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Assessment of shoreline changes in the western side of Zanzibar channel using satellite remote sensing

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Abstract. The present study uses a satellite remote sensing approach for assessing coastal sediment dynamics in the western side of the Zanzibar channel, Tanzania. Four Landsat images (1986, 1998, 1999 and 2000) were used for the study. Investigation of the four images revealed that the Ruvu delta north of the river mouth has been growing rapidly, especially between 1986 and 1998, with an annual northward linear growth rate of about 133 m year^{-1} and an areal growth rate of about 1 km^2 every 3 years. The study identified a palaeo-shoreline feature that is parallel to the present shoreline and located about 1.9 km inland from the present shoreline. An important sediment contributor to river Ruvu is derived from the Uluguru Mountains, a tropical mountainous area located about 200 km from the coastline of the Tanzania mainland. The working hypothesis is that either the observed growth of the delta occurred at a gradual rate between 1986 and 1998 or it was mainly an episodic event related to the extreme rainfall events such as the 1997/98 El Niño–Southern Oscillation (ENSO) event, which was associated with extreme rainfall and widespread landslides.

1. Introduction

Tanzania coastal marine ecosystem is composed of the following major habitats: mangroves, seagrass beds, coral reefs, lagoons, sand flats, mudflats, coastal forests and grasslands, beaches and sand dunes (Semesi *et al*. 1999). These habitats provide important sources of protein livelihood, building materials and tourism potential for coastal and inland rural communities. Like many other parts of East Africa, the Tanzania marine ecosystem is currently facing an increasing pressure from urban sprawl, marine traffic, runoff from coastal agricultural water, fishing activities and coastal tourism. The conflicting interests and competing demands for the use of the coastal zone and its resources have required trade-offs between sustainable resource management and commercial development. Given the current economic situation in many of the countries, protection of the environment has taken second place to the more pressing needs of food production, import substitution and the general

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refocusing of large international loans towards an economic stabilization programme, rather than environmental management support.

Tropical coastal areas can be described on various hierarchical levels of detail, including their geomorphology and distinct species assemblage or biotopes. Often remote sensing techniques are proposed when mapping and monitoring of the coastal and marine habitats is required (e.g. Sydow 1999). Whether remote sensing can resolve temporal changes, depends on its spatial and spectral resolution as well as the type of image analysis conducted. Remote sensing techniques are however the most cost-effective means of mapping physiognomic habitats, including mangroves, coral, algae, sand and seagrass beds, as well as coastline morphology. Some of the socio-economic and social anthropological effects and changes in the coastal communities can also be estimated, i.e. the spatial and structural changes of agriculture over time.

Acquisition of baseline information on coastal sediment dynamics is one of the biggest challenges facing coastal states with long coastlines. Monitoring of sediment dynamics by conventional methods of gathering sedimentological data along the coast using research boats is time consuming and also expensive. This challenge is particularly acute for poor developing countries, which often have limited resources. The remote sensing approach is an important tool for resource management and monitoring because of its ability to provide quantitative information quickly and relatively inexpensively compared to the cost of employing researchers to observe an equivalent area with conventional methods (Mumby *et al.* 1998, Hardy *et al.* 1992).

One of the major limitations of satellite remote sensing so far is its precision, which is limited by the relatively large pixel size of the sensors (Holden *et al.* 2000). However, this drawback can be accommodated with ground verification of the data, which generally involves the physical observation of the data at relatively few locations, focusing on areas that appear to be changing through time. Remote sensing can also be used with other field surveys, and in this case, the required data sampling density can be estimated from the remote sensing. Thus, the limited resources of time, money and labour may be optimized. Our primary objective in this study is to use satellite remote sensing data to make an assessment of shoreline changes on the western side of the Zanzibar channel.

1.1. *The study area*

The Tanzania mainland coastal area in the vicinity of the Ruvu delta was selected for the present study. This part of the coastline, including its major river, Ruvu, and the associated mangrove forests is very important both from an ecological and geological point of view. From the ecological point of view, mangrove forests and their ecosystems are considered to be important for nutrient enrichment, breeding, feeding and nursery grounds of fish species, supporting a variety of insects, birds and small animals and also in shore protection and stabilization (Semesi *et al.* 1999). From the geological point of view, this coast is currently accreting as opposed to many other coasts in Tanzania which are threatened by erosion (Shaghude *et al.* 1994, Mohamed and Betlem 1996).

Further, this part of the coast has been the focus of other recent integrated coastal zone management studies (e.g. Howell and Semesi 1999). However, there is a general lack of geological science in most of the Tanzania integrated coastal zone

management studies. Thus, the long term objective of the study is to use satellite remote sensing for the acquisition of baseline information in various types of geomorphologic coastal regimes as a strategy for Tanzania integrated coastal zone management studies. The development of the Ruvu delta is of great importance from geological perspective as the river is one of the major sources of siliciclastic sediments to the sea (Shaghude and Wannäs 1998). The development of the delta can also be linked with socio-economic as well as human activities undertaken on the catchment of the river during the few decades. The choice of this coastal area for the remote sensing study was based on the fact that the study can take the advantage of the previous, up-to-date field studies.

The study area is on the western side of the Zanzibar channel, which separates the Tanzania mainland from one of its major islands, Zanzibar Island (figure 1). The channel is approximately north–south oriented, and is about 120 km long and 35 km wide. The dominant current in the channel is the East African Coastal Current (EACC), but the tides and the local wind generated waves become

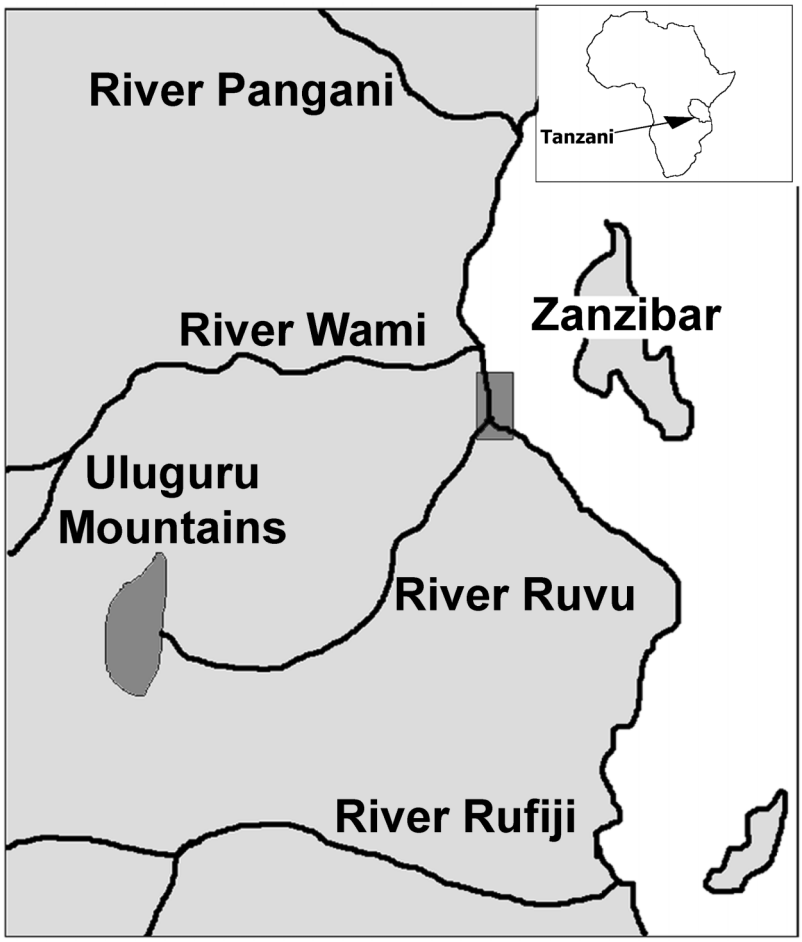


Figure 1. Location map showing the investigated coastal area proximal to river Ruvu. Observe also the Uluguru mountains in the hinterland indicated as light shading.

increasingly more important than the EACC as one gets closer to the shore (Brampton 1996). Various studies show that these oceanographic phenomena are often affected by the seasonal monsoon variability (Newell 1957, Mohammed *et al.* 1993, Lwiza 1994). The EACC attains a maximum speed of $2\,m\,s^{-1}$ during the south-east monsoon season (April to September) but during the north-east monsoon season (October to March) its speed is only $0.25\,m\,s^{-1}$ (Newell 1957, Mohammed *et al.* 1993, Ngusaru 1997). Tides are semi-diurnal with spring tidal range of about 3.2 m and the neap tidal range of about 0.9 m (Cederöf *et al.* 1995). The study of Lwiza (1994) in the Kunduchi area about 40 km south of the river Ruvu noted that the direction of the incident waves to the shore is also affected by the monsoon variability. During the north-east monsoon winds, most waves were generally aligned to the wind direction, and during the south-east monsoon winds, most of the waves were from the south-east.

Marine sedimentological and morphological studies on the Tanzania coastal waters are scarce, but include those conducted at Msasani Bay north of Dar es Salaam harbour (Fay *et al.* 1992, Muzuka and Shaghude 2000) and from the Zanzibar channel (Shaghude and Wannäs 1998, 2000). The first two studies discuss the hydrodynamic setting of back-reef platform sediments of the Msasani Bay. The later studies describe the morphology, composition and distribution of sediments in the Zanzibar Channel. The studies further noted that river Ruvu strongly influences the sea bottom morphology and the sediment composition on the mainland side of the channel. In particular, the study of Shaghude and Wannäs (1998) noted that the smooth topography that characterize the sea bottom morphology west of Zanzibar channel is to a great extent due to the high terrigenous input by river Ruvu, and another river Wami, located about 10 km north of the present study area. The study also noted that due to high terrigenous supply from these rivers, the near-shore area of the mainland and nearly the whole western side of the channel in the vicinity of river Ruvu is dominated by siliciclastic sediments (with carbonate content less than 30%). The authors are not aware of any studies undertaken to estimate the sediment discharge of the river, but the monthly flow rate of the Ruvu is reported as varying from 3 to $41\,m^3\,s^{-1}$ (Semesi *et al.* 1999) with highest flow rates during rainy seasons. The size of Ruvu drainage basin is reported to be $18\,389\,km^2$ (Temple 1972).

2. Materials and methods

Four Landsat satellite image scenes acquired on 22 October 1986, 29 March 1998, 30 July 1999 and 22 January 2000 were used for this study. The selection of the scenes was based on the minimization of sea-water level differences due to the tidal effects. Thus, the selected scenes had similar sea-water levels (low tides). The first two images had primarily been used in other studies on mangroves and biomass offshore Zanzibar Island, as well as a morphological study of the sea bottom (e.g. Lundén *et al.* 2000). The later two scenes (1999 and 2000) were primarily part of another study project, whose objective is to investigate changes (on an annual scale) on sediment movement in Tanzania coastal areas due to the monsoon variability.

The 1986 and 1998 images were from Landsat 5 Thematic Mapper (TM) and the later images were Landsat 7 ETM (Enhanced Thematic Mapper) scenes. The spectral bands representing the visible region were mainly used due to their capacity

to penetrate water. The factual maximum depths of penetration for the TM bands 1, 2 and 3 (the blue, green and red bands) have in previous studies in the region been calculated to 26, 15 and 5 m, respectively (Lundén *et al.* 2000).

Before the analyses of the images, they were geometrically corrected, optimally enhanced and histogram matched to be comparable during the visual interpretation. The four scenes were then visually investigated to determine: (1) the major features found along the Tanzania mainland coastal band proximal to the Ruvu delta, and (2) spatial and temporal changes (between 1986 and 2000) along and close to the Tanzania mainland coastal band proximal to the delta.

The actual analysis of the satellite image scenes involved tracing some major features of interest and estimation of the physical dimensions of some of the features. The data (interpreted features) were then imported into the basemap of the area. Each of the satellite sub-scenes consisted of 530×300 pixels corresponding to an overall physical dimension of $15.9\,\text{km} \times 9\,\text{km}$ (since one pixel has a dimension of $30\,\text{m} \times 30\,\text{m}$). Physical dimensions on the image scenes were estimated using this scaling factor.

3. Results

Two of the scenes (1986 and 1998) are shown in figure 2. The 2000 scene and the interpreted features on the images are presented in figure 3. The 1999 imagery is not presented, as it is very similar to the 2000 imagery. The shoreline north of river Ruvu can be described as a north–south, bow (curved) shaped feature approximately 12 km long. The Ruvu delta is the only point concentrated depocentre where sediments from the hinterland are transported from the draining system of the river to the shoreline before they are redistributed and deposited by the basinal ocean processes. The river mouth is about 0.8 km wide.

The Ruvu delta has well-developed subaqueous levee systems occurring both north and south of the river mouth. It is important to note that the levee system north of the river mouth is growing northward. Within the levee systems, some small-scale wave or tidal current features (sedimentary structures) are also evident. The small-scale features are particularly evident in the 1998 imagery and the later images, but are not evident in the earlier image. The small-scale features are probably a combination of swash bars and sand dunes, but might also reflect different depositional events. The sedimentary structures are clearly evident in the levee north of the river mouth and not very evident in the levee south of the river mouth. Some of the sedimentary structures, namely those which are proximal to the river mouth are oriented oblique to the shoreline while others (those further north) are nearly parallel to the shoreline.

Our estimate of the dimensions of the levee system north and south of the river for three of the satellite scenes is summarized in table 1. It is evident that significant changes in the dimensions of both levees occurred between 1986 and 1998, with relatively slight changes between 1998 and 2000. Further, the levee system north of the river mouth is larger than the system to the south, and the levee system seems to be growing toward the north.

Another prominent feature that is easily identifiable is the long continuous sand beach (figures 2 and 3), which occurs as a narrow elongate feature defining the shoreline of most of the area north of the river mouth. However, the sand beach merges into the mangrove area towards the river mouth. On the backshore area

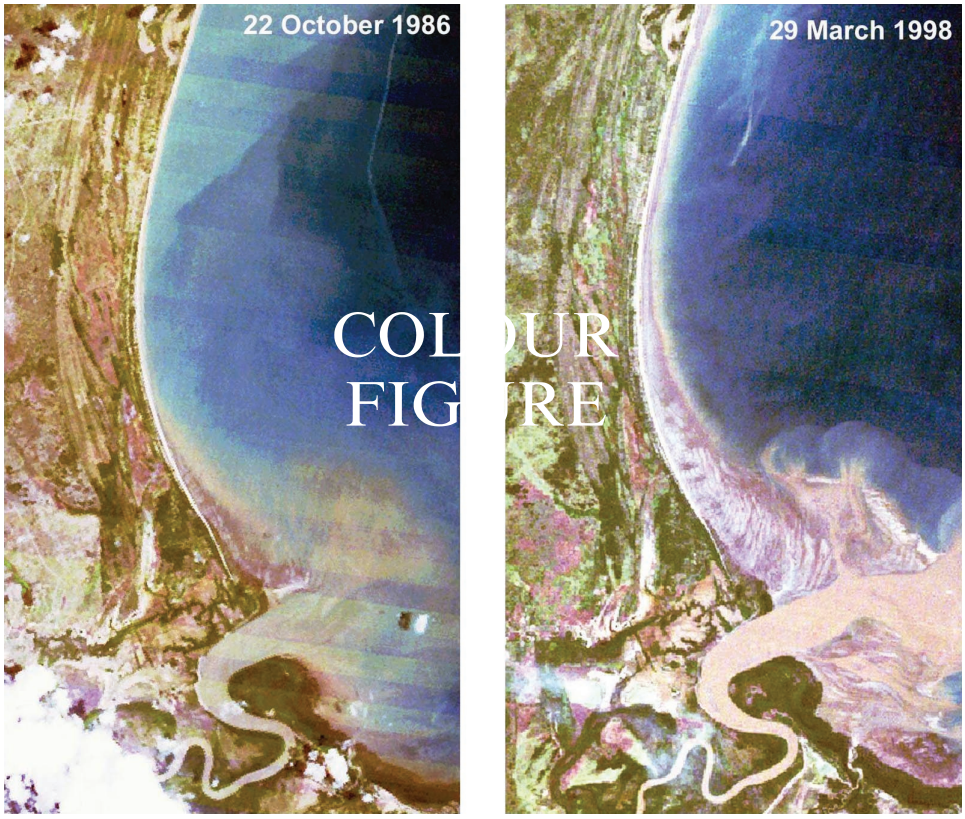


Figure 2. Map showing two of the investigated satellite images, 22 October 1986 (left) and 29 March 1998 (right). The scale is indicated in figure 3.

(about 1.9 km inland from the present shoreline), there is another bow-shaped feature which is parallel to the present shoreline. This feature is identified in all the four images and it has almost the same north–south extent as the sand beach feature.

A sediment plume projecting offshore (figure 2) is evident in the 1998 imagery. The plume extends beyond the coverage of the image. This feature is not evident in the 1986 imagery, but it is evident in the 2000 image (figure 3). Finally, an offshore sandbar (about 1.8 km long) is another important feature identified in the 1998–2000 scenes. This feature could also represent the delta front, where the offshore waves break.

4. Discussion

4.1. *Factors affecting delta systems*

Deltas are fed by drainage systems that culminate in a trunk stream and supply sediment to a restricted area of a shoreline (Elliott 1986). Both the hinterland (constituting the drainage basin and the fluvial system) and the receiving basin (which could be oceans, semi-enclosed seas, lakes or lagoons) control the development of the delta. From the hinterland, variables such as geology, climate, relief and human activities interact to determine the water and sediment supply (Milliman and Meade 1983, Elliott 1986, Milliman and Syvitski 1992, Milliman

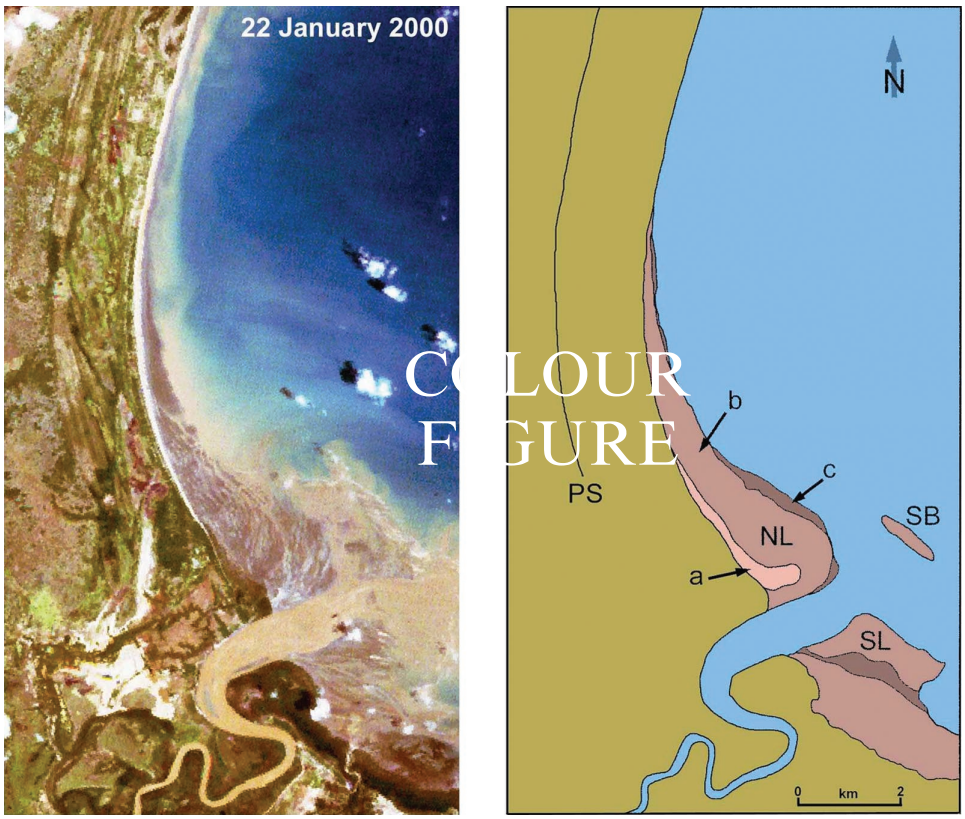


Figure 3. Map showing the 2000 image (left) and the major features interpreted from all the investigated images. NL, Northern subaqueous levee; SL, southern subaqueous levee; PS, palaeo-shoreline; SB, offshore sandbar. Observe the aerial growth of the northern levee from 1986 (*a*) brightest tone, 1998, (*b*) intermediate tone and 2000, (*c*) darkest tone. Same colour codes are used for northern and southern levee. 8

Table 1. The estimated physical dimensions of the levee systems north and south of the river mouth from three satellite scenes.

	Area of the levee (km^2)	
Imagery	Northern	Southern
1986	1.4	0.9
1998	5.4	4.5
2000	5.7	5.0

1995). In the receiving basin, features such as basin shape, size, bathymetry and climatic setting are among the most important variables that control the energy regime (Elliott 1986).

The weathering processes in rocks and the subsequent erosion are generally controlled by the climatic variables such as rainfall and temperature (Rapp *et al.* 1972a,b, Larsson 1986, Westerberg 1999). Milliman and Syvitski (1992) and

Milliman (1995) have discussed the importance of topography (relief) in controlling sediment erosion and this factor is the most important variable controlling the sediment discharge to the sea for most rivers. These studies show that, globally, most rivers from mountainous areas have greater sediment loads and yields than rivers from lowlands. Soil erodability is accelerated by anthropogenic human activities such as deforestation, overgrazing and farming (Rapp *et al*. 1972b, Christiansson 1986, Ng'ethe, 1986, Larsson 1986).

For deltas that form on continental margins, the full range of basinal processes (waves, tides and ocean currents) may affect the delta. In semi-enclosed or enclosed seas, wave energy may be reduced due to reduced fetch, and tidal influence is minimal. Topographic structures on the sea bottom, such as reef platforms may modify the wave energy due to refraction and diffraction, giving rise to concentration or dissipation of wave energy in specific locations (Lwiza 1994). Deltas located in narrow elongate basins or gulfs connected to an ocean may experience great tidal influence as the tidal currents are amplified. Smaller scale deltas prograding into lagoons or lakes may be dominated by fluvial processes as the influence of basinal processes is limited (Donaldson *et al*. 1970, cited in Elliott 1986).

4.2. *The hydrodynamic regime of the investigated area*

In view of the controlling factors presented above, the following remain to be explained: (1) important variables that control the progradation of Ruvu delta and (2) the interrelationship between the shoreline and the basinal and fluvial energy processes. The variables which may potentially affect both the long-term and the present development of the Ruvu delta and the shoreline in general may be divided into the basinal and fluvial processes acting on the river mouth and the coastal area, and the hinterland processes that control the total and rate of sediment supply to the marine basin.

4.3. *The fluvial and basinal processes at the river mouth and the coastal zone*

The Ruvu delta, as well as most parts of the Zanzibar channel, does not have a direct connection to the open ocean, and the area may be considered protected from the effect of long period waves, from the open ocean. However, the effect of locally generated short period waves that affect the coastal area of Zanzibar channel, cannot be neglected (Brampton 1996). The EACC, which affects the continental shelf and the central parts of the channel, may be of less importance in the coastal area investigated. As the tides are mesotidal, they are considered to be moderate. Moreover, field investigation on the delta found no evidence of linear tidal shoals or other feature indicative of tidal dominated river mouths. Both tides and waves are therefore considered to control the redistribution of the sediment laden river output from the river mouth to other parts of the coastal area.

The accretion rate of the delta north of the river mouth is one of the most unique features observed by our study. On the basis of the mapping results presented using the four satellite images, the net linear and areal growth of the delta between 1986 and 1998 is about 1.6 km and 4 km^2, respectively. There was not much delta growth between 1998 and 2000. The annual lineal and aerial growth rates between 1986 and 1998 are about 0.13 km and 0.33 km^2.

In Zanzibar Island, it is a common phenomenon to find near-shore sandbanks or pocket beaches showing significant net accumulation of sand during one monsoon season and net sand deficit during the following season. These phenomena are considered to be influenced by the wind patterns, which change during the different monsoon seasons and affect the wave and tidal current dynamics. Our investigation of the two Landsat scenes (1999 and 2000) representing the two periods, revealed that the technique was not useful in resolving the seasonal sediment dynamics on these beaches or sandbanks, probably due to the spatial resolution and the small changes.

However, our results on the investigated satellite scenes (1986–2000) on the Ruvu delta show that the delta is preferentially prograding northward despite the annual monsoon influences. The results are consistent with other studies (Muzuka and Shaghude 2000, Muzuka 2001), which were conducted about 15 km north of Dar es Salaam harbour (about 50 km south of Ruvu delta). Both of these studies noted preferential northward transport of the sediments in the area. This also seems to be the case in the investigated Tanzania mainland coastal area north of river Ruvu.

Our study has identified a palaeo-shoreline feature located about 1.9 km inland from the present shoreline. Dating of this feature was not part of our study, but it would be something worth undertaking for future studies. It would be of interest to investigate the rate at which the sea has been receding during the Recent time, as it is also interesting to note that the coastline in the investigated area has been accreting more or less uniformly along its length without major morphological changes. The area between the palaeo-shoreline feature and the present shoreline is characterized by longitudinal beach ridges which are described by Alexander (1968, 1969) to be well developed in the lowest terrace (the Mtoni terrace) on some parts of the Tanzania mainland backshore area (e.g. between rivers Ruvu and Wami). The palaeo-shoreline feature itself marks the boundary between the Mtoni terrace and the Tanga terrace (the next higher terrace).

4.4. *The hinterland processes*

The river Ruvu is the most important fluvial system controlling the supply of the terrigenous material in the investigated area (Shaghude and Wannäs 1998). A major contribution of the sediments from the river Ruvu is the Uluguru Mountains, which is a tropical mountainous area located about 200 km from the coastline of the Tanzania mainland (figure 1). The bedrock geology consists of metamorphic crystalline rocks of the Mozambique belt, believed to have been formed during the Pan African episode, about 550 ± 100 m.y. ago (Windley 1977) and probably uplifted before Upper Carboniferous (Samson and Wright 1964, cited in Westerberg 1999). The local relief of the mountains is over 2600 m above sea level (Jones 1996a). The Uluguru mountains cover an area of more than $90\,\text{km} \times 70\,\text{km}$ (Westerberg 1999) and its steepness, altitude and the presence of Neogene upwarped surfaces suggest that the uplift has been continuing during the Quaternary (Samson and Wright 1964, cited in Westerberg 1999).

The rainfall pattern over the Uluguru mountains, as in most parts of the eastern Tanzania is controlled by the Inter-tropical Convergence Zone (ITCZ) and the monsoon winds from the Indian Ocean (Nyenzi *et al.* 1999, Westerberg 1999). Most of the Tanzania highlands including the Uluguru Mountains receive abundant

precipitation. According to Nyenzi *et al.* (1999), the rainfall pattern in Tanzania is characterized by two main regimes: (1) the unimodal regime, which produces continuous rainfall from December to April, and (2) the bimodal regime characterized by a non-continuous rainy season (October to December and March to May). The rainfall pattern on the Uluguru mountains has been described as unimodal (Jones 1996a).

Several studies undertaken on the Uluguru mountains (Temple and Rapp 1972, Rapp *et al.* 1972b, Westerberg 1999) shows that the annual precipitation on the Uluguru mountains is generally higher than on the surrounding plains. On the basis of the generalized maps which show the annual rainfall distribution in Tanzania (Rapp *et al.* 1972a,b, Nyenzi *et al.* 1999) the average annual precipitation at the Uluguru mountains is over 1400 mm, and in some places reaches 1900 mm $year^{-1}$ (Rapp *et al.* 1972a).

The studies cited above also discuss the interrelationship between the human settlements on the Uluguru Mountains, natural vegetation, land use and land degradation. The natural vegetation consists of forest and woodland that are altitude dependent (Temple 1972, Westerberg 1999). Most of the forest and woodland clearing took place during the last two or three centuries (Temple 1972, Jones 1996b, Westerberg 1999), when the Luguru migrated from the southern parts of Tanzania and settled on the Uluguru mountains. Three factors dictated the initial settlements of the Luguru on the Uluguru mountains (Jones 1996b). The first factor was the higher soil fertility of the mountains relative to the plains, and the second factor is the higher rainfall of the mountains relative to the plains. They also used the mountains as a secure place of refuge against their enemies.

The account of Westerberg (1999) shows that humans have exerted a considerable pressure on the natural vegetation, as almost all woodland on the foot-slopes of the mountains has been cut to make way for human settlement and agriculture fields. Consequently, woodland and forest are generally found on the steepest slopes and at altitudes where cultivation is less viable. Surface erosion on the East African highlands, especially on the unprotected (non-vegetated) area has been recognized as a problem despite the soil conservation methods that have been widely practised in some of the highlands, including the Uluguru mountains (Jones 1996a,b, Westerberg 1999). Thus, the overall high rainfall on the mountains, its unimodal nature and the anthropogenic effects are potentially important in controlling soil erosion on the Uluguru mountains and ultimately the regular discharges of the sediments to the ocean.

The influence of rapid mass movements such as landslides on soil erosion problems in the East African highlands has also been a subject of discussion by some workers (Temple and Rapp 1972, Westerberg 1999, Westerberg and Christiansson 1999). Landslides are natural and conspicuous geomorphic processes, which often occur during extreme rainfall events, leading to widespread destruction of arable land and other human properties. Due to the general high precipitation and deep rigolith in most of the East African highlands, landslide events are generally common in the highlands (Westerberg 1999, Westerberg and Christiansson 1999). Temple and Rapp (1972) report on one such extreme rainfall event on an approximately 20 km^2 catchment on the Uluguru Mountains where between 58 and 185 mm of rainfall was concentrated in a 3 h period. The rainfall event triggered more than 1000 landslides in the area, corresponding to about 270 000 m^3 of

sediment. The landslides affected the cultivated land and grasslands equally, but showed less effect in the woodlands.

According to Jones (1996b), rainfall events of such intensity are locally known by the indigenous people and are considered to be the major causative sources of erosion in the area. Jones (1996b) point out that the landslide events triggered by extreme rainfall events are estimated by the indigenous people to occur approximately every 10 years. Studies on the rainfall patterns in north-central part of Tanzania (e.g. Sandström 1995, cited in Simonsson 2001) report that the long-term (30 years rainfall data) annual precipitation is characterized by a cyclic pattern of wet and dry years with a periodicity of about 8–10 years. A spectral analysis of rainfall oscillation in Tanzania (Nyenzi *et al*. 1999) observed a 9–12 year cycle in the annual rainfall data, suggesting that the cycle is probably linked with the Sun spot activity of 10 years.

The 1997/98 El Niño–Southern Oscillation (ENSO) was also associated with extraordinary landslides in many parts of Tanzania, especially the highland areas. Our investigation on the monthly rainfall data from one of the rainfall station located along the slopes of the Uluguru mountain (figure 4) show that most of the

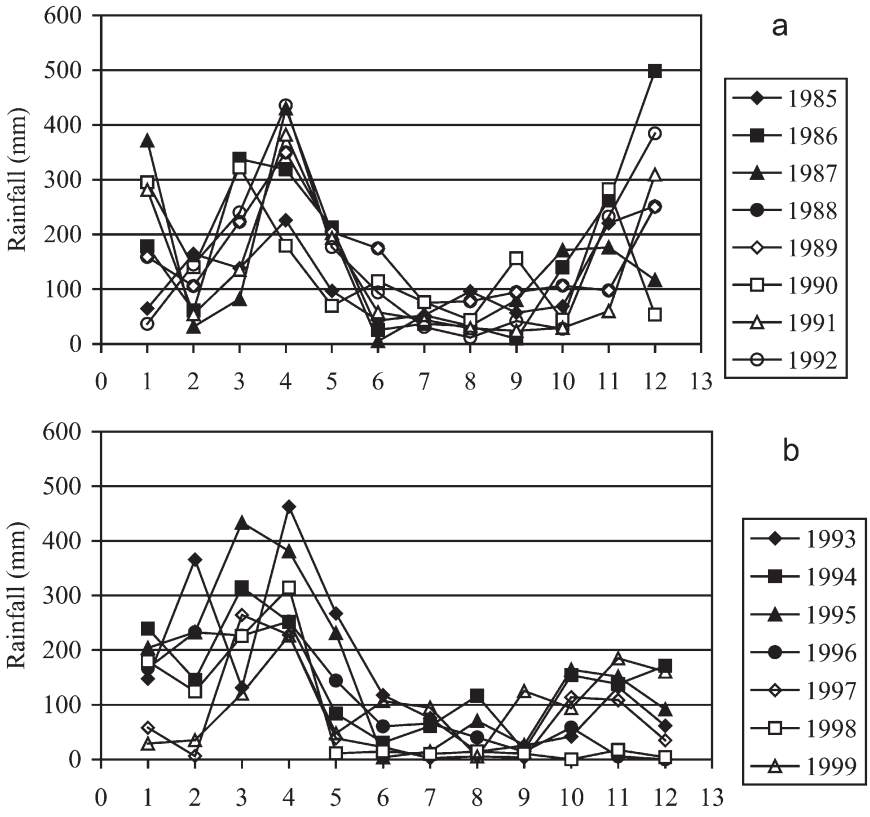


Figure 4. Fifteen years (*a*, 1985–1992 and *b*, 1993–1999) monthly rainfall record for Matombo station located along the slopes of the Uluguru mountains. Observe that the numbers 1 to 12 on the *x*-axis correspond to the months January to December. Source: Tanzania Meteorological Authority.

rainfall is received during October to May and little rainfall is received between June and September. Further, the main rain season (October to May) is characterized by two peaks, the first in November/December and the other in March/April. The results further show that besides the 1997/98 rainfall season there were other rainfall seasons between 1986 and 1998 with extreme rainfalls (e.g. 1985/86, 1986/87, 1991/92, 1992/93, 1993/94 and 1994/95). It appears therefore that if landslide events in the Uluguru Mountains are associated with extreme rainfall events, one should not only consider the 1997/98 ENSO rainfall season, as there were other high rainfall seasons between 1986 and 1998.

It must be pointed out that the monthly precipitation data is not very informative as far as landslide events are concerned. The frequency and intensity of precipitation (Temple and Rapp 1972, Westerberg 1999) generally control landslide events. The daily precipitation records, which may give some clues on rainfall intensity, would for this case be more important than the monthly records, but this data is more difficult to find. It is therefore not possible to make direct linkage of the extreme rainfall events between 1986 and 1998 with the observed fast growth of the Ruvu delta between 1986 and 1998. However, the possibility that the Ruvu delta growth was associated with the landslides during the extreme rainfall events between 1986 and 1998 cannot completely be ruled out.

Finally, some of the ongoing studies in the area reveal significant change in land use patterns from 1985 which is exemplified by a relatively large conversion of more woodland and forest areas of the river Ruvu catchment into agricultural fields (Lennart Strömquist, Uppsala University, personal communication). This significant change in land use patterns from 1985 might also have a direct linkage with the fast growth of the delta between 1986 and 1998, as the previous study of Temple and Rapp (1972) show that soil erosion in the area generally affects the cultivated areas more than the forested or woodland areas.

5. Summary and conclusions

The challenge for future management and monitoring of the Tanzania coastal resources may be solved by using satellite remote sensing methods. Our present study has used the approach on an accreting coastal area on the western side of the Zanzibar channel, proximal to river Ruvu. The focus of the future study is to use a similar approach to eroding coastlines on the Tanzania coast.

The Ruvu river sediment discharge to the ocean is controlled by the high relief of the Uluguru Mountains. The growth of the delta between 1986 and 1998 can be explained by a gradual depositional process from 1986 and 1998 or a sporadic depositional process such as landslide events associated with season's extreme rainfalls, including the 1997/98 ENSO event. Alternatively, it may be associated with the significant changes being observed in the land use pattern, which have been taking place during the last two decades. The temporal resolution of the available data does not permit us to make a conclusive decision on which hypothesis is the most likely. This issue will be the focus of future studies.

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