Estuaries of the World

Salif Diop
Peter Scheren
John Machiwa *Editors*

Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean

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Estuaries of the World

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Fishing boats resting on Pemba Island, Tanzania (photo by Peter Scheren, February 2010)

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“. . .*Doubling the share of African University graduates in science and technology fields within a decade, by 2025 is the key to transform Africa into a knowledge-driven continent within a generation. . ...*”

From ***Makhtar Diop***, World Bank’s Vice President for Africa. *Extracted from an article written 24th May, 2014 for an Ethiopian Journal* “*The Reporter*” *by Moctar Diop on* “*Powering Science, technology for Africa’s economic transformation. . .*

“***Put your thoughts*** *in order by reflection, pen in hand****.*** *Appropriate you the power of the pen. Read, read,* ***read*** *every day, pen in hand.*”

From Nelson **Rolihlahla** *Mandela* “*Madiba*” (1918–2013).

Foreword

It is in estuaries and deltas where the richness of the land meets the abundance of the sea, creating an environment of high diversity, dynamism and productivity. Nevertheless, the important contributions estuaries make to local livelihoods and national economies, as well as to their complex role in the functioning of the land-ocean interface, are often overlooked.

The Western Indian Ocean is dotted with important estuaries and deltas, including the Tana and Sabaki in Kenya, Pangani, Rufiji and Ruvuma in Tanzania, Zambezi, Incomati, Maputo, Pungwe and Limpopo in Mozambique, Thukela in South Africa and Betsiboka in Madagascar. With numerous plans and investments in place for a massive acceleration in infrastructure development and energy and food production, human activities will increasingly impact these important estuarine and coastal ecosystems and the life-supporting services they provide. In this regard, the unique, diverse and productive estuaries and deltas of the Western Indian Ocean stand at a crucial crossroad.

The Western Indian Ocean is internationally recognized as a hot spot of biodiversity, hosting one-third of the 38 globally, recognized marine and coastal habitats, an abundance of fish species and marine mammals, all five marine turtle species, over 40 species of seabirds and the longest fringing reef in the world. The region is also home to the charismatic coelacanth, nicknamed the living fossil, and the critically, endangered sawfish and seahorse. Furthermore, the region's coastal and marine waters are important fishing grounds, supporting the livelihoods of the local population. Its marine parks and other protected areas are also the basis for an active tourism industry.

The unfortunate reality, however, is that human activities in these river catchments are having increasingly serious impacts on these sensitive downstream estuarine and coastal ecosystems. The damming of rivers over the past 50 years, combined with reduced rainfall, expansion of irrigated agriculture and other increasing water abstraction and land uses within various catchments, are among the underlying causes of those changes. Furthermore, pollution from municipal and industrial effluents is exacerbating the serious degradation of waters and sediment quality that is being observed in these rivers, estuaries and coastal waters, resulting in a loss of biodiversity, increasing eutrophication and reduced fish catches in many locations in the Western Indian Ocean.

To set the stage for addressing the continuing degradation of these important land-sea interfacing water systems, this publication was made possible due to the leadership of four scientists: Prof. Salif Diop from the University of Dakar; Dr. Peter Scheren from WWF; Prof. John Machiwa from the University of Dar es Salaam and Prof. Jean-Paul Ducrotoy from the Institute of Estuarine and Coastal Studies, The University of Hull, UK.

The focus of this book is on estuaries, but its scope and implications extend well beyond this particular coastal feature. Indeed, estuaries can only be considered as part of the life cycle of the entire river basins draining into them and the downstream marine areas that receive these riverine inputs. These interlinked systems and the life-supporting ecosystem services they provide are particularly sensitive to human and natural pressures; hence the title of this book "**Estuaries: a Lifeline of Ecosystem Services in the Western Indian Ocean**". It is our belief that this book will be a valuable source of information and guidance for the numerous scientists, researchers, managers and decision makers concerned with the integrated management of estuaries, deltas, lagoons, and the coastal and marine areas of the Western Indian Ocean and will help facilitating their sustainable use.

UNEP, Nairobi, Kenya	Ibrahim Thiaw
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Preface

This volume “Estuaries: a lifeline of ecosystem services in the Western Indian Ocean” published in the book series “Estuaries of the World” (EOTW) by Springer is the second of its nature focusing on Africa. The case studies presented in this book provide clear evidence of the fact that the estuarine ecosystems of this region are extremely valuable in providing cultural (recreational, spiritual, etc.), provisioning (food, timber, etc.) and regulatory (flood protection, climate regulation, etc.) services that are not only at the core of the coastal ecosystem functioning, but also an important basis of livelihoods of over 60 million inhabitants living in the region; the coastal ecosystems of the region, and in particular estuaries, represent important socio-economic values based on irreplaceable ecosystem functions. However, these valuable ecosystems are subject to a range of human pressures that may compromise the health of living human residents. These disturbances are multiple and include pollutants, excess nutrients (causing eutrophication), loss and transformation of habitats and disturbance of hydrological regimes causing flooding and unpredictable flow patterns. The effects of these impacts, often acting in cumulative and synergistic manners, affect the overall stability of the system and threaten its strength and resilience.

Unfortunately, due to inadequacies in the management and governance of these ecosystems, local management is often unable to control the basic causes of these attacks on ecosystem integrity, instead passively responding to their consequences without treating the cause. In addition, the exogenous pressures imposed by global climate change amplify the scale of stress on ecosystems. Its consequences (e.g. the increase in temperature, sea level rise, increased risks of flooding, etc.) may intensify the risk of seeing abrupt and nonlinear changes in natural systems. This will have an impact on flora and fauna, their structure (species richness and biological diversity), their functioning and their biological productivity.

At risk of compromising future development, policy makers are confronted with economic and legal constraints which often are antagonistic. The complexity of understanding human-marine coastal environment interactions as evidenced in this book, explain why the ecosystem-based approach constitutes one of the most valuable frameworks for promoting the sustainable development of marine and coastal ecosystems in the Western Indian Ocean as elsewhere in the world. Indeed, the book shows that adequate knowledge, scientific information and capacity, awareness and governance on ecological processes and the important role and value of ecosystems goods and services they provide are the key to allowing coastal communities and policy makers to define adequate responses to the threats at hand.

The potential of coastal or estuarine systems to provide crucial ecosystem functions and services depends on the stability of prevailing abiotic conditions, organised along gradual gradients and ecotones; a good understanding of the diversity of ecological processes in estuaries is therefore critical to apprehend the complexity of the system. More so, it is important to understand the linkages between these ecosystems and the economic realm, including aspects of market, land and other property rights regimes, as well as their related government structures and social networks. Unfortunately, more often than not, economic forces have considered ecosystems and the resources they provide as “free”, not taking account of their economic externalities in terms of the adverse effects of their use.

Based on the above underlying philosophy, the present book chapters describe the various ecosystem functions and values of the region's estuarine ecosystems and their respective habitats, including the land/ocean interactions that define and impact ecosystem services. The Western Indian Ocean region covered by this volume consists of the continental coastal states of Kenya, Mozambique, South Africa and Tanzania and the island states of Madagascar, Seychelles, Comoros and Mauritius, all being signatories to the Nairobi Convention for the protection, management and development of the marine environment of the region. One of the main goals of the Nairobi Convention is "to promote a mechanism for regional cooperation, coordination and collaborative actions in the Eastern and Southern African region that enable the contracting parties to harness resources and expertise from a wide range of stakeholders and interest groups towards solving interlinked problems of coastal and marine environment, including critical and transboundary issues".[1]

The authors of the book do hope that their scientific contribution will help support decision making and promote robust capacity building and management programmes tailored to the region's needs. In this regard, this book aims to provide a good scientific assessment of ecological conditions prevailing in the region which undoubtedly will benefit any future commitment to sustainable development of coastal areas of the Western Indian Ocean.

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[1] *extract from the* "*Nairobi Convention*".

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Prof. S. Diop is a water expert with number of referred related publications and broad experience in various aspects of scientific assessment of freshwater, coastal and marine resources as well as in areas related to the management and sustainable development of the environment. So far, he pursued the coordination of important international programmes on freshwater, marine and coastal processes, including scientific assessment of marine and coastal waters, assessment of groundwater resources in Africa and in other regions of the world, on evaluation processes and scientific assessment of the world oceans and coasts; on geosphere-biosphere interactions; on integrated management of marine areas and coastal interfaces land/sea/water and atmosphere; on assessment of water resources as a key factor for sustainable development; on the development of modules for the evaluation of freshwater resources, wetlands, marine waters and coastal areas, including the relations and impacts of climate change. Prof. S. Diop has worked at the United Nations, in particular at UNEP's Division of Early Warning and Assessment (DEWA) as a Senior Officer for nearly 16 years. He holds from University Louis Pasteur/Strasbourg/France, a 3rd cycle doctorate he defended in 1978 and a state doctorate he defended in 1986. As Senior Fulbright Scholar, he spent one year sabbatical in Rosenstiel School of Marine and Atmospheric Sciences of the University of Miami/USA, Division of Biological and Living Resources in 1986/87. For more details, including his most recent publications, consult the website of Professor Salif DIOP at http://www.esalifdiop.org

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Peter Scheren holds a PhD from the University of Eindhoven and University of Wageningen in the Netherlands, with a focus on integrated environmental assessment of large water bodies. He has worked for various research institutions, consultancy offices and managed several large-scale coastal and marine programmes in Africa for the United Nations Environment Programme and the United Nations Industrial Development Organisation.

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Tana Delta and Sabaki Estuaries of Kenya: Freshwater and Sediment Input, Upstream Threats and Management Challenges

Johnson U. Kitheka and Kenneth M. Mavuti

Abstract

This study is focused on the determination of the extent to which changes in river freshwater and sediment input affects the sustainability of the Tana Delta and Sabaki estuaries in Kenya. The study involved the determination of river freshwater and sediment fluxes, as well as water exchange and sediment fluxes at the mouths of the two estuaries. The horizontal and vertical distributions of tidal current velocities, salinity and total suspended sediment concentrations (TSSC) within the estuaries enabled determination of the degree of stratification and the extent to which mixing of seawater and freshwater leads to the formation of the maximum turbidity zone (TMZ) in the two estuaries. The two estuaries are important for biodiversity conservation, sustainability of socio-economic livelihoods and provision of global environmental benefits. The study shows that the hydrologic dynamics controlling water circulation including the trapping and exchange of terrigenous sediments in the two estuaries is a function of the river discharge and tidal forcing. In the much smaller Sabaki estuary, there has been a reduction in freshwater input and an increase in sediment supply leading to heavy accretion. The shallow nature of the Sabaki estuary ensures reduced penetration of the semi-diurnal tidal wave into the estuary and seawater intrusion is restricted to 2.5 km of the estuary. On the other hand, there has been a substantial reduction in both freshwater input and sediment supply into the Tana Delta. This has led to deepening of the estuary channels with the result that tidal wave penetrates much deeper into the estuary and seawater intrudes up to 10 km inside the estuary. The tidal asymmetry in the two estuaries is characterized by ebb tidal flow dominance due to presence of mangrove forests, wide intertidal areas and freshwater input. This has resulted in net export of sediments out of the two estuaries. However, the cohesive clay sediments are trapped within the estuaries in mangrove forest wetlands and in sheltered intertidal areas that are now occupied by mudflats. The shallow Sabaki estuary experiences greater rates of water and sediment exchange as compared to the relatively deeper Tana estuary. The changes in freshwater and sediment supply into the two estuaries were attributed to landuse change, damming and climatic variability. The major impacts in both estuaries include high turbidity, heavy sedimentation, changes in beach morphology and degradation of the marine ecosystems such as the coral reefs and seagrass beds. In

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the Tana delta system, the impacts include high turbidity, alteration of the morphology of the delta, degradation of the mangrove forests, coastal erosion and sea water intrusion. The study notes that the proposed large-scale hydropower and irrigation projects in the Athi-Sabaki and Tana river basins have the potential of causing massive degradation of the two estuaries. The paper puts forward recommendations for sustainable management of the two estuaries in Kenya.

Keywords
Tana and Athi • Sabaki • River basins • Estuaries • Freshwater supply • Sediment input • Water exchange • Sediment trapping • Landuse change • Climate variability • Hydrology

Introduction

Tana Delta and Sabaki estuaries are two major estuaries found along the Kenya coast in East Africa. The two estuaries are important for biodiversity conservation and sustainability of livelihoods. The two estuaries are highly vulnerable to global climate variability because there are sustained by freshwater inflows which are depended on rainfall which in the recent past has shown significant variability due to climate change. The estuaries are also facing diverse range of anthropogenic stresses related to landuse change, damming and water abstraction. The natural and human-related stresses in the two estuaries are influencing the key drivers of estuarine ecosystem health such as river runoff and tidal seawater incursion. The stresses associated with land-based development activities in the river basins are causing more stresses to the two estuaries as compared to marine-based stresses. The impacts of climate variability are being exacerbated by over-exploitation of natural resources and land use change as a result of rapid population growth and expansion. The increasing magnitude of natural and anthropogenic stresses in the two systems makes it important that information is generated to guide decision–makers in the processes of approving development projects in the upstream areas including also the formulation of strategies for the protection of the two estuaries at the coast.

The two estuaries present interesting contracts in terms of their spatial extent, hydrology, geomorphology, land uses and pressures. Tana Delta has several distributaries and estuaries, making it much larger as compared to the Sabaki Estuary. The Tana Delta receives much greater river runoff on account of its origin from the high rainfall region of Central Kenya Highlands. In addition, the Delta has a much larger extent of mangrove forest including riverine forests along the upper reaches of the Tana river. The Sabaki estuary has a small patch of mangrove forest and lacks a well-formed riverine forest in its upper course. In terms of development, the Tana river basin has been subject of major development projects which includes hydropower development, water supply and irrigation schemes. There are few major development projects in the upper course of the Athi River with the exception of industrial development in Nairobi region. Both estuaries are considered important for biodiversity conservation and they also support livelihoods of coastal communities including the sustainability of the productivity of Kenya's most important fishing ground through the supply of freshwater, sediments and nutrients.

Previous studies on the two estuaries have focused mainly on estuarine hydrodynamics (Kitheka et al. 2003a, b, 2005). These studies have been critical in understanding key features of the two estuaries. Past studies in the two estuaries and Ungwana Bay have also elucidated on the seasonal changes in the movement of turbid water plume (Brakel 1984; McClanahan and Obura 1997; Kitheka (2013). There have also being several investigations on the impact on high sediment load on the biodiversity particularly on corals within the Malindi bay (McClanahan and Obura 1997). Most of the previous hydrological investigations have been focused on the upper Tana Basin, with few studies on the Athi-Sabaki river Basin (e.g. Ongwenyi 1983; Pacini et al. 1998; Maingi and Marsh 2001; Maingi and Marsh 2002). There is lack of information on the effects of hydrologic alteration of the rivers discharging into the two estuaries. This study attempts to fill this gap by examining the dynamics of freshwater and sediment input into the two estuaries and how changes in the magnitude of freshwater and sediment supply have influenced the two estuarine systems. The study also examines how changes in the magnitude of river freshwater and sediment input influences estuarine water exchange and the morphological structure of the two estuaries. The study is also important in understanding the impacts of global environmental change on tropical estuaries as it also examines the effects of climatic variability of freshwater input in the two estuaries. The study provides information that can be used to guide the processes for the formulation of strategies for sustainable management of the Tana and Athi-Sabaki estuaries in view of their importance for biodiversity conservation, provision of livelihoods and global environmental benefits such as carbon sequestration. The later is important in mitigating the effects of climate change.

Description of the Study Area

Tana Delta and Estuary

The Tana Delta (Longitude 2°30’0”S & Latitude 40°18’20” E) receives runoff from the Tana river- the largest and the most important river in Kenya (GOK 1979). The delta consists of several distributaries in which the river divides into several branches in the area south of Garsen (Fig. 1). The river drains from the Central Kenya highlands as shown in Fig. 2. The points of outflow of the Tana river have changed significantly in the past as evidenced by the present drainage pattern of the delta (cf. Ojany 1984; Kairu 1997). The current main branch is at Kipini (Photo 2). The Tana delta is broad and crescent shaped at the coast covering a distance of nearly 40 km from Kipini distributary to the east to Mto Kilifi distributary to the south. The width of the delta decreases at an exponential rate from 40 km at the coast to about 10 km near Garsen- a distance of about 60 km. The estuaries are fringed by mangrove forests within the tide affected zone and in the upper freshwater zone is found a large freshwater water swamp. Riverine forests are found along the river banks but these been cleared in most areas within the river flood plains and only scattered patches are remaining. The mangrove forest is the most important ecosystem at the delta with dominant mangrove species such as *Xylocarpus granatum*, *Avicennia marina*, *Rhizophora mucrunata* and *Ceriops tagal*. The estuary and the turbid coastal waters are an important nursery ground for prawns and numerous species of fish and crustaceans. The sandy shores along Ungwana are considered important breeding grounds of turtles (FAO 1981; UNEP 1998; KMFRI 2002). Rainfall in the basin varies from 1500 mm per annum in the upper Tana Basin to about 500 mm in the semi-arid lower Tana Delta region.

Athi-Sabaki Estuary

The Sabaki Estuary (Longitude: 3.2°S & Latitude: 40.15°E) is located about 10 km north of Malindi town in Kenya (Fig. 3). The estuary receives freshwater and terrigenous sediment load from a 70,000 km^2 Athi-Sabaki river basin (Fig. 4). The estuary is characterized by heavy sedimentation (Photo 1). The estuary is vital for marine biodiversity conservation as it is considered an important bird sanctuary. Thousands of birds of various species forage on the inter-tidal mudflats during low tide. The estuary and the nearby turbid coastal waters are also an important nursery ground for prawns and numerous species of fish and crustaceans, some of which are of commercial importance (Ruwa et al. 2001; KMFRI 2002). The sandy shores flanking either sides of the mouth of the estuary extending into Malindi Bay are important breeding grounds of turtles (FAO 1981; UNEP 1998). The estuary also has a small mangrove forest habitat. High sediment load of the river has led the heavy siltation of the estuary and the adjacent Malindi Bay (Abuodha 1998; Delft Hydraulics 1970; GOK-TARDA 1981a–c; Ongwenyi 1983; McClanaham and Young 1996; Munyao 2001; Blom et al. 1985; Brakel 1984). Rainfall in the basin ranges from 1200 mm.yr^{-1} in the upper regions to less than 750 mm.yr^{-1} in the lower Sabaki estuary region. The rainy season is in the period between March and May and also in the period between October and December (Ojany and Ogendo 1986).

Methodology

Determination of Freshwater Input

The monitoring of river freshwater input was undertaken at River Gauging Stations located at Malindi and Garsen (RGS 4G02) for two years (2001–2003). Measurements were carried out on a monthly basis using standard hydrological procedures involving determination of river flow velocities using the cross-sectional-area velocity approach as described in Linsley et al. (1988). The past records of the discharges of the two rivers were obtained from the Water Resources Management Authority (WARMA). The rainfall data for stations located in the basins were obtained from Kenya Meteorological Department. These were used to establish the relationship between rainfall and river discharges in the two basins.

Determination of River Sediment Input

The river total suspended sediment concentrations (TSSC) were determined through filtration using Whatman GF filters according to APHA (1992) methods. Water samples were drawn at the middle of the main channel of the river, using a Niskin Sampler. These were subsequently analysed at the Kenya Marine and Fisheries Research Institute (KMFRI) marine environmental studies laboratory in Mombasa.

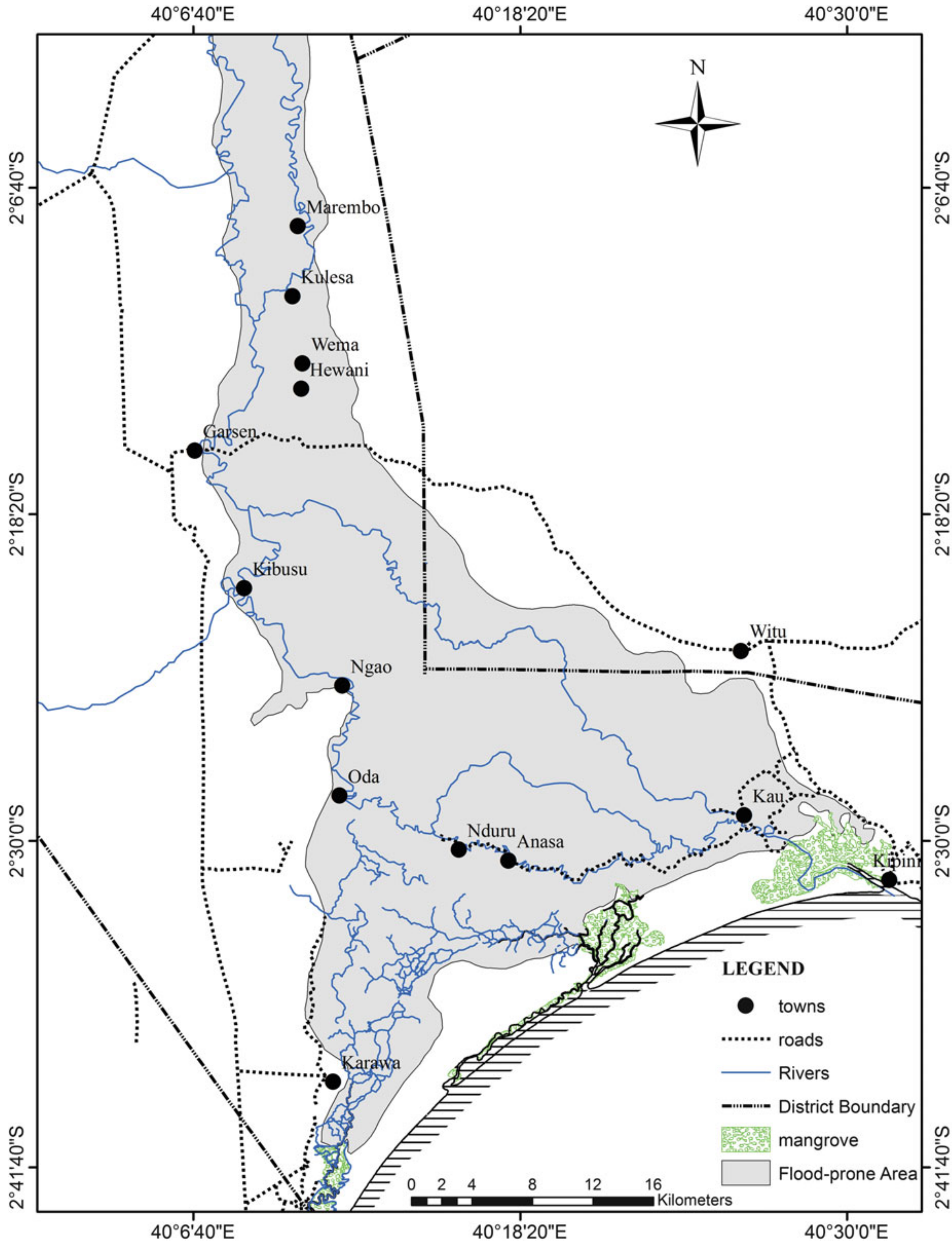


Fig. 1 The extent of the Tana Delta including the drainage network and mangrove forests

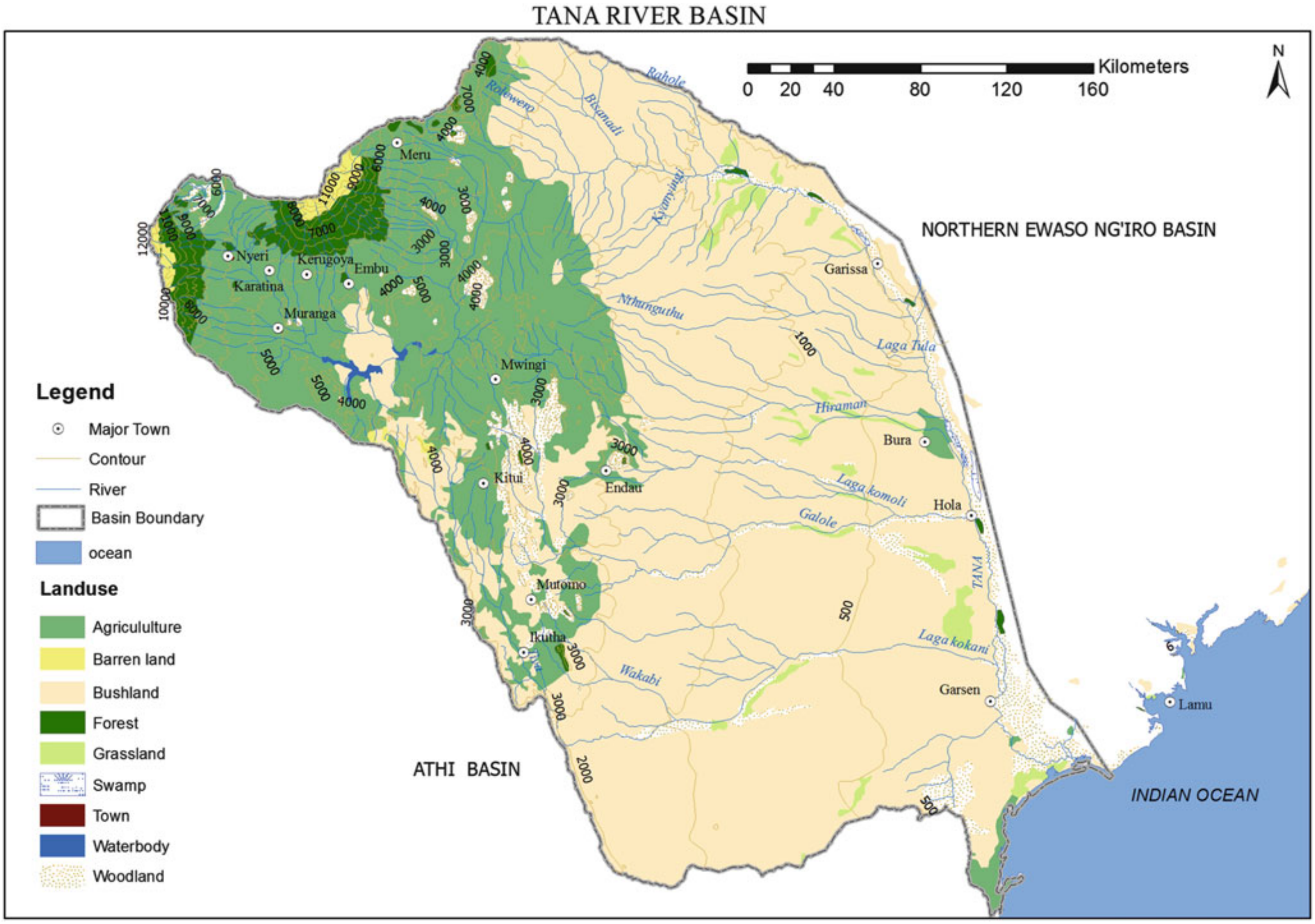


Fig. 2 The extent of the Tana River Basin in Kenya

Determination of Changes in River Freshwater Input

The study relied on past river discharge records archived by WARMA to determine the changes in the flow of the Athi and Tana river. In order to determine the changes of the Tana River, the past river discharge data for the Garsen river gauging station was split into pre-dam and post-dam periods. The pre-dam period was between 1951 and 1981 while the post-dam period was between 1982 and 1993. The pre-dam period was limited to the year 1981 because Masinga Dam which has had the most important impact on the river was commissioned in that year. The construction of the Masinga Dam in 1981 led to major impoundment of the river leading to significant impacts as compared to other relatively small dams that were constructed earlier before 1981. It is on this basis that we have used the construction of Masinga dam in 1981 as an important delineation of the period when significant impacts on the flow of the Tana river started being experienced. The past data for the Athi river for the period between 1952 and 1995 were also analysed to determine whether there has been any significant changes in the freshwater input at the Sabaki estuary. The most current river discharge records for the two rivers were unavailable partly as a result of the cessation of river discharge monitoring programme in 1998.

Using the past river discharge data, the daily and monthly river discharges were summed up and the mean and maximum flows were computed. The mean and maximum flows were plotted to establish key trends. The assessment of the impacts of water abstractions was based on the review of the findings of the past technical reports and development plans produced by the various consultancy companies for the Government of Kenya and the Tana and Athi Rivers Development Authority (TARDA) (e.g. ILACO 1971; GOK 1979; GOK TARDA 1982; GOK-JICA 1998).

Determination of Estuarine Water Circulation Dynamics

A field monitoring campaign was undertaken to establish the horizontal and vertical distribution of TSSC concentrations, ebb and flood tide current velocities and tidal elevations in

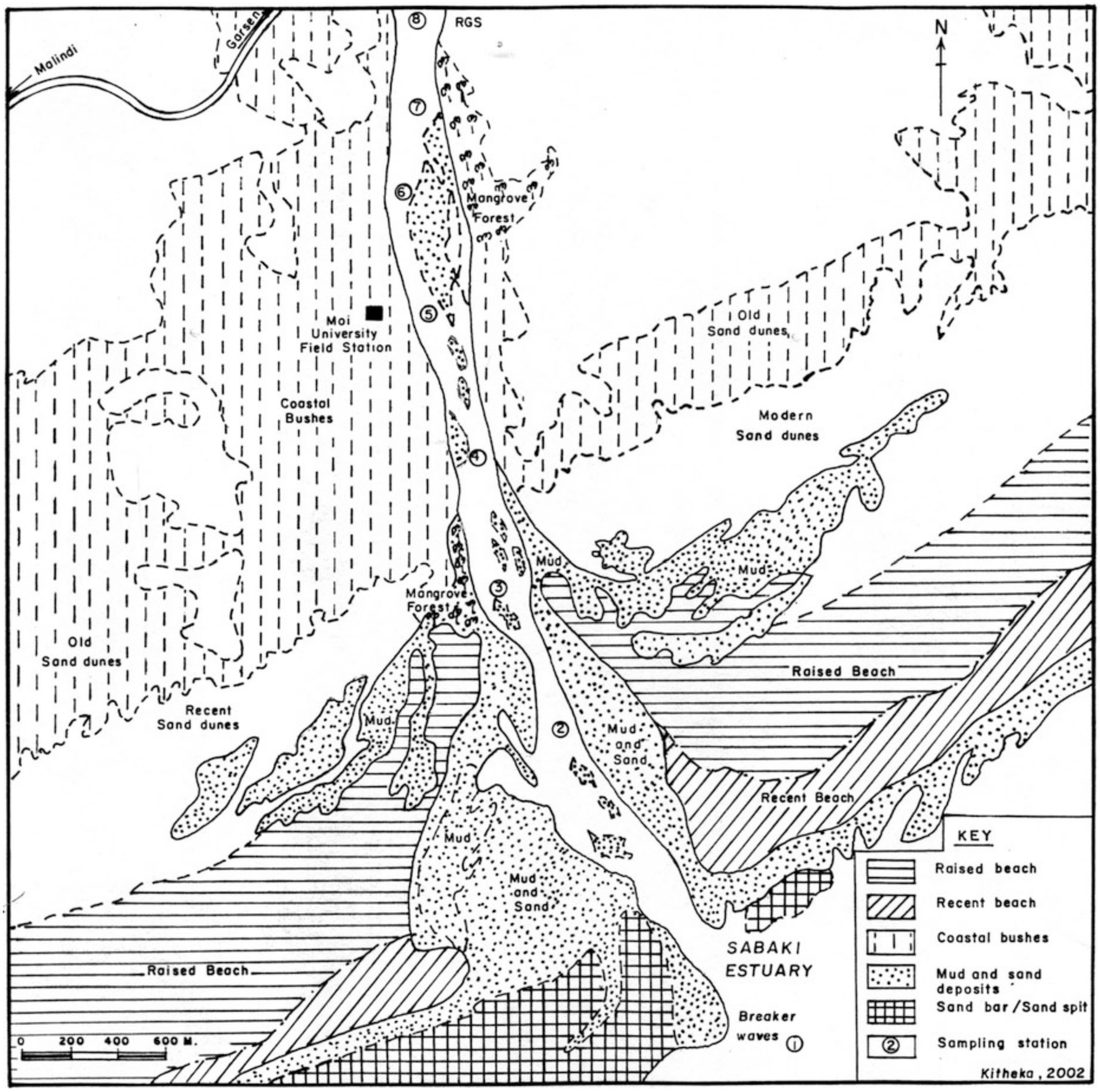


Fig. 3 Main physical features of the Sabaki Estuary and the immediate areas. Locations of sampling stations are also shown

the estuaries. Measurements of these parameters were undertaken in eight (8) sampling stations established in both Sabaki and Tana estuaries. For the Sabaki estuary, the sampling stations were located 0.5 km apart while in the Tana estuary they were located 1–1.5 km apart with stations 1 being located at the mouth of the estuary and stations 8 being located at the maximum limit of tidal excursion.

The TSS concentrations were determined using two approaches. The first approach involved the use of a turbidity sensor fitted on an Aanderaa Recording Current Meter (RCM-9) which was moored in different periods at stations 3 in the two estuaries. The turbidity sensor was programmed to log in turbidity at interval of 5 minutes. The second approach involved filtration of water-sediment mixture in the laboratory using Whatman GF filters according to APHA (1992) methods. In this method, water-sediment mixture samples at each station were drawn using a Niskin sampler at 0.2h, 0.4h, 0.6h and 0.8h, where h is the local water depth. Salinity in each of the sampling stations was measured at same vertical depths using a hand-held Aanderaa Salinometer and was expressed in terms of Practical Salinity Units (PSU). Tidal water levels were measured using divers' pressure gauges mounted on a RCM-9, which also logged in water level data at intervals of 5 minutes. Using a fast rubber dinghy, spot measurements of TSSC, salinity, tidal current velocities and water depths were carried out during high water (HW) in each of the 8 stations established in the Tana and Sabaki estuaries.

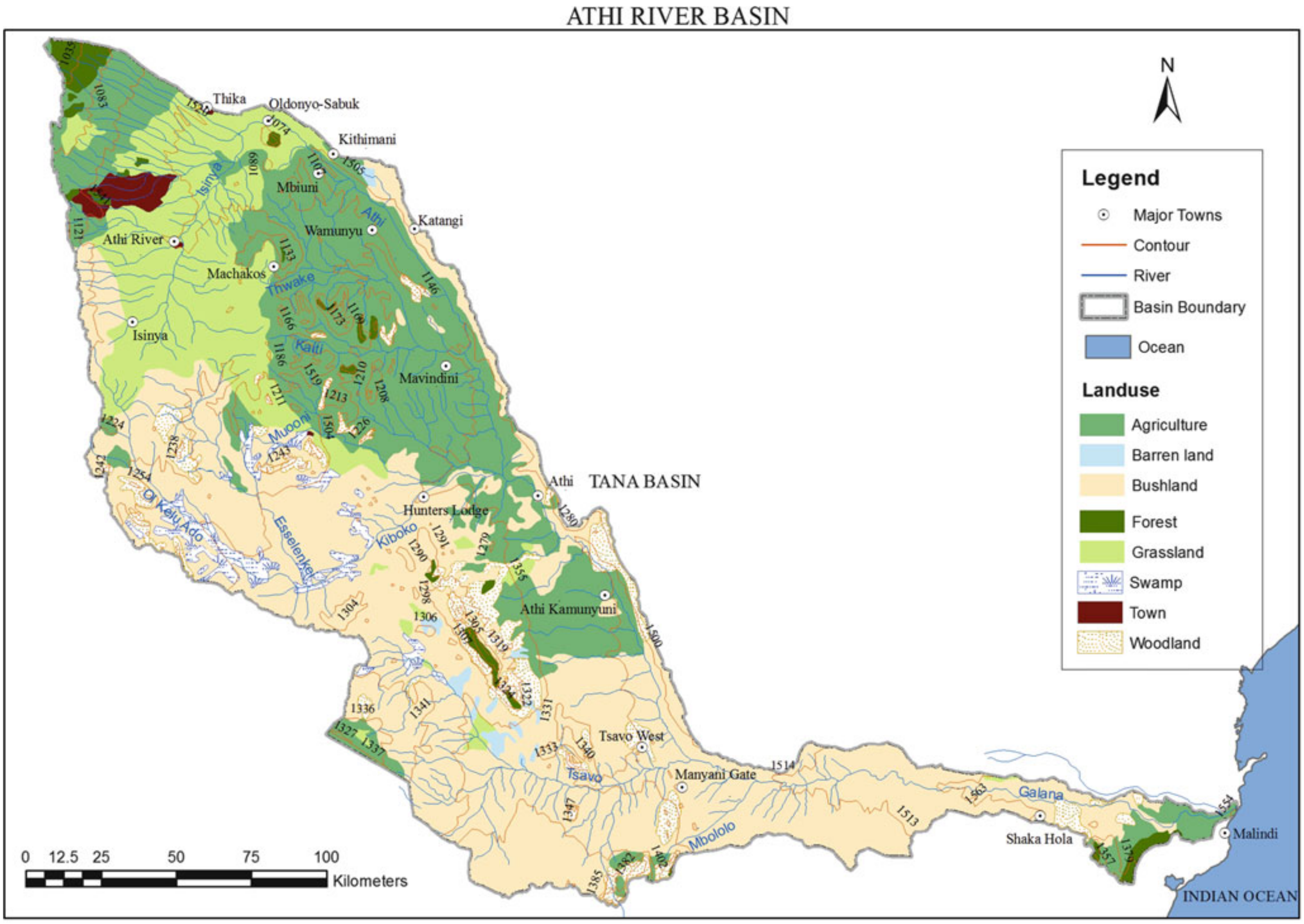


Fig. 4 The extent of the Athi-Sabaki River Basin in Kenya.

Photo 1 The mouth of the Sabaki Estuary showing heavy deposition of sediments and debris. The main channel and sand dunes are visibility on the far edge of the photograph

Photo 2 The Tana Estuary at Kipini showing the mangrove-fringed main channel and turbid water at high tide

Determination of the Coastal State Changes

The determination of coastal state changes was done through rapid field assessments. Field surveys were undertaken within the estuaries to determine the extent of sediment accretion and erosion, and the state of mangrove forests, among others. Observations were also made on the nature of sediment deposition within the mangrove forests, tidal channels, intertidal areas and along the shorelines. Sediment samples taken in these areas were subjected particle-size analysis using sediment sieves. Additional details on anticipated impacts were made through literature review of the findings of past studies.

Results

Input of Freshwater into the Estuaries

The freshwater input in the Tana Delta and Sabaki estuaries is important in controlling estuarine processes. The freshwater inputs are however highly variable with that of Sabaki estuary showing greater variability as compared to that of the Tana estuary. The river runoff in the upper zone of the Tana delta varied from 60 m^3s^{-1} in the driest period to 730 m^3s^{-1} in the wettest period. In the Sabaki estuary, the river runoff varied from 7 m^3s^{-1} in the driest period to 680 m^3s^{-1} in the wettest period (Figs. 5a, 5b, 6a and 6b). The river freshwater inputs in the Tana delta were in most cases >50 m^3s^{-1} as compared to the Sabaki estuary where it was low as 2 m^3s^{-1} during dry season. For the Sabaki estuary, the freshwater inputs $<$ 70 m^3s^{-1} were more common they occurred 90% of the time. The high freshwater inputs $>$ 150 m^3s^{-1} that are normally experienced during rainy season were less frequent in that they occurred in $<$ 10% of the time. For the Tana delta, the freshwater inputs <300 m^3s^{-1} were more frequent. The mean annual freshwater discharge into the Sabaki and Tana Delta estuaries were estimated to be 2,300 $\times$ 10^6 $m^3.yr^{-1}$ and 4,700 $\times$ 10^6 $m^3.yr^{-1}$, respectively.

The input of freshwater in the two estuaries shows significant seasonal variability. There are in general two periods of high freshwater input that are usually separated by dry periods in which the river freshwater input is of the order 50 m^3s^{-1} and 2 m^3s^{-1} for the Tana Delta and Sabaki estuaries, respectively. The periods of high freshwater inputs are also characterised by high sediment supply (Figs. 6a and 6b). These are March-April-May-June period (MAMJ) during the South-East Monsoon and the October-November-December-January (ONDJ) period during the North-East monsoon. The river freshwater inputs during the MAMJ period are in general much higher than those during the ONDJ period. There is evidence of significant inter-annual variability of river freshwater inputs in the two estuaries which is related to rainfall in the river basins (cf. Ovuka and Lindqvist 2000). Figure 7 show the time-series plot of rainfall and the corresponding river discharges in the Tana delta. Figures 6a, b shows the inter-annual variability of the Athi-Sabaki river discharge.

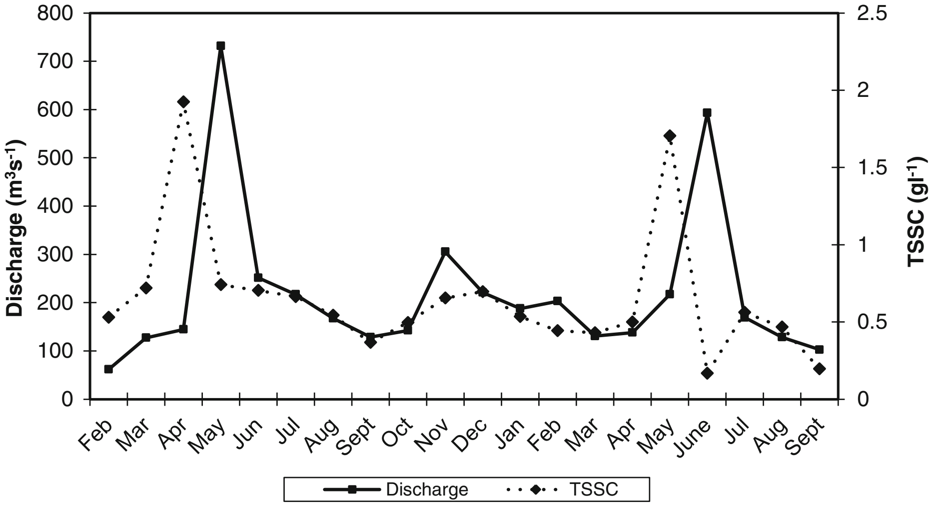


Fig. 5a Tana Delta freshwater input and TSSC in the period between January 2001 and September 2003

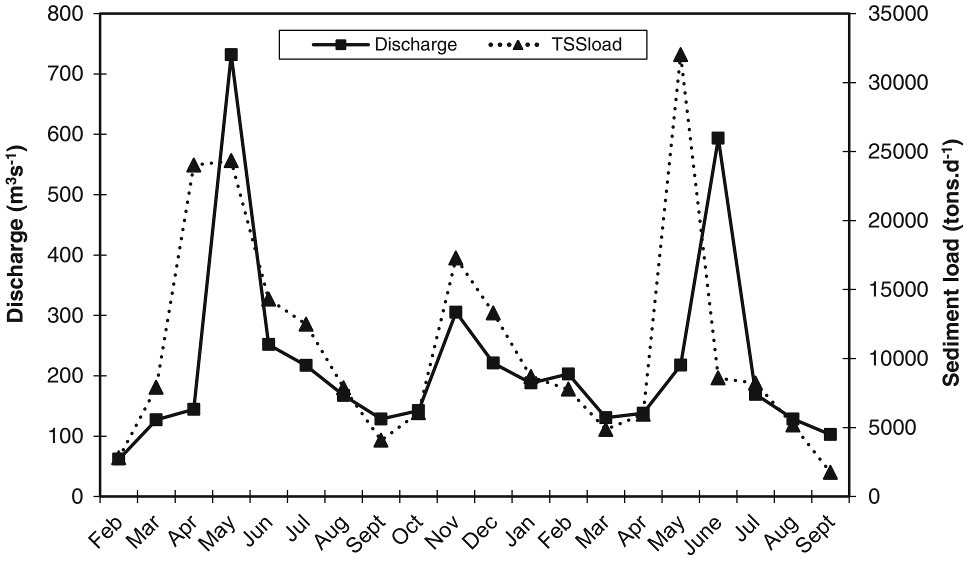


Fig. 5b Tana Delta freshwater input and sediment load in the period between January 2001 and September 2003

The Input of Sediment Load into the Estuaries

The river runoff into the Sabaki and Tana estuaries is characterized by highly turbidity as a result of high suspended sediment concentrations (TSSC). However, the Tana river was relatively less turbid as the TSSC varied from 0.53 to 1.5 $g.l^{-1}$. The Sabaki river was relatively more turbid as the TSSC ranged from 0.3 to 2.5 gl^{-1}. The peak river TSSC was measured in both rivers during the long rain season in the months of April and May. For both estuaries, the relationship between river runoff and river TSSC was such that at the beginning of the rainy season, the relatively low river discharges were characterized by high TSSC. There was a decline in TSSC as the rainy season progressed due to reduction of materials to be transported and also improvement of vegetation cover that retards soil erosion.

The total sediment load input into the Tana Delta was relatively lower than that of the Athi Sabaki as it ranged from 2,797 to 24,322 $tons.day^{-1}$ while in the Sabaki estuary it ranged from 30 $tons.day^{-1}$ to 133,000 $tons.day^{-1}$. The annual sediment load for the Tana river was estimated to be 6.8×10^6 $tons.yr^{-1}$ while that of the Sabaki was estimated to be 5.7×10^6 $ton.yr^{-1}$. The peak sediment load in both rivers occurred in May during the South-East monsoon in a period when high flows were measured (Figs. 5a, 5b, 6a and 6b). There have been significant changes in the sediment loads of the two rivers based on data from previous studies. Ongwenyi (1983) estimated sediment load of the Tana river before the damming of the river to be 12×10^6 $tons.yr^{-1}$ which is much higher as compared to the sediment load of the Tana upstream of Masinga dam (8.5×10^6 tons.yr-^{1}) (Otieno and Maingi 2002) which provides an indication of

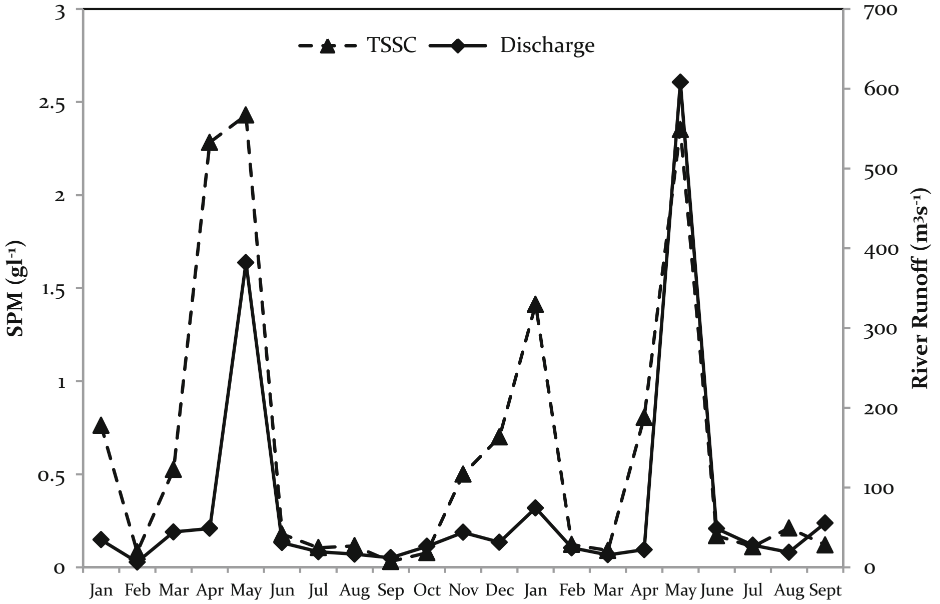


Fig. 6a The monthly averaged instantaneous river discharges and TSSC in the Athi Sabaki river between January 2001 and December 2003

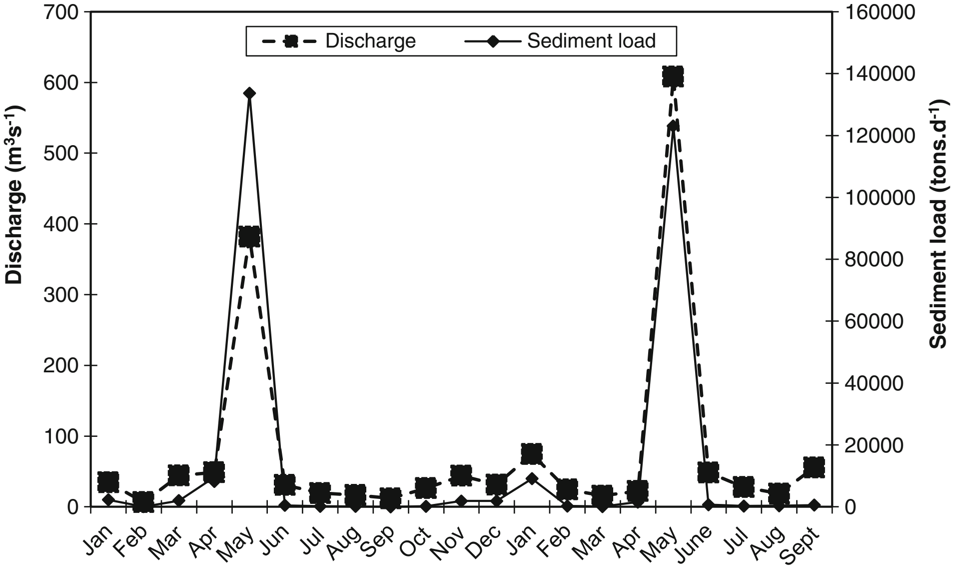


Fig. 6b The monthly averaged river discharges and sediment load in the Athi Sabaki river between January 2001 and December 2003

pre-damming sediment loads. This study found the sediment load of the Tana river at Garsen in 2003 to be 6.8 × 10^6 tons.yr^{-1} which is still much lower than that measured before the damming of the river. Assuming that these data are accurate, it can be argued that the sediment load of the Tana river has reduced by 30 to 60% as a result of damming of the river in its upper course (Gibb 1959; ILACO 1971). While there has been a reduction in sediment load of the Tana river, data shows that there has been a substantial increase in sediment load of the Athi -Sabaki river. In the pre-colonial periods, it was estimated that the sediment load of the Athi river was of the order 50,000 tons.yr^{-1} (Ongwenyi 1983), which is much lower than the sediment load of 5.7 × 10^6 ton.yr^{-1} measured in 2003. Assuming that the pre-colonial period sediment load data is accurate, it would mean that there has been almost 100% increase in sediment supply to the Sabaki estuary in the last 80 years.

Hydrologic Alterations of the River Tana and Athi-Sabaki

There have been significant changes in the hydrology of the two river systems as a result of landuse changes and

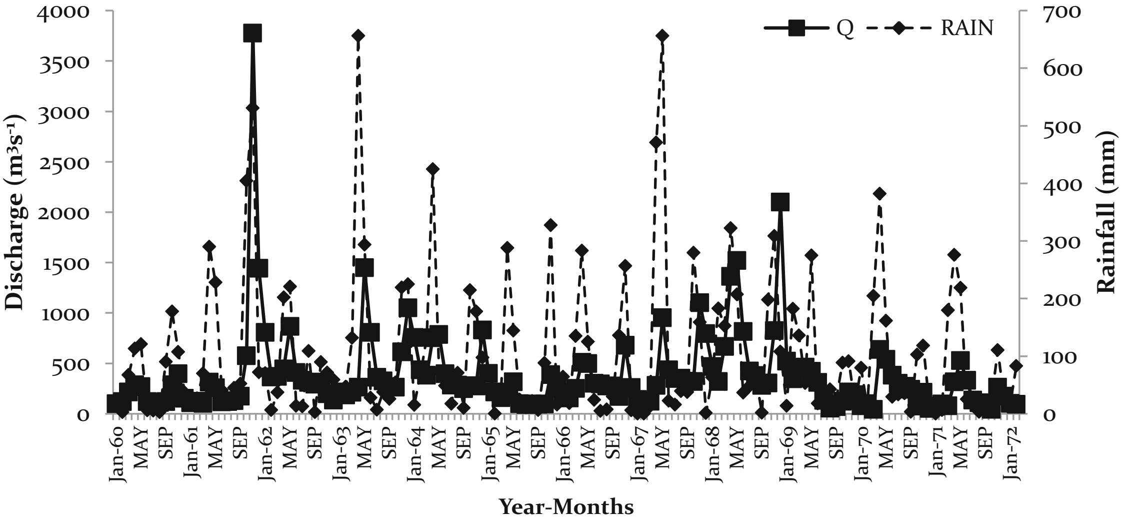


Fig. 7 The relationship between rainfall and Tana river discharge at Garsen in the period between 1960 and 1972

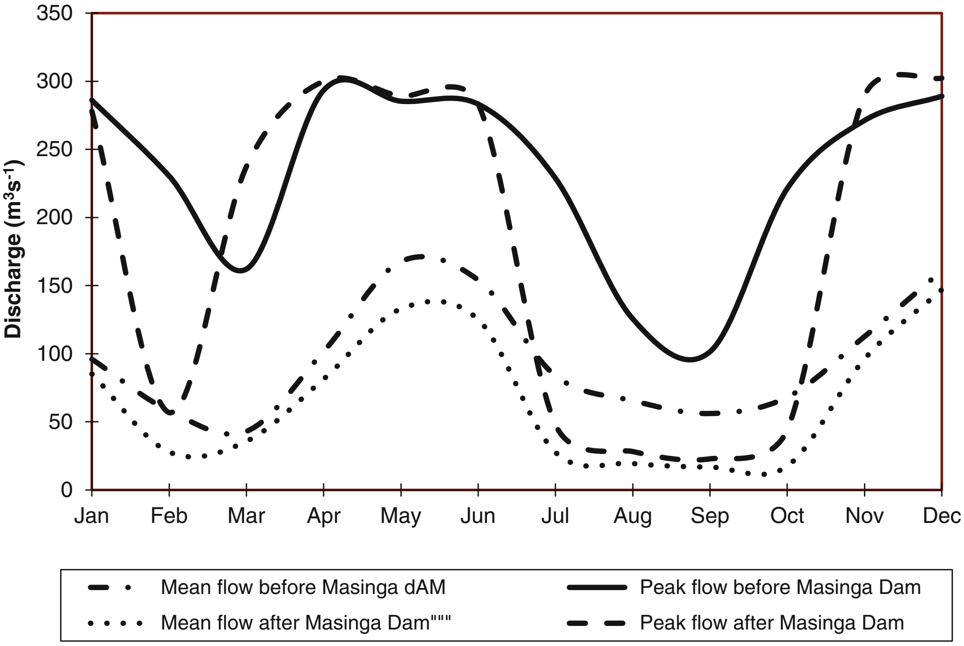
developments in the river basins. The damming of the Tana river by construction of Masinga dam in the Upper Tana Basin in 1981 effectively regulated the flow of the river downstream. As compared to other dams in the Upper Tana Basin, Masinga dam has had more significant impact on the flow of the Tana in view of its large spatial extent (surface area of 113 km^2) and volume (1,560 × 10^6 m^3). An attempt was made to establish whether there are significant changes in the maximum and mean flows of the river during both dry and wet seasons after and before construction of Masinga dam. Figure 7 show the mean and peak river freshwater input into the delta at Garsen before and after the construction of Masinga dam. The maximum river discharges in MAMJ and ONDJ period refers to the flood events during which there is high input of freshwater into the delta. However, the maximum river discharges during periods of relatively low river discharges (JFM and JAS) refers to the maximum streamflows during those specific periods. It can be seen that the magnitude of flood flows in the period before and after the construction of the dam are quite similar. There has however been a reduction in mean river freshwater input into the delta. There has also been a significant shift in the period of maximum river freshwater input into the delta during rainy season – in that they now occur about one month later. Before damming of the Tana River, the maximum river freshwater input into the Tana Delta occurred in the months of April and December. However, following the construction of Masinga dam, this has shifted to the period between May and June and also in November. It can also be seen that following damming of the river, the period of occurrence of maximum mean river discharge coincides with the period of maximum flood flows (Fig. 8).

In the case of the Athi river, available data indicates a significant progressive decline in the mean daily river discharges as well as the maximum daily discharges that occurs in the two rainy seasons (Figs. 9a and 9b). This significant reduction in river runoff in the upper course of the Athi river can be attributed to human related factors such as landuse change. The natural climate variability also seems to be important although there is a need for further investigation in this area. It is however important to note that in the past 100 years, there has been substantial changes in landuse in the Athi river basin as evidenced by extensive deforestation, overgrazing and expansion of settlements in the catchment areas of the river situated in Eastern and Central Kenya (Kiambu, Kajiado and Machakos Counties).

Salinity and Seawater Intrusion in the Estuaries

In both the Tana and Sabaki estuaries, the distribution of salinity and TSSC showed significant horizontal and vertical variation attributable to tidal incursion of seawater and river freshwater and sediment input (Figs. 10 and 11). The degree of salinity variation in both estuaries was more-or less similar despite differences in the magnitude of freshwater supply. The salinity in the Tana estuary (with greater freshwater input) however tended to fall to much lower levels of 0.02 PSU in the inner zones as compared to those in the Sabaki estuary which dropped to 0.2 PSU. The maximum salinities were largely similar in the two estuaries as they ranged between 34 and 35.5 PSU in the region fronting the ocean. The low salinities were experienced during low tide when freshwater supply was dominant and high salinities were experienced during high tide when the influx of seawater

Fig. 8 The flow of the Tana at Garsen before (1942–1981) and after (1982–2000) construction of Masinga Dam



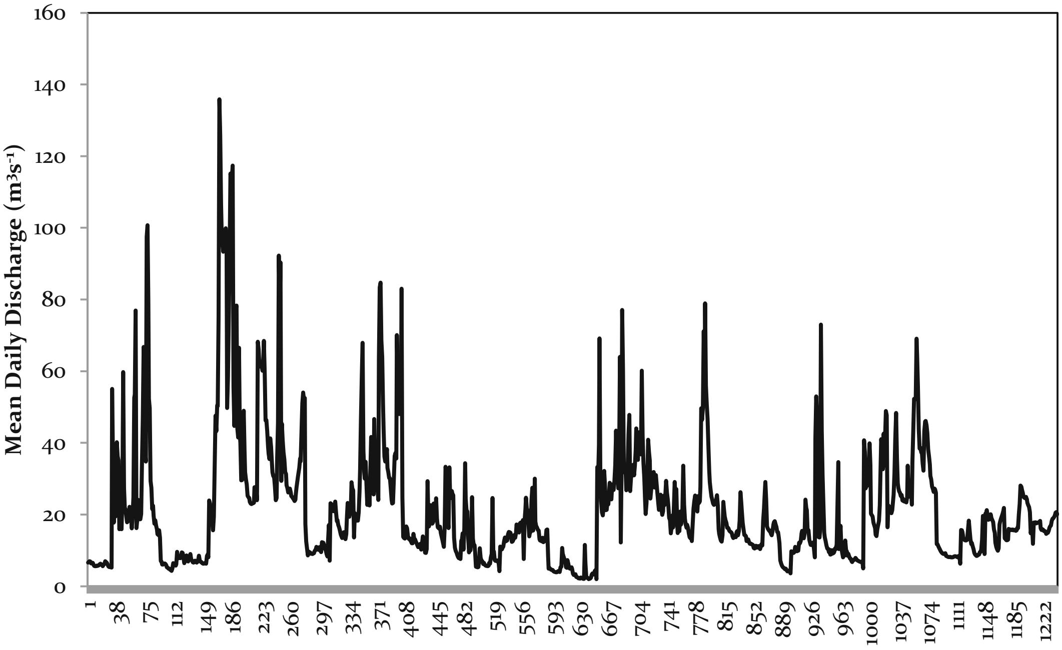


Fig. 9a The mean daily discharges of the Athi River at RGS 3DA02 in the period between 1952 and 1995. Horizontal axis shows the number of months

from the ocean was dominant. The data on salinity distribution indicated that there is a significant intrusion of seawater in both estuaries during high tide. However, saltwater intrusion was more prevalent in the much deeper Tana estuary where bottom water with salinity ranging between 5 and 10 PSU was found 10 km from the mouth of the estuary. In the Sabaki estuary, the saltwater intrusion was limited to only 2.5 km from the mouth of the estuary. In both estuaries, there is significant stratification in terms of both salinity and suspended sediments. Far much greater salinity stratification occurred in neap tide than in spring tide in the middle lower zones of the estuaries. During neap tide, the frontwater zones were partially well-mixed and during spring tide these zones were largely well-mixed. The middle zones of the two

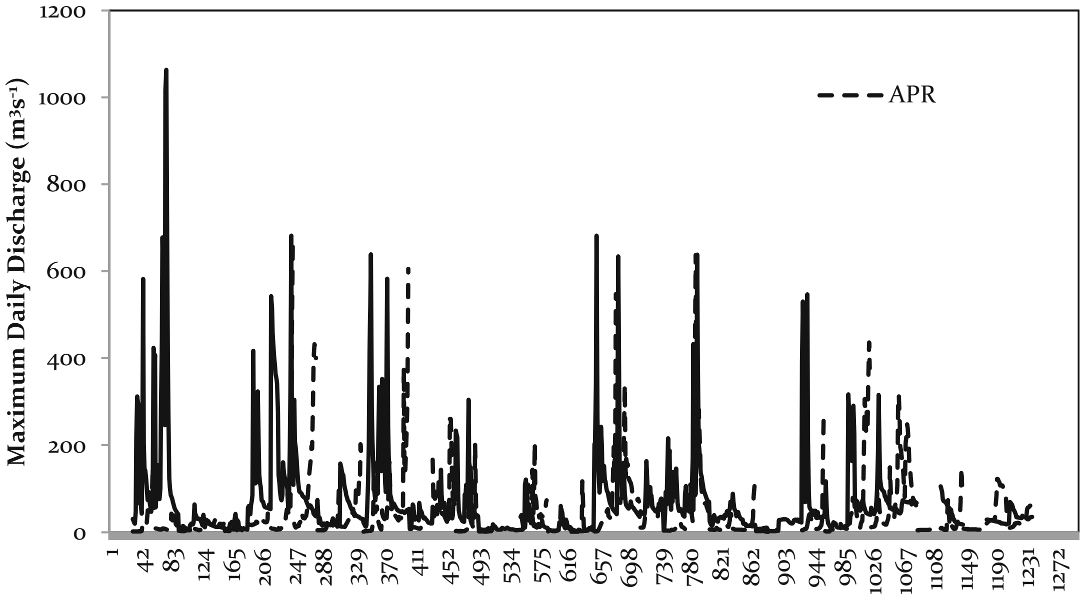


Fig. 9b The change in the maximum daily discharges experienced in April and June in the Athi River at RGS 3DA02 in the period between 1952 and 1995. Horizontal axis shows the number of months

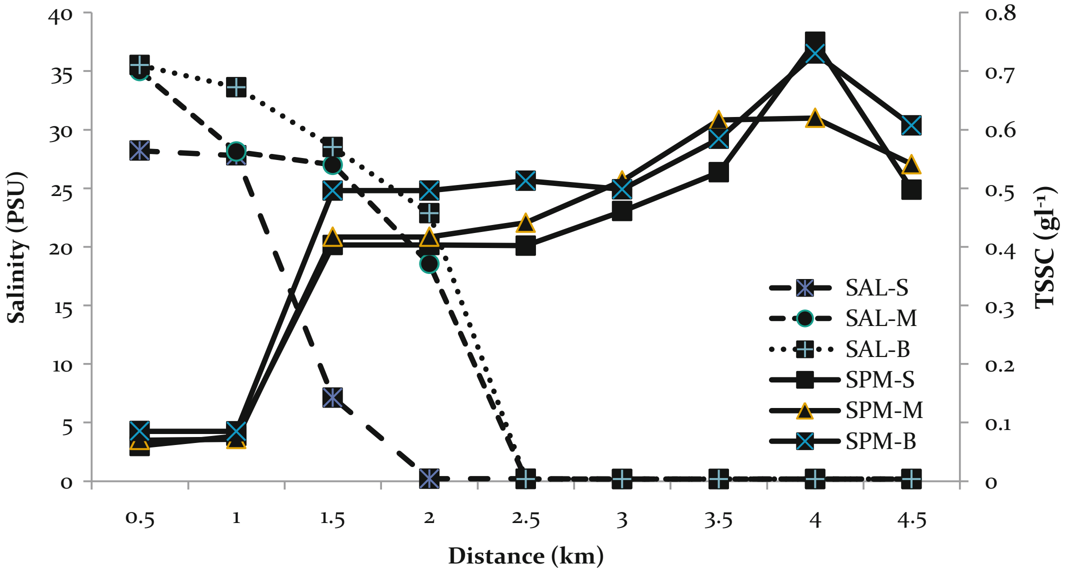


Fig. 10 The horizontal variations of depth-averaged salinity and TSSC in the Sabaki estuary at high tide during medium river discharge conditions. The 0.5 km is at the mouth of the estuary and 4.5 km is at the bridge.

estuaries tended to be stratified in neap tide but were partially well-mixed during spring tide. The riverine zones in both estuaries were largely well-mixed in both neap and spring tides. The differences in the degree of stratification were attributed to differences in the degree of mixing by the tidal currents in the down-estuary and mid-estuary regions and mixing by the river currents in the up-estuary regions.

TSSC and Turbidity Maximum Zones

In both estuaries, there was a region where the TSSC was relatively higher as compared to the up-estuary riverine zone and the down-estuary marine region (Figs. 10 and 11). This turbidity maximum zone (TMZ) was attributed to gravitational circulation at the seawater-freshwater interface and

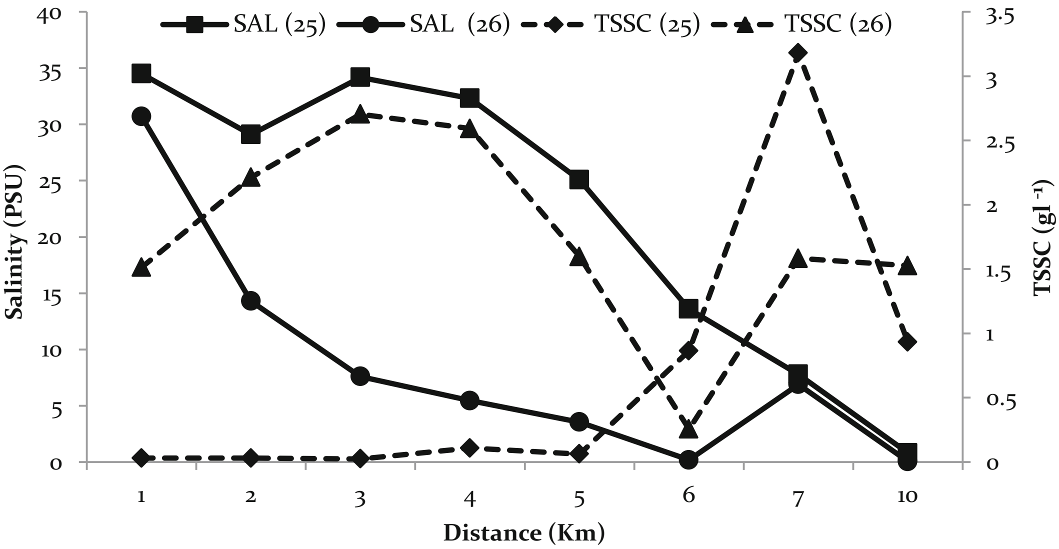


Fig. 11 The horizontal variations of depth-averaged salinity and TSSC at HW in the Tana Estuary at high tide (25) and low tide (26) during medium river discharge conditions. The 1 km is at the mouth of the estuary and 10 km is up-estuary at Ozi

sediment resuspension–deposition cycle driven by semi-diurnal tides (Kitheka et al. 2005). The levels of TSSC in the TMZ's of the two estuaries were however different. In the Tana estuary TSSC in the TMZ ranged from 1 and 3.5 g. l^{-1} while in the Sabaki estuary, TSSC in the TMZ were relatively higher as they ranged from 1.5 to 11 g.l^{-1} (see also Kitheka et al. 2003a, b). In both estuaries, the TMZ s were located at the lower middle zones of estuaries and there was a tendency for the TMZs to shift location depending on the phase of the tide. During ebb tide, the TMZ was advected down-estuary leading to trapping of cohesive clay sediments in the sheltered zones (with low current velocities) near the mouths of two estuaries. The cohesive clay sediments settling in these zones is responsible for creating mudflats that consist of sediment particles that were <38 μm. These are essentially clay mud. Within the main channels of the estuaries where velocities were relatively high, sediments were mainly fine sand with particle diameter of 125 μm.

Tidal Water Circulation, Sediment Import and Export in the Estuaries

The water circulation in the Sabaki and Tana estuaries is driven mainly by the tides and freshwater input and to a certain extent winds. The two estuaries experiences semi-diurnal tides that are largely asymmetrical with mean spring and neap tidal range of 3 m and 1.5 m, respectively along the coast. Within the Tana estuary, the region of tidal influence is 10 km while that in the Sabaki estuary is limited to 2.5 km. In both estuaries, the tidal currents exhibited a significant asymmetry with the ebb current velocities being relatively much stronger and of longer duration as compared to the flood tide currents in both neap and spring tides (cf. Kitheka et al. 2003a, b). In the Tana estuary, the flood periods were much shorter (4–5 hrs) as compared to ebb periods, which were longer (8–9 hrs). The peak ebb tide current velocities reached up to 0.87 m.s^{-1} in the Tana estuary while the flood ones reached up to 0.64 m.s^{-1}. The ebb tide currents were in general 30% greater than flood tide currents.

In the Sabaki estuary, the ebb tide current velocities attained a maximum of 0.70 m.s^{-1} in the middle region and lasted 6–7 hrs, while the flood tide current velocities attained a relatively lower peak of 0.30 m.s^{-1} and lasted 3 to 4 hours. The ebb tide currents in the Sabaki estuary were in general 50% greater than flood tide currents a manifestation of significant tidal current asymmetry. This asymmetry was attributed to channel geometry, presence of mangrove swamps, presence of intertidal areas and river freshwater input. Previous studies elsewhere have shown that tidal asymmetry is an important indicator of tidal pumping which is crucial in the export of sediments out of estuaries (cf. Wolanski et al. 1998a, b; Wolanski et al. 2001). The same is true in the case of the Tana and Sabaki estuaries. The variations in the width of the channels (w_{tide}) at station 3 as a function of tidal elevation (h_{tide}) were used to determine the channel cross-sectional area as a function of tidal elevation (A_{tide}). This was multiplied with the tide varying curent velocities (V_{tide}), to obtain the tidal discharges ($Q_{tide} = V_{tide}$ x A_{tide}) during flood and ebb periods (Tables 1 and 2). The tidal discharges (Q_{tide}) as a function of tidal elevation (h_{tide})

Table 1 Typical suspended sediment budget for the Tana Estuary

	Sources		Sinks	
	(kg.m^2.tidal cycle^{-1})	(tons.yr^{-1})	(kg.m^2.tidal cycle^{-1})	(tons.yr^{-1})
River supply	1.43	5.21×10^6		
Erosion (export)			0.075	0.55×10^6
Deposition (within the Estuary)			1.355	4.66×10^6
Total	**1.43**	$\mathbf{5.21 \times 10^6}$	**1.430**	$\mathbf{5.21 \times 10^6}$

Table 2 Typical suspended sediment budget for the Sabaki estuary

	Sources		Sinks	
	(kg.m^2.tidal cycle^{-1})	(tons.yr^{-1})	(kg.m^2.tidal cycle^{-1})	(tons.yr^{-1})
River supply	2.29	1.60×10^6		
Erosion (export)			0.22	0.19×10^6
Deposition (within the Estuary)			2.12	1.45×10^6
Total	**2.34**	$\mathbf{1.64 \times 10^6}$	**2.34**	$\mathbf{1.64 \times 10^6}$

Table 3 Mean spring tide water volumes and tidal prism at the Tana estuary

	Surface area (m^2)	Mean depth (m) high water in bracket	Volume at low tide (m^3)	Volume at high tide (m^3)
Estuary channel	3.82×10^6	5 (8)	19×10^6	30×10^6
Mangrove forest	23.2×10^6	0.3	0	7×10^6
Total	27.02×10^6		19×10^6	37×10^6
Tidal prism 18×10^6 (60%)				

were related to TSSC (C_{tide}) to determine the sediment fluxes ($Qsed_{tide} = Q_{tide}$ x C_{tide}) during ebb and flood periods. The ebb sediment fluxes were considered as the sediment export out of the estuary while the flood tide sediment fluxes were designated as sediment import into the estuaries. The difference between ebb and flood tide sediment fluxes was the net sediment export out of the estuary. When the flood sediment flux was greater than the ebb sediment flux, there was a net sediment import into the estuary causing deposition of sediments. In both estuaries, our results showed that although there is net export of sediments out of estuaries, there is accumulation of cohesive sediments in the two estuaries, as evidenced by presence of extensive mud flats in the inner zones of the two estuaries. Most of sediments exported out of the estuaries was silt and fine sand, with a much smaller proportion of clay sediments. This explains the presence of sandspits and sandbars at the mouth of the estuaries. The magnitude of the export and import of sediments is also influenced by the volume of water in the two estuaries that is exchanged per every tidal cycle (tidal prisms). Data shown in Tables 3 and 4 shows that in the Sabaki estuary almost 97% of the entire volume of water is exchanged after every tidal cycle, as compared to the Tana estuary where only about 60% is exchanged after every tidal cycle during spring tide.

Despite relatively high water exchange rates, there is net trapping of cohesive sediments in the mangrove forest wetlands. This was attributed to the reduction in the capacity of the ebb currents in the wetland to transport the cohesive sediments back to the main channel. The turbid flood tide water entering the mangrove wetlands has relatively high TSSC ranging between 0.2 and 2 gl^{-1} as compared to the TSSC in the ebb tide TSSC which was usually <0.02 gl^{-1}. The current velocities in the mangrove forest wetland were generally <0.10 ms^{-1} which is consistent to those reported in other similar systems (Wolanski et al. 2001; Kitheka et al. 2003a, b). These low current velocities were below the threshold for keeping the cohesive sediments in suspension resulting in rapid sedimentation in the wetland. This was evidenced by the presence of thick deposits of brown clay sediments in the mangrove forest. During periods of high river discharge and high TSSC, there was heavy sedimentation in the mangrove forest. There was evidence of smothering of mangrove pneumatophores in areas where sedimentation was high. These areas were characterized by stunted mangroves and in some areas dead mangroves were observed. The extent of smothering was more prevalent in the Sabaki estuary as compared to the Tana estuary which could be as a result of differences in the magnitude of sediment supply in the estuaries.

Table 4 Water volumes and tidal prism at the Sabaki estuary

	Surface area (m^2)	Mean depth (m) high water in bracket	Volume at low tide (m^3)	Volume at high tide (m^3)
Estuary channel	6.25×10^5	2 (5)	3.0×10^5	97.0×10^5
Mangrove forest	0.50×10^5	2.5	0	1.25×10^5
Total	6.75×10^6	2.25 (6)	3.0×10^6	98.25×10^5
Tidal prism 95×10^5 (97%)				

Discussions

Alterations of the Freshwater Input and Coastal State Changes in the Tana Delta

The supply of freshwater and terrigenous sediments into the Tana Delta estuaries has experienced significant changes in the recent past. This supply shows significant seasonal and inter-annual variability that can be attributed to a number of factors. These include landuse change, damming, water abstraction and natural climatic variability. While it is difficult to most conclusively attribute a particular factor to recent changes in river freshwater and sediment supply, this study has relied on available data to elucidate on the possible linkages. It is however important to note that rainfall variability in Central Kenya Highlands plays an important role in determining the magnitude of river freshwater discharge and subsequent, river sediment load. During periods of high magnitude rainfall in Central Kenya Highlands, there is usually a significant increase in freshwater supply and sediment load transported into the Tana Delta estuaries. The opposite is true during periods of low magnitude rainfall. This study including previous studies have shown that there is no significant change in the patterns of seasonal and inter-annual variability rainfall in Central Kenya Highlands (see Ovuka and Lindqvist 2000). Therefore, the decrease in sediment load in the Tana river, can be attributed to the anthropogenic influences. The discharge of the Tana river portrays rapid response to rainfall which is an indication of the low storage capacity of the reservoirs and degradation of the basin (cf. Brown et al. 1996; Pacini et al. 1998; Kauffman et al. 2007). The effects of abstraction of Tana river water for rural-urban water supply and irrigation schemes is equivalent to 11.5% of the mean flow of the Tana river with the total water abstraction of about 72×10^6 m^3 $month^{-1}$ for both rural-urban water supply and supply of water to irrigation schemes. The water abstraction has reduced the flow of the Tana by about 40 m^3s^{-1} which is equivalent to about 11% of the total flow of the river. This reduction in flow has much greater effects during periods of low flows in dry seasons. As compared to water abstraction, the construction of dams in the Upper Tana Basin has had major impacts in terms of modifying the flow of the Tana river by storing a substantial portion of the runoff in the reservoirs. This has significantly reduced the mean flows during both periods of high and low flows. The effect has been such that the current mean flows of the river are much lower during both wet and dry seasons. There has also been a reduction in the maximum monthly flows in periods of high and low flows. However, it is important to note that there does not seem to have been a major dampening of the river flow as evidenced by significant seasonal variability of the river (cf. Poff et al. 1997, 2007).

The reduction of the sediment load of the Tana river cannot be attributed to the reduction in the river discharge but to the presence of the Seven Folk Dams that traps most of the sediments emanating from the upper Tana basin (Maingi 1991; Schneider 2000). However, the river still has high sediment loads which is attributed to significant flow contributions from undammed tributaries of the river. It is thus expected the Mutonga/Grand Falls dam that is planned to be constructed downstream of Kiambere dam (GOK-JICA 1998) will trap most of the sediment load emanating from the presently undammed tributaries of the Tana river leading to major reduction in sediment supply to the Tana Delta.

Studies elsewhere have shown that alteration of flood flows and changes in low flows in the downstream sections of a river can induce major changes in the river morphology and ecosystem (cf. Basson 2013). Although the Tana river has deepened as a result of reduction in sediment load, the ecosystem impacts of the alteration of the Tana river system appeared moderate as compared to those observed in extensively dammed river systems. The moderate impacts of the Tana river is expected due to lack of significant dampening of the seasonal variability of the river due to small sizes of the reservoirs (cf. Poff et al. 2007). The major impacts observable in the Tana Delta include degradation of the riverine forest which now occurs in small patches along the river. Although the disappearance of the once extensive riverine forest can be attributed to reduction in maximum floods flows, it is also important to note that other contributors have a played a role. These include unregulated clearance of the forests for agriculture, settlement, timber and fuel wood. It is however important to emphasise that the reduction of the maximum flood flow following damming of the river must have also played a significant role in the degradation of the riverine forests, due to reduction in the influx of flood water into the far edges of the forest (see also Maingi and Marsh 2001, 2002).

Reservoirs are known to have a tendency of modifying the biogeochemical cycles of rivers by interrupting the flow of organic carbon and also by changing the nutrient and sediment load. This affects aquatic habitats by increasing habitat fragmentation (cf. Cushman 1985; Pringle et al. 2000; Friedl and Wuest 2002). The reduction in sediment load supply into the delta indicates a reduction in organic carbon, silicates as well as nutrients load since most of these are retained in the Upper Tana reservoirs (cf. Ittekkot et al. 2000). The retention of these materials in the reservoir has deprived the Tana Delta of much required nutrients and sediment materials and this has had significant effects on the downstream ecosystems, particularly on the productivity of marine ecosystems as demonstrated in changes in the productivity of Ungwana Bay fisheries (KMFRI 2002).

Field observations at mouth of the Tana Delta, showed significant erosion of the beaches. Although, coastal erosion can also be attributed to sea level rise, the reduction in sediment supply into the delta is considered important due to alteration of the sediment budget (cf. Ojany 1984; Kairu 1997). This is not unique in the Tana Delta since similar observations have been reported for the Zambezi Delta in Mozambique following construction of Cahora Bassa dam (see Beilfuss and dos Santos 2001; Basson 2013). The reduction in sediment supply to the delta also seems to be responsible for the deepening of the tidal channels fringing the mangrove forest ecosystem. These have deepened by 10 m as a result of increased channel-bed erosion due to reduced availability of sediments to be transported during ebb flows (Kitheka et al. 2003a, b). There was indication that this erosion of the channels is progressively extending into the mangrove forests ecosystem. There is also increased intrusion of seawater into the delta due to the reduction in river freshwater input and deepening of the main tidal channels. Seawater intrudes to more than 10 km into the delta at high tide. This has a potential of affecting aquatic ecosystem community structure, including contamination of freshwater supplies. Perhaps one of the major impacts of hydrologic alteration of the Tana river can be considered to be the reduction in flood-recession agriculture and loss of dry season pastures in the Tana Delta. This is due to the reduction in the frequency of influx of flood waters into the flood plains where flood-recession agriculture is practiced and where the dry-season pastures are usually found.

Alteration of Freshwater Input and Coastal State Changes in the Sabaki Estuary

There was evidence of progressive decline in the mean and maximum river discharges and an increase in sediment load of the Athi river. The Athi river runoff and sediment discharge exhibits significant seasonal and inter-annual variability and the long-term trend indicates a significant decline in freshwater supply to the Sabaki estuary. While the seasonal variability in river freshwater input can be attributed to the seasonal variations of rainfall, the long-term decline in runoff can only be attributed to the global climatic variability and landuse change. Although climatic variability is considered important, landuse change in the basin seems to have contributed to the decline. Previous studies have shown that there have been major landuse changes in the basin in the last 100–300 years (Fleitmann et al. (2007). These change have been attributed to the rapid increase in both human and livestock population in the catchment areas as well as massive destruction of forests, cultivation on steep slopes, overgrazing and burning of the fragile semi-arid lands vegetation (Edwards 1979; Denga et al. 2000). It is thus important to note that the effects of climatic variability or change are being intensified by landuse change. There is however a need for further research is this area. As compared to the Tana delta, the reduction in freshwater supply has not led to major intrusion of seawater into the Sabaki estuary. This is attributed to the shallow nature of the estuary with mean water depths of 3 m at HW which limits the propagation of the tidal wave into the estuary. In the much deeper Tana Estuary, the seawater intrudes almost 10 km inland.

The massive increase in sediment load of the Athi river (Ongwenyi 1983; Munyao 2001; Kitheka et al. 2003a, b) to levels above 5×10^6 ton.yr^{-1} can be attributed to land use change particularly the destruction of catchment areas through deforestation, cultivation, overgrazing and settlements. The impacts of climatic variability could be in terms of causing more aridity which combined with catchment degradation can trigger increased soil erosion. The effects of high sediment supply into the Sabaki estuary is evidenced by heavy accretion on the beaches and high turbidity. Beaches within the vicinity of the estuary have accreted by nearly 200 m (cf. Edwards 1979; Kairu 1997). This has also led to the siltation of Malindi harbour (Delft Hydraulics 1970; GOK-TARDA 1981; Ongwenyi 1983) and has also affected the coral reef ecosystem in the Malindi Marine National Park (Brakel 1984; Blom et al. 1985; van Katwijk et al. 1993; Obura 1995; McClanahan and Young 1996; Abuodha 1998).

Sediment Trapping in the Mangrove Wetlands

There is significant trapping of cohesive sediments in mangrove forest wetlands within both the Tana Delta and the Sabaki estuary, although this is more important in the later due to its large spatial extent.

This is due to the reduction in the capacity of the ebb tide currents in the mangrove forest wetland to transport the cohesive sediments back to the main channel. This reduction in sediment transport capacity is attributed to the low gradient and resistant to flow due to the presence of dense mangrove vegetation. The flow into the mangrove system during flood tide is generally driven by an increase in the horizontal pressure gradient occasioned by the increased water level in the main channel (cf. Wolanski et al. 2001). This results in rapid entry of turbid flood tide water with high TSSC (0.2–2 gl^{-1}) into the mangrove forest wetland. The flocculated cohesive sediments settle rapidly due to low flow velocities ($<0.10\ ms^{-1}$) inside the wetland which are below the threshold for keeping sediments in suspension (Wolanski et al. 2001; Kitheka et al. 2003a, b). Between 50% and 80% of the cohesive sediments brought in by the flood tide are trapped inside the mangrove forest. This is important in the sense that it helps the wetland keep up with sea level rise.

The level of TSSC in the incoming flood tide water which is a function of river sediment supply has important implication on the magnitude of sedimentation in the mangrove forest wetland. High TSSC water during periods of high river sediment inputs results in more heavy sedimentation. This is detrimental to mangroves since pneumatophores are smothered leading to stunted growth and in some cases, complete death of mangroves. This was evident in the upper sections of the Sabaki estuary where only a small patch of old stunted mangroves were observed and also in the Tana Delta where there has been degradation of mangroves in some locations. The degradation of mangroves in the two estuaries cannot be attributed to the decline in freshwater input, but to the heavy sedimentation. This is also applicable in the case of the Tana delta because there is still a significant sediment supply into the delta (8×10^6 tons. yr^{-1}). Mangroves are able to extract freshwater from seawater and thus reduction in freshwater supply should not significantly stress them. Furthermore, there is still a significant input of freshwater in the two estuaries. It is however important to note mangroves in the Sabaki estuary are re-establishing in the lower sections of the estuary where mudflats have formed due to deposition of cohesive clay sediments at high tide. These mudflat areas coincides with the turbidity maximum zones (TMZ) where gravitational circulation and flocculation induces rapid settling of cohesive sediments in a null zone where the flood tide induced bottom current and the river induced surface current converges.

Seawater Intrusion

The saltwater intrusion in the Tana and Sabaki estuaries is attributed to the geometry of the estuary, the volume of freshwater input and the intensity of tidal incursion which is usually stronger during spring tide as compared to neap tide. Saltwater intrusion was more prevalent in the Tana estuary where water with salinity of up to 10 PSU was found 10 km inside the estuary. In the Sabaki estuary, the saltwater intrusion extended upto 2.5 km inside the estuary. The relatively greater intrusion of seawater in the Tana estuary was attributed to its relatively greater depth (up to 10 m) which allows rapid penetration of the tidal wave. However, in the case of the Sabaki estuary, relatively shallow depths (up to 6 m) induce greater frictional effect on the tidal wave. The differences are also due to the volume of freshwater entering the estuaries. The relatively greater volume of the Tana estuaries allows greater gravitational circulation with much greater saltwater-freshwater interface that results in stronger bottom flow of seawater. The reduction of freshwater and sediment inflow into the estuaries under the scenario of rising sea level would further deepen the tidal channels and cause more intrusion of seawater into the two estuaries. On the other hand, increased sediment supply as in the case of the Sabaki estuary will lead to increased accretion and shallow channels with less penetration of the tidal wave and hence reduced seawater intrusion.

Sediment Export and Trapping of Cohesive Sediments in the Estuaries

The import and export of sediments are important features of estuaries. There is net export of sediments in both the Tana and Sabaki estuaries. This is expected due to the strong tidal asymmetry that exists in both estuaries. The net export of sediments is partly evident by the sediment accretion on beaches found adjacent to the mouths of estuaries and also the presence of highly turbid sediment plume that moves along the coast depending on the direction of the prevailing monsoon winds (Brakel 1984; Kitheka 2013). The net export of sediments ensures that the estuaries do not fill up with the sediments. However, a substantial quantity of cohesive clay sediments is usually trapped within the estuaries due to processes associated with the TMZ. The magnitude of river freshwater input and sediment load supply has important implication on the magnitude of sediment export out of the estuaries. High river sediment supply results in more sediment export while reduction in river sediment supply leads to reduced sediment export. Where the river sediment supply is reduced significantly, the estuary compensates through increased channel erosion which deepens the tidal channels as in the case of the Tana delta estuaries.

At this juncture, it would be important to examine the anticipated impacts of major development projects that are planned for the Athi river and Tana river basins. These include large-scale irrigation projects such as Galana-Kulalu 1.7 million acre irrigation project and the planned construction of Thwake and Munyu dams in the upper Athi River Basin. In the Upper Tana Basin, a large multipurpose dam is planned to be constructed at Grand Falls to produce electricity and supply water for various purposes including irrigation. These projects are bound to have major impacts on the supply of freshwater and terrigenous sediments into the two estuaries. In case of the Sabaki, it is expected that there would be a major reduction in sediment supply which would lead to rapid erosion of the estuary. The damming of the river would decrease the freshwater input into the estuary and also reduce flood flows considerably. Although the dry season low flows would be augmented due to damming, the overall mean flow of the river would decrease due to reduction in the magnitude of flood flows. This will alter the geometric configuration of the estuary due accelerated channel deepening which will eventually lead to increased seawater intrusion. In case of the Tana delta estuaries, further damming of the Tana river will lead to major reduction of sediment supply to the delta and cut off completely the flood flows. The reduction in sediment supply will result in more accelerated erosion of the estuaries in the delta with potential to reduce the extent of mangroves. The loss of flood flows will spell doom to the remaining riverine forests and flood recession agriculture in the Tana Delta. The reduction in freshwater input will further increase saltwater intrusion in the Tana delta to more than 10 km inland impacting on agriculture, horticulture, pastures, freshwater supplies and fisheries for numerous villages in the Tana Delta. These impacts will severely limit the livelihoods of coastal communities leading to overexploitation and conflicts in the use of few available natural resources.

Conclusions

The Tana delta and the Sabaki estuaries are facing stresses that originate from their river basins. While the Tana delta has been impacted by the reduction of sediment supply due to upstream damming, the Sabaki estuary has been experiencing heavy sediment supply due to landuse change and climatic variability in the Athi River basin. Also, there is a decline in river runoff in both rivers as a result of damming, landuse change and climatic variability. The current impacts of the reduction in river freshwater input and sediment discharge in the Tana Delta are increased seawater intrusion, high turbidity, degradation of mangrove wetland and riverine forests (leading biodiversity loss) and beach erosion. In the Sabaki estuary, the major impacts of reduction in freshwater input and increase in sediment load are heavy accretion, degradation of coral reefs and mangroves and high turbidity.

The water circulation dynamics within the estuaries is a function of river freshwater input and tidal forcing and there is significant stratification of the water column in terms of salinity and TSSC. The tidal asymmetry characterized by much stronger ebb tide flows as compared to flood tide flows, results in the net export of sediments from the two estuaries. The cohesive sediments are trapped within the estuaries in intertidal areas and in the mangrove forest wetlands. The relatively coarse sand particles are exported out of the estuaries forming beaches, sandspits and sand bars at the mouth of the estuaries. Further changes in freshwater and sediment input in the two estuaries is expected to negatively impact the two estuaries with a high possibility of massive seawater intrusion, coastal erosion, degradation of mangroves and coral reef ecosystems, reduced nutrients levels, and decline in coastal fisheries. These will ultimately impact on the socio-economic livelihoods of coastal communities. There is therefore a need for an integrated management of the Tana and Athi River basins to maintain required balance of freshwater and sediment input into the estuaries. Large-scale development projects planned in the two basins have a huge potential of causing major alteration of the freshwater and sediment inputs into the two estuaries under the current scenario of high climatic variability and change. It is recommended that these projects be planned such that they take into consideration the potential impacts in the two estuaries. Where the anticipated impacts are major, these mega projects should be avoided altogether, otherwise they will spell doom to the future of the Tana and Sabaki estuaries.

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