	2	1	0	10
253°	2	3	3	2	1	0	11
254°	2	3	3	2	1	0	11
255°	2	4	3	3	2	0	14
256°	3	4	3	3	2	0	15
257°	3	4	3	3	3	0	16
258°	3	4	3	4	3	1	18
259°	3	3	3	4	3	1	17
260°	3	3	3	5	4	2	20
261°	3	1	2	5	4	2	17
262°	3	0	1	5	4	3	16
263°	2	0	1	4	4	3	14
264°	2	0	1	4	4	3	14
265°	2	0	1	3	4	3	13
266°	2	0	1	3	4	4	14
267°	2	0	1	1	4	4	12
268°	2	0	1	0	4	4	11
269°	2	0	1	0	5	4	12
270°	2	0	1	0	5	4	12

MAE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	0	2	3	2	0	0	7
251°	1	3	3	2	0	0	9
252°	1	3	3	2	0	0	9
253°	1	3	3	2	0	0	9
254°	2	4	3	2	0	0	11
255°	2	4	3	2	0	0	11
256°	2	4	3	3	1	0	13
257°	3	4	3	3	2	0	15
258°	3	4	3	4	2	0	16
259°	3	4	3	4	3	0	17
260°	3	3	2	5	3	0	16
261°	3	2	2	5	3	1	16
262°	3	0	1	4	4	1	13
263°	3	0	1	4	4	1	13
264°	2	0	0	4	4	1	11
265°	2	0	0	3	4	1	10
266°	2	0	0	3	4	2	11
267°	2	0	0	1	4	2	9
268°	2	0	0	0	4	2	8
269°	1	0	1	0	4	2	8
270°	1	0	1	0	4	2	8

RMSE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	0	2	2	2	0	0	6
251°	0	2	2	2	0	0	6
252°	0	2	2	2	0	0	6
253°	1	3	2	2	0	0	8
254°	1	3	2	2	0	0	8
255°	1	4	2	2	0	0	9
256°	1	4	2	2	1	0	10
257°	1	4	2	3	1	0	11
258°	2	3	2	3	2	0	12
259°	2	2	2	4	2	0	12
260°	2	2	2	4	3	0	13
261°	2	1	2	4	3	0	12
262°	2	0	1	4	3	0	10
263°	2	0	1	3	4	1	11
264°	1	0	1	3	4	1	10
265°	1	0	1	2	4	2	10
266°	1	0	1	1	4	2	9
267°	1	0	1	1	3	2	8
268°	1	0	1	0	3	2	7
269°	1	0	1	0	3	2	7
270°	1	0	1	0	3	2	7

NMSE							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	2	4	4	4	1	1	16
251°	2	4	4	4	1	1	16
252°	2	4	4	4	1	1	16
253°	3	5	4	4	1	1	18
254°	3	5	4	4	1	1	18
255°	3	5	4	4	2	1	19
256°	4	5	4	4	2	1	20
257°	4	5	4	4	3	2	22
258°	4	5	4	5	4	2	24
259°	4	4	4	5	4	3	24
260°	4	4	4	5	5	3	25
261°	4	2	4	5	5	3	23
262°	4	1	3	5	5	4	22
263°	4	1	3	5	5	4	22
264°	4	1	3	4	5	4	21
265°	4	1	3	4	5	4	21
266°	4	1	3	3	5	5	21
267°	4	1	3	2	5	5	20
268°	3	1	3	1	5	5	18
269°	3	1	3	1	5	5	18
270°	3	1	3	1	5	5	18

BSS							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	1	3	3	2	0	0	9
251°	1	3	3	2	0	0	9
252°	1	3	3	2	0	0	9
253°	1	4	3	2	0	0	10
254°	1	4	3	2	0	0	10
255°	2	4	3	3	1	0	13
256°	2	5	3	3	1	0	14
257°	2	4	3	3	2	1	15
258°	3	4	3	4	2	1	17
259°	3	3	3	4	3	1	17
260°	3	2	3	5	4	2	19
261°	3	1	2	5	4	2	17
262°	3	0	2	5	4	2	16
263°	2	0	2	4	4	3	15
264°	2	0	2	4	5	3	16
265°	2	0	2	3	5	3	15
266°	2	0	2	2	4	4	14
267°	2	0	2	1	4	4	13
268°	2	0	2	0	4	4	12
269°	2	0	2	0	4	4	12
270°	1	0	2	0	4	4	11

Distortion Length							
Shoreline Angle	**FULL**	**CELL A**	**CELL B**	**CELL C**	**CELL D**	**CELL E**	**TOTAL**
250°	0	0	2	0	0	0	2
251°	1	0	2	0	0	0	3
252°	2	1	2	0	0	0	5
253°	2	2	3	0	0	0	7
254°	2	3	2	1	0	0	8
255°	2	3	2	1	0	0	8
256°	2	3	2	1	0	0	8
257°	2	3	3	2	0	0	10
258°	3	3	3	3	1	0	13
259°	3	3	2	3	1	0	12
260°	3	3	2	4	2	1	15
261°	3	2	2	4	3	1	15
262°	3	1	1	4	3	2	14
263°	2	0	1	4	3	2	12
264°	1	0	1	3	3	3	11
265°	0	0	0	2	3	3	8
266°	0	0	0	1	3	3	7
267°	0	0	0	0	3	3	6
268°	0	0	0	0	3	3	6
269°	0	0	0	0	3	2	5
270°	0	0	0	0	3	2	5