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Beach Sand Supply and Transport at Kunduchi in Tanzania and Bamburi in Kenya

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Abstract—Beach-head erosion of sandy beach plains in eastern Africa threatens tourism-related infrastructure and the livelihoods of beach users. The nature and drivers of physical shoreline change at Kunduchi, Dar es Salaam, and Bamburi, Mombasa, are described with analyses of beach sand transport through the annual monsoon cycle and the provenance and sustainability of the beach sand supply. Time-series records of wind-vectors at Dar es Salaam and Mombasa show similar averaged patterns. Because of the contrasting alignments of these coasts, the net wind-wave driven longshore transport at Kunduchi (trending NNW) is north-north-westwards, while at Bamburi (trending NNE) there is little net transport. At Bamburi, the beaches are recharged with reef/platform-derived calcium carbonate sand and siliciclastic sand discharged from the hinterland via tidal channels. At Kunduchi, recharge comprises mostly river-borne siliciclastic sand, but riverine sand mining threatens natural replenishment, jeopardising beach maintenance. Eroding beach plain deposits contribute siliciclastic sand at both sites.

INTRODUCTION

Shoreline change, in particular coastal erosion and its socio-economic consequences, has been widely reported in the Western Indian Ocean region (Mushala, 1978; Shaghude *et al*., 1994; Francis *et al*., 1997; Mwanje, 1997; Kairu & Nyandwi, 2000; Makota *et al*., 2004; IOC, 1994; Nyandwi, 2010). After episodes of serious erosion in the 1980s which destroyed or threatened several beach hotels (Griffiths & Lwiza, 1987; Nyandwi, 2001a), hoteliers and other stakeholders invested heavily in protective structures.

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Suggested causes of erosion include the increased severity of storms (Joottun *et al*., 1994), high easterly winds coinciding with extreme high tides (Lwiza, 1987; Dubi, 2001; Nyandwi & Dubi, 2001; Nyandwi, 2001a), sand mining in rivers leading to reduced riverine input to beach sand budgets (Griffiths, 1987; Masalu, 2002; Veland, 2005) and sea-level rise (Fay, 1992). In some cases, coastal protection structures have aggravated erosion (Kairu, 1997; Dubi, 2000; Nyandwi, 2001a).

This paper considers two possible contributors to shoreline change – the impact of seasonally changing wind vectors on beach sand transport, and variability in the supply of sand for natural beach replenishment. The study formed part of a WIOMSA MASMA (Marine Science for Management)-funded project on shoreline change, undertaken from June 2006 to July 2009 at two mainland coastal sites, one at Bamburi near Mombasa in Kenya (Fig. 1a), the other at Kunduchi near Dar es Salaam in Tanzania (Fig. 1b).

MATERIALS and METHODS

The study sites

The Bamburi site extends 15 km between Mtwapa Creek and Tudor Creek (Fig. 1a), lying within the Mombasa Marine Park and Reserve (Munga *et al*., 2010). It is characterized by low cliffs of Pleistocene limestone with embayments occupied by sandy beach plains, a lagoon platform up to 1600 m wide and a fringing reef flanking the deep ocean (Arthurton, 2003). Extensive to pocket sandy beaches occur along most of the shore. Beach rock outcrops are found locally in the mid-intertidal zone (Fig. 2a). One seasonal river, the Mtopanga, discharges to the shore, but its mouth is usually blocked by a littoral sand barrier. The site is developed with hotels and private residences, and the beaches and lagoon are used for tourism, recreation and fishing.

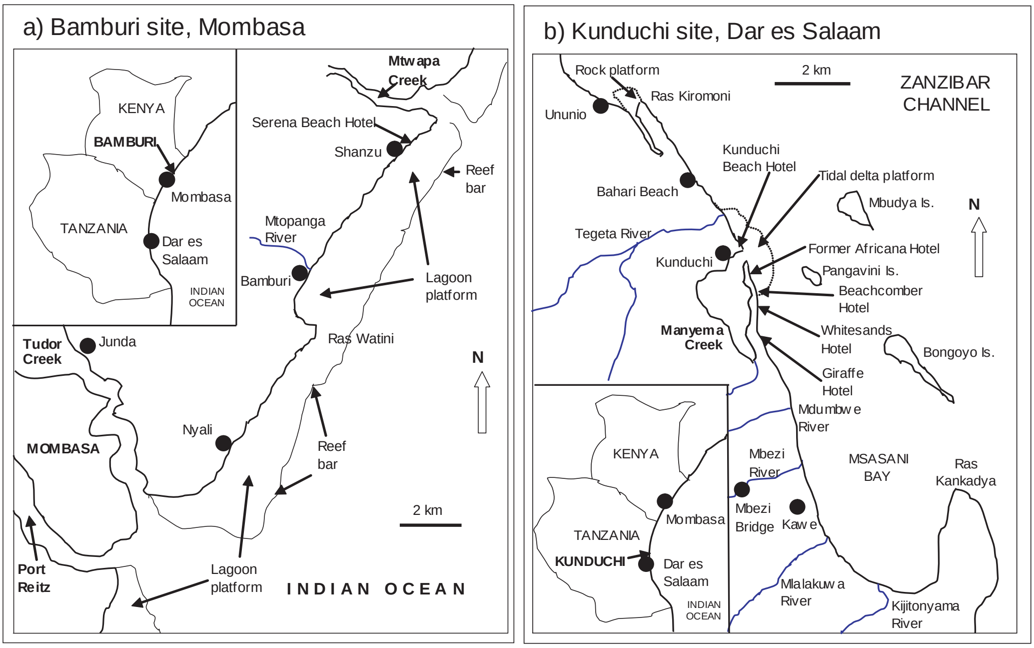


Figure 1. The study sites: a) the Bamburi site on the Kenyan coast, north of Mombasa; b) the Kunduchi site on the Tanzanian coast, north of Dar es Salaam.

The Kunduchi site extends 18 km between Ras Kiromoni and Msasani Bay (Fig. 1b), forming part of the Dar es Salaam Seascape (Wagner, 2007). It has an extensive sandy beach and some mid-intertidal outcrops of beach rock (Fig. 2b). The shore is flanked mostly by a sandy beach plain, including a 3 km-long spit bounding Manyema Creek, a mangrove ecosystem partially cleared for salt-extraction pans. There are low cliffs and an associated intertidal platform of Pleistocene limestone around Ras Kiromoni. Unlike the Bamburi site, there is no fringing reef. The shore is characterised by sandy, inter- to sub-tidal platforms, with extensive seagrass meadows and, off Manyema Creek, a tidal delta platform with migrating sandbars (Nyandwi *et al*., this volume). Further offshore lies the Zanzibar Channel, with shoals and patch reefs around islands designated as marine reserves, administered by Tanzania's Marine Parks and Reserves Unit. Five seasonal rivers discharge to the shore. As at Bamburi, the site has been developed for private residences and beach hotels and is an important asset for recreation and fishing activities.

Both sites are mesotidal, with semi-diurnal tidal cycles. The maximum spring tidal range is almost four metres and the minimum neap, about one metre. There are two periods of especially high spring tides, mid-March to early June and mid-September to mid-December, associated with the equinox (Pugh, 1987). The climate is influenced by the seasonal shifts of the Inter-Tropical Convergence Zone, resulting in an alternating regime of the SE monsoon from April to October and NE monsoon from November to March (Mahongo *et al*.,2012). Monsoon-associated "long rains" (*Masika*) usually occur between March and June and "short rains" (*Vuli*) between October and December (Fig. 3).

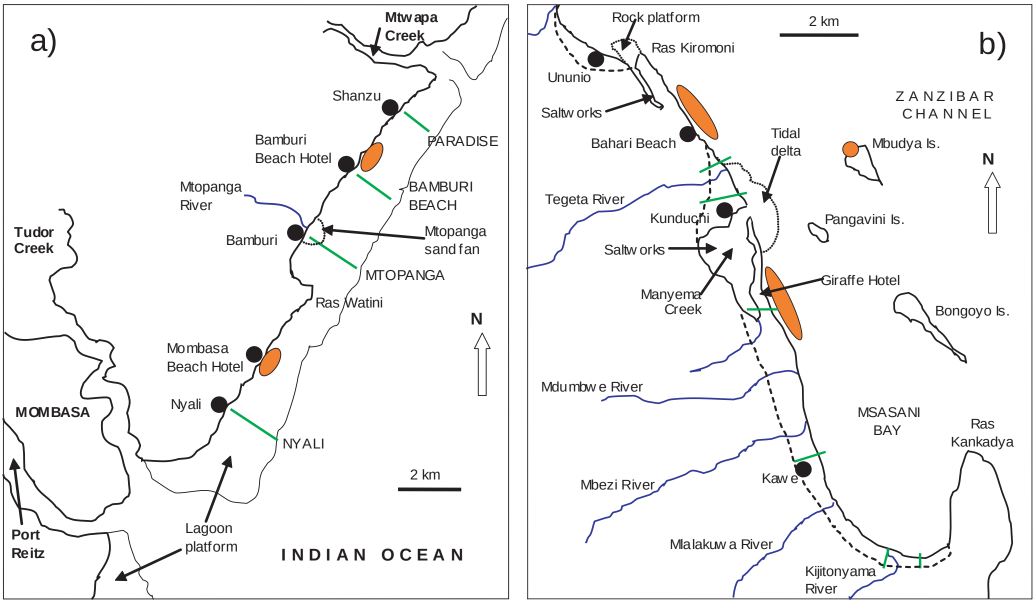


Figure 2. a) Reef-platform transects at Bamburi. b) Beach plain sand transects at Kunduchi (green lines) with approximate inland limits of beach plain sand (broken line). The six beach plain transects at Kunduchi are referred to as P1, P2, P3, P4, P5 and P6 from south to north. Intertidal beach rock outcrops at both sites are shown in brown.

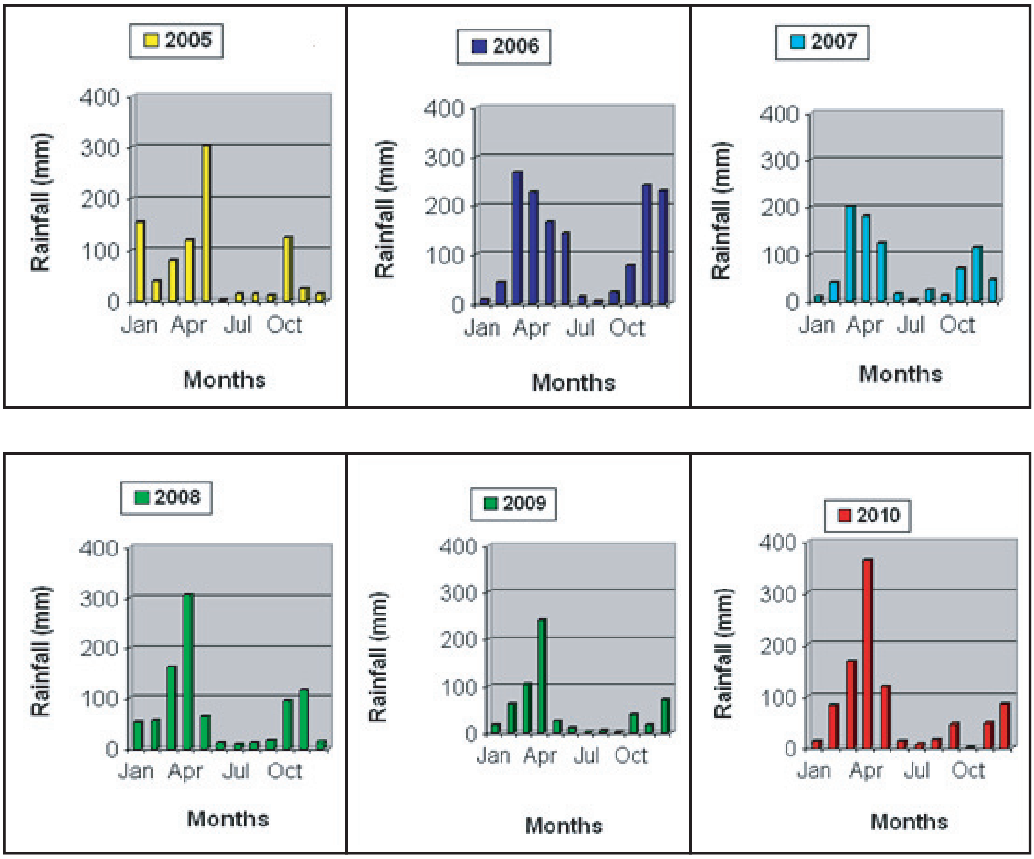


Figure 3. Monthly rainfall record (mm) for Dar es Salaam area, January 2005 – December 2010. Source: Tanzania Meteorological Agency.

Shoreline change analysis

Anecdotal accounts of shoreline change were compiled at both sites. At Bamburi, interviews were carried out with 57 stakeholders using qualitative interview guides and semi-structured questionnaires, and focused group discussions using open-ended questions (Bunce *et al.*, 2000). The reported shoreline changes were documented using a hand-held GPS (Global Positioning System). At Kunduchi, qualitative interviews were held with 20 stakeholders, mostly local fishermen and residents from Kunduchi village (Fig. 1b).

Five sets of aerial photographs (1954, 1969, 1988, 1994 and 2007) were acquired for the Bamburi site and analysed for changes in shoreline position. This process involved scanning and geo-referencing the aerial photographs (Scale 1:3,000 to 1:60,000) relative to topographic maps (Scale 1:50,000) using Arc-GIS 9.2 software. Control points (features) that were clearly identifiable in both the aerial photographs and the maps were used for geo-referencing. As many control points as possible were used in each photo to stretch the coordinates to their correct geographical locations and ensure the accuracy of the process. For comparison, the shorelines were digitized at a scale of 1:60,000, this being the smallest scale of all the photographs.

Wind trend analysis

The mean wind regimes were analysed to determine the intra- and inter-annual trends in wind strength and direction using data from the meteorological stations at Dar es Salaam International Airport (1980–2004) and Moi International Airport (1992–2005), Mombasa. These meteorological stations lie within 15–25 km of the Bamburi and Kunduchi sites and their wind strength and direction are recorded daily at 9 a.m. and 3 p.m. local time (06.00 and 12.00 GMT).

Beach profiling at Bamburi

At Bamburi, beach profiles were measured at 20 locations (Fig. 4; BP00 to BP19) perpendicular to the shoreline from the backshore to the low water mark (or about 1.0 m water depth at low tide) to analyse longshore and cross-shore sand transport. The profile locations were marked at the backshore using a temporary concrete benchmark and steel pin, the coordinates of which were recorded using a hand-held GPS. The beach profiles were monitored eight times (C1 to C9) over a two-year period (2007–2008) using a standard levelling method with OTS 632N Electronic Total Station equipment. Monitoring was carried out during the middle of the SE and NE monsoons and the inter-monsoonal periods at low spring tides to allow access to the foreshore. The profiling data were recorded and the relative heights were plotted perpendicular to the backshore relative to the benchmark following the method used in the Texas Shoreline Change Project (James *et al*., 2000). Maximum changes in the beach profiles observed 10, 20, 30 and 60 m from the benchmark were analysed for the periods representing the NE and SE monsoon seasons. Additional observations were made at Bamburi during the SE monsoon to record the impacts of local wind-waves and swell waves on beach sands during the spring tidal cycle.

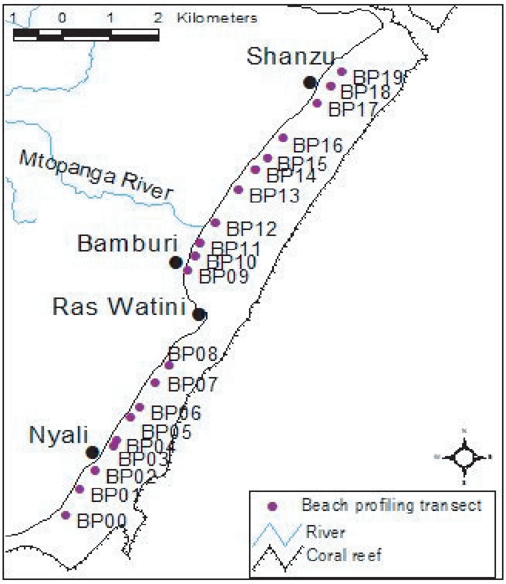


Figure 4. Location of beach profiles BP00–BP19 (purple spots) at Bamburi.

Beach profiling was not conducted at Kunduchi. Instead, the prevailing long-term beach sand transport regime was interpreted from the coastal geomorphological features and time-series satellite imagery.

Beach sand supply

Surveys of the siliciclastic sand discharge of five rivers were carried out at Kunduchi during 2007-2008. This involved recording evidence of mining activity, noting the replenishment of deposits during flood spates and estimating the volumes of river bed sand deposits by measuring their extent (width, length and depth).

Possible pathways for siliciclastic sand transport from the hinterland were appraised at Bamburi; pathways included the Mtopanga River and Tudor and Mtwapa tidal creeks (Fig. 1a). Four transects were surveyed at low tide (17–27 July, 2007; Fig. 2a) to assess the potential contribution of marine, calcium carbonate-fixing biota on the reef and reef platform to the beach sand budget. Sampling sites were on the landward side of the reef flat, in mid-lagoon and on the beach, approximately midway between the toe and the crest. Triplicate sediment samples were collected to a depth of 10 cm using a 35 mm diameter core and assessed for sources of biogenic carbonate sand. Biogenic substrate cover was estimated in twenty quadrats of 50 cm x 50 cm (see Lin & Shao, 1998) to confirm the presence of fauna and flora contributing sedimentary components at the sampling sites. Their absence would mean that they had been transported from elsewhere.

The contribution by wave erosion of beach plain sand deposits to the beach sand budget was assessed at both sites. At Kunduchi, the beach sand was auger-sampled along five transects (P1-P6; Fig. 2b). Samples of about 1 kg were collected from depths of 0.5, 1 and 2 m at each sample location. Only one transect was auger-sampled at Bamburi.

Laboratory procedures

Sand samples from the rivers, beaches and beach plains were washed with fresh water to remove salts, dried in an oven at 60^{o} C for 24 hours and then analyzed for carbonate content. Carbonate analyses of the samples were undertaken using the acid leaching method in which a subsample of known weight of the dried sand is leached using dilute (25%) hydrochloric acid until no more bubbles emanate from the subsample (Shaghude & Wannäs, 2000) . The carbonate content was calculated from the weight lost during leaching. The augered sand samples from the Kunduchi backshore sediments were analyzed for grain size by sieving, the mean grain size being calculated according to Folk & Ward (1957). Carbonate analysis was not undertaken on the Kunduchi nearshore surface sediments as this had already been done in a previous study (Shaghude *et al*., 2006).

The samples from the Bamburi reef-platform-beach transects were oven-dried at 60^{o} C for 24 hours, examined microscopically and the biogenic components were categorized following the method outlined by Shaghude & Wannäs (2000) and Erftemeijer & Koch (2001). This was accomplished by placing a subsample of the sediment on a grid for counting and categorization. The percentage composition of each category was calculated from the total number of particles counted in the subsample.

RESULTS

Shoreline change

The profiling data recorded at Bamburi and the maximum changes measured in the beach profiles during the NE and SE monsoon seasons are presented respectively in Figures 5 and 6.

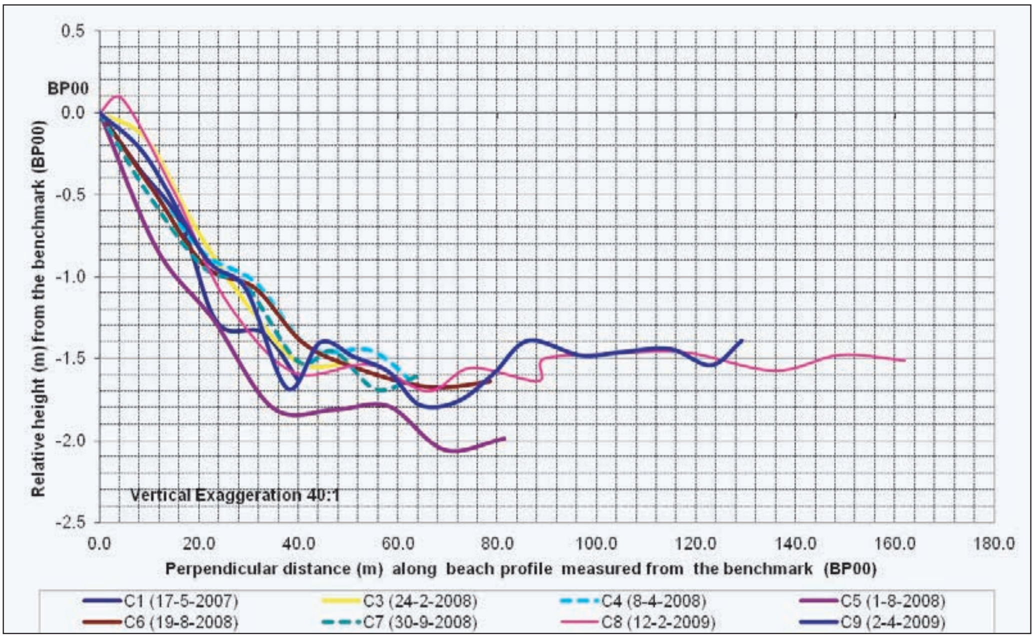
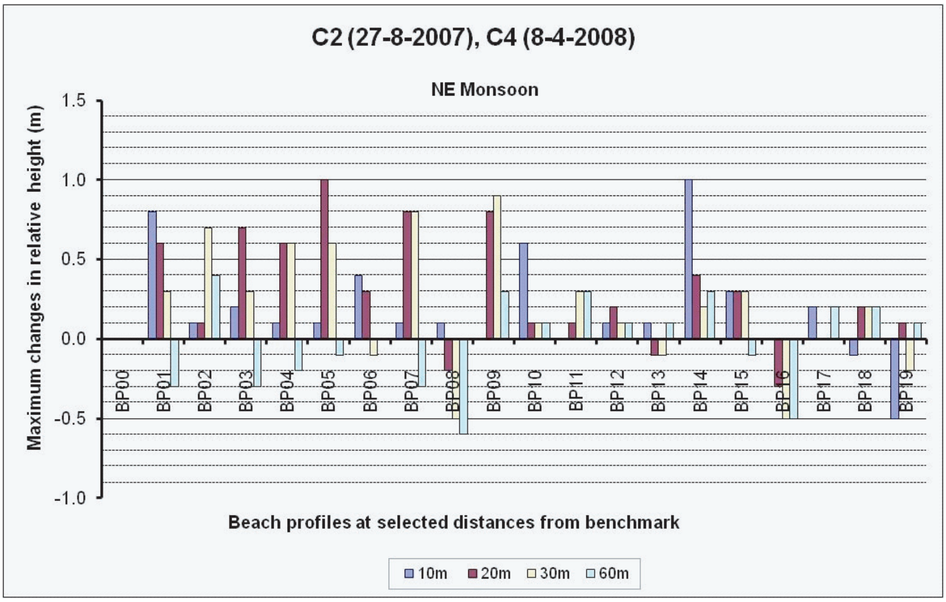


Figure 5. Example of serial plots of beach profiles from one of the transects (BP00) at Bamburi. C = profile campaign number.



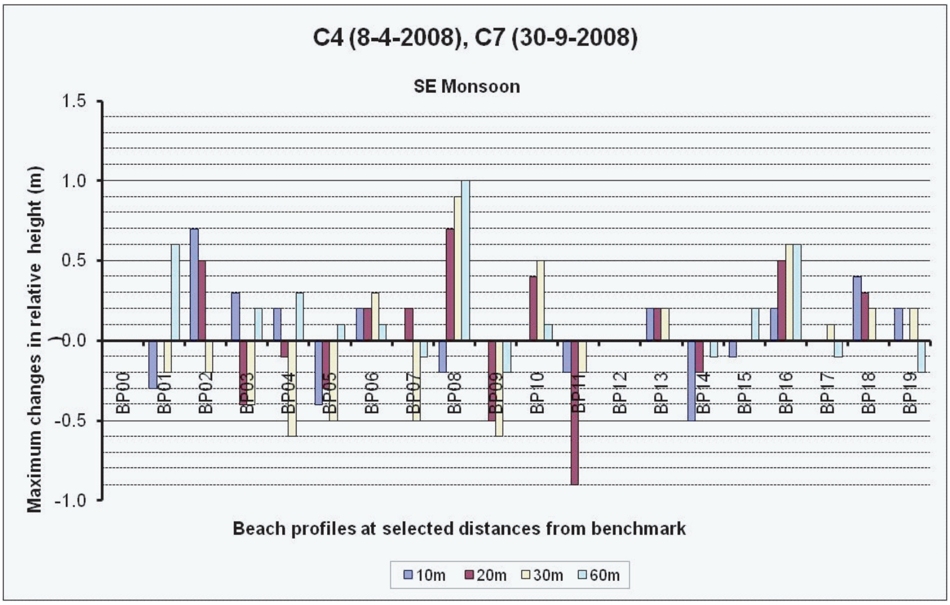


Figure 6. Maximum changes in the beach profiles at selected distances from the benchmark at Bamburi in the NE and SE monsoon.

Anecdotal accounts regarding shoreline erosion at Bamburi went back almost 60 years. Sixty per cent of the interviewees stated that it had increased over the last 20 years, resulting in a significant loss of beach area. Erosion was reported by respondents to be severe during the SE monsoon, when the waves were stronger and the beach as well as the land bordering it was washed away. According to respondents who have operated at Bamburi for more than 20 years, erosion has resulted in shoreline regression of about 200 m in some areas along Nyali Beach (Fig. 2a). During the NE monsoon season, wind-driven sand was said to be deposited on parts of the beach.

Comparison of the Bamburi shoreline in the 1954, 1969, 1988 and 1994 aerial photographs showed that it underwent discernible change in the order of 10 to 50 m. However, the change was not uniform along the entire shoreline and appeared as a thick line at the digitized scale of 1:60,000 (where a one millimetre thick line at this scale represents a change of 60 m). Moreover, the set of photographs was incomplete and lacked 60% overlap or 30% side lap. Some of the historical photos also lacked clarity and this posed a challenge when merging the coastline with existing maps.

At Kunduchi, respondents reported that shoreline changes were most intense on the coastal section between the Kunduchi Beach Hotel and the Whitesands Hotel (Fig. 1b). Erosion was said to have been recurrent south of the creek mouth (including the site of the former Africana Hotel) over the past 40 years, leading to localised shoreline retreat of more than 200 m over this period. Interviewees stated that erosion of the shore was more intense during the SE monsoon than during the NE monsoon.

Analysis of imagery covering Kunduchi over the period 2003-2010 revealed no significant net shoreline change except at the site of the former Africana Hotel which adjoined the mouth of Manyema Creek (Fig. 1b), where seawall and groyne construction has resulted in a seaward shift.

The wind datasets

Wind rose diagrams (Fig. 7) and vector analyses (Fig. 8) are presented for each site relative to their coastal orientation.

Analyses of 25 years (1980–2004) of wind data from the Dar es Salaam International Airport meteorological station revealed that wind speeds exceeding 8 m/s (16 knots) were generally rare. Most of the wind speeds were within the 2–3 m/s (4–6 knots), 3.5–5 m/s (7–10 knots) and 5.5–8 m/s (11–16 knots) categories; corresponding to a light breeze, gentle breeze or moderate breeze on the Beaufort scale (Wheeler, 1999). Wind speeds within the 0.5–1.5 m/s (light air) category were relatively rare.

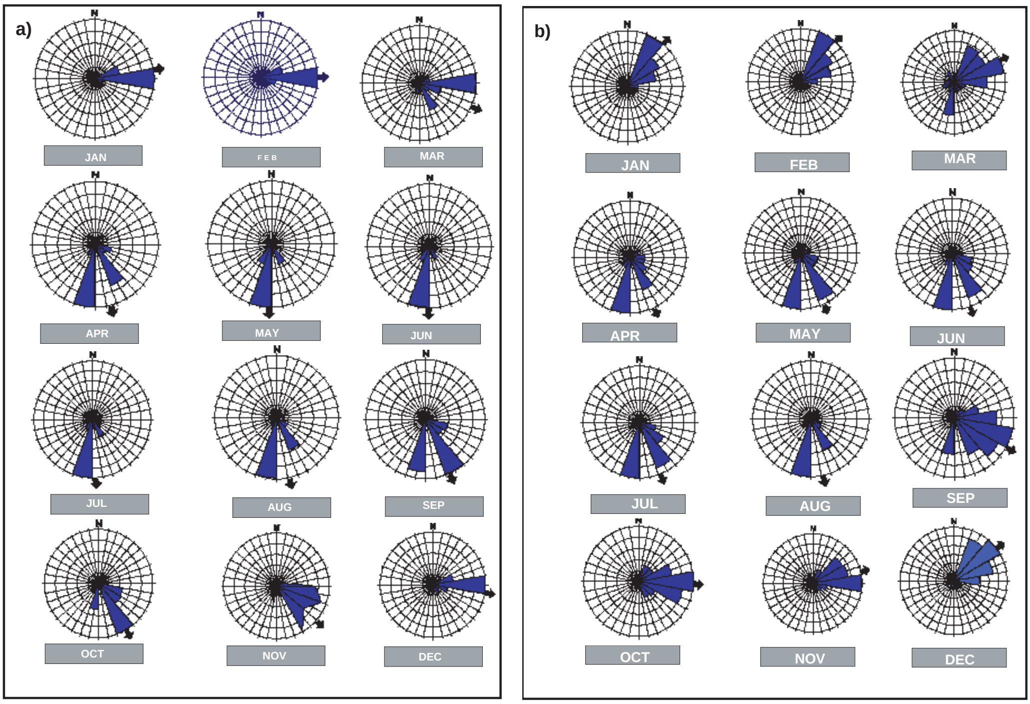


Figure 7. Mean monthly wind roses at 3 pm at a) Moi International Airport, Mombasa, 1992–2005, and b) Dar es Salaam International Airport 1980–2004. The arrow at the perimeter of each wind rose indicates the mean wind direction. Data sources: a) Kenyan Meteorological Department and b) Tanzanian Meteorological Agency.

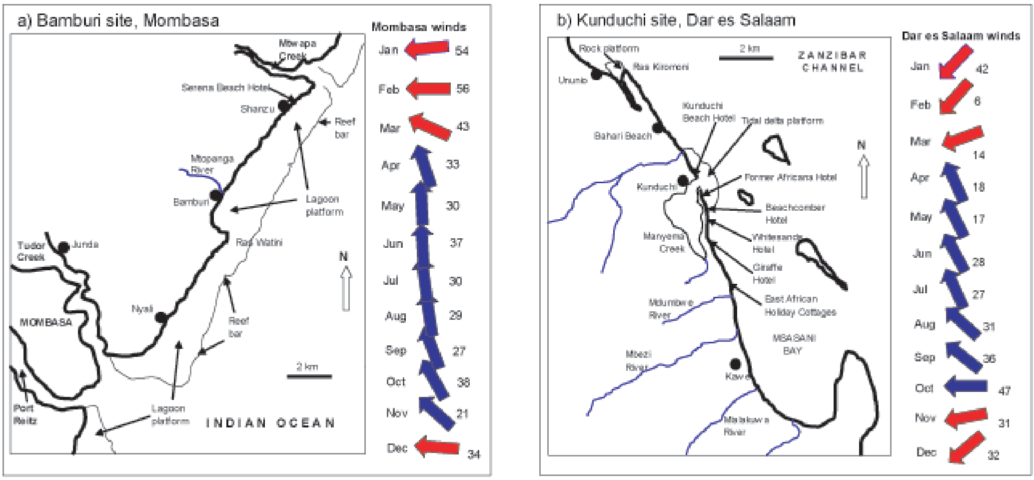


Figure 8. Seasonal variation in mean monthly wind vectors at 3 pm at a) Mombasa and b) Dar es Salaam, shown relative to the shorelines of Bamburi and Kunduchi. The average monthly totals of the mean surface wind frequency for wind speeds >5 m/s are shown as percentages. Red arrows = NE Monsoon; blue arrows = SE Monsoon.

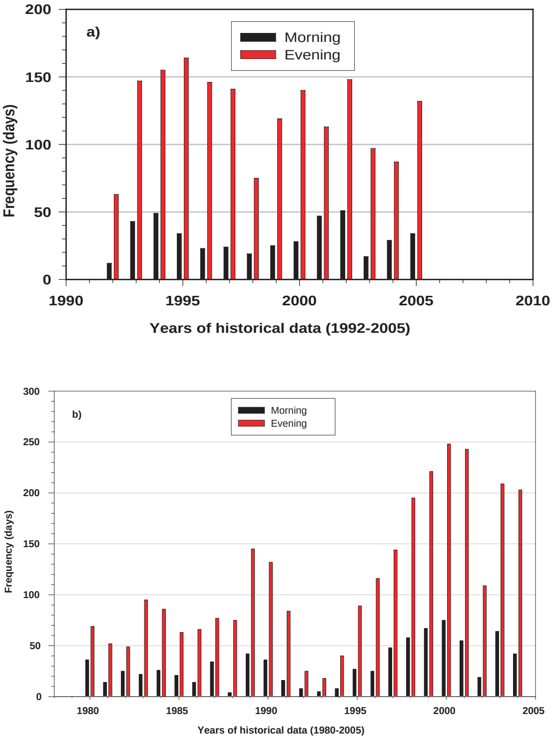


Figure 9. Number of days per year during which winds >5 m/s blew in the morning (9 am) and afternoon (3 pm) at a) Moi International Airport, Mombasa, 1992–2005 and b) Dar es Salaam International Airport, 1980–2004. Data sources: a) Kenyan Meteorological Department and b) Tanzanian Meteorological Agency.

In Mombasa, analysis of 14 years of raw wind data (1992–2005) from the Moi International Airport meteorological station showed that morning wind frequencies >5 m/s were low (less than 20%). Frequencies of these velocities were, however, much higher in the afternoon, approaching 50% of the total range. Also, the frequency of higher wind speeds varied both seasonally and inter-annually (as noted in the foregoing paragraphs). However, significant inter-annual variation can be inferred from the analysis of the mean monthly wind speeds.

Wind data analysis revealed that the highest wind frequencies at both sites occurred during September to March, with peaks in October, January and February for Mombasa, and September, October and January, for Dar es Salaam (Fig. 8); strong winds were generally lower in frequency (<30%) during the remainder of the year. The analyses also showed that winds at Mombasa were stronger than at Dar es Salaam from December to July, and vice versa from August to November. Analysis of the total number of days in a year with wind speeds >5 m/s revealed a significant change in the wind regime during the 25-year data span at Dar es Salaam; winds during 1995–2004 were generally stronger than before (Fig. 9).

Wind roses (Fig. 7) showed that wind vectors varied in the afternoon throughout the year at both Mombasa and Dar es Salaam. The NE monsoon records indicated that, at Mombasa, the winds blew from the E or ESE, while at Dar es Salaam they blew from the NE or ENE from November to March, the strongest winds occurring in each case in January. The monthly wind vectors are summarized in Figures 8a and b, where they are shown relative to the respective coastlines, the Bamburi shore generally trends NNE, and the Kunduchi shore NNW.

The wind-wave regime

Both sites are subject to locally generated waves formed by coastal winds, with typical maximum heights of about 20 cm, and much larger swell-generated waves, driven by persistent strong oceanic winds. The meteorological data for Dar es Salaam and Mombasa (Fig. 7) provided an indication of the patterns of wind-wave forcing at their respective shores.

Observations at the Bamburi site during the SE monsoon indicated that locally generated wind-waves were dominant during the mid- to upper mid-stages of the tidal cycle, with obliquely breaking waves transporting sand along the shore. The process tended to be more effective in the afternoons and evenings than the mornings, reflecting the stronger winds at those times. In the upper part of the tidal cycle, particularly during spring tides, the locally generated waves became subordinated by the swell waves, which advance parallel to the shore. During high tides, significant perpendicular cross-shore sand transport occurred in the swash zone, first up the beach slope, and then down, entrained in the swash drainage. No discernible longshore sand transport was observed during this stage, though this may have been masked by the cross-shore movement. No such effects were observed during the neap cycle.

The monthly wind vectors were broadly similar at the two sites (Figs 8a & b) and thus, it is assumed, so were the seasonal forcing patterns of the locally generated waves at the shore. However, the effect of wind-wave forcing on the NNE-trending Bamburi shoreline contrasted with that on the NNW-trending Kunduchi shoreline. The Bamburi shore experiences a balance between the NE and SE monsoonal wind-wave forcing while, on the Kunduchi shore, the SE monsoonal forcing is predominant, with a consequent net longshore drift to the north-northwest.

Beach profiles at Bamburi

Monitoring of the 20 beach profiles (BP) at the Bamburi site during the monsoon cycle (Figs 4 & 5) revealed marked changes in the distribution of beach sand. The profiles were observed to fluctuate between campaigns as indicated by the difference in the relative heights (Fig. 6). Sand was transported along and across the shore with the overall budget being maintained (Fig. 6). The reversible trends during the NE and SE Monsoon were clearly illustrated by a rise (accumulation of sand) or fall (depletion of sand) in the relative heights of the profiles at each location (Fig. 6). For example, at BP00 and BP17, respectively on the Nyali and Serena beaches, there was a major long-shore drift in sand transport northwards toward BP01 and BP19 during the SE monsoon, leaving a bare rock platform. This transport reversed during the NE monsoon when the beach was naturally replenished. A complete reversal in the accumulation and depletion of beach sand was also witnessed at BP01, 05, 08, 14, 16 and 18 (Fig. 6).

Beach sand supply

Sand from hinterland sources

At Bamburi, the beach sands were a mixture of siliciclastic and calcium carbonate grains (Table 1). On beaches towards the northern and southern ends of the site (Shanzu and Nyali, Fig. 4), siliciclastic grains were predominant; on others (e.g. off Bamburi village and Mtopanga River, Fig. 4), carbonate grains formed the major constituent. The bed of the Mtopanga River was examined as a possible feeder of siliciclastic sand, but no significant siliciclastic sand load was found.

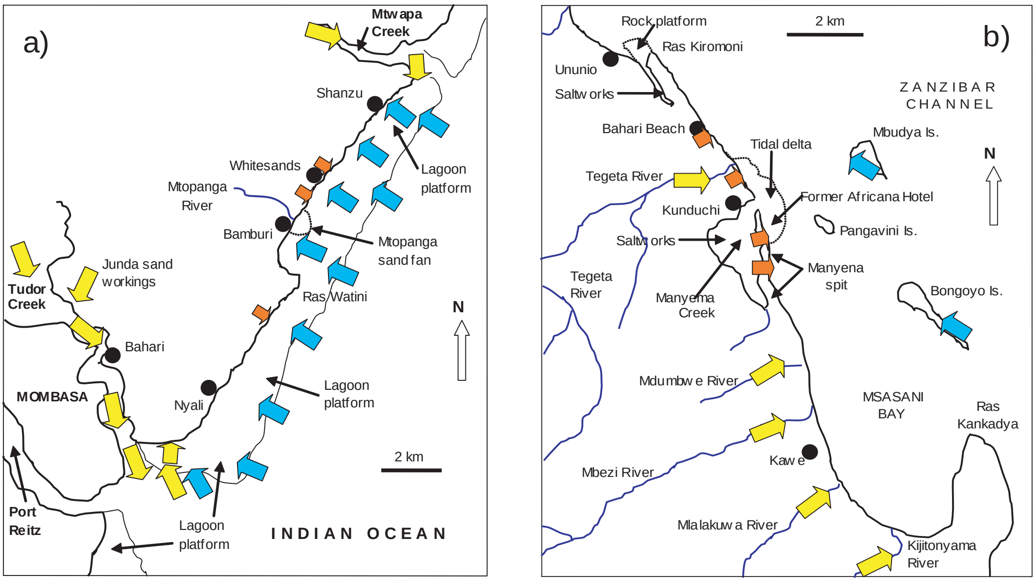


Figure 10. Principal sources and pathways of sand supplied to the beaches and adjacent island shores of a) Bamburi and b) Kunduchi: Yellow arrows – siliciclastic sand from the hinterland; brown arrows – silicilastic sand from erosion of the beach plains; blue arrows – biogenic sand from the reefs and platforms.

The intertidal depositional fan at the outflow of the Mtopanga River at Kenyatta public beach (Fig. 2a) was construed to be largely the product of the rupture of a littoral sand bar by river flooding. Examination of the platform at English Point, adjoining Tudor Creek, at low spring tide revealed mixed siliciclastic and carbonate sand, with sand waves indicating transport from the seaward rim (apparently deposited by currents from the creek) towards Nyali's southern shore (Fig. 10a).

Siliciclastic grains were predominant in the beach sand throughout the Kunduchi site. Their principal supply was via seasonal rivers from the hinterland (Fig. 10b), discharging directly to the shore or to coastal ponds dammed by littoral bars. Surveys carried out in July and August 2007 showed that sand mining is intensive in these river beds. Stockpiles of sand were awaiting transportation along the lower courses of the Mbezi, Mlalakuwa, Mdumbwe and Tegeta rivers (Fig. 10b). The Mbezi, Mlalakuwa and Tegeta river courses had been mined extensively, leaving most of their beds almost bare. The Mbezi and Mdumbwe rivers were re-visited in January 2008. On the Mbezi, in the vicinity of Mbezi Bridge (Fig. 1b), siliciclastic sand deposits to the volume of about 13,000 m^3 had been replenished by flood spates. Our survey of the Mlalakuwa and Mdumbwe rivers indicated similar replenishment totalling at least 10,000 m^3.

Sand from beach plain deposits

At both sites, unlithified sand deposits form beach plain terraces at about 4 m above mean sea level (as seen in Google Earth imagery). Where unprotected, these deposits were prone to wave erosion during high tidal states, as witnessed near the outflow of the Tegeta River (Fig. 10b), making a significant contribution to beach sand budgets. On the Bamburi shore, these deposits occurred in embayments along the Pleistocene limestone-cliffed shores; analysis of an augered sample (BP12) yielded an even mix of carbonate and siliciclastic material (Fig. 2a, Table 1). At Kunduchi, beach plain sand deposits form most of the immediate hinterland, extending as much as 500 m inland from the present shoreline (Fig. 2b). Analysis of samples from auger transects revealed that the sediments in most cases comprised <10% carbonate content (Table 2).

Table 1: Petrological analysis of beach sand at the Bamburi site. H, M and L denote High, Mid and Low tide levels.

Sampling Site	Carbonate (%)	Quartz (%)	Other minerals (%)
B19 (H)	20	75	5
B19 (M)	35	40	15
B19 (L)	15	80	5
BP17 (M)	40	60	0
BP17 (L)	40	60	0
BP14 (H)	40	60	0
BP14 (M)	30	70	0
BP14 (L)	80	20	0
BP12 (beach plain, 1 m deep)	50	40	10
BP11 (M)	60	30	10
BP11 (L)	60	30	10
Bamburi Mtopanga river	80	15	5
BP08 (H)	15	70	15
BP08 (M)	15	70	15
BP08 (L)	30	60	10
BP06 (H)	15	75	10
BP06 (M)	25	65	10
BP06 (L)	70	20	10
BP03 (H)	40	50	10
BP03 (M)	55	40	5
BP03 (L)	50	40	10
BP01 (H)	10	85	5
BP01 (M)	10	85	5
BP01 (L)	25	60	15
Junda 2	0	90	10

Sand from biological sources (Bamburi)

Lagoonal substrata in the Nyali and Mtopanga reef-to-beach transects (Figs 2a & 11) were dominated by sand with seagrass. The Bamburi lagoon had more seagrass compared to the other sites, while the substratum in the Paradise transect had the highest proportion of calcareous algae (mostly *Halimeda* spp.). Reef substrata in all transects were composed of carbonate sand. Coral cover on the reef was highest at Paradise. Unlike the Paradise reef site, Bamburi, Mtopanga and Nyali reef sites comprised coral debris covered by turf algae and fleshy algae.

The composition of the sediments in the reef-lagoon-beach transects is shown in Figure 12 and Table 3. At Nyali, close to Tudor Creek, siliciclastic sand dominated the beach sediments. Northwards, siliciclastics remained an important component, with an increase at the northernmost transect, Paradise, indicative of an influx via Mtwapa Creek. Whereas the Nyali beach sediments contained very low quantitites of material from biogenic sources, the contribution from *Halimeda* spp., corals and molluscs increased northwards, reflecting an abundance of these biogenic materials in the substrata north

Table 2: Mean grain size, sorting values and $CaCO_3$ content of 16 augered samples (S1 to S16) taken along six transects (P1 to P6) from the beach plain at the Kunduchi site, with the descriptive mean grain size and sorting values shown in brackets. The location of transects is shown in Figure 2. m = medium sand, c = coarse sand, f = fine sand; ps = poorly sorted, vps = very poorly sorted, ms = moderately sorted, s = sorted, ws = well sorted. The subscripts, 50, 100 and 200 denote depths of the samples (in cm).

Transect	Sample	Mean	Sorting	Carbonate	Transect	Sample	Mean	Sorting	Carbonate
P1	$S1_{50}$	1.60 (m)	1.456 (ps)	12.7	P4	$S9_{50}$	2.02 (f)	0.42 (ws)	4.1
	$S1_{100}$	1.93 (m)	0.65 (ms)	9.7		$S9_{100}$	1.90 (m)	0.36 (ws)	5.5
	$S1_{200}$	0.71 (c)	0.60 (ms)	6.8		$S9_{200}$	1.55 (m)	0.61 (ms)	9.2
P1	$S2_{50}$	1.24 (m)	0.93 (s)	26.6	P4	$S10_{50}$	1.45 (m)	0.45 (ws)	11.6
	$S2_{100}$	0.33 (c)	2.03 (vps)	51.6		$S10_{100}$	1.08 (m)	0.33 (ws)	1.9
	$S2_{200}$	1.09 (m)	1.04 (ps)	14.0		$S10_{200}$	0.73 (c)	0.47 (ws)	3.7
P2	$S3_{50}$	1.35 (m)	0.31 (ws)	7.8	P4	$S11_{50}$	1.70 (m)	0.58 (ms)	4.4
	$S3_{100}$	0.77 (c)	0.58 (ms)	16.4		$S11_{100}$	1.65 (m)	0.53 (ms)	1.8
	$S3_{200}$	0.77 (c)	0.57 (ms)	8.8		$S11_{200}$	1.70 (m)	0.60 (ms)	6.8
P2	$S4_{50}$	2.15 (f)	0.45 (ws)	1.7	P5	$S12_{50}$	1.62 (m)	0.57 (ms)	5.4
	$S4_{100}$	2.18 (f)	0.50 (ms)	5.0		$S12_{100}$	1.62 (m)	0.41 (ws)	11.2
	$S4_{200}$	1.16 (m)	0.79 (s)	1.1		$S12_{200}$	1.57 (m)	0.56 (ms)	12.0
P2	$S5_{50}$	1.59 (m)	0.77 (s)	1.5	P5	$S13_{50}$	1.37 (m)	0.71 (ms)	7.8
	$S5_{100}$	1.47 (m)	0.83 (s)	8.1		$S13_{100}$	1.02 (m)	0.70 (ms)	5.4
	$S5_{200}$	1.55 (m)	0.85 (s)	7.8		$S13_{200}$	0.61 (c)	0.69 (ms)	5.0
P3	$S6_{50}$	2.03 (f)	0.30 (ws)	3.0	P6	$S14_{50}$	1.93 (m)	0.47 (ws)	4.8
	$S6_{100}$	1.80 (m)	0.36 (ws)	11.9		$S14_{100}$	1.69 (m)	0.66 (ms)	5.1
	$S6_{200}$	0.97 (c)	0.52 (ms)	11.4		$S141_{200}$	1.56 (m)	0.58 (ms)	6.2
P3	$S7_{50}$	1.92 (m)	0.46 (ws)	4.9	P6	$S15_{50}$	1.76 (m)	0.63 (ms)	2.5
	$S7_{100}$	1.80 (m)	0.52 (ms)	9.7		$S15_{100}$	1.52 (m)	0.61 (ms)	3.6
	$S7_{200}$	1.75 (m)	0.50 (ws)	7.7		$S15_{200}$	1.71 (m)	0.68 (ms)	2.1
P3	$S8_{50}$	1.83 (m)	0.52 (ms)	8.7	P6	$S16_{50}$	1.24 (m)	0.61 (ms)	3.8
	$S8_{100}$	1.68 (m)	0.52 (ms)	6.8		$S16_{100}$	1.29 (m)	0.60 (ms)	2.6
	$S8_{200}$	1.72 (m)	0.45 (ws)	1.5		$S16_{200}$	1.12 (m)	0.57 (ms)	3.5

of Nyali. Coral debris on Paradise Beach corresponded to the greatest live coral cover in the Paradise reef area, this material being transported over the lagoon floor to the beach.

Within the lagoons, corals made a substantial contribution to the sediment composition, occurring in all sediment size classes. At least 50% of the coral fragments were in the coarse size class of >2 mm, the remainder were broken into finer fractions. The contribution by corals was greatest in the Paradise lagoon. Although the lagoons had no corals, their sediment was predominantly composed of coral material, indicating reefal input where corals were common.

Fragments of *Halimeda* spp. were a conspicuous component of the lagoonal sand. However, on further laboratory analysis, the contribution of these calcareous algae was not as high as expected. It may be that *Halimeda* grains settle on the surface and appear to form a major component of the surface grains but do not penetrate the deeper sediments.

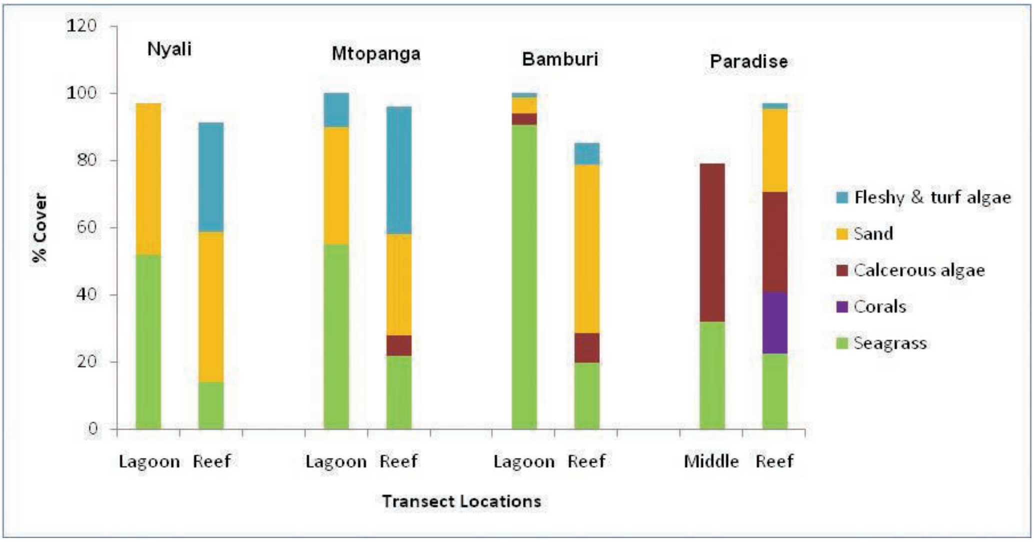


Figure 11. Comparison of substrata in the lagoon and reef transects at Bamburi. "Sand" represents siliciclastic (non-biogenic) material. The location of transects is shown in Figure 2.

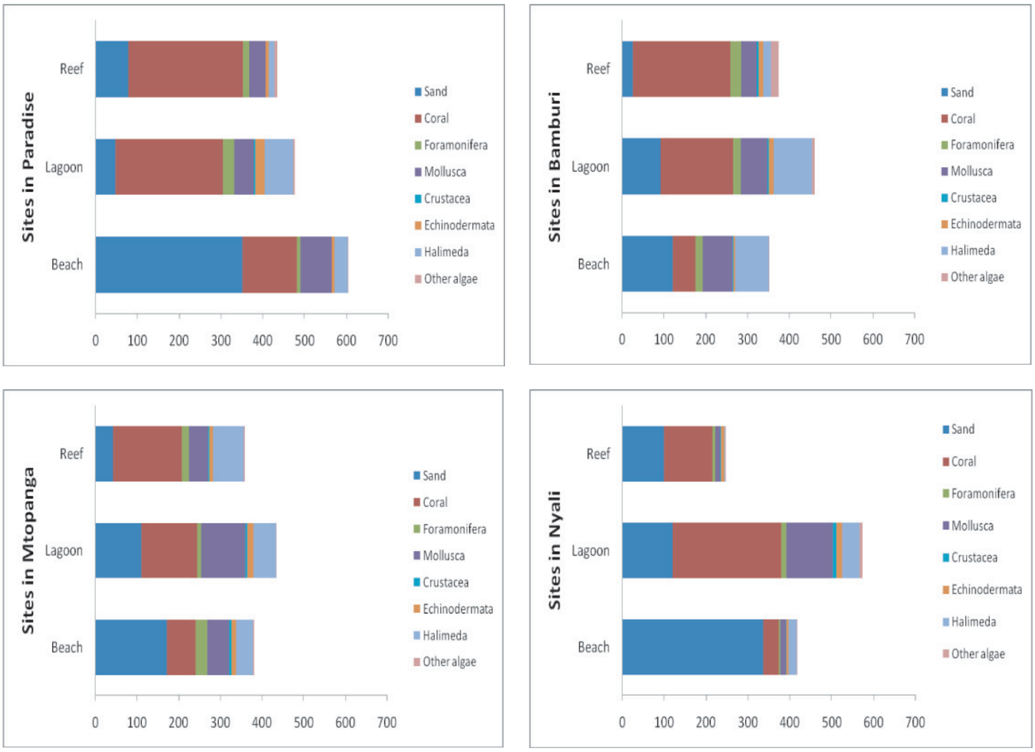


Figure 12. Comparison of sand composition in beach-lagoon-reef transects at Bamburi. "Sand" represents siliciclastic (non-biogenic) material (The x axis shows the number of particles counted in the sediment sample). The location of transects is shown in Figure 2.

DISCUSSION

Shoreline change

The wave-cut Pleistocene limestone platform and cliff features as well as the beach rock outcrops (Fig. 2) which typified both sites were broadly coincident with the present shoreline. Thus, in general, the net shoreline change has actually been rather small during recent geological time. However, there have been fluctuations in the shoreline's position. Anecdotal accounts suggest that, in some places, the shoreline has retreated by up to 200 m over the last 20-40 years. Other parts of the shore appear to have been stable or accretive, or to have alternated between erosion and accretion intra- or inter-annually.

On the Kunduchi shore, the 3 km-long sand spit to the south of the Manyema creek mouth indicates the long-term dominance of the SE monsoon. Northward transport of beach sand by wind-wave forcing is prevalent (Alexander, 1969; Muzuka & Shaghude, 2000; Shaghude *et al*., 2003; Nyandwi, 2010; Nyandwi *et al*., this volume). Systematic beach profiling studies undertaken by Hemed (1987) and Nyandwi (2001b) revealed marked erosion during the SE monsoon, followed by weaker accretion during the NE monsoon. Recurrent erosion of the spit's exposed shore threatens hotels and residences, though these have been protected to some extent by the construction of an elaborate groyne field. The shoreline around the mouth of the creek has been particularly dynamic, its position being significantly changed in recent decades by erosion and accretion (Makota *et al*., 2004).

Beach sand transport

The study has shown how the beaches with their different coastal orientations at the two sites, respond differently to the monsoonal forcing. At Bamburi, the beach profiles change intra-annually from relative abundance to relative deficiency, reflecting the switching transport regimes generated by the alternating monsoon seasons. The NNE orientation of the coast relative to the monsoonal forcing favours a general balance of the opposing NE and SE forcing conditions. Reductions in the inherent protective potential of the beaches appear to be temporary and seasonal, made good in the subsequent monsoon season (Fig. 6). Despite their apparent good health, beach head erosion occurs from time to time, especially in January and October, when extreme swell-generated waves coincide with periods of beach deficiency.

At Kunduchi, the NNW coastal orientation favours forcing by the SE monsoon, probably resulting in long-term erosion and the "loss" of sand around Ras Kiromoni and its accretion on the adjoining shore at Ununio (Fig. 2b).

Beach sand supply

Beaches at Bamburi are being replenished both by calcium carbonate sand derived from reefs and their associated platforms, and by siliciclastic sand from hinterland sources, presumed to be transported through Tudor and Mtwapa creeks by the ebb-dominant flushing described by Magori (2004). The mechanism of sand transfer from the creeks to the platform has not been elucidated. There are no indications that the supply of carbonate sand is under threat, though the possibility of the long term the degradation of the carbonate-producing biota on the reef and its platform through coral bleaching and ocean acidification should not be ruled out (IPCC, 2005). However, studies by McClanahan *et al*. (2009) and Ateweberhan & McClanahan (2010) show that adaptation by the coral communities or their resilience to climate change is possible, and this source of carbonate sediments will be maintained.

At Kunduchi, where siliciclastic grains were predominant in the beach sand throughout – although siliciclastic-carbonate transitions have been described by Fay *et al*. (1992) and Shaghude *et al*. (2006) – maintenance of the supply of siliclastic sand to the beach is precarious because of intensive and recurrent extraction, albeit illegal, from local rivers (Tanzania Environment Management Act, 2004; Veland, 2005). The more sand that is extracted from the feeder rivers, the less is available for discharge to the Kunduchi beaches. Rapid urbanization around Dar es Salaam has increased the demand for construction materials, putting pressure on such natural sand resources.

Griffiths (1987) estimated that the annual extraction of sand from streams draining the Kunduchi hinterland totalled at least 100,000 m^3. The riverine discharge of sand is constrained by the scale and frequency of natural recharge. This occurs in spate events during the "long rains" at the beginning of the SE monsoon between March and June, and during the "short rains" at the beginning of the NE monsoon, between October and December. The extraction recorded in the July-August 2007 survey would have comprised material introduced by run-off from the hinterland during the 2007 long rains; and the deposits surveyed in January 2008 in the Mbezi and Mdumbwe River courses would have accumulated during the subsequent short rains (Fig. 3). Since the extraction is illegal, estimates of the yield are speculative. Our estimates of the river-bed deposits suggest that Griffiths' (1987) were of the right order though perhaps excessive, and indicate that the annual volume of sand reaching the shore via these rivers could be 50,000 to 100,000 m^3 less than would be expected without extraction.

At both sites, the beach plain deposits are another source of sand supply. They mark a former period of extensive accretion, being indicative according to Fay (1987) of a past abundance of supply to the Kunduchi shore, derived from hinterland sources. Similar beach plain terraces, with characteristic shore-parallel beach ridges, are widespread in the region (Kairu & Nyandwi, 2000). Based on present trends, wave erosion of the extensive beach plain sands at Kunduchi (Fig. 2) could contribute sediment to the beach budgets for the foreseeable future. At Bamburi, where Pleistocene limestone cliffs form extensive beach heads, the potential contribution from beach plain sands is much more limited. Any erosion of the beach plain deposits thus results in shoreline regression, though this has been extensively countered by the construction of protective seawalls.

Concluding remarks

Maintaining the natural coastal protection afforded by beach deposits at the local scale in response to changes in sand supply and wind-wave forcing is a key element in coastal management. In situations where monsoonal forcing causes a long-term loss of sand from a shore system, as at Kunduchi, particular efforts should be made to safeguard the natural replenishment of sand – notably by enforcement of river sand mining regulations – so that the protection afforded by beaches can be maximised. In situations where seasonal beach losses and subsequent natural replenishment are broadly in balance within the monsoonal cycle, as at Bamburi, a management priority should be to promote coastal land use that affords scope for this natural variability to take place.

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