Fourth LACCEI International Latin American and Caribbean Conference for Engineering and Technology (LACCET'2006)
"Breaking Frontiers and Barriers in Engineering: Education, Research and Practice"
21-23 June 2006, Mayagüez, Puerto Rico.

Towards the effective prediction of long-term beach morphology on Caribbean coastlines

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Abstract

Caribbean beaches are regions of major economic investment and possess significant social amenity. These fragile regions are in constant motion under the day-to-day hydrodynamic forcing in the nearshore zone, and rarely achieve any state of dynamic equilibrium, with its surrounding environment. Periodically, man intrudes or nature demonstrates her strength, producing unexpected and sometimes disastrous effects in these coastal areas. Hurricanes and tsunamis are but two examples of nature's fury that intermittently wreak havoc on Caribbean coastlines. An additional threat, to coastlines around the world, is the imminent sea level changes influenced somewhat by man's actions. Furthermore, man has had a direct impact on the coastal region through the absolute desire to drive development and derive economic benefits.

In the past, little attention was paid to either the impact of man on the coastal environment, or the impact of the coastal environment on man. However, the increasing population and investments in coastal regions, over the last few decades, have resulted in a major impetus in coastal research around the world. The Caribbean region must invest heavily in the preservation of its beaches, and one such method is through the development of predictive models. These stochastically-based numerical models will provide a basis for making sound decisions for future developments and planning activities. However, to achieve this aim, supporting research must proceed throughout the region, in tandem, with any model development.

Keywords

long-term, beach morphology, numerical model, coastal environment

1. Introduction

The Caribbean coastal environment represents a complex relationship, which balances economic, demographic and environmental pressures. However, the establishment of any level of stability, within this chaotic relationship, requires detailed knowledge of the physical environment, and the role of man in that changing environment. Regionally, man has a significant role within the coastal environment. In Latin America and the Caribbean, where a predicted 75 percent of the population is urban, 57 out of 77 major regional cities are in the coastal zone (Hinrichsen, 1995). In the Caribbean region, developments dominate the coastline, and in some cases the natural environment has been destroyed, as is the case in the Gulf of Paria, in Trinidad, where most of the coastal vegetation has disappeared (UNEP-IMA/CEPNET/IDB, 2001). The islands of Trinidad and Tobago also exemplify many Caribbean small island states, where the main urban centres are all located in the coastal region (UNEP-

IMA/CEPNET/IDB, 2001). A regional study (UNEP/CRCU, 2001) has shown that an estimated 40 percent of the human population in the wider Caribbean region reside within 2 kilometres of the coast. However, the greater risk is that this percentage of people is expected to rise over the next two decades. Wisner et al. (2004) indicated that worldwide 20 to 30 million inhabitants are expected to reside in cities that are at risk to coastal hazards, by the year 2025. Undoubtedly, the Caribbean region is expected to follow global trends. The expected increase in regional coastal urbanization can be attributed to two major causes: an increasing population in Caribbean countries and a greater growth in the tourism industry, which is the region's foremost industry. Consequently, the present situation in the Caribbean is one of a high concentration of population and economic activity within coastal regions, with the associated high risk of loss of human lives and economic loss.

All the islands of the Caribbean are susceptible to menaces along the coastline. These threats may result in disastrous events, the most frequent of which result from the region's susceptibility to hurricanes and tropical storms. These meteorological threats cause a substantial part of economic losses from disasters in the Caribbean. Unfortunately, recent studies have shown that the increase in global atmospheric temperature can increase hurricane intensity and frequency. Specifically, research has shown that for a sea surface temperature warming of about 2.2 °C, simulations yielded hurricanes that were intensified by 3 to 7 metres per second (5 – 12 %) for wind speed and 7 to 20 millibars for central surface pressure (Knutson et al., 1998). Caribbean islands should be better prepared for these more intense hurricane periods.

Some islands in the Caribbean, particularly the eastern Caribbean, are prone to tsunamis. Tsunamis are waves of extraordinarily long wavelengths, caused by earthquakes, volcanic eruptions or large-scale landslides (Deane, 1972). Tsunami events have been reported in the Caribbean and adjacent regions since the 16th century (Maul, 1999). Moreover, five tsunami events have been recorded in the Caribbean during the period 1983 through the end of 1999 (Lander et al., 2002). These tsunami events have been generated by both local and distant sources. A single major tsunami event has the potential for destruction to life and property greater than that lost in hurricanes, or in any other natural hazard in the region. However, the Caribbean nations are unprepared for any tsunami event and are for the most part, uninformed of tsunami risks (IOC, 1996). The region has averaged about one damaging tsunami every 21 years, but it has not had one in over 55 years; so a destructive tsunami is overdue (Lander et al., 2002).

Database development is the most relevant sphere of study for the islands of the Caribbean. Although, there has been coastal data collected by a variety of organizations (private or public), for the wider Caribbean region, these are not available in a comprehensive format. The non-availability of collected data in a suitable format prohibits its widespread application, and hence its use in research is limited. All past research efforts should be aggregated into ascribed modern data formats, whilst new research schemes are being implemented. Constituent areas of research activity may be done with the intention to be included in this regional database. One such research effort may involve the assessment of existing coastal structures including the delineation of past successes and failures of these structures. Alternatively, comprehensive studies of the impacts of natural events are required. Such studies would include the direct impact of a high-energy wave climate, such as beach erosion and the evaluation of the flood damage potential along the coastline, with the subsequent development of flood hazard maps and setback distances. Furthermore, the loss of sediment volumes from coastal areas must be quantified for varying degrees of storm intensity, with its associated likelihood of occurrence. Anthropogenic activities, such as the construction of coastal structures, affect the coastline immediately and/or have long-term consequences. These consequences may be far-reaching and should be described not only in a qualitative manner, but also quantitatively. The effects of proposed projects must be understood before these activities can be sanctioned.

In order to facilitate many computational tasks, it is essential to use and/or develop numerical models for coastal applications. Although, the existing commercial models are able to produce data to assist coastal planners, these models are not specifically designed with the Caribbean region at its centre. Therefore, existing models may be adapted and calibrated or new models developed and verified. This paper introduces a new model that has been developed to determine long-term beach morphology. Long-term morphological models are needed to assess the effects of the natural environment on Caribbean beaches, and in so doing, serve as a guide to decision makers.

2. Objective

The purpose of this paper is to discuss a numerical model, targeted for use in the prediction of the long-term morphology of coastlines in the Caribbean. Models that simulate morphological changes on the order of years are referred to as long-term models. This numerically-based model can represent the varied bathymetry and hurricane-influenced wave climate that typically distinguish Caribbean coastlines. This long-term morphological model is shown to be competent in the qualitative description of the changes in a coastal region. The absolute predictive capability of long-term models can only be ascertained if models have been validated against a suitable data set. Unfortunately, comprehensive data sets, that demonstrate long-term morphological change, are quite rare. A systematic data set must identify, not only the change itself, but also all the driving mechanisms associated with the change. Consequently, a quantitative assessment of the predictive model can only be demonstrated for short-term predictions.

3. Scope of Work

Coastal morphology models generally couple a sediment transport mathematical model with a hydrodynamic model. The hydrodynamic model represents the wave action, water levels and currents. The accompanying transport model then uses the principle of conservation of sediment mass, and the current and wave shear stresses calculated by the hydrodynamic model, to determine the sediment transport capacity. Physically based long-term models, which are used to predict bathymetric responses, have been developed by integrating short time-scale processes; an approach referred to as process modelling. Generally, these process-based models make two major assumptions. Firstly, it is assumed that processes that occur at smaller temporal scales are relevant over longer time periods, and secondly, processes that are not relevant at these short time scales do not become important at larger temporal scales. The regional morphological model, hereafter referred to as the "the model", was developed as a framework of inter-connected modules: bed topography, wave climate, wave transformation, sediment transport and sediment balance. Figure 1 shows the various modules that are incorporated in the model. Each module interacts, directly or indirectly, with other modules by either supplying input, receiving output or both. Additionally, in an effort to represent the relevant physical processes, each of the modules has employed both existing and new mathematical expressions, derived from theoretical analyses or empiricisms.

The model employs a probabilistic modelling technique to derive descriptions of the morphological response. This method of modelling requires random sampling of independent variables (or input parameters) from a given distribution, to obtain a possible outcome of the dependent variable (or the response parameter). Each input parameter is usually described stochastically, and therefore the outcome is only one likely description of the dependent variable. Each simulation run will produce alternative responses, and in this way, the morphological response is assigned a probabilistic description. Ideally, the sampling distributions of the input parameters are derived from long-term measurements.

The model represents a unique effort in morphological response in the Caribbean. It does not solve all the regional coastal problems, but does possess distinct features, which distinguishes this model from similar models developed elsewhere. The major characteristics that have distinguished this model from existing ones are:

- the ability to transform waves over relatively complex bathymetry
- the simple representation of the effects of non-linear waves within the nearshore zone, to facilitate inclusion in a long-term model
- the use of a depth-averaged scheme to represent undertow velocities in the nearshore zone
- the coupling of surf zone and swash zone sediment models to predict long-term morphological behaviour
- the use of long-term wave statistics for a Caribbean coastline
- the impacts of storm/hurricane conditions on the coastal morphology
- the consideration of sheltering of some Caribbean coasts

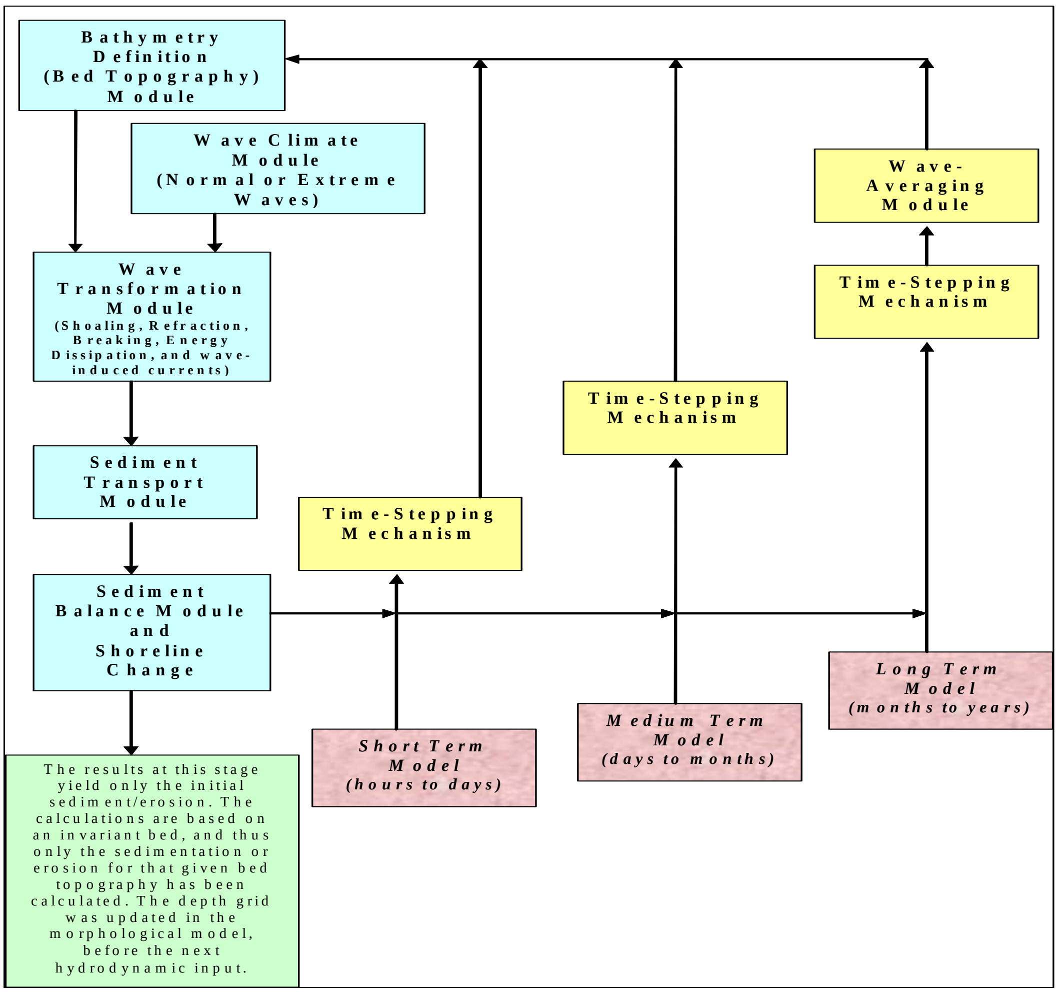


Figure 1 Interaction Diagram showing the modules of the proposed numerical model

4. Methodologies

4.1 Model Description

Morphological models exist that use either finite difference or finite element techniques. Kamphuis (1992) has stated that finite difference solutions are preferable over finite element solutions when solving wave propagation problems. Additionally, certain researchers (Dalrymple, 1992; Leont'yev, 2003; Rakha et al., 1997; De Vriend et al., 1993) have found that explicit finite difference schemes are adequate for the solution of the conservation of wave energy and sediment mass equations. One approach in these explicit finite difference schemes uses a two-step Lax-Wendroff explicit scheme for the solution of these equations. Moreover, Leont'yev (2003) stated that this scheme provides a high stability for the numerical procedure even for locally uneven bottom topographies. The major governing differential equations are written in finite-difference form for the model. This method was chosen because it was the easiest to implement, and solutions can be solved simply, from the most seaward node, landward. Further, an explicit finite difference method is used, thus providing a "forward-marching" of the grid solution. Since the two-step explicit Lax–Wendroff scheme has been shown to exhibit numerical stability, it is this numerical scheme that was chosen for the discretization of the two main differential equations, the wave propagation equation and the conservation of energy equations.

The model is phase-averaged, where the wave field is modelled in terms of the wave energy density. Phase-averaged models can be based on a single representative wave height (parametric or single wave approach) or on a discrete series of wave height classes (probabilistic, multi-wave or wave-by-wave approach), and simulate the processes involved over at least one wave period. These models are computationally efficient, and hence the reason it was chosen for use in this model. The effect of phenomena, such as long waves and wave asymmetry have only been included in an approximate manner, as is the usual case with these types of models (Rakha et al., 1997). Phase-averaged models contrast the phase resolving class of models, which simulates the wave conditions across a coastal profile by a model based on descriptive equations of fluid motion, such as the Boussinesq equations. These models provide potentially accurate predictions of the wave skewness and asymmetry for shoaling and breaking waves, but are computationally intensive, and not easily applied to time-dependent nearshore morphodynamic modelling (Rakha et al., 1997).

4.2 Model Components

4.2.1 Bed topography module

This module supplies the bathymetrical data to the wave transformation module. This is achieved through the representation of the coastal area as a system of rectangular grid cells. A single node, situated at the centre of each rectangular grid element, provides the grid cell characteristic of importance in this module, which is the depth at the given node. An option is also provided, within this module, to increase the resolution of the initial depth grid. Additionally, the module receives information on bed level changes from the sediment balance module and is updated at the beginning of each calculation step. The resulting depth grid is described in such a manner, that the grid cells located at the most offshore position, must lie in deep water. Figure 2 shows the co-ordinate axes used in the numerical model, for grid orientation.

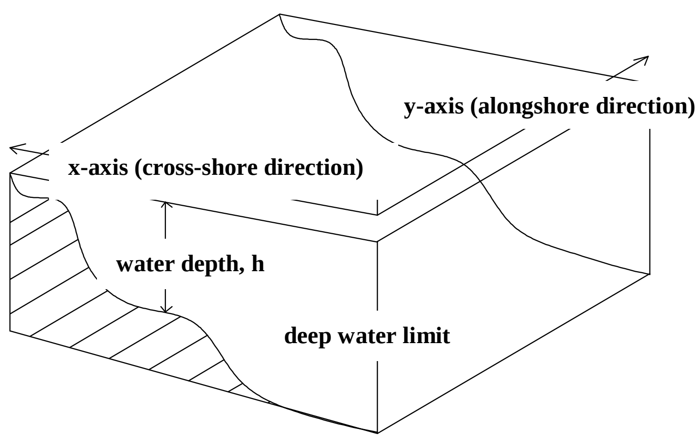


Figure 2 Co-ordinate axis system used in the numerical morphological model

4.2.2 Wave Climate Module

This module applies randomly selected deep-water wave states at the offshore gridline. A wave state is described by the parameters of wave height, wave period and wave direction. The wave climate is decomposed into two main types: the 'storm' climate and the 'normal' climate. The 'storm' climate describes the periods of high wave energy in the coastal environment, whereas the 'normal' climate is associated with relatively lower wave energy in the nearshore. The latter type of wave activity, which occurs for the majority of the time, is contrasted with extreme or storm wave activity, which produces major changes on a beach. The approximate probability distributions for the normal wave climate is derived from ship observations in Area 47 of the "Global Wave Statistics", which divides the earth into 104 areas. The model is only allowed to select storm wave parameters during a three-month period, defined as the model "hurricane season". Model storms are selected from seven pre-determined storm categories, which provide the wave parameters, the storm duration and the maximum storm surge level.

4.2.3 Wave Transformation Module

This module provides the features of each grid cell using the representative depth at that node. The characteristics of interest are the wave parameters. Mathematical methods are used to obtain the wave parameters as the wave transforms in the nearshore zone, and includes transformation processes of wave shoaling, wave refraction and wave breaking. Wave asymmetry about a horizontal axis is included only approximately, and no vertical asymmetry was considered. The wind at the surface of the sea is assumed to have no effect on the waves, and the depth at the node primarily controls wave characteristics. In addition, wave-induced undertow velocities are determined from the given wave parameters at each node. Once the hydrodynamic character of each cell is determined, it is used as input into the sediment transport module, which determines the potential sediment transport rate at the grid cell node.

4.2.4 Sediment Transport Module

This module uses the phase-averaged sediment transport expressions to ascertain the expected sediment transport rates. Potential sediment rates are determined, for both the surf and swash zones, using the Bailard (1981) expression, which is an energetics type expression. The swash zone does not form part of the coastal area grid, and is dealt with in a separate subroutine. Further, the swash zone area is not decomposed into constituent parts, but rather is treated using a 'bulk' approach, the results of which are sent to the main model. Both cross-shore and longshore sediment transport rates are determined for each grid element, and are used in the sediment balance module.

4.2.5 Sediment Balance Module and Shoreline change

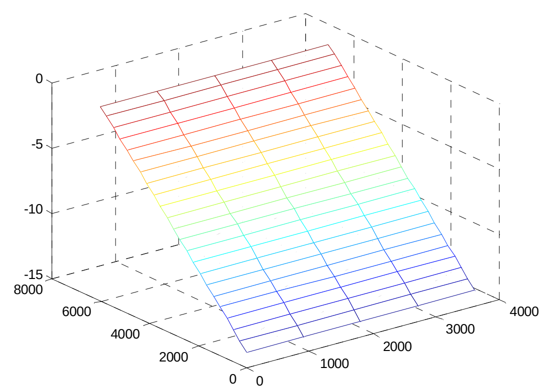
The sediment balance module employs the principle of sediment mass conservation to determine the resultant sediment retained in a grid cell. A resultant sediment deposition results in a decrease of the water depth; alternatively, a resultant sediment loss results in an increase of the water depth at that node. In this way, the bathymetry is updated after each simulation run. The new shoreline position is determined using the updated bathymetry, and these latest values are used for the next calculation stage. Included also in this module is an avalanching routine, which limits the beach slope in both the x-and y-direction.

4.2.6 Wave-Averaging for long-term phenomena

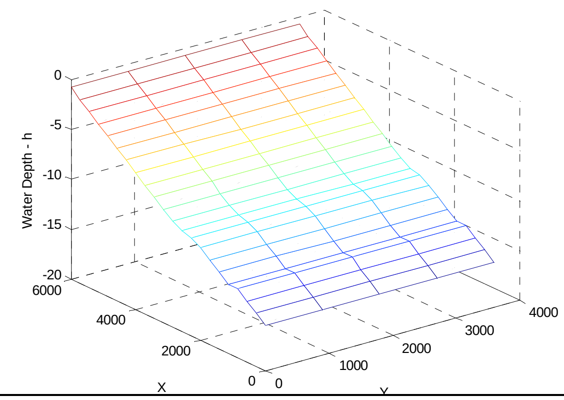
If unadjusted, the model requires significant computational effort to estimate short to medium term shoreline change for a series of randomly selected waves. Long-term changes require large amounts of computing time, and it is necessary to increase the computing efficiency of the model through use of a wave-averaging mechanism. This wave-averaging is accomplished by defining a 'wave interaction' period, over which the bathymetry is assumed to remain unchanged and the incident offshore wave is also constant.

5. Results

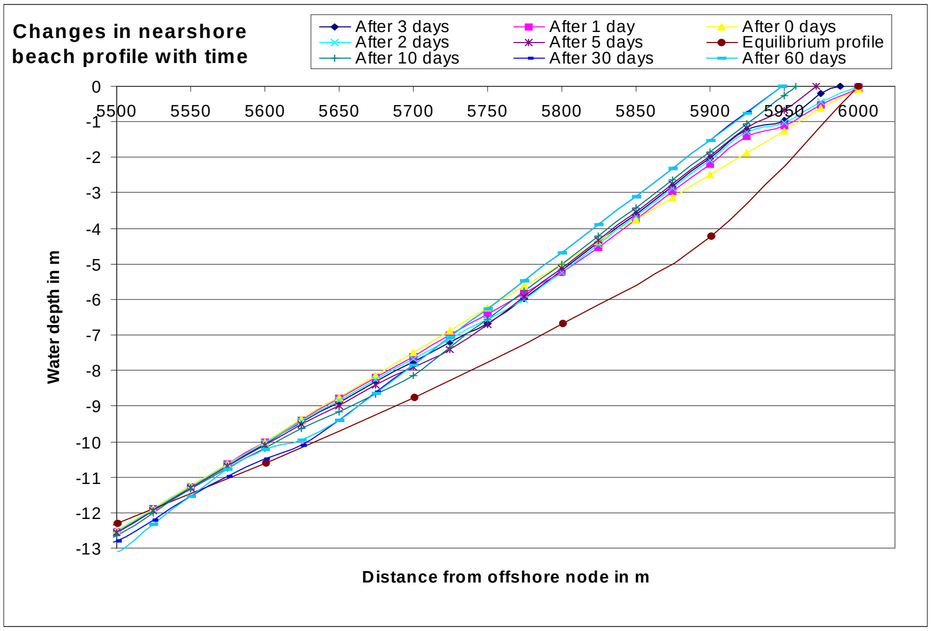
A planar test beach is used to perform the qualitative assessment of the model, in its probabilistic mode. The initial beach profile, shown in Figures 3(a) and 4(a), was subjected to waves randomly selected, first from the regionally-defined normal wave climate, and then subjected to waves during the model "hurricane season". Figures 3(b) and 3(c) show the beach response for a 60-day simulation during the defined normal wave climate. Alternatively, figures 4(b) and 4(c) show the beach response for a 30-day simulation during the higher wave energy period. For the 30-day simulation, during the "model hurricane season", a storm impacts the beach 4.75 hours, after the initiation of the simulation. The storm selected has deep-water wave parameters given as $H_o = 5.64m$, $T = 10.71s$ and a maximum storm surge of 0.5m. The duration of the selected storm was 1000 waves, which was equivalent to 2.975 hours.



(a) Initial Planar Beach Profile of the test beach, with a beach slope of $\frac{1}{40}$ in the surf zone, and a foreshore slope of $\frac{7}{50}$

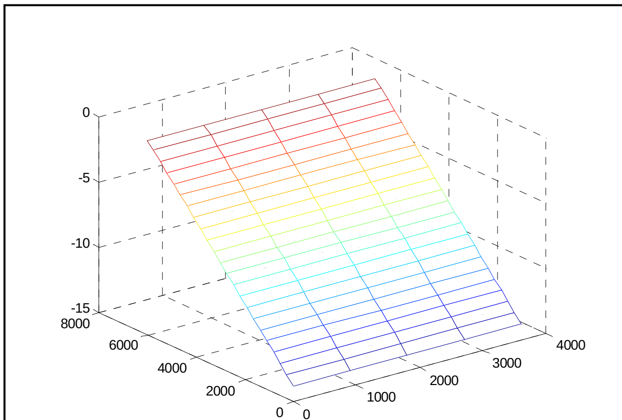


(b) Beach profile after a 60-day simulation during the non-hurricane period

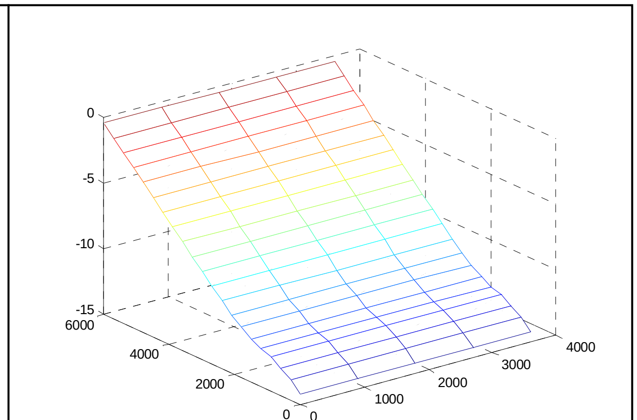


(c) Graph showing changes in nearshore beach profile for the various simulation lengths during the non-hurricane periods

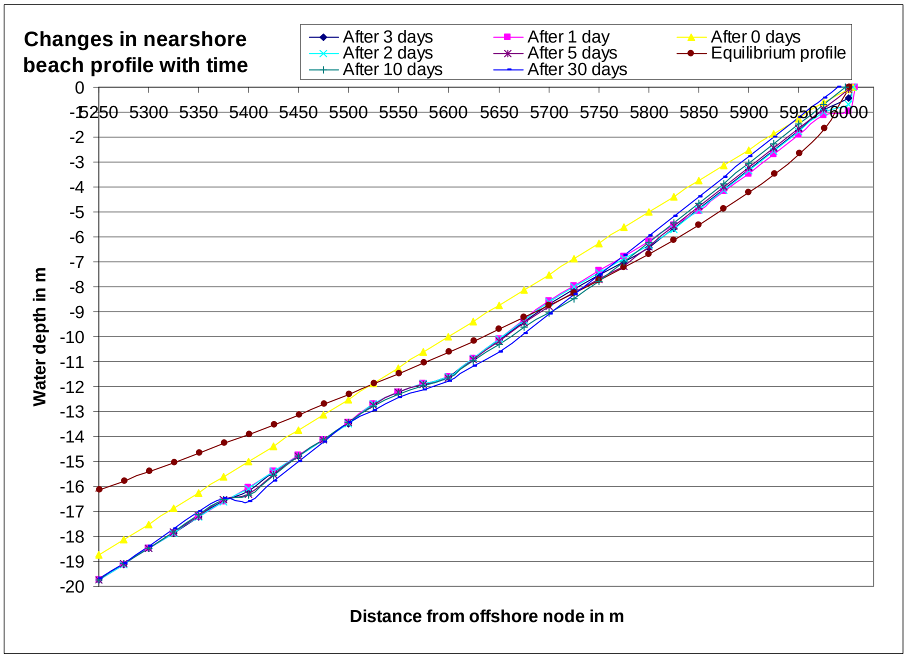
Figure 3 Results of model simulation for non-hurricane period



(a) **Initial Planar Beach Profile of the test beach, with a beach slope of $\frac{1}{40}$ in the surf zone, and a foreshore slope of $\frac{7}{50}$**



(b) **Beach profile after a 30-day simulation during the hurricane period**



(c) **Graph showing changes in nearshore beach profile for the various simulation lengths during the hurricane periods**

Figure 4 Results of model simulation for hurricane period

The results, in figures 3 and 4, show beach profile changes, where those changes are averaged over ten waves. Generally, the results show that the model is able to develop and maintain a barred profile, from an initially planar beach profile. This demonstrates its suitability to depict natural coastal features. Additionally, it is apparent that the model beach has a propensity to accrete during the non-hurricane months with the reverse being true for high wave energy events. Additionally, the rate of accretion, following the storm event, is smaller than pre-storm accretion due primarily to the deeper water in the nearshore zone following the storm.

A quantitative assessment of the model, in its deterministic mode, uses the results of a small-scale laboratory test done at Delft Hydraulics in the Netherlands. The initially planar beach was subjected to a series of waves with $H_{rms} = 0.123m$ and $T = 2.0s$ for 12 hours. In addition to which, the sediment bed consisted of grains with a median sediment size of $D_{50} = 0.1mm$. Figure 5 shows the results of this validation exercise.

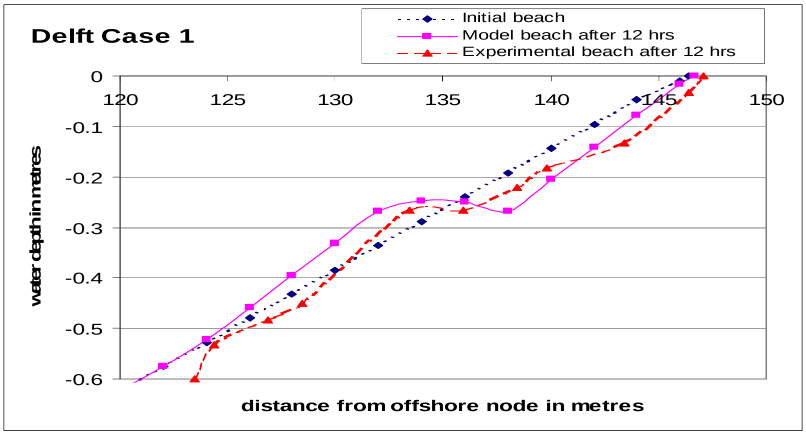


Figure 5 Comparison of the profile change of the model beach with the experimental results after 12 hours

It is evident from the results that the model imitates the erosion and accretion patterns along the beach profile. It is capable of predicting the location and extent of the longshore bar development within the same morphological time period. However, the build-up of sediment on the seaward side of the bar is more substantial in the model, than it is for the experimental beach. Alternatively, the sediment build-up on the landward side of the bar is more substantial in the experimental beach than it is for the model results.

6. Conclusion

This paper has emphasised the need for comprehensive regional coastal studies, and the assimilation of all findings, in such a format, to advance research in the region. The results of historical studies should also be incorporated into a regional database, to prevent duplication of past investigations. One primary application of the coastal data, is the validation of numerical models that are used in designing or planning activities. A long-term model, developed to ascertain morphological trends on Caribbean coastlines, has been discussed in this paper. The various modules within the model were introduced and their functions briefly outlined. These constituent modules are significant as they represent processes that affect the beach response. The model is capable of simulating erosional/accretional patterns on beaches, as well as, providing a good indication of the actual magnitude of those changes. The validation exercise presented, considers only the morphological response of the beach, which is the parameter of main interest. The model has conclusively demonstrated its ability to simulate trends that exist in the natural state, and thus may be used in the prediction of long-term beach morphology.

7. Recommendations

Although the model has shown correlation with limited experimental results, its true test would be its comparison to a long-term regional data set. It is only at that juncture that true predictive capability may be assessed, and its regional application proven to be more acceptable. The model is also limited in that not all the physical processes of relevance have been modelled. Physical processes that have not been simulated in the present stage of development include the effects of infragravity wave energy in the surf zone, and wave transformation processes such as the diffraction, reflection and energy dissipation due to frictional effects.

This model at its current stage of development may be employed to provide guidance to the decision makers in society, but may be improved to serve as a superior predictive model to be applied for regional use.

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