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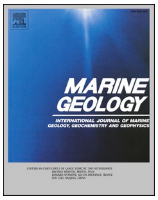

Research Article

Shoreline change on a tropical island beach, Seven Mile Beach, Grand Cayman: The influence of beachrock and shore protection structures

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ABSTRACT

Contemporary and near-future shoreline change is widely regarded as an issue on small tropical islands. While it is widely anticipated that sea-level rise will precipitate shoreline recession on tropical islands, studies to date record both accretion and recession at historical timescales. This study of Seven Mile Beach, Grand Cayman presents a case study of historical shoreline change in which the local geomorphic setting is shown to be an important influence on shoreline behaviour. Consistent with its leeside setting, historic shoreline analysis (1958–2019) reveals erosion on the margins and accretion in the central part of the headland-embayment beach where no beachrock is present. The beach comprises five discrete, but interlinked subcells delineated by low headlands of exposed beachrock. These headlands have emerged through shoreline recession post-1971 but once exposed have become loci of persistent erosion, suggesting a positive feedback between beachrock and waves. A Category 5 Hurricane generated waves directly opposed to long-term modes and throughout the beach, long-term patterns of shoreline change were temporarily reversed, however, the historic pattern of shoreline change was restored within 2 years. The contemporary patterns of erosion and cell development suggest a reduction in sediment supply leading to cannibalization of relict beachridges on the margins of the embayment and emergence of formerly buried beachrock. The effects of coastal structures and erosion abatement measures were assessed and recommendations for coastal management, including development setback lines are presented.

1. Introduction

Tropical island beaches can display variable morphology and characteristics over comparatively small distances (Gore et al., 2019). Their most common characteristics are the presence of nearshore coral reefs that contribute to a high percentage of biogenic carbonate grains (Romine et al., 2016) and provide shelter in already modally low wave-energy environments. Seasonal variations in wave energy may exist and episodic high-magnitude storms (hurricanes/typhoons/tropical cyclones) affect many tropical island beaches at multi-annual intervals and in diverse ways (Etienne, 2012; Spiske et al., 2022; Harvey et al., 2021; Kench et al., 2022). The persistence or destruction of reef islands in the face of sea level rise has received much attention in the literature (McLean and Kench, 2015; Tuck et al., 2021; Sengupta et al., 2021) and a global review (Duvat, 2019) showed that almost 90% of atoll islands are stable or accreting at decadal timescales. Duvat (2019) also reported marked spatial variability in tropical beach response to dynamic forcing, and called (p.12) for a "better understanding of interactions between the drivers of island change". In that regard, a detailed study in Hawaii (Mikkelsen et al., 2022) revealed a complex pattern of tropical beach behaviour with seasonal as well as interannual signals in the beach change record. Alongside a well-developed sub-cell network of subtidal-intertidal sediment exchange, those authors identified variations in water level and wave energy flux as key drivers of change.

There is also a growing literature on the effect of human structures on tropical shoreline behaviour with a general observation that shoreline hardening aggravates both long-term erosion rates (Fletcher et al., 1997; Fletcher et al., 2012; Duvat, 2013) and sediment loss during tropical cyclones (Duvat et al., 2019).

A tropical island setting provides a strong constraint on accommodation space for beach development while adjacent rock outcrops and reefs modify incident waves and influence beach profile and planform.

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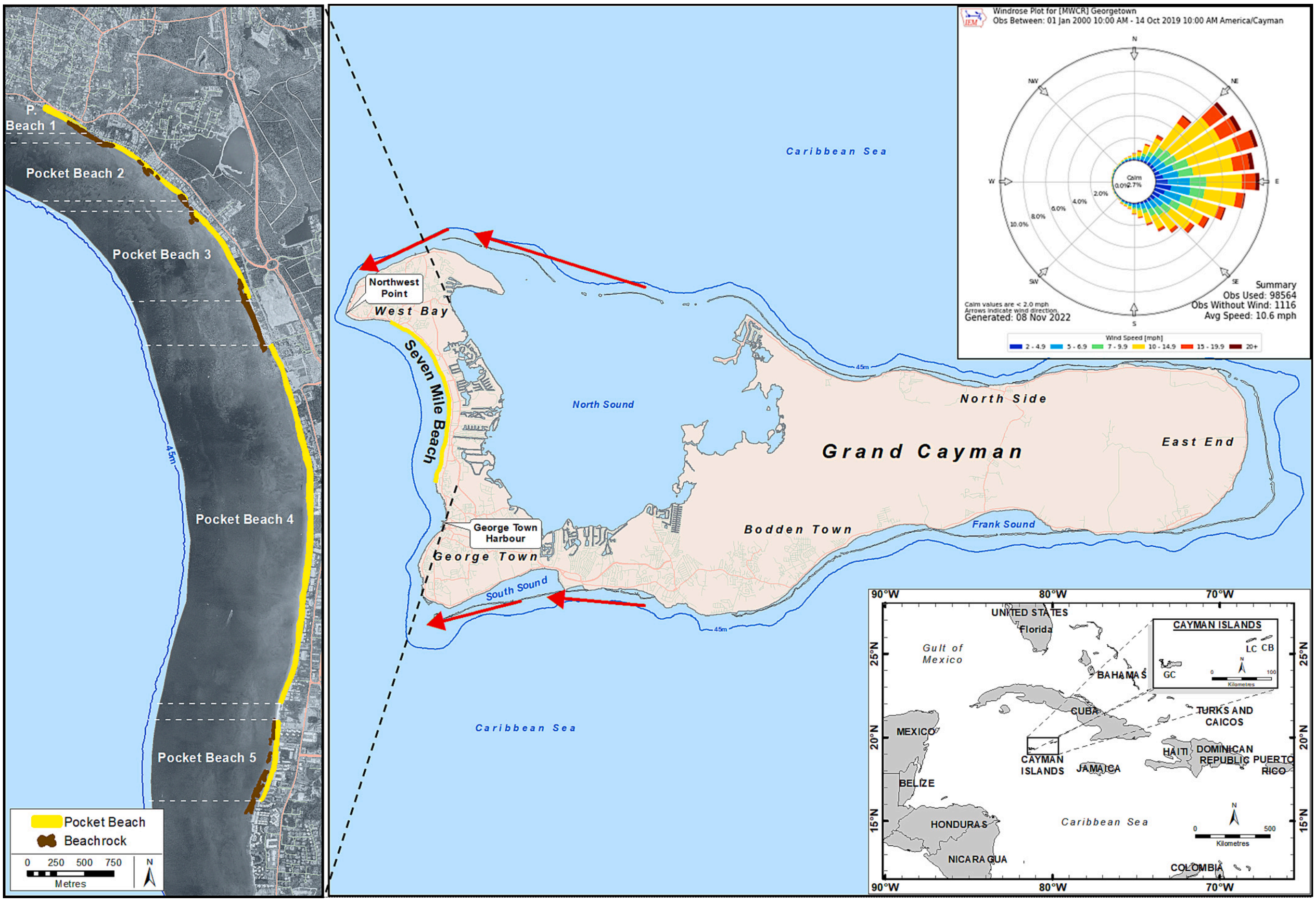


Fig. 1. Locality of Grand Cayman and Seven Mile Beach study area. Red arrows mark dominant longshore transport pathways around the island; only the northern drift system delivers appreciable quantities of sediment to Seven Mile Beach. Inset shows wind rose for Grand Cayman, 1 Jan 2000 to 14 Oct 2019 (Iowa State University, 2020). Left hand panel shows morphodynamic cells and headlands on Seven Mile Beach. Each cell exhibits a distinctive long-term and seasonal behaviour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

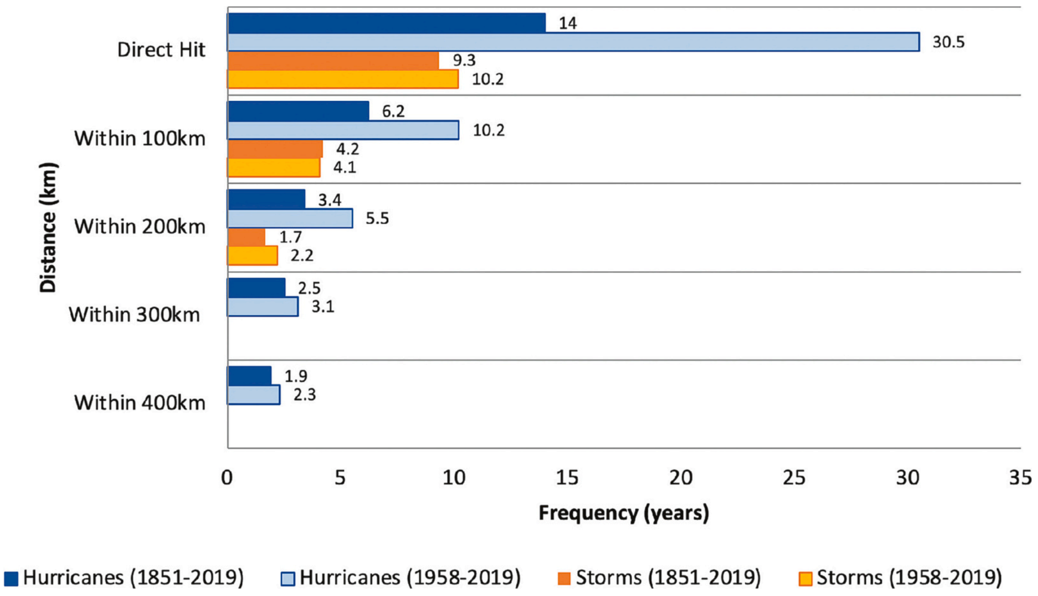


Fig. 2a. Frequency of hurricanes passing within 400 km and storms passing within 200 km of Grand Cayman (Based on data from HURDAT2, 2020).

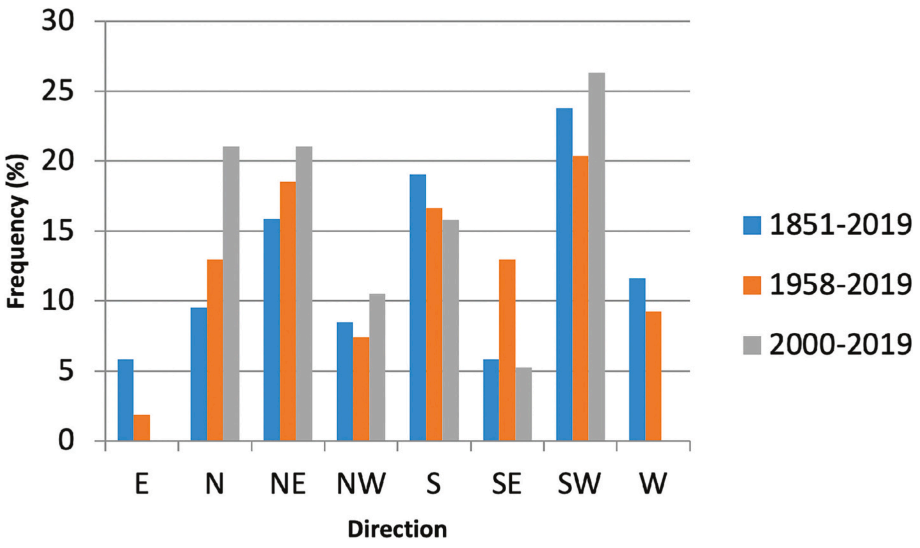


Fig. 2b. Direction and frequency of hurricanes passing within 400 km of Grand Cayman and storms within 200 km (NOAA, 2020).

The early formation of beachrock at low water and presence of nearshore seagrass provide added complexity to tropical beach morphology. Beach profiles are often steep as a result of coarse grain sizes and low wave energy. In low energy settings, the beachface is fronted by a beach step, swash processes alone being sufficient to dissipate incoming wave energy, and surf zones are often poorly developed or entirely absent. In common with trade-wind-dominated oceanic islands (Hernandez-Calvento et al., 2017), persistent wind and wave approach from a narrow window, can result in sediment accumulation on the leeward side of islands.

In light of the need for more detailed understanding of tropical beach behaviour at decadal timescales, the aim in this study is to assess and interpret historical and recent shoreline changes using a 61-year (1958–2019) dataset of shoreline change. The dataset includes mapped historic shoreline position and surveyed cross-shore beach profiles at various timescales. These are interrogated for potential seasonal, long-term and episodic (hurricane-related) patterns of change in the cross-shore and alongshore dimensions. The results are interpreted in the context of specific tropical island-associated local constraints on beach behaviour, particularly beachrock outcrops as well as the influence of shoreline stabilization interventions.

2. Study area

2.1. Geological setting

The Cayman Islands comprise three islands (Grand Cayman, Cayman Brac and Little Cayman) in the Greater Antilles chain, in the NW Caribbean Sea (19° N 81° W) (Fig. 1). These islands are formed around peaks of the Cayman Ridge which extends from the Sierra Maestra mountain range of Cuba to the Bay of Honduras (Roberts, 1977). They are formed entirely of calcareous marine deposits as a result of tectonic uplift at the Mid-Cayman Rise and are flat, and very low lying (Jones, 1994). Grand Cayman is the largest of the islands, covering 122 km^2; it has an average elevation of 1.8 m and maximum of 28 m. Seven Mile Beach is backed by a series of beachridges, suggesting long-term

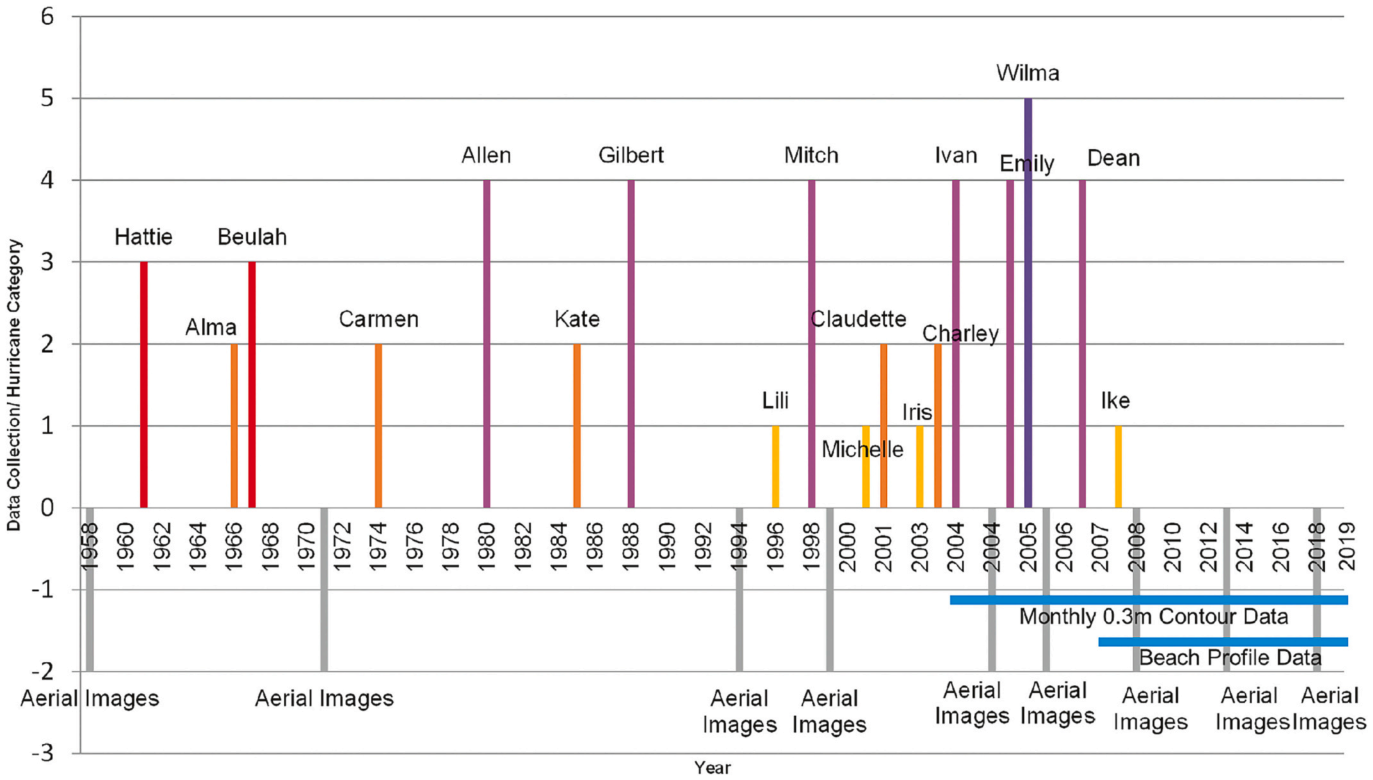


Fig. 3. Timeline of hurricanes impacting Seven Mile Beach (yellow = Cat 1; orange = Cat 2; red = Cat 3; pink = Cat 4; purple = Cat 5). Events are contextualized in relation to available shoreline data indicated on image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

progradation (Sauer, 1982).

2.2. Climate

The climate is tropical with two seasons: summer (May to October) and winter (November to April). Air temperatures average 27.1 °C per annum with the hottest month over a 30-year average being July at 28.8 °C, and the coolest month on average is February at 25.1 °C (Cayman Islands National Climate Change Committee, 2011). Prevailing winds are from the north-east and east (Fig. 1). From August to October, the majority of the wave energy along Seven Mile Beach comes from the south-west quadrant, with wave energy from the north-west from October through January, locally referred to as Nor'westers (Smith Warner International, 2015).

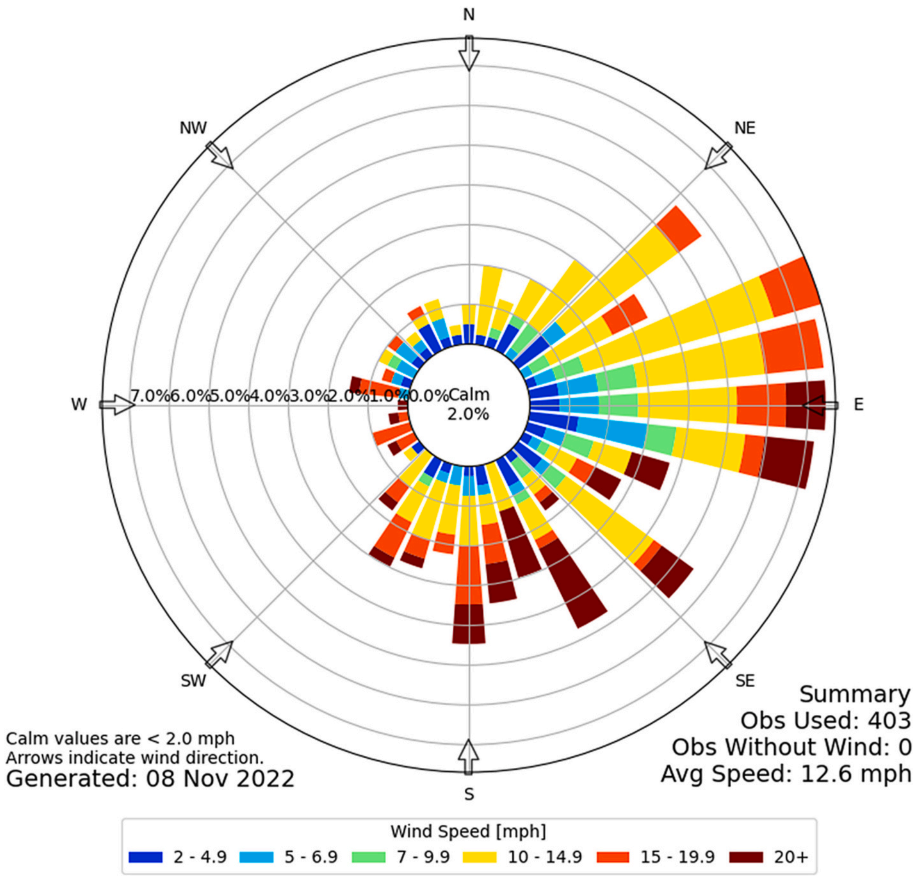
The mean tidal range is 0.4 m, with increases in tidal levels occurring during El Nino and perigean spring tides (NOAA, 2019). Between 1950 and 2009, Caribbean sea-level rise was approximately 2 mm/year (Palanisamy et al., 2012).

Between 1887 and 1987 one tropical storm passed directly over Grand Cayman every 12.5 years (Clark, 1988). A storm or hurricane passed within 50 miles of Grand Cayman every 4.3 years and within 100 miles every 2.7 years. Given the known impacts of more distant storms, such as Category 5 Hurricane Mitch in 1998, which was 324 km away at its closest point (HURDAT2, 2020), we analysed storm and hurricane frequency at greater distances (Fig. 2a). Observations suggest a reduction in frequency but an increase in intensity of hurricanes reaching Grand Cayman. From 1851 to 2019, 72% of hurricanes were category 1 or 2, 10% were category 3, and 18% were Category 4 or 5. From 1958 to 2019, 54% were Category 1 or 2, 12% Category 3 and 35% Category 4 or 5. From 2000 to 2019, Category 1 or 2 hurricanes dropped to 46%, 8% were Category 3 and 40% were Category 4 or 5. In the past 11 years no hurricanes have passed within 400 km of Grand Cayman and in the past 9 years no tropical storms have passed within 200 km (HURDAT2, 2020). Future predictions are for no change, or a slight decrease in hurricane frequency, but with an increase in the frequency of category 4 and 5 hurricanes over the next 80 years using the IPCC's 2012 A1B scenario (University of the West Indies, 2014). The 6th Assessment Report (IPCC, 2021) predicts, with medium confidence, more extreme tropical cyclones in the Caribbean. The observed increase in hurricane intensity in recent years is consistent with these predictions.

Seven Mile Beach is exposed to storm and hurricane activity from south-west to north-west quadrants. From 2000 to 2019 there was an increase in the percentage of south-westerly storms (over 25% of storm activity from this direction) and north-westerly storms (over 10%), with no storm activity directly from the west (Fig. 2b). Fig. 3 shows the frequency of hurricanes that are likely to have affected the Seven Mile Beach corridor, based on their direction of travel. The figure also indicates the shoreline data utilised in this analysis.

In October 2005, Category 5 Hurricane Wilma passed the south-west coast of Grand Cayman, at a distance of 272 km at its closest point (HURDAT2, 2020). A wind rose for Grand Cayman during the period 1 October to 1 November 2005 (Fig. 4) illustrates winds of over 20 mph (9 m/s) from the south and south-west. The effects of this on the shoreline of Seven Mile Beach has been analysed in this study. In October 2004, the Islands were also impacted by Category 4 Hurricane Ivan which was a direct hit, but had the greatest effects on the south and east coasts of Grand Cayman. Ivan had little impact on Seven Mile Beach (National Climate Change Committee, 2011).

Wave conditions along Seven Mile Beach are characterised by (a) day-to-day seas and (b) seasonal winter swells. The winter swells are generally experienced from December to May. The day-to-day sea conditions are created by the NE Trade Winds, with the west coast of Grand Cayman being exposed to a small component of those waves that refract and diffract around the tips of the Island. The swells are generated by seasonal north Atlantic cold fronts and these waves approach from the north to north-west.



Calm values are < 2.0 mph
Arrows indicate wind direction.
Generated: 08 Nov 2022

Summary
Obs Used: 403
Obs Without Wind: 0
Avg Speed: 12.6 mph

Fig. 4. Windrose for Grand Cayman, 1 October – 1 November 2005, spanning Hurricane Wilma (Iowa State University, 2020). Note the occurrence of winds from the SW quadrat compared to the long-term conditions shown in Fig. 1.

Acoustic Doppler Current Profiler (ADCP) data from a commercial investigation (Smith Warner International, 2015) provide more detailed local information on the wave climate. A southern ADCP was deployed in George Town Harbour (south of Seven Mile Beach) at a depth of 10 m. A northern ADCP was deployed at a depth of 15 m located offshore of the central section of Seven Mile. During summer (June to September) waves mostly came from the southwest at the northern ADCP, while the southern ADCP had lower waves coming from various directional sectors. During the winter, larger waves came from the northwest at the southern ADCP while the north ADCP recorded waves coming from the north-west as well as larger swells from the southwest. Dominant waves came from the south-east from June to September, and north-west between November and December. Hindcast wave data (1980 to 2014) showed that most waves come from the south-east, but the highest waves (>1.5 m) come from north to north-west (Smith Warner International, 2015).

2.3. Geomorphology

Seven Mile Beach (Fig. 1) is a 9.3 km-long, semi-continuous sandy beach on the leeward, western coast of Grand Cayman (Seymour, 2000). The beach and adjacent beach ridges are composed of coralgal sand (Woodroffe, 1982). It is fronted by a 750 m-wide, low relief (1–3 m), forereef with well-developed spur and groove structures (Clark, 1988). At depths >40 m the reefs end in near vertical walls which drop to 2000 m (Manfrino et al., 2003).

Two large sediment transport pathways run east to west along the north and south coasts of Grand Cayman, although only the northern pathway is believed to provide a source of sediment for Seven Mile Beach (Roberts, 1977). Longshore sediment transport on Seven Mile Beach is regarded as predominantly north to south (Roberts, 1977; Seymour, 2000), due to the predominant wave energy required to mobilise sediment occurring during north-westerly storms (Clark, 1988). This is reflected in sediment grain size trends; coarser granules in the north, and finer sediment particles at the southern extent (Seymour, 2000). However, recent current and wave modelling associated with an adjacent major infrastructure development also indicated a trend of nearshore sediment movement from south to north, for the limited duration of the modelling, with the exception of the very northern section of Seven Mile Beach, where it was to the east and south (Smith Warner International, 52,015).

The beach planform is anchored in the north and south by headlands of the Pleistocene Ironshore Formation (Jones, 1994). These shelter the beach system from high energy waves from the north and north-west (Seymour, 2000). The lower profile and orientation of the Ironshore Formation at the southern end of the beach offers less protection from south-westerly swells. Several submerged and emergent shore-parallel ridges of beachrock along the shoreline act as minor headlands, creating a series of beach cells.

Clark (1988) identified seasonal beach profile changes on Seven Mile Beach related to offshore sediment transport during winter storms. A net shoreline retreat of 0.3 to 0.6 m per year between 1946 and 1985 was attributed to net offshore sediment losses through gaps in the outer reef terrace (Clark, 2003), and from the south end of the beach (Seymour, 2000). The southern end of the beach experiences rapid narrowing during southerly storms and a historic beach ridge which would have provided sediment during periods of erosion has been lost due to extensive beachfront development (Seymour, 2000).

Table 1

Qualitative descriptors assigned to shoreline change rates at the study site.

Rate of change (m/year)	Shoreline classification	Rate of change (m/year)	Shoreline classification
>-0.5	very high erosion	>0 and <0.24	moderate accretion
>-0.25 and <-0.49	high erosion	>0.25 and <0.49	high accretion
>0 and <-0.24	moderate erosion	>0.5	very high accretion
0	stable		

3. Methods

A combination of aerial imagery and monthly Mean High Water Mark data were analysed for the period 1958 to 2019, obtained from the Cayman Islands Department of Lands & Survey. Aerial imagery was assessed for the years 1958, 1971, 1994, 1999, 2004, 2005, 2008, 2013 and 2018. With the exception of 2005, all imagery was collected in April. The shoreline positions based on the wet/dry water boundary were digitised from aerial images to enable a long-term shoreline analysis.

Monthly data for the position of the Mean High Water mark (0.3 m/1 ft. contour line) from 2004 to 2019 were analysed to assess seasonal and episodic shoreline changes. To capture seasonal changes, these 15 years of data were separated into summer (May to October) and winter (November to April) and the average winter and summer shoreline positions were compared. Hurricane impact was analysed by comparing the measured position of the 0.3 m contour one month pre- and one month-post Hurricane Wilma. The monthly contours were also analysed for two years after Hurricane Wilma to assess recovery rates of the beach.

Shoreline changes were analysed using ArcGIS Desktop v10.4.1 with spatial analyst and the Digital Shoreline Analysis System (DSAS) 5.0 extension (Himmelstoss et al., 2018). For shoreline change statistics to be computed, each shoreline must have an associated positional uncertainty. Shorelines derived from different data sources and the various process steps from the source data to the line represented on the map contribute to the overall uncertainty of that shoreline position (Anders and Byrnes, 1991; Crowell et al., 1991; Thieler and Danforth, 1994; Moore, 2000) and the uncertainty value needs to account both for positional uncertainties associated with natural influences over the shoreline position (wind, waves, and tides) and measurement uncertainties (for example, digitisation or global-positioning-system errors).

Aerial photography-derived shorelines are subject to several potential sources of error (Romine et al., 2009; Hapke et al., 2011; Virdis et al., 2012; Cenci et al., 2013; Ruggiero et al., 2013; Manno et al., 2017). Assuming that errors are independent of each other, the total error associated with each shoreline position is given by the root sum of squares of the individual uncertainties associated with each dataset:

$$\sigma_T = \pm\sqrt{\sigma_d^2 + \sigma_p^2 + \sigma_g^2} \tag{1}$$

The digitising error (σ_d) was calculated by delineating the same feature several times on the same map or aerial photo and calculating the Root Mean Square Error of position residuals at regular intervals for that feature (Virdis et al., 2012; Cenci et al., 2013). This error was calculated using the Spatial Adjustment tool in the Editor tab of ArcMap®. The pixel error (σ_p) was assumed to be equal to the pixel size (i.e. spatial resolution) of the dataset below which it is not possible to resolve any feature. The georectification error (σ_g) is equivalent to the RMSE error for control points during the digital triangulation process (Virdis et al., 2012). The aerial photographs used were already professionally georeferenced using a second-order polynomial transformation with multiple control points per photograph. The calculated uncertainty was +/− 3 m. The influence of large shoreline position errors on long-term rates of change is regarded as less important when the period of analysis is long (Morton et al., 2004; Morton and Miller, 2005).

For the Mean High Water Mark surveyed contours, which were created using survey-grade GPS units (and professional surveying personnel), it was assumed that the horizontal positional accuracy level was very high and a positional uncertainty value of 0.25 m was applied. A DSAS 'Baseline' was established using a digitised polyline of the 1971 vegetation line that was buffered 25 m inland to ensure that all shorelines/contours were seaward of the baseline. Transects for calculation of shoreline change rates were spaced at 10 m.

The end result of the DSAS computation is a series of statistics that measure various aspects of beach morphology. The Net Shoreline Movement (NSM) is the distance between the oldest and youngest shorelines for each transect, displayed in metres. Shoreline Change Envelope (SCE) reports a distance in metres (not a rate) and represents the greatest distance among all the shorelines that intersect a given transect. End Point Rate (EPR) is calculated by dividing the distance of shoreline movement (NSM) by the time elapsed between the oldest and the most recent shoreline. It is computationally simple as it only relies on two dates, however it ignores all other input shoreline contours. Linear Regression Rate (LRR) is determined by fitting a least-squares regression line to all shoreline points for a transect. The regression line is placed such that the sum of the squared residuals is minimised. The LRR is the slope of the line. This method is susceptible to outlier effects and tends to underestimate the rate of change relative to other statistics (Dolan et al., 1991; Genz et al., 2007). Qualitative descriptors for categories of rates of change were established based on the local range of results (Table 1). The overall mean Uncertainty of the End Point Rate (EPRunc) for all transects is +/− 0.07. The overall mean Confidence Interval of Linear Regression (LCI) is 0.14.

Topographic beach profiles measured from the water line to the vegetation line at 25 sites along the beach, collected from 2007 to 2019 by the Cayman Islands Department of Lands & Survey on an annual or bi-annual basis, have also been analysed. These profiles were graphed to assess changes in beach profile and volume. Vertical and horizontal accuracies of ±1 cm can be obtained using such approaches (Mason et al., 2000) although in practice vertical accuracy across the beach is typically +/− 5 cm (Gorman et al., 1998).

4. Results

4.1. Shoreline change

For ease of presentation, the beach was divided into five sections (A to E) from north to south. Shoreline changes are described below for each section based on the long-term net shoreline change (1958–2018), inter-annual variations (1958–2004, 2004–2013 and 2013–2019), seasonal changes (summer/winter) and pre/post Hurricane Wilma. The inter-annual analysis is based on the following: a) 1958–2004 shorelines digitised from aerial imagery taken in April; and, b) 2004–2013 and 2013–2019 annual GPS-surveyed shoreline positions recorded in April,

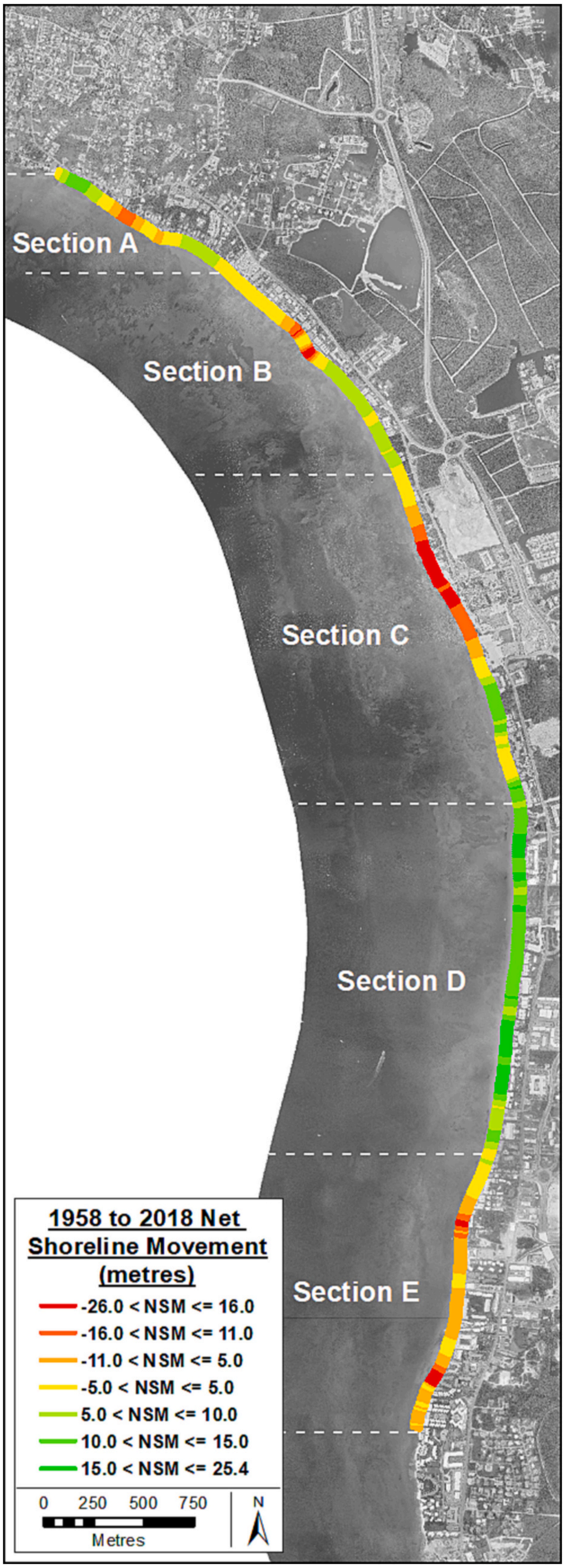


Fig. 5. Seven Mile Beach is divided into Sections A-E that are discussed in the text. Net shoreline movement (1958–2018) along the beach is indicated by colour-coded categories (Green = accretion; Red = erosion). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Aggregated shoreline change statistics 1958–2018. For location of beach segments see Fig. 5 Mean, maximum and minimum shoreline change values refer to all transects within each shoreline sector. Cell colours refer to Table 1.

	Section A	**Section B**	**Section C**	**Section D**	**Section E**
Total no. transects	102	138	176	178	153
Total length (km)	1	1.4	1.8	1.8	1.5
Mean rate shoreline change m/y					
EPR	0.04	0.02	-0.07	0.22	-0.12
LRR	0.02	0.02	-0.04	0.20	-0.20
Max positive shoreline change m/y					
EPR	0.22	0.15	0.25	0.42	0.09
LRR	0.15	0.16	0.36	0.36	0.05
Max negative shoreline change m/y					
EPR	-0.25	-0.32	-0.43	0.06	-0.37
LRR	-0.21	-0.4	-0.53	0.02	-0.47
NSM					
Mean	2.27	1.04	-4.19	13.39	-6.91
Max	13.44	8.90	-15.12	25.40	5.27
Min	-15.04	-19.01	-25.98	3.85	-22.18
SCE					
Mean	11.19	9.77	22.04	18.07	17.48
Max	22.60	24.55	34.49	28.07	32.23
Min	0.00	21.80	5.14	10.66	6.55
Total transects that record erosion (LRR)	34	56	96	0	140
% transects that record erosion (LRR)	33.0	41.0	55.0	0	92
Total transects that record accretion (LRR)	68	82	80	178	13
% transects that record accretion(LRR)	67.0	59.0	45	100	8

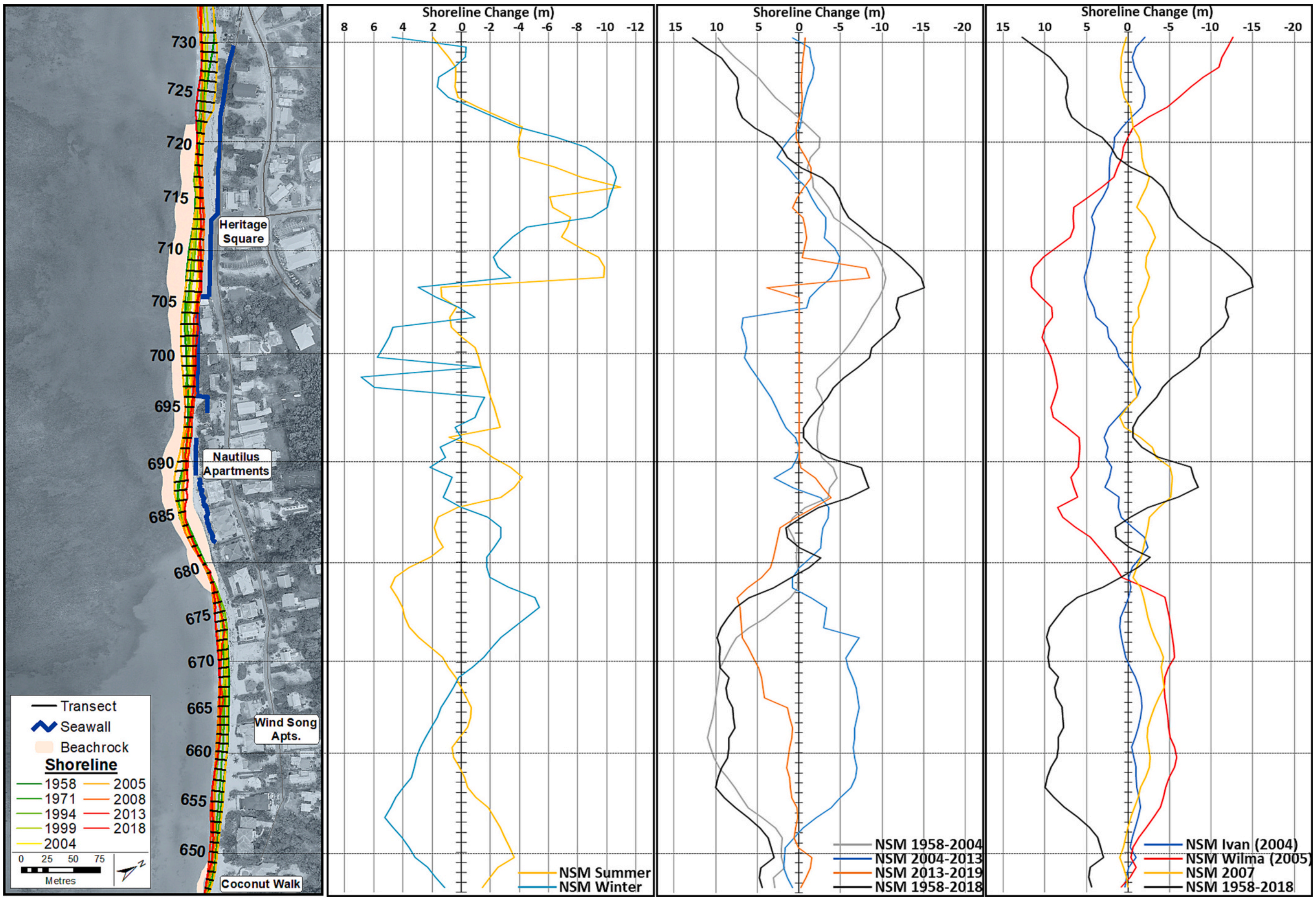


Fig. 6. Beach section A showing transect IDs, beachrock (shaded peach) and location of seawalls (blue line). Darker offshore areas are coral reefs (Cayman Islands Government aerial imagery, LIS 2018), with Net Shoreline Movement (NSM) graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or the closest month recorded. Fig. 5 shows the net shoreline movement from 1958 to 2018 (orange and red depict erosion; green depicts accretion) and Table 2 summarises the DSAS-generated statistics for this period.

4.1.1. Section A

4.1.1.1. Long-term change 1958–2018. In the long-term, the northern and southern extents of this section accreted while the central part retreated (Fig. 6). The area of retreat coincides with a 500 m-long beachrock platform, which has increased in prominence since 2009 as the sand cover has been removed, and forms a headland at its southern end. Section A had a mean SCE of 11.19 m, a maximum of 22.6 m and a minimum of 0 m. 50% of transects showed erosion and 50% showed accretion. NSM ranged from 13.44 m to −15.04 m. The maximum positive LRR was 0.15 m/y (moderate accretion) and the maximum negative LRR was −0.21 m/y (high erosion). For the beachrock-influenced stretch the mean NSM was −5.26 m and mean LRR was −0.07 m/y, however, there are pockets of significantly higher erosion.

Significant construction of residential development along the northern and central shoreline, parallel to the submerged beachrock, occurred from 1971 to 1994. In 2005, a large, sheet-piled retaining seawall was built. The greatest negative NSM runs parallel to a 75 m stretch of this seawall. The mean NSM in this location is −10 m, with a mean EPR of −0.17 m/y and LRR of −0.14 m/y (moderate erosion). The coastline was a continuous sandy shoreline as late as 1971 but has since transitioned to two beaches separated by a beachrock headland backed by seawalls.

4.1.1.2. Interannual. From 1958 to 2004, Section A had a mean SCE of 6.5 m and a mean NSM of 2.3 m. The shoreline followed the long-term trend of accretion at the northern and southern extents, with erosion in the central section. Both the north-west and south-east areas of shoreline growth had a maximum LRR of up to 0.22 m/y (moderate accretion). The erosion corresponds with the position of the north end of Boggy Sand Road beachfront development and the beachrock platform, with the greatest rate of erosion coinciding with the seawalled beachfront development, which had a LRR of −0.17 m/y (moderate erosion) and a maximum NSM of -8 m.

From 2004 to 2013, there was reversal in the long-term trend of shoreline movement (Fig. 6). The north-west and south-east sections eroded and the central section, alongside the beachrock, accreted by up to 12 m. This period spans the occurrence of hurricanes Ivan and Wilma in 2004 and 2005, respectively (Fig. 3). From 2013 onwards, the SCE was small (average of 4.62 m) and the long-term pattern of erosion in the central part of the section and accretion to the north-west and south-east was reinstated. The shoreline parallel to the beachrock had fully retreated to the seawall with no sand cover.

4.1.1.3. Hurricane activity and seasonal trends. From 2004 to 2005 this shoreline saw dramatic change. The northern and southern extents had shoreline loss and the central section had shoreline gains of up to 12 m. The seawall-backed shoreline had the greatest negative shoreline change during summer (Fig. 6). Parallel to the beachrock there is a

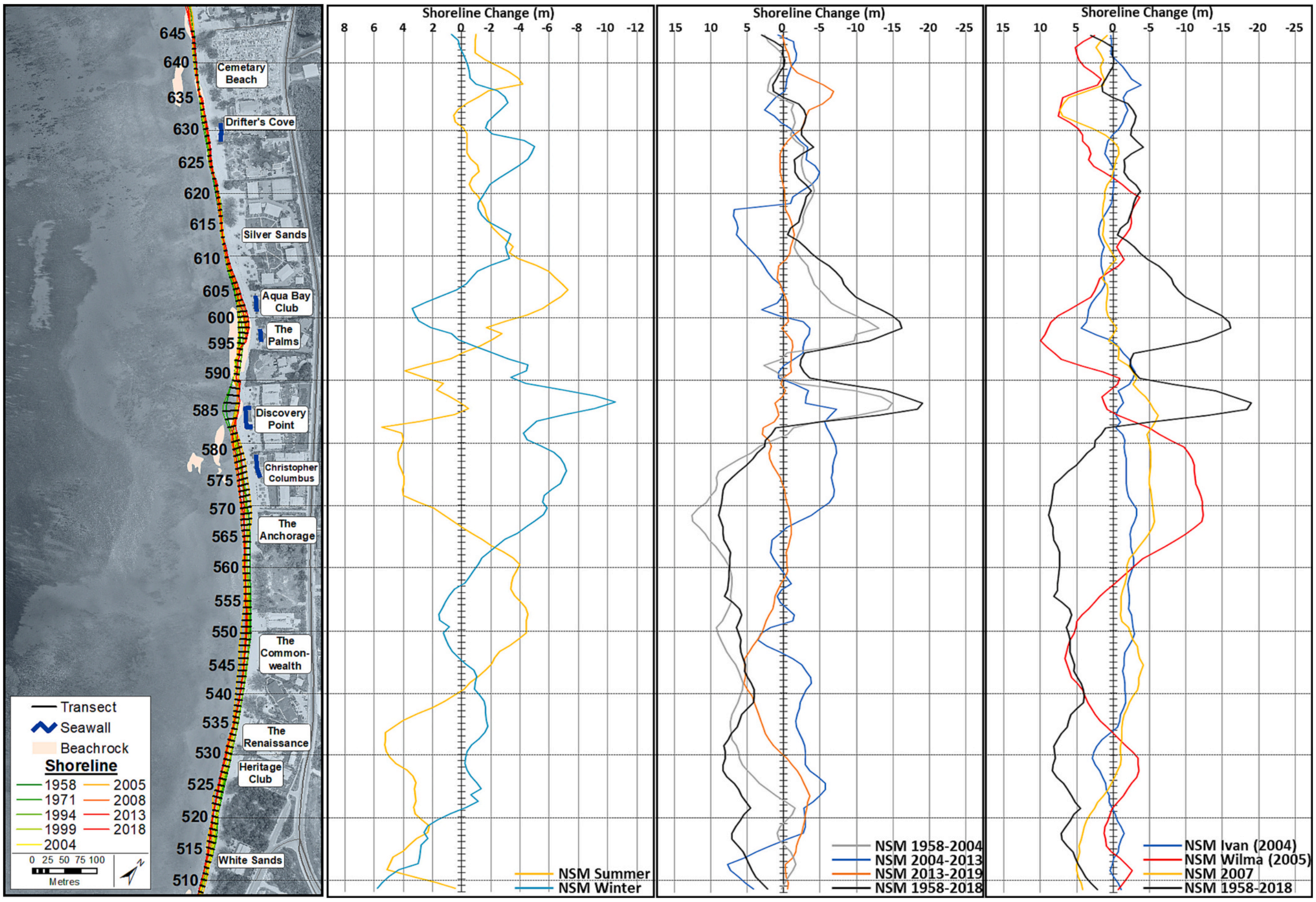


Fig. 7. Beach section B showing transect IDs, beachrock (shaded peach) and location of seawalls (blue line). Darker offshore areas are coral reefs (Cayman Islands Government aerial imagery, LIS 2018), with Net Shoreline Movement (NSM) graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

notable increase in beach width during winter, with beach width growth of over 5 m, which is lost during the summer period. South of the beachrock headland the shoreline immediately retreats during winter and recovers during summer, and in the extreme SE there is an increase in beach width during winter.

4.1.2. Section B

4.1.2.1. Long-term change 1958–2018. This section of beach shows erosion in the north and accretion in the south. In the north are a series of 30–50 m-long beachrock outcrops while a 300 m-long submerged and emergent beachrock platform (Fig. 7) forms a headland at its southern extent. The beachrock headland was covered by emergent sand deposits in images from 1958 and 1971 but was subsequently exposed by shoreline recession. With a few exceptions, most properties are well set back from the sea. The NSM ranges from 8.9 m to −19.01 m (average 1.04 m). The mean LRR is 0.02 m/y (moderate accretion), with a maximum positive LRR of 0.16 m/y (moderate accretion) and a maximum erosion rate of −0.4 m/y (high erosion).

The shoreline change envelope (mean SCE of 9.77 m) is higher than in Section A. The greatest retreat is on the beachrock headland, which has an EPR of −0.32 m/y (high erosion) and an LRR of −0.4 m/y (high erosion).

4.1.2.2. Interannual. The northern part of this section was stable during the period 1958 to 2004 while areas adjacent to the central beachrock headland showed a moderate rate of erosion (mean EPR −0.14 m/y), resulting in a mean NSM of −6.31 m. From 2004 to 2013 the SCE increased to between 5.23 m to 14.86 m, the largest SCE being coincident with beachrock outcrops. However, the behaviour of the shoreline adjacent to the beachrock was variable. The shoreline at the northern end of the beachrock advanced at a mean rate of 0.51 m/y (high accretion) while the southern end retreated at an average rate of −0.66 m /y (very high erosion). The maximum retreat occurred south of the beachrock headland.

From 2013 to 2019, the shore to the north of the main beachrock ledge gradually eroded at a mean rate of −0.22 m/y EPR (moderate erosion). South of the shoreline accreted until the southern-most part of this section, from transect ID 529, which retreated at a mean rate of −0.39 m/y EPR (high erosion).

4.1.2.3. Hurricane activity and seasonal trends. Following Hurricane Wilma the northern sections of the beach accreted, with substantial sand deposition parallel to the beachrock headland (NSM up to 9.97 m) (Fig. 7). Immediately south of the main beachrock outcrop (Transect ID 582 to 558) where long-term accretion had previously been recorded, the shoreline eroded, with a maximum NSM of −12.33 m.

This section of coastline exhibits some distinct seasonal patterns of erosion and accretion. The beaches at Discovery Club and Christopher Columbus (south of the beachrock outcrop, Fig. 7) have very distinct accretion in summer and erosion in winter. However, beaches north of the outcrop undergo erosion in the summer and accretion in winter.

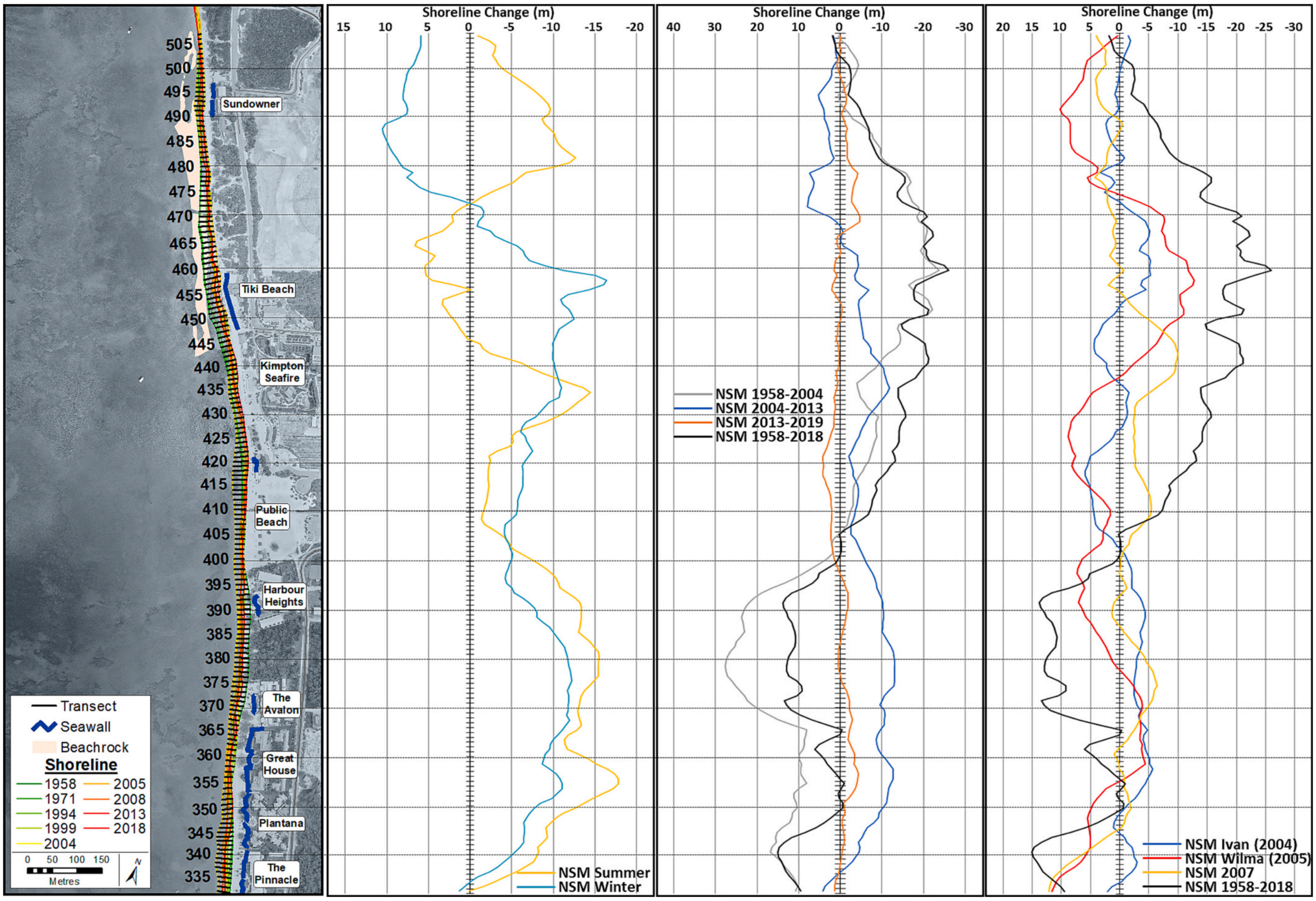


Fig. 8. Beach section C showing transect IDs, beachrock (shaded peach) and location of seawalls (blue line). Darker offshore areas are coral reefs (Cayman Islands Government aerial imagery, LIS 2018), with Net Shoreline Movement (NSM) graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1.3. Section C

4.1.3.1. Long-term change 1958–2018. This central part of Seven Mile Beach contains the longest contiguous length of undeveloped coastal land (Fig. 8). A number of beach bars have been built close to the high water mark and some have seawalls. The substantial seawall at Tikki Beach was constructed between 1999 and 2004.

Section C has the highest mean rate of shoreline retreat (Fig. 8). The mean LRR is −0.04 m/y (moderate erosion), with a maximum positive LRR of 0.36 m/y (high accretion) and a maximum negative LRR of −0.53 m/y (very high erosion). It also has the highest SCE of all sections; a mean SCE of 22.04 m, a maximum of 34.49 m and a minimum of 5.14 m. The highest SCE coincides with the location of the Tikki Beach seawall. The transects along the seawall have an LRR of between −0.3 m/y (high erosion) and − 0.51 m/y (very high erosion) and an NSM of −22.98 m.

The northern shoreline comprises a 550 m-long stretch of submerged beachrock (Fig. 8). This separates a zone of accretion to the north, and the largest contiguous length of shoreline retreat along Seven Mile Beach to the south. Erosion along the beachrock stretch reaches a maximum LRR of −0.53 m/y (very high erosion) at its southern end. The shoreline adjacent to the beachrock has a mean NSM of −12.5 m and an EPR of −0.21 m/y (moderate erosion).

4.1.3.2. Interannual. Shoreline behaviour in this sector shows marked temporal variability (Fig. 9). From 1958 to 2004 the northern part experienced modest retreat and the entire length of the elongated beachrock platform retreated markedly (maximum EPR = −0.52 m/y and mean of −0.27 m/yr). The mean NSM for the beachrock-fronted shoreline was −12.34 m. The maximum NSM for the zone of accretion, south of Public Beach was 26.07 m, which equated to a maximum EPR of 0.6 m/y (very high accretion).

From 2004 to 2013, the north section of this shoreline, including mid-way along the beachrock platform, accreted. Over 95% of the shoreline transects to the south of this eroded (mean NSM of −7.26 m, mean EPR -1 m/y). The beachrock-fringed shoreline experienced moderate accretion. From 2013 this pattern reversed with the northern end of the shoreline adjacent to the beachrock eroding and a small area at the southern end (approximately 150 linear metres) accreting slightly at a rate of 0.2 m/y (moderate accretion).

From 2013 to 2019, the SCE was greatest at the Tikki Beach seawall, with a mean SCE of 15.44 m and a maximum SCE of 19.3 m. The highest erosion occurred parallel to the beachrock platform (mean EPR −0.44 m/y). South of the beachrock a 0.5 km stretch of shoreline experienced a high rate of accretion (mean EPR of 0.31 m/y and mean NSM of 1.79 m), before transitioning to erosion for the remainder of this section.

4.1.3.3. Hurricane activity and seasonal trends. This shoreline underwent dramatic change during the 2004 and 2005 hurricane season (Fig. 9). Accretion occurred along the northern end of the beachrock, along the central section of the shoreline (including Public Beach) and immediately to the south. The southern part of the beachrock-fronted shoreline underwent shoreline retreat. By 2007 a clear redistribution of sediment had occurred. The area that had accreted during Hurricane

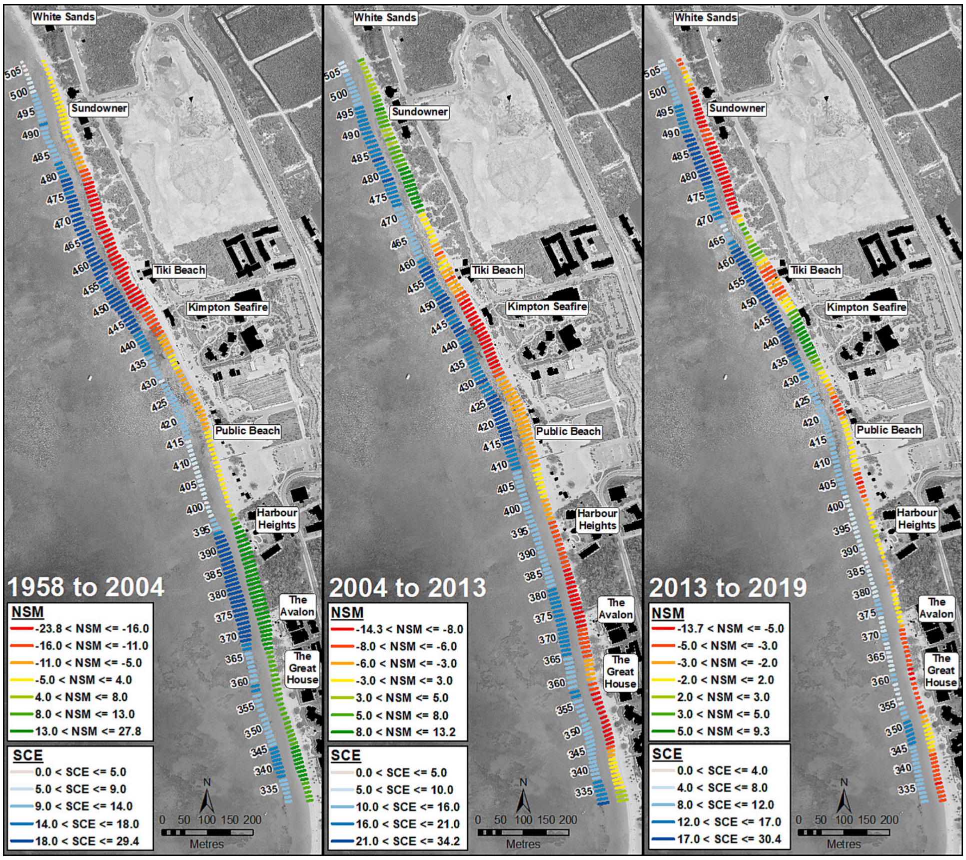


Fig. 9. Section C inter-annual Shoreline Change Envelope (SCE) and Net Shoreline Movement (NSM) (Cayman Islands Government aerial imagery, LIS 2018).

Wilma had eroded once again, although not fully to its pre-hurricane position. The southern half of the beachrock headland (Transect IDs 466–436), which lost sediment during both Hurricanes Ivan and Wilma, experienced shoreline growth of over 15 m between 2005 and 2007.

Large portions of this shoreline show little seasonal variation. North of Transect ID 471 the shoreline advances in winter while immediately south of this it retreats.

4.1.4. Section D

4.1.4.1. Long-term change 1958–2018. Section D is a highly developed shoreline in the mid-section of Seven Mile Beach; by 2004 almost every parcel of land had been developed. There are no beachrock outcrops in Section D. All of the transects in this section show long-term accretion (Fig. 10). The mean LRR was 0.2 m/y and maximum LRR was 0.36 m/y (high accretion). The EPR also closely reflects these growth rates.

4.1.4.2. Interannual. From 1958 to 2004, this section showed consistent accretion, with a mean NSM of 8.6 m (Fig. 10). The mean NSM reduced from 2.8 m (2004–2013) to 1.4 m (2013–2019). From 2004 to 2013 the maximum shoreline growth was at an EPR of 1.43 m/y (very high accretion) at the Westin Resort. From 2013 to 2019, the northern part of this section eroded significantly at an average net shoreline retreat of −2.28 m. The central and southern section predominantly accreted with the rate of accretion increasing in a southerly direction, with a maximum EPR of 1.8 m/y growth (very high accretion).

4.1.4.3. Hurricane activity and seasonal trends. Hurricane Wilma caused pockets of shoreline retreat and growth along this section (Fig. 10). The greatest retreat was from the centre of the section moving south, for approximately 0.5 km. Here recession reached a maximum of over 10 m. North and south of this were approximately 0.5 km stretches of accretion. The eroded section accreted significantly and reverted to an accreting shoreline in the two years post-Wilma.

The beach north of transect 223, accretes in winter while to the south it accretes in summer. The significant SCE for this section appears to be representative of these seasonal fluctuations.

4.1.5. Section E

4.1.5.1. Long-term change 1958–2018. This southern part of Seven Mile Beach (Fig. 11) is quite narrow and a series of beachrock platforms run parallel to the shoreline in its southernmost section. It is characterised by residential and tourism developments built on the active beach, many of which have seawalls that reflect the well-documented history of erosion (Clark, 1988; Seymour, 2000; & Clark, 2003). The Grand Cayman Marriott Beach Resort (previously the Radisson), for example, has made a number of responses to shoreline recession over the past 25 years (Table 3).

The mean LRR was −0.20 m/y (moderate erosion), with a maximum positive LRR of 0.05 m/y (moderate accretion) and a maximum negative LRR of −0.47 m/y (very high erosion). 92% of the transects recorded erosion and 8% accretion. The southern end of Seven Mile Beach had a mean NSM of - > 15 m. The greatest shoreline retreat is at Plantation Village Beach Resort with a mean NSM of −26 m, and mean EPR and LRR of −0.42 m/y and − 0.41 m/y, respectively.

4.1.5.2. Interannual. From 1958 to 1971, Section E was an accreting coastline, however, from 1971 to 1994 this began to change, with maximum erosion of −17.5 m on the southern end of the shoreline (Fig. 11). From 1994 to 1999, dramatic erosion occurred along its full extent with a maximum retreat of −15.8 m. The area of greatest recession coincided with the Marriott Beach Resort and properties immediately to the north and south. Erosion continued from 1999 to 2004,

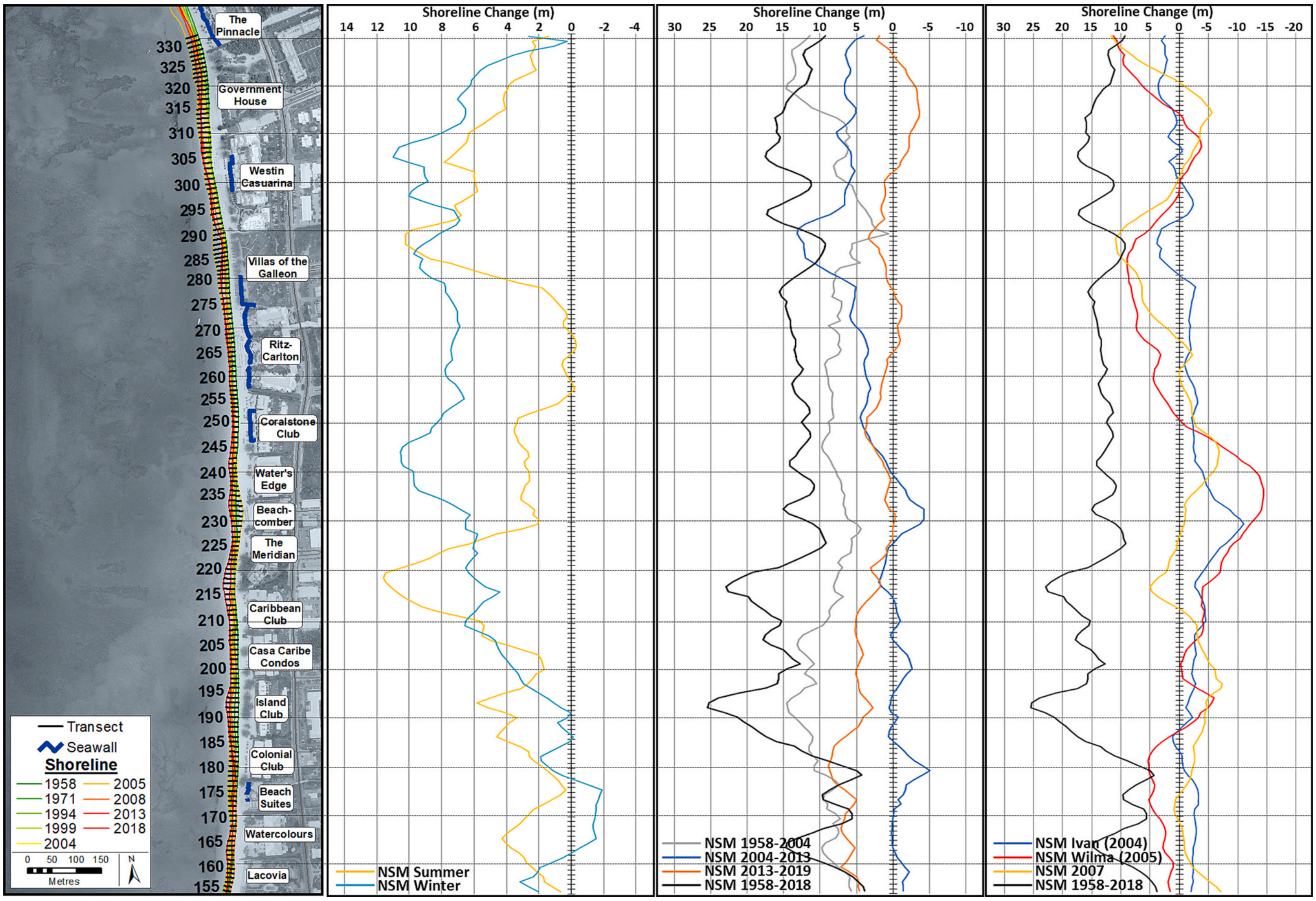


Fig. 10. Beach section D showing transect IDs, beachrock (shaded peach) and location of seawalls (blue line). Darker offshore areas are coral reefs (Cayman Islands Government aerial imagery, LIS 2018), with Net Shoreline Movement (NSM) graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

albeit at a lower rate, with a mean NSM of −7.91 m. From 1958 to 2004, Section E had a mean SCE of 14.58 m and mean NSM of −7.91 m. The maximum negative NSM was −20.74 m and the maximum positive was 5.36 m.

Following Hurricane-related shoreline changes in 2004–2005 (see below), eroded sectors gained sediment and accreted areas retreated from 2005 to 2008. The greatest shoreline advance was along the southern section, adjacent to the Marriott and its neighbouring properties, with a shoreline advance of up to 13.6 m. This coincided with a beach nourishment in 2005 (Table 2). From 2008 to 2013, however, the shoreline retreated along the entire section, with the greatest losses seen in the area that had been nourished in 2005. From 2004 to 2013, Section D had a mean SCE of 9.66 m and a mean NSM of −0.31 m. The maximum net shoreline accretion (9.08 m) was at Regal Beach Club (immediately north of the Marriott Beach Resort) and maximum erosion (−11.15 m) was to the south of Plantation Village Beach Resort.

From 2013 to 2019, Section E had a mean NSM of -3 m. The northern 200 m of this section accreted at a mean EPR of 0.51 m/y. The rest of this shoreline exhibited erosion at a mean rate of −1.13 m/y (very high erosion). The greatest net shoreline retreat was parallel to the developments along the southern end of Seven Mile Beach where beachrock outcrops are prominent. The maximum NSM was −7.92 m, with an EPR of −1.62 m/y.

A temporal sequence of beach profiles measured adjacent to the Marriott resort (Fig. 12a) from 2007 to 2019 show marked variability in beach morphology. The widest beach was attained in May 2016. although the height of the back beach was 0.5 m lower than its maximum recorded in 2007. The most dramatic changes in beach profile are in the last two years of the record (2018 and 2019) when both beach height and volume reduced almost to the point of beach extinction.

4.1.5.3. Hurricane activity and seasonal trends. The majority of this section retreated during Hurricane Wilma by up to −8.8 m. Whilst this is not as significant retreat as in other sections, the seawalls acted as a backstop to erosion. Immediately following Hurricane Wilma, a beach nourishment exercise was carried out at the Marriott Resort which distorts the post hurricane recovery rate. By 2007, south of Transect ID 130 the beach accreted while to the north it experienced major erosion of up to −11.49 m.

Fig. 12b shows shoreline change on transects in the vicinity of the 2005 beach nourishment project at the Marriott Resort. The properties immediately to the north (Laguna del Mar) and south (Tamarind Bay) were not nourished directly, however all show the same temporal trends. From 2009 to 2011 all properties saw significant shoreline retreat, although this did recover to a shoreline position in 2016 that was comparable to or exceeded beach width experienced at the time of the artificial beach nourishment.

Shoreline accretion from 2011 to 2012 coincided with a north-westerly storm from 25 to 29 October 2012, associated with the passage of Hurricane Sandy, over 400 km from the Cayman Islands (HURDAT2, 2020). Fig. 13a shows the shoreline at the Marriott hotel days before the event and one month after (Fig. 13b).

There is a clear seasonal pattern in this sector with the majority of the shoreline retreat occurring during the summer and any growth

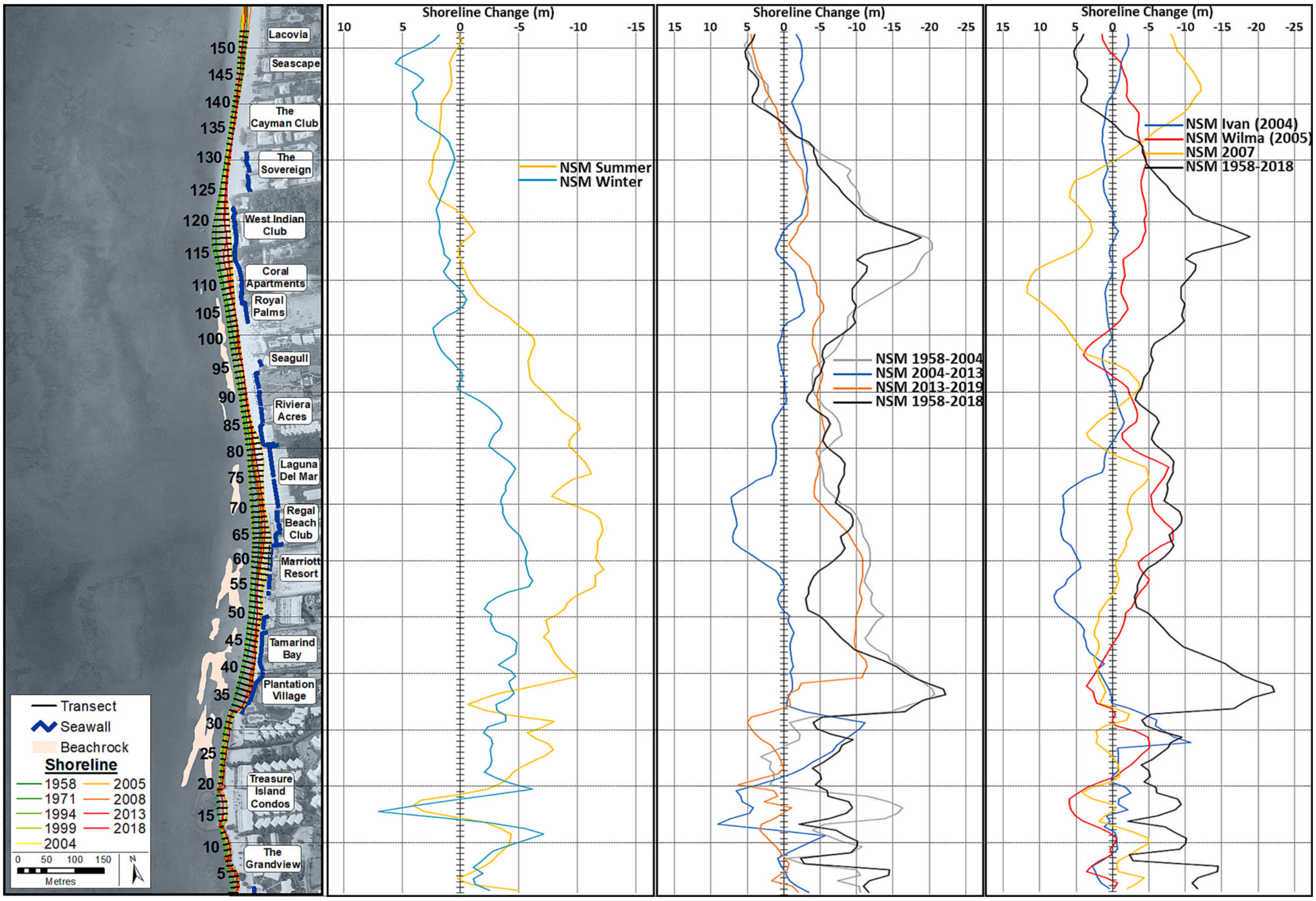


Fig. 11. Beach section E showing transect IDs, beachrock (shaded peach) and location of seawalls (blue line). Darker offshore areas are coral reefs (Cayman Islands Government aerial imagery, LIS 2018), with Net Shoreline Movement (NSM) graphs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

occurring during the winter.

4.2. *Summary*

Shoreline recession is generally associated with the presence of beachrock outcrops. The 568 transects that lack beachrock outcrop are historically stable (average EPR = 0.07 m/yr; S.D. = 0.16) whereas the 176 transects that are fronted by beachrock are eroding (average EPR = −0.14 m/yr; S.D. = 0.13) (*t*-test: 16.06, *p*-value = 0.0001, as shown on Fig. 14). The resulting emergence of several beachrock headlands is a notable phenomenon in the historic evolution of the shoreline in the past few decades. The laterally continuous beach sand cover recorded in the 1950s and 1970s throughout the entire beach, has given way in Sectors A, B, C and E to discrete beachrock headlands that have gradually emerged as persistent features that now separate adjacent sandy beach cells. The patterns of shoreline change indicate that, once exposed, these beachrock headlands become the focus of sustained erosion while adjacent areas variously retreat or erode.

The historic patterns of shoreline change also suggest that a link between these emergent headlands and the adjacent coast. In Sector A, areas on both sides of the eroding headland exhibit long-term accretion, while in Sectors B and C, the headlands exhibit a groyne-like effect with sediment accumulation on their updrift side and focussed erosion on the downdrift side. South of the beachrock headland in Sector C long term-retreat rates are up to −0.53 m/y.

5. Discussion

The overall geomorphology of Seven Mile Beach is controlled by its geological setting on the leeward coast of Grand Cayman at the convergence of two island-encapsulating longshore drift systems. The contemporary beach is located in an embayment bounded by prominent rock headlands and is bounded offshore by a coral reef platform. The presence of multiple beach ridges at the rear of the modern beach, alongside contemporary accretion along much of its length attest to its role as a long-term sink for sediment derived from its adjacent coastlines and the offshore reef. Its gross morphology consists of a west-facing concave planform but long-term and seasonal shoreline change analysis identifies a series of distinctive sub-zones or beach cells (May and Tanner, 1973) separated by low beachrock headlands. These headlands anchor the beach planform in the intervening littoral cells, creating five incipient pocket beaches (Fig. 1). The low (intertidal) nature of the beachrock means that the role of these headlands varies according to the amount of sand cover and that the cell boundaries are "leaky", enabling periodic bypassing of sediment between cells via longshore drift (Klein et al., 2020).

5.1. *Long-term shoreline change*

Historical shoreline analysis reveals considerable longshore variability in shoreline behaviour. Although the general direction of shoreline change (erosion/accretion) has remained broadly similar for each time period analysed, the *rates* of change vary with time. As a

Table 3
Chronology of shoreline stabilization and beach nourishment applications submitted at the site of the Marriott Beach Resort.

Date	Proposal	Decision	Outcome
Sep 1997	Permission sought for 1000 cu yds. of beach nourishment (upland source of sand)	Coastal works licence issued 13 Oct 1997.	Works conducted late Oct 1997 & 5 months later permission was sought again as sand did not remain on the beach.
Mar 1998	Permission sought for 1000 cu yds. of beach nourishment (offshore source of sand)	No permission given.	No works.
Oct 1999	Permission sought for installation of 7640 sq. ft. of beach stabilization mats (polypropylene strips attached to an anchoring matrix to function as seagrass)	Permission granted	Mats installed Nov 1999[1]. Oct 2000 mats torn off seabed and found floating in the sea (Cayman Compass, 2000[2]).
Sep 2000	Permission sought for 1300–1400 cu yds. beach nourishment using offshore sand sources.	No permission given.	No works.
Sep 2002	Permission sought for installation of 200 concrete reef balls to form an artificial breakwater	Permission granted and reef balls installed in Oct 2002.	No notable change to the beach profile and the reefballs are still in place (Fig. 11).
Oct 2002	Permission sought to renourish beach using 1600 cu yds. of upland sand.	No permission given.	
May 2003	Permission sought for an additional 32 reef balls.	Permission granted.	No installation took place.
2005	Cayman Islands Government undertook major beach renourishment at Marriott Resort (approx. 5350 cubic metres).	N/A	Significant shoreline enhancement due to direct placement of sand onto the beach.
2019	Permission sought for installation of geotubes, sand mattress and beach nourishment	Awaited	Awaited

[1] 18 November 1999, Cayman Compass.
[2] 5 October 2000, Cayman Compass.

whole, the beach (Fig. 5) shows long-term shoreline recession in the north and south, with accretion in the central portion (Section D). Accretion in the central parts of the beach on all of transects 155–400 appears to reflect the leeside convergence of the two island-encapsulating longshore drift systems (Fig. 1). Historic shoreline recession north and south of this sector axiomatically suggests that these adjacent areas of the beach are acting as contemporary sources of sediment that is accumulating in the central part. The presence of beach ridges landward of the beach suggest that erosion on the peripheral areas may be a recent development, linked to a reduction in contemporary sediment supply from updrift sources.

Emergent beachrock outcrop exerts a strong influence on subsequent beach behaviour and morphology. In the long term it (a) reduces the volume of littoral sediment through cementation, and (b) thereby creates fixed points in an otherwise mobile beach system (Cooper, 1991). Its influence on beach morphology at Seven Mile beach is manifest in several ways. Firstly, on the beachrock-fringed parts of the shoreline, beaches tend to be absent or narrower and are associated with the highest rates of erosion. Although beachrock headlands in the study area show some variability in the extent of sand cover superimposed on long-term shoreline retreat, once beachrock is exposed, net erosion persists. This is tentatively attributed to a lack of accommodation space for beach sand accumulation, coupled with enhanced turbulence and wave reflection on the hard beachrock surfaces. This potential positive feedback creates ever bigger exposed areas, as shown in the evolution of the northernmost section of the study area. Once beachrock headlands emerge, they exert increasing influence on the planform of the beach (Fig. 1) and the associated longshore movement of sediment.

Beachrock tends to occur as linear features parallel to the shoreline at the time of their cementation. They often are of restricted width and, after emergence continued shoreline recession is likely to lead to beachrock becoming detached from the shoreline. At that point they are likely to act more like an offshore breakwater than a headland or natural groyne.

5.2. Seasonal shoreline change

High rates of shoreline change are considered typical of steep, reflective beaches (Qi et al., 2010) and the magnitude of seasonal variability throughout the study area is 25–30 m. This is, however, based on the average winter versus average summer shoreline position on each transect over a 15-year monthly record. The northern and southern-most portions of the beach (Sections A & E) advance and become wider in winter. Similarly, the central beach sector with sustained long-term shoreline accretion rates (Section D) experiences most accretion during the winter.

In Section C (Fig. 8) there are micro-scale variations in beach behaviour within the beach cells that are suggestive of short-term beach rotation (Short and Masselink, 1999; Klein and Menezes, 2001). Beach rotation creates large variations in shoreline position and is generally attributed to periodic changes in wave climate, particularly direction, without a net gain or loss of sediment in the overall system (Klein et al., 2002). In the study area this is consistent with alternations between north-westerly wind-generated waves during winter, and summer swells from the south-west. Sediment deposition on the beachrock-fringed shorelines also shows seasonal patterns. Their northern portions accrete in the winter while the southern parts accrete in the summer.

5.3. Hurricane impacts

Hurricane Wilma (2005) was the only Category 5 storm to affect the study area in the time period covered by the historical records. It approached from the south-west (opposite to the prevailing wind and wave approach) and produced immediate effects that were generally opposite to the long-term trends. In Sectors A B and C, the beachrock-fronted shoreline sectors (e.g., transects 720–681; 605–585; 445–500) that had exhibited long-term recession, were subject to accretion by up to 10 m as a result of the Hurricane depositing sand on the outcrops. The intervening, historically accreting areas in contrast were subject to erosion by up to 5 m. The reversals in behaviour, however, were not sustained and the long-term patterns of shoreline change were re-established within 2 years. In Sector E, accretion on beachrock-fronted sectors was initiated during Wilma but continued for two years post-hurricane before reverting to the long-term trend, suggesting the delivery of a body of sediment to the nearshore and its subsequent emplacement on the beach under fairweather conditions. The non-beachrock-fronted, accreting central sector of the beach generally experienced accretion of up to 10 m during Wilma. Erosion was focussed on transects 210–250 where a maximum of 15 m recession occurred.

The reversals of behaviour during Hurricane Wilma reflect the

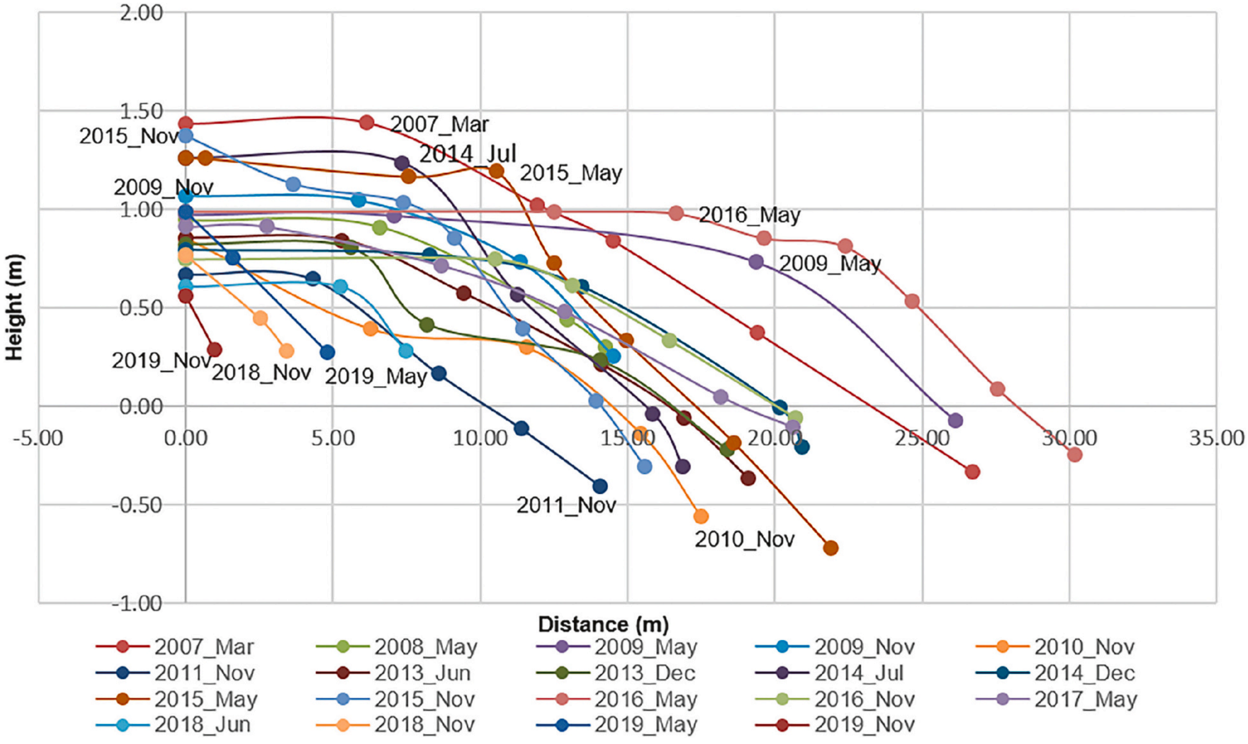


Fig. 12a. Sequence of measured beach profiles at Marriott Resort 2007–2016.

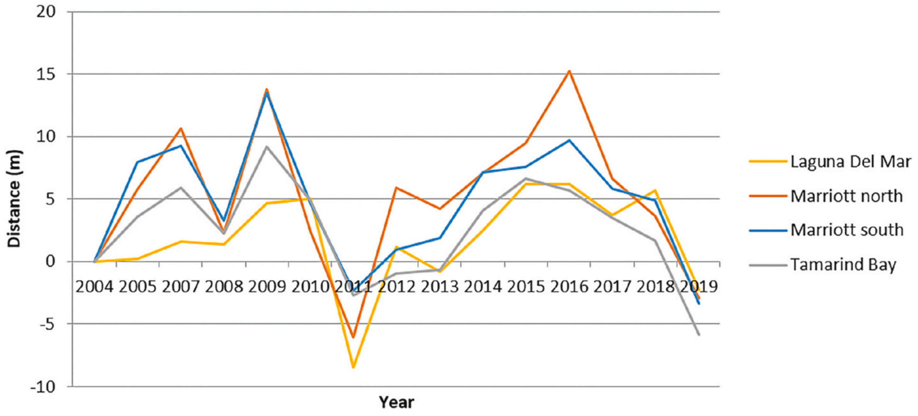


Fig. 12b. Temporal plot of shoreline position for 4 transects at south end of Seven Mile Beach.

infrequent occurrence of winds and waves from this quadrant (Figs. 1 and 4) but the hurricane impacts were short-lived. Nonetheless, the hurricane-induced deposition of sand on the beachrock headlands may be an indication of an episodic headland bypassing process.

5.4. Shoreline stabilization

Most beachrock-lined shorelines in the study area show long-term erosion. In several instances this has led to seawall construction to protect adjacent developments. At several locations these seawalls appear to have caused increases in recession rate and complete beach loss. For example, prior to the construction of the Boggy Sand Road seawall (Section A, Fig. 6) the mean rate of erosion (1958–2004) was −0.17 m/y. Following seawall construction in 2005, the mean rate of erosion doubled to −0.37 m/y between 2004 and 2019 and at the north end of Boggy Sand Road, the beach was completely eroded between 2013 and 2019. At the Tikki Beach seawall (Section C, Fig. 8) the historic rate of erosion for the was −0.21 m/y. This increased to −0.44 m/y after seawall construction. In addition to these dynamic effects of the seawalls (Pilkey and Wright III, 1988), they have also isolated the beach from natural reserves of sand in landward beach ridges on which buildings have been constructed.

5.5. Coastal management implications

Coastal setbacks on Seven Mile Beach are determined based on the mean high watermark and are applied uniformly. Clarke's (2003) suggestion that the permanent vegetation line of 1971 should be utilised to help define setbacks has been incorporated in the draft National Planning Framework (Cayman Islands Government, 2019; Johnston and Cooper, 2022). The shoreline change analysis, however, shows that the shoreline position can fluctuate by up 47.5 m. Applying a uniform approach to setbacks under these circumstances fails to recognise major spatial variability in behaviour.

Fig. 13a. Marriott Beach Resort shoreline October 2012. Note the wooden steps onto the beach which indicate long-term reduction in beach volume.

Fig. 13b. Marriott Beach Resort shoreline November 2012. Note the wooden steps onto the beach which indicate long-term reduction in beach volume.

The landward limit of the existing shoreline change envelope is significantly landward of the 1971 vegetation line in many locations and in Sections A and E, several developments are currently positioned at or seaward of the most landward historical shoreline position. This is an area of concern for development setbacks, particularly given recent changes in the Development and Planning Regulations (Cayman Islands Government, 2018a, 2018b) which now allow for buildings of up to 10 storeys on Seven Mile Beach. As low-rise properties come forward for redevelopment, it would be opportune to revisit coastal setbacks based on the established shoreline change envelope. For some zones, such as Section D the analysis reveals moderate long-term accretion, but with seasonal and event-scale variability that still pose a threat to infrastructure. In order to support this continued process, responsible setbacks would provide a valuable contribution.

Progressive shoreline retreat is evident at the southern end of Seven Mile Beach (Section E), where much development is already close to the mean high-water line. Much of this construction took place following a period of net accretion between 1958 and 1971 (Fig. 15). A change to net erosion followed thereafter and prompted widespread deployment of a variety of shoreline stabilization initiatives. The erosive effects of waves from the south west on the southern end of the beach has been well-documented (Seymour, 2000; Clark, 2003). From 2000 to 2019 there was an increase in documented storms and hurricanes from the south-west (25% of storm activity; Fig. 2), which could have contributed to these losses.

The deployment of reefballs in 2002 (Krumholz and Barber, 2011) and removal of beachrock in 2010 (Olsen and Associates, 2018) had no discernible impact on long-term shoreline behaviour. The beach nourishment exercise in 2005 yielded a positive shoreline position for approximately 6 years post-nourishment, but the shoreline retreated landward of its pre-nourishment position in 2011. Subsequent accretion to a point seaward of the nourished beach position (Fig. 12b) suggests that the nourishment's impact was insignificant in the longer-term shoreline behaviour, being within the historic envelope of mobility. In the presence of long stretches of seawall, a series of weather events from the south-west, can result in full beach loss for extended periods with natural recovery of the beach being dependent on north-westerly wave energy ("Nor-westers") to mobilise and deposit sediment. The duration of beach loss is amplified at times when there is an absence of north-westerly swells.

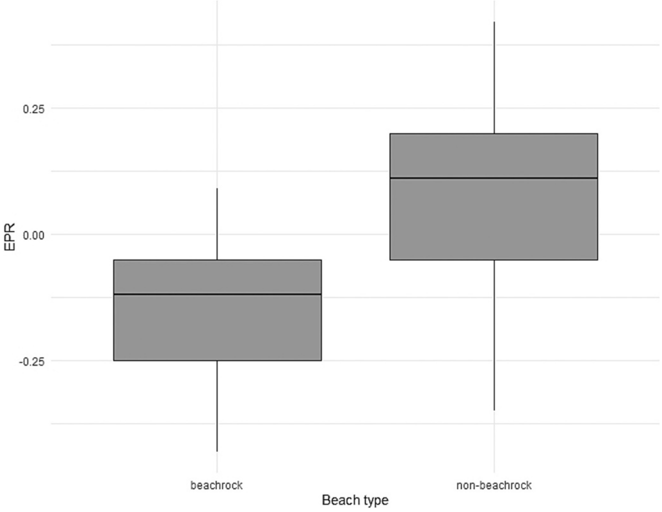


Fig. 14. Box plot of End Point Rate of beachrock and non-beachrock fronted shorelines.

6. Conclusions

Seven Mile Beach sits at the western downdrift end of Grand Cayman, on the leeward side of the island. It can be sub-divided into several interconnected headland-embayment cells, that exhibit characteristic behaviour. Multi-decadal shoreline behaviour is characterised by sustained accretion in the central parts and alternating periods of accretion and erosion on the margins. Beachrock exerts a distinct influence on its evolving morphology with the transects that lack beachrock being historically stable (mean EPR = 0.07 m/yr; S.D. = 0.16) and the transects fronted by beachrock eroding (mean EPR = −0.14 m/yr; S.D. = 0.13). Beachrock headland emergence is accompanied by reduced sand cover and accelerated rates of erosion. The magnitude of seasonal, hurricane-related shoreline change is spatially variable, but can typically be measured in tens of metres. The emergence of beachrock headlands and the pattern of sediment accumulation in the central sector of the bay with erosion in the north and south suggest a reduced sediment supply; relict beachridges at the rear of the beach accumulated under more sediment-rich conditions, but are now being eroded. Human activity has influenced the long-term behaviour of Seven Mile Beach through construction activity in the active beach zone and associated hard defences appear to contribute to beach loss. Beach nourishment was short-lived and produced changes comparable to natural shoreline fluctuations.

The multiple temporal scales at which shoreline changes occur (seasonal, interannual, multi-decadal and event-driven) and the magnitude of changes at these timescales are important for understanding and managing human activities adjacent to the shoreline. They

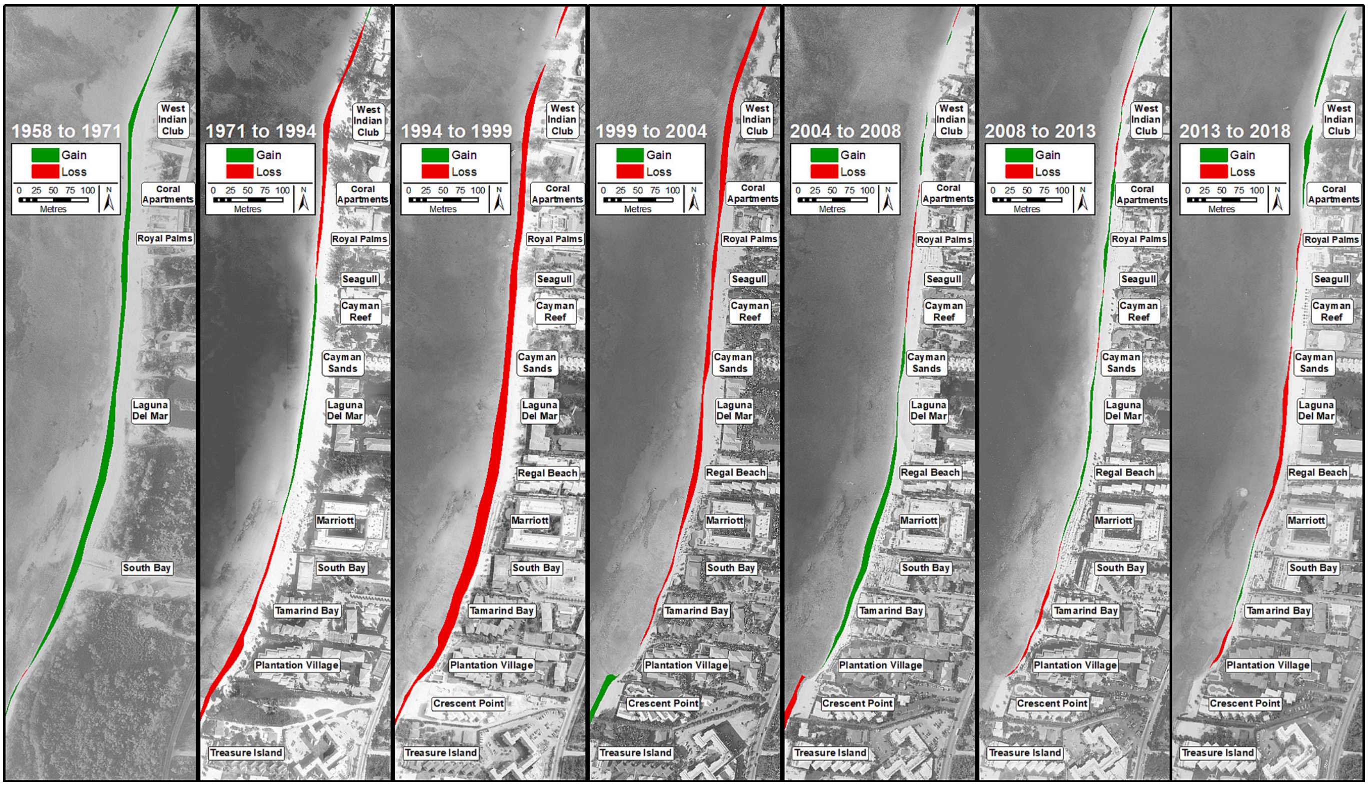


Fig. 15. Net shoreline movement in section E.

should be used to inform the development of more appropriate development planning and in particular, setback lines and the development of adaptation plans to cope with shoreline change.

Data sharing

The research data from this study will be available in Mendeley Data repository and a DOI for the repository will be provided.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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