

#### **4.11 The Niger Delta as a receptacle and the Niger River flux into the Atlantic Ocean – the role of upstream change and coastal hydrodynamics**

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##### Extended abstract

The Niger Delta lies between latitudes 4°30'N and 7°N, and longitudes 5°E and 9°E. It covers an estimated land area of some 67,140 km<sup>2</sup> and currently has five states (Bayelsa River, Akwa-Ibom Delta and Cross River) as its constituent administrative divisions. Its climate is typically humid with total annual rainfall in excess of 2400 mm annually. Rainfall distribution also defines the double maxima characteristic of such areas. Temperature ranges between 27°C and 30°C.

The total population is approximately 11.4 million, but population densities are high as only 30% of the entire region is habitable. Population density may average 169.5 persons/km<sup>2</sup>, but densities of 400/km<sup>2</sup> occur in some places. The main occupations traditionally are fishing, farming and other land-based activities such as hunting and fuel-wood harvesting and selling. This is mostly the situation in the rural riverine areas from where the crude oil and associated gases are exploited. In cities, secular and other service occupations predominate.

The hydrology of the area is controlled by major and minor rivers that have intricate links with a creek network that serves as transportation channels for sediments and other materials from the hinterland. In response to tidal dynamics, these either experience fluxes or become sinks for nutrients, sediments and other materials. Characteristically, low tides bring about flow towards the Atlantic Ocean while high tides effect flow in the other direction.

Due to the generally low-lying nature of a significant part of the Niger Delta and the prevailing high groundwater table, more than 70% of the land area is wetlands that are submerged for different periods of the year. Vegetation varies from freshwater to mangrove (saline) species, depending to a large extent on the biochemistry of the existing waters, sediments and soils. The uniqueness of each of these ecological units and their sensitivity to modification and change are predicated on these innate characteristics.

Geologically, the Niger Delta is a zone of active recent sedimentation. The Sombreiro-Warri Deltaic Plain sediments of early Holocene to late Pleistocene era are the oldest Quaternary sediments. They are principally coarse and fine sands with minor silt and clay. These are overlain by sediments of mangrove swamp origin that vary from fine to medium sands, the wooded back- and freshwater-swamps, and the meander belts which consist mainly of sand, silt and clay in different proportions. Two hydrogeological provinces, the coastal alluvial and the coastal sedimentary lowlands, are identifiable. A high water table, usually at less than 2 m depth, characterises the former, while the latter consists of unconsolidated and highly porous material. The high permeability and the shallow groundwater table enhance interactions between surface and groundwater in the region and that relationship also accentuates the risk of groundwater pollution particularly in the case of oil spills.

The Niger Delta is endowed with diverse natural resources. The most prominent of these are the vast reservoirs of crude oil and associated gas which have become the mainstay of the national economy. The location of this 'vehicle' of economic empowerment within that environment that has brought the entire area into limelight. The area has also attracted much attention and discussion because of the degradation that has occurred in the process of exploiting those resources. The agents of impairment of the coastal and marine environment include domestic sewage, industrial effluents, petroleum hydrocarbons, dredged materials and garbage. These have degraded the aquatic resources for recreation and transportation. The effects of mineral oil mining are aggravated by rapid urbanization and industrialization in coastal settlements. Frequent oil spills have adversely affected fish stocks, wildlife and the fragile mangrove ecosystem.

The situation has assumed such critical social and political dimensions that the environmental neglect of the area and its people over the years has threatened the corporate existence of Nigeria. In fact, the rebellious youths in the Niger Delta are yet to be placated, as there are still incidents of interference with oil prospecting and production activities within the predominantly riverine area.

As noted above, the Niger Delta is mostly a flat, low-lying swampy sub-basin criss-crossed by a myriad of rivers and creeks. Its topography, geology and soil properties and heavy and frequent rainfall subject the area to severe annual flooding and erosion. The Niger Delta is subsiding as a result of both natural compaction of sediments and also due to oil, gas and water extraction. The rate of subsidence during the last 10 years is as much as 7 cm at Bonny. Superimposed on the subsidence is the accelerated sea-level rise (ASLAR) driven by global warming which could add up to 30 cm of sea-level rise in the next three decades. The implication of such changes at the coastline and for the coastal zone could be grave for the natural resources and the inhabitants. A zone of 40 km could be lost to the ocean in the next two decades.

The Niger Delta has its apex south of Onitsha, some 375 km from the ocean. The Niger River bifurcates south of the Nun and Forcados rivers. From there the depth expands to 270 km of coastline using the considerable discharges of water and sediments in building up and progressively extending into the Atlantic Ocean. The seaward hydrodynamic zone of the delta is completely tidal while that of the freshwater zone is determined largely by the discharge from the river. The transitional/estuarine areas are dominated by tidal flows during the dry season and by freshwater during the wet or flood season of the river system.

The delta is the receptacle of the floodwaters of the Niger River system and stores much of the inflow for varying periods of time. During the wet season (July-October), about  $119 \times 10^9 \text{ m}^3$  of water is discharged into the delta and constitutes the principal source of water. The run-off is distributed through a dense network of distributory rivers, creeks and estuaries of which the principal ones are the Forcados, Nun, Ase, Imo, Warri and the Sombriero which form an interconnected network that ensures rapid communication of pollutants such as oil-spills. The network also maintains and delivers a dynamic equilibrium between saline, estuarine and freshwater bodies with a complex groundwater system of pathways and reservoirs.

The intersection of the Niger basin with the ocean is effected by the delta through a series of exchanges which impact the coastal zone significantly through 20 river outlets. The Niger River finally discharges its water and sediments fluxes into the Atlantic Ocean where distributive forces come into play:

- ⇒ flooding of the coastal wetlands
- ⇒ coastal erosion and destruction of infrastructure.
- ⇒ saltwater intrusion into swampy freshwater and groundwater resources
- ⇒ through coastal lagoon and estuaries which have their own effects.

The delta also mirrors the impact of upstream water projects (dams and their reservoirs) as well as the prolonged 30-year drought of the Sudan and Sahel. There was a sudden decrease in river run-off soon after the construction of dams and reservoirs, which unfortunately coincided with the severe drought years (e.g., 1971-73, 1983-84.) The discharge rate in the 1983-84 was observed to have dropped by 20% in the Niger Delta. In general, regulation by dams lowered the flood levels and reduced the capacity of flows to transport large volume of sediments during the wet season, which normally accounts for the bulk of the annual sediment transport. As another result of high evaporation rates and the extensive nature of these shallow reservoirs, large volumes of their storages are lost to evaporation and to the Niger basin (though not to the global hydrological system). These losses in terms of the total annual inflow into the reservoirs amount to 20-30%. In addition, the dams retain the bulk of the sediments. As Nigeria's dams are traditionally over-designed, they tend to retain over 70% of dissolved sediments intercepted by them.

Extreme construction and dredging of canals for transportation and communication in the many isolated riverine communities have contributed to anthropogenic impact in the Niger-delta. These structures often change the water flow pattern, disrupt sediment transport and deposition and the level of salinity and could lead to destruction of fishing grounds and death of forests. The dredged spoils produced are found to constitute a serious ecological hazard. The proposed dredging of the lower Niger has attracted much outcry from the general public and NGO's and the individuals as well as groups of stakeholders

knowledgeable in environmental issues. Environmental assessments have indicated that the impact of the huge volumes of dredge spoils on the aquatic and forest environments are expected to be severe.

Over-abstraction of groundwater in coastal/estuarine cities such as Port Harcourt and Warri may result in the lowering of the water table/piezometric level and hence reversal of the hydraulic gradient at the groundwater-seawater interface. If this happens, the saline water intrusion at the interface will extend the zone of contamination.

The most probable agent of change is oil prospecting/mining. Activities undertaken in the search and production of oil have already been implicated in some oil-spills. Gas flaring, regarded as a “safety measure” put in place by all the oil prospecting companies in the Niger Delta field in the absence of a more cost-effective measure, is another source of impact. Finally, there are implications of negative impacts on humans within the area, most of whom are already living below the poverty line and who directly bear the brunt of such mishaps.

#### **4.12 Nutrient fluxes between land and ocean, and effects of human-induced activities: case study of Ondo State coastal wetlands, Nigeria**

***Yemi Akegbejo-Samsons and A.M. Gbadebo***

##### *Abstract*

This paper examines the chemical composition of the rivers, creeks and floodplains that constitute the Ondo state coastal wetland system. The report is based on part of the work done for a Ph.D research in 1995. Water samples were analysed for general chemical factors, nutrients and trace elements.

Results show that the wetland system can be categorised as freshwater, brackish water and marine. While the freshwater was slightly acidic and very rich in organic matter and biogenic nutrients, the brackish water was alkaline and full of chloride and magnesium. The chemical composition varies with season and tides for all the three categories: generally high in the dry season and dilute in the wet season. Effects of the chemicals and nutrients values on fish production were not significant.

Effects of human-induced activities such as dredging, sand harvesting, marine transportation and other fisheries-related activities are highlighted. The need for a regular monitoring of the coastal wetlands is advocated.

Keywords: Nutrient fluxes – land – ocean – coastal wetlands.

##### **Introduction**

Ondo state is one of the eight coastal states of Nigeria, bordering the Atlantic ocean. The state consists of 18 local government areas and has a population of over 2.8 million. The lowland wetland area is bounded in the east by the Benin River of Edo State, in the west by the Ogun waterside and in the north by a land mass whose inhabitants are predominantly farmers, hunters and fishermen.

The coastal wetland system is parallel to Nigeria's south-west coastline, and is characterised by extensive lagoons, creeks, estuaries and river delta systems. It lies between latitudes 6°N and 7°N, and longitudes 4°E and 5°E. While the remaining parts of Ondo state can be reached by a network of roads, these coastal plains and swamps can only be reached and explored by boats and canoes. Quite recently, a large reserve of bitumen was discovered close to these areas. This wetland, which is pierced by the Oluwa River, is the major fish resources ground of Ondo state (Akegbejo-Samsons 1995, 1997, 1998, 1999).

This study is concerned with the nutrient fluxes between the land and the ocean that constitute the Ondo State coastal wetland. The main object is to determine the levels of some important nutrients and trace elements in the study area and their effects on fish distribution and yield in the area.

##### **Materials and methods**

###### *Study area*

The study area was divided into three categories for effective data collection and verification:

- (i) fresh water (rivers, canals, flood-plains);
- (ii) brackish water (creeks, lagoons, estuaries); and
- (iii) salt water (the coastal fringe).

Within each of the categories, sampling stations were selected as follows:

- fresh water - Oluwa 1, Oluwa 2, Igbokoda;
- brackish water - Mahin, Atijere, Igbekebo; and
- marine - Aiyetoro, Orioke Iwamimo, Zion Pepe and Alagbon.

###### *Water analysis*

Water samples were taken from the selected stations in Winkler's bottles and plastic containers and brought in iced containers to the laboratory of the Federal University of Technology, Akure for analysis during 1994

and 1995. The following parameters were analysed based on the methods specified in AOAC (1984): calcium, magnesium, sodium, potassium, alkalinity, sulphate, chloride, silicate, nitrate and phosphate. Trace elements such as copper, nickel, chromium, cobalt and iron were also analysed to show their level of concentration.

#### *Resources evaluation and human activities*

A desk review was carried out to collect information on the location of fishing communities and human population in the study area. Questionnaires and on-the-spot evaluations of the following were done:

- (a) fauna availability, management and conservation;
- (b) (b) inventory of all coastal resources based on harvest data of fishermen groups, and
- (c) (c) decision-making in resource allocation and exploitation.

#### *Data analysis*

Data collected from the various study sites were then computed as follows:

- (i) Fish species harvest trends were observed over time from the various locations; the fish species were identified and their composition and abundance determined.
- (ii) The coastal resources were inventoried and categorised to their various 'utility units'. Their various levels and modes of utilisation were assessed.

## **Results and discussion**

#### *Hydrological characteristics*

The major hydrological and tidal characteristics of the study area are shown in Table 1. While the Oluwa River is the major distributary, other tributaries include the Kurawe Stream, the Talita River, the Mahin Canal and Alape Creek. The estimated total mangrove swamp area is about 60,000 hectares with a surface area of rivers, creeks and streams of about 38,000 hectares. Table 2 shows the information on the sampling sites. This is presented to show the variability in location as determined by the ecological niche of the individual stations and their relevance to spatial concentration of the tested parameters.

#### *Trace elements concentration*

The concentration of the trace elements is presented in Table 3. Iron concentration was highest in all the sampled sites, followed by copper and then cobalt. Concentrations were highest in the freshwater areas for iron, copper and cobalt, while nickel concentrations were high for marine sites. Generally, concentrations of trace elements decreased from the freshwater towards the marine.

**Table 1. Major hydrological characteristics of Ondo state coastal wetland.**

<b>Major distributary</b>	River Oluwa.
<b>Major tributaries</b>	Apostle Canal, Alape Creek, Ipare Stream, Talita River, Kurawe Stream, Mahin Canal.
<b>Mangrove swamp area (hac):</b>	60,000
<b>Water mass area (hac) :</b>	38,000
<b>Mean depth of water level:</b>	River Oluwa - 4.6 m Apostle canal - 4.8 m Mahin canal - 4.9 m

**Table 2. Information on sampling stations.**

No.	Category	Sampling site	Latitude	Longitude
1	Freshwater	Oluwa 1	6°36	4°04
2	Freshwater	Oluwa 2	6°36	4°04
3	Tidal freshwater	Igbokoda	6°34	4°06
4	Brackish water	Mahin	6°35	4°06
5	Brackish water	Atijere	6°36	4°07
6	Brackish water	Igbekebo	6°39	4°05
7	Marine	Ayetoro	6°26	4°08
8	Marine	Orioke Iwamimo	6°24	4°08
9	Marine	Zion pepe	6°22	4°07
10	Marine	Alagbon	6°28	4°06

**Table 3. Concentration of trace elements (mg/l) in Ondo State coastal wetland.** The sampling program was carried out during June-December 1995.

Sampling site	Trace Elements				
	Iron	Nickel	Chromium	Copper	Cobalt
(1) Oluwa 1	0.71	0.01	0.01	0.30	0.24
(2) Oluwa 2	0.73	0.01	0.01	0.31	0.26
(3) Igbokoda	0.68	0.01	0.01	0.30	0.26
(4) Mahin	0.51	0.01	0.01	0.24	0.25
(5) Atijere	0.41	0.01	0.01	0.21	0.19
(6) Igbekebo	0.02	0.01	0.01	0.20	0.16
(7) Ayetoro	0.01	0.11	0.01	0.18	0.08
(8) O' Iwa mimo	0.02	0.10	0.00	0.17	0.08
(9) Zion Pepe	0.03	0.11	0.01	0.06	0.07
(10) Alagbon	0.03	0.11	0.01	0.06	0.06

Table 4 shows the chemical and nutrient composition. Values of pH, calcium and organic matter decrease as one moves from freshwater to the marine. However, values of major nutrients such as nitrate, chloride, sulphate, silicate, magnesium and sodium increase from the fresh water to the marine systems. Levels of salinity and alkalinity increase as we move from the fresh water to the marine environment. However, the level of phosphate remains significantly steady in all the ecosystems.

There was no significant result ( $P=0.05$ ) between nutrient composition and fish species abundance. Higher values of calcium and potassium were recorded for the freshwater areas, probably due to the presence of Oluwa glass industry which empties its discharges into the upper region of the river. However during the dry season fish populations were found to be at the lowest levels. Farming activities were highest in the freshwater areas, while fishing was highest in the brackish water ecosystems.

#### Coastal communities and their activities

The fishing communities did not differ from one ecosystem to the other. However their activities varied from freshwater to brackish and marine environments. This constituted a significant impact on the intra- and inter-coastal activities within the study area. More than 82% of the members of the communities belong to co-operative societies where resource exploitation and management are formulated and passed as by-laws. This is more effective within the marine area than the freshwater, because human activities in the freshwater zone are restricted and specialised. These include using the water for irrigation and fish ponds. Socio-economic activities here include river fishing, farming and aquaculture.

**Table 4. Chemical and nutrient composition (June to December 1995) in Ondo state coastal wetland.**

Parameter	Unit	Sampling station									
		1	2	3	4	5	6	7	8	9	10
Hydrogen ion	pH	6.8	6.9	6.8	6.2	6.2	6.3	6.0	6.1	6.1	6.1
Salinity	‰	0.05	0.06	0.05	0.30	0.36	0.37	1.20	1.23	1.36	1.40
(estimate)											
Oxygen	mg/l	6.5	6.8	6.9	7.0	7.0	7.1	7.3	7.0	7.2	7.1
Calcium	mg/l	132	131	136	93	94	96	63	64	63	63
Magnesium	mg/l	68	69	70	81	83	86	86	103	103	106
Sodium	mg/l	64	63	63	76	803	821	821	902	905	905
Potassium	mg/l	171	173	169	64	68	63	71	72	72	73
Alkalinity	mg/l	23	23	22	25	25	26	24	36	38	36
	CaCo <sub>3</sub>										
Sulphate	mg/l	28	28	27	26	27	28	28	28	29	30
Chloride	mg/l	65	64	63	107	108	108	109	207	206	207
Silicate	mg/l	1.0	1.0	1.1	2.3	2.1	2.4	2.5	2.3	2.3	2.4
Nitrate	ig/l	18	21	22	20	26	24	24	25	25	26
Phosphate	mg/l	34	36	38	32	33	34	33	33	30	28
O. matter	mg/l	3.6	2.7	3.2	3.1	3.2	2.8	2.8	2.6	2.7	2.8

Coastal communities within the brackish and marine zones rely mainly on capture fishery resources and other related aquatic resources. During the fishing months of the year, usually during the months of May to October, there is a population shift from the adjoining towns to the marine fishery. This is accompanied by over-capitalisation and an increase in fishing efforts to the detriment of the fishery. For example, an increase of over 68% of adult fishers occur every fishing season, a situation which is not good for the fishery.

### ***Coastal resources and effects of human activities***

An inventory of the coastal resources and the resultant effects of human induced activities is presented and discussed.

#### ***(a) Fisheries***

The bulk of the living coastal resources exploited for food in Nigeria falls under the category of 'fish'. Nine distinct fish species of major and commercial importance were identified and their relative abundance rated using the landing size (weight and number). The fish of commercial importance were *Clarias anguillaris*, *C. gariepinus*, *Oreochromis niloticus*, *Gymnarchus niloticus*, *Chrysichthys nigrodigitatus*, *Polydactylus quadrifilis*, *Synodontis membernaceous*, *Bagrus bayad*, *Heterotis niloticus* and *Heterobranchus bidorsalis*.

#### ***(b) Dredging and sand-harvesting***

Dredging and sand-harvesting together constitute a major economic activity in both the freshwater and marine zones of the study area. In the freshwater zone, sand is stockpiled using human labour, then the sand is transported using special trucks to the construction sites.

In the marine zone, special boats are used to ferry the sand to sites which are always many kilometres from the point of harvest. This activity has been found to be highly hazardous to the environment and to the fishery. While it disturbs other fishing activities, it also destroys the habitats of the fish species that nest close to the shoreline. For example, over 230,000 m<sup>2</sup> of sand is excavated annually within the Lagos Lagoon and reports show that certain endemic fish species are no longer found in the lagoon as a result of this disturbance. In this study area, man-made pools of water and artificial 'cayons' are some of the consequences of this environmental disturbance.

*(c) Marine transportation*

This sector of human activities is mainly a 'water-use' rather than a resource. Traffic of motorised large canoes and model boats was found to be very high along the main Oluwa River and in the canals, where over 75% of the fisher-folk rely on such mode of movement.

Generally the use of motorised canoes and boats was found to enhance resource exploitation. For example, a census of the boats used to convey passengers between Igbokoda and Ayetoro found there were about 22 boats, each doing three trips per day. Fish catches along these routes have been drastically reduced, presumably as a result of this river traffic. Incidences of oil pollution via discharges from petrol and diesel engines have been reported.

*(d) Proposed bitumen project*

A bitumen exploratory plant is to start soon, a few kilometres from this study area. This report seems very timely since there is a need to highlight the consequences of exploratory activities on the adjacent Oluwa River, which invariably will carry effluent(s) to the marine environment down stream.

## **Conclusion**

Water quality in riverine estuaries is related to season. Quite often seasonal rains increase river discharge and watershed runoff, which serves to dilute nutrient concentrations in the riverine estuaries. This can be seen in Table 3.

Nutrient sources for the brackish and marine zones include load in the form of river discharge and rainfall runoff, and other 'contaminants' that might have been introduced by the various human activities, especially from fish pond effluents.

When the data from this study was compared to some of the data collected in the area before the commencement of the operations of the Oluwa Glass Industry, an increase in concentration of over 60% of the chemicals and nutrients was observed. This is probably due to the operations of the industry, coupled with the increasing human pressure on the coastal area, especially since the beginning of the exploratory surveys of the bitumen site, which is just a few kilometer to the coast of Ondo state.

It is recommended that constant monitoring of these parameters be carried out every year to ascertain the annual implication of the human activities in this area.

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#### **4.13 Movement of minerals and nutrients from river basins in south-western Nigeria into the Atlantic Ocean**

***G.A. Bolaji, O.S. Awokola, A.M. Gbadebo and O. Martins***

##### *Abstract*

South-western Nigeria is highly populated and experiences moderate to high industrial and agricultural activities. The major river basins located in this zone are the Ogun, Oshun, Yewa, Benin and Owena. Serving as a source of water supply to the communities along their courses, they also transport major effluents that result from human activities and dissolution of rocks underlying the watercourse. This paper summarizes a study carried out to determine the concentrations of nutrients and minerals carried by some of the rivers and the variations in quantities discharged into the ocean via lagoons.

##### **Introduction**

Research efforts on the hydrochemistry of rivers in Nigeria has centered mostly on major rivers. There are numerous drainage basins suitable for modelling studies but to date only very limited information is available on riverwater quality and quantity. Effort is being made to publish new data on the rivers of south-western Nigeria.

Surface waters in the region transport domestic and industrial wastes and most of these rivers also serve as important sources of water; the Ogun, for example, supplies the sprawling city of Lagos (11 million inhabitants) with water from the Oyan Dam, 60 km to the north.

The area is characterized by low relief with a N-S gradient and a NW-SE striking escarpment at an elevation of about 500 m in the north-west, where most of the rivers rise. Three vegetation zones can be identified in the hinterland: the savanna in the west, distinctively different from the high forest vegetation of the central and eastern sectors. Significant changes in land-use patterns have taken place over the years; extensive natural forests and forest reserves have disappeared due to rapid urbanization, commercial logging and agricultural activities. Swamps and mangrove forests cover the southern coastal and riverine areas adjacent to the lagoons.

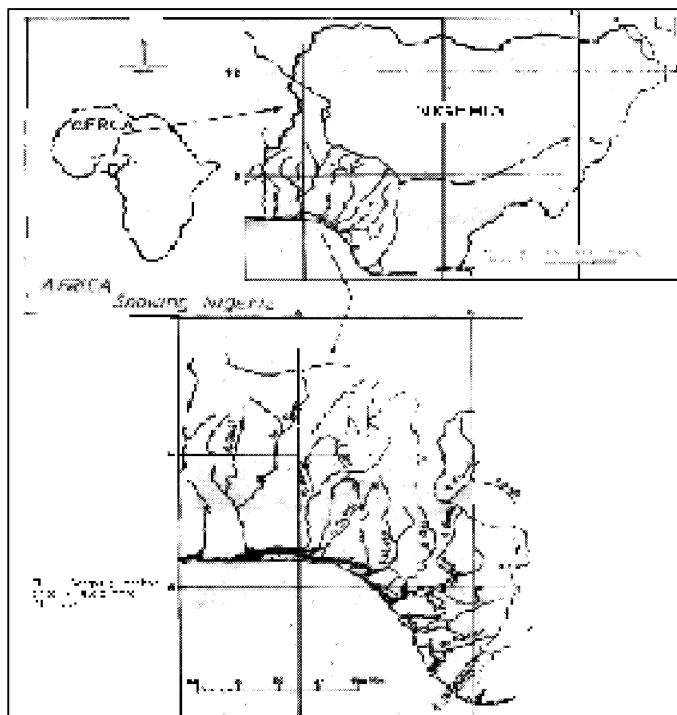
The development of the Nigerian coastal zone is closely related to the separation of the African and South American continents between the upper Jurassic and the Upper Cretaceous. The coastal zone today consists of a series of estuaries and lagoons that provides a transition belt between the rivers and the Atlantic Ocean. Notable are Lagos and Lekki lagoons, Badagry, Omu and Ope creeks. These lagoons and creeks receive the discharges and effluents brought by the rivers from the hinterland. The Lagos Lagoon is a receptacle of domestic and industrial wastes from the city of Lagos adjacent to it. Lagos has the largest concentration of inhabitants (1700 people/km<sup>2</sup>) in Nigeria and it has been the commercial center of the country since the middle of the 19th century. In addition to the seaport, the city houses about 40% of Nigeria's industry, thus supplying a complex mixture of domestic and industrial wastes into the lagoon.

This study was prompted by a decline in catch levels of a hitherto prolific commercial fishery in the lagoons, possibly a result of degradation of the aquatic environment. The transport of materials from six river basins to the Atlantic Ocean via the lagoons is being examined on the basis of the major chemicals carried as dissolved or particulate materials and the major environmental factors controlling the concentrations and loads.

This paper provides a summary of many field surveys carried out (Martins and Awokola 1995; Martins *et al.* 1999; Bolaji and Martins, accepted). It outlines the transport of dissolved materials from the drainage basins into the Atlantic Ocean through the lagoons and creeks. The significance of the work is to establish the catchment-ocean interaction and determine the relative contribution of dissolved and particulate materials by rivers into the coastal environment and their potential effects on the commercial fishing industry.

## The Study Area

The river basins studied are in south-western Nigeria, 6°26'N - 9°10'N, 3°58'E - 5°00'E (Figure 1).



**Figure 1. River basins under study in south-western Nigeria.**

The rivers are highly seasonal in the northern sector of the basins, where they flow between May and November, displaying a mono-modal type of hydrograph, while the characteristic bi-modal hydrograph pertains towards the southern end of the basins. The mean annual rainfall ranges from 990 mm in the north-west zone to 2000 mm towards the south. Thus water levels in the lagoons are relatively low from December to March, during which there is an inflow of saline water from the Atlantic Ocean into the lagoons. Water and sediments are flushed from the lagoons during the rainy season.

The rock sequence in the area starts from the Precambrian Basement. This consists of quartzites and biotite schist, hornblende-biotite, granite and gneiss. The foliation and joints on these rocks control the course of the rivers, leading to a trellis drainage pattern, particularly towards the north of the study area. Sedimentary rocks towards the south of the study area are Cretaceous and Recent. The oldest of them, the Abeokuta Formation, consists of gray sand intercalated with brown to dark gray clay. It is overlain by Ewekoro formation, which typically contains thick limestone layers at its base. The Ilaro formation and the coastal plain sands (Benin Formation) are similar lithologically, distinguishable only by poorly developed unconformities.

## Materials and Methods

### *Water analysis*

Water samples for chemical analysis were taken in 25 ml plastic bottles. They were stored in cool bags and transported to the laboratory for analysis. Sampling points are between 20 km and 60 km from the Atlantic Ocean and well-distributed to reflect inputs from areas of different land uses. Chemical parameters were analyzed by Colorimetric, Electro-photometric and atomic absorption spectro-photometric (AAS) methods (Martins and Awokola 1995; Martins *et al.* 1999).

### Sediment Samples Analysis

Sediment samples from the top 4 cm layer of the cores obtained at specific locations in the lagoon were stored in clean, labeled polythene bags at -18°C. Sampling stations were selected on the basis of their nearness to known sources of inputs of domestic and industrial wastes and of river water washed into the lagoons. The analyses were performed using Perkin Elmer 1100 AAS and Perkin Elmer 5000 AAS machines (see Martins *et al.* 1999).

## Results and Discussion

Table 1 shows the results of minerals and nutrients concentrations in some of the rivers studied. The river discharges reflect the relationship between water quantity and the amount of materials being carried in solution. The sum of the total dissolved solids (TDS) was derived from conductivity values. The minerals content of the rivers is generally low, varying between 18 and 121  $\mu\text{s/cm}$  at 25°C. Rivers in the Yewa basin have the lowest conductivity values, mostly 18-20  $\mu\text{s/cm}$  at 25 °C except in the Ela/Ilaro and Irori/Aiyetoro where conductivities are around 59  $\mu\text{s/cm}$  at 25°C. The main rivers, Ogun, Oshun, Ibu and Yewa have the highest values (103, 101, 107 and 111  $\mu\text{s/cm}$  at 25°C respectively).

**Table 1. Chemical characteristics of rivers under study.**

River Locality	Discharges (m <sup>3</sup> /s)	Cond. ( $\mu\text{S/cm}$ at 25°C)	Dissolved Oxygen(mg/l)	Sodium (mg/l)	Potassium (mg/l)	Calcium (mg/l)	Magnesium (mg/l)	Bicarbonate (mg/l)	Chloride (mg/l)	Sulfate (mg/l)	Nitrate (mg/l)	Total Diss. Solids (mg/l)
Igbin/Ifo	0.56	80	5.5	6.7	0.8	6.0	2.6	30.8	2.8	2.0	2.5	61.1
Ilo/Otta	0.105	52.4	5.0	7.1	1.2	6.0	2.7	22.2	6.0	1.5	2.4	51.6
Iju/Otta	Nd	83.2	6.4	10.3	1.2	9.8	4.1	23.8	6.7	1.4	3.0	79.8
Yewa/Ajilete	1.0	111	6.0	9.0	1.2	8.8	3.8	42.7	6.8	2.0	3.1	63.6
Ela/Ilaro	0.12	58.6	5.8	6.2	0.2	7.2	3.0	33.8	6.7	2.0	3.1	63.6
Orori/Aiyetoro	0.30	58.7	7.5	8.5	1.2	7.4	3.0	43.8	3.2	0.96	3.0	70.2
Owuru/Shagoye	0.09	63.4	6.8	6.7	0.4	7.0	2.9	45.4	3.1	2.4	2.5	77.3
Ibu/Ajura	Nd	107	8.0	12.9	5.6	15.4	6.4	57.3	4.6	1.9	2.9	136.1
Erin-Ogun/Ogere	0.07	51.8	4.8	4.1	0.4	4.2	1.8	22.2	3.3	2.0	1.9	41.0
Ibu/Sagamu	1.7	121.6	8.5	13.8	1.9	11.8	5.0	48.2	2.1		2.5	113.9
Eren/Odogbolu	1.3	37.6	5.0	4.0	0.4	3.4	1.5	22.0	3.2	2.9	3.1	40.1
Eren/Ikenne	0.25	56.3	6.0	7.6	1.6	5.2	2.2	30.0	3.1	1.9	2.5	67.1
Yemoji/Ijebu-ode	1.5	27.5	6.0	2.8	0.4	2.8	0.98	12.2	3.3	2.4	2.6	36.5
Oshun/Apoje	Nd	101	8.5	13.8	3.5	8.6	3.4	54.3	4.3	0.5	2.5	108.3
Oshun/Ogbere	Nd	101.3	9.2	40.0	3.5	7.8	3.7	41.5	4.2	0.9	3.1	93.2
Lepiya/Ogbere	Nd	48.2	8.5	6.7	1.6	4.8	1.8	12.2	3.2	0.5	1.9	43.6
Ifara/Abigi	Nd	20	7.8	1.8	0.2	1.8	0.7	5.4	3.5	1.4	2.9	24.1
Agbure/Agbure	0.15	18.2	5.2	1.4	0.2	1.4	0.5	5.5	3.2	1.5	3.2	22.3
Ilusin/Erifun	0.40	18.2	5.6	1.6	0.3	1.2	0.5	5.6	2.8	1.9	3.0	21.5
Aofa/Aofo	0.15	18.8	6.2	1.8	0.2	1.8	0.7	5.5	2.9	2.0	2.5	26.6
Sowore/Ibiade	0.21	20.4	5.8	2.1	0.4	1.0	0.5	5.4	4.2	0.9	2.6	20.5
Ogun/Abeokuta	Nd	103.6	7.6	13.6	3.1	8.6	3.8	58.5	2.7	2.9	2.0	116.8

Nd. – Not determined

Source: Adapted from : Martins and Awokola (1995)

Predominant drainage basin lithology is the principal factor determining the type of dissolved substances found in surface waters (Meybeck 1980; Martins 1988). Other factors that play a modifying role are climate, vegetation, relief, chemical reactions and atmospheric input. The influence of the latter depends on the distance of the sampling points to the ocean, amount of atmospheric pollution and the prevailing wind direction (Bolaji and Martins, accepted).

With the exception of the Ogun and Oshun basins, where crystalline rocks cover most of the upper reaches, sedimentary rocks predominate in the drainage basins of all the rivers under study. The rock types are mostly recycled sands and clayey materials that must have originated from eroded crystalline rocks. They are derivatives of the chemical weathering of minerals mostly from feldspar, mica and amphibolite groups under the influence of atmospheric carbon dioxide according to the following reaction:



It is apparent from this reaction that the bicarbonate, which forms a major part of the TDS, is derived from the atmosphere and soil carbon dioxide.

In a similar study carried out on the Ogun River, but sampled at locations far downstream, and the results presented on Table 2, the concentration of chloride remained almost constant but that of nitrate increased considerably. The average value of chloride dropped from 2 mg/l upstream to 1.93 mg/l downstream while that of nitrate increased from 2 mg/l upstream to 4.7 mg/l downstream. The nutrients, especially nitrates, may have originated from agricultural effluent that found its way to the river course. Iron is the most abundant mineral followed by manganese, nickel and cyanide. The iron and manganese may have come from the erosion of laterite crusts that dominate the drainage basin while traces of nickel and cyanide are likely to be derived from inputs of untreated domestic and industrial wastewater.

**Table 2. Minerals and nutrients concentration in the Ogun River.**

Sample	Manganese Mn (Mg/l)	Iron Fe (mg/l)	Nickel Ni (mg/l)	Cyanide Cn (mg/l)	Chloride Cl (mg/l)	Nitrate No3 (mg/l)
1	0.01	0.09	Nd	0.001	2.0	7.0
2	0.04	0.19	0.01	0.001	1.0	8.0
3	0.06	0.08	Nd	0.001	2.0	5.0
4	0.05	0.10	0.00	0.002	2.0	10.0
5	0.06	0.09	0.00	0.002	2.0	7.0
6	Nd	0.05	Nd	0.001	2.0	6.0
7	0.13	0.17	0.08	0.005	2.0	7.0
8	0.03	0.08	0.00	0.002	3.0	1.0
9	0.03	0.46	0.04	0.001	2.0	5.0
10	0.05	0.11	0.08	0.003	2.0	2.0
11	0.08	0.14	0.09	0.003	2.0	6.0
12	0.12	0.05	0.11	0.004	2.0	2.0
13	0.07	0.06	0.06	0.003	2.0	3.0
14	0.06	0.07	0.05	0.002	2.0	0.0
15	0.03	0.04	0.03	0.001	1.0	1.0

Nd – Not detected

The results of a study on two tributaries to the Ogun River, the Ewekoro and Onijanganjangan rivers, are presented in Tables 3 and 4. Average concentration values obtained from the Ewekoro River indicate that, as well as  $\text{CaCO}_3$ , silicate is also predominant. Calcium carbonate and silica are from silicon dioxide; tricalcium silicate ( $3\text{CaSiO}_2$ ) and dicalcium silicate ( $2\text{CaSiO}_2$ ) are used in cement manufacturing (West African Portland Cement Plc.) in the area. Effluent runoffs from the mining and industrial premises are channelled into the Ewekoro River. Results of average concentration values obtained from the Onijanganjangan River (Table 4) also indicate that calcium carbonate and silica are dominant, but in far lower quantities than in the Ewekoro River. The Onijanganjangan River is also being polluted by effluents from some other industries located close to the river. The Ewekoro and Onijanganjangan rivers join the Ogun River at locations about 5 km apart.

**Table 3. Average concentration values at three points along the Ewekoro River.**

Station	Fe (mg/l)	Al (mg/l)	Si (mg/l)	Ni (mg/l)	Cn (mg/l)	Zn (mg/l)	Ca (mg/l)	$\text{CaCO}_3$ (mg/l)
A	0.04	0.03	0.51	0.227	0.007	0.30	50	125
B	0.077	0.003	0.45	0.013	0.010	0.30	60	150
C	0.06	0.000	0.46	0.00	0.000	0.30	61	152

**Table 4. Average concentration values at three points along the Onijanganjangan River.**

Station	Fe (mg/l)	Al (mg/l)	Si (mg/l)	Ni (mg/l)	Cn (mg/l)	Zn (mg/l)	Ca (mg/l)	CaCO <sub>3</sub> (mg/l)
A	0.053	0.007	0.500	0.227	0.004	0.267	30	75
B	0.083	0.000	0.483	0.033	0.007	0.200	17	43
C	0.230	0.000	0.427	0.053	0.007	1.000	17	42

A summary of the results of trace metal concentrations in the surface sediments is presented in Table 5.

**Table 5. Concentrations of acid-leachate (non-residual) trace elements (mg/kg dry weight) in surface sediments of specific effluents in Lagos Lagoon.**

Samples	Cadmium	Lead	Nickel	Vanadium	Chromium	Copper	Zinc	Iron
1	0.04	4.4	6.5	4.8	4.2	1.3	43.1	26217
2	0.02	1.9	1.1	1.5	0.6	1.6	16.3	1902
3	0.013	6.3	8.9	16.9	5.1	5.2	53.4	18727
4	0.09	4.9	3.3	12.3	1.8	3.8	36.7	7481
5	0.02	1.1	0.6	1.8	0.3	0.9	8.3	734
6	0.12	0.6	0.3	1.3	0.5	0.6	7.3	1166
7	0.26	40.6	5.6	23.9	7.2	9.0	227.7	8236
8	0.39	29.4	8.5	27.2	8.5	9.7	174.0	5637
9	0.03	0.8	3.6	2.7	2.3	1.2	19.1	8439
10	0.11	3.3	12.6	18.9	7.9	6.9	67.3	31375

Iron has the highest concentration of followed by manganese lead, nickel and zinc. While most of the iron and manganese may have come from the erosion of laterite crust predominant in the adjacent drainage basins (Ogun and Oshun river basins), the same cannot be said for lead, nickel, zinc and copper. High concentrations of these metals in some tributaries of the Ogun River can be attributed to untreated effluents from the galvanizing paint, textile and beverage industries scattered within a distance of less than 30 km from the lagoon. Ajao *et al.* (1996) found that high concentrations of cadmium, nickel, vanadium, chromium, copper and mercury come from inputs of untreated domestic sewage, municipal garbage, wood shavings and industrial waste waters from factories located on the shores of the lagoon. Though not properly documented, it is assumed that inputs of minerals and nutrients received by the coastal waters have been affecting the fragile aquatic environment and might have been responsible for the rapid decline of economic fishing from the lagoons. An informal survey among the fishing communities also revealed that fishermen are now venturing into open ocean waters beyond the lagoon environment to obtain viable catches.

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#### 4.14 Impacts of proposed dams on the Thukela estuary and inshore marine environment, KwaZulu-Natal, South Africa

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##### Introduction

South Africa is a dry country with a national rainfall average less than 500 mm. This is about half the global average. Rainfall is patchy and variable, declining rapidly from peaks of *ca.* 1,250 mm *per annum* in parts of the east to less than 200 mm in the extreme west. Areas of high water demand do not coincide with areas of high availability with the result that virtually all major rivers are dammed and South Africa is one of the world's leaders in techniques of inter-basin transfer. Present forecasts indicate that despite innovative techniques in relation to the use of national precipitation, demand will outstrip supply in the next 10 to 20 years. It is probably fair comment that the water-associated problems faced by the country revolve primarily around availability of the resource rather than simply water quality, although water pollution problems do exist and salinisation and eutrophication are locally significant.

In the coastal zone, many estuarine systems have been affected through physical development of the banks and floodplains including inconsiderate placing of road, rail and bridge systems and the development of harbours in estuaries at East London, Durban and Richards Bay. Water quality can be a problem in these environments, but the biota of estuaries and coastal water bodies is still surprisingly rich even in harbour areas. Inshore water quality, despite the presence of marine outfalls, is typically high as a result of the generally narrow continental shelf, the high energy, wave-washed coastline and the associated strong currents all of which combine to generate high dispersive powers. Marine pollution events are primarily the result of periodic but relatively uncommon oil spills.

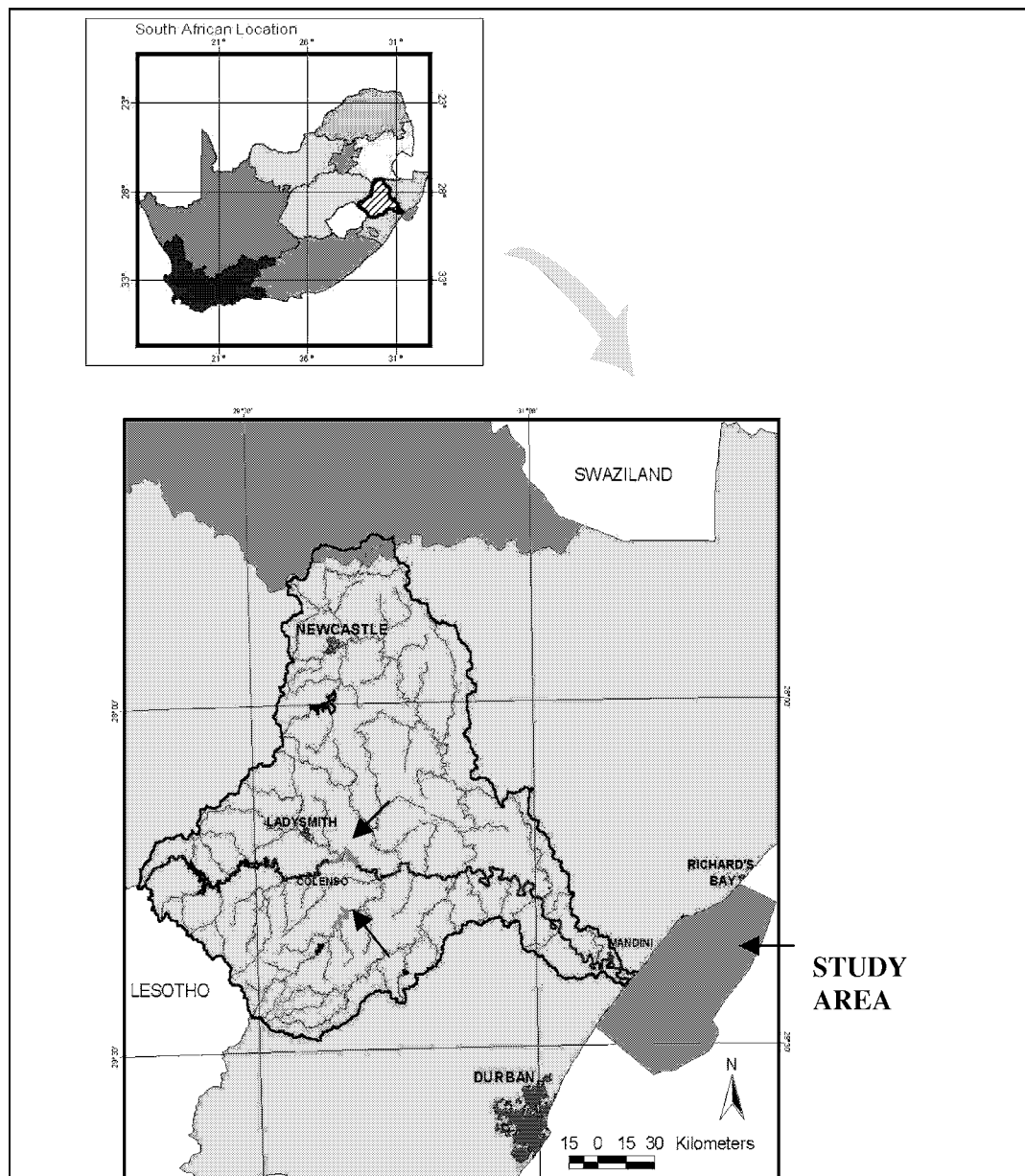
Arguably one of the greatest threats faced by South African inland waters and estuaries at present arises out of the demand for fresh water. This has resulted in the construction of large numbers of dams which have greatly modified natural flow patterns. Concomitantly there have been major changes in environmental legislation which now recognizes the significance of minimum flow levels in rivers for the functioning of these ecosystems. Simultaneously there has been an increasing appreciation of the significance of freshwater inputs into estuaries and most recently the significance of freshwater inputs into the inshore marine environment. These concepts are now becoming embodied in legislation. The South African Department of Water Affairs and Forestry (DWAF), which formerly concerned itself with landlocked freshwater bodies, now finds itself at an interface between the freshwater and marine environments and having to concern itself with the potential environmental impacts of dams in the Thukela catchment on the Thukela Banks, the only significant coastal shelf area in the sub-tropical part of the country. Although there are some impoundments, the bulk of the Thukela catchment remains undammed and the present proposals for two dams represent potential significant effects on the system. This study was therefore undertaken with the aim of assessing the potential ecological and economic impact of these dams on the coastal and shelf environments. The study is ongoing and the planned date of completion of this phase is the end of July 2000.

##### The Thukela system

The Thukela (Tugela) River catchment (Figure 1) lies on the east coast of South Africa in the province of KwaZulu-Natal. The area has the distinction of having one of the steepest gradients in the world, rising from sealevel to the Drakensberg plateau at an altitude of *ca.* 2,000 m, with peaks of *ca.* 3,000 m, within a distance of 180 km from the coast. This mountain massif is the country's major watershed.

The catchment of the Thukela has an area of 29,100 km<sup>2</sup> and a Mean Annual Runoff (MAR) of *ca.* 4 600x10<sup>6</sup> m<sup>3</sup>. It is the largest eastward flowing river in the country being exceeded only by the Orange-Vaal system which rises on the same plateau but flows westwards to the Atlantic Ocean. The Thukela source

lies at an altitude of 3,100 m at a point 250 km from the coast. Along its 405 km course it flows through an incised bedrock channel within a narrow floodplain never more than 1 km wide.



**Figure 1. The Thukela catchment and study area.** The proposed dams are arrowed.

The average annual sediment load is  $6.79 \times 10^6 \text{ m}^3$  of which  $1.02 \times 10^6 \text{ m}^3$ , or roughly 15% is bedload. Accelerated erosion occurred from the 1930's onwards, due, depending on the authority quoted, to bad farming practices or climatic factors. Present trends are towards less erosion.

Flooding is a characteristic of virtually all South African rivers and major floods were recorded in 1893, 1925, 1984 and 1987. The peak flood volume in the 1925 event reached 15,100 cumecs and a total sediment discharge of  $42.8 \times 10^6 \text{ m}^3$  or nearly six times the annual average. 60% of the sediment was derived from channel scour and 40% from the catchment.

The Thukela River lies in a summer rainfall area. Floods in September at the end of the austral mid-year dry season carry more sediment than floods in the tropical cyclone season (January-February). The catchment straddles the zones influenced by sub-tropical, frontal systems and tropical cyclones which peak in September and December-March respectively. Both weather systems can produce significant floods.

The September 1987 event was caused by a frontal system and caused a peak discharge of 10,500 cumecs. The tropical cyclone of March 1925 generated a peak of 15,100 cumecs.

The geological interpretation of the appearance of the river course is that extreme flood events are responsible for channel formation. The regional maximum flood has been calculated at 20,000 cumecs and the estimated sediment load during such an event has been estimated at several orders of magnitude higher than the 1987 figure. This would make such extreme events highly significant in the sediment dynamics of the shelf. Flood conditions result in major sediment efflux and a plume extending 3-5 km offshore and up to 15 km northwards with a limited extent to the south because of the prevailing northerly long shore drift. Two of the six sub-catchments of the system will be affected by the proposed dams and these are responsible for 40% of the total discharge and 25-30% of the total sediment load.

The Thukela estuary is dominated by river flow, thus qualifying it as a "river mouth" rather than a true estuary. The northern limit of the estuary mouth is fixed by a rocky promontory towards which the mouth tends to meander. The normal cycle is for a flood to scour the barrier, after which the barrier begins to re-establish itself, usually with the mouth located to the south side of the estuary. It then begins to migrate northwards under the influence of longshore drift until again breached. A shallow, braided, sandy channel forms during low-flow conditions and the mouth may close. The mouth is typically closed for about 5% of the time.

The coastline south of the mouth consists of a Holocene beach backed by a stabilised dune which forms part of the river mouth barrier. Beaches are narrow and controlled by bedrock outcrops. This contrasts strongly with the coastline to the north, which is one of only three accretionary areas along the South African coastline. The prograding coastal zone has given rise to a beach ridge plain characterised by wide beaches which grade into a series of low, shore-parallel, aeolian sand dunes. The accretion process dates back to the earliest photographic records of 1937 and probably to 5 000 B.P. Recent records show that after 1937 there was an erosion period during the drought years of 1978-83 coinciding with a strong El Nino. Coastal retreats up to 11 m/yr were recorded. During 1957-1960, the end of the 1953-61 wet period, the process was reversed and progradation in excess of 30 m/yr was recorded.

There is relatively little industrial development in the catchment, where human activities are mainly agricultural and pastoral. There is consequently relatively little industrial pollution and the major anthropogenic effects on the river come about through water abstraction and the still controversial effects on rates of soil erosion.

### ***The Thukela Shelf***

The south-east African continental shelf is generally narrow, being about 12 km wide off Durban but widening to more than 45 km off the Thukela River (Figure 2). Much of this shelf is derived from sediments from the Thukela River. A feature of the shelf is a series of submerged aeolianite outcrops which represent submerged coastal dune cordons, formed during lower Pleistocene sea levels which were drowned during subsequent Holocene transgressions. The shelf break is at approximately 100 m depth.

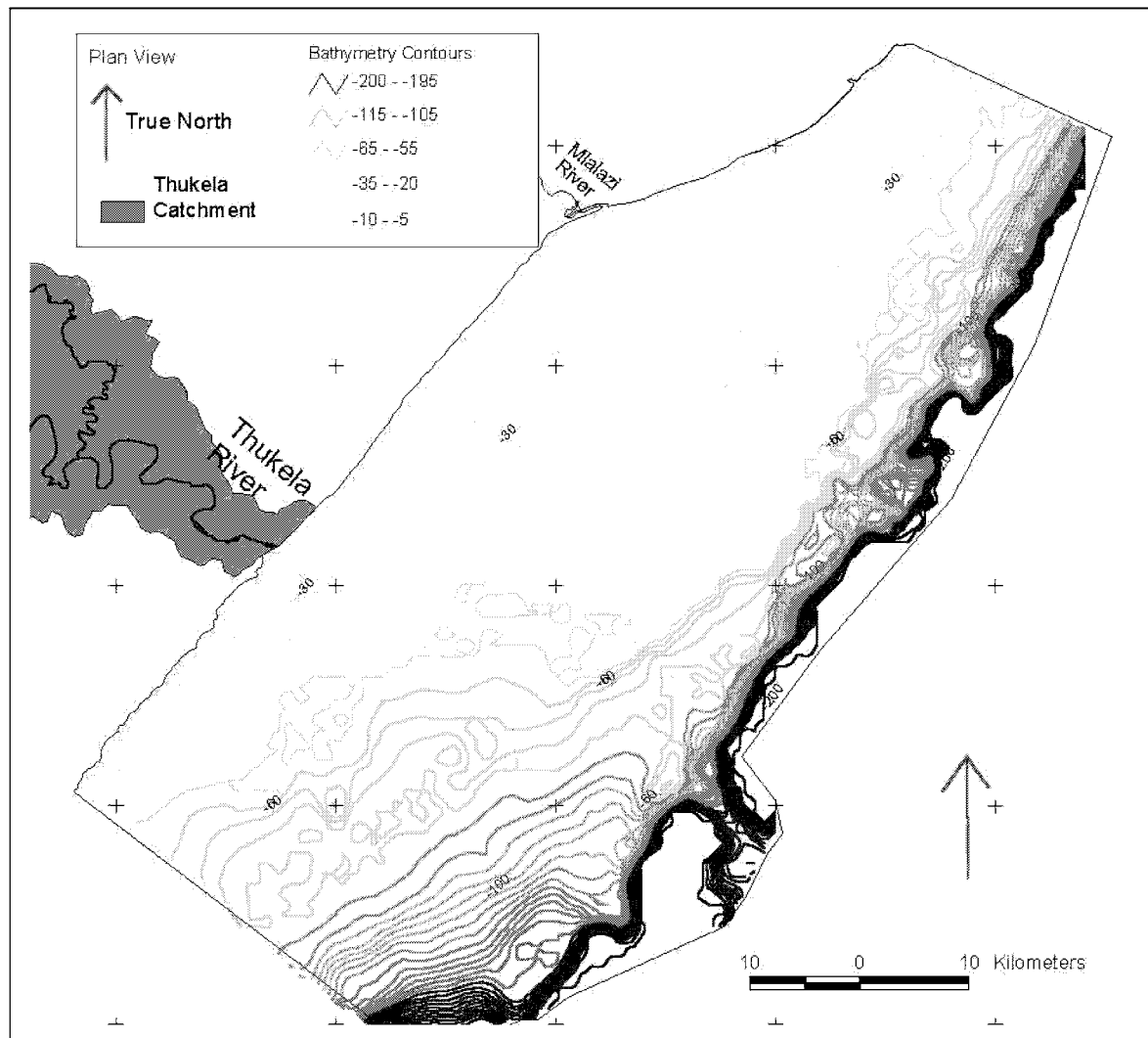
The southern part of the shelf is dominated by terrigenous sediment; it has the thickest sediment accumulation and has extensive flat areas. The northern part of the shelf is more uneven with a greater proportion of reef areas. The influence of the Thukela River on the shelf is most apparent during summer rains via the silt plume. Slight salinity reductions can be detected offshore.

The most important oceanographic feature of the area is the southward flowing Agulhas current. This is a major western boundary current with a mean width of 100 km and speeds of  $> 2.5 \text{ m.sec}^{-1}$ . Its depth has been traced to 2 500 m.

In assessing the potential effects of the dams on the coast and shelf it was realised that these could be modified or over-ridden by climatic changes. Wet and dry phases are products of prevailing climatic factors which have been shown to have major effects on the coastline north of the Thukela. A sea level rise of 20



cm is forecast in the next 35 years and 1.5 m in the next century. Available estimates indicate a consequent loss of 25 m of shoreline in the next 100 years. Projected climatic changes suggest that the local climate will become more dominated by tropical cyclonic weather. Changes in predominant wind patterns could reverse current conditions and foster accelerated erosion of the presently accreting beach zone. More cyclonic weather could however produce fewer swells, moving less sediment offshore and leaving it for fair weather waves to move it inshore, thereby favouring beach progradation.



**Figure 2. Bathymetry of the Thukela Bank.**

### ***Effects of the proposed dams on the coastal and shelf environments***

#### ***Physical effects***

The anticipated scenarios are as follows. Dam building will cause a short-term increase in the sediment load. In the longer term, however, the dams will affect the outflow and sediment input from 30% of the catchment. Floods will be attenuated and sediment output reduced. At the same time climatic change appears to be directed towards a slowing-down or halting of coastal progradation. Sediment retention by dams would accentuate this process.

It is expected that any dam-induced changes in the coastline will extend progressively northwards from the mouth and the effect(s) will be greater during dry phases than wet. Estimated distance and time scales

indicate that effects in the area up to 13 km north of the Thukela mouth will be noticeable within 10 years and up to 30 km north within the next 50 years.

Effects on the shelf are less certain. The shelf-coastline system is in dynamic equilibrium and any changes in one component will be reflected in others. The following are two of the presently significant expected changes:

1. Muddy areas of the Bank are expected to grow at the expense of more sandy areas.
2. A sediment decrease will result in the exposure of more sub-tidal reef.

#### Ecological effects

An assessment and forecasting of these effects is being attempted on the basis of the anticipated geomorphological changes. As the study is ongoing only results available to date are summarised here.

The 20-45 km wide Thukela Bank and the adjoining coastline provide a unique environmental combination in the South African context as it is the only shelf area and prograding beach on the east coast of the country. The frequently turbid conditions associated with the output of the Thukela River and the extensive areas of muddy sediments contrast with much of the rest of the east coast where the continental shelf generally extends less than 12 km offshore and the water, especially to the north, is clear enough to support the country's only significant coral growth areas. The muddy sediments of the Bank are interspersed with the submerged aeolianite reef described earlier and the combination of the two habitats provides significant line fishing grounds and the only shallow water penaeid prawn trawling grounds in the country.

The sandy beaches to the north of the Thukela are likely to become coarser, favouring some benthic species but greater significance probably lies in the reduction of detrital inputs which are important in the generally oligotrophic conditions of the east coast of South Africa. The effects of reduced sandy beach productivity are difficult to predict.

The only rocky shores in the possible impact area lie south of the Thukela mouth. High densities of brown mussels *Perna perna* occur in the vicinity and concern has again been expressed that a reduction in the detrital input could adversely affect inter-tidal filterfeeders. The dependence of rocky-shore filter feeders on terrestrially derived detritus has been established elsewhere in the province. Both oysters and mussels are harvested but the extent of any impact and the possible economic consequences are uncertain.

Of potential significance to subtidal reef communities are the factors mentioned above plus possible reduced turbidity which could favour corals and greater primary productivity in the water column as well as from fixed algae. Line fisheries dependent largely on reef fish are locally important at present. Changes in fish community composition are possible with a shift away from turbid water species to those favouring clearer water. Greater water clarity would also favour diving activities, especially spearfishing. The likelihood of turbidity changes and the direction of change remain, however, as moot points.

The forecast increase in total area of soft sediments presumably would favour species associated with such habitats. It would be important to establish whether sustained input of fine sediments would be accompanied by inputs of nutrients and detritus as it appears that areas off the Amazon and the Fly River of Papua New Guinea rely heavily on riverine inputs. The prawn trawl fishery is associated with muddy sediments and it might be expected that an increase in the area of this type of habitat would favour these species and ultimately the fishery. It is not certain, however, that a simple increase in the type of physical habitat favoured by the prawns would result in an increase in numbers.

The pelagic system would be altered by any change in turbidity. Decreased turbidity would enhance phytoplankton production, assuming that nutrient levels remain adequate. Unfortunately there are no measures of the relative inputs of nutrients derived from the low levels of upwelling that occur in the region and that derive from riverine inputs.

## Conclusions

An unresolved problem is centred around the relative importance of flood events and average seasonal flow levels. The contrast between MAR's and extreme flood events has been emphasised and it is clear that one major flood can discharge more water and transport more sediments than might be found in an average year. Data from the offshore prawn trawl fisheries show that catches rose and remained high for three years following the flood caused by Cyclone Domoina in January 1984.

As far as the coast is concerned, there is relatively little infrastructure development along the coast in the main impact area to the north of the Thukela mouth, although the prograding beaches and the backing dunes to the south of the Mlalazi River (Figure 2) are backed by superb examples of coastal dune vegetation succession from beach pioneers to climax dune forest.

At this stage, possible biotic responses to environmental changes resulting from changed sedimentation patterns on the coast and shelf can be surmised although, as mentioned above, the contrasts and relative significance of the effects of normal flows and flood events require clarification. Equally the comparative effects of the dams on normal flows and flood events requires clarification. Changed water flow patterns have been considered very largely in terms of associated sedimentological events and processes rather than in terms of transport of other materials or the input of fresh water *per se*. This emphasis can be justified on the basis of present knowledge which suggests that the river is not a significant source of pollutants for the coastal zone and that this situation should not change in the short term. This comes about largely because water storage in the Thukela catchment is intended for transfer and use in the Vaal River basin and the Johannesburg-Pretoria complex rather than in the Thukela basin where industrialisation is minimal in comparison.

The major unanswered question at this stage relates to the extent and significance of carbon and nutrient input into the coastal zone and the shelf system. Available information on primary production is very scanty, but indicates generally oligotrophic conditions both in estuaries and offshore. This again raises the question whether the dams will significantly affect average flows as well as flood events or whether flood events are of such a magnitude that the dams are of little consequence.

#### 4.15 Water quality and nutrient fluxes within the Zambezi River system: a review

***Lindah Mhlanga***

##### Abstract

The water quality of the Upper Zambezi River is influenced by the Baroste Flood Plains and the Chobe Swamps that act as sediment traps such that the Zambezi River enters Lake Kariba as fairly clean water with a reduced sediment and nutrient load. DDT, metal and sewage contaminants have been detected in Lake Kariba but have not been assessed in the outflow. The outflow from Lake Kariba is richer in ionic composition than the Zambezi inflow. The mid-Zambezi tributaries, the Sengwa, Gwayi and Sanyati rivers, bring nutrient-rich water into the lake. The nutrients from these rivers are temporarily locked in the hypolimnion partly to be released into the Zambezi through turbine discharges. An estimated 5.2% of the phosphorus leaves the lake via the Zambezi. Orthophosphate, total phosphorus and nitrate-nitrogen losses from Lake Kariba are estimated to be 52,216 and 1,146 tonnes respectively. The Luangwa, Hunyani, Kafue and Musengezi rivers bring nutrient-rich water into the Zambezi and into Lake Cahora Bassa. Most nutrients and sediments are trapped within Lake Cahora Bassa. There is a need to determine how much of the nutrients are released into the Lower Zambezi and consequently into the sea. A routine monitoring programme is required to make a detailed assessment of nutrient fluxes between the Zambezi River catchment and the sea.

##### **Introduction**

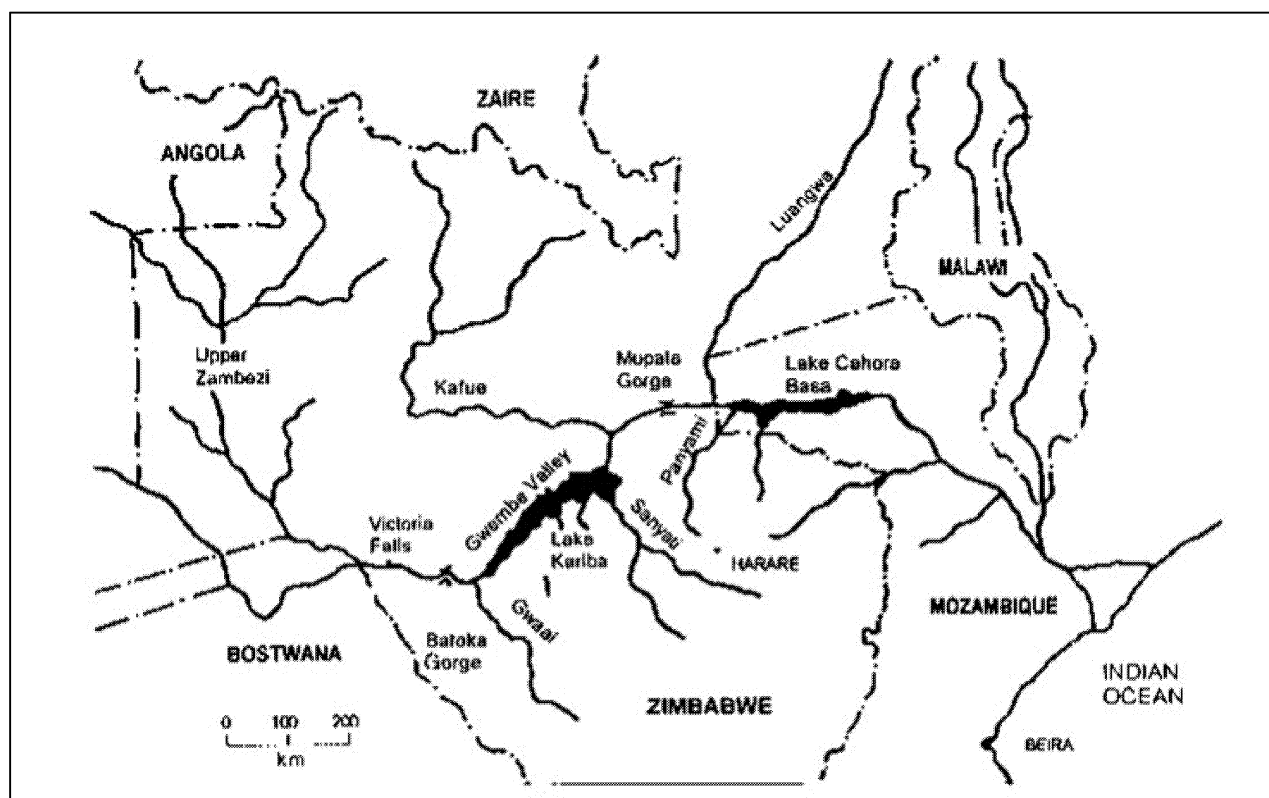
The Zambezi River, one of Africa's four major rivers, originates from a swamp at 1,400 m altitude along the Zaire-Zambia border (Balon and Coche 1974) and covers a catchment area of  $1.4 \times 10^6$  km<sup>2</sup> (Pinay 1988). It flows over a distance of 3,000 km, dropping in altitude from 1,400 m at its source in western Zambia to sea-level at its delta on the Indian Ocean coast, north of Beira in Mozambique (Masundire and Matiza 1995).

The Zambezi River basin is one of the most complex catchments in Africa and the most important watershed in southern Africa (Balek 1971; Balon and Coche 1974). The catchment spans eight countries and the proportion of the catchment is 18.3%, 2.8%, 7.7%, 11.4%, 1.2%, 2%, 15.9% and 40% in Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe respectively (Masundire and Matiza 1995).

The course of the Zambezi River is composed of three ecologically distinct zones, the Upper, Middle and Lower Zambezi (Balon and Coche 1974). The Upper Zambezi basin covers an area of 513,000 km<sup>2</sup> (excluding the Okavango system) through which the Zambezi meanders over 1,078 km between its headwaters in northern Zambia and Victoria Falls (Pinay 1988). The Middle Zambezi stretches 853 km from Victoria Falls to the Cahora Bassa dam in Mozambique and the Lower Zambezi covers the remaining 593 km to the Indian Ocean in Mozambique (Balon and Coche 1974). These sections are distinct geographical and biological entities (Masundire and Matiza 1995).

During its course, the Zambezi River crosses a number of flat plains and is interrupted by steep sections of rapids and falls. The middle course of the Zambezi River has been interrupted by two artificial impoundments: Lake Kariba and Lake Cahora Bassa, which are 5,364 km<sup>2</sup> and 2,739 km<sup>2</sup> respectively.

It is assumed that water quality and nutrient fluxes within the Middle Zambezi, especially Lake Kariba and Lake Cahora Bassa, affect processes further downstream and into the Indian Ocean - i.e. the Zambezi River is a pathway of dissolved and particulate materials between the Zambezi basin catchment and the Indian Ocean. However, information about its influence on marine resources on the Indian Ocean coast was not obtained. This review discusses the water quality of the Zambezi River including the influence of the tributaries on the water quality and the effect of the Zambezi River on the coast environment.

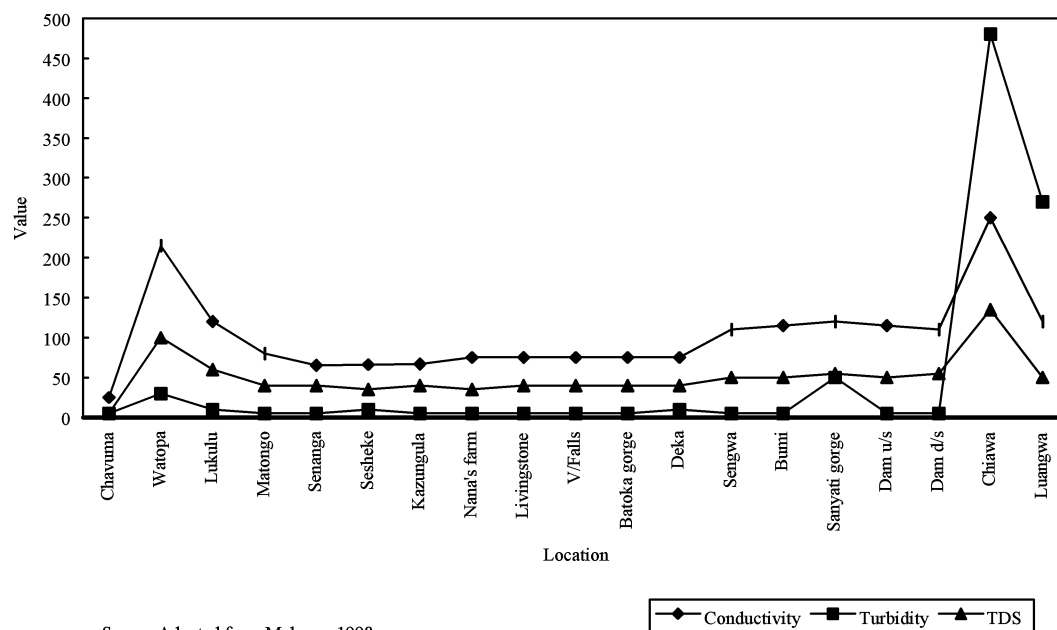


**Figure 1. The Zambezi River.**

### **Limnological characteristics of the Middle and Lower Zambezi**

The physico-chemical status of the Middle and Lower Zambezi was assessed prior to the closure of the Cahora Bassa dam (Hall *et al.* 1977). An assessment in 1973 and 1974 showed that the water quality of the Middle Zambezi is mainly determined by the Kariba dam with the Kafue River, which enters the Zambezi below the Kariba dam (see Figure 1), playing a minor role (Hall *et al.* 1977). The concentration of dissolved metals in the Zambezi River was mainly determined by the outflow from Lake Kariba and in the Shire River.

Water quality of the Zambezi River from Chavuma to Luangwa has been monitored over three years (1995 to 1998) (Mukono 1998). The variation in physico-chemical parameters of the Zambezi River from Chavuma Falls (Upper Zambezi, Zambia) to Luangwa and Zambezi River confluence (on the border with Mozambique, just above Lake Cahora Bassa) is shown in Figure 2. Conductivity, turbidity and total dissolved solids levels were high between Chavuma Falls and the Lukulu River. This section falls within the northern highlands of Zambia. Conductivity, turbidity and total dissolved solids increased from 25 $\mu$ S, 5, and 5 mg/l to 215 $\mu$ S, 30 and 100 mg/l respectively between Chavuma Falls and Watopa. There is a notable decrease in these parameters as the river flows through the Barotse Flood Plains and the Chobe Swamps (Upper Zambezi). The Barotse Plain and the Chobe Swamps act as sediment traps (Balon and Coche 1994; Mukono 1998). The Barotse Flood Plains reduce the dissolved solids, conductivity and turbidity by 55%, 65% and 80% respectively (Mukono 1998). The silt load is reduced to relatively low levels before the river enters Lake Kariba.



**Figure 2. Variation in conductivity ( $\mu\text{S}$ ), turbidity and total dissolved solids ( $\text{mg/l}$ ) along the Zambezi River.**

The values remain relatively constant between Matongo and Batoka Gorge (just downstream of Victoria Falls). The Zambezi River picks up mainly finer sand between the last sediment area (Chobe Swamps) and the lake because the geological formations comprises mainly of hard Batoka basalt (Balon and Coche 1974). A general increase of these parameters at river stations within Lake Kariba (Sengwa, Bumi and Sanyati Gorge) indicates the influence of the seasonal Middle Zambezi catchment rivers: the Sengwa, Gwayi and Sanyati rivers. The Sanyati River drains the upland Zimbabwe farmlands and brings down to Lake Kariba highly mineralized water (Balon and Coche 1974). Conductivity, total dissolved solids and turbidity are higher in the outflowing water than in the inflow.

The average outflowing water is proportionally richer in average ionic composition than the Zambezi River water entering the lake (Balon and Coche, 1974). Peak values were observed at Chiawa and Luangwa rivers before entering the Cahora Bassa dam.

### Estimates of N and P inputs into Lake Kariba

The preliminary estimates of nitrates and orthophosphates inputs into the lake from rivers are  $13.6\mu\text{g l}^{-1}$  and  $21.8\mu\text{g l}^{-1}$  respectively (Magadza *et al.* 1986). After assuming the same values for the Zambezi River and an annual inflow of  $47\text{ km}^3$ , nitrogen and phosphorus loading into the lake were estimated as 704 tonnes and 1,025 tonnes respectively (Magadza *et al.* 1986). The N:P ratio in the lake is 1:1.45. More phosphorus than nitrogen enters the lake. 5.2% of the phosphorus was estimated to leave via the Zambezi, 12.8% as harvested fish, 15% as particulate phosphorus while 67% is retained in the lake (Magadza *et al.* 1986).

The outflow from Lake Kariba was proportionally richer in calcium, potassium and fixed carbonates (Balon and Coche 1974). The lake enriches the original river water by ion exchange rather than by concentration and dilution (Balon and Coche 1974).

### Nutrients in the Zambezi River below the Lake Kariba turbines

Magadza *et al.* (1986) made preliminary estimates of nitrates, phosphates and total phosphorus from Lake Kariba via the Zambezi. The estimates were based on preliminary data on phosphorus and nitrogen measurements in Lake Kariba in 1986. Nutrient losses via the Zambezi River were calculated from river

flow data. A loss of approximately 52 tonnes of orthophosphate per annum was estimated. Through extrapolation using available data, total phosphorus losses were estimated at 216 tonnes per annum. The bulk of the total phosphorus is lost as particulate phosphorus in form of silt. An estimate of 1,146 tonnes of nitrate-nitrogen is lost via the Zambezi. The molar ratio loss of PO<sub>4</sub>-P:N and T-P:N loss via the turbine discharge was estimated to be 1:51 and 1:12 respectively.

### Lake Cahora Bassa

The Cahora Bassa dam, which has created Lake Cahora Bassa, the second largest reservoir on the Zambezi River, is located approximately 220 km downstream of the Kariba dam. 71% of the water in the lake is supplied by the Zambezi River and consists of water discharged from the Kariba dam while the Kafue and Luangwa rivers provide 10% and 18% respectively (Gliwicz 1984).

Activities upstream have a significant impact on the limnology of Lake Cahora Bassa, especially within the Lake Kariba catchment. Lake Kariba is the major source of orthophosphate to Lake Cahora Bassa (Hall *et al.* 1977). The outflow into the Zambezi from the turbines (at 485 m.a.s.l. average operating level) is drawn from around 20 m depth which is the hypolimnion of the lake (Coche 1968). Phosphates carried into Lake Kariba by the main tributaries are temporarily locked (trapped) in the hypolimnion. They become available at overturn at the end of July when they are released into the Zambezi. The discharge of hypolimnetic water from the dam increases the nutrient load of the river downstream (Begg 1973) and has been noted to produce a nutrient peak in Cahora Bassa (Hall *et al.* 1977). A recent assessment showed that discharged water below the Lake Kariba dam wall was richer in ammonia, nitrates and total nitrogen with concentrations of 72.3, 34.8 and 790.4 µg l<sup>-1</sup> respectively. The concentrations of ammonia, nitrates and total nitrogen above the dam were 31.3, 4.8 and 748.5 µg l<sup>-1</sup> respectively.

A survey in July 1994 assessed the water quality of Lake Cahora Bassa (Mandima 1997). Recurrent droughts between 1981 and 1992 led to reduced inflows in the dam. Nitrogen and phosphorus levels had both declined from the levels recorded in the 1970s and 1980s (Mandima 1997; Table 1).

**Table 1. Concentration of chemicals recorded in Lake Cahora Bassa.**

Chemical	1970s	1980s	1994
Nitrate-nitrogen µg l <sup>-1</sup>	70	140	211.6
Ammonia µg l <sup>-1</sup>	170	n.d	26.8
Orthophosphate µg l <sup>-1</sup>	80	75	4.9
Total phosphorus µg l <sup>-1</sup>	n.d	n.d	32.7

Source: Mandima 1997

This was attributed to reduced inflow of water to the lake during the severe droughts that affected the catchment area in the preceding decade. The mean concentrations of ammonia and total nitrogen in the dam were 26.8 µg l<sup>-1</sup> and 1 267 µg l<sup>-1</sup> respectively. Orthophosphate ranged from 2.0-9.5 µg l<sup>-1</sup>. Changes in nutrients reflect the impact of drought (Mandima 1997).

The decline in the eutrophic status affected planktonic organisms. Species abundance declined, except for *Bosmina longirostris* (Mandima 1997; Table 2). This could have also affected the marine fisheries.

**Table 2. Abundance (number m<sup>-3</sup>) of plankton species in Lake Cahora Bassa.**

Zooplankton	1980s	1994
<i>B. longirostris</i>	1 423	3 172
<i>Diaphanosoma</i> (sp.)	2 827	513
<i>Calanoida</i>	6 560	707
<i>Cyclopoida</i>	17 998	422
<i>Keratella</i>	1 600	293

Source: Mandima 1997

Information on nutrient input and output in Lake Cahora Bassa would provide an idea of the nutrient contribution of the Zambezi to the marine environment.

### **Impact of the tributaries on the Zambezi River**

The major tributary rivers that influence the chemistry of the Zambezi are the Luangwa, Hunyani, Musengezi, Shire and Kafue rivers. The Luangwa, Hunyani and Musengezi drain into Lake Cahora Bassa. Information available on the water quality of the tributaries is limited to the early years. Tributaries to the Zambezi bring nutrient-rich water. Hall *et al.* (1976) observed that the Zambezi entering Mozambique is richer in inorganic nutrients than the pre-Kariba Zambezi (Zimbabwe). The outflow from Kariba in 1965 had lower inorganic nutrients than the Zambezi entering Mozambique (Coche 1968). This indicated that the Kafue River contributed a considerable quantity of nutrients. Major tributaries feeding the Zambezi River pass through sites of extensive mining activities. The Kafue River drains the entire copper mining region of Zambia and the Mazowe River drains the mining operations in the Shamva region of Zimbabwe. There is however, limited information on the impacts of mining on water quality.

The Kafue River basin covers 152,000 km<sup>2</sup>. The Kafue River carries the outflow of the man-made Lake Kafue. It is a major tributary that enters the middle Zambezi between Kariba and Cahora Bassa and it contributes 12% of basin flow at its confluence with the Zambezi River (Kasimona and Makwaya 1995). There are major industrial towns and centres located along the Kafue River.

The Luangwa river basin covers 165 000 km<sup>2</sup> and contributes 500 cumecs as mean annual run-off to the Zambezi basin at its confluence with the Zambezi (Kasimona and Makwaya 1995). Luangwa River joins the Zambezi just upstream of Lake Cahora Bassa. It contributes an estimated mean yearly sediment load of 8 million tonnes and is characterised by high turbidity and high sediment load that influences the water at its confluence with the Zambezi (Kasimona and Makwaya, 1995). Hall *et al.* (1977) noted that the Luangwa River is poor in ions than Zambezi and consequently it does not appreciably affect the chemical composition of the Zambezi main stream. However, in flood the Luangwa carries a heavy silt load that dramatically changes the transparency of the Zambezi (Hall *et al.* 1977).

### **Lower Zambezi**

The lower section of the Zambezi is from Cahora Bassa rapids to the delta on the Indian Ocean coast in Mozambique. The Shire River joins the Zambezi about 150 km from the delta. Land use activities carried upstream have a direct impact on the lower section. Although information may be available, none was obtained regarding the impact of water quality and nutrient fluxes on the ecology of the Zambezi delta.

The Shire River is another major tributary of the Zambezi. It joins the Zambezi downstream from the dam wall about 150 km from the sea. Shire is extremely rich in inorganic nutrients and exerts a considerable effect upon the Zambezi below their confluence (Davies *et al.* 1975). While information on the current physico-chemical status of Shire was not obtained, it is apparent that there has been an increase in its nutrient content as evidenced by the invasion of water hyacinth in Lake Malawi. Most of the dissolved salts transported by the Shire originate from Lake Malawi (Jackson *et al.* 1976) but some of the nutrients particularly phosphate and nitrate are also contributed by the soil of the section of the valley in Mozambique which is intensively farmed (Davies *et al.* 1975). The Shire has a significant influence on the chemistry of the Zambezi (Hall *et al.* 1977) and is the most important tributary of the Zambezi in Mozambique. Its water has a tremendous impact upon the chemistry of the Zambezi River water. It establishes a different nutrient regime downstream from its confluence with the Zambezi.

The Hunyani and Musengezi rivers drain agriculturally and industrially developed parts of Zimbabwe. They consequently contribute appreciable quantities of nutrients to the Zambezi. Assessments in 1974 (Hall *et al.* 1977) showed that Hunyani and Musengezi had conductivities of 350  $\mu\text{Scm}^{-1}$  and 506  $\mu\text{Scm}^{-1}$  respectively. Hunyani water was richer in bicarbonate, chloride, ammonia, nitrate, sodium and magnesium than the Zambezi water. Large concentrates of sodium, potassium, calcium, magnesium and phosphate occurred in Musengezi River.



The Zambezi delta which is rich in mangrove vegetation supports marine aquatic resources; fish shrimps, prawns and other sea resources. The ecosystem has been subjected to deforestation at a rate of 2.4% from 1972 to 1990 (SARDC CEP Factsheet 1998). Mangroves have been extensively cut for poles for construction of houses, firewood and timber for boats while their leaves are used for animal fodder. The impact of environmental degradation on marine fisheries and other marine resources has not been assessed.

## Discussion and Conclusion

The water quality and nutrient fluxes to the Zambezi River has been described in a generalised way because there is a general lack of information on nutrient losses from point and non-point sources. The information available is limited to objectives of specific studies. A detailed assessment of nutrient loads to the Zambezi (including Lake Kariba and Cahora Bassa dam) and the sea requires data on nutrient concentrations from major tributaries and hydrological data on water flow to the main river and the two lakes. The Zambezi River Authority is in the process of establishing a monitoring programme. This will be confined to the part of the Zambezi commonly shared by Zimbabwe and Zambia which comprises mainly the Upper and part of the Middle Zambezi up to Luangwa. To have a clearer picture of nutrient fluxes within the whole river system it may be necessary to include the lower Zambezi. This will enable impact assessment of upstream activities on the marine environment.

There are also monitoring programmes being carried out that will enable more detailed assessment of nutrient fluxes within the Zambezi River System. For example, the Environmental Council of Zambia is monitoring nutrient loads in the Lower Kafue.

The major environmental problems within the Zambezi valley that may affect nutrient fluxes to the sea include:

- ❑ Environmental degradation through unsustainable and destructive land and water use patterns.
- ❑ Poor watershed management, sewage and industrial pollution, drainage of wetland and water abstraction
- ❑ Flood regulation
- ❑ Rapid population growth which is currently estimated at 3% per year
- ❑ Deforestation resulting in increased soil erosion, sedimentation, siltation and siltation induced flooding
- ❑ High rates of urbanisation and industrial activity affecting water quality in the basin.

Lack of data makes quantification of nutrient fluxes from the river to the ocean difficult. Surveys are needed in the three ecological zones of the river in order to assess nutrient fluxes to the ocean, determine variations and assess the impact of the dams. The two dams on the Zambezi act as silt traps (Davies *et al.* 1975; Balon and Coche 1974). The estuary and delta area have both experienced a general decrease in the amount of silt reaching them (Davies *et al.* 1975). Such a decline in silt load may allow the incursion of the sea into the delta where normal sea erosion will no longer be countered by floodwater deposition of silt from the now regulated river. The major environmental concerns for the coastal zone are the impacts on the shrimp industry and on the mangroves.

In order to understand the effects of human-induced activities of the Zambezi River on the Indian coast there is need to generate relevant data. At present there is relatively little scientific information on the impact of the Zambezi on the seacoast. Investigations can be carried-out to generate data on:

- ❑ Effects of upstream impoundments and flood regulation on the Mozambique coast since the river has many artificial impoundments
- ❑ Impact of the cessation of silt transport to the Mozambique coast
- ❑ Impacts of the Zambezi basin dams on the shrimp industry of Mozambique at the Zambezi delta.

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#### **4.16 Human impact on groundwater quality along the Kenyan coast: A case study on an unconfined aquifer to the north of the coastal town of Malindi, Kilifi District, Kenya**

*N. Opiyo-Akech, D.O. Olago, E.W. Dindi and M.M. Ndege*

##### Abstract

Potable water is a scarce resource in the coastal parts of Kenya. Most of the water used in the larger coastal towns originates from inland sources. Mombasa, the largest city along the coast, gets most of its water from the Mzima springs, on the slopes of Mt Kilimanjaro. The waters from the inland sources are inadequate and are supplemented by groundwater. Most of the groundwater aquifers yield either saline or brackish water, and the few freshwater aquifers are currently in danger of being over-extracted or polluted. Studies are underway for ways to utilise the groundwater resources along the Kenya coast in a sustainable manner.

There are two types of aquifer along the coast, confined and unconfined aquifers. The area studied is a N-S oriented unconfined aquifer. It is in a V-shaped, clayey lagoonal depression bordered by Pleistocene sands on the west and Recent dune sands on the east. The freshwater aquifer in the area is the main source of potable water for the urban centres of Gongoni and Timboni and the main Mombasa Salt Works processing plant. The aim of the study was to look at the impact of sand harvesting, and possible saline contamination of the aquifer by activities at the nearby salt harvesting plant and by seawater intrusion. The major factor abetting pollution of the freshwater aquifer is the sand harvesting activity which exposes the aquifer to the atmosphere. Extension of the salt works closer to the aquifer field combined with high abstraction rates may also lead to saline water intrusion and contamination of the aquifer.

Key words: Freshwater aquifer - Sand harvesting - Salt harvesting - Pollution

##### **Introduction**

In developing countries, untreated water is the most commonly-encountered health threat and still causes an estimated 25,000 deaths a day - either because infected water is directly consumed or because its use leads indirectly to infection from vector-borne diseases such as malaria and bilharzia (UNEP/GEMS 1991). Water pollution in these countries has been accelerated by industrialisation and urbanisation, accompanied by poor waste treatment practices.

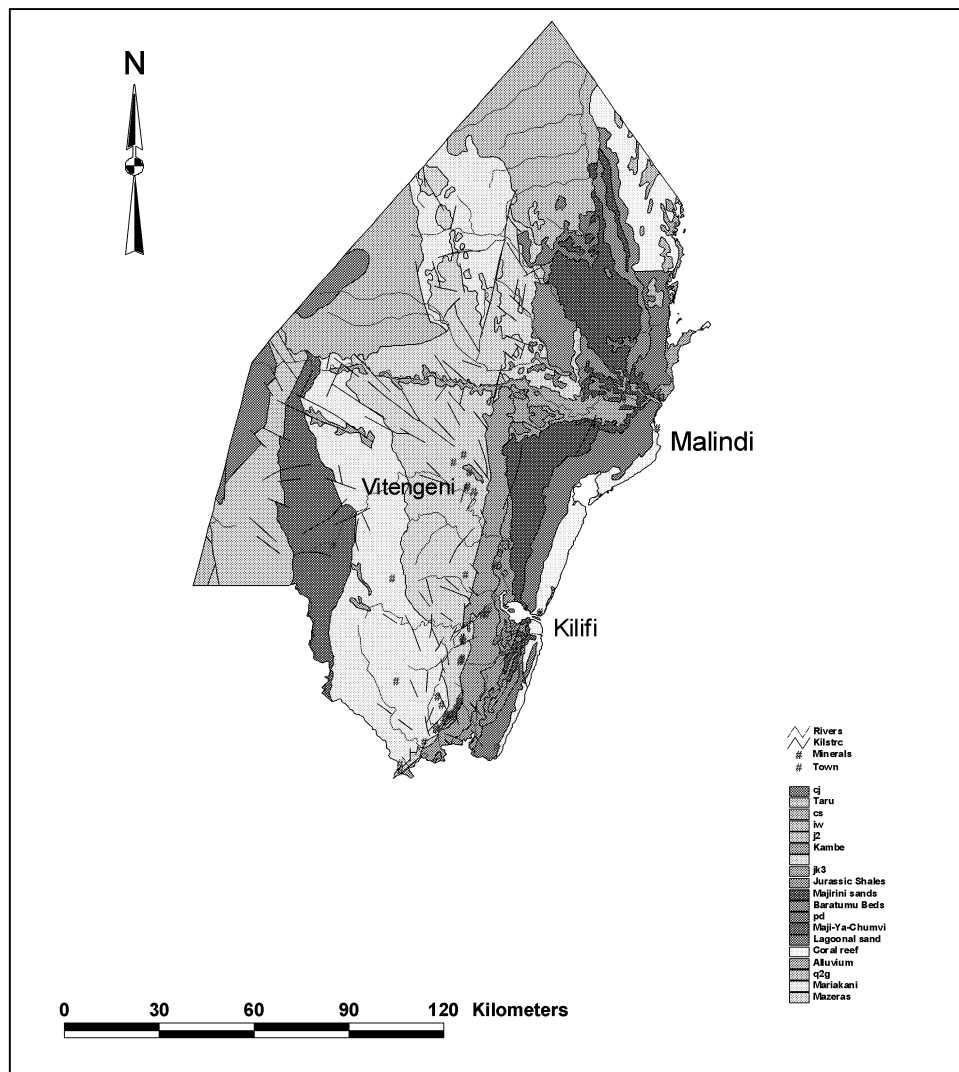
Today, over 300 million people in Africa do not have reasonable access to safe water, and even more lack adequate sanitation (UNEP 1999a). In addition, an estimated 80% of all diseases and over one third of all deaths in developing countries are caused by contaminated water and, on average, as much as one tenth of each person's productive time is sacrificed to water-related diseases (UNEP 1999a).

Most of the groundwater aquifers along the coast (confined and unconfined) are either saline or brackish. The few freshwater aquifers are now in danger of being over-extracted or polluted due to a number of factors, including urbanisation and the consequent increase in population, intensification of agriculture (particularly in watershed areas) and industrial growth. Due to the scarcity of fresh groundwater resources at the coast, most of the water used in the larger coastal towns originates from inland sources. Mombasa, the largest city along the coast, gets most of its water from the Mzima springs, on the slopes of Mt Kilimanjaro. This supply is inadequate and is supplemented by coastal freshwater aquifers. In most of the smaller towns along the coast, communities depend almost entirely on water from largely unconfined aquifers. Studies are therefore underway to look at ways and means of utilising the groundwater resources along the Kenya coast in a manner that:

- 1) is sustainable over the long term, and protects the resource;
- 2) maximises water-related benefits for the majority of people in a particular area;
- 3) addresses all significant human and ecosystem water needs; and
- 4) ensures the participation of all relevant parties in the water allocation process and at the appropriate level (UNEP 1999b).

## Brief review of coastal geology: Kilifi district

The rocks in the Kilifi district are characterised by sedimentary rocks ranging in age from the Permo-Triassic Duruma rocks comprised of Taru, Maji-Ya-Jumvi, Mariakani and Mazeras sandstones, the Jurassic-Cretaceous rocks represented by the Kambe limestones, the Tertiary rocks of the Baratumu, Marafa and Magarini formations consisting of sandstone intercalated with limestone and shale beds, with the youngest Magarini Formation composed of red unconsolidated sand rich in ferrous minerals. The Pleistocene rocks consisting of coral reefs and detrital sediments mark the upper end of the lithified sedimentary rocks in the area. All these formations dip gently eastwards and become progressively younger towards the coast (Figure 1).



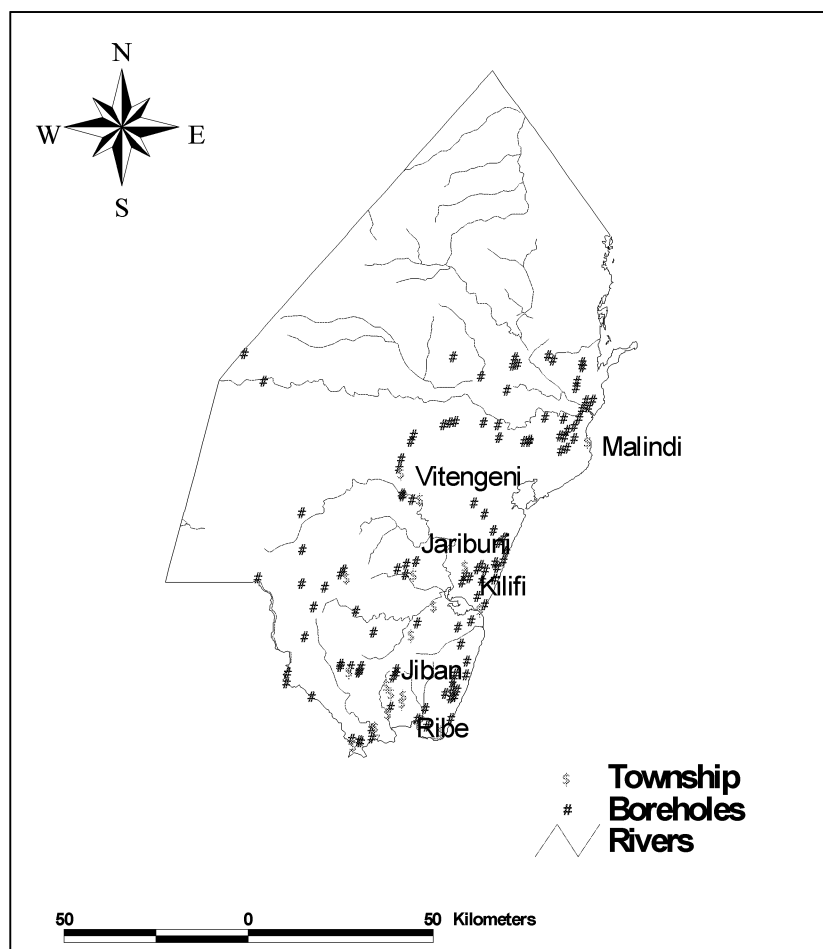
**Figure 1. Geology of Kilifi district.**

Geochemical analysis of soil and water samples indicate that the chemical composition of the soils and water in the area is greatly influenced by the mineralisation (JICA and MMAJ 1993) so that mineralisation and water quality are related. The largest mineral deposits of the area occur in the Kinangoni and Vitengi areas and are predominantly of argentiferous galena with marcasite, sphalerite, barite, chalcopyrite and arsenopyrite (Bugg 1982). Because the mineralization is to a large extent structurally controlled, and to a very large extent may have great impact in areas adjacent to the fault lines, the groundwater generally contains high levels of lead, zinc, copper and mercury. Therefore groundwater quality varies within the area

(Ongweny 1975) and boreholes are drilled without considering the geological structure and hydrogeochemistry of the area. This has had serious consequences. A lot of money has been spent to drill boreholes, but most of the boreholes contain poor quality water and are subsequently abandoned. There is also growing concern about pollution of groundwater from the recharge areas upcountry. The rivers are becoming more vulnerable to contamination from human activities such as mineral mining and waste disposal from developed centres upcountry (Davies 1994).

### Waterways in Kilifi District

Several large rivers drain into the Indian Ocean from the interior, for example the Tana and Sabaki rivers (Figure 2). These rivers undoubtedly recharge some of the coastal unconfined aquifers as they cut through the coastal plain sands before emptying into the Indian Ocean, particularly during high flood periods. No scientific investigations have, however, been carried out to examine the relationship between the fluvial inputs and unconfined groundwater aquifer recharge along the coastal zone.



**Figure 2. Waterways of Kilifi district.**

The Kenyan hinterland is becoming increasingly populated, and settlements, as well as agricultural and small-scale industrial activities (and related deforestation) are fast expanding along the formerly pristine river valleys. These have resulted in increased sediment load in the rivers draining to the sea, which can degrade the water quality, storativity and transmissivity of a freshwater aquifer, pollutants from increasing use of agricultural fertilisers, raw domestic and industrial sewage could pose a serious threat to such fluvial-linked unconfined aquifers in the long term.

Some large urban centres such as Nairobi and its suburbs are in areas with numerous waterways which eventually discharge into the larger rivers that drain into the ocean. Nairobi is already a major source of

pollution, and the Nairobi River, which drains into the Athi River east of Nairobi, is now virtually devoid of fish and macro-invertebrates and has high concentrations of faecal coliform, heavy metals, organochlorine pesticides, and solid waste amongst a myriad of other pollutants. Traces of some of these pollutants, particularly the persistent organic pollutants, may reach the ocean despite flushing/dilution by other relatively clean tributaries and natural processes of in-river degradation or sediment absorption, and affect the quality of coastal unconfined freshwater aquifers.

Where the near-surface, unconfined aquifers are far removed from fluvial sources and influences, the major recharge is from direct precipitation. The amount and quality of water retained in such aquifers is critically balanced between the prevailing climate/rainfall regime, geology and structures, the size of the recharge area, type of land cover, anthropogenic activities within the recharge area and abstraction demand.

### The study area

Gongoni-Fundi-Issa-Timboni is a N-S oriented, V-shaped, flat, lagoonal depression lying in the coastal plain of Kenya at an altitude less than 45 m a.s.l. It is characterised by clays, and is bordered by Pleistocene sands on the west and Recent dune sands on the east (Figure 3). The average annual rainfall is *ca.* 850 mm/yr (Survey of Kenya 1977).

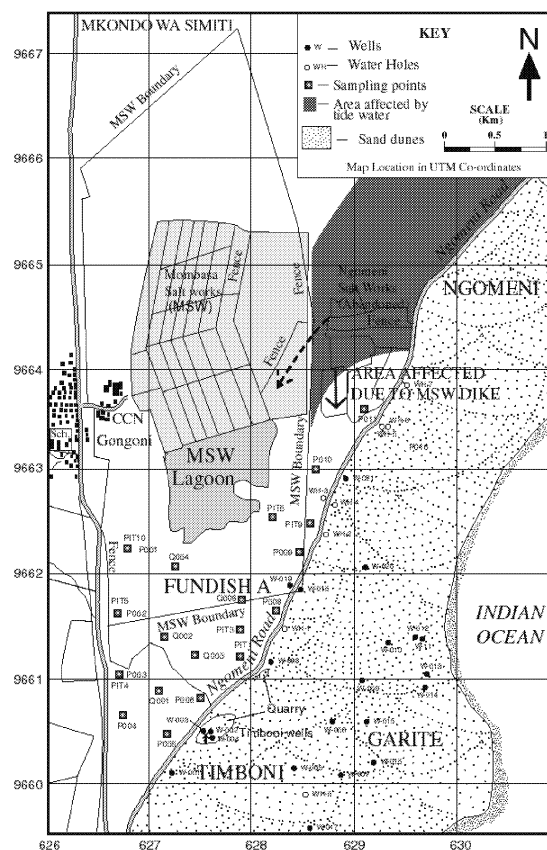


Figure 3. The study area.

Because it lies more or less at sea level, the lagoonal depression experiences daily incursions of seawater during high tide in the north-eastern sector (Figure 3). The lagoon typically ponds in most sectors following heavy rains, but generally dries out during the dry season. Consequently, it can be regarded as a seasonal swamp. Vegetation is mainly grassland/bushland, with negligible tree cover.

There are numerous water points dotted along Ngomeni Road which marks the boundary between the dune system to the east and the lagoonal depression to the west (Figure 3). The Timboni wellfield (Figure 3), located at a sand quarry near the road, is the main water supply source in the entire Gongoni area. Well W003, which is equipped with a diesel pump, was found flooded and not in use. The well currently in use is W002. Another major well located along the road is W018. This well belongs to Mombasa Salt Works

Limited and is equipped with a diesel pump. A majority of the water points along the road are shallow and are poorly protected.

Sand quarries have been developed along the line of potable groundwater supply, posing a serious threat to its quality. In addition, Mombasa Salt Works Ltd., which carries out its salt harvesting activities in the lagoonal area (largely restricted to the north-west part of the lagoonal depression) intend to expand their facility towards the line of springs along Ngomeni Road, sharply raising the possibility of salt water contamination of the freshwater aquifer(s). The aim of the study was to evaluate the possible impacts of continued sand harvesting and extension of the salt harvesting works on the quality of the potable groundwater aquifer within the area, and included: geological and soils studies, geophysical studies, and hydrogeological and water quality studies.

## **Materials and methods**

### 1. Geological survey

The area is underlain by soils and unconsolidated sands, with no bedrock exposure. The geological survey therefore focused on mapping and determination of the sand dune morphology, sedimentology, structure and interface with the lagoonal clays.

### 2. Soil survey

Soil samples were collected by auger and from excavation pit profiles within a gridded spatial network at intervals of 500m, with higher sampling density in areas of particular interest (close to the spring line) (Figure 3). Laboratory analysis included particle size analysis, plasticity and dry bulk density measurements. Chemical analyses determined soil pH, organic carbon content, concentrations of the major cations Mg, K, Na, and Ca and cation exchange capacities of the soils.

### 3. Geophysical survey

The geophysical investigations consisted entirely of vertical electrical soundings (VES) conducted along three profiles using a SYSCAL R2 signal averaging terrameter with Schlumberger electrode configuration. In the dune area, other soundings were performed using an ABEM 300B terrameter. A maximum current electrode spacing of 100m was used.

### 4. Hydrogeology and groundwater quality survey

The hydrogeological studies involved elevation measurements of water points and test pits using a theodolite; assessment of groundwater quality; and assessment of the water balance. The water points were mapped with the aid of a Geographical Position System (GARMIN GPS 12XL model). The hydraulic properties of the aquifer were determined from pump tests which were conducted at the existing main Timboni well W002 and at well W018 belonging to Mombasa Salt Works Ltd. The pump test data were analysed using the Cooper-Jacob solution method to non-equilibrium equations because only one observation well is required, assumptions of the steady state of flow are not necessary, storativity value can be obtained, and the pumping period does not have to be long.

Waters from the existing water points were analysed for electrical conductivity (Ec), pH, total dissolved solids (TDS), temperature, Cl, Ca and Mg. Selected wells were also sampled for bacteriological analysis. Ec, TDS, and temperature measurements were determined using a HACH conductivity meter model 44600-00. Chloride was measured by both titrimetric and paqualab methods, while cations were determined by titrimetric methods. Bacteriological analysis of faecal coliform and total coliform counts was carried out by membrane and fermentation methods.

## **Geology and soils**

### 1. Pleistocene and Recent dunes and sands

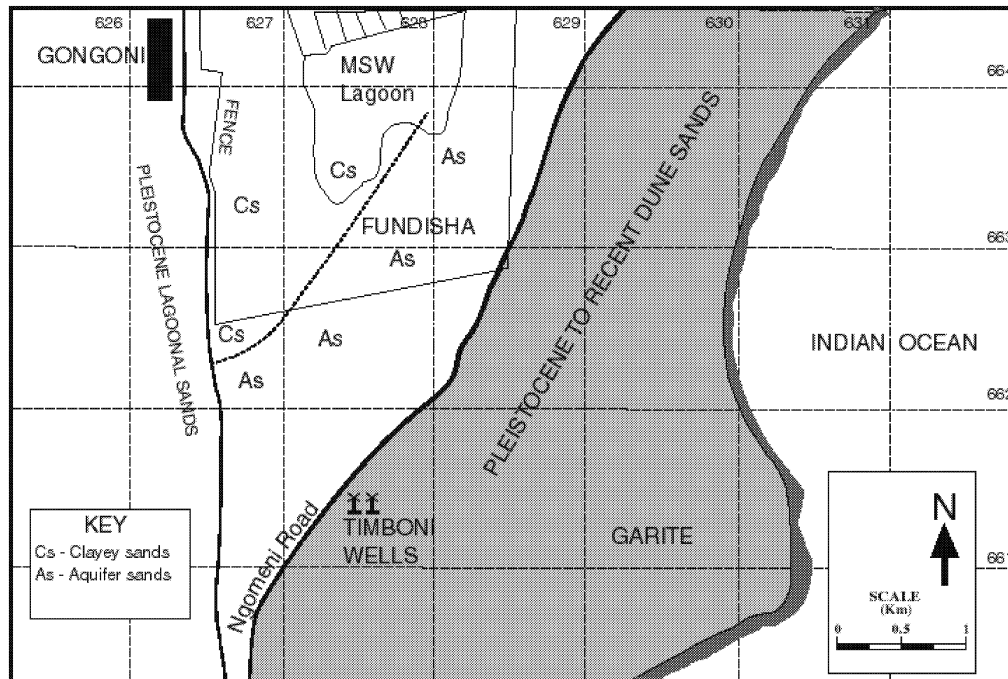
The very low degree of soil formation on the dune sands, which border the lagoon on the east, reflects their Recent origin. The dunes generally have heights greater than 30 m, are aligned parallel to the coastline and consist mostly of white or creamy coloured unconsolidated sands (Thompson 1956). The sands are derived mainly from detritus transported from the interior by the Sabaki River, which drains into the Indian Ocean south of the study area. The dune formation north of the Sabaki River mouth is controlled by the south-east monsoon winds and the northward flow of long-shore currents (Thompson 1956). The Pleistocene

sands which border the study area to the west are believed to have accumulated as lagoonal sands (Caswell 1953; Thompson 1956).

## 2. Soils

### (a) Spatial distribution

The soils are thickest in the northern sector (up to 250 cm) and thin toward the south (110 cm). The A horizon of soils in the area (10 to 32 cm thick) consists mainly of black organic clay/brown organic clay (with mineralised organic matter) (Figure 4). In the extreme eastern sector, bordering the sand dunes, the A horizon consists of a complex inter-fingering of organic clays, sandy clays, clayey sands and mineral clays. Excavation by Mombasa Salt Works in the western sector has exposed grey-brown clays, representing the B horizon (30 to 70 cm thick) at the surface.



**Figure 4. Spatial distribution of the A-horizon.**

At greater depths, sandy clays are dominant in the southern sector, while clayey sands dominate in the western sector, although there are pockets of light-grey clays. In the eastern and southern sectors, aquifer sands occur between 130 and 160 cm. In the western sector, no aquifer was encountered after excavation to 250 cm. These results suggest that the inferred contact between the aquifer sands (sand dunes) in the east and the clayey sands in the west dips steeply westwards.

### (b) Drainage characteristics

Salinization appears to be a problem in the north-east sector, where plants show evidence of injury. This may be due to both the expansion of the Mombasa Salt Works and to increased withdrawal of groundwater (Wicks and Herman 1995). Subsurface drainage is, however, probably enhanced by desiccation cracks which develop from the alternating dry and wet seasonal climate and extend to a depth of at least 50 cm below the surface. In addition, vertical and lateral interfingering of clays and sands are observed in this area. These two factors may have formed an expansive lateral network of interconnected conduits (micro-fractures) with relatively high permeability within the generally impermeable clays. The lateral extent of micro-fractures may explain the effects of salinization, which are related to the proximity of the sea-water inlet and artificial salt lagoons to the west. Although the waters in the aquifer sands underlying the soils in the lagoonal depression are saline, there appears to be little or no up-draw of cations from the lower to the upper parts of the soil profile (see below), ruling out significant top-soil salinization by upward capillary movement. In addition, as the configuration of the saline - freshwater mixing zone and the location of the



halocline are functions of the porosity and permeability distribution of the aquifer (Wicks and Herman 1995), the inter-fingered clay/sand lenses in this area may have shifted the position of the mixing zone in the aquifer higher relative to the rest of the aquifer, resulting in increased salinization.

*(c) Properties*

The texture of the clays is fairly uniform throughout the area and tends to become more silty and sandy with depth (Table 1a and 1b). The underlying aquifer sands are strongly dominated by sand-sized quartz grains. They are normally distributed except for PIT 2 sand which has a positively-skewed grain size distribution.

**Table 1a. Texture of the clays.**

	Sample Number	% Sand	% Silt	% Clay	Texture Grade
1.	P001, 45-50cm	68	6	25	Sandy clay loam
2.	P004, 45-50cm	42	10	48	Clay
3.	P005, 45-50cm	40	12	48	Clay
4.	P006, 45-50cm	40	12	48	Clay
5.	PIT 1, 55-60cm	54	6	40	Sandy clay
6.	PIT 1, 80-85cm	62	8	30	Sandy clay loam
7.	PIT 3, 45-50cm	22	14	64	Clay
8.	PIT 3, 90-95cm	30	20	50	Clay
9.	PIT 4, 40-45cm	28	16	56	Clay
10.	PIT 4, 70-75cm	72	8	20	Sandy clay loam/sandy loam
11.	PIT 5, 45-50cm	28	12	60	Clay
12.	PIT 5, 80-85cm	40	16	44	Clay
13.	PIT 6, 40-45cm	40	16	44	Clay
14.	PIT 5, 90-95cm	74	8	18	Sandy loam
15.	PIT 7, 50-55cm	28	14	58	Clay
16.	PIT 7, 120-125cm	76	6	18	Sandy loam
17.	PIT 8, 95-00cm	48	26	26	Sandy clay loam

**Table 1b. Texture of the aquifer sands**

Phi value	Aquifer sands %					Texture grade
	PIT 1	PIT 2	PIT 4	PIT 9	Timboni	
0	7.74	3.98	17.56	1.68	7.28	Gravels + very coarse sand
1	19.89	84.15	15.90	20.27	9.90	Coarse sand
2	36.87	10.79	33.37	61.42	61.55	Medium sand
3	22.10	0.08	21.70	16.26	16.65	Fine sand
4	7.69	0.02	6.80	0.58	2.70	Very fine sand
5	2.68	0.03	3.99	0.07	0.94	Silt and clay

The clays are extremely plastic and fairly cohesive (M.M. Ndege, unpublished data). They have dry bulk densities ranging between 1250 and 1500 kg/m<sup>3</sup>, which is characteristic of clays with low organic carbon contents (Table 2). The pH values in the upper portion of the clay strata are in the alkaline range and decrease with depth. They reflect the relatively high concentration of bases as compared to the deeper clay strata (Table 2). The low cation exchange capacities of the clays suggests that they are probably dominated by kaolinite-halloysite (or other types of 1:1 structured clays) with some hydroxides of Fe and Al (Kenya Soil Survey 1987; Brady 1990), suggesting that the major cations in the acidic clays immediately overlying the aquifer sands are probably Al<sup>3+</sup> and Fe<sup>3+</sup>.

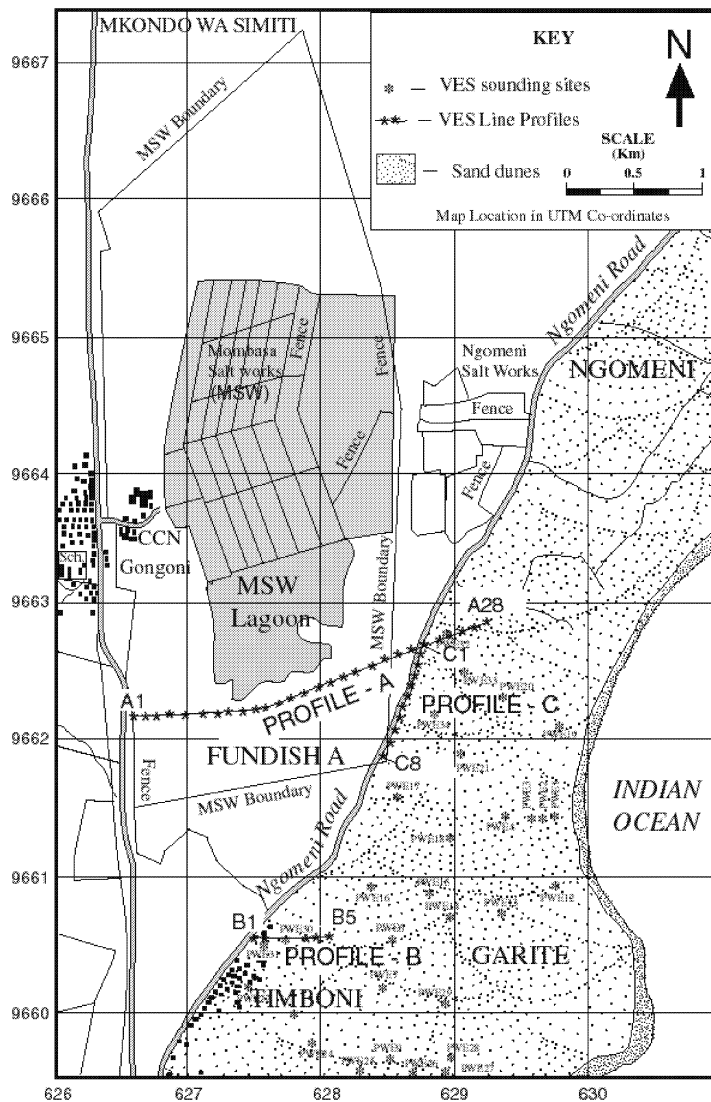
**Table 2. Physical and chemical characteristics of the clays.**

Sample No.	Sample ID (cm)	Org. C (%)	Dry density kg/m <sup>3</sup>	C.E.C. me/100g	Mg ppm	K ppm	Na ppm	Ca ppm
<b>PIT 1</b>								
1	50-60	1.23	1330	11.76	221.31	320.64	936.00	2300
2	80-85	2.01	1320	8.40	63.23	N.D.	335.40	460
<b>PIT 3</b>								
3	45-50	1.35	1250	20.16	502.21	156.31	296.40	1035
4	90-95	3.64	1350	18.48	447.49	78.16	234.00	2415
<b>PIT 4</b>								
5	40-45	1.63	1420	11.62	470.59	3653.29	421.20	1265
6	115-120	1.61	1470	10.78	177.54	400.80	156.00	690
<b>PIT 5</b>								
7	45-50	2.61	1360	24.78	68.10	1372.74	514.80	1495
8	80-85	2.91	1490	21.56	68.10	1474.94	475.80	1840
9	140-145	1.85	1500	9.52	149.57	182.36	140.40	460
<b>PIT 6</b>								
10	40-45	2.44	1440	17.36	72.96	3356.70	280.70	690
11	55-60	2.71	1390	23.94	72.96	5482.94	280.80	460
<b>PIT 7</b>								
12	50-55	3.09	1380	17.64	390.34	1250.50	148.2	1035
13	120-125	2.52	1460	12.32	176.32	192.38	218.40	1035
<b>PIT 8</b>								
14	50-55	2.08	1340	15.68	150.78	266.53	171.60	575
15	95-100	1.89	1390	17.08	390.34	899.80	530.40	575

## Geophysical studies

The aim of the geophysical investigation was to delineate the salt/fresh water boundary between: 1) the saline aquifer underlying the lagoonal depression and the freshwater aquifer; and 2) the freshwater aquifer and saltwater incursion from the Indian Ocean. Three VES profiles (Figure 5) were run with a maximum current electrode spacing of 100 m. In addition, two soundings were performed close to the beach on the eastern side of the dune sands.

The profile across the lagoon area (Profile A, Figure 6a) is characterised by very low resistivities with values of about 3 ohm-m close to the surface, decreasing with spacing to less than 1 ohm-m at a spacing of 100 m. These resistivities represent a fairly thick saline clay layer which may be sandy in places. This suggests that the possibilities of surface salt water leaking deep into the subsurface is minimal. Surface and near-surface materials in the dune area, which is topographically slightly higher relative to the lagoon area, are characterised by high resistivities, ranging between 1000 and 5000 ohm-m, consistent with expected values for dry sands. The aquifer depth increases from about 1.6m near the road to 6m about 400m from the road. This variation may be due to the increasing height of the measurement point on the dunes rather than a change in water table height. The aquifer under the dune has a resistivity of about 30 ohm-m, and its thickness varies from about 6 m at the spring line to an estimated 10 m at a distance of 500 m east of the

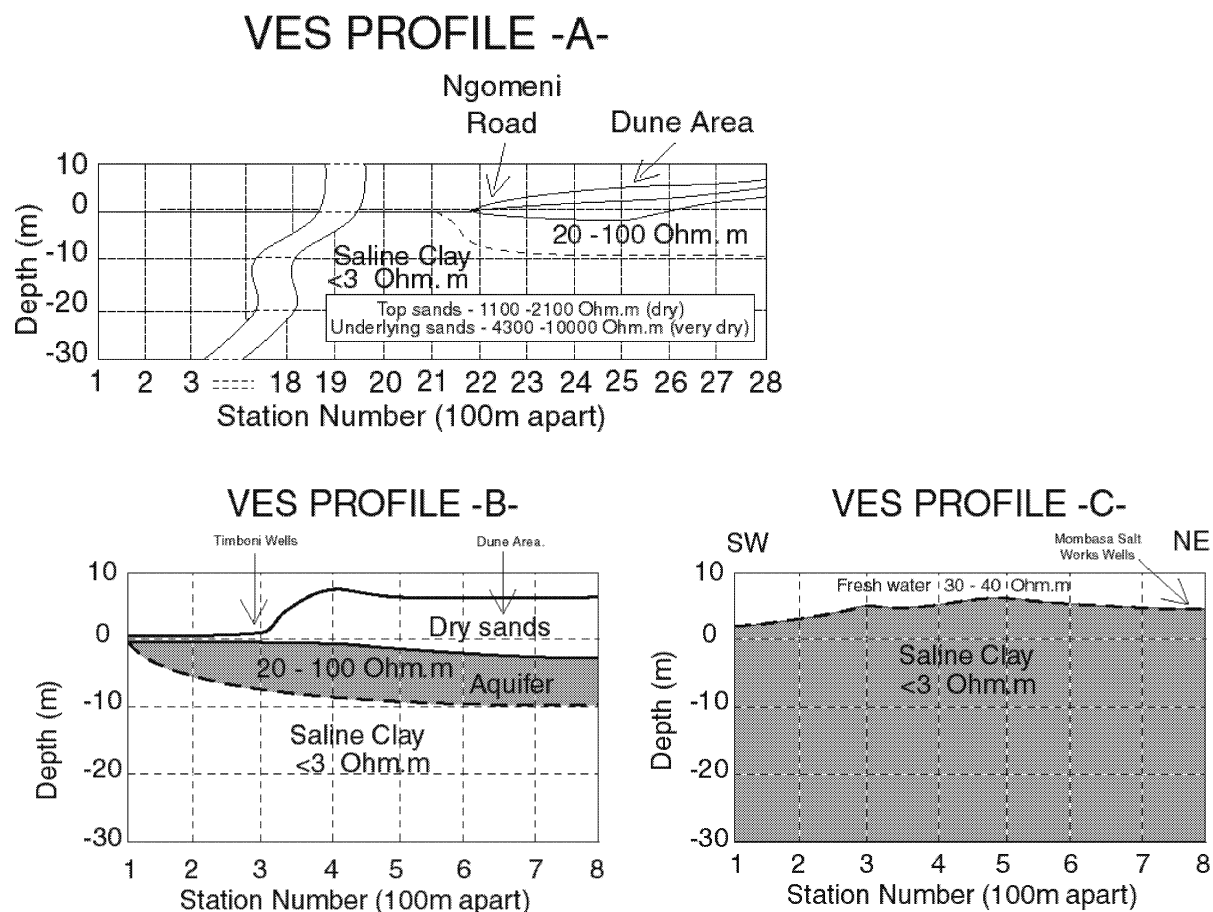


**Figure 5. Study area showing VES profiles and sounding sites.**

spring line. The exact bottom of the freshwater body could not be established due to the scatter of data in this depth range over the dune.

Profile B, which passes through the Timboni wells (Figure 5) shows similar characteristics to those of Profile A. The aquifer depth on the dune sands east of the Timboni wells is about 6 m (Figure 6b). Within the wells the saline layer is at a depth of 20 m. Within the dune area, but east of the wells, the saline layer could not be defined because of data scatter. Additional soundings conducted using an ABEM Terrameter did not resolve the data scatter problem, which made it difficult to better estimate the exact bottom of the freshwater body. However, based on the results from Profile A (where the aquifer thickness is between 6 and 10m at about 500m east of the spring line and within the dune area), it was inferred that the freshwater aquifer along Profile B has a maximum thickness of 10 m.

Profile C, taken along the Ngomeni-Timboni road (Figure 5), clearly delineated the freshwater/saline water boundary. The aquifer thickness along the line of springs was found to be 6 m thick with a resistivity of about 30 ohm-m (Figure 6c). The salt water, which occurred at a depth of 7 metres, had very low resistivities of 1-2 ohm-m. These values are similar to those obtained under the lagoon area.



**Figure 6. VES profiles.**

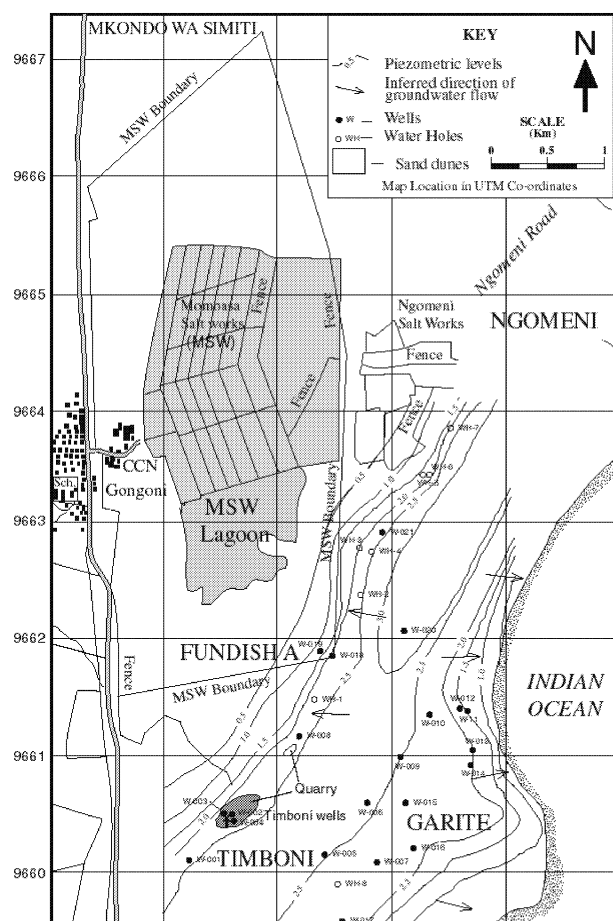
The geophysical data suggests that there is a boundary between the freshwater and saline water at Profile C (Figure 6c), an inferred boundary between the freshwater and saline water at profiles A and B, and that the freshwater/saline water layer dips gently eastwards into the dune area. The freshwater/aquifer occurs to the east of the lagoons, and is overlain by highly resistive dune sands.

### Hydrogeological studies

The aquifer is generally characterised by high transmissivity (Well W002 : 447.6m<sup>3</sup>/day; Well W018 : 266.2 m<sup>3</sup>/day) and storativity (W002 : 0.505; W018 : 0.161). This is an indication of relatively good hydraulic properties within the aquifer and its high potential.

The piezometric surface is, in general, relatively higher at locations of higher topography, and there is a positive hydraulic gradient from the dune system to the clayey area west of Ngomeni Road. The flow directions of groundwater in the area are from the dunes to the sea in one direction and to the clays in the other direction (Figure 7). The piezometric surface is lower in the wells than in the surrounding area due to abstraction and could pose a serious threat of seawater contamination. In addition, due to the nature of the hydraulic gradient, the natural flushing of the groundwater to the sea could be hampered by over-pumping, which can lead to hydrological depressions, which form hydrologic traps from which contaminants cannot be flushed out to sea by the natural groundwater flow (Nativ and Weisbrod 1994).

Most of the wells and water holes have relatively low electrical conductivity and chloride levels (Tables 3 and 4).



**Figure 7. Flow directions of groundwater in the well area.**

**Table 3. Chemical analysis results for the water points.**

Water Point No.	Ec mS/cm	TDS mg/l	Temp. °C	Cl mg/l	Ca mg/l	Mg mg/l	pH	Remarks
W002	473	236	29.5	<100	54	31	8	heavily used
W003	517	260	30.1	<100	78	25	8	flooded
W008	445	224	29.4	<100	25	37	8	in use
W009	610	300	29.4	<100	34	65	7	protected
W011	1060	530	28.1	100	24	77	8	in use
W012	900	450	28.1	<100	60	59	7	protected
W014	1950	980	27.2	200	19	98	8	protected
W018	930	470	31.8	100	22	126	8	heavily used
W019	7250	3640	30.4	>>500	45	72	8	abandoned
W021	720	360	30.4	<100	36	25	9	in use
WH1	400	200	31.5	<100	28	27	7	in use
WH2	540	270	30.6	<100	15	40	8	in use
WH3	2640	1320	32.5	400	49	51	9	abandoned
WH4	1740	870	32.1	200	42	92	9	in use
WH5	6430	3320	33.2	>>500	23	116	7	never in use
WH6	880	400	33.3	100	36	6	7	limited use
WH7	220	110	33.7	<100	32	7	7	in use

There is, however, a marked difference on the water points at either side of Ngomeni Road. The water points west from the road within the clayey area have relatively higher Ec and chloride values than those within the dune system to the east. These higher Ec and chloride levels could be due to infiltration of salt

water from the lagoons and/or leaching of bases from the overlying clays. The chemical analyses suggest that the main factors influencing the Ec, TDS and chloride values within the dune area are the proximity to the sea and the boundary with the clayey formation.

**Table 4. Chemical analyses results for the test-pits.**

Test-pit Number	Ec mS/cm	TDS g/l	Temperature	Chloride	pH
TP1	76600	38300	28.6	22540	5
TP2	49200	24600	27.0	15620	6
TP3	29600	14800	27.0	20380	6
TP4	13540	6770	32.4	3770	6
TP5	23460	11730	29.4	4800	5
TP6	67550	33780	29.2	25000	5
TP7	11720	5860	28.2	-	6
TP8	39580	19790	29.8	13500	7
TP9	106080	53040	29.8	15000	6
TP10	66560	33280	29.4	23500	5
TP11	51080	25540	30.0	17650	5
TP12	52920	26460	29.0	-	6
TP13	22200	11100	29.2	4045	7
TP15	8550	4280	28.2	2300	6
TP16	33940	16690	27.6	12000	6
TP17	12300	6200	28.9	-	6
TP19	8660	4330	27.9	-	8
TP22	13160	6500	27.0	1000	7

#### Groundwater quality

The results of bacteriological analyses (Table 5a and 5b) reveal contamination of the groundwater resources in the area of study. The contamination is higher in public wells than in the private wells used by fewer individuals. With the exception of W018, the wells along Ngomeni Road have values in excess of 340 faecal colon counts per 100 ml. W011 in the beach area is also heavily contaminated. Relatively high groundwater contamination in water points along Ngomeni Road is largely due to the surface exposure of groundwater at the sand-harvesting quarries. Other contributing factors are settlements and high population density, poor sanitation, use of contaminated containers to obtain water, and lack of proper protection of most water points.

**Table 5a. Results of the Bacteriological analysis using the membrane method.**

Well No.	Faecal coliform/100ml	Total coliform count per 100ml	Protection
W002	340	780	Open well/public
W008	480	820	Open well/public
W018	10	320	Open well/public – few users
WH2	720	TNTC*	Open well/public

\*TNTC = too many to count

**Table 5b. Results of the bacteriological analysis using the fermentation method.**

Well No.	Faecal coliform MPN/100ml	Total coliform MPN/100ml	Protection
W014	2400	2400	Makuti roof cover/public
W011	38	2400	Open well/public
W012	9	240	Makuti roof cover/private
W009	9	43	Covered with concrete slab/private

## Summary and conclusions

Sand harvesting at the Timboni wellfield has exposed the aquifer to contamination from human and animal waste, and destroyed the water pumping stations. Over-abstraction is the single most significant threat to the chemical quality of water in the wells. Only one well is currently in use as the others have collapsed due to sand harvesting. The Timboni well is located where the aquifer is relatively shallow, so the threat from seawater intrusion is very high and a reduction or rearrangement of the pattern of groundwater abstraction (Freeze and Cherry 1979) should be initiated. During periods of extended drought, the threat from seawater intrusion is even higher as the groundwater level decreases. Because the aquifer is now exposed, it is subject to depletion by evaporation, and possibly, undesirable increases in salt concentration. The proposed Mombasa Salt Works (MSW) extension, on the other hand, may not adversely affect the adjacent freshwater Timboni Wellfield aquifer by percolation into the aquifer below, because of the physical and chemical characteristics of the clays and the hydraulic gradient of the freshwater system. Soil studies above the aquifer, however, suggest that lateral movement of salt water in the upper portion of the micro-fractured allophone-type clays with intercalated sands could extend for considerable distances beyond the artificial earth lagoon barriers erected by Mombasa Salt Works, and contaminate the unconfined aquifer through the clay/sand boundary. It is therefore necessary that the salt lagoon extension be kept some distance away from the freshwater/saltwater interface and water wells. For continued sustainability of the wellfields, it is necessary to stop sand harvesting in the Timboni area and to locate alternative sites further away from the freshwater aquifer. In addition, it is important that the wells are properly sited to minimise the effects of saline intrusion (Edworthy 1985). It is also necessary to rehabilitate the wellfield by covering the exposed sections of the aquifer with sand. Furthermore, the main production wells currently at the clay/sand interface should be removed from this boundary area and relocated in the middle parts of the dune system, where there is more chance of getting water of better chemical quality and free from saltwater contamination or intrusion. Due to the relatively small size of the aquifer, production should be spread over several smaller and far-spaced wells rather than rely on a large single well, to avoid over-abstraction from one point.

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#### **4.17 Dry season sediment fluxes in the frontwater zone of the mangrove-fringed Mwache Creek, Kenya**

***Johnson U. Kitheka***

##### *Abstract*

Mwache Creek is a typical mangrove creek along the Kenya coast. The creek receives terrigenous sediments on a seasonal basis and there is tremendous tidal influence. The supply of terrigenous sediments increases greatly during periods associated with major flood events. Most of the sediments supplied by the seasonal rivers are trapped in the upper parts of the creek with very little export to the lower frontwater zone of the creek. In the frontwater zone, sediments are imported during periods of low river discharge. This sediment import is related to the flood-tide resuspension of the bottom sediments in the frontwater zone of the creek. The resuspension of the bottom sediments is more dominant during flood tide than during ebb tide. Sediments resuspended in the main channel enter the relatively dense frontwater mangrove forest where they are trapped due to the high vegetation density and gentle slope that induce enormous friction on the water flow inside the forest.

##### **Introduction**

Much of the sediment load supplied to tidal creeks by rivers is associated with poor land-use activities at river basin level (Kitheka 1996b). The input of terrigenous sediments has both positive and negative implications. High sediment load leads to trapping of large volumes of sediments in mangrove forests, which eventually die if smothering is extensive. Sediment also increases turbidity of the water, limiting light penetration and subsequently primary and secondary production. On the positive side, input of sediments enable the mangroves to build up their environment and therefore keep in pace with sea level rise (*cf.* Ellison 1993). Studies on sediment transport provide coastal scientists and natural resources managers with information on how sediments are redistributed in mangrove wetlands and how this redistribution ultimately affects both the long- and short-term sustainability of the ecosystem. This helps in the formulation of suitable management strategies for the mangrove wetlands. However, data and information on sediment transport dynamics in mangrove creeks is not readily available (Kitheka 1996a).

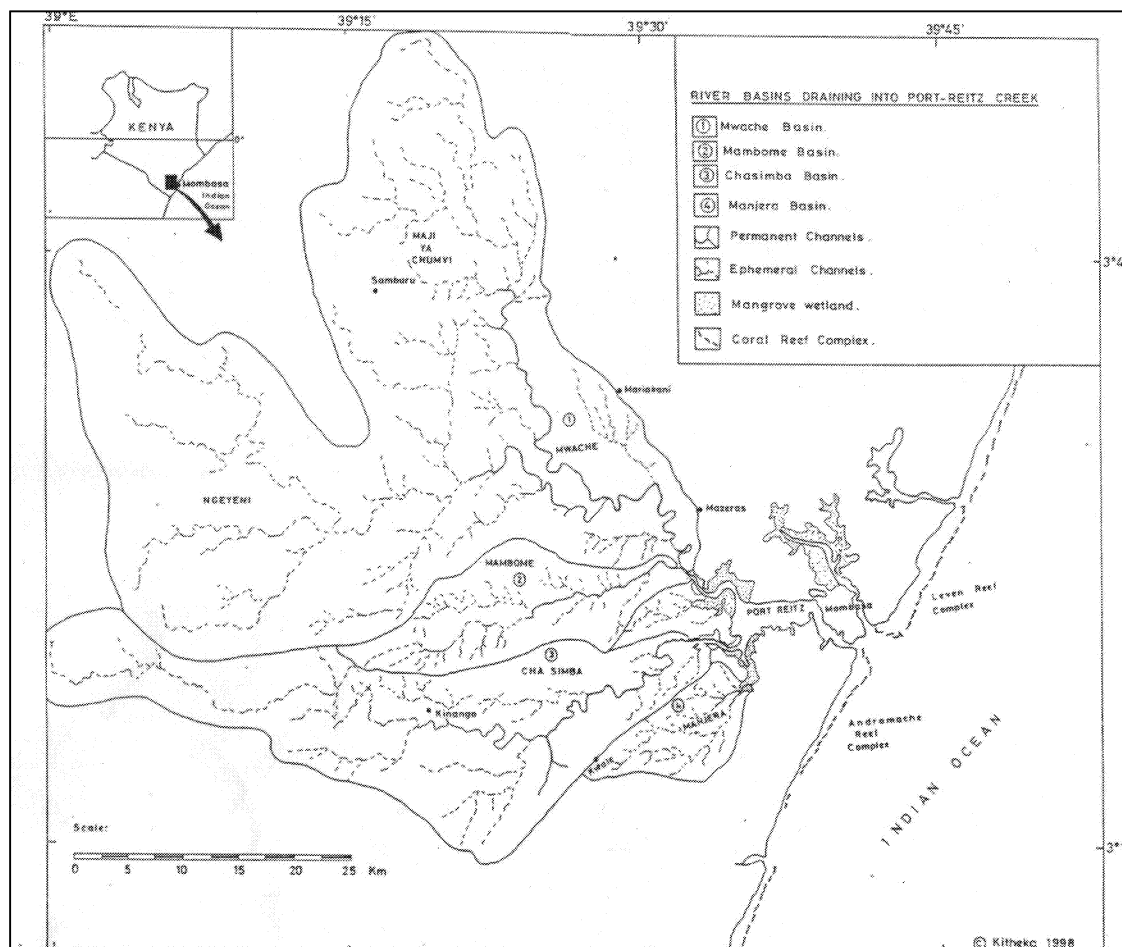
Among the wide range of factors influencing sediment transport in tidal creeks, tidal range and current speed are the most important (Althausen and Kjerfve 1992; Lindsay *et al.* 1996). Channel erosion and deposition are dependent on certain critical velocities, which vary depending on the nature of tidal channel geometry and sediment supply. Given that constant resuspension by strong currents erodes the tidal channels and keeps them free of sediments, it is expected that this will prevent them from silting up even when there is enormous supply of terrigenous sediments from the rivers.

This paper examines the patterns of sediment fluxes in mangrove-fringed Mwache Creek situated along the Kenya coast. The paper also highlights the pressures in the Mwache Creek basin and how changes in the creek and the river basin may feed back on the human population.

##### **Description of Mwache Creek**

Mwache mangrove wetland occurs in the upper parts of Port-Reitz Creek (4°3'S, 39°38'E) (Figure 1). It is one of the two main tidal mangrove-fringed creeks found in Mombasa District, Kenya. The total creek area was determined from a topographic map to be 17 km<sup>2</sup>. The mangrove forest covers an area of 12 km<sup>2</sup>, roughly 70% of the total area of the creek. The length of Mwache Creek from the entrance to Kipevu basin is approximately 12 km.





**Figure 1. Mwache Creek drainage basin, Kenya.**

The tidal channels are shallow, <11 m deep at the creek's entrance to Kipevu basin and less than 6 m in tidal channels fringing the mangroves. Tidal creeks meander through the wetland cutting the soft Jurassic shales and sandstone rocks which rise approximately 120 m above the creek low water level. The creek receives freshwater and terrigenous sediments from two seasonal waterways, Mwache and Mambome. Their mean discharges and basin areas are shown in Table 1. The total drainage basin area of rivers draining into Mwache Creek is 2,600 km<sup>2</sup>. The Mwache River, with a catchment area of about 1,700 km<sup>2</sup>, is one of the largest with freshwater discharge of the order 10 m<sup>3</sup> s<sup>-1</sup> in normal rainfall months. The dominant mangrove species are *Avicennia marina* and *Rhizophora mucronata*. The port of Mombasa, one of the largest in East Africa, is located about 4 km from the creek's entrance to Kipevu basin. Previous studies at Port Reitz Creek have been undertaken within the Mombasa port area (GOK 1975; Grosskopf and Onyango 1991), about 4 km downstream of Mwache Creek.

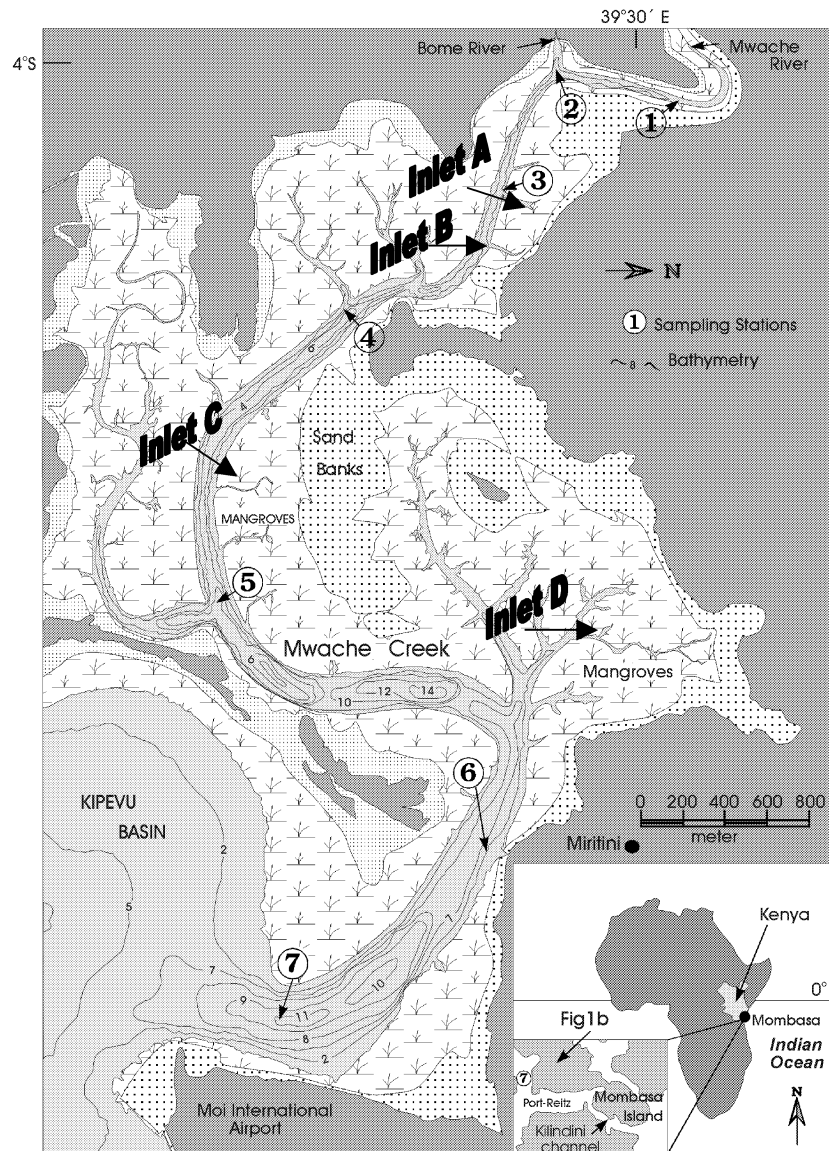
**Table 1. The drainage basins, mean river discharges and mean sediment supply to Port Reitz Creek.**

Basin	Area (km <sup>2</sup> )	Discharge (m <sup>3</sup> s <sup>-1</sup> )	Sediment supply (kg s <sup>-1</sup> )	Sediment discharge (t yr <sup>-1</sup> )
Mwache	1703	8.64	4.30	4.46x10 <sup>4</sup>
Cha-Simba	614	3.12	1.60	1.16x10 <sup>4</sup>
Mambome	212	1.07	0.50	0.50x10 <sup>4</sup>
Manjera	98	0.50	0.25	0.26x10 <sup>4</sup>
<b>TOTAL</b>				<b>6.88x10<sup>4</sup></b>

## Materials and methods

### *Determination of sediment concentrations*

Suspended sediment concentrations (SSC) were determined using gravimetric and automated methods (*cf* McGave 1979). In the gravimetric method, water-sediment mixture samples were drawn from the surface, middle and bottom water columns using a Niskin water sampler. Samples were filtered in the laboratory using pre-weighed 47 mm Whatman GF/C filters with 0.45  $\mu\text{m}$  pore diameters. Salts were flushed from filtered samples using distilled water after which the samples were wrapped in aluminum foil and oven-dried at 120°C for 24 hrs. The dried filtrates were then re-weighed to determine the weight of filtered sediments, which were taken as the difference between the weight of the filter with the filtrate and the original weight of the filter. This was then related to the filtered volume of seawater to determine SSC as the amount of sediments present in a filtered volume of seawater. In the second method, an Orbital Backscatter suspended sediment sensor connected to a MicroTide pressure gauge was moored at a central location of the channel at Station 6 (see Figure 2) and used to measure SSC automatically. The instrument was programmed using a portable computer and logged in SSC at intervals of 5 minutes between January 26 and 30, 1999 and also between February 2 and 23, 1999.



**Figure 2.** Map of Mwache Creek with the locations of sampling stations. For surface area and volume computations, the whole mangrove extent and tidal creeks above Station 7 were included.

## Physical variables and sampling strategy

Both spot-sampling and automated continuous time-series measurements were used for salinity, temperature, tidal currents and tidal elevation. Spot surveys were carried out in the seven stations (Figure 2) using a rubber dinghy. The sampling cruise with a boat from Station 1 to Station 7 took 1-1.5 hours. Station 6 was chosen as the principal station for instrumented time-series measurements of SSC, tidal elevation and current velocities, in view of its accessibility and the availability of adequate security for the moored pressure gauges and rotor SD-6000 current meter. These instruments were moored about 1 m above the channel bed at Station 6 during the sampling periods. Water salinity and temperature were measured using an Aanderaa salinity-temperature meter. These measurements were mainly conducted in dry periods and covered both neap and spring tides. During the period of the study, river discharges were very low.

## Data treatment and analysis

### Sediment mass transport

The hypsometric curve of Mwache Creek was plotted from the tide-corrected bathymetric data. The surface areas ( $A_n$ ) covered by specific depths ( $h_n$ ) were then determined and the corresponding water volumes ( $V_n$ ) computed as

$$A_n \frac{h_{n+1} + h_n}{2} = V \quad (1)$$

Equation 1 basically refers to the volume enclosed in a specific water depth. However, since water depth changes with time ( $t$ ), the tidal volume flux  $Q(t)$  is computed as

$$Q(t) = A(t) \frac{dh}{dt} \quad (2)$$

With data on corresponding instantaneous SSC  $C_o(t)$ , suspended sediment flux  $Q_s(t)$  was then computed as

$$Q_s(t) = Q(t) C_o(t) \quad (3)$$

The tidal volume flux  $Q(t)$  is also computed using current velocity  $U$  and surface area  $A_s$  as

$$Q(t) = UA_s \quad (4)$$

This method assumes uniform velocity distribution across the channel. Similar approaches have been applied in salt marsh tidal creeks and estuaries (Lindsay *et al* (1996).

### Erosion and deposition of sediments

The time series data on SSC and current velocities measured in the period February 15 - 23, 1999 were used to derive empirical constants in the sediment transport relation. The standard vertically averaged sediment mass conservation equation applied in a finite section of the channel (about 100 m) is simplified as follows:

$$\frac{\partial(HC)}{\partial t} = M_e - M_d \quad (5)$$

where  $H$  is the water depth,  $C$  is the depth-averaged SSC and  $t$  is the time. The source and sink terms are erosion ( $M_e$ ) and deposition ( $M_d$ ) respectively. These terms are governed by specific critical velocities, which were determined by examination of the simultaneous plots of SSC and current velocities. The sediment deposition rate ( $M_d$ ) was computed as:

$$M_d = \begin{cases} CW_s \left(1 - \frac{U}{U_d}\right)^2; & U < U_d \\ 0; & U > U_d \end{cases} \quad (6)$$

where  $U$  is the current velocity outside boundary layer,  $U_d$  is the critical velocity for settling and  $W_s$  is the sediment settling rate (0.0005 m/s). The critical deposition stress  $\tau_d$  is computed as:

$$\tau_d = \rho C_d U_d^2 \quad (7)$$

and the erosion of sediments from the channel bottom ( $M_e$ ) was calculated as:

$$M_e = \alpha \left( \frac{U}{U_e} \right)^2 - 1 \quad (8)$$

The above equation is applicable if the current velocity is higher than the critical erosion velocity ( $U > U_e$ ).  $U_e$  is the critical velocity for erosion and  $\alpha$  is an empirical constant that can be derived from equation 7.

## Results

### Tidal characteristics and current velocities

Tides measured at the frontwater zone of the creek are purely semi-diurnal with two low and two high waters occurring approximately every 25 hours. The neap and spring tidal ranges are 1.3 m and 3.1 m respectively. The dominant low frequency signal approximates 12.3 hrs, which is typical of modulation caused by tidal forcing. The maximum flood and ebb tidal current velocities at Station 6 during spring tide are 1.25 m/s and 1.38 m/s respectively and at neap, the maximum ebb and flood tide current velocities are 0.55 m/s and 0.52 m/s respectively.

The spring high tide water volume at Mwache Creek is approximately  $60 \times 10^6 \text{ m}^3$  while the spring low water volume is  $17 \times 10^6 \text{ m}^3$  when the depth change due to a 3 m tidal range is taken into consideration. This yields a tidal prism of about  $43 \times 10^6 \text{ m}^3$  which is equivalent to the frontwater zone tidal volume exchange of roughly 70 % per tidal cycle in spring tide. The average tidal volume flux is estimated to be  $2,300 \text{ m}^3 \text{ s}^{-1}$ . Since there is no significant sink or source of freshwater, the mean frontwater zone tidal volume fluxes of  $2,233 \text{ m}^3 \text{ s}^{-1}$  and  $937 \text{ m}^3 \text{ s}^{-1}$  could be considered as representative tidal flows during spring and neap tides respectively. These data are within acceptable limits given the assumptions that sea level spatial variations upstream of Station 7 are not significantly different.

### Zonal SSC variations and gradients

Large seasonal and neap-spring SSC variations were noted for the inner mangrove stations. The SSC variations during the period of this study could not be attributed to changes in river discharge since drought prevailed in 1998-1999 and there was no significant supply of sediments from the river basins. The seasonal river discharges were often less than  $0.05 \text{ m}^3 \text{ s}^{-1}$  and SSC in riverwater was less than  $0.04 \text{ g l}^{-1}$ . This means the river sediment supply into the creek was less than  $0.002 \text{ kg s}^{-1}$  which is much lower than the long-term average of  $7 \text{ kg s}^{-1}$ .

Even with this rather low river discharge, the highest SSC was found mainly in the backwater mangrove zone where SSC reached  $0.50 \text{ g l}^{-1}$ . This zone had also relatively high dry season salinities ranging 36-38 psu. In the frontwater zone, SSC was less than  $0.09 \text{ g l}^{-1}$  and salinities were 2-3 psu lower than those measured in the backwater zone. The prevalence of high SSC in the backwater zone and relatively low SSC in the frontwater zone implies a general decrease towards the open Indian Ocean, and trapping of sediments in the inner zones of the creek. The backwater zone also showed a relatively large SSC standard deviation of  $0.30 \text{ g l}^{-1}$ .

### Resuspension of bottom sediments in main tidal channel

There was evidence of flood-tide resuspension of bottom sediments in the frontwater zone during the dry seasons. Rapid increase in SSC occurred during flood tide followed by a rapid decline during high waters and also during ebb tide. This is possibly because most of the suspended sediments are trapped in the mangrove forest, so that only a small quantity is available for transport seaward during ebb tide. Periods of bottom sediment re-suspension were associated with maximum current velocities of the order of  $1.0 \text{ m s}^{-1}$ . Significant erosion occurred for flood-tide current velocities above  $0.30 \text{ m s}^{-1}$ . There were also spring-neap variations in the magnitude of suspended sediment concentrations. The maximum SSC occurred during spring tide and there was a reduction in SSC level during neap tide. Maximum resuspension of the bottom sediments in the frontwater zone also occurred in spring tide because strong velocities are usually experienced in spring. Since the magnitude of tidal current velocities decline substantially during neap tide, the magnitude of resuspension is also reduced by about 50% in the frontwater zone during neap tide.

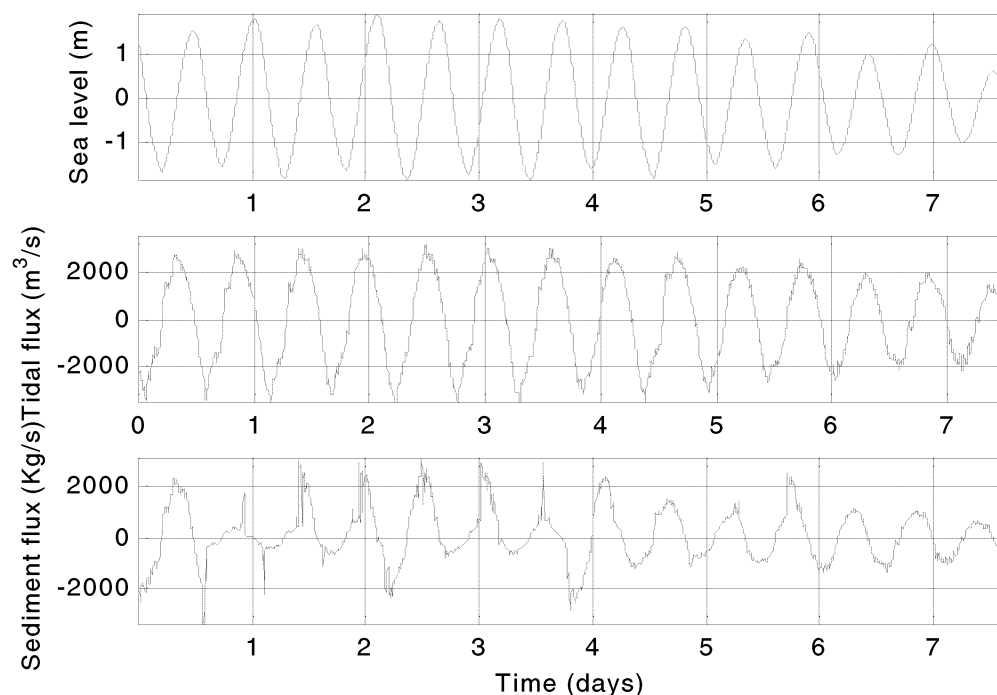
The computation of erosion and deposition rates in the frontwater zone (using equations 6 and 8) showed that rates of erosion reach  $10 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$  and those of deposition reach  $5.0 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ . Thus sediment production through erosion of the bottom sediments is of the order of  $5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ . The higher rate of main channel bottom erosion compared to deposition points to the fact that the main tidal channel in the frontwater zone does not silt up. This explains why the channel remains free of sediments even after a period of major sediment inflow into the creek.

### Suspended sediment fluxes

The suspended sediment fluxes, computed using equation 3, were higher in spring tide ( $1200 \text{ kg s}^{-1}$ ) and lower in neap tide ( $400 \text{ kg s}^{-1}$ ). The mean spring ebb tide sediment flux is  $690 \text{ kg s}^{-1}$  and the mean flood tide sediment flux is  $1740 \text{ kg s}^{-1}$ . In neap tide, mean ebb tide sediment flux is  $340 \text{ kg s}^{-1}$  while that in flood tide is  $460 \text{ kg s}^{-1}$  (Table 2). The difference between neap flood-/ebb-tide sediment fluxes is  $+121 \text{ kg s}^{-1}$ , while that in spring is  $+1057 \text{ kg s}^{-1}$ . There is thus spring neap-tide sediment flux difference of about 30%. These high spring sediment fluxes are probably due to high spring tidal volume fluxes, which are 3 times higher than those experienced during neap tide (Table 2). During the period of this study, the flood tide sediment fluxes in both spring and neap tide were much greater than the ebb tide. There was therefore a net sediment import of the order 80,000 tonnes into the creek. The imported sediment was probably sediment that was discharged into the creek by the Mwache River during the 1997 *El Nino* event. Sediment flux patterns are illustrated in Figure 3.

**Table 2. The mean spring -neap tidal current velocities, tidal volume fluxes and mean sediment fluxes at station 6 in the period February 2-23, 1999.**

	Spring tide	Neap tide
Mean flood tidal volume flux ( $\text{m}^3 \text{ s}^{-1}$ )	2179	914
Mean ebb tidal volume flux ( $\text{m}^3 \text{ s}^{-1}$ )	2286	959
Mean flood velocity ( $\text{m s}^{-1}$ )	1.25	0.52
Mean ebb velocity ( $\text{m s}^{-1}$ )	1.31	0.55
Mean flood sediment flux ( $\text{kg s}^{-1}$ )	1740	460
Mean ebb sediment flux ( $\text{kg s}^{-1}$ )	690	340



**Figure 3. The key patterns of sediment fluxes in the frontwater zone of Mwache Creek during a period of relatively low river discharge.**

#### Trapping of sediments in the frontwater zone mangrove forests

The patterns of sediment flux in the Mwache Creek frontwater zone mangrove forest in spring tide was determined along 450 m transects running from the bank of the main tidal creek to the upper tidal limit of the forest. The mean SSC within the mangrove forest was  $0.054 \text{ g l}^{-1}$  ( $\pm 0.02 \text{ g l}^{-1}$ ,  $N=15$ ). The maximum mangrove forest SSC was  $0.096 \text{ g l}^{-1}$ . The mean flood-tide sedimentation rate calculated using the relation  $W_s C$  was  $0.027 \text{ g m}^{-2} \text{ s}^{-1}$  ( $\pm 0.01 \text{ g m}^{-2} \text{ s}^{-1}$ ,  $N=15$ ) with the maximum sedimentation rate of  $0.48 \text{ g/m}^2/\text{s}$ . The SSC mode in the mangrove forest was  $0.05 \text{ g l}^{-1}$  which with the typical sediment particle settling velocity ( $W_s$ ) of  $0.0005 \text{ m/s}$  yield flood tide sedimentation rate of  $250 \text{ g m}^{-2}$  per tide per spring tidal cycle. However, if the mean SSC is used, the mean flood tide sedimentation per tidal cycle increases slightly to  $270 \text{ g m}^{-2}$  per tide which is still within the same order of magnitude as that computed using the mode SSC. It must be noted that this approach provides only an estimate of sediment flux during flood tide and does not provide an estimate of the ebb-tide sediment flux. The net sedimentation in the mangrove forest is therefore much lower than the flood-tide sedimentation since it is the difference between flood-tide and ebb-tide sediment fluxes. In fact, the magnitude of ebb-tide sediment flux is slightly lower (of the order  $260 \text{ g m}^{-2}$  per tide) than that of flood tide, which means the net sediment flux into the mangroves is of the order  $10 \text{ g m}^{-2}$  per tide. These results show that there is trapping of sediments in the frontwater mangrove forest. Trapping occurs because of dense mangrove forest cover as well as gentle slope, which induce friction on the tidal flow, resulting into very low current velocities less than  $0.10 \text{ m s}^{-1}$  (see also Wolanski and Ridd 1986; Furukawa and Wolanski 1996; Furukawa *et al.* 1997). However, the magnitude of the net sediment flux into the mangrove forest is a function of the tidal range and bottom sediment resuspension in the main channel.

#### Importance of river supply of sediments

This study was implemented in relatively dry period. Both short and long rains were below average in the coastal region of Kenya. There was therefore no significant generation of river runoff in the Mwache River basin as the river discharges were less than  $0.05 \text{ m}^3 \text{ s}^{-1}$  in most period of the study. The river SSC was also very low, often less than  $0.04 \text{ g l}^{-1}$ . This means that the river sediment supply into the creek was less than

0.002 kg s<sup>-1</sup>, which is much lower than the long-term average of 7 kg s<sup>-1</sup>. However in the period between October and November 1997, heavy rainfall associated with the *El Nino* event caused a tremendous increase in river discharge of both freshwater and terrigenous sediments. During this period, it was estimated that the river discharge was 500 m<sup>3</sup>/s and river SSC was of the order 0.5 g l<sup>-1</sup>, so sediment discharge was of the order 500 kg s<sup>-1</sup>. The sediment supply into the creek over the two months period of high flow was estimated to be 1.3×10<sup>6</sup> tonnes. This estimate was later confirmed by determination (using sediment cores) of the volume and depth of the deposited terrigenous sediments within the backwater zone mangrove forest. In normal rainfall years, seasonal rivers draining into Mwache Creek usually flow for about 120 days and supply an equivalent of 5×10<sup>4</sup> tonnes of sediments, which is less than 4% of that discharged into the creek during the 1997 *El-Nino* event. A survey conducted to determine the spatial distribution of deposited terrigenous sediments and SSC showed that most of the sediments discharged into the creek are trapped in the backwater zone of the creek, particularly in the zone above Station 4. Most of the trapping of silt and fine sand occurred on the backwater zone mangrove forest and clay particles were trapped within the main channel above Station 4. The frontwater zone mangrove forest was surprisingly not affected in any significant way from the enormous input of terrigenous sediments into the creek.

### Human pressures

Human pressures in the Mwache basin may be classified into two major categories: (1) anthropogenic pressures at the Mwache Creek coastal-marine system level and (2) pressures at Mwache River basin level. The anthropogenic pressures are mainly felt more seriously in the mangrove forest wetland. There is evidence that the cutting down of mangrove trees beyond sustainable level is reducing their sediment trapping capability. There is also evidence that the area under mangrove cover in the creek is reducing. This reduction has increased in recent years due to an increase in demand for building material and fuelwood in the Mombasa Municipality.

Within the Mwache River basin, poor land-use activities associated with shifting cultivation, livestock grazing and deforestation have lead to an increase in the rates of soil erosion (Kitheka 1996b). Substantial quantities of terrigenous sediments therefore reach the creek during rainy seasons. The implication for the sustainability of both marine ecological systems and human cultural features are enormous, particularly in periods of high rainfall events such as those associated with *El-Nino* conditions. The enormous supply of sediments increases turbidity in the creek and thus affects light penetration into the deep layers of the water column. This in turn affects primary production and fisheries, on which the large population within the basin depends for their livelihood and daily sustenance. As a result of heavy sediment supply during the 1997 floods, mangrove roots were smothered and this led to death of nearly 10% of the mangroves in the upper zone of the creek. This is already affecting the inhabitants due to reduced fish catches, since mangroves act as nursery grounds and habitats for fishes and crustaceans of commercial importance. Further reduction of mangrove hectareage in the creek may in future lead to a drastic reduction in catches of these organisms. Another major effect is the siltation of the potential harbor sites at Kipevu. Unless remedial measures are taken to conserve the mangrove forest and manage land use in the Mwache basin, it will be necessary to incur high expenditure on maintenance dredging of the Port of Mombasa.

### **Conclusions**

Sediment load into Mwache Creek from the seasonal rivers in normal rainfall years is low so that most of the terrigenous sediments are trapped in the upper parts of the creek. During such periods, there is very little export to the lower frontwater zone of the creek. Most of the sediments supplied by the Mwache River do not reach the Indian Ocean. In fact there is import of sediments in the frontwater zone of the creek during periods of low river discharge in dry season. This import of sediments is due to the flood-tide resuspension of the bottom sediments in the frontwater zone of the creek. Resuspension of the bottom sediments is more dominant in flood tide than in ebb tide. The sediments resuspended in the main channel enter the relatively dense frontwater mangrove forest where they are trapped due to the dense mangrove vegetation and gentle slope, which induces enormous friction on the flow inside the forest. This study has dwelled more on the sediment transport dynamics in the frontwater zone. Conditions in the degraded

backwater zone may differ from those in the frontwater zone, where the mangrove vegetation is less dense and the rate of tidal flushing in the backwater zone above Station 4 is low. More studies, focussing on the relationship between sediment fluxes and tidal dynamics, will be implemented for both frontwater and backwater zones of the creek. Future studies will also aim at determining the patterns of sediment fluxes in the tidal inlets that link the mangrove forest with the main tidal channel. Such studies should target both the degraded and non-degraded zones of the creek.

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#### **4.18 The Tana River Basin and the opportunity for research on the land-ocean interaction in the Tana Delta**

*Johnson U. Kitheka and George S. Ongwenyi*

##### **Introduction**

The Tana River basin is one of the five main drainage basins in the Republic of Kenya. In terms of river discharge, it is one of the largest and also one of the most important drainage basins. It occupies about 23% of the total land area and contributes 32% of the total river runoff in Kenya. The basin is composed of the vast eastern plateau forelands, which sprawl between the Central Kenya Highlands to the west and the coastal strip on the east. The river flows down a gentle slope towards the Indian Ocean. The government of Kenya has initiated a number of significant water resources development projects in the basin. These include agricultural projects, particularly large-scale irrigation and hydroelectric power development schemes. As the river drains into the Indian Ocean, it passes through a mangrove-fringed estuary at Kipini. Apart from discharge of freshwater and terrigenous sediments into the Indian Ocean, the river also supplies a large quantity of dissolved and particulate nutrients, which makes Ungwana Bay and the Tana Delta one of the most productive fishery grounds in Kenya. Most previous studies have focussed on the Upper Tana Basin and very few studies have been implemented for the Lower Tana Basin and the Tana Delta. This paper examines the hydrological and geographical characteristics of the basin and discusses the need for studies on land-ocean interaction at the Delta.

##### **Hydrology and climatic conditions**

The Tana River Basin has a spatial extent of approximately 132,000 km<sup>2</sup> which is equivalent to about 23% of the total area of the Republic of Kenya (Table 1) (Ojany and Ogendo 1985). The main catchment area of the river is Mount Kenya (5199 m) and the Aberdare Ranges in the Central Highlands of Kenya. The snow-covered peaks of Mount Kenya provide continuous replenishment of the river, making it one of the few perennial river systems in East Africa. However, despite the high rainfall in elevations greater than 1800 m, the Tana River displays marked seasonal variations in river flow. As a result of rainfall pattern, the river usually has two distinct periods of high flow of three months total duration, separated by dry seasons when the flow frequently drops to one-fifth of the long-term average.

The total length of the river is about 1,102 km, from the Central Kenya Highlands to the Indian Ocean. The river takes a north-easterly course as it flows from the Kenya Highlands and then plunges over the Gtaru Falls (134 m) into the semi-arid landscape that constitutes the middle course. It forms a wide arch, then veers south and opens into a wide valley where it meanders through a floodplain into the Lower Tana Basin. The most important tributaries in the Kenya Highlands include the Sagana, Chania, Thika, Saba Saba, Maragua, Ruamuthambi and Mathioya rivers. In the Lower semi-arid zones, the river receives contributions in the rainy season from several ephemeral tributaries such as Tiva, Hiriman, and Kokani.

The Upper Tana catchment area in Central Kenya covers an area of 7,950 km<sup>2</sup> (Schneider 2000) which is about 6% of the total basin area, but it contributes more than 70% of the river runoff. The Upper Tana Basin has been the focus of a number of studies geared toward understanding soil erosion and sediment transport dynamics (Dunne and Ongwenyi 1976; Ongwenyi 1983; Schneider 2000).

**Table 1. The main drainage areas in Kenya.**

Drainage basin	Area (km <sup>2</sup> )	% of the total area of Kenya
Lake Victoria	49,000	8.4
Rift Valley	127,000	21.8
Athi River	70,000	12.0
Tana River	132,000	22.7
Ewaso Ngiro	205,000	35.1

Rainfall in the Upper Tana Basin is controlled by the Indian Ocean monsoons in combination with pronounced orographic effects of the inland hills and mountains (Ewbank and Partners 1974). The Aberdare and Mount Kenya regions receive heavy rainfall (>1800 mm/year). Between 1800 and 1200 m ASL, rainfall is high, 1000-1800 mm yr<sup>-1</sup>. However, in the Lower semi-arid regions, rainfall is much Lower ranging 500-750 mm yr<sup>-1</sup>. This is particularly so in semi-arid zones of the basin such as Embu, Kitui, Mwingi and Tana River districts. Evaporation in these areas is about 1800 mm yr<sup>-1</sup>, but there are significant seasonal variations.

The basin in general experiences two rainfall seasons controlled by the south-east (between March and September) and north-east (between October and early March) monsoons (Ojany and Ogendo 1985). The southe-east monsoon is associated with the long rains, which occur between March and June, with maximum rainfall in May. The north-east monsoon is associated with the short rains (November and December) with peak rainfall in November. However there are often great inter-annual variations in rainfall, partly due to *El-Nino* and *La Nina* southern oscillation cycles.

Rainfall in the Upper Tana Basin is more important than snow melting on Mt. Kenya in increasing the river runoff, with a good relationship between rainfall in the Central Kenya Highlands and river runoff in the basin. The maximum river discharge at Garsen in the Lower Tana Basin is experienced in June and December, implying a time lag of about one month between peak rainfall and peak river discharge in the Lower Tana Basin. The river discharge varies from less than 10 m<sup>3</sup> s<sup>-1</sup> in the dry seasons to over 2,000 m<sup>3</sup> s<sup>-1</sup> during flood flow conditions (UNEP, 1998). During normal rainfall years, river discharge ranging 100-500 m<sup>3</sup> s<sup>-1</sup> is common in the Lower Tana Basin. The mean annual river runoff has been estimated to be 4,700x10<sup>6</sup> m<sup>3</sup> per year, or about 32% of the total mean river runoff in Kenya estimated to be 14,836 x10<sup>6</sup> m<sup>3</sup> per year (Ojany and Ogendo 1985). Due to rainfall anomalies in the Western Indian Ocean which result in exceptionally high rainfall in Central Kenya, the Lower Tana Basin experienced extreme floods in 1937, 1947, 1951, 1957-8 and 1961 (Ojany and Ogendo 1985). However the severity of these floods has been reduced since the construction of Masinga high dam in the Upper Tana Basin (Otieno and Maingi 2000).

### **Land use and water resources programmes**

The Upper Tana catchment area in Central Kenya covers an area of 7,950 km<sup>2</sup> (Schneider 2000) which is about 6% of the total basin area. ample rainfall and good volcanic soils have favoured maximum exploitation of the agricultural potential of the highlands and heavy human population settlement (Ojany and Ogendo 1986), predominantly encompassing the Central Kenya administrative districts of Kirinyaga, Murang'a, Nyeri, Thika, Meru and Embu. The main urban centers include Thika (also an important industrial center), Murang'a, Embu and Meru.

The soils of Central Kenya are well-covered with dense evergreen forests. There are mainly deeply weathered loams with high infiltration rates and low erodibility despite the steepness of the land (Ewbank and Partners 1974). Between 1800 and 1200 m ASL, rainfall is high (1000-1800 mm per year) and slopes are steep with loamy soils. However, where the former woodland vegetation has been removed and replaced with cultivated agricultural crops such as tea and coffee, bananas, vegetables, maize and beans, continuous tillage has reduced the natural fertility of the soil and this has necessitated the use of industrial fertilizers to boost crop production. Most of the crops grown in the region do not provide adequate ground cover, so the rate of erosion is greatly accelerated despite the generally low erodability of the soils

(Otieno and Maingi 2000). Major sediment-contributing areas are the densely populated and intensively cultivated foothills of the Aberdares, rather than the semi-arid lowlands (Schneider 2000). In the Murang'a and Nyeri districts the steep, intensively cultivated slopes are the main contributors of sediment into the Masinga Dam and the Tana River (Dunne 1974).

The main hydroelectric power-(HEP) generating dams constructed across the Tana River are in the Upper Tana Basin. These include Masinga, Kamburu, Gtaru and Kiambere HEP dams. Masinga Dam, the Uppermost reservoir, has impounded 45 km of the 1,102 km long Tana River and created a body of water covering 25 km<sup>2</sup>, one of the largest artificial lakes in East Africa. Masinga Dam acts as a high dam, controlling water storage and discharge for the turbines of the dams downstream (Kamburu, Gtaru and Kiambere). Data showing the contribution of the main Tana River tributaries to the total sediment discharge into Masinga Dam is shown in Table 2. In addition to these reservoirs, Sasumua reservoir provides much of the water used in the Kenya's capital city, Nairobi.

**Table 2. Mean annual discharge and sediment inflow into Masinga reservoir.**

<b>Tributary</b>	<b>Water Discharge (m<sup>3</sup>)</b>	<b>Suspended sediment inflow (t yr<sup>-1</sup>)</b>	<b>Bedload discharge (t yr<sup>-1</sup>)</b>
Tana	2239	3,890,000	390,000
Maragua	412	2,290,000	230,000
Saba Saba	120	990,000	100,000
Chania	205	870,000	90,000
Thika	252	420,000	40,000
<b>Total</b>	<b>3228</b>	<b>8,460,000</b>	<b>850,000</b>

Source: Otieno and Maingi (2000).

Poor land-use practices in the rich agricultural Upper Tana basin have increased soil erosion and a large quantity of sediments enters the reservoirs annually (Dunne and Ongwenyi 1976; Ongwenyi 1983). The long-term sustainability of these dams is in doubt due to reduction of their design capacities from heavy siltation (Schneider 2000; Otieno and Maingi 2000). The Tana River sediment load is 1-7 million t yr<sup>-1</sup> during high-flow conditions (Schneider 2000). However, the mean annual discharge of water-suspended sediment into Masinga reservoir is 8.46 million tonnes against a mean annual water discharge of 3,228x10<sup>6</sup> m<sup>3</sup> (Otieno and Maingi 2000). This means that the sediment discharge downstream of the Masinga Dam is slightly less than 8 million tonnes per year, because the reservoirs trap a large portion of sediments from the Upper Tana Basin which is the main source of sediments carried by the river.

Various studies have yielded different sediment load estimates (Table 3). This is due to differences in the accuracy of the river runoff data, varying periods of data analysis and differences in techniques applied in the computation of sediment fluxes. Quantitative sediment yield estimates are difficult to produce with any degree of certainty. Prediction of the future rates of sediment yield is even more problematic given the variation in the annual discharge of the river. Most of the previous studies have extensively relied on the use of historical river discharge and suspended sediment concentration records to determine the sediment yield in the Upper Tana catchment (Schneider 2000). River and sediment discharge records include large gaps in some of the data and inaccurate analytical and river-gauging approaches result in erroneous estimates. There is a need to improve on the river and sediment discharge monitoring through regular maintenance of river gauging stations and regular collection of suspended sediment concentration data at representative river gauging stations.

**Table 3. Sediment yield for the Upper Tana River basin.**

Source of data	Sediment yield (t yr <sup>-1</sup> )
Gibb (1959)	280,000
ILACO (1971)	250,000
Dunne (1975)	1,283,000
Dunne and Ongwenyi (1976)	568,547
Edwards (1979)	334,730

the Lower Tana Basin is mainly semi-arid with rainfall of 500-750 mm yr<sup>-1</sup>. Low rainfall, hot climatic conditions (30-35°C) and poor soils have resulted in low agricultural potential and therefore low human population densities. The human population is concentrated along the floodplains of the river, particularly in Tana River district, where the annual influx of floodwater during rainy seasons deposits fertile silt on the floodplains which in turn sustains the cultivation of rice and bananas by the riverine tribal communities. In the more arid zones of the basin, the main land-use activity is livestock grazing.

The Lower Tana Basin also has relatively flat coastal plains, which have encouraged the development of large-scale irrigation schemes such as the Bura, Hola and Tana Delta schemes. These development ventures were initiated by the Kenya government with generous bilateral and multilateral financial assistance from donor countries. However, these schemes have proved uneconomical and have failed. The main crops grown in these irrigation schemes were cotton and rice. As a result of the low nutrient status of soils in the Lower Tana Basin, there was heavy application of industrial fertilizers to improve production. At present, the only surviving large-scale irrigation project is Mwea-Tebere Irrigation and Settlement scheme in the Upper Tana Basin.

### **The Tana Delta dynamics**

Despite being the largest deltaic system in Kenya, the Tana River delta and its associated estuaries has not been targeted for comprehensive research studies. Thus the hydrological and ecological dynamics within the delta are poorly known. The processes within the delta can be discussed only on the basis of very limited field investigations and reconnaissance surveys that have been carried out in the area.

The Tana River in its lower reaches forms a complicated drainage pattern of braided channels and meanders, with ox-bow lakes formed as a result of the interlocking erosion-deposition events. Downstream of Garsen, the river starts to break up into several distributaries which combine to form what is loosely referred to as the Tana Delta. In fact these distributaries are thought to be former channels of the river that have since been abandoned when the river shifted its course as it headed towards the Indian Ocean. The Tana River has changed its course over different time-scales (Ojany and Ogendo 1985), but the reasons for doing so are poorly known. The present main course of the river is to the north of the delta, where it enters into the Indian Ocean through a mangrove-fringed estuary at Kipini. Its former outlet is about 32 km south-west of Kipini.

The flow of nutrient-rich freshwater to the Indian Ocean has led to the formation of a rich fishery at Ungwana Bay, which is regularly targeted by large-scale commercial fishing companies because of the abundance of prawns (UNEP 1998).

The tidal influx from the Indian Ocean penetrates approximately 2-7 km into the estuary at Kipini, taking saline water into the inner portions of the delta. As evidence of the outflow of river water into the Indian Ocean, there is no coral reef complex in Ungwana Bay. Within the bay, circulation is driven by the river discharge, tides, monsoon winds and the coastal current systems, particularly the seasonally reversing Somali Current and the East African Coastal Current. Unfortunately, there are no studies detailing the degree of influence of these forcing factors on water circulation in the bay and delta. There have also been no hydrological studies geared at examining the main circulation patterns in the delta, including also the patterns of material (nutrient and sediment) transport and exchange. This is unfortunate since the Tana

Delta is one of the most important riverine systems in Kenya and is regarded as an important wetland for wildlife conservation by the Ramsar convention, of which Kenya is a signatory. Lack of studies in the area seem to have mainly been due to insecurity and inaccessibility. The delta is located in a remote part of the Coast Province with a poor transport network and facilities. Encroachment by armed bandits has also compromised security and development in the area.

The Tana Delta is certainly different from the Mwache, Mida and Gazi creeks (Kitheka 1998; Kitheka *et al.* 1999; Kitheka 2000), but there are certain fundamental aspects that could be similar given that these systems are fringed with mangroves and all receives freshwater discharge. Mangrove wetlands have been known to modify water and sediment circulation patterns and their presence along the estuary is certain to alter sediment transport dynamics.

### **Anthropogenic impacts and synergies**

In the absence of any reliable data on anthropogenic impacts in the Tana Delta, it is difficult to offer a concrete synthesis of the likely relationship between man and the biophysical system at the delta. However, experience in similar systems helps us to understand the possible connections between the two (Kitheka 1998; Kitheka *et al.* 1999; Kitheka 2000).

There is no doubt that soil erosion in the Central Kenya highlands is impacting negatively on hydroelectric power reservoirs in the Upper Tana Basin (Ongwenyi 1979; Ongwenyi 1983; Schneider 2000; Otieno and Maingi 2000). The design capacities of these dams declined over the years with the result that the Masinga reservoir cannot hold enough water for the generation of electricity. The reservoir also cannot hold enough water in periods of high river discharges and therefore its role in flood mitigation is being reduced steadily. In periods of severe droughts, there is rationing of electricity throughout the country, which severely constrains the industrial sector since industrial production in Kenya is highly depended on power supplied from the Tana River HEP dams.

Reduction in the design capacities of the Upper Tana River reservoirs has also complicated water supply schemes in both rural and urban areas due to heavy expenditure required for water treatment particularly in the removal of silt. This has increased the cost of treating water for domestic and industrial uses. Low storage capacities of the reservoirs has also reduced the volume of water available for rural and urban water supply, large and small-scale irrigation schemes.

In irrigation schemes located in the Lower Tana Basin, siltation of irrigation channels has necessitated expensive irrigation canal maintenance works, and irrigation water pumps constantly break down as a result of clogging due to high silt content of the river water.

In the Tana Delta, the main impact of heavy siltation has been the destruction of large hectareage of mangrove forests, which are important coastal ecosystems. Mangroves are thought to be nursery grounds of fishes and crustaceans of high commercial value, so their destruction affects the fisheries sector. This will definitely impact negatively on the socio-economic status of the local population. However, apart from destruction due to high sediment supply, destruction of mangroves also occurs through extensive uncontrolled cutting by local inhabitants. The destruction of the mangrove wetlands through these processes reduces the sediment-trapping role of the mangroves, allowing more terrigenous sediment to enter directly into the Indian Ocean where the resulting highly turbid water may be detrimental to marine ecosystems.

### **Research needs in the Tana Delta in the context of LOICZ**

A comprehensive hydrological study should be initiated under the auspices of the Land-Ocean Interaction in the Coastal Zone (LOICZ) project, to examine the main circulation and material transport (both sediments and nutrients) patterns in the delta, and the influence of the mangrove forests in trapping terrigenous sediments from Tana River with a view of advising on their management. The project should

also aim at determining the dynamics of sediment and nutrient transport along the Ungwana Bay coast, taking into account the patterns of the south-east and north-east monsoons as well as the dynamics of the coastal current systems. The project should run for two to four years, targeting both high and low river flow conditions, with time-series measurements of tides, tidal flow, tidal current velocities and directions, river discharge, suspended sediment concentrations, salinity, temperature and nutrient concentrations particularly silicates, nitrite-nitrogen, nitrate-nitrogen and orthophosphates. These parameters should be measured with reliable and accurate scientific equipment, including Orbital Backscatter turbidity sensors, MicroTide pressure gauges, Aanderaa Recording current meters (RCM-9), Atomic Absorption Spectrometer (AAS) and Auto-Analyser. Some of this equipment is currently available at the Kenya Marine and Fisheries Research Institute (KMFRI) at Mombasa. KMFRI is a government of Kenya research organisation with the mandate of conducting all aspects of aquatic research in Kenya.

## Conclusions

Although the Tana River is one of the largest and most important river system in Kenya, its linkage with the Indian Ocean is at present poorly known. There have never been comprehensive studies on the hydrology of the Tana Delta. Variations in material concentrations and fluxes to the Indian Ocean are only poorly known. Most studies have been concentrated in the Upper Tana Basin but, because delivery ratios of different materials transported by the river have not been established, it would be scientifically inappropriate to use Upper Tana data to compute water and material fluxes to the Indian Ocean. The Tana River Basin, including the Tana Delta, offers a good location for determining how changes in the coastal system may feed back on the human system. It is recommended as perhaps the best case study site in Africa for studying Land Ocean Interactions in the Coastal Zone.

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#### **4. 19 Determining patterns of contaminant flux through basins and the coastal zone over time: methodologies and applications for Africa**

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##### Abstract

Integrated coastal zone management is increasingly focused on links between catchments and coasts in which the coastal zone is seen as part of a continuum between the river basin and the open sea. To enable effective environmental management decisions to be made there is a need for a good appreciation of which human activities and natural processes are the most important controls on the flux of key materials, such as C, N, P, sediments and contaminants through this continuum. To achieve this it is necessary to link spatial and temporal patterns of both human activities and natural change within river basins and along coasts with the flux of key materials to the sea. This is done best using sedimentary records and two UK research programmes, the Land-Ocean Interaction Study and the Land-Ocean Contamination Study have developed simple, cost-effective, methodologies that may be applied readily to the flux of contaminants (principally heavy metals) from land sources to the sea. The methodologies use pre-existing geochemical datasets, where available, and are based on comparison of the characteristic natural geochemical variability in river basins and on coasts with the geochemical record contained in sediment cores from contaminated sites in fluvial or nearshore settings. Examples are described, including cases from Kenya and Zimbabwe, and the potential for their adaption to calculating the flux of other key materials, mainly sediments, is discussed. The benefits of applying the methodologies to other parts of Africa, largely using pre-existing data, and a typological approach to scaling-up conclusions as utilized by LOICZ are set out.