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Research article

The influence of fluvial dynamics and North Atlantic swells on the beach habitat of leatherback turtles at Grande Riviere Trinidad

Junior Darsan [a, *], Adam Jehu [b, c], Hamish Asmath [a, c], Asha Singh [d], Matthew Wilson [a]

[a] Department of Geography, University of the West Indies, St Augustine, Trinidad and Tobago
[b] Department of Geomatics and Land Management, University of the West Indies, St Augustine, Trinidad and Tobago
[c] Institute of Marine Affairs, Hilltop Lane, Chaguramas, Trinidad and Tobago
[d] Organisation of Eastern Caribbean States, P.O. Box 179, Castries, Saint Lucia

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ABSTRACT

Grande Riviere beach, located on the north coast of Trinidad, West Indies, is internationally recognised as a critical habitat/nesting ground for the endangered leatherback turtles (*Dermochelys coriacea*). Episodic extreme flooding of the Grande Riviere River led to the shifting of the river mouth and resulted in backshore beach erosion, with the most recent recorded event occurring in 2012. Following this event, the construction of a sand dam to arrest further erosion which threatened coastal infrastructure, precipitated a host of new problems ranging from beach instability to public health threats. In January 2013, high energy swell waves naturally in-filled the erosion channel, and the beach recovery continued over the successive months, thereby rendering the intervention in the previous year questionable. This paper presents a geomorphological analysis of beach dynamics for Grande Riviere, within the context of this erosion event. Data on beach profiles, sediment and coastal processes were collected using standard geomorphological techniques. Beach topographic analysis and water quality tests on impounded water in the erosion channel were conducted. Results indicate that the event created an erosion channel of 4843.42 m^3 over a contiguous area of 2794.25 m^2. While swell waves were able to naturally infill the channel, they also eroded 17,762 m^3 of sand overall across the beach. Water quality tests revealed that the impounded water was classified as a pollutant, and created challenges for remediation. Hydrologic and coastal geomorphologic interplay is responsible for the existence and sustainability of this coastal system. It is also evident that the beach system is able to recover naturally following extreme events. Our results demonstrate that effective and integrated management of such critical habitats remains dependent upon continuous monitoring data which should be used to inform policy and decision making.

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1. Introduction

Coastal dunes, beaches and shorefaces are linked by sediment transport pathways and morphodynamic feedbacks. Collectively, they make up coastal barriers and are considered the basic depositional elements of wave-dominated coasts (Roy et al., 1994). Nearshore processes shape beach morphology (Hardisty, 1990), but there is evidence to support that morphology can influence the processes in the nearshore (Komar, 1997). Beaches and their adjacent nearshore zones act as buffers to wave energy. As a result, they are prone to change over varying timescales ranging from a few seconds to several years (Komar, 1997; Darsan, 2013a, 2013b).

Previous research on mid-latitude beaches (e.g. Norcross et al., 2002; Aleman et al., 2015), demonstrates that the beach and near-shore exchange sediment within a winter-summer cycle. During the summer, low, flat swell waves build up the berm, causing the beach face to prograde seawards and form a steep profile; conversely, in winter, high and steep storm waves erode the beach face and transport the sediment seawards where it is deposited to form a long-shore bar. The work of Cambers (1998) on Caribbean beaches has also indicated the existence of this winter-summer cycle phenomenon for low latitudes. However, Short (1979), Nordstrom (1980) and Darsan (2005, 2013a) indicate that there may not be a defined seasonal pattern to beach change, but that the beach will go through cycles of erosion or accretion. A proper understanding of coastal processes and beach dynamics are

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* Corresponding author. Tel.: +1 868 726 9171.
E-mail addresses: Junior.Darsan@sta.uwi.edu, junior.darsan@gmail.com (J. Darsan).

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therefore critical to management in terms of habitat provisioning.

Beaches provide a range of ecosystem services (Dugan et al., 2010; Schlacher et al., 2014a; Singh, 2016), with different expectations by the public in terms of their uses (McLachlan et al., 2013). The inherent dichotomous issues stem from recreational and developmental use of the beach, while protecting the beach habitat upon which the ecosystem depends (McLachlan et al., 2013). Species found on beaches are functionally dependent on these habitats (Maslo et al., 2011; Schlacher et al., 2012; 2014a; Schoeman et al., 2014), particularly marine turtles (Wallace et al., 2011). The most severe threat facing sandy beaches is coastal erosion, coastal squeeze (Schlacher et al., 2006, 2007, 2008; Schleupner, 2008; Defeo et al., 2009) and climate variability (Ortega et al., 2012, 2013).

Most management approaches to these issues involve beach nourishment (Nordstrom, 2000; Nordstrom and Mauriello, 2001; Schlacher et al., 2006), with beach habitat conservation as a minor component (Peterson and Bishop, 2005). Micallef and Williams (2002) argue that beach management decisions should be based on the analysis of empirical data. Others have identified metrics of beach size, geometry, orientation/configuration and sediment characteristics to be important (Barnard et al., 2012; Bathrellos et al., 2012; Harris et al., 2011a; Ortega et al., 2013; Schlacher et al., 2012; Schlacher and Thompson, 2012), while Schlacher et al. (2014b) has outlined a selection criteria of metrics that can be applied to beach management scenarios. Others have investigated the issues related to land-use planning, zoning and enforcement (Hossain and Kwei Lin, 2001), and set-back regulations within the context of climate change and sea level rise (Micallef and Williams, 2002; Caldwell and Segall, 2007; Fish et al., 2008).

The case presented in this paper, highlights backshore beach erosion by a river flood at an internationally important nesting ground for endangered leatherback turtles. The erosion event prompted reactionary sand dam construction (to arrest further damage to infrastructure) and created several new problems at the beach. Subsequent beach repair by swell waves pre-empted the public pressure to apply engineering solutions to in-fill the erosion channel in lieu of the upcoming nesting season of the leatherback turtles. In view of this, the primary aim of this study was to apply a multidisciplinary approach to analyse the impacts of the extreme event and advise on management of such occurrences by (a) analysing the coastal processes which occurred, (b) assessing the beach's topographic changes in response to hydrological, coastal and ecological forcing, (c) investigating the quality of the impounded water in the erosion channel and, (d) highlighting the management issues and challenges that arose. Further, a number of recommendations are provided for consideration to manage such future occurrences.

1.1. Study setting

Trinidad and Tobago is situated in the southernmost end of the Caribbean island chain (Fig. 1) and experiences a tropical marine climate with two distinct seasons. The tidal regime is that of a mixed semi-diurnal type, influenced by tide waves from the Caribbean Sea and the Atlantic Ocean (Darsan et al., 2013). Some waves occur as a result of the action of trade winds on the water's surface, storms and squalls throughout the hurricane months and swell waves originating from the North Atlantic (Deane, 1973). At high spring tides the maximum range is 1.2 m with some slight variation from north to south. At other times, the tidal range is less than 1 m, averaging 50–60 cm between high and low tides (Kenny, 2008). Swell waves are most often experienced in the Caribbean between the months of October to April, and is usually caused by intense mid-latitude storms in the North Atlantic Ocean (Cambers, 1998).

Grande Riviere bay, located on the north coast of Trinidad is exposed to the Caribbean Sea (Fig. 1), approximately 970 m long and arcuate in shape, making it a typical semi-enclosed pocket beach. Grande Riviere had an agro-economy based on cocoa in the early 1900's (Sookram and Sutherland, 2011). However, by 2000, with declining cocoa prices, ecotourism had taken over (Harrison, 2007), driven largely by the recognition of the importance of conservation efforts and recognition of the area as a prime nesting ground for the endangered leatherback turtles (*Dermochelys coriacea*) and the blue-throated piping-guan (*Pipile cumanensis*).

1.2. 2012 Grande Riviere erosion event

The Grande Riviere River usually exits through the berm flowing northerly with only marginal deviations to mouth width and location. Annually, during the beach's accretionary cycle, the river mouth may become blocked. However, members of the village routinely clear the mouth to allow for boat access to berth their fishing boats up river. In April 2012, the course of the Grande Riviere River had begun shifting westward, deviating from its normal path (Fig. 2).

Progression of this shift continued and by June 2012, the river had eroded a channel in the backshore, flowing westerly and parallel to the shoreline for approximately 150 m before entering the bay (Fig. 2). In July 2012, the Drainage Division (Ministry of Works and Infrastructure, Government of the Republic of Trinidad and Tobago) intervened and constructed a sand barrier to arrest the westward flow of the Grande Riviere River, which was threatening coastal infrastructure. Sand for the dam construction was mined from eastern section of the bay using heavy machinery. The narrower Ferdinand River in the bay's central region also shifted its path in a westerly direction along the backshore of the beach, though with less deleterious effects, given its much lower discharge. The Drainage Division also altered the Ferdinand River's course by straightening its mouth to flow directly into the sea in a northerly direction, arresting any further backshore erosion. The river was also dredged and widened to accommodate heavy flows in the upcoming rainy season and levees constructed from the spoil in an attempt to prevent any future shifting. These engineering interventions resulted in destruction of turtle nests and reduction in the beach habitat from sand excavation, pooling of stagnant water in the backshore erosion channel from dam construction, restricted beach access and reduced eco-tourists to the area.

2. Methodology

Analysis of the major threats to the physical, ecological and socio-economic facets of Grande Riviere required a multidisciplinary and holistic approach in dealing with the negative impacts of river shifting. In this study, several types of data were collected, including coastal geomorphological data on coastal processes, beach sediment and beach profiles (2003–2013), topographic data (October 2012, January 2013), and water quality data (October 2012, January 2013). Analysis of these data components was then made in order to inform on the best course of action to remedy the negative issues.

2.1. Coastal geomorphology

Beach profile, beach sediment and coastal processes data were collected at four monitoring stations (Fig. 1) using standard surveying methods as outlined by Goudie et al. (1990). Beach profiles were conducted at low tide, using the “break-in-slope” method where uneven horizontal distances were used to reflect

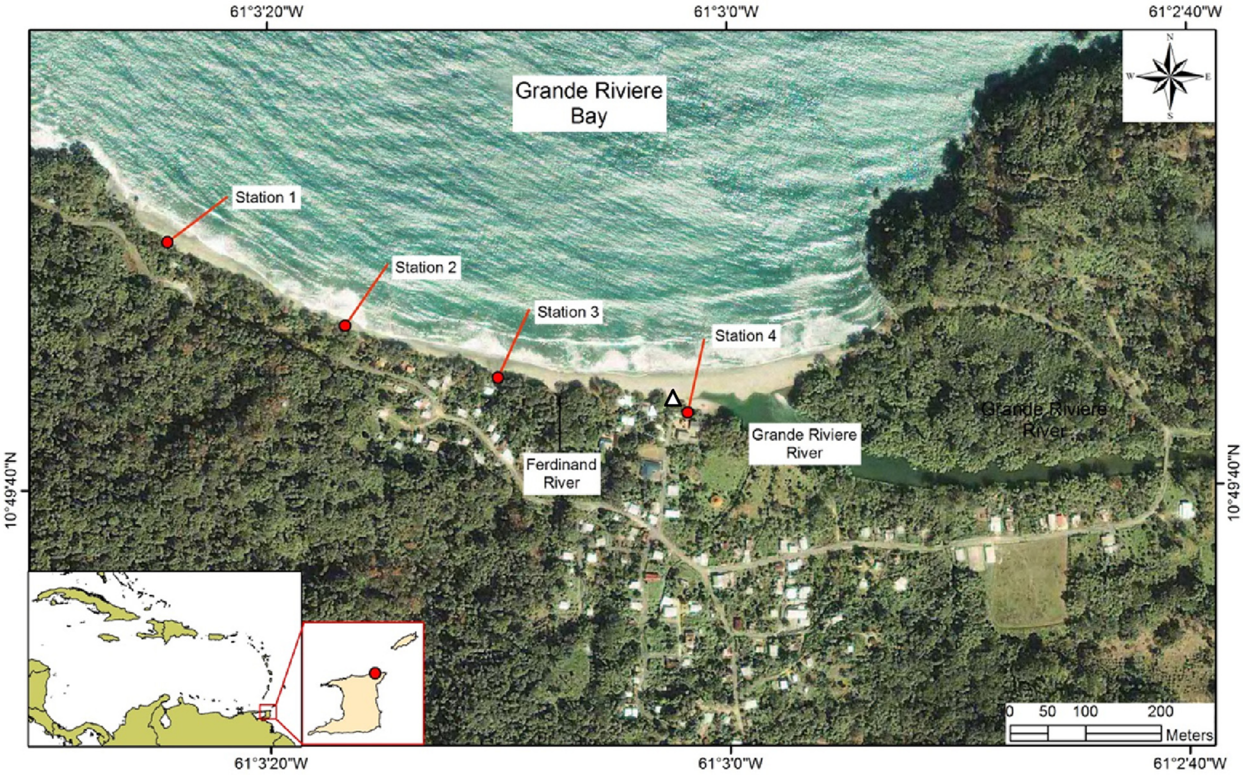

Fig. 1. Location of Grande Riviere beach in Trinidad showing beach profiling stations. The triangle indicates the location shown in Fig. 2.

Fig. 2. Beach changes (a) 2011 beach looking south (inland); (b) 2012 erosion channel for the same location; (c) 2012 impounded water in erosion channel, looking east from (b); and (d) destroyed turtle nests. The triangle in (a) and (b) is included for ease of orientation and indicates the termination of Hosang St. at 10°49′43.6″N 61°03′02.4″W.

changes in beach slope. Profiles were overlain to allow for morphological comparisons and calculations of sand elevation changes relative to a permanent beach profiling station. Beach sediments were collected at three sections along each transect (upper, mid-beach, and lower beach). Samples were oven dried and 120 g sieved at half phi intervals to obtain Folk and Ward (1957) parameters. Littoral data were collected as outlined by Schneider (1981) and Goudie et al. (1990), using an average of 3 readings. Wind speed was collected using a digital anemometer and measured in meters per second (m/s). Wind direction was obtained with a Brunton direct pointing compass. Wave height was measured using a graduated survey staff and was taken as the height between the crest and trough of the waves. Wave approach was measured from the shoreline with a Brunton direct pointing compass pointed perpendicularly toward the oncoming waves. Longshore speed was measured as the distance moved by a float object over a period of 1 min and calculated in centimetres per second (cm/s). The longshore direction in which the float moved was obtained with the compass.

2.2. *Topographic data acquisition & processing*

The physical structure of the entire beach and the estimated sediment loss was determined through topographic surveys utilizing Global Navigation Satellite System (GNSS) equipment. A permanent benchmark for the purpose of Real Time Kinematic (RTK) Surveys was created in close proximity to the beach area, and referenced horizontally to the World Geodetic System 1984 (WGS, 1984) Datum and vertically to the Earth Gravitational Model 2008 (EGM2008) Geoid. Points were acquired at a spacing of approximately 4 m for the entire beach area, yielding around 2500 observations per field mission. These data were imported to 3D GIS for interpolation using spline polynomial methodology. These raster data were then transformed to have a vertical reference to Mean Sea Level (MSL) utilizing a benchmark established by Seeram (2011). Topographic information acquired prior to the river shifting event conducted by Seeram (2011) was utilized as baseline data for the determination in GIS of volumetric sediment loss from the backshore.

2.3. *Microbial & water quality analysis*

For the determination of remedial action to the public health hazard, water physico-chemical and microbiological testing was conducted. The determination of the parameters to be assessed – for both water quality and microbial load - was determined primarily on the nature of the water contained in the erosion channel. Various parameters were measured including Ph, dissolved Oxygen (DO) and total suspended solids (TSS) among others as outlined in Table 1.

Five samples (3 @ 500 ml samples each) were taken at equidistant locations within the erosion channel where the topography dictated water settling. Several chemical and microbiological analyses were conducted including faecal coliforms and *Escherichia coli* among others (Table 1). The levels were compared to two standards:

- Environmental Management Act of the Government of the Republic of Trinidad and Tobago: Water Pollution Rules 2001 (WPR) – Schedules one and two (S1 and S2 respectively)
- United States Environmental Protection Agency (USEPA): Ambient Water Quality Criteria for Bacteria, 1986 – Criteria for Indicator for Bacteriological Densities

3. Results

An integrated approach was adopted to adequately assess the interactions of the many physical, ecological and socio-economic characteristics of the region towards answering the objectives set out in this study.

3.1. *Geomorphological analysis*

3.1.1. *Coastal processes*

Wind speed at this bay averaged 2.1 m/s, and waves approached from the north- northeast under the influence of the north east Trade Winds. Mean significant wave height was 0.8 m with a period of 7.4 s, while plunging breakers averaged 1.0 m in height. Mean longshore current averaged 11.1 cm/s and flowed northwest. The dominant longshore current direction indicates that sediment will normally be transported in a westerly direction by the action of longshore drift.

3.1.2. *Beach sediment*

The average beach sediment at Grande Riviere consists of medium grained sand that is moderately well sorted. Mean sediment grain size varies cross-shore and along-shore. The lower beach samples are coarsest being located close to wave break-point which winnows the fines (Fig. 3). The upper and lower beach sediment (station 3) adjacent to the Ferdinand River is coarser than at other sites because its proximity would introduce coarser sediments during flood flow. The mid-beach sample displays a fining of sediments in the westward direction along the bay. Sediments are generally unimodal with the exception of the lower beach sediment at stations 1 and 3 which display bimodal distributions. These sediment characteristics particularly at station 1 and 2, appear to be

Table 1
Microbiological and physico-chemical water quality.

Station	Microbiological water quality				Physico-chemical water quality				
	Faecal coliforms /100 ml	*Escherichia coli* /100 ml	*Enterococci* /100 ml		pH	DO (mg/l)	Temp (°C)	NH_3–N (mg/L)	TSS (mg/L)
1	6.9×10^3	6.6×10^3	3.6×10^1		7.5	5.44	30.9	0.012	13.8
2	9.0×10^3	6.9×10^3	5.0×10^1		7.73	5.69	30.9	0.012	13.1
3	5.3×10^3	1.8×10^3	3.6×10^1		7.66	6.29	30.3	0.01	14.2
4	3.8×10^3	2.1×10^3	1.1×10^2		7.56	4.62	29.3	0.11	10.3
5	1.9×10^3	8.2×10^2	1.3×10^2		7.53	4.17	28.7	0.27	5.7
USEPA 1986 standards				WPR 2001 standards					
Fresh water	✖	✖	✖	S1	✓	✖	✓	✖	✓
Marine water	✖	✖	✖	S2	✓	✖	✓	✖	✓

Pass (✓) or Fail (✖) based on permissible levels

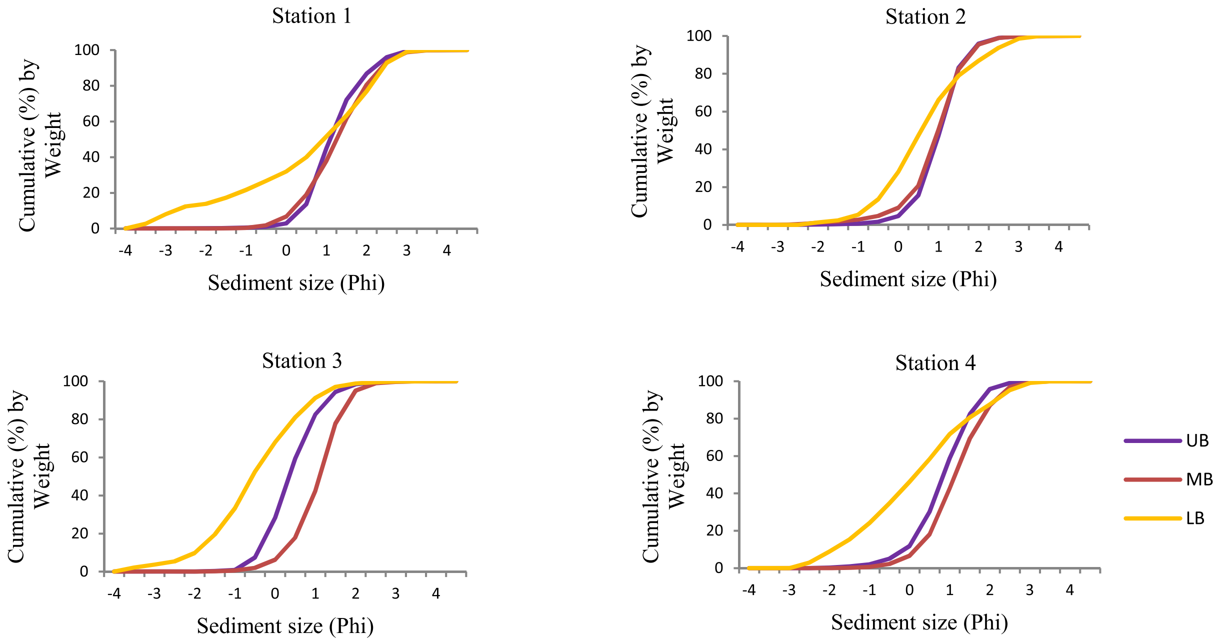

Fig. 3. Grain size distribution at Grande Riviere (where UB = upper beach; MD = mid beach; LB = lower beach).

preferred by nesting sea turtles as indicated by the nesting densities at Grande Riviere.

3.1.3. Beach profiles

At the western section of Grande Riviere Bay (Station 1) the beach was found to be in dynamic equilibrium. The backshore area is very stable due to the resistant metamorphic rocks. The berm however, was very dynamic and experienced changes in sediment elevations. Since the river shifting event, this section of the beach has been experiencing significant berm accretion; possibly from the re-distribution of the eroded sediments, although it could also be due to the normal accretionary cycle at this bay. At the central region of the bay (Station 2) the beach was less dynamic but fairly stable, with the berm experiencing continuous accretion. Dynamic equilibrium was exhibited at Station 3 also located in the central section of the bay, where the beach maintained a moderate to steep gradient. In addition to berm accretion at this station, the berm has also prograded landward (Fig. 4).

Beach profiles at Station 4 indicated that prior to the erosion event, the berm was located further seaward, producing a maximum beach-width. Subsequent to the erosion event, wave erosion on the seaward side, and overwashing of the berm forced the landward migration of the berm, which resulted in a reduced beach-width. While some vertical berm accretion has occurred after the erosion event, the berm remained significantly lower than baseline sand levels (Fig. 4).

Cyclical patterns, as observed by historical beach profile data collected by the Institute of Marine Affairs (IMA) for this area, indicate a high likelihood for the regeneration of a gentler beach slope from the high elevation area, eventually allowing for equilibrium status to be achieved over time (Darsan et al., 2012). The lack of nearshore and off-shore wave data, sediment transport and sediment budget analysis however renders the timeframe uncertain. The continued westward shift in nest distribution after May as the season progresses until August, occurs when beach erosion in the eastern section becomes predominant Lee Lum (2005). Such cyclical patterns of sediment deposition was found to be positively correlated to the spatial shift in turtle nesting behaviour whereby gravid females tended towards regions of higher relative beach elevation, following the gradual shift in accretion throughout the nesting season.

3.1.4. Episodic river mouth shifting

Historical data revealed that a river shifting event also occurred in 2003. A comparison of these two profiles indicate very similar topographical characteristics in terms of berm height and the erosion channel created (Fig. 5a). This suggests that the beach at Grande Riviere may be in a state of dynamic equilibrium that revolves around seasonal high energy swell wave events, as well as longer term episodic extreme river flooding events. These data from 2003, alongside local knowledge from the community suggests that these events occur approximately every 9–10 years (Fig. 5b).

These data indicate that the erosion channel was created during the 2003 wet season, and by March 2004, following the winter swell activity, there was infilling of the channel. By 2006 (at the time of the next survey), the profile was completely recovered (Fig. 5b). Based upon the analysis of these beach profile data it was recommended that no further anthropogenic remediative action be taken to infill the 2012 erosion channel as winter swells which would begin acting upon the beach by January 2013 would naturally infill the erosion channel.

3.2. Topographical analysis

From 13 to 16 January 2013, a swell event occurred impacting the beach and causing significant changes to beach topography. Fig. 6 illustrates the beach topography around three months after the construction of the sand dam (October 2012) and after the following swell event (January 2013). The inset box indicates the beach's eastern extent illustrated in Fig. 7. The impact of the winter swell event was more dramatic at the scale of the entire beach in comparison to the eastern area of the beach. Some 17,762 m^3 of sand was lost overall (Fig. 6c). The western area of the beach lost most of the sediment, with the protective berm completely removed by the swell event.

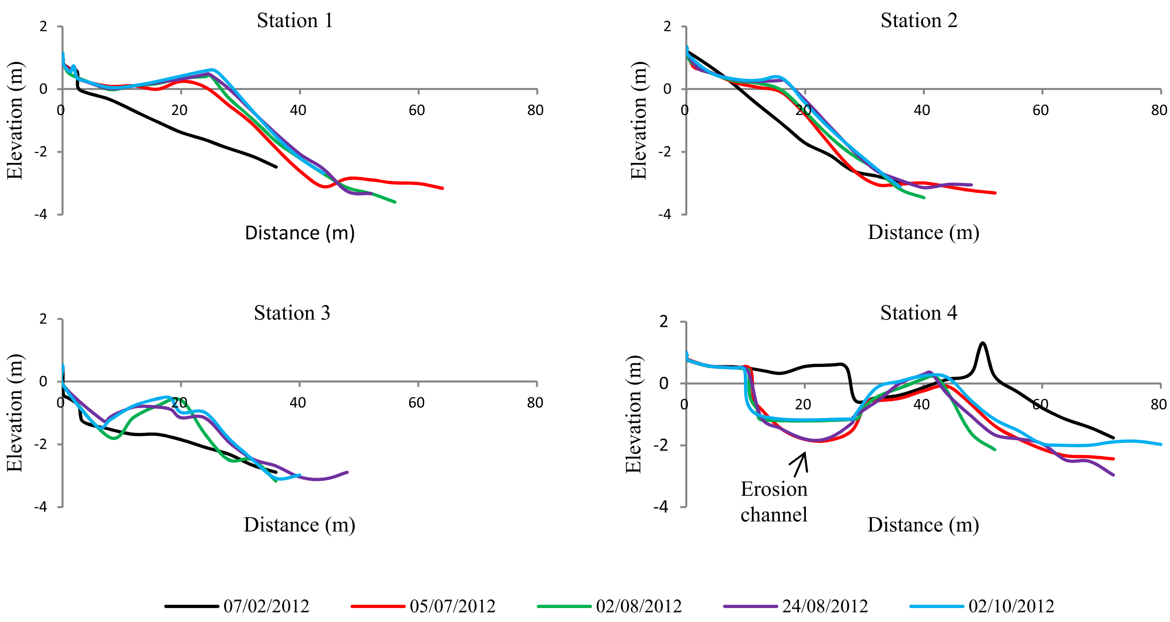

Fig. 4. Beach profiles at Grande Riviere in 2012.

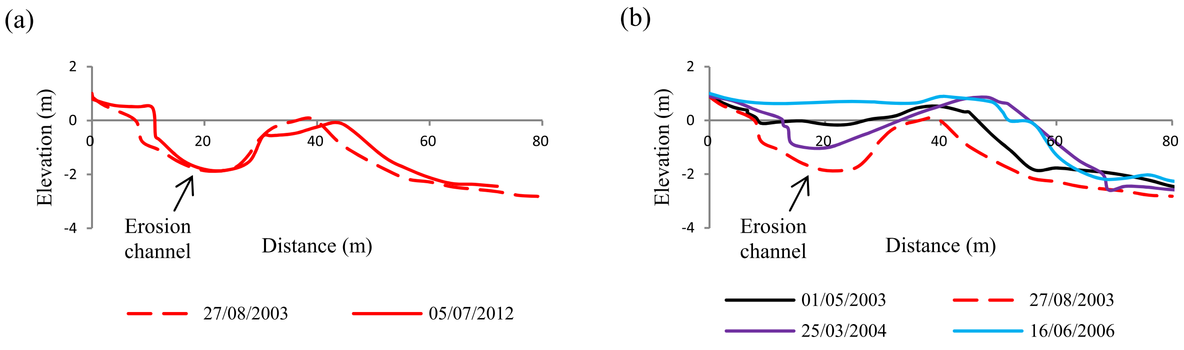

Fig. 5. Comparisons at station 4: (a) beach profiles of the erosion channel in 2003 versus 2012; (b) beach profile of the erosion channel and beach recovery in 2003.

Topographic data indicated the total amount of sediment excavated by the erosion channel to be 4843.42 m^3 over a contiguous area of 2794.25 m^2. Wave action during the period of high intensity swells (January 2013) shifted sand landwards into the erosion channel, in-filling it and making the erosion channel indiscernible (Fig. 7).

The swell event in-filled the erosion channel and remedied the negative effects it had created, however, this area of the beach lost 369 m^3 of sediment overall (Fig. 7c). The geomorphological change was extensive with the complete destruction of the mid-beach berm and the constructed sand dam but, more importantly, there was an overall decrease in the beach elevation with the exception of the in-filled erosion channel (Fig. 8).

Post swell event, the beach's topography had overall lower relief, no characteristic berm, thereby rendering the backshore vulnerable to wave erosion from over-topping (Fig. 9). In the absence of pre- and post-event bathymetric data, the sediment transport that occurred can only be inferred. However, based on the environmental setting of this coastal system, with its fairly enclosed pocket beach geomorphology, reasonable conclusions can be drawn with respect to the beach sediment response. During the river flooding event, eroded sediment from the backshore would have been deposited in the shallow surf zone regions of the bay. With the introduction of swells, the berm and sand dam at Station 4 would have been forced landwards leading to the infilling of the erosion channel. This would have resulted in the lowering of the beach profile seen following the swell waves. In the following months however, normal wind waves were able to return sediment landward towards full recovery of the berm by May 2013 (Fig. 9).

3.3. *Water quality analysis*

Water quality analysis, while not having a direct bearing on the geomorphological and topographic analysis of the beach, illustrates the indirect impact upon the health and wellbeing of the villagers and potential revenue from ecotourism activities. Channel water source was determined to be from four separate sources; road run-off during periods of rainfall and observed leaking potable water lines, groundwater and saline water from berm overtopping. The

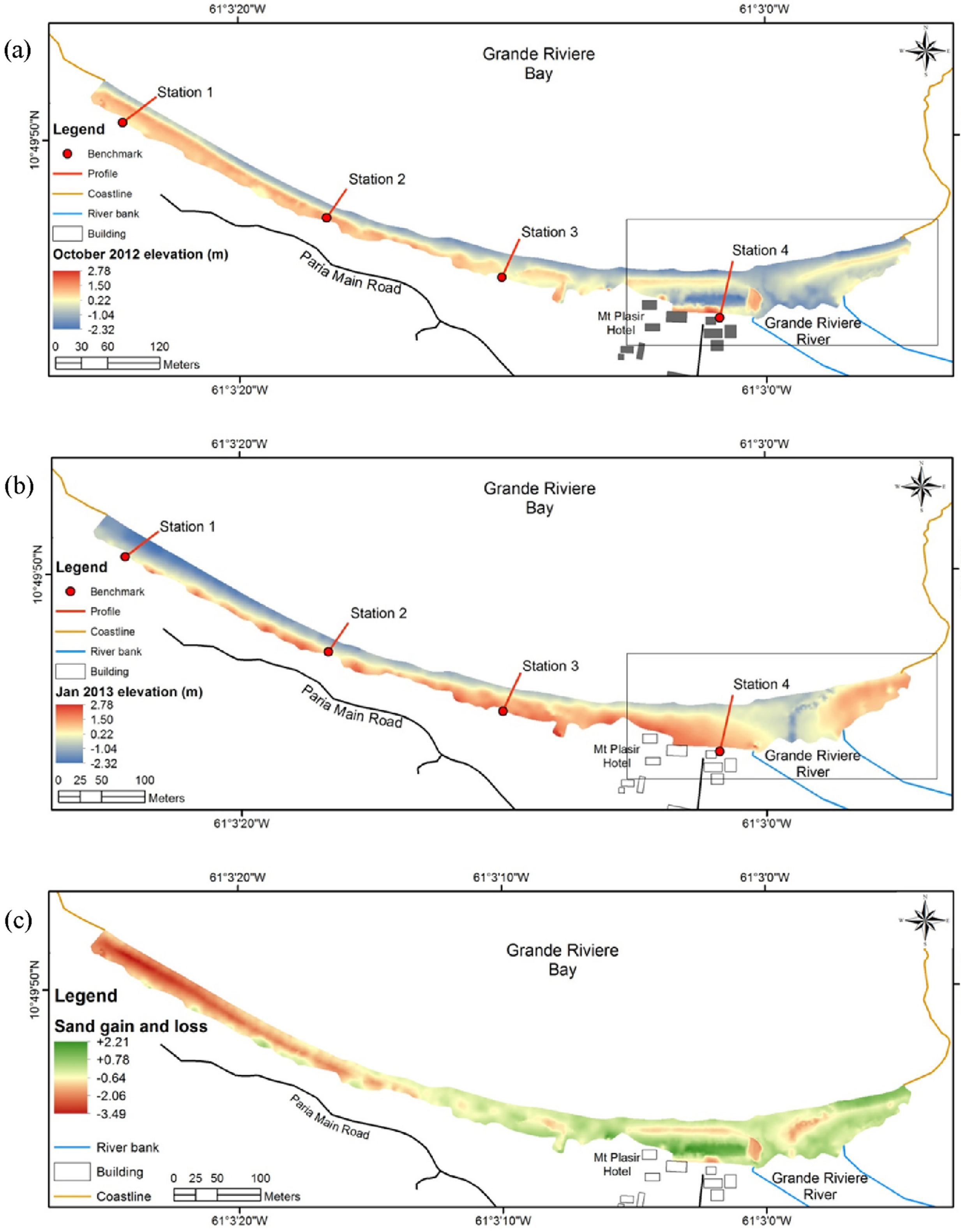

Fig. 6. Topography of Grande Riviere beach, (a) October 2012; (b) January 2013; (c) change in beach elevation between October 2012 and January 2013. The box in (a) and (b) indicates the area shown in detail in Fig. 7.

parameters pH, temperature and total suspended solids, characterized the channel water outside the definition of a pollutant. However, the values for dissolved oxygen, ammonia nitrogen and all microbial analyses define the stagnant water in the channel as being a pollutant for bathing beach quality (USEPA), and a point source pollution if pumped directly into the bay (WPR S1) and unfit for discharge into the near-shore area (WPR S2) (Table 1). Options for discharge into the marine or river environment would therefore

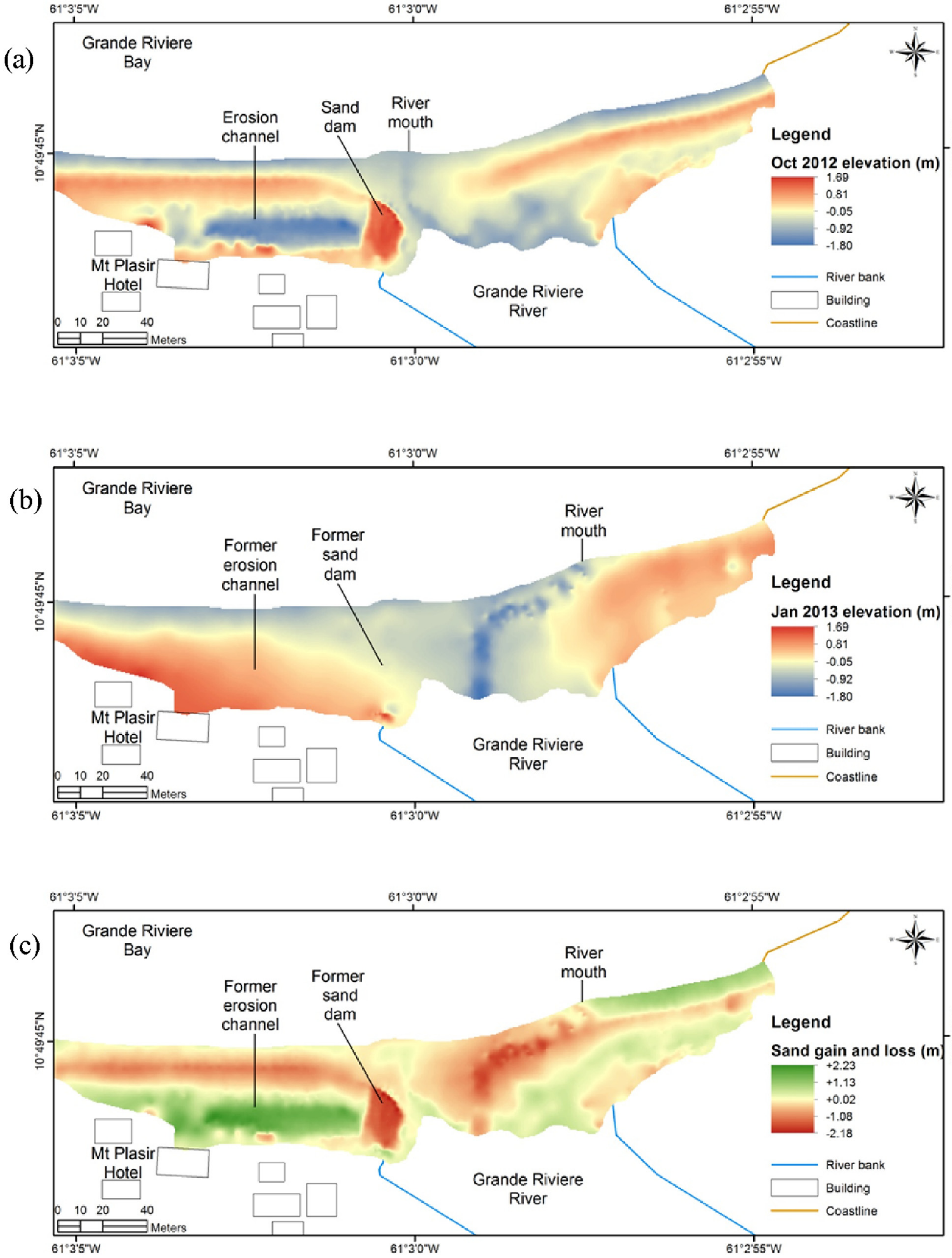

Fig. 7. Topography of eastern Grande Riviere beach, (a) October 2012; (b) January 2013; (c) change in beach elevation between October 2012 and January 2013.

constitute pollution - thus rejecting viability of this option. Water treatment options were then considered by trucking the water extracted from the channel and carrying to a proper treatment facility, however the estimated rate of recharge from groundwater and wave overtopping rendered this option unfeasible as well; and the impounded water was left.

Fig. 8. (a) Before and (b) after beach repair by swell waves.

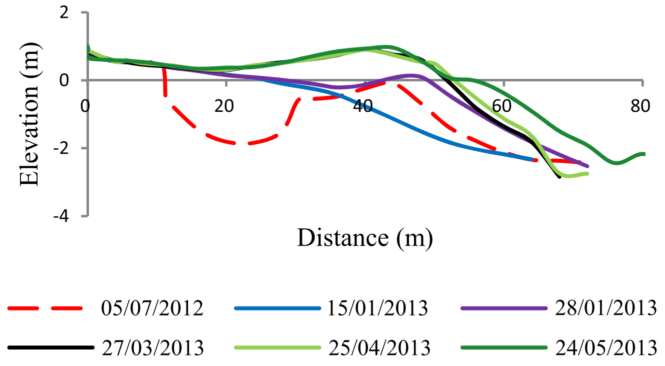

Fig. 9. Beach recovery at station 4 post 2012 event, during swells starting January 2013.

4. Discussion

The anthropogenic intervention undertaken by the construction of the sand dam was conducted without adequate consideration of the natural processes and cycles at Grande Riviere beach, and this lead to the negative impacts, summarised in Fig. 10.

4.1. *Environmental factors at Grande Riviere*

4.1.1. *River flooding*

The causative forcing factors of river shifting at Grande Riviere are poorly understood, primarily due to the lack of *in-situ* hydrologic and oceanographic data during the 2003 and 2012 events. However, the most likely scenario points to the interaction between both the oceanographic and hydrological facets of the study area. The shift in the river's directionality of flow was most likely caused by an increased hydraulic pressure (the interface between a significant high tide within the bay and river storm peak discharge) at the river mouth (Fig. 10).

A spillway was constructed by the Drainage Division in the 1970s to diminish the hydraulic pressure at the ocean-river interface by channelling water out of the river and into the bay on the eastern beach boundary. However, the spillway is rendered non-functional during the beach's accretionary phase, becoming blocked by beach sand which accreted as far as 40 m into the spillway's channel. This increased hydraulic pressure, alongside an elevated berm (which developed naturally during the beach's accretionary phase), would have forced the river's flow along a path of least resistance in the backshore. In March 2012 there was some indication of little backshore erosion by the river. However, it was a single storm event in early June 2012 that resulted in very high river discharge and hydraulic head pressure that resulted in the severe backshore erosion.

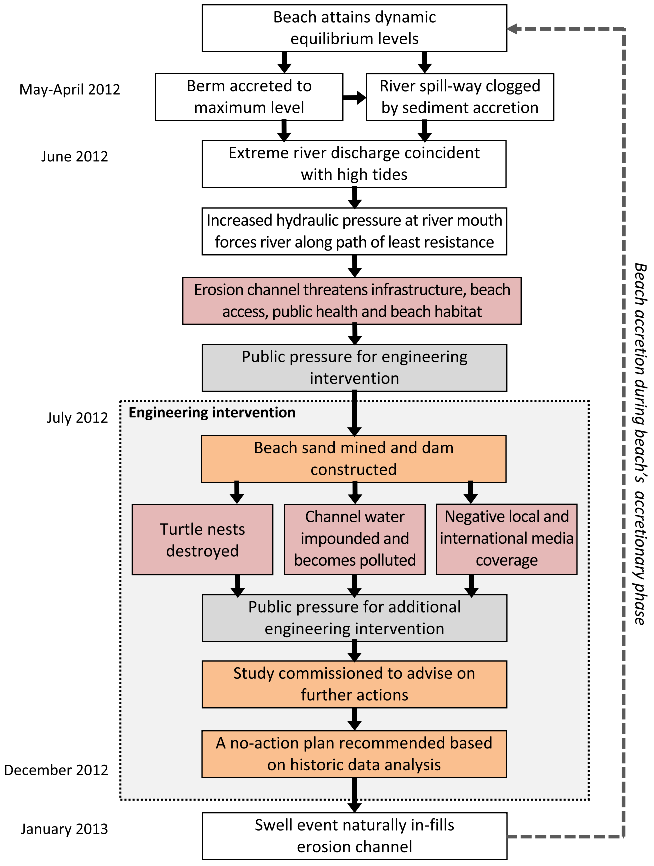

Fig. 10. Flowchart of events at Grande Riviere.

4.1.2. *Beach dynamics*

Storm impacts have been demonstrated to greatly impact the physical characteristics that structure sandy beaches. Storms also affect the local sediment dynamic functions and alter the morphodynamics of the beach. In instances where the storm impacts to the sediment are severe, species that utilize the sediment as habitat (such as nesting leatherback turtles) are impacted particularly negatively (Harris et al., 2011b). Swell waves can erode the beach face and deposit sediment seaward, forming a long-shore bar (e.g. Komar, 1997; Norcross et al., 2002). This occurred on the vast majority of the western side of the beach which decreased considerably in elevation, making it susceptible to further erosion and inundation. The berm which plays an important role in mitigating the effect of high energy waves was reduced, leaving a shallow beach slope from waterline to backshore. However, the swell waves were also responsible for backshore beach accretion through in-filling of the erosion channel at Station 4. These results indicate that the beach may not have a defined seasonal pattern to beach change, but that the beach will go through cycles of erosion or accretion (Short, 1979; Nordstrom, 1980; Darsan, 2005, 2013a). Therefore the areas which were eroded by the flooding event, were repaired by high energy swells, whereas other areas that had no prior evidence of erosion, experienced beachface erosion.

4.2. Local management issues & challenges

4.2.1. Erosion channel

Impacts from river shifting presented a collage of ecosystem, geomorphology and management interactions which needed to be adequately studied and their inter-linkages identified. The major concerns identified varied from physical stability of the beach, the beach habitat for the upcoming nesting season, the eco-tourism economy and human health (Fig. 10). The erosion channel also undermined the economic livelihoods arising from beach access, ecotourism and fishing activities in the area. The impounded water in the erosion channel was tested and regarded as a pollutant, and unsafe for discharge into the nearshore zone. This situation persisted through to the end of 2012, and prompted calls from the villagers and hoteliers who reported a diminished visitor booking trend, to in-fill the backshore erosion channel.

Beach excavation and compaction by heavy machinery can have several negative impacts on both the physical stability and ecological functioning of the beach habitat. Grande Riviere has the highest leatherback turtle nesting density in Trinidad and supports one of the largest nesting populations in the world (Muhammad, 2013; Eckert et al., 2012). Anthropogenic interference of the geomorphological characteristics of the beach can and has exacerbated the impact of sand loss given the fragility of the ecological services it provides to nesting females. This, coupled with eroded nests (Fig. 2d) and diminished nesting range caused by the river shifting event, placed added competition for space by females which resulted in nests being destroyed by other gravid females (Reece et al., 2013; Olesu and Ntiamoa-Baidu, 1998). When this is placed in the context of this species being regarded as critically endangered (it appears on the CITIES red list) and the known migratory and birthing patterns, then preserving habitats such as Grand Riviere becomes a fundamental part of the global preservation efforts, hence the significance of this area.

The anthropogenic action taken was deemed necessary and urgent to prevent further damage to infrastructure in the area which was under threat of collapse from the undermined backshore, including a hotel, the office of the Grande Riviere Nature Tour Guide Association and a roadway. However, the dam construction isolated a large pool of stagnated water in the backshore, which persisted given the lack of adequate sediment transport by wave action, and this eventually developed into a human health issue as it became a refuge for breeding mosquitoes.

After the sand dam construction, the Government of Trinidad and Tobago faced calls from various parties to provide an engineering solution to the erosion channel. These proposals included further sand mining from the central to western areas of Grande Riviere beach, and infilling the erosion channel using beach sediment sourced from other beaches. The first strategy, if allowed, would have impacted greatly existing and future turtle nests.

The second solution, beach nourishment with sediment from another beach can be an environmentally friendly instrument to arrest and remediate against erosion (Adriaanse and Coosen, 1991; Hamm et al., 2002; Speybroeck et al., 2006). However the ecological impacts are often negative (Speybroeck et al., 2006). Turtle nesting at Grande Riviere beach is so prolific because of the unique sand characteristics that nesting turtles value. A great amount of attention would have to be paid to the sediment characteristics including the mean, skewness and kurtosis of grain sizes and sediment sorting parameters (Folk and Ward, 1957) and mineralogy of the sediment source material. Avoiding further changes to the beach structure and littoral processes through remedial work, the adoption of a *no action plan* was deemed a success as it prevented unforeseen impacts which could lead to both physical and ecological destruction – with the specific affects to its function as a considerably large turtle nesting ground and the socio-economic reliance of the village on this ecological facet. The prevalence of sound investigative science into the potential for negative impacts on the beach from remedial works must be explored prior to any decision on engineering solutions. Modelling must be part of the strategy taking into consideration emerging challenges which impact beach integrity including climate change impacts in the form of sea level rise, which would provide information on the likely response of the beach dynamics. Such information will play a vital role in supporting policy decisions in prioritising the present and future use of the area (conservation verses infrastructure protection or relocation).

4.3. Implications for management of sandy beaches

This study has demonstrated the need to consider the dynamic nature of all facets of the environment in making sound management decisions. It further points to the dangers posed when such decisions are taken in a short-sighted manner, focusing on a single aspect of beach management. Beach management has often focused primarily on the physical considerations of sand budgets and erosion control (Schlacher et al., 2006, 2007), while ignoring the other aspects of beaches such as habitat provisioning and biodiversity (Dugan and Hubbard, 2006; Schlacher et al., 2006). More recently, alternate approaches have been proposed that envision the beach as a multidimensional environmental system comprised of interacting natural, socio-economic, cultural and management systems and is required to view the beach holistically. Often each of these facets are considered separately and this has resulted in negative impacts upon other components of the beach environment (James, 2000; Micallef and Williams, 2002). In the case of this event at Grande Riviere the physical environment was altered by natural processes. The subsequent anthropogenic intervention which was undertaken to protect properties also resulted in the loss of a large number of turtle eggs and beach nesting area where the sand was removed for dam construction.

Perhaps the most severe threat facing sandy beaches is coastal squeeze (Schlacher et al., 2006, 2007, 2008; Defeo et al., 2009). Grande Riviere beach is trapped between rising sea levels on the seaward side and coastal development on the landward side. This leaves no chance for the beach to migrate inland as would occur naturally with sea level rise provided that there was no coastal infrastructure (Galbraith et al., 2002; Leewis et al., 2012). Potential climate change impacts are likely to have severe negative impacts upon turtle nesting at Grande Riviere (Ortega et al., 2012, 2013). Optimal turtle nesting locations require a combination of factors including low inundation frequency and sufficient space above the high tide line for nesting (Hawkes et al., 2009). Anecdotal evidence from older villagers indicates that the beach on the western side of the beach used to be considerably wider 30 years ago, and this loss could be due to sea level rise. Currently at Grande Riviere many of the coastal structures are built in the backshore area or on the beach itself (Figs. 1, 2 and 8). Based on these observations, there is a lack of adequate coastal setback at Grande Riviere beach. This is a major impediment towards the management of this fragile environment, particularly given its ecological significance.

4.4. Recommendations for management

The infilling of the erosion channel by winter swells in January 2013 illustrated that remediative action was not necessary. This study demonstrates that, if allowed time, naturally occurring processes can repair degraded areas in the coastal zone. However, these natural processes can be assisted by reducing the pressure emanating from poor tenure systems including planning, land zoning, compliance and enforcement. The “hastily done” engineering response was prompted because of the direct threat posed to some of the infrastructure from riverine flows. However, when the situation is viewed holistically, the better course of action would have been to prevent infrastructural development in such close proximity to the beach (Hossain and Kwei Lin, 2001). It is clear that land use planning, approval and regulation at Grande Riviere need to be more strongly informed by a multidisciplinary and holistic scientific approach (Micallef and Williams, 2002; Caldwell and Segall, 2007; Fish et al., 2008).

To reduce the chance of a river shifting event occurring in the future, a thorough hydrological assessment of the Grande Riviere watershed is required, with investigative emphasis on rehabilitating and maintaining the spillway which connects Grande Riviere River to the eastern end of the bay. The spillway could reduce the river hydraulic head during high flow events. Coupled with this recommendation, maintenance of the river mouth by manual clearing of sediment accumulation during the eastern beach's accretionary period would also limit the river's meandering – a practice which has traditionally been carried out by the villagers. Although 2011–2012 represented a period of unprecedented sediment berm accretion, employing both strategies in tandem has the potential to limit river mouth shifting and subsequent beach erosion.

In an era of erratic ocean changes due to inter alia external activities such as the effects of climate change, such phenomena which occurred in 2011–2012 may very well become a norm and thus, these findings should be mainstreamed into the management of the Grande Riviere area. Further, the land use and land planning in the area is also a cause for concern, where compliance with building code in such a dynamic area remain lax at best. Therefore, it would be prudent to accompany sound land management decisions with the in-depth hydrologic assessment and to pursue an integrated coastal zone management approach recognising the duality of human wellbeing and habitat protection for nesting of the endangered leatherback turtle. The findings of this study help to support better decision making in Trinidad regarding coastal management similar to interventions conducted at Colombus Bay (Leung Chee et al., 2014).

5. Conclusion

This study set out to analyse the coastal processes, the beach's topographical response, investigate the water quality of the impounded water, and highlight the management issues and challenges in dealing with such extreme events. The study illustrates that Grand Riviere is a dynamic area and the episodic events of 2012 resulted in river shifting but shows that if allowed time, such changes can be repaired by natural coastal processes and engineering solutions may not be the best intervention in this area. Grande Riviere beach is a site of international importance for its acclaimed contribution to population enhancement of the critically endangered (IUCN Redlist Category) leatherback turtle. This river shifting event at Grande Riviere presented an example of the need for sound science to inform management actions. The results indicate that the beach habitat is highly reactive to both the hydrological and coastal influences.

The beach goes through seasonal changes by accreting in the summer period, and eroding in the winter period. The turtle nesting shifts to the west in response to the beach's summer accretional cycle. Under extreme episodic river flooding as occurred in 2003 and 2012, the beach erosion in the backshore was repaired over a few days with the initiation of swell waves. Subsequent to the infilling of the erosion channel by swells, local waves were able to fully repair the berm and beach in the following months.

Historical geomorphological data served as the key decision making factor in whether further anthropogenic changes to the beach were to be effected. These data were able to inform that such river shifts have occurred in the past and the beach was able to repair itself naturally with the aid of winter swell waves. The importance of the beach as a prime nesting site relies not only in the geographical location, but more importantly in the sediment characteristics (medium grained, moderately well sorted sand) that are unique to this beach. Anthropogenic infilling of the channel could have been done by simply translocating sand from a donor region along the beach. While this would have preserved the similarity of mineralogy in the beach sediment, it would have been impossible to manually recreate the sorting of grains under normal wave processes; a critical factor in the usability of the backshore for turtle nesting.

Anthropogenic beach alteration without sufficient evidence to scientifically simulate the potential for natural disruption of geomorphological and oceanographic characteristics of a given area is ill advised. The interrelated facets of biodiversity, environment and socio-economic standing as is the case with Grande Riviere – provides a sound argument as to why policy must be grounded in multidisciplinary scientific approaches with equal weighting to understanding the interlinkages of how the environment functions.

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