Influence of high-energy conditions on beach changes in tide-dominated (Amazon, Brazil) and wave-dominated (NSW, Australia) coastal environments

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ABSTRACT

Pereira, L.C.C., Vila-Concejo, A., Trindade, W.N. and Short, A.D., 2011. Influence of high-energy conditions on beach changes in tide-dominated (Amazon, Brazil) and wave-dominated (NSW, Australia) coastal environments. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 115 – 119. Szczecin, Poland, ISSN 0749-0208

Two beaches located near the mouth of estuaries in contrasting environments were analyzed in the present study. São Luís’ beaches are located on the Amazon coast (Brazil), a coast dominated by tidal processes. Jimmy’s beach is located on the SE coast of Australia, a wave-dominated coastal environment. The aim of this paper is to compare the evolution of the two areas under different wave-tide conditions. Hydrodynamic and topographic surveys were undertaken during seasonal conditions in both areas. The most obvious differences are the tide ranges, incident waves and rainfall patterns, together with the sources and availability of sediments. It appears also that anthropogenic changes often override natural change at both locations. The beaches of São Luís are undergoing erosion, mainly in the outer section of the bay, while the inner-middle sections often register accumulation in the wet season (river supply, inner section) and in the dry season (aeolian dune supply, middle section). Jimmy’s beach is a sediment-starved environment that undergoes continuous erosion. Sources of sediment are limited, but they seem to be linked to the dynamics of the outer parts of the flood-tide delta that provides sediment that is transported into the estuary by severe and extreme storms. This paper shows that high-energy events do not necessarily cause major erosion to all areas, which normally exist under low-energy conditions. In fact, high energy events seem to have the capability of activating sediment sources that are not normally connected to the sediment budget of the area, thus bringing ‘new’ sediment into the system.

ADDITIONAL INDEX WORDS: Morphodynamic, hydrodynamic, sediment sources.

INTRODUCTION

Coastal regions that incorporate bays and estuaries are characterized normally by the presence of a long length of shoreline (Galloway, 1981; Nordstrom, 1992), and the site of some of the most densely populated areas of the world. These environments are normally sheltered (Eliot et al., 2006; Short et al., 2006; Travers, 2007) and wave action is minimal when compared with exposed coasts (Jackson et al., 2002; Short, 2007; Vila-Concejo et al., 2010). Most of the available studies in the literature have been undertaken on oceanic beaches, with less attention paid to sheltered environments and consequently there is a scarcity of information with regards to their morphodynamic processes (Masselink and Pattiaratchi, 2001; Jackson et al., 2002; Short, 2007). This might have a negative impact on the present and future planning and management actions, as a consequence of the uncertainties about natural and anthropogenic conditions, e.g. climate changes, urban development, population growth, amongst others (Nordstrom, 1992).

Research reported here shows the response of wave-sheltered sandy beaches under the influence of high-energy conditions in a tide-dominated bay (Amazon, Brazil) and a wave-dominated estuarine beach (New South Wales, Australia). These sites were selected because they present different morphodynamic patterns, under episodic high-energy conditions. In addition, both sites are undergoing erosion and are strongly affected by human activity.

The aim of this study is to show the influence of episodic high energy conditions at the two estuarine sites, one tide-dominated and one wave-dominated, together with variations in climate and anthropogenic conditions. These results will be available for the elaboration of future planning or management actions, in these or other regions under similar dynamic processes.

STUDY AREAS

In this study, two beach systems located near the mouth of estuaries under contrasting wave-tide regimes and climate patterns were analysed. The beaches of the São Luís area are located on the Amazon coast of Northern Brazil, a coast dominated by tidal processes (Figure 1). Jimmy’s beach is located on the SE coast of Australia, a wave-dominated coastal environment (Figure 2).

The Amazon littoral represents just over one third of the country’s 8,500 km coastline. Hydrodynamic patterns in this region are controlled by a series of factors, including the macrotidal regime, tidal currents, northeasterly trade winds, low
Coriolis effect, high rainfall, and a large fluvial discharge (Meade et al., 1985; Marengo, 1995; Kineke et al., 1996). The maximum inshore wave height ranges normally from 0.8 to 1.5 m, whilst the wave energy is modulated by the low tide as a result of the wave attenuation on sand banks (Monteiro et al., 2009). Topographic features are also important— the continental shelf is both extensive and gently sloping, whilst the coastline is highly irregular, with numerous bays and estuaries, mangrove systems crisscrossed with tidal creeks, and with sandbanks or sand long-shore bars (Nittrouer and DeMaster, 1996; Pereira et al., 2009). São Luís littoral is 12 km long (Figure 1) and its sandy beaches are dominated by semidiurnal macrotidal conditions (neap and spring tides are 4.5 m and 6.2 m, respectively). Equinoctial spring tide events provide the greatest hydrodynamic energy. Therefore, sediment transport results mainly from the dominance of the tidal currents. The area is located in the tropics (2° S) and the climate is characterized by a summer dry and winter wet season.

Port Stephens is located in New South Wales (NSW), SE Australia (Figure 2), 230 km north of Sydney. It is a ria-like drowned river valley estuary (Roy et al., 2001). Tides in the area are semidiurnal and microtidal with mean tidal ranges of 1.6 m and 1.3 m for spring and neap tides, respectively (Short, 1985). According to Short and Trenaman (1992), the wave climate is moderate with mean significant wave heights (Hs) of 1.5 m and 8s mean wave period (T). The same authors state comment that the central NSW coast receives a significant amount of high-energy waves (2-3 m, 21%; 3-5 m, 5%) with few low-energy waves (<1 m, 10%). Waves from the NE dominate during summer and E-SE waves are prevalent for the rest of the year. Although SE storms may occur at any time of the year, they are more frequent between April and September (Short and Trenaman, 1992). Winds in the area are strongly influenced by a daily breeze pattern, with onshore winds (>30 km/h) occurring in the afternoon from Spring to Autumn; W-SW winds with speeds over 30 km/h dominate the winter months (BOM, 2006). Port Stephens has a well developed flood-tide delta (Figure 2) that is regularly affected by swell propagation into the estuary. Several authors (i.e., PWD, 1985; DPWS, 1999) have also pointed out the importance of locally generated wind-waves that influence the flood-tide delta and the associated beaches. Jimmy’s beach is located on the northern shoreline of Port Stephens estuary, on the New South Wales coast. It extends more than 4 km into the estuary and ranges from wave-exposed near the entrance to more sheltered further into the estuary.

Figure 2. (a) Location of Port Stephens within Australia; (b) Map showing Port Stephens the outer port, to the East, is the subject of this investigation; (c) Aerial photo (April 2006) of the outer port (from Vila-Concejo et al. (2007)).

METHODS

In São Luís, data were obtained during four seasonal conditions: December 2008 – dry season/lowest river discharge; March 2009 – wet season/rising river discharge; June 2009 – wet season/highest river discharge; and September 2009 – dry season/falling river discharge. Hydrodynamic data (waves, tides and currents) were measured off the São Marcos, Calhau and Olho d’água. Part of the hydrodynamic data was collected with a bottom-mounted mooring to which a mini-current meter, a CTD, and wave and tide data loggers were attached. The mooring was mounted on the seafloor at 1.7 m depth during low spring tide. The tidal current was measured every 10 min, and its direction recorded in relation to the magnetic North. Waves were measured at a rate of 4 Hz (512 samples per 10 min). Tide data were acquired every 2s and mean values were obtained every 10 min. Morphological data were obtained through four topographic surveys. Meteorological (speed winds and rainfall) and hydrodynamic data (tide elevation and offshore significant wave) were obtained, between December 2008 and November 2009 from the Brazilian Institute of Meteorology (INMET), the Hydrographic and Navigational Department of he Brazilian Navy (DHN), and...
the Weather Forecasting and Climatic Studies Center of the Brazilian Space Agency (CPETEC-INPE), respectively.

At Jimmy’s beach, data used for this study include: (i) short-term, winds, currents and waves; and (ii) medium-term, seasonal beach profiles and offshore wave data. Measurements took place between March 2007 and April 2008. Hourly offshore wave data were obtained and hydrodynamic conditions (waves and tides) were measured during summer and winter conditions. Topographic surveys using total stations and a Real Time Kinematic Global Navigation Satellite System were undertaken periodically. Wave power was calculated for the entire study period using standard linear theory for a window of incidence between 70 and 180 deg N (Vila-Concejo et al., 2010).

In situ measurements of waves and currents were undertaken using an Acoustic Doppler Velocimeter (ADV) which was deployed shore-aligned, to measure across-shore and alongshore currents. Topographic data were analysed using standard techniques following procedures given in Vila-Concejo et al. (2010).

RESULTS AND DISCUSSION

The results showed that at São Luís, the monthly average wind speed is up to 5.2 m/s in the wet season and 8.1 m/s in the dry season (Figure 3A). During the dry season, the winds blow mainly from NE, while during the wet season the SE winds are dominant. Tides were semi-diurnal and macrotidal with tide elevation higher than 6.0 m during spring tide periods (Figure 3B). Offshore significant wave heights (Hos) (Figure 3C) were normally less than 1.2 m, except in March, 2009 (up to 1.5 m). Tide ranges were between 4 and 5 m (Figure 3D-3F). Tidal currents (Figure 3G-3I) attained maximal speeds in outer-a. March 2009 (in inner-middle) and June 2009 (in outer-a and outer-b) were the months with the highest current speeds (up to 0.5 m/s). Nearshore waves were modulated by the tide due to sand shoals that prevent wave propagation during low tide. As a consequence Hs values (Figure 3J-3L) ranged between 0.2 m (low tide) and 1.4 m (high tide) in March 2009 and from 0.6 m (low tide) to 1.2 m (high tide) in September 2009. During the study period, this 12 km

Figure 3. (A) Meteorological, (B-L) hydrodynamical and (M) volumetric balance in São Luís beaches. The symbol /\ indicates the dates of the field surveys.
long beach coast (approximately 3 km for each section) underwent overall erosion of 32,000 m³. Severe erosion problems usually occurred during the wet season, with the exception of the inner section, which underwent accumulation. During the dry season, with the strong northeast winds, aeolian sand transport causes accumulation in the middle section while erosion occurred in the inner and outer sections (Figure 3M).

The São Luís area is one of the most urbanised zones of the Amazon littoral, and unregulated occupation on the dunes and intertidal zones has contributed for the erosive processes in the studied area (Silva et al., 2009). Anthropogenic processes associated to natural conditions resulted in three different patterns: (i) March (the most energetic period) registered several erosion events in the middle and outer sections, with sediment accumulation in the inner section (river supply); (ii) June registered accumulation in the inner and middle sections (river supply), with erosion in the outer section; and, (iii) September registered accumulation in the middle section, but erosion in the inner and outer sections.

At Jimmy’s beach, SE waves (Figure 4) dominated during most of the study, with several extreme SE storms (Hos > 5 m) occurring in June-July 2007. During the rest of the study period, there were several high-frequency storms (2.5 > Hos > 5m). Intense W winds (6.1 m/s) also occurred in June 2007; this was concurrent with SE Hos (2.3 m). This 4 km long coast underwent overall erosion of 42,000 m³ during the study period; maximum erosion occurred in May 2007 when storms struck after a period of extended fair weather conditions (Figure 4). The largest erosion on the beach occurs in an occupied area within the easternmost section of the sandspit that forms Winda Woppa (Figure 2). The large storms of June 2007 caused accumulation in the areas near the entrance to the estuary and erosion on the remaining areas of the beach (Vila-Concejo et al., 2010). Few changes occurred on the beach in July and November 2007, whereas in April 2008, sediment accumulation was measured (mostly of anthropogenic origin). Overall, the area experienced net erosion on the beach sections and accumulation on the sandwave (Vila-Concejo et al., 2009). It is important to note that human intervention occurred as emergency nourishment (less than 10,000 m³ and also as pipelines were buried along the beach for future nourishment interventions; erosion on the beach would have been more severe if these interventions had not occurred (Figure 4 shows accumulation in westernmost section and along the central areas of the beach). It was found that high-frequency (low energy) storms cause acute erosion at Jimmy’s beach while low-frequency (high energy) storms cause sediment accumulation in the outer the parts of the beach, near the estuary entrance (Vila-Concejo et al., 2010).

Short-term measurements showed that, under fair weather conditions, the currents were modulated by the tides and reversed according to the tidal stage. With SE waves Hos > 1 m propagating into the estuary, alongshore currents were westwards in the outer areas of Jimmy’s beach, and they were negligible on the area of the erosion zone (waves arrived shore normal). Under westerly conditions there were eastward currents at the erosion spot, but westward currents in the outer areas of the beach (near the sandwave). More details on the current measurements in Jimmy’s beach can be found in Vila-Concejo et al. (2011).

**Effects of high-energy events**

Both studied areas normally experience low energy conditions with little wave activity. High-energy events are different in both areas: while the highest energy at Jimmy’s beach is caused by SE incident waves, the highest energy at São Luís’ beaches can be caused by large equinoctial tides, fluvial discharge during the wet season and strong winds during the dry season. While high energy events cause generalised erosion on the studied beaches, it has been shown that, under certain conditions, those high energy events allow sediment transport into the system. This happens with extreme storms in Jimmy’s beach that bring sediment into the sandwave (outer, the most exposed to incident waves, sector of the beach), thus implying that sediment sources are seawards from the beach, perhaps in the outer sections of the FTD (Vila-Concejo et al., 2010). In the case of the Amazonian beaches, aeolian dune sediment accumulation occurs in the middle sector of the study area, during the dry season; while accumulation is observed in the inner sector during the wet season, implying a riverine sediment source.

![Figure 4](image-url)

**CONCLUSIONS**

Both areas studied are located in lower-energy, partly sheltered, environments and are undergoing erosion. The most obvious differences between the two are tidal range, incident
waves and rainfall patterns, together with sources and availability of sediments. It also seems clear that anthropogenic changes may override natural change at both locations. The beaches of São Luís island are undergoing erosion, mainly in the outer section (more exposed area), while the inner section often register accumulation in the wet season (river supply, high fluvial discharge and lowest wave energy), and the middle section in the dry season (aeolian dune supply, low rainfall values and strong northeast winds). Jimmy’s beach is a sediment-starved environment that undergoes continuous erosion. Sources of sediment are limited, but they appear to be linked to the dynamics of the outer parts of the flood-tide delta that provide the sediment carried into the estuary by severe and extreme storms. Other sources of sediment in the area are anthropogenic.

In summary, we can conclude that high-energy events do not necessarily cause major erosion over all areas which normally exist under low-energy conditions. In fact, high energy events may have the capability of activating sediment sources that are not normally connected to the sediment budget of the area, thus bringing new sediment into the system.

LITERATURE CITED


ACKNOWLEDGEMENTS

In Brazil, this research was funded by CNPq and FAPESP. The authors Pereira and Trindade would also like to thank CNPq and CAPES for research grants.

In Australia, this research was funded by the Australian Research Council (ARC) in collaboration with the NSW Department of Environment Climate Change and Water (DECCW), Great Lakes Council, Port Stephens Council and Jimmy’s Beach Restoration Society Inc. through Linkage Grant LP0668979. The NSW Department of Commerce Manly Hydraulics Laboratory (MHL) is acknowledged who on behalf of the NSW DECCW provided the wave data. Many thanks to everyone who worked hard on the beach, especially to Dave Mitchell, Tim Austin, Lara Ainley, Hannah Power, Genoveffa Pezzimenti and Brad Morris. Thank you to Mitch Harley for helping with the implementation of his MALT system for dealing with embayed beaches.