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The Influence of Tidal Currents on Coastal Erosion in a Tropical Micro-Tidal Environment – the Case of Columbus Bay, Trinidad

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Abstract- Trinidad as a Small Island Developing State (SID) has limited land resources which must be managed against the threat of coastal erosion. Columbus Bay, located on the south-western peninsula of the island is negatively affected by high rates of coastal erosion. Erosion in this area has resulted in a reduction in beach amenity, loss of valuable agricultural land, critical mangrove habitats and damage to infrastructure. Although the erosion problem is well documented, the challenges lie in management due to the limited understanding of the interaction of coastal processes and sediment transport in the area. While other studies have identified the existence and causal link between coastal erosion and tidal currents in macro-tidal environments, this study examines the interaction of tides on coastal processes and sediment transport in a micro-tidal setting. The study combines traditional field and levelling techniques alongside numerical modelling on data from 2009-2013. It utilizes the Spectral Wave (SW), Hydrodynamic (HD) and Sediment Transport (ST) modules of MIKE 21.

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Candice Leung Chee [α], Asha Singh [σ], Rameez Persad [ρ] & Junior Darsan [ω]

Abstract- Trinidad as a Small Island Developing State (SID) has limited land resources which must be managed against the threat of coastal erosion. Columbus Bay, located on the south-western peninsula of the island is negatively affected by high rates of coastal erosion. Erosion in this area has resulted in a reduction in beach amenity, loss of valuable agricultural land, critical mangrove habitats and damage to infrastructure. Although the erosion problem is well documented, the challenges lie in management due to the limited understanding of the interaction of coastal processes and sediment transport in the area. While other studies have identified the existence and causal link between coastal erosion and tidal currents in macro-tidal environments, this study examines the interaction of tides on coastal processes and sediment transport in a micro-tidal setting. The study combines traditional field and levelling techniques alongside numerical modelling on data from 2009-2013. It utilizes the Spectral Wave (SW), Hydrodynamic (HD) and Sediment Transport (ST) modules of MIKE 21. Results indicate that tidal current speed and direction are the main drivers of sediment transport in the bay with most of the erosion occurring during the ebb state. Computed ebb current speeds have a range between 0.18 and 0.36 m/s during spring conditions and 0.36 and 0.54 m/s during neap conditions, with a north easterly direction. Recommendations are made for engineered groynes in an attempt to reduce coastal erosion as targeted management interventions for the area.

Keywords: sediment transport, erosion, Columbus Bay, MIKE 21, sustainable land management.

I. Introduction

The formation of coastal morphology such as cliffs, platforms, headlands and bays are as a result of the interaction between marine processes in the coastal zone. Waves, currents and tides interact (Park and Edge, 2011) and in doing so, contribute to shoreline changes such as erosion (Coelho *et al.,* 2009). The interruption of these natural coastal processes by human interjection in the absence of adequate research has highlighted negative impacts (Barnard, Hansen, and Erikson, 2012; Bromhead and Ibsen, 2006; Cambers, 2009; Hsu, Lin, and Tseng, 2007; Komar, 2010; Lorenzo, Alonso, and Pages, 2007). Independently, the effect of tides on coastlines has been well documented and is identified as being responsible for sediment transport in estuaries and macro-tidal environments globally (Masselink and Hughes, 2003). However, there remains a paucity of data as it relates to coastal erosion in a tropical embayed micro-tidal setting, which affects the way in which these types of environments are integrated into management concerns. In the Caribbean, these are as are severely understudied, although they are also the areas of high value for development. A poor understanding of the impact of tides in these are as leads to weak management strategies resulting in the loss of valuable land in varying magnitudes.

The effect of tides on beach dynamics and coastal erosion was studied for a number of places such as Gulf of California (Alvarez and Jones, 2004), West Palm Beach, Florida (Trenhaile, 2004), Dauphin Island, Alabama (Froede, 2007), North Shore of Oahu, Hawaii (Caldwell, Vitousek, and Aucan, 2009), North Yorkshire, England (Lim *et al.,* 2011) and Ocean Beach, California (Barnard, Hansen and Erikson, 2012). Darsan (2013) examined the influence of tidal cycles on beach dynamics at Cocos Bay, east coast Trinidad over a short term. The study found that erosion was linked to rising tide while accretion was due to falling tide diurnally. Erosion also dominated the spring tide conditions and accretion during neap tides. In addition to the tidal cycles that occur over the short-term, a study conducted by (Gratiot *et al.,* 2008) has demonstrated that the 18.6 year nodal tidal cycle contributes significantly to regional coastal changes.

Although the threats of coastal erosion due to existing oceanographic conditions, in particularly tides are well recognized, the challenge of incorporating this into management decisions is limited by the understanding of coastal erosion processes. The latter requires complex mathematical analysis coupled with an extensive cohort of data acquisition of various parameters which include, but are not limited to tides, currents, waves and wind data. This data collection often requires substantial human and financial resources which are sometimes unavailable, resulting in an absence of coastal dynamics considerations into

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land use planning (Martinez del Pozo and Anfuso, 2008; Sayah *et al.,* 2005). This usually translates into coastal infrastructure installations with reduced life spans, which lead to huge finacial burdens.

Over the last decade, there is evidence of a change towards the use and incorporation of coastal processes into management, thanks to growing appreciation and recognition of numerical modelling (Gonzalez-Leija *et al.,* 2013), (Johnson *et al.,* 2005; Kabiling and Odroniec, 2010; Kankara *et al.,* 2013; Rajith *et al.,* 2008; Xue, 2001; Warren and Bach, 1992). Predicting hydrodynamics due to tides is shown to provide a better understanding of near shore current behavior (Mazio *et al.,* 2004). This has afforded coastal engineers the ability to use these models to simulate existing oceanographic processes and use this information to predict the behavior and influences of dynamic coastal erosion processes. However, in the Caribbean SIDS and in Trinidad and Tobago, usage of numerical modelling remain scarce.

Sediment transport modeling utilizing the MIKE 21 model has proven to be useful in simulating existing hydrodynamics due to tides (Sorensen, Kofoed-Hansen, and Jones, 2006), currents and waves (Appendini *et al.,* 2012; Dupont, 2010; Niemann *et al.,* 2010; Remya *et al.,* 2012). Further, this model supports the identification of areas of potential erosion or accretion given its ability to simulate these conditions (Broker *et al.,* 2007; Zyserman and Johnson, 2002). Such modeling provides calculated wave power, wave height, wave radiation stresses, wave direction, current speed and direction, total load magnitude and direction and rate of bed level change in relation to the existing oceanographic conditions. These collectively form the basis of defining sediment transport in an area and thereby determine the erosion potential. The end result is that more environmental data is available for inclusion into effective land management decisions.

Land management is critical to a sustainable pathway for Trinidad (Singh, 2005),there fore one of the policy decisions is to ensure that sustainable management of its resources remains a priority. Columbus Bay located on the south west peninsula of Trinidad, has experienced erosion of the land for the past forty years (Oostdam, 1982). This area is important because it supports a sensitive mangrove habitat which provides a natural buffer to the south western coastline against storm surge and further coastal erosion. It also sustains a vibrant agricultural industry which contributes significantly to local livelihoods. Recently, this bay has been earmarked for possible infrastructural development to support the projected growth in the oil industry- an activity which is prominent on the west coast of Trinidad.

Columbus bay, located on the south western peninsula in Trinidad has been eroding for the past forty years and the problem persists despite some management interventions. (Deane, 1973) suggests that long shore currents generated by waves approaching from storms and squalls create long shore currents capable of moving sediment. (Oostdam, 1982) also supports this theory and adds that tidal currents may also be responsible for the movement of sediment. Dean (1973) used modeled wave data and computed near shore wave events due to shoaling and refraction. Oostdam (1982) employed langrarian measurements of currents at various locations in the bay, but does not provide current magnitudes throughout the bay. Both studies used values of near shore coastal conditions (wave height and current speeds) to indicate the resulting impact on sediment transport, but neither provided quantitative values for sediment transport, nor identified the factors responsible for the observed coastal erosion. In view of this, the objective of this study is to adopt a modeling approach to investigate the effect of tides on coastal processes in a low-energy micro-tidal tropical environment using Columbus Bay, Trinidad as the study area. Further, the outputs from the model will be used to deduce the main drivers of sediment transport and by extension coastal erosion in the bay. Complimentary to these findings, are targeted approaches which are recommended to effectively manage the erosion problem in the study area.

II. Study Area

The tidal regime experienced in Trinidad is a function of tidal waves from both the Caribbean Sea and the Atlantic Ocean (Gade, 1961). Trinidad's tidal type is described as mixed, with a predominantly semi-diurnal influence (Bertrand *et al.,* 1992). The maximum tidal range experienced in Trinidad is 1.3m (Edwards, 1983).Columbus Bay is characterized by a 4km stretch of beach situated between Los Gallos headland in the north-west and Corral Point in the south-west situated in the island of Trinidad **(Fig. 1)**. Interspersed along the coastline are mangroves, agricultural activity and other geomorphological features including a recently collapsed arch, and caves which are eroding. In the open waters adjacent to Los Gallos are three eroded stacks which are believed to be remnants of the headland (Deane, 1973).

The study area is influenced by a large anti-cyclonic gyre which characterizes its current patterns (Gopaul and Wolf, 1995) and a residual flow from south to north fed by the Guiana current (van Andel and Postma, 1954). According to Oostdam (1982), the flows occurring through the Serpents Mouth register bottom speeds of 17cms^{-1} and is dominated by a northerly flow pattern which is directed offshore. The author further reported a reduction in speed 5cms^{-1} in the central part of Columbus Bay. Adding to this pattern are southwardly directed currents with magnitudes of 4cm^{-1} in the vicinity of Los Gallos. Oostdam (1982) postulated that the influx of water through the Serpents Mouth partially returns southward in both the bottom and surface layers in the form of an eddy. Long-shore currents have a predominant southward direction and are generated by approaching waves. This current coupled with the southward return of water subsequently converges with the northerly flow in the vicinity of Corral Point and Punta del Arena, resulting in a sediment plume at Corral Point. Longshore currents at Columbus bay were recorded on an average of 22cms^{-1} (Oostdam, 1982). These longshore currents have the potential to influence the existing circulation patterns by increasing or decreasing resultant magnitudes thus influencing the potential for sediment transport, and coastal erosion.

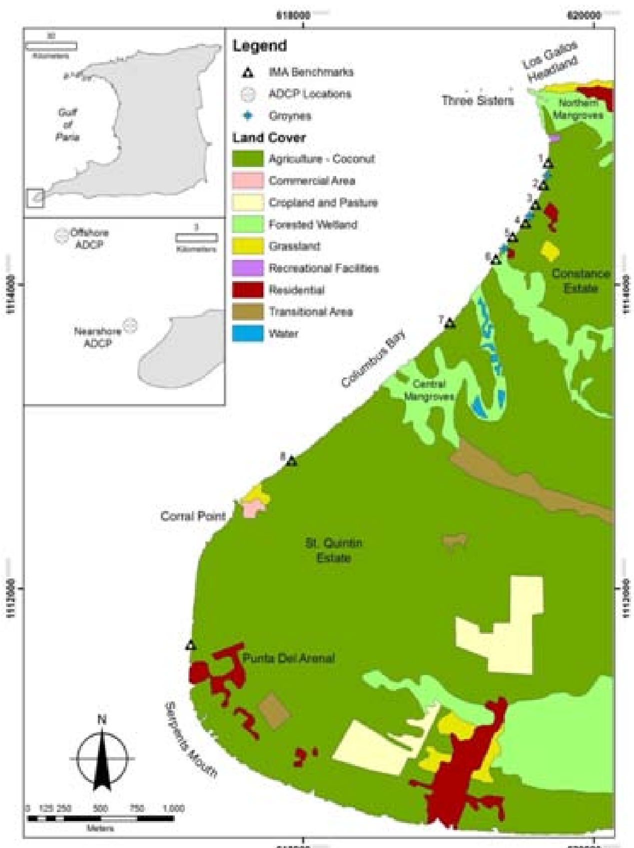


Figure 1 : Study area located at Columbus Bay, south-western peninsula, Trinidad

Wave processes also play a critical role in sediment transport and by extension erosion. In the study area, wave conditions are characterized by low wave heights of periods less than 4secs. These waves generated from the North East Trade Winds result in wind waves ranging between 0.39m and 0.46m (Deane, 1973). However, swell wave events which mainly occur in the hurricane season (June to November) have wave amplitudes that range between 0.76m and 1.5m (Deane, 1973). Tides are micro-tidal with a spring range of approximately 1.5m and these were also found to influence current speed and direction experienced in the bay (Oostdam, 1982).

Sediment analysis provides an indication of transport trends and can point to origins which are important in coastal processes studies. At Columbus Bay, the sediments range from fine to very fine-grained quartz sands. Silt forms part of the sediment composition but is found mainly in the north of the bay. Minor deposits of gravel are observed at Los Gallos and Corral Point. Bathymetry reveals that the area is gently sloping with isobaths between 2m to 22m. Mapping of the bathymetry indicates a narrow channel at Corral point which can play a potentially significant role in sediment transport. Young unconsolidated sediments (sandstone formation) of varying degrees of mineralization characterize the coastline of Columbus Bay thus making the area highly vulnerable to erosion, especially from the influence of tides, wave and currents (Deane, 1973). The continual coastal erosion at Columbus Bay has witnessed the decimation of agricultural crops, which is an annual occurrence (Fig. 2b,d, g). In an attempt to arrest this erosion and protect the agricultural estate, the land owner installed three sandbag groynes in the northern section of the bay, between stations 1 to 5 (Fig.2b,d).

The coastal erosion at Columbus Bay has been studied in an attempt to understand the causative factors (Darsan, Ramnath, and Alexis, 2012; Deane, 1971; Deane, 1973; Hudson, 1988; Kanhai, 2009; Kenny, 2002; Kenny, 2007;Oostdam, 1982). Most recently, (Alexis, 2012) noted accretion within the groyne field, with enhanced coastline retreat rates of -2.87m/yr outside of the groyne field in the southern section of the bay at station 7 (Figs. 1& 2).

Figure 2 : Visible coastline erosion at Columbus Bay

III. Methods

The methodology combines traditional levelling techniques and numerical modelling. The study utilizes the MIKE 21 numerical model and applies the MIKE 21 Spectral Wave (SW) model, the MIKE 21 Hydrodynamic (HD) flow model and the MIKE 21 Sediment Transport (ST) model. Field data are integral to the model and in this regard various parameters were measured and input into the model (Table 1). Data were collected at the offshore location using an Acoustic Doppler Current Profiler (ADCP) and used to 'impose' the wave and flow models. Similarly data were collected at the near shore location were used to calibrate and verify the models.

Table 1 : Oceanographic data collected and used as input for MIKE 21 models

Type	Parameters Measured	Data Period and Interval	Data Input into the Coupled MIKE 21 Model*	
			Spectral Wave (SW)	Hydrodynamic (HD)
Offshore: Geographic Co-ordinates 611 627 E 1121079 N				
Waves	Significant Wave Height, Hs (m) Wave period, Tp (sec) Wave Direction, θ (˚)	18/04/2013 to 16/07/2013 1 hour intervals	✓	
Currents	Current Speed (ms^{-1})	18/04/2013 to 16/07/2013 10 minutes intervals		✓
Water Levels	Water Level (m)	18/04/2013 to 16/07/2013 10 minute intervals		✓
Nearshore: Geographic Co-ordinates 616 653 E 1114791 N				
Waves	Significant Wave Height, Hs (m) Wave period, Tp (sec) Wave Direction, θ (˚)	26/03/2013 to 17/07/2013 hourly intervals	✓✓	
Currents	Current Speed (ms^{-1})	26/03/2013 to 17/07/2013 10 minute intervals		✓✓
Water Levels	Water Level (m)	26/03/2013 to 17/07/2013. 10 minute intervals		✓✓

Key ✓- used input for models ✓✓- used for calibration/validation of models * - output from these models used as inputs for sediment transport model

The basis of the model development is the creation of a computational mesh and boundary conditions. The former provides bathymetry information by incorporating bathymetric data which was collected using a dual frequency echo-sounder and global positioning satellite survey devices in real time kinematic mode. This bathymetry topography forms a critical component in determining the influence of waves and currents on sediment transport rates which effect morphological change. These computations are provided at each simulation time step. Boundary conditions are the principal drivers that influence sediment transport and morphology and were used to provide initial conditions to support computation of nearshore parameters. The results from the SW and HD modules were input in to the ST module to compute the along shore sediment transport rates which are used to modify the existing bathymetry. This modified bathymetry is then used by the SW and HD modules to compute the wave and current patterns in the subsequent time step after Broker *et al.,* (2007) **(Fig.3)**.

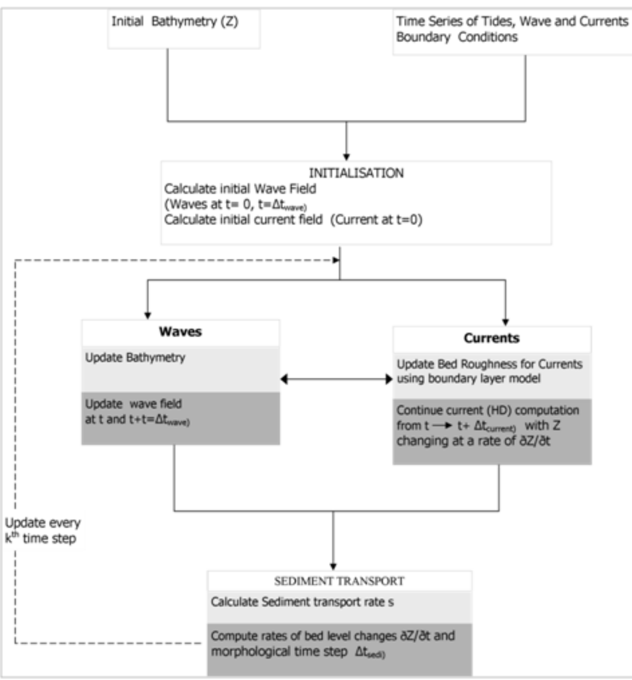


Figure 3 : Flow diagram of methodology (Modified from Broker *et al.,* 2007)

a) Development of Flexible Mesh

The development of a flexible mesh is a critical component in this modeling process which incorporates the bathymetry using a triangular grid. These triangular elements are contoured to the curved coastline of Columbus Bay which represents the bathymetry. Given that sediment transport occurs mainly in the near-shore, the choice of triangular elements range from a maximum of 4.5km^2 to a minimum of 9m^2 in the near-shore area. In total, the flexible mesh developed for this study contained 34,282 nodes and 54,702 elements.

b) Boundary Conditions

- *MIKE 21 SW boundary conditions*

Offshore wave parameters of e significant wave height (Hs), wave period (T), wave direction (θ) and dimensionless factor (n) were input into the model along the east, west and north boundaries **(Fig.4)**.

- *MIKE 21 HD boundary conditions*

Estimating flow conditions in the bay using this model require a two time varying data sets to be specified as boundary conditions. These are: a) horizontal (u) and vertical (v) components of current magnitude, specified in m/s and b) water levels referenced to mean sea level (MSL), specified in meters (m). These data were collected simultaneously with wave data at the time interval and period specified in **Table 1**. These data were specified along all the boundaries.

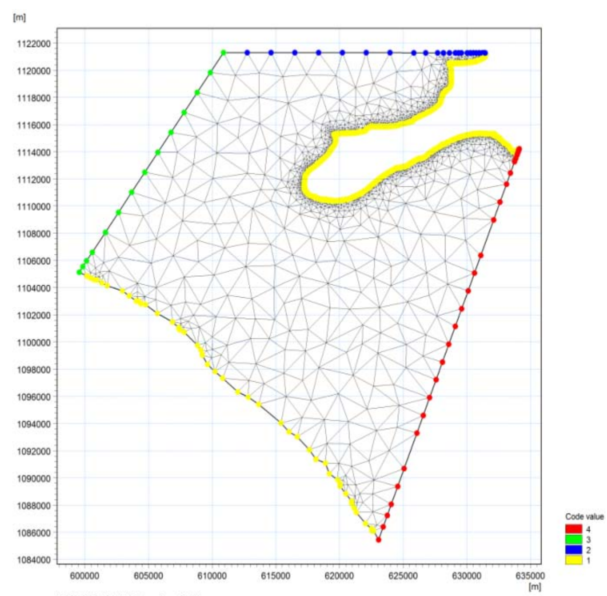


Figure 4 : Model boundaries used for SW and HD model. The east (red), west (green), and north (blue) boundaries allow oceanographic parameters to be specified for the model area. The yellow boundaries represent land and do not allow water to enter

IV. Model Set-up

The MIKE 21 SW model was run in a quasi-stationary mode using directionally decoupled parametric formulation with time series wave data at the specified boundaries. The model was run for a period of six days from19th April to 24th April, 2013, with a time step of one hour, to produce model results which were used for the calibration process. During this process, the frictional co-efficient was varied a number of times starting with the default value of 0.04 until the results achieved in the model were similar to that of the parameters measured at the near shore location **(Fig. 5)**.

Similarly the MIKE 21 HD model was computed using shallow water equations with a low order time integration using a minimum time step of 0.01 secs and a maximum time step of 300 secs. The model was run at a time step of 1800 secs. The bed resistance was defined using a Manning coefficient and turbulence was introduced using the Smagorinsky eddy viscosity model. The model was run for a period of six days between the 19th April to the 24th April, 2013 to support the calibration process as per the established duration as seen in (Broker *et al.,* 2007). For this process, the Manning number was varied starting from the default value of 32m m$^{(1/3)}$/s together with the Smagorinsky eddy viscosity which was varied from the default value of 0.28. These co-efficients were varied until the modeled time series data and that of the measured were similar.

Results from the SW and HD models were then used as the forcing input for computing the sediment transport model at each element in the triangular mesh. A sediment transport table was formulated by discretizing measured data into bands. This ensured that combinations of bathymetry, current, wave and sediment conditions appearing in the model were within the range of measured data. This provided a basis for the ST model to derive sediment transport with significant levels of efficiency. The transport tables were calculated using the Cnoidal wave theory (Scoones and Theron, 1995; Isobe, 1985). A mean grain size of 0.11mm was used, a porosity of 0.4 and a grading coefficient of 1.1 were taken as constraints for the sediment properties (Alexis, 2012).

a) Calibration and verification

The calibration process involved the computation of the root mean square error (RMSE) of modeled and measured data, of the coefficients used in the model. Further, the SW and HD models were validated by running the models for a three month period (19th April to 16th June, 2013) and one month period (19th April to 18th May, 2013) respectively, in order to determine the RMSE of measured and modeled data.

i. SW model

For the SW model, a final value of 0.25 was used in the calibration process as the frictional coefficient. This resulted in a RMSE of 0.2 for measured and modeled data obtained from the nearshore site. This frictional co-efficient was then used for further model simulation between the period 19th April to 16th June, 2013. The modeled and measured data for parameters on wave height, wave period and wave direction are illustrated in Fig. 5. Further the resultant modeled data when compared with measured data shows significant similarity with a calculated RMSE of 0.2.

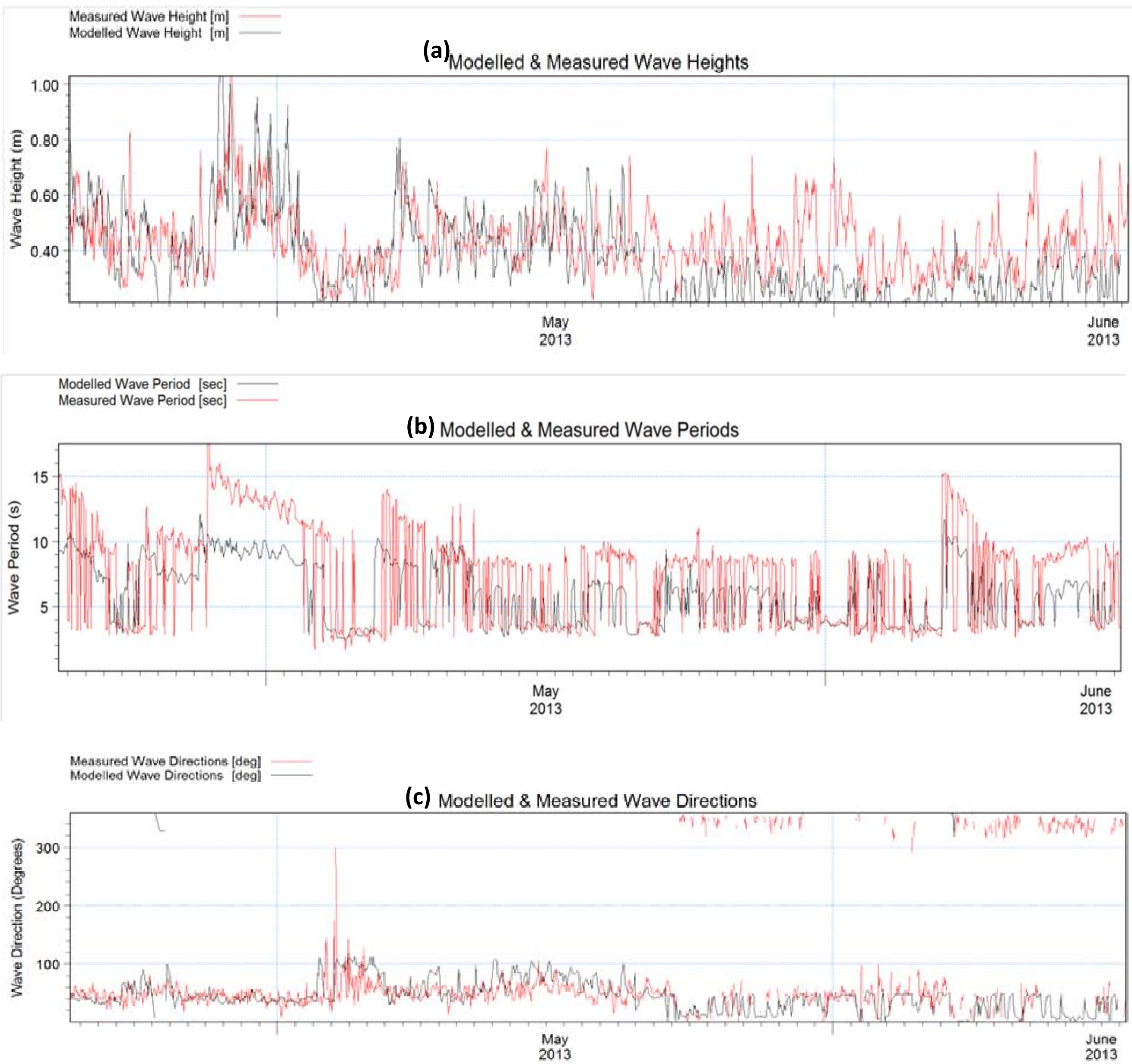
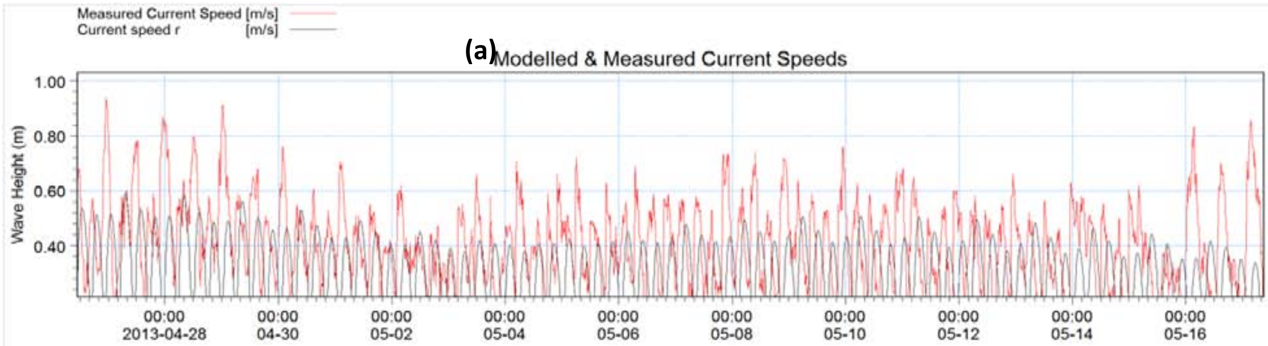


Figure 5 : Modelled and measured (a) wave heights (b) wave periods and (c) wave directions from (19th April to 16th June, 2013) showing similar trends

ii. *HD model*

A similar process was conducted for the calibration of the HD model. Upon the completion of the calibration process, the final Manning number in put into the model was 26m$^{1/3}$/s. This value was used to perform further model simulations and a comparison was made between measured and modeled current magnitudes and direction. This model ran for a period of one month from 19th April to 18th May, 2013. Resultant modeled current magnitudes and speeds were graphically plotted against measured magnitudes and direction (Fig. 6). Finally, to ensure that the model results reflect the measured data, the measured and modeled data were verified by computing the RMSE which produced a value of 0.2.



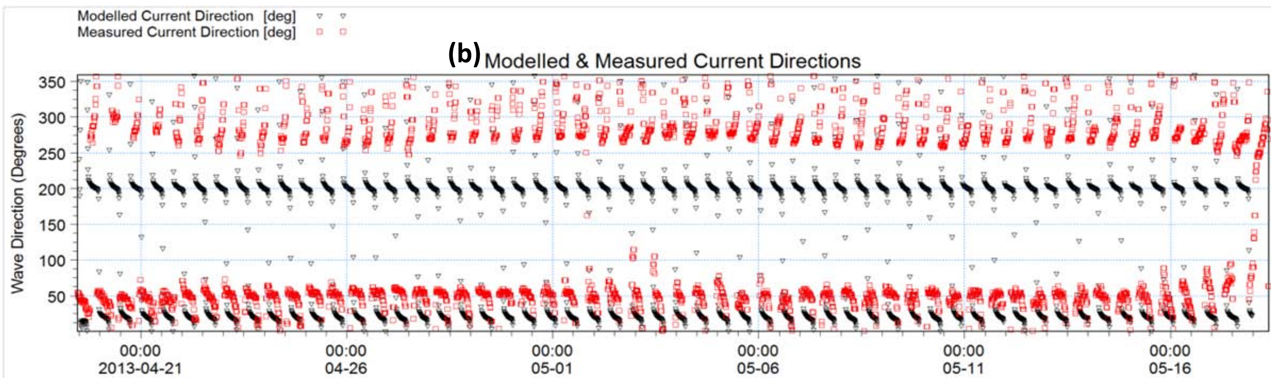


Figure 6 : Modelled and measured (a) current speeds and (b) current directions from (19th April to 18th May, 2013) showing similar trends

b) Beach profiling

Beach profiles were measured using standard surveying techniques, with the use of a Sokkia B20 automatic survey level, a dome-head tripod, a 100m measuring tape, a 7.60m survey staff and a Brunt on direct pointing compass. Readings were taken from the station at a 4m interval along the profile direction and to a water depth of approximately 1.50m. The break in slope method was also employed so that notable changes along the profile direction such as the vegetation line, high water mark or a change in gradient such as a scarp or cusp, were also accounted for and recorded. Beach profiles were monitored monthly at the 8 shore-normal beach profile transects situated along Columbus Bay. These profiling stations were surveyed from October, 2009 to April, 2013 and the beach profiles were conducted during a spring low tide to maximise profile lengths. These profile data were used to monitor the coastline retreat and erosion rates over the study period.

V. Results

The coupled model produced a number of results such as wave power, wave height, wave radiation stresses, wave direction, current speed and direction, total load magnitude and direction and rate of bed level change. These were analyzed against the tidal influences which are spring and neap conditions at flood and ebb states.

a) Wave conditions at Columbus Bay

i. *Wave power*

Results indicate that the wave direction is constant and approaches from the north-west. Flood conditions in terms of wave power show values between 1.6kWm^{-1} and 4.0kWm^{-1} which were higher when compared to ebb conditions of 0kWm^{-1} to 3.2kWm^{-1} (Fig.7). These values seem to suggest that during a flood tide condition, it is likely that more sediment is mobilized thereby increasing the potential for transport and influencing the rate of erosion.

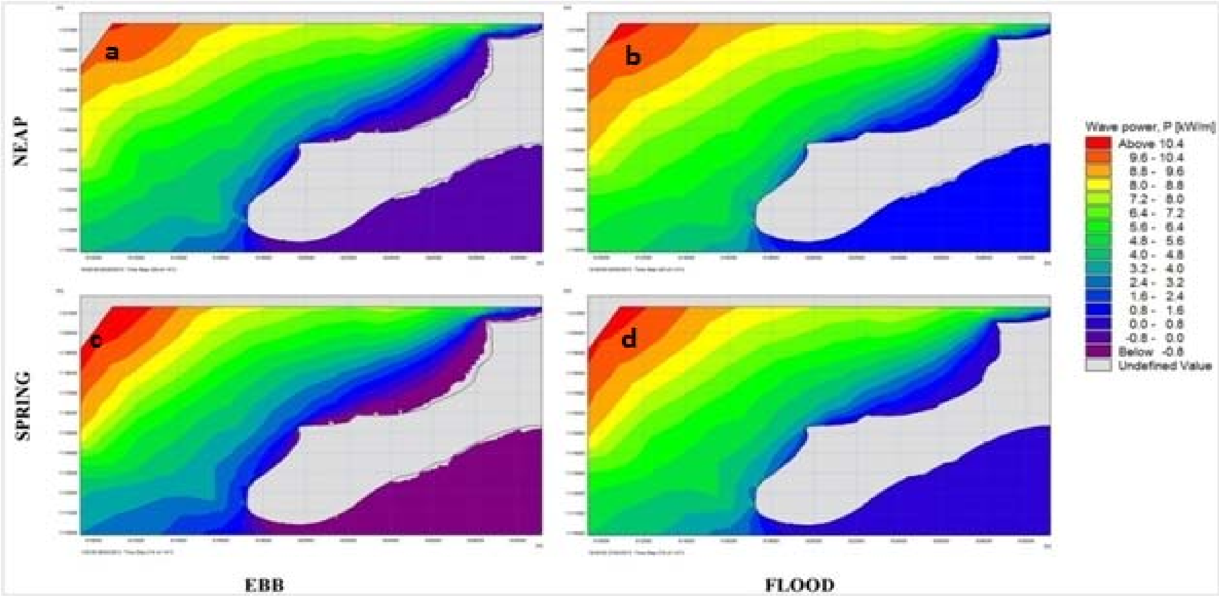


Figure 7 : Modelled wave power during Spring and Neap Cycles (a) wave power ranging between 0 and 3.2kW/m during neap ebb, (b) wave power ranging between 1.6 and 4.8kW/m during neap flood, (c) wave power ranging between 0 and 2.4kW/m during spring ebb and (d) wave power ranging between 1.6 and 4.0kW/m during spring flood. Generally low wave power is noted in Columbus Bay < 4.0kW/m which suggest little sediment transport due to waves

ii. *Wave height and direction*

The differences observed between spring and neap conditions regarding wave heights were minimal (Fig. 8). For both cycles, wave approached from the north west with offshore wave conditions ranging between 1.04m and 1.2m and near shore waves between 0.64m and 0.96m. This observation points to a reduction in wave energy caused by dissipation as a result of bathymetry interaction.

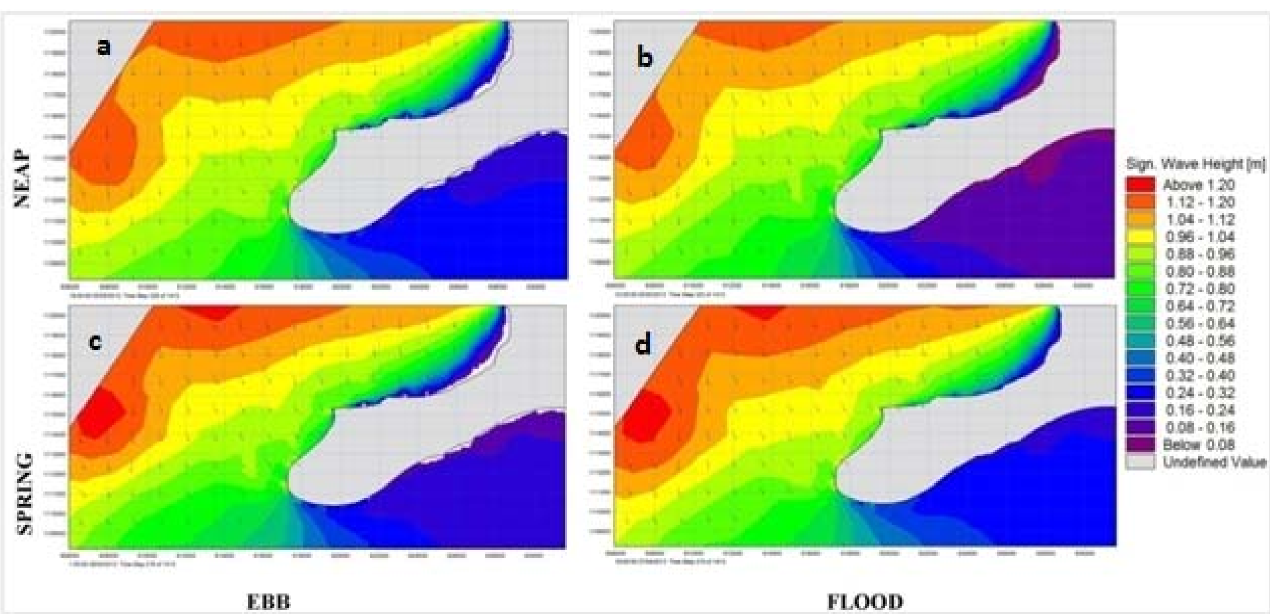


Figure 8 : Modelled significant wave height during Spring and Neap Cycles. (Arrows indicate wave direction). (a) wave height ranging between 0.72 and 0.88m during neap ebb, (b) wave height ranging between 0.64 and 0.80 m during neap flood, (c) wave height ranging between 0.72 and 0.88m during ebb spring, (d) wave height ranging between 0.80 and 0.96m. Modelled waves in Columbus Bay are from the north-west forming a perpendicular angle to the shoreline. This suggests very little sediment transport occurs due to waves as the angle to the shoreline is not oblique.

iii. *Wave radiation stresses (Sxy)*

The ebb and flood conditions for both spring and neap cycles show similar values. Observed values ranged between -0.175m^3/s^2 and -0.075m^3/s^2 for both ebb and flood conditions respectively (Fig. 9). These negative values indicate that sediment from the beach area is being removed as a result of wave radiation stresses.

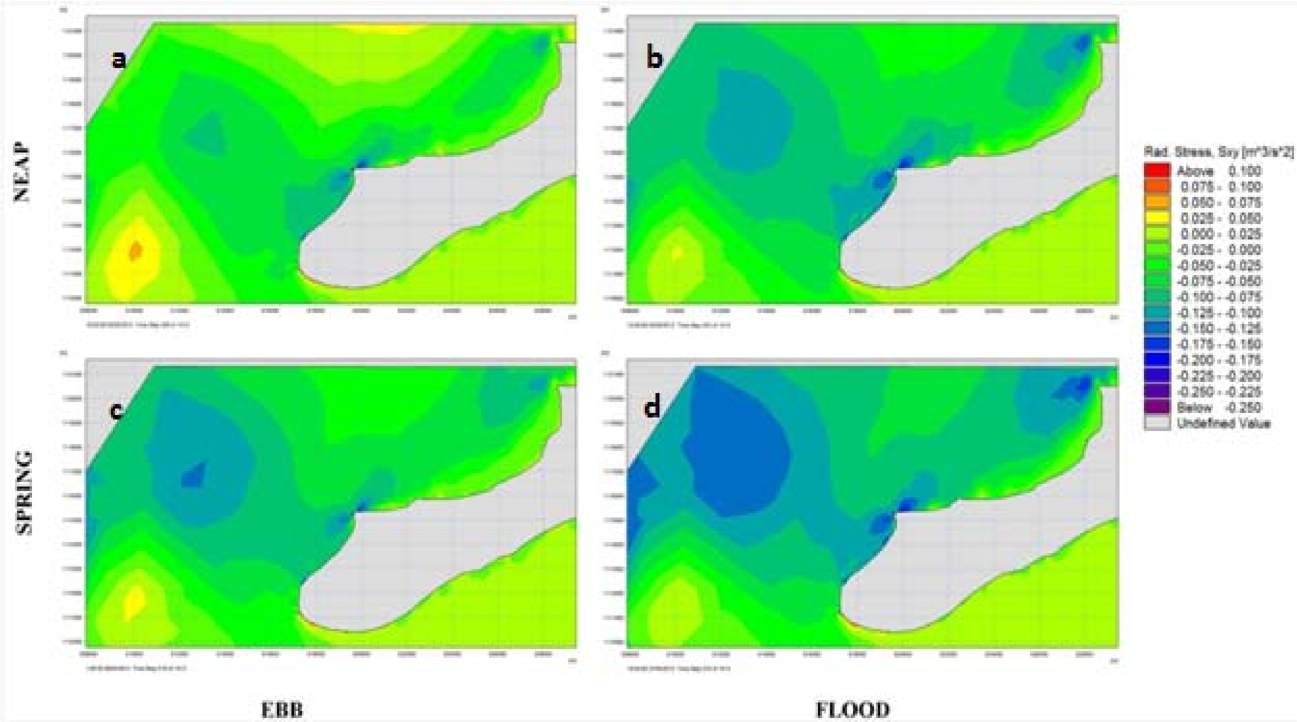


Figure 9 : Modelled wave radiation stresses during Spring and Neap Cycles. (a) wave radiation stress ranging between -0.125 and -0.075 during neap ebb, (b) wave radiation stress ranging between -0.175 and -0.075 during neap flood, (c) wave radiation stress ranging between -0.175 and -0.075 during spring ebb, (d) wave radiation stress ranging between -0.175 and -0.100 during spring flood. In Columbus Bay wave radiation stress is low and does not suggest significant sediment transport. Higher wave radiation stresses are noted around the headland possibly due to small eddies being formed

b) *Hydrodynamic conditions at Columbus Bay*

i. *Current speeds and directions*

The modeled results illustrate that there is a difference in speed between ebb and flow tidal states, in particular the ebb currents producing a higher magnitude (Fig. 10). Ebb currents are shown to be stronger than flood currents with values ranging between 0.18 to 0.36ms^{-1} on a spring tide and 0.36 to 0.54ms^{-1} on a neap tide. During a spring flood tide, currents range between 0.06 and 0.24ms^{-1} and a neap flood tide produce currents between 0.06 and 0.12ms^{-1}. Maximum speeds of 0.54ms^{-1} were observed on the ebb neap tide. In terms of current direction, there is a marked reversal in the flow during the ebb and flood tidal states. This difference is translated into a southwest flow during a flood tide and north east flow on an ebb. These results suggest that tidal flows are more influential on sediment transport when compared to waves.

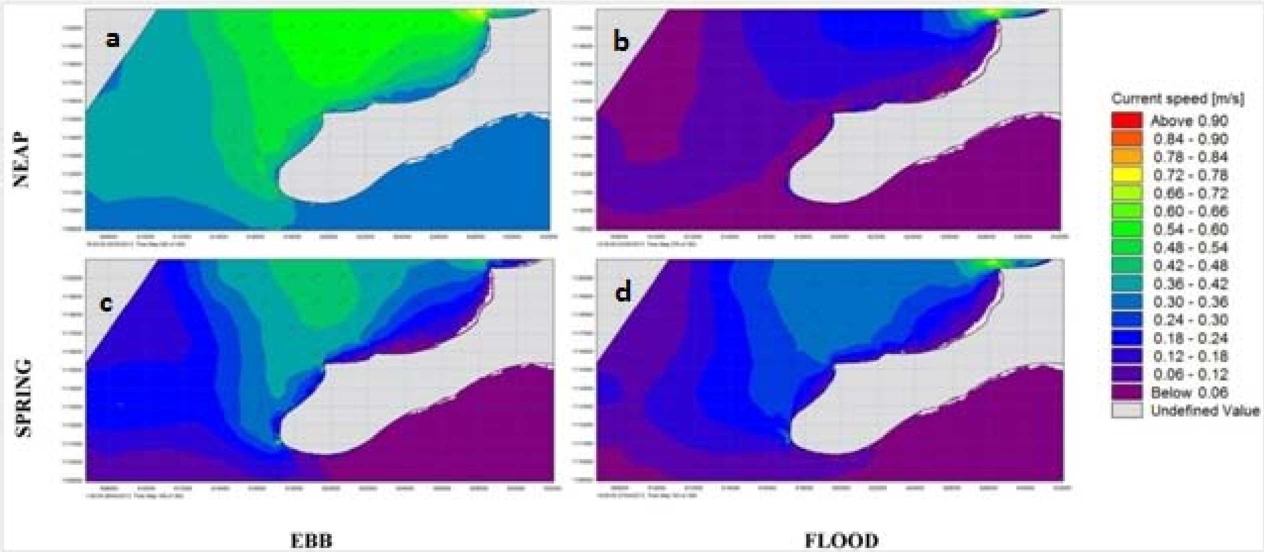


Figure 10 : Modelled current speed and direction during Spring and Neap Cycles. (Arrows indicate current direction). (a) current speed ranging between 0.36 and 0.54ms^{-1} during neap ebb and current is directed to the north east (b) current speed ranging between 0.06 and 0.12ms^{-1} during neap flood and directed to the south west, (c) current speed ranging between 0.18 and 0.36ms^{-1} during ebb spring and directed to the north east, (d) current speed ranging between 0.06 and 0.24ms^{-1} during spring flood and directed to the south west. Currents within Columbus Bay have the potential to move sediment but have higher potential to do so during the ebb than the flood state. During the ebb state sediment is pushed to the north east consistent with the current direction

c) *Sediment transport conditions*

i. *Rate of bed level change*

The rate of bed level change for spring and neap cycles is negligible, measuring -1.0 to 0.2m in the spring and -0.8 to 0.8m in the neap .In contrast, there are marked differences between tidal ebb and flood states. During ebb conditions negative values of rate of bed level change were observed, with rate of bed level changes ranging between -0.8 and -0.4m during spring ebb and -1.0 and -0.6m during neap ebb (Fig.11).These negative values indicate erosion during the ebb tides. During flood conditions for spring and neap tides, positive rates of bed level change (between 0.0 and 0.8m) are observed, indicative of accretion.

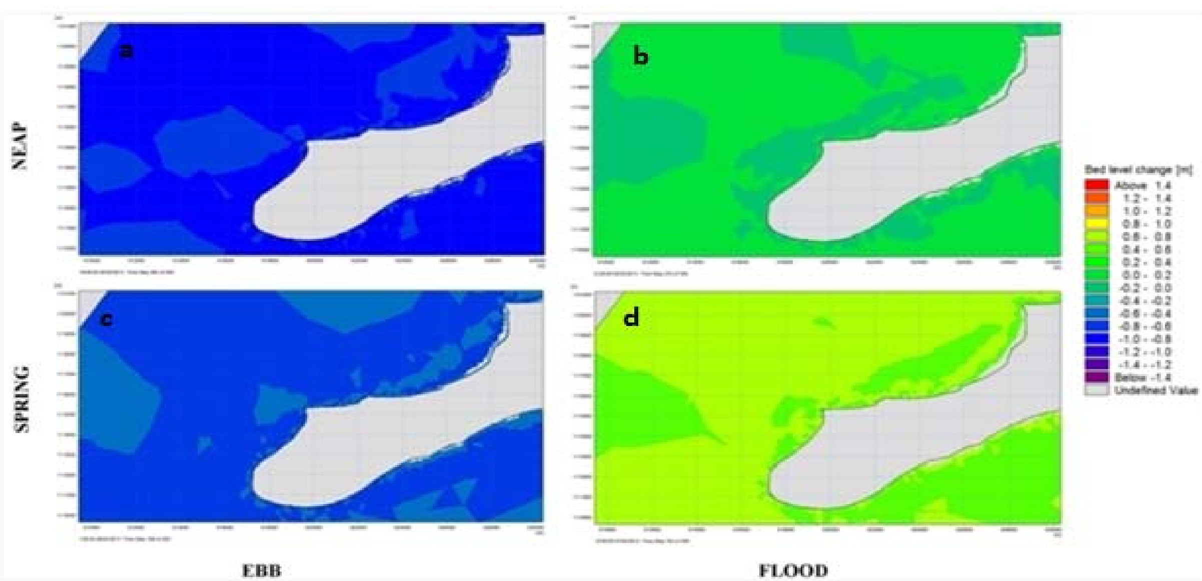


Figure 11 : Rate of bed level change during Spring and Neap Cycles. (a) rate of bed level change ranging between -1.0 and -0.6 during neap ebb. (b) rate of bed level change ranging between 0 to 0.2 neap flow, (c) rate of bed level change ranging between -0.8 and -0.4 spring ebb (d) rate of bed level change ranging between 0.4 and 0.8 during spring flood. Positive bed level change occurs during the flood state and during the ebb negative bed level change occurs. This negative bed level change coincides with higher current speeds during the ebb tide state

d) Beach profile analysis

The information on the monthly beach profile monitoring was collated to annual profiles for this study using eight stations in the study area. This was done to complement the modeling output and to provide an indication of the coastline retreat observed over the study period (Fig.12). Station1 located just updrift of the first groyne has recorded accretion on the berm, but the rest of the profile experienced a general lowering of sand levels over the study period. In contrast, Station 2 located (just downdrift of the first groyne) has accreted from 2009 to 2010 after the installation of groynes. Further, no coastline retreat was observed at this location, although dynamic profile changes have occurred between 2010 and 2013. Station 3 located updrift of the second groyne shows signs of erosion due to lowering of sand levels, and not as coastline retreat. At station 4, located between the second and third groynes, the profile has recorded accretion from 2009 to 2010. From 2013 to 2013, the profile continues to display dynamism though at higher sand elevations when compared to 2009.

At station 5, (located just downdrift of the third groyne) there was no coastline retreat, and with the exception of January 2012, the profile was not as dynamic as at the other stations. The benchmark at Station 6 located just outside of the groyne field was lost to coastline erosion, and as such was not surveyed thereafter. Station 7 located at the central section of the bay has continued to experience high rates (just over 2 m/yr) of coastline retreat. Station 8 located in the southern section of the bay is the most vulnerable. In addition to high rates of coastline retreat (approx. 2 m/yr), the profile is also experiencing a significant level of lowering of sand elevations. These results support the continued erosion trend as reported by Alexis (2012). Accretion was observed in the lee of the sand bag groynes located between stations 1 to 6. From station 7 in a southward direction, the coastal erosion continues to be a serious problem. This is evident by the coastline retreat recorded at stations 7 and 8 (Fig. 12).

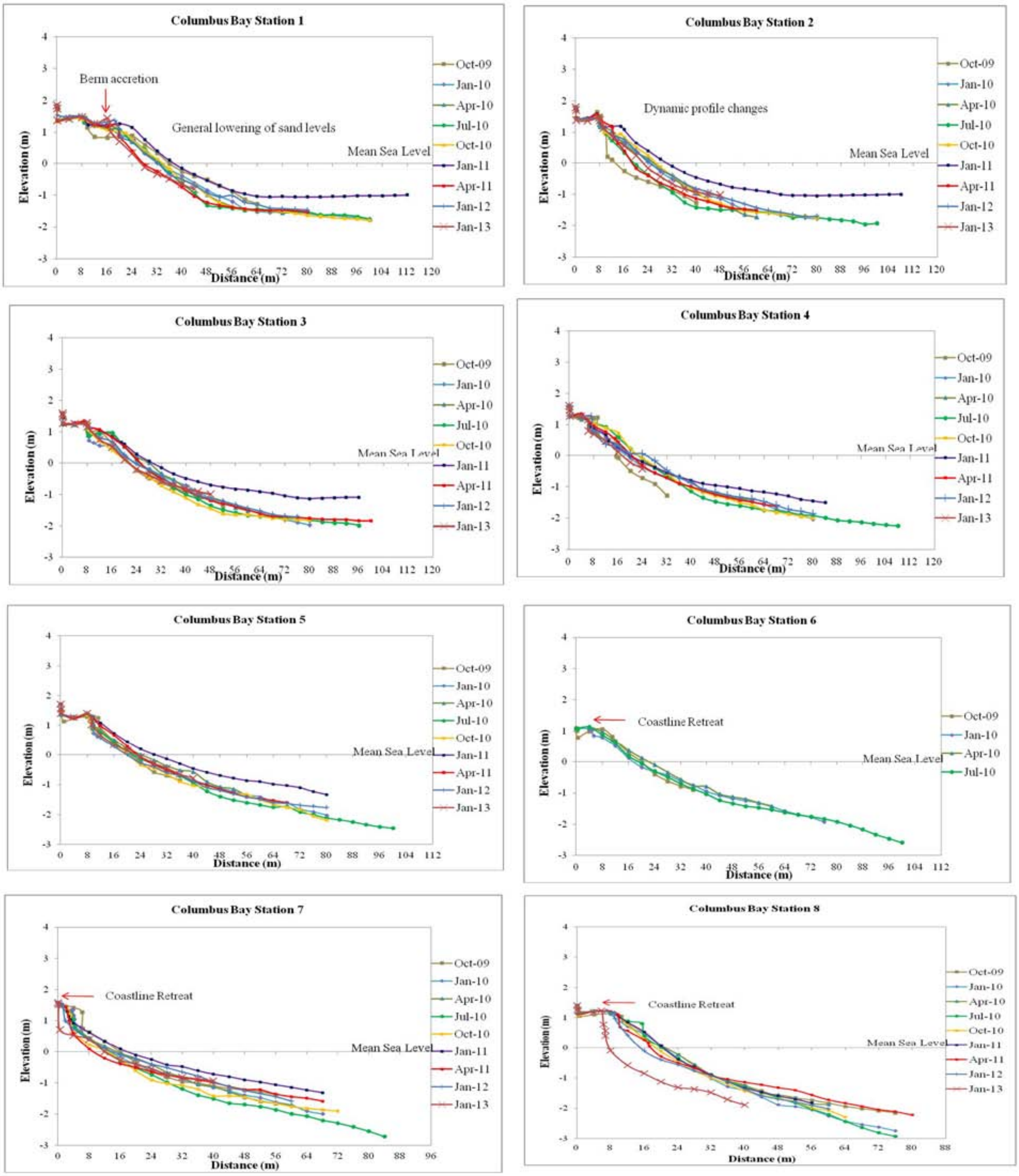


Figure 12 : Selected beach profiles for stations 1-8 (October 2009 to January 2013). Coastline retreat is noted at Stations 6, 7 and 8

VI. Discussion

a) *Wave conditions at Columbus Bay*

The difference in wave power during spring and neap tide cycles was negligible. This seems to suggest that these cycles do not influence the waves at Columbus Bay to any noticeable extent. Wave power was observed to be negligible in the lee of the Los Gallos headland. This result is expected as the headland acts as a buffer to wave energy. Overall, the output from the modeled wave power suggests that waves are not a determinant factor for sediment transport in the bay. The demonstrated low wave height values in the near shore area translate into a low energy environment which suggests a minimal influence on sediment transport. Sediment transport is influenced by simultaneous interaction of both wave height and direction. The observed low wave heights and wave direction are not conducive to sediment transport as it makes a perpendicular angle with the shoreline, and would not set up strong long shore currents. Under fair weather conditions, these wave characteristics have little or no influence on the sediment transport operating in the bay.

b) Hydrodynamic conditions at Columbus Bay

Results suggest that currents during the ebb flow are responsible for the majority of sediment transport along Columbus Bay. The currents during an ebb flow have a north-easterly direction causing sediment to be transported in that direction. It is also evident that in the vicinity of the headland, such phenomenon is influential in causing sediment accretion in this area. Due to the semi-diurnal nature of the tidal regime, it is possible that the flow reversal experienced also aids in tidal re-suspension of sediments, which promote sediment transport. These findings concur with those of Alvarez and Jones (2004) and Darsan (2013).

c) Sediment transport conditions

The study area is influenced by the Guiana current which has a residual flow from south to north through the Serpents Mouth (van Andel and Postma, 1954; Oostdam, 1982; Gopaul and Wolf, 1995). Results show that the current speed and direction are the main drivers of sediment transport in the bay with most of the erosion occurring during the ebb state. Based on this modeled result, it is possible that during the ebb flow, the combined effect of tidal ebb currents and the Guiana current flowing in the same direction, leads to increased sediment transport. Given that the bay experiences ebb states on a semi diurnal basis, this therefore amounts to significant erosion mainly driven by tides. Such findings are invaluable to management decisions as it aids in targeted intervention toward arresting erosion and promoting sustainable land management.

d) Beach profile analysis

The installed groynes in the northern section of the bay would undoubtedly interrupt sediment transport within the area of installation. The long shore current direction is towards the south-west, and under typical conditions, accretion would be observed up drift of each groyne, with erosion occurring on the down drift side. Beach profile data indicated accretion at site 2 just down drift of groyne 1, which is unusual. Station 3 located updrift of the second groyne also showed signs of erosion, and should have been accreting under the dominant long shore current direction. The accretion observed at station 2, and the erosion at station 3 may be due to the influence of the stronger tidal ebb current from the opposite direction - and is in agreement with the modelled hydrodynamic conditions of the bay. These findings suggest the presence of the combined effect of long shore currents and tidal ebb currents which are keeping the sediment entrained and thereby promoting erosion in the observed areas along the bay.

e) Contribution to land management

Erosion of any magnitude in Columbus Bay can affect sustainable land management given the level of interaction between the coastal processes in the form of erosion and the land use in the area. Columbus Bay has a mixture of land use including a critical mangrove habitat which provides valuable ecosystem services especially in soil stabilization. In addition, the presence of agricultural and residential activities forms the micro–economic activities in the area. These activities over the years are been affecting by land loss. In an effort to promote sustainable land management of this area, one prudent approach will be to institute some measures which considers the coastal dynamics to protect the land from coastal erosion. Such approach will be beneficial as it will allow the wetlands to continue to provide the environmental services while simultaneously allowing agricultural activities to strive, thereby sustaining the economy of the area. The results shows that the coastal processes in Columbus Bay is dynamic and therefore consideration needs to be given to some form of engineered solutions. However, the choice of coastal defense must be carefully considered as improper utilization or poorly designed engineering structures can actually exacerbate the erosion problems.

Given that currents are one of the major contributing factors to erosion in this area, perhaps the use of strategically placed groynes may be an option for planners which will reduce currents in the lee of structures thereby promoting accretion. These groynes could be used to trap sediment being transported with the north easterly directed ebb current. Given that accretion was noted in the lee of the groynes 1 to 6, further evaluation of conceptual groyne field layouts should be further tested using the MIKE 21 coupled model. A note of caution is that any proposed groyne field should be tested with various spacing and lengths for groynes to determine the impact on sediment transport as these parameters influence the efficiency of the groynes (Reeve and Fleming, 2004).

The outcomes of this study are relevant as it furthers the understanding of the existing conditions at the bay. These data can be used as a baseline to which further comparison can be made of oceanographic conditions, should engineering solutions be given greater consideration as an option in sustainable land management. In broader terms, this study has given policy makers an opportunity of incorporating marine data into land planning. Traditionally, land use planning involves solely the land area of the country which has proven to be less effective in coastal areas. This has led to more reactive approaches to coastal management in the event of erosion and storm surges among others, thereby resulting in a significant financial implication in terms of sea defense and in the long term, settlement relocation. These problems are set to increase given the predicted and actual impacts from the effects of climate change.

The integration of marine processes and their impacts into land planning can lead to more comprehensive planning which can minimize some of the issues cited above. This approach is highly beneficial especially in Small Island States (SIDS) such as Trinidad where land resource is limited coupled with growing population pressure (Singh, 2008; Singh, 2005). Therefore this approach of incorporating the marine component into land planning as exemplified by this study seems to be the way forward.

VII. Conclusions

The coastal area of Columbus Bay is part of a very dynamic system due to its geographic and oceanographic setting. The ongoing coastal erosion directly influences the shoreline evolution of the bay and poses challenges for effective land management. Results indicated that the most influential factor in effecting sediment transport was current speed and direction during the ebb state. While tidally generated currents in macro-tidal, estuarine, and tidal inlets have been well documented to be influential in coastal erosion, this study has revealed a similar influence in a tropical micro-tidal setting. Wave energy, although present, plays a negligible role in this environmental setting, and as such, appropriate measures to mitigate the coastal erosion must address the tidal currents operating in the bay. The deploying of sand bag groynes has proven to be somewhat effective in the northern section of the bay, though more engineering considerations need to be given in an effort to develop a design that suits the conditions present. In addition, proper placement of the groynes needs consideration in order to ensure effectiveness.

This study has demonstrated the influences offshore phenomena such as sediment transport can have on the shoreline, and the role such information could play in informing land use planning. Often land management decisions are made without the use of robust scientific data, often leading to more pronounced problems such as increased erosion, further damage of infrastructure and loss of amenity thereby affecting human well being. This study has demonstrated the importance of understanding the coastal dynamic processes and also points to the potential benefits such work plays in supporting sustainable land management approaches, a notion being highly advocated as needed in SIDS around the world.

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