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Coastal Erosion at Mombasa Beaches
Hydrodynamic and Morphological Interactions

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ABSTRACT

Complex interactions of various natural processes together with anthropogenic activities on the beaches have encouraged coastal erosion along the Kenyan coast. Inadequate information on site-specific hydrodynamic and morphological interactions on the shores has encouraged mitigation measures which are ineffective and expensive to implement.

Hydrodynamic and morphological parameters were measured both in the field and laboratory. Hydrodynamic variables contributed significantly to the morphological variability which consequently accelerated beach erosion and shoreline instability. Nyali beach which was dominantly fine sand (Ø 2.62-2.83), moderately well sorted (Ø 0.56-0.75) and negatively skewed was characterised by low energy surging waves with high swash and low backwash velocity at high periodicity. Sediment composition was mainly quartz. Bamburi beach was of medium sized calcareous sand (Ø 2.79-1.84), moderately to poorly sorted (Ø 1.34-0.87) and negatively skewed. The hydrodynamic conditions were of high energy plunging waves and high backwash velocities. Wave energy contributed about 74.2% to the slope changes and about 83.0% to sediment distribution on the beaches. Generally steep shores of coarse sediments showed active erosion activities with a rate of retreat of about 0.15 m/month to 0.22 m/month of the shoreline.

It is therefore recommended that measures be taken to dissipate wave energy before waves break on the shoreline and to develop effective legislation to protect the shoreline for sustainable planning utilisation and management of the marine ecosystems.

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Introduction

Coastal erosion due to hydrodynamics is a serious environmental problem affecting the contiguous shoreline of the East African Coast. In many places the rate of coastal erosion and shoreline retreat is rapid and the resultant environmental degradation and economic loss are cause of concern. Many locations along the Kenya coast show signs of wave erosion, which impact the existing coastal developments and marine ecosystems. It is becoming increasingly difficult and expensive to conserve and protect the shorelines, particularly in the absence of a comprehensive and integrated framework for policy planning, implementation and management of resources.

Coastal erosion is caused by a complex interaction of different processes, which are intensified by human activities. Previous studies have generally attributed coastal erosion to the geomorphologic, geological and economic aspects of the shoreline (Ase 1978; Turyahikayo 1987; Oosterom 1988; Munyao 1992; Abuodha 1995; Komora 1995; Odada 1995; Kairu 1997; Mwanje 1997). Natural processes such as hydrodynamics affect sediment distribution and dispersal thus giving a continuously changing environment. Wave erosion has received little attention in Kenya probably because of the complex nature of the hydrodynamics involved. Inadequate knowledge of the hydrodynamics along the coastline and the absence of regulations to deal specifically with coastal erosion have perpetuated the problem of wave erosion (Mwanje 1997). Increased site developments, on low lying coastal settings that are vulnerable to shoreline instability, threaten the tourism infrastructure and marine ecology. The mitigation measures employed by individual beach front owners such as seawalls, have proved ineffective and instead have aggravated shoreline instability and interfered with the aesthetic beauty of the beaches. To protect the coastal environment and beaches from continued erosion and for sustainable planning and management of coastal resources, there is need for adequate knowledge of site-specific hydrodynamic and shoreline processes (Abuodha 1995; ICAM 1996; Marifa 1998).

Study Area

The study area is situated on the Kenya coast along the Nyali-Bamburi shoreline, about 6 km north of Mombasa Island (Map 1: p.98). The area is representative of the erosive part of the Kenyan shoreline with the presence of threatened infrastructure, vulnerability to shoreline retreat and instability due to wave attack.

The Nyali -Bamburi area is characterised by sandy beaches, active cliffs, dunes, a lagoon and fringing coral reefs. The coastal plain is less than 30m above sea level, with some places exposed and covered by tidal waves during low and high tidal fluctuations respectively. It is an area of active wave erosion and sediment exchange. The fringing reef provides shoreline protection, except where it is interrupted by the outflow of the fresh water from rivers.

The climatic conditions are influenced by the passage of the Inter Tropical Convergence Zone (ITCZ) which creates a bimodal rainfall regime. The wind systems are migratory in nature due to the movement of the ITCZ giving four distinct wind regimes along the Kenya coast (Norconsult 1977; Turyahikayo 1987). The north-east monsoon regime is experienced from December to February; a transitional regime from March to April; the south-east monsoon from May to October and a further transitional regime in November. The north-east trade winds on the western Indian Ocean are strongest near the coast of Somalia, causing upwelling but they are calmer towards the Kenyan coast (Norconsult 1977; Marifa 1998). In Kenya the south-east monsoon is stronger and causes rough seas and extensive coastal erosion. The wind systems influence the impact of the wave attack on the shoreline, the stronger the winds the higher the wave heights causing a relatively greater impact on the shoreline. Weak wind systems are associated with a calm ocean and consequently less wave attack.

The tidal period is about 12 hrs 25 min with an average tidal range of about 2.0-2.8 m. The near shore is subjected to a semi-diurnal tides, with two high and low water levels (Odido 1993; Abuodha 1995). This shows the duration of wave attack on the shoreline. The breaker types change with changes in the wind systems, with surging breakers during the north-east and plunging waves during the south-east monsoon.

METHOD

Beach morphological parameters were measured and sediment samples collected. Ten (10) transects were selected along the beach in the study area. Aerial photographs (scale 1:5,000) and topo-cadestral maps (scale 1:50,000) were used to assist in the selection of transects. The specific sites were selected according to morphological characteristics of interest. Human activities on the shoreline were observed and analysed.

Morphological parameters included beach orientation, measured with a prismatic compass with reference to the magnetic north. Beach slope and profile were obtained using a surveyors level and graduated staff along each transect at an interval of 10-20 m beyond the beach. Beach width was measured using a steel tape. Beach sediment samples were collected at 3 sites along each transect, using a scooping technique at a depth of about 1-10 cm where the effect of the percolating water is felt. Statistical grain size distribution analysis was computed using a graphic procedure by Larson, Morgan & Gorman (1997).

Hydrodynamic variables were measured as well. Wave height was obtained by measuring the trough and crest heights on a graduated staff at the breaking point as waves reached the shores. Breaker angle was obtained using a prismatic compass. Surface longshore current velocity was measured on the surf zone by timing the distance covered by a cork attached to a string of known length. Swash and backwash velocities were obtained at the middle of the beach. Swash was measured by releasing a cork when a wave broke, and timing the distance covered by the cork as it was carried by the swash until it stopped on the beach. Backwash velocity was estimated by timing the distance travelled by the cork down the beach as it was carried by backwash until it met a successive coming swash. Wave energy was computed per unit crest.[3]

Laboratory analysis involved sediment grain sizes and tabulation of data. An automatic shaker was used, fitted with standard sieves of the Wentworth scale ranging from Ø -1 to Ø -5, at an interval of Ø 1. The aperture sizes were chosen because beach sediment materials are mainly sand sized along the Kenyan shoreline. Weights of sediments retained from each sieve were converted into percentage of the total sediment samples. Cumulative curves were plotted for graphical grain size analysis.

Carbonate content was established by digesting 5 gm of sub-samples with diluted hydrochloric acid (30%) and further determined by standard laboratory procedures.[4] The weights of the calcium carbonate and non-carbonate residue were converted into a percentage of the total original weight.

Results

Anthropogenic Influences

Shoreline activities such as construction of buildings are common along the Nyali-Bamburi shoreline. Hotels have been constructed up to the shoreline, such that during high tide they are flooded with water surges. Mombasa, Giriama, Pirates and Whitesands Hotels extend beyond the high water mark and are reinforced by sand infilling and concrete walls. Seawalls

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3 Using the formula; $E=1/8pgH^2$ where g=acceleration due to gravity ($9.81m/s^2$); H=wave height (m); p=density of ocean water (g/m^3) (Dyer 1986).

4 Detailed information on laboratory procedures, calculations and results are given in Mwakumanya (1998).

constructed on the shoreline have aggravated shoreline instability and they collapse under intensive wave erosion and energy. Sand sack reinforcements have been placed in front of threatened buildings.

Other activities such as sweeping dead sea weeds, playing games and walking on the beaches have accelerated erosion by exposing and loosening of the sand such that during high tides sediments are likely to be washed into the sea. Destruction of coral reefs and sea grass has given a chance for the waves to attack beaches and shorelines. Human activities have a destabilising effect, causing drastic changes by enhancing or deflecting wave attack, leading to shoreline instability.

Morphological Variations

The Nyali-Bamburi shoreline is relatively straight with limited indentations. Bathymetry generally showed that the passive continental shelf is gently sloping for about 2-3 km from the shoreline, after which the continental slope connects to the deep sea beds.

Beach slope varied distinctively from fore beach to the foot of the beach on each transect and season. The slope ranged from 2.62^0-3.34^0 in Nyali and 4.18^0-5.51^0 in Bamburi (Appendix 8.2: p.144). The beach profile along the shoreline depicted deposition at Nyali and erosion at Bamburi. The morphological changes along the shoreline vary from site to site, prompting unequal longitudinal shoreline retreat.

Sediment Analysis

The mean grain size of the sediments generally fell in the fine-sand grade (Ø 2.83-2.62) at Nyali and the medium- and fine-sand grade (Ø 2.79-1.84) at Bamburi (Table 8.1). Beach sediments grain sizes tended to diminish from the fore beach to the foot of the beach. The fore beach is characterised by relatively coarse sediments while the foot of the beach is dominated by relatively fine sediments (Table 8.2). The sediments at the Nyali shoreline were fine, moderately well sorted (Ø 0.75-0.56) and negatively skewed (Ø 0.32-0.13), containing a limited range of grain size indicating long distance transport or reworking and good sorting of materials (Table 8.1). Nyali beach had predominantly quartz sand, with small percentages of calcareous materials from erosion of cliffs and coral reefs. The source of the quartz sand is probably through Mwachi and Kilindini creeks as evidenced by the variation and prevalence of sediment composition along the transects (Table 8.2). Bamburi beach had an approximately equal percentage of recent and mature calcareous and quartzite sand as shown by the shells of molluscs and skeletal remains of marine organisms observed in the field. Bamburi sediments were poorly sorted (Ø 1.34-0.87), negatively skewed and contained a wide range of grain sizes indicating a local source. High energy waves and destruction of the coral reef at this point contribute to the high percentage of shell fragments ($CaCO_3$), which are transported by the long shore current. The seasonal river Bamburi originating from Nguu Tatu brings terrigenous materials to the beach, but at a lower rate than that at which calcium carbonate materials from the sea are transported by waves. The small percentage of calcareous materials along the river could originate from river erosion of limestone beds.

Table 8.1 *Sediment distribution at Nyali and Bamburi beaches*

	MEAN GRAIN SIZE (Ø)	SORTING	SKEWNESS	KURTOSIS	CALCIUM CARBONATE CONTENT (%)	QUARTZ (%)
Nyali						
NY01	2.73	0.65	0.31	2.34	22.50	77.50
NY02	2.76	0.50	0.24	1.49	21.56	78.44
NY03	2.65	0.63	0.13	1.59	22.85	77.15
NY04	2.85	0.75	0.32	2.12	25.05	74.95
NY05	2.63	0.56	0.18	2.25	22.72	77.28
NY06	2.63	0.59	0.13	2.17	25.23	74.77
Bamburi						
BB07	1.84	1.10	0.99	1.23	53.77	46.23
BB08	2.34	0.95	0.18	2.41	56.95	43.05
BB09	1.99	1.06	0.15	1.36	71.10	28.90
BB10	1.94	1.34	0.47	1.15	58.75	41.25
BB08D	2.38	1.19	0.14	2.67	54.95	45.05
BB09D	2.38	0.87	0.14	1.83	55.85	44.15
BB10D	2.79	0.99	0.31	1.92	65.82	34.18

The study revealed strong correlations between mean beach slope and most of the other morphological variables ranging between 0.6629 against mean grain size to 0.9324 against skewness at Nyali (Appendix 8.1: p.143). Mean grain size accounted for 46.5% (R^2= 0.465) of the slope changes. At Bamburi, mean slope also correlated with most of the other morphological variables. Mean grain size accounted for 83.8% of the slope changes. The slope of the beach increases as the sediment grain size increases. Coarse-grained shores have steep slopes while fine sand shores have gentle slopes. The shorelines at Nyali and Bamburi beaches experienced intensive shoreline retreat of 0.15-0.22 m/month during the study period indicating morphological instability. Wave height varied remarkably. Nearshore mean wave heights ranged from 0.33-0.50 m at Nyali beach and 0.33-0.52 m at Bamburi beach (Appendix 8.2). Transitional regimes (September) are generally calm with low wave heights, while the south-east monsoon is characterised by turbulent waves of high wave heights.

Table 8.2
Sediment mean grain size and mineral composition along transects

	MEAN GRAIN SIZE (Ø)		CALCIUM CARBONATE CONTENT (%)		QUARTZ CONTENT (%)	
	Nyali	*Bamburi*	*Nyali*	*Bamburi*	*Nyali*	*Bamburi*
SITE 1*	2.33	2.07	9.67	40.01	90.33	63.37
SITE 2	2.49	2.24	16.57	57.00	83.59	43.00
SITE 3	2.60	2.40	28.73	59.44	71.69	40.56

* Sites: 1=Forebeach; 2=Middle of the beach; 3=Foot of the beach.

Nyali beach was dominated by waves of relatively low wave energy, low periodicity, high swash velocity and low backwash velocity, and slow longshore current velocity that did not encourage much erosion. Bamburi generally experienced high wave energy, high period waves, high longshore current velocity, high backwash velocity and relatively low swash velocity (Appendix 8.2). The disparities in these hydrodynamic variables between the two study sites may be due to the fact that the Nyali shoreline has a fringing coral reef while at Bamburi the reef is discontinued due to siltation from the Bamburi river.

The hydrodynamic nature along the shoreline is determined by the prevailing wind systems (Turyahikayo 1987). Wave breaker angle and breaker type were observed to be changing with changes in the wind system. Nyali-Bamburi shoreline experienced surging and plunging waves. During the south-east monsoon the shoreline was dominated by plunging waves with a breaker coefficient of about 80%. November (transitional regime) was characterised by surging waves of breaker coefficient of about 10%. The area being out of the cyclone zone it is unlikely to experience catastrophic waves and therefore shows gradual changes, which may go unnoticed until damage starts to occur.

Discussion

Hydrodynamic conditions contribute significantly to changes of the shoreline morphology that consequently cause erosion and/or deposition on the shores. The morphology of the beach also limits the hydrodynamic process. The gently sloping Nyali shoreline, characterised by fine sand sediments, experienced less erosion. Steep sloping Bamburi shoreline with short fetch experienced relatively strong hydrodynamic processes that caused shoreline erosion. The rate of retreat at Nyali was about 0.08-0.27 m/month and about 0.05-1.90 m/month in the case of the Bamburi shoreline. Regression analysis showed that wave height accounted for about 79.69% of slope changes and 87.75% of changes in sediment diameter size in Bamburi respectively. Thus wave height contributes significantly to beach instability and beach erosion.

Human activities seem to have aggravated the wave erosion; where human activities were dominant it was observed that there was remarkable shoreline retreat and beach instability. The problem has been noted to be more serious in the areas that are most attractive for tourism development.

Along the Nyali-Bamburi shoreline properties are being protected from wave attack with walls of sand sacks and vertical walls. These mitigation measures have proved ineffective and expensive. Hotels spend millions of shillings annually in man-made structures (ICAM 1996). These shoreline protection measures exacerbate the erosion problem and loss of aesthetic qualities of the beach areas and affect tourist activities such as sand bathing and strolling (Msuya & Nyandwi 1997). The impacts of wave erosion and shoreline instability can be summarised as:

- Erosion of beaches;
- Destruction of fishing grounds as a result of the scouring effect of waves;
- Destruction of coastal developments such as hotels;
- Loss of aesthetic value due to erosion control structures along the shoreline;
- Decline in tourist activities and fish production.

For planning and management purposes, the beach zone should be identified as a problem as well as a resource potential region. Wave erosion is the main factor in beach degradation and erosion along the Kenyan shoreline. Appropriate measures of shoreline protection should be based on the site-specific wave conditions to cause gradual dissipation of wave energy. Positive corrective measures should be capable of intercepting and dissipating wave energy before breaking on the shores. Sediments in the study area are dominantly sand of quartzite and carbonate materials, especially along the Bamburi shoreline. A suggested measure to restore the beaches in case of severe storm erosion is artificial beach nourishment.

Beach erosion and shoreline retreat are influenced by hydrodynamic processes. Beaches as micro-level spatial units between the low and high tide limits characterised by unconsolidated sediments should be conserved to maintain their aesthetic value. Planning and management are necessary at all levels. The government in conjunction with the private sector should intensify measures to curb further shoreline and marine ecosystem degradation.

CONCLUSION

Waves and currents vigorously erode and transport unconsolidated shoreline materials resulting in both erosion and deposition on the beaches. Not all places along the shoreline are equally vulnerable to wave erosion. Shorelines of unconsolidated materials and relatively steep slopes seem to be much affected. Wave conditions contribute greatly to the sediment behaviour changes, which consequently result in morphological shoreline instability. High wave energy levels are associated with medium size sediment and steep shoreline slopes while low wave energy levels are dominant in low shoreline slopes with fine sand sediment. The shoreline retreat is rapid at between 0.15-0.22m/month.

Quartz fine sand indicates travel over a long distance and long-time reworking, found in gentle and stable shorelines. Calcareous materials of fine to medium grain size are found mostly in steep shores that generally appear to be fragile and susceptible to shoreline instability and beach erosion. The main sources of sediment are the creeks and rivers, which supply mainly terrigenous materials. Coral reefs and cliff erosion are the main sources of shell fragments of calcareous materials; shoreline erosion provides additional terrigenous materials.

Seasonal variations of the wind systems influence both sediment distribution, sediment composition and wave conditions. South-east trade winds bring materials with a high percentage of quartz that tend to decrease going northwards. The north-east monsoon shows an increasing percentage of calcareous materials from the creek systems. Tudor and Kilindini creeks and the Bamburi river supply terrigenous materials although at Bamburi the supply of terrigenous materials shoreline is less than that of the supply of carbonate materials by wave attack. The inflow of the river along the shore is the main source of sediments materials, which are distributed and dispersed along the shore by wave action. Human activities along the fragile coastal environment exacerbate the erosion process.

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Appendix 8.1

Correlation coefficient (R) for hydrodynamic and morphological variables along Nyali and Bamburi beaches

		1 MBS	2 MGS	3 SK	4 WH	5 LCV	6 WP	7 SV	8 BV
1. Mean Beach Slope (degrees)	MBS	1.00 *1.00*							
2. Mean Grain Size Ø	MGS	.6629 *.9152*	1.00 *1.00*						
3. Skewness	SK	.9324 *.6652*	.8652 *.6210*	1.00 *1.00*					
4. Wave Height (m)	WH	.7969 *.7306*	.8775 *.9429*	.5421 *.2659*	1.00 *1.00*				
5. Longshore Current Velocity (m/esc)	LCV	.7324 *.2519*	.7279 *.6998*	.3498 *.7851*	.6126 *.6296*	1.00 *1.00*			
6. Wave Period (waves/se)	WP	.4111 *.4059*	.0482 *.5104*	.4048 *.7081*	.2418 *.1222*	.5699 *.3702*	1.00 *1.00*		
7. Swash Velocity (m/sec)	SV	.8059 *.6880*	.5551 *.7454*	.6814 *.3324*	.8115 *.7511*	.8135 *.2833*	.5059 *.6329*	1.00 *1.00*	
8. Backwash Velocity (m/sec)	BV	.8429 *.6380*	.5835 *.7230*	.8070 *.5642*	.1401 *.6561*	.7449 *.2584*	.3580 *.4749*	.6734 *.9903*	1.00 *1.00*

N.B. Figures in italics represent Bamburi coefficients.

Appendix 8.2

Hydrodynamic characteristics at Nyali and Bamburi beaches

	MEAN BEACH SLOPE (degrees)	MEAN WAVE HEIGHT (m)	MEAN WAVE PERIOD (waves/ sec.)	SWASH VELOCITY (m/sec.)	BACKWASH VELOCITY (m/sec.)	LONGSHORE CURRENT VELOCITY (m/sec.)	WAVE ENERGY (joules)
Nyali							
NY01	2.98	0.39	5.46	0.91	0.92	0.15	215.31
NY02	3.34	0.45	6.32	1.22	0.85	0.11	317.99
NY03	2.70	0.40	6.44	1.26	0.80	0.12	258.85
NY04	2.62	0.36	5.84	1.14	0.54	0.16	170.08
NY05	2.62	0.33	6.30	1.02	0.56	0.16	153.23
NY06	3.05	0.50	5.62	0.92	1.10	0.14	324.67
Bamburi							
BB07	5.51	0.45	6.98	1.72	1.97	0.13	294.87
BB08	5.49	0.52	6.20	1.78	1.93	0.14	374.88
BB09	ND	0.50	6.52	1.21	1.21	0.14	326.79
BB10	4.18	0.33	6.40	1.33	1.25	0.14	136.01