EFFECTS OF UMBA RIVER SEDIMENTATION ON THE DISTRIBUTION AND ROOT MORPHOLOGY OF MANGROVES OF VANGA, KENYA

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DECLARATION

This thesis is my original work and has not been presented for degree or other awards in any other university.

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This work is dedicated to my mother, Rael Ng’elechei and siblings, Jacklyne, Kelly, and Kyra for their unequalled love, endless support, encouragement, and endurance during this study.

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ABBREVIATIONS AND ACRONYMS

BA:	Basal Area
DBH:	Diameter at Breath Height
DFR:	Distance From the River
GPS:	Global Positioning System
IPCC:	Intergovernmental Panel on Climate Change
ICZM:	Integrated coastal zone management
IV:	Importance value
IUCN:	International Union for Conservation of Nature
IWRM:	Integrated Water Resource Management
TBCA:	Trans-boundary Conservation Area
TOC/TP:	Total Organic Carbon/ Total Phosphorus
UNEP:	United Nation Environmental Program

ABSTRACT

The study examined the influence of Umba River, a trans-boundary resource draining approximately 16 million m^3 of freshwater into the Indian Ocean, on the distribution and root morphology of mangrove of Vanga. Mangroves of Vanga, situated a few kilometers from the border that transverse the Kenya-Tanzania border, south coast of Kenya, harbor countless marine and coastal biodiversity and contributes to the socioeconomics wellbeing of the adjacent communities. This ecological survey aimed at understanding the influence of the river on sediment surface elevation change, physicochemical parameters, and the resultant effect on mangrove distribution and root morphology. Sixty-three plots were sampled along twenty-two belt transects laid perpendicular to the river within three forest blocks (A, B and C) representing landward, midstream and seaward sites respectively. Highest mangrove stem density (3268±325 stem/ha) was recorded seaward at relatively lower burial levels (2.69±0.49 cm) and relatively high salinity (30.09±13.85). Nutrient concentration was relatively low across all study blocks but mainly dominated by ammonia (70%), signifying hypoxia in sediment. Among the three blocks, *Avicennia marina* recorded the largest number ($242\pm45/m^2$) and longest (>15 cm) pneumatophores in the landward block. The difference in the height of *Rhizophora mucronata* prop roots was however not significant within the blocks. These findings suggest that sediment elevation change had the most influence on mangrove. Increase in sediment deposition influenced mangrove distribution, species zonation and root morphology, with high stem density being recorded at lower burial levels and species demonstrating a specific range of tolerance to related environmental variables. In addition, mangrove complex root system, depending on species, may adjust to cope with the increasing sedimentation. It is therefore important to use these findings to inform the development and management of the proposed Kenya-Tanzania Transboundary Conservation Area (TBCA).

CHAPTER 1: INTRODUCTION

1.1 Background information

Mangroves occur in intertidal zones of sheltered shores, estuaries, tidal creeks, backwaters, lagoons, and marshes within the tropics and subtropics, mainly between latitudes 30° N and 37° S (Mukherjee *et al.,* 2014). The range of mangrove distribution is influenced by various geological, hydrological, and oceanographic factors that vary in intensity and periodicity, both locally and regionally (Twilley and Day, 1999). Mangrove trees are in turn equipped with unique adaptive features that enable them to survive in such environments. Among other mangrove features are the complex root system that traps sediments and nutrients brought from the hinterland, thus protecting adjacent seagrass beds and coral reef ecosystems (Ewel *et al.,* 1998). The trapped sediments create new mudflats that facilitate further colonization and consequent expansion of the mangrove forest (Ellison, 1998). Besides, it helps the mangroves cope with the sea level rise (Woodroffe *et al.,* 2016).

The process of sediment accretion by the mangrove roots system is postulated to be slow (Woodroffe *et al.,* 1992; Woodroffe *et al.,* 2016), and it therefore enhances the growth of the trees through creating new mud banks that facilitate further colonization (Furukawa *et al.,* 1996; Ellis *et al.,* 2004; Alongi *et al.,* 2005). However, an increase in sediment input, exceeding 1 cm year^{-1}, contributes to the burial and suffocation of mangrove roots leading to mangrove stunted growth and diebacks (Ellison, 1998). The loss of mangroves due to such phenomena, among others, negatively affects the provision of goods and services derived from mangroves. Some of the services include providing breeding grounds and habitats for marine organisms, sequestering carbon, protecting coastline, as well as, supplying goods such as wood and fuelwood products (Wolanski *et al.,* 1997; Donato *et al.,* 2011; Kathiresan, 2012). In addition to sedimentation, other anthropogenic practices contributing to mangrove degradation include encroachment to the forest area, conversion to mariculture, coastal development, overexploitation, and pollution (Saenger *et al.,* 1983; FAO, 2007; Cunha-Lignon *et al.,* 2011). Besides causing degradation, these practices increase sedimentation processes within and out of the mangrove areas (Ellison, 1998). Loss of trees in the tropics due to high demand for wood and non-wood products result in rampant clearance of forests leaving the land bare and prone to soil erosion. In addition, poor farming practices along the riparian zones and unplanned settlements accelerate soil erosion. Transport media (rivers) aid in the transportation and delivery of these sediments into the coastal ecosystems (Ellison, 1998; Alongi *et al.,* 2005; Mohamed *et al.,* 2009). In addition, high precipitation associated with climate change exacerbates sedimentation by increasing the amount of load and the frequency of deposition (Alongi, 2015; Ward *et al.,* 2016). Cumulatively these threats have led to the loss of approximately 50% of the original global mangrove cover (Saenger *et al.,* 1983; Spalding *et al.,* 1997).

Umba River, the primary source of terrigenous sediments in the mangroves ecosystem of Vanga estuary, flows through a trans-boundary catchment area traversing Kenya and Tanzania (IUCN, 2003). The river originates from the Usambara Mountains, north of Tanzania, and its catchment area covers approximately 8070 km^2, with 40% of the catchment lying within the Republic of Kenya (IUCN, 2003). Water from this river is used for large-scale irrigation of rice plantations and for domestic water supply (Valimba, 2008). These land-based activities tend to alter the physicochemical characteristics of sediments drained by the river into the Indian Ocean through the mangroves of Vanga estuary located on the South Coast of Kenya (Lerise, 2005; Munga *et al*., 2007).

1.2 Problem statement

Excess deposition of the sea and terrestrial sediments may result in the reduction of mangrove tree growth, smothering of the breathing roots, and partial or complete burial of the regeneration. Several studies have been conducted to investigate the impacts of excess sedimentation on mangrove distribution and growth (Woodroffe *et al*., 1992; Ellison 1998; Thampanya *et al*., 2002; Kathiresan 2003; Okello *et al.,* 2019). The impacts range from reduced vigor to death of the trees depending on the amount of sediments and the species involved. While Umba River sediment loads and subsequent deposition downstream has not been quantified (Munga *et al.,* 2007), poor land use practices, such as large-scale irrigation of rice plantations and unplanned settlement in the hinterland coupled with high precipitation associated with climate changes have been recorded within its catchment (Valimba, 2008). These factors could be contributing to sedimentation within the mangroves of Vanga estuary.

A study by Tesfamariam (2018) determined the characteristics of Umba River, including the streamflow and flow patterns, relationships between hydrology and ecology, and mangrove recruitment and inundation. However, the study does not elaborate on how the hydrology of Umba River affects the distribution and root morphology of mangroves of Vanga estuary. Considering Umba River catchment is a transboundary resource, managing and monitoring the amount of sediment transported and deposited and the resultant impacts on the mangrove ecosystem faces many challenges.

All over the world, transboundary resources generally present unique challenges. For instance, conflict may arise when an environmental problem caused by one nation spill over to the other (Phillip and Jägerskog, 2006). Existing cooperative environmental management, for instance (i) Memorandum of Understanding (MoU) for Joint Cooperative Framework for Transboundary Management for Chale and Jibe Lakes and the Umba River ecosystem between Kenya and Tanzania (ii) Water Act 2002, Kenya and National Water Policy 2002, Tanzania, enacted to provide for management conservation meant to address issues of mutual concerns are complicated (Phillip and Jägerskog, 2006; Muigua, 2014; Gastorn, 2015). These laws and regulations usually differ on either side of the border and implementation involves several institutions with different agendas and mandates.

This study is aimed at (a) understanding the rate of sedimentation, (b) assessing the resilience in terms of species composition, distribution and root morphology of mangroves of Vanga estuary to sediment deposition by Umba River and (c) providing science based information to support the development and management of the proposed Kenya - Tanzania Transboundary Conservation Area (TBCA).

1.3 Justification of the study

Umba Rivers drains approximately 16 million m^3 of freshwater into the Indian Ocean. Previous reports (Munga *et al.,* 2007; Tesfamariam, 2018) only quote the volume of water and the amount of sediment transported and deposited by some of the semi-perennial rivers (Ramisi, Umba, Mwache, Mkurumuji, Pemba, and others) along the

Kenyan coast. Still, it does not quantify the effects of excess sedimentation to the biodiversity, one represented by the mangrove ecosystem of Vanga estuary. Lack of this information limits the knowledge needed to effectively make decisions that cut across mangrove conservation plans. To fill this knowledge gap, this study contributes towards availing the information needed for a better understanding of the effects of excess sedimentation on the distribution and root morphology of mangroves. It contributes towards informed conservation and restoration of the mangrove of Vanga by providing science-based knowledge on how Umba River influences the riverine mangroves of Vanga in terms of mangrove distribution and the root morphology of *Avicennia marina* and *Rhizophora mucronata*. Apart from being the most commonly found species along the Kenya coast and around the Indian Ocean, the effect of sedimentation on their root morphology has been widely studied (Ellison, 1998; Abuodha *et al*., 2001; Kathiresan, 2003; Thampanya *et al*., 2002; Okello *et al.,* 2014; Okello *et al*., 2019). Additionally, addressing issues of mutual concerns in line with management and conservation of Umba River resources and other ecosystems influenced by Kenya and Tanzania can be complicated. This study, therefore, supports the implementation of the already existing conservation policies and guides the development of new strategies for establishing the Trans-boundary Conservation Area (TBCA).

1.4 Null hypotheses

i. Sedimentation does not influence the physicochemical parameters within the mangroves of Vanga estuary
ii. Sedimentation has no effect on mangrove species distribution along Vanga estuary
iii. Sedimentation has no effect on mangrove root morphology within the mangroves of Vanga estuary

1.5 Objectives

1.5.1 General objective

To determine the effects of Umba River sedimentation on the distribution and root morphology of mangrove of Vanga estuary.

1.5.2 Specific objectives

i. To determine the variation in sedimentation and related physicochemical parameters (salinity and nutrient) within the mangroves of Vanga estuary
ii. To assess the impact of selected sedimentation related environmental variable on mangrove species distribution in Vanga estuary
iii. To examine the effect of river sedimentation on the root morphology of dominant mangrove species in Vanga estuary

1.6 Significance of the study

Mangrove forests of Kenya are an essential resource to the adjacent communities who rely on and use it as a source of wood for building material and firewood, as well as, non-wood products such as fish, medicine, dyes, insecticides, and coastal protection (Lang'at and Kairo, 2008). Over time, mangrove forest cover has reduced due to natural and human-induced factors, which threaten the availability of these goods and services.

This study examined the influence of Umba River (a trans-boundary resource) on the distribution and root morphology of mangrove of Vanga estuary, which harbors highly significant marine and coastal biodiversity. While various effects of excess sedimentation on mangrove in different regions have been widely documented (Ellison, 1998; Mckee and Faulkner, 2000; Saenger, 2002; Sidik *et al*., 2016; Goldstein and Santiago, 2016; Okello *et al.,* 2019), information on the effects on the distribution and root morphology of mangrove of Vanga estuary is lacking. This information is vital in the management and conservation of 4,428 ha of mangroves. These ecosystem supports 7 species of mangroves, 12 species of seagrass, 20 genera of coral reef, and 42 identified fish species, as well as, contributes to the socioeconomics wellbeing of the local communities (7018 people), who mainly depend on fishing as their main source of livelihood (Nunan *et al*., 2019). In addition, mangrove ecosystem of Vanga has been recognized as an important natural resource by several international bodies such as the International Union for Conservation of Nature (IUNC), World Wildlife Fund for Nature (WWF) and the Convention on Biological Diversity (CBD).

1.7 Assumption of the study

Owing to the complexity of mangrove systems and the dynamism of factors that influence tree development along river mouths, the study was based upon two main assumptions:

i. That there is both sea-borne and river-borne sediment coming into the system, but the tidal influence on sedimentation is not large enough to mask the effect of sedimentation because of Umba River.
ii. That Umba River transports and deposits quantity of sediment that significantly influence the structural composition and root morphology of mangrove trees in Vanga.

CHAPTER 2: LITERATURE REVIEW

2.1 Mangrove ecological requirements

Mangroves are salt-tolerant trees growing in sheltered tidal waters (Macnae, 1968). Mangrove species development is dependent on some specific requirements, which include temperature, salinity, tidal range, muddy substrate and wave protection (Martens, 1996).

The Kenya coastline, approximately 536 km long, provides an ideal environment for mangrove. Along the coastline, mangroves grow on protected shores such as inlets, creeks, lagoons and estuaries, where the environment is protected from strong currents and wave. Intrusion of seawater (approximately 35 ppt) coupled with local topography (tidal range and muddy substrate) influences the extent of mangrove development along the coastline. In addition, the hot and humid tropical climate (mean temperatures ranging from 24°C to 30°C and mean annual rainfall ranging from 500 to 1600 mm yr^{-1}) at the coastal area of Kenya supports optimal development of mangroves (NMEMP, 2017).

2.2 Mangrove distribution

2.2.1 Global distribution of mangroves

Mangroves are widely restricted to the intertidal zone of the tropics and subtropical regions (Mukherjee *et al.,* 2014). Globally, mangroves are estimated to cover approximately 17,075,600 ha, with 38.5% occurring in Asia, 20.7% in Africa, 15.0% in North and Central America, 13% in South America, and 12.9 % in Australia (FAO, 1994; FAO, 2005; FAO, 2007; Giri *et al.,* 2015) (Table 1).

Table 1: Mangrove forest coverage in the world (FAO, 2005)

Region	**Area (ha)**
Asia	6,047,798
Africa	3,242,754
North and Central America	2,358,105
South America	2,037,764
Australia	2,018,537

Mangroves are distributed in three major coastal sections: western Atlantic (1.5 million ha, 49%), Western Indian Ocean (1.2 million ha, 37%), and Central Atlantic (0.4 million ha, 14%). In Africa, mangrove forests cover over 3.2 million hectares (ha) of the continent, constituting about 19% of the global coverage. The forests are found in almost all countries along the east and west coasts of Africa, spreading from Egypt to South Africa on the east coast, including Madagascar and several other islands and from Mauritania to Angola on the west coast (FAO, 2007).

It is estimated that more than 50% of the original total cover of the global mangrove forest has been lost due to either conversion pressure, over-exploitation or pollution (Saenger *et al.*, 1983; Spalding *et al.*, 1997).

2.2.2 Mangrove distribution in Kenya

There are nine mangrove species in Kenya, with *Rhizophora mucronata*, *Ceriops tagal,* and *Avicennia marina* commonly found along the Kenya coast and around the Indian Ocean (Semesi and Howell., 1992) (Table 2).

Table 2: Mangrove species common in Kenya (NMEMP, 2017)

Species	**Local name**
Rhizophora mucronata	Mkoko
Ceriops tagal	Mkandaa
Avicennia marina	Mchu
Bruguiera gymnorhiza	Muia
Sonneratia alba	Mlilana
Lumnitzera racemosa	Kikandaa
Xylocarpus granatum	Mkomafi
Xylocarpus moluccensis	Mkomafi dume
Heritiera littoralis	Msikundazi

Mangrove of Kenya occupy 61,271 ha with 60% occurring in Lamu County. Smaller and isolated patches are found in Kilifi, Mida Creek, Mtwapa Creek, Gazi Bay, Funzi-Shirazi, and around Vanga (NMEMP, 2017; Table 3).

Table 3: Mangrove coverage in the five counties along the Coast of Kenya (NMEMP, 2017)

County	**Area (ha)**
Lamu	37,350
Kilifi	8536
Kwale	8354
Mombasa	3771
Tana River	3260
Total	**61,271**

The nine mangrove species depict some level of zonation controlled by the tidal regime with a typical pattern from the sea to the land, as represented in figure one. Mangroves in Vanga estuary (study area) are dominated by six complex mangrove species, namely *A. marina*, *B. gymnorhiza*, *C. tagal*, *R. mucronata*, *S. alba* and *X. granatum* (Lang'at and Kairo, 2008).

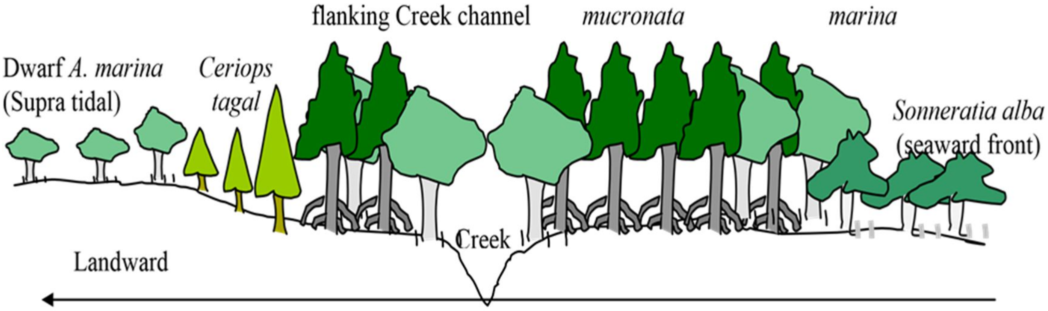

Figure 1: Mangrove vegetation zonation of the mangrove of Kenya forests (Lang'at *and Kairo*, 2008)

2.3 Importance of mangrove

Mangrove ecosystem, being one of the critical coastal ecosystems, is valued for a variety of ecological and societal goods and services. Mangroves are effective filters of materials transferred between the land and the sea; for instance, they trap sediments, nutrients, and pollutants transported in surface runoff, thus preventing their entry into adjacent ecosystems (Mckee and Faulkner, 2000). Besides providing nursery grounds and refuge for many organisms, mangroves are critical to the biological productivity of coastal waters. Owing to their adaptation abilities to varieties of environmental changes, they represent a self-sustaining ecosystem. Mangroves act as a first-line protective barrier, buffering the destructive force of tsunami before it reaches land thereby protecting humans and properties (Dahdouh-Guebas *et al.,* 2005; Danielsen *et al.*, 2005; Kathiresan and Rajendram, 2005; Barbier, 2006). They also play an integral role in shoreline stabilization by consolidating unstable mineral sediments and peat formation (Horstman *et al.,* 2015). Mangroves are also efficient carbon sinks, a role that helps mitigate global warming by reducing the amount of atmospheric carbon, a process known as carbon sequestration (Donato *et al.,* 2011; Ray *et al.,* 2012; Ray and Jana*,* 2017; Alongi 2012). Other mangrove uses include providing building material (poles for houses and timber for boats), wood fuel (charcoal and firewood), and food (honey, tannin and fish) (Lee *et al.,* 2014; Duke and Schmitt, 2015).

Mangrove ecosystem of Vanga harbors important marine and coastal biodiversity which include 7 mangroves species, 12 seagrass species and 20 coral reefs speicies ecosystems consisting of rich macrofauna and meiofauna, crabs, mollusks and over 40 species of water birds (KMFRI, 2015). The ecosystem also provides nesting grounds for two marine turtles, i.e., Green turtles (*Cheloniamydas*) and Hawksbill turtles

(*Eretmochelys imbricate*). Additionally, 70% of livelihood for the local community in Vanga emanates from non-wood forest resources from the mangrove forests; these are fish, herbal medicines, tannins, and fodder. A larger population of people, 98%, in the area depend on mangroves for energy and wood, 54% extract mangroves for firewood, 44% for poles, and 2% for timber (Omondi, 2013).

2.4 Threats to mangrove

Duke *et al.,* (2007) estimated that mangrove is disappearing at the rate of up to 2% per year (57.87 ha/yr), exceeding the estimated global rate of 1% per year. This rate goes beyond the degradation rate for coral reefs and tropical rainforests.

Mangroves face numerous threats arising from both anthropogenic and natural causes. Human induced threats include (i) overexploitation for wood products (Mohamed *et al*., 2009), (ii) hydrological alterations (Blasco *et al*., 2001), (iii) agricultural land change and nutrient increase (Lovelock *et al*., 2009), (iv) conversion of mangrove area to other land use, for instance, aquaculture (Vaiphasa *et al*., 2007), and (v) infrastructure and development causing pollution and sedimentation in the mangrove forests (Ellison, 1998; Abuodha and Kairo, 2001; Okello *et al.,* 2019). Other natural causes of mangroves degradation include pest infestation and desiccation (Gilman *et al.,* 2008; Huxham *et al.,* 2010; Mukherjee *et al.,* 2014; Jenoh *et al.,* 2019).

These pressures have reduced the global coverage of mangrove forests to less than 35% of the total original cover (MEA, 2005). According to an assessment conducted in 2005, Eastern Africa region has lost 8% of its mangrove (FAO, 2005). Kenya has lost 18% of her mangrove cover since 1980 (Kirui *et al.,* 2013). In Vanga, the area of mangroves cover has declined by 1736 ha over the past 30 years (NMEMP, 2017; Mungai *et al.*, 2019).

2.5 Sedimentation in mangrove

Mangroves are often associated with fine-grained sediment, mainly biogenic sediments (containing at least 30% skeletal remains of marine organisms) characterized by more than 80 % silt and clay (particle size <63 µm), but they can grow on a broad range of substrate types (Kathiresan and Bingham, 2001; Ong *et al.*, 2012). Sedimentation, which is a natural slow process can be said to occur when small pieces of a solid material settle to the bottom and form a layer (https://www.britannica.com/science/sedimentation-geology; https://www.dictionary.com/browse/sediment). The process of sedimentation in mangroves, including the deposition of fine-grained clay-dominant particles, is considered one of the driving factors of land-building and shoreline progradation (Woodroffe *et al.*, 1992). Mangrove forests, as such, function as land builders by piling up between one and eight millimeters of sediment annually (Kathiresan, 2003; Smoak *et al.,* 2013). In a high-density plantation, the forests accrete up to 13 mm of sediments per year. The deposition pattern may vary spatially depending on the distance from the coastal fringe and the mangrove species present (Kathiresan, 2003; Kumara *et al.*, 2010; Smoak *et al.*, 2013). Sediment elevation changes may be due to accretion or erosion. Drivers of erosion include sediment leaving the system, compaction, and shrink/swell of aerially exposed sediment. Drivers of accretion include sediment trapping and subsurface expansion from root growth and groundwater influx (Kathiresan, 2003). Although mangroves require a continuous supply of sediment for their survival, regeneration and to cope with sea level rise, large and sometimes episodic delivery of sediment can be detrimental to their growth and development (Woodroffe *et al*., 1992; Ellison 1998; Thampanya *et al*., 2002; Kathiresan 2003; Okello *et al.,* 2019). This may be through the modification of geomorphological setup and influence on soil characteristics, groundwater reach, and substrate salinity determining mangrove zonation and species distribution. It may also result in low water availability triggered by increased difficulty in root water absorption due to increased soil compaction, which reduces sediment pore sizes and thereby requiring greater tension for water extraction (Tomlinson, 1986). Additionally, sedimentation may lead to increased hypoxia in the substrate (Thrush *et al.,* 2004) and consequently increased physiological drought as water channel proteins (aquaporins) are downregulated by hypoxia (Laur and Hacke, 2014) and, as such, may equally result in decreased water uptake by the roots.

2.5.1 Effects of excess sedimentation on the growth and distribution of mangrove

Sediment build up creates new mudflats for mangrove to colonize. However, large sediment loads associated with anthropogenic activities and increased flooding due to climate change related activities (Bamroongrugsa and Yuanlaie, 1995; Caldeira, 2012) can cause stress to some mangroves species (Ellison 1998; Okello *et al.,* 2014; Okello *et al.,* 2019). Sediment accretion exceeding 1 cm per year could lead to mangrove mortality (Ellison, 1998). Mangroves have shown a lower growth rate under increased sedimentation (Thampanya *et al*., 2002; Sidik *et al*., 2016). The most obvious effect of sedimentation is the smothering of mangrove roots resulting in oxidative stress (Ellison, 1998). The oxygen deficiency, and consequent damage to the roots is brought about by the inhibited gaseous exchange pathways between the atmosphere, soil and the roots

(Ellison, 1998; Abuodha and Kairo, 2001; Thampanya *et al*., 2002). This has been found to result in a decline in mangrove seedlings survival, as well as, mature tree growth (Thampanya *et al*., 2002; Sidik *et al*., 2016; Okello *et al.,* 2019). However, the findings by Thampanya *et al.,* (2002) and Okello *et al.,* (2019) indicated that increased levels of sedimentation among mangrove species vary substantially depending on their sensitivity and threshold tolerance levels.

2.5.2 Morph anatomical effects of sedimentation on mangrove

Studies on the effects of sediment burial, mimicking large sedimentation events and their probable contribution to the survival and mortality of mangrove, have been demonstrated experimentally by Okello *et al.,* (2014) and Okello *et al.,* (2019). These studies revealed that an increase in sediment burial can cause stress to mangroves and, in the worst case, the mortality of some species. Increased sedimentation levels affect species distribution with sensitive species experiencing high mortality at relatively lower burial levels. A study by De Deurwaerder *et al.,* (2016) reported how high sediment deposition from the flush flood in 1997 and land use changes, which induce anthropogenic land erosion and runoff in Mikindini Kenya, negatively influenced the anatomic and hydraulic features of the adjacent mangroves. According to McKee (1996) and Thampanya (2002), increased sediment accretion results in hypoxia in the root zone, a condition that affects biomass allocation during tree growth. In such conditions, trees allocate more biomass to the roots and therefore they tend to inhibit above ground growth resulting in stunted growth (McKee, 1996; Saenger, 2002; Lovelock *et al*., 2016).

Additionally, the redox state of sediments in mangroves can be highly heterogeneous, facilitating several biogeochemical processes that influence nutrient availability (Chapin *et al.,* 1987). Increased sedimentation in mangroves reduces the contact time between organic matter (plants and animals in situ or derived from natural and anthropogenic sources) and dissolved oxygen in the water column, thereby contributing to low concentrations of carbon and nutrients available for tree intake (Gray *et al*., 2002). Nutrient availability has repeatedly been found to be an important factor limiting productivity in mangroves (Onuf *et al*., 1977; Feller *et al*., 2003). Nutrient addition can stimulate mangrove growth; however, nutrient deficiency results in stunted growth, death of plant tissues, and yellowing of leaves caused by reduced production of chlorophyll (McCauley *et al*., 2009). Nutrient availability is also a factor that plays an important role in determining the allocation of root biomass. When there is high nutrient availability, mangrove seedlings invest more in above ground biomass than in roots development, while when the nutrient availability is low, seedlings redirect resources to enhance their root biomass (Mckee 1996; Naidoo 2009). Nitrogen and phosphorus have been identified as the nutrient most likely to limit growth in mangroves (Lovelock *et al.,* 2009), with most mangrove species highly sensitive to variation in their availability both in the lab (Boto *et al.,* 1985; Mckee 1996) and in situ (Lovelock *et al.,* 2007; Feller *et al.,* 2003). Nitrogen was found to limit growth of *A. marina* in South Africa (Naidoo, 2009) and New Zealand (Lovelock *et al.,* 2007).

Low oxygen concentration in sediments also influences sediment salinity. It reduces the root extension rates, and even causes root dieback in some species (McKee, 1996). Mangroves are more luxuriant in relatively lower salinity (33-35 ppt) and experimental evidence indicates that, at high salinity mangroves spend more energy to maintain water balance and ion concentration rather than for primary production and growth. Salt stress in mangrove can cause osmotic stress and reduce water availability resulting in stomatal closure and reduced supply of carbon dioxide (Parida and Das, 2005). It can also induce ion toxicities such as membrane disorganization, production of reactive oxygen species, and disturbance of nutrient balance. On the other hand, during long-term acclimation to saline conditions, mangroves evolve various strategies to cope with high salinity including anatomical, physiological, and molecular mechanisms. For instance, *A. marina* increases contents of leaf proline to alleviate NaCl stress while other species are equipped with oxygen radical detoxifying enzymes such as superoxide dismutase, peroxidase and catalase, and accumulate inorganic ions in their vacuoles to increase cellular osmolarity to counter osmotic stress and avoid increases in ionic strength of the cytoplasm (Clough, 1984; Krauss *et al.,* 2008; Hoppe-Speer *et al.,* 2011). However, previous studies on salinity mostly focused on a certain growth stage of mangroves. How salinity influences mangroves in a dynamic developmental process is not well known.

2.5.3 Mangrove adaptive mechanism to cope with sedimentation

Mangrove trees are adapted to survive in mudflats built from the gradual deposition of sufficient sediment facilitated by the unique root structure (Fig 2). The complexity of mangrove root structure enhances sediment deposition by trapping sediments introduced to coastal areas through river discharge, dumping of dredged material and floods (Wolanski 1995; Kathiresan, 2003). Mangroves create a turbulent zone that maintain the sediments in suspension and letting them be deposited just before slack tide. The aerial roots also ensure that the deposited sediments are not re-suspended during ebb by creating an opposite force to the ebbing tides (Kathiresan, 2003). As a result, fine particles are not just passively imported into the mangroves, but the trees structurally capture silt, clay, and organic matter (Furukawa *et al.,* 1996; Alongi, 2009). This contributes to vertical sediment accretion (Alongi, 2009; Kimeli, 2013) and further promotes growth and expansion (Adame *et al*., 2010). Furukawa *et al.,* (1996) reported that about 80% of suspended sediments brought into an Australian mangrove forest were trapped. Long-term accumulation of sediment through accretion and subsurface accumulation of refractory mangrove roots results in raising the elevation of the soil surface and hence may help mangroves adjust to sea level rise (McKee *et al.,* 2007; Smoak *et al.,* 2013). Although mangrove root structures are an important agent in the accretion process, they may also be vulnerable to extreme sedimentation events, which may result in their complete burial. Ellison (1998) reviewed cases of sediment burial in roots of different mangrove species and noted that in cases where accretion rates does not go beyond 10 mm year^{-1}, the trees show some degree of tolerance. However, burial events within ranges of 10–70 mm show a large variation in responses by species and by location (Ellison 1998; Okello *et al.,* 2014; Okello *et al.,* 2019).

Apart from enhancing sediment deposition, these complex root networks also provide anchorage and facilitation of gaseous exchange (Kathiresan and Bingham, 2001). The aerial roots are characterized by extensive coverage of lenticels (Blasco *et al.,* 1996) and a spongy cortex made up of large aerenchyma lacunae (Metcalfe and Chalk 1957; Pi *et al.,* 2009), which enhances efficient internal oxygen transfer (Jackson and Armstrong, 1999; Colmer, 2003). Since low oxygen concentrations can impede root growth (Mckee, 1996), mangrove coping mechanisms can be critical for plant survival.

Mangrove adaptation mechanisms that are mostly species and location specific include the modification of hydraulic architecture to avoid or overcome cavitation and its effects or reduction in stomatal area which minimizes transpiration for an optimal water transport capacity (Okello *et al.,* 2014), and the morpho anatomical response of mangrove trees (Okello *et al.,* 2019). These are indicators of resilience of mangrove forests to changes associated with sedimentation.

Aerial roots may take five major forms, which are characteristic of specific mangrove tree species or genera (Tomlinson 1986): stilt/prop roots, pneumatophores, knee roots, peg roots and plank roots. Stilt/prop, typical of the *Rhizophora* species, arch from the tree trunk or branches of the mangrove and grow towards the soil. Pneumatophores, pencil-like structures protruding from the ground are found in *Avicennia* species. Knee roots, which form pronounced loops appearing as a blunt knoblike structure raised from the soil surface, are found in *Ceriops* and *Bruguiera* species. Peg roots, similar to pneumatophore but stouter and may become knob or mushroom like in some cases, are common to the *Sonneratia* species. Plank roots in *Xylocarpus* species are vertically wavy and plank-like (Fig 2).

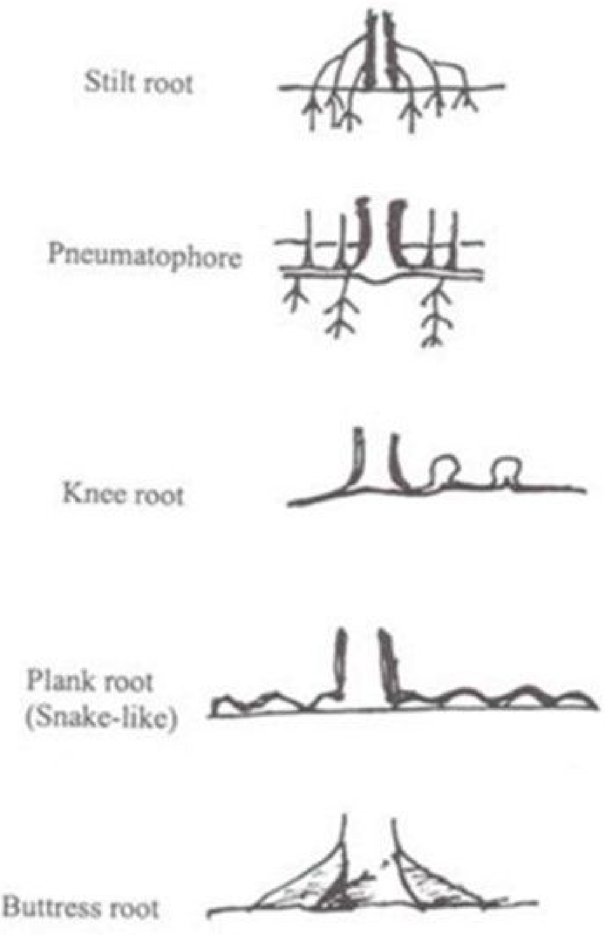

Figure 2: The different aerial root structure for mangrove species (Kathiresan *et al*., 2001)

The adaptations that aid in root aeration in partially or completely buried *A. marina* and *R. mucronata* (common to the WIO) include an increase in root density to facilitate aeration throughout sediment burial (Young and Harvey 1996; Ellison 1998; Okello *et al.,* 2019). Pneumatophore density increase in *A. marina* is not only from the original cable root but also through the development of new cable roots. Pneumatophores from the original cable root also grow longer to reach the new sediment surface (Saifullah and Elahi, 1992; Okello *et al*., 2019). In *R. mucronata* new prop roots form above the new sediment level. These adjustments are likely to maintain oxygen diffusion from aerated root parts to the buried sections and facilitate the elimination of by-products of anaerobic respiration from the buried root section (Srikanth *et al.,* 2016). Despite these adaptations, deposition of sediments exceeding the threshold reduces oxygen and nutrient levels in sediments (Ellison, 1998; Saenger, 2002; Thampanya *et al*., 2002; Okello *et al.,* 2019) and eventually their intake by mangroves, which influence mangrove growth and regeneration (Uchida, 2000).

2.6 Challenges associated with trans-boundary mangrove areas

Out of 192 countries in the world, 153 share 310 rivers and lakes and 592 aquifers. These shared water resources serve 2.8 billion people or 42% of the global population. As such, transboundary resources present unique challenges. Conflict, for instance, can arise when an environmental problem caused in one country spills over into another country (Wouters, 2013).

Trans-boundary ecosystems are governed by different policies, legal and institutional structures, management and governance regimes (Phillip and Jägerskog2006). Such ecosystems are also affected by various social, cultural and economic pressures. As water bodies cross over different political jurisdictions, it becomes challenging to identify commonly accepted solutions to satisfy competing uses because governance of transboundary waters requires cooperation among countries, sectors and stakeholders. In some places, water pollution in one country also worsens cooperative management efforts (Scheumann and Neubert, 2006). Effective trans-boundary conservation is, therefore, necessary to achieve conservation goals across one or more international boundaries (Vasilijević *et al*., 2015).

Kenya shares its borders with five of the East Africa countries. Inevitably, many of its ecosystem and natural resources are transboundary. Umba River falls within a trans-boundary catchment traversing the Northeastern border of Tanzania into Kenya. It originates from the Usambara Mountains in Tanzania and flows into the Indian Ocean through Vanga,which is located in the South Coast of Kenya. Umba River supports large-scale irrigation of rice plantations and supplies domestic and environmental water flows. Several streams and river valleys within the Umba ecosystem in Lushoto, Tanzania have been converted into rice-irrigated fields. In the Kitivo scheme, Mnazi, Kivingo-Mnazi, and Mwakijembe more than 1000 ha is under modern irrigation. Along Umba river on the Kenyan side, there is the Vanga irrigation project which occupies about 400 ha. These uncoordinated agricultural activities upstream and downstream loosen the soil promoting erosion and runoff. Population increase on riparian land has led to an expansion of settlements along the stream particularly at the source of the river, resulting in increasing risks associated with anthropogenic activities such as pollution and sedimentation (Plate 1) (Lerise, 2005; McGrane, 2016).

Plate 1: Poorly planned settlement expansion upstream along Umba river- Mlalo Minor Settlement (Pamoja and PBWO; Lerise, 2005)

Additionally, seasonal rains within a river catchment contribute to sediment load being transported and deposited into the coastal areas because of runoff and flooding (Chakrapani, 2005). According to Zheng *et al.,* (2000), up to 10 cm high of sediment is deposited downstream during a single downpour event. The effect of global warming has exacerbated this process, with frequent and excess precipitation (Caldeira, 2012), resulting in higher sedimentation rates within the mangrove forests. Umba River discharges an average of 16 million m^3 of freshwater into Funzi-Shirazi Bay (Vanga, Shimoni, Msambweni, and Gazi) annually (Munga *et al*., 2007). Runoff is also discharged into the ocean from precipitation of about 1000-1600 mm yr^- experienced within coastal regions (NMEMP, 2017). The dynamics or Umba River eventually influences the mangroves ecosystem in Vanga where the polluted and highly turbid water is deposited and is likely to slow the growth and regeneration of mangrove (Mcleod and Salm, 2006).

2.7 Laws governing transboundary resources in Kenya

The Water Policy 2012, repealed under the Water Act 2016, is a legislation that governs how water resources in the country are to be shared. It further provides, *inter alia*, that the government is to maximize the use of transboundary water resources in coordination with other riparian countries.

The National Land Policy 2009, repealed under the Land Act 2012, highlights guidelines on the protection of the ecosystems and their sustainable management. It recognizes the fact that Kenya has diverse shared ecosystems in need of protection. However, implementation is faced with a challenge especially managing ecosystem for conservation due to conflicting uses and varied governance frameworks.

The Forest Policy 2014, repealed under Forest Act 2016, necessitates the cooperation of states in both regional and international spheres. It recognizes the effective management of transboundary forest resources.

Kenya being a signatory to a number of multilateral and regional agreements, listed below, ensures that these frameworks are integrated into the national policies and plans.

i. Environment (Management and Coordination) Act, 1999
ii. The African Convention on the Conservation of Nature and Natural Resources
iii. East Africa Community Treaty, 1999
iv. The Protocol on Environment and Natural resources Management
v. The EAC Regional Environment Impact Assessment Guidelines for Shared Ecosystem.

CHAPTER 3: MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Geographical location

Vanga is located on the border of Kenya and Tanzania within coordinates 39^{0}20ˈ30ˈˈE, 4^{0}33ˈ57ˈˈS to 39^{0}12ˈ52’’E, 4^{0}40ˈ23ˈˈS. Vanga estuary receives freshwater from Umba River, which originates from the Usambara Mountains, Northeastern of Tanzania and empties into the Indian Ocean in Kenya (Fig 3). This site was chosen because Vanga estuary is within a proposed transboundary conservation area (TBCA) between Tanzania and Kenya.

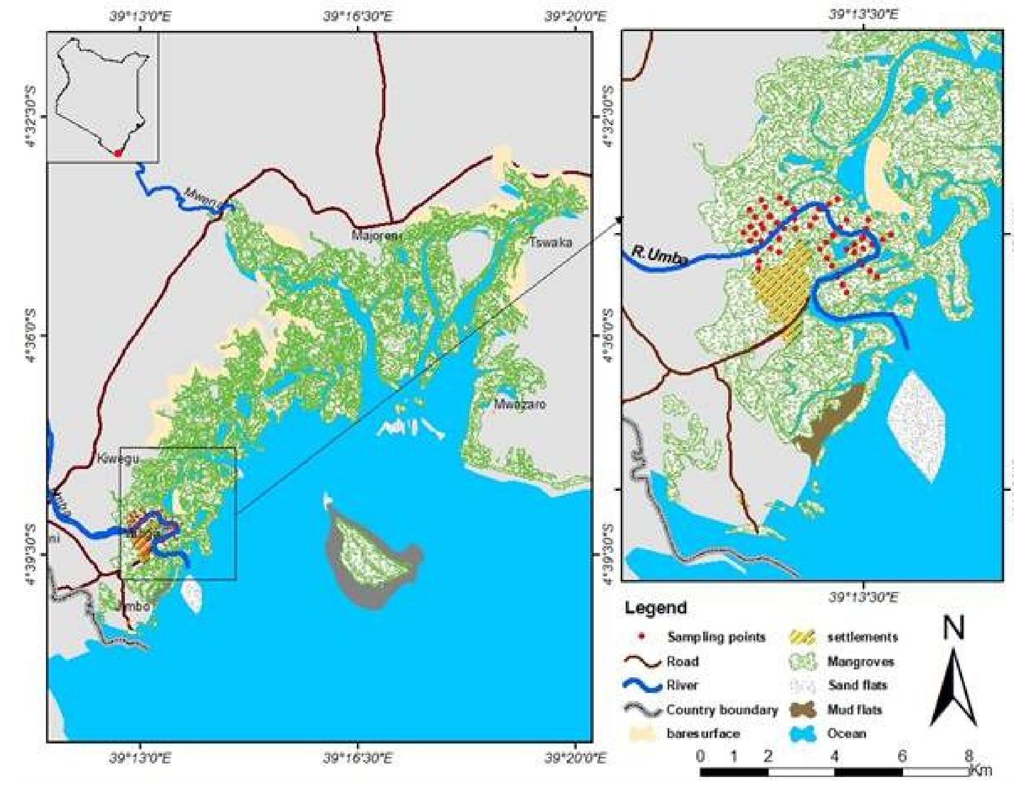

Figure 3: Location of the study area showing the riverine mangroves of Vanga, Umba River and the study design (sampling plots within forest blocks A, B and C). Inset is the map of Kenya indicating the location of Vanga.

3.1.2 Climate

Vanga is characterized by a warm climate (25^0 C to 30^0 C) with an average rainfall of 1352 mm/yr (NMEMP, 2017). The area experiences a bimodal rainfall pattern; long rains occur in April-June and short rains in October-November (Fig 4).

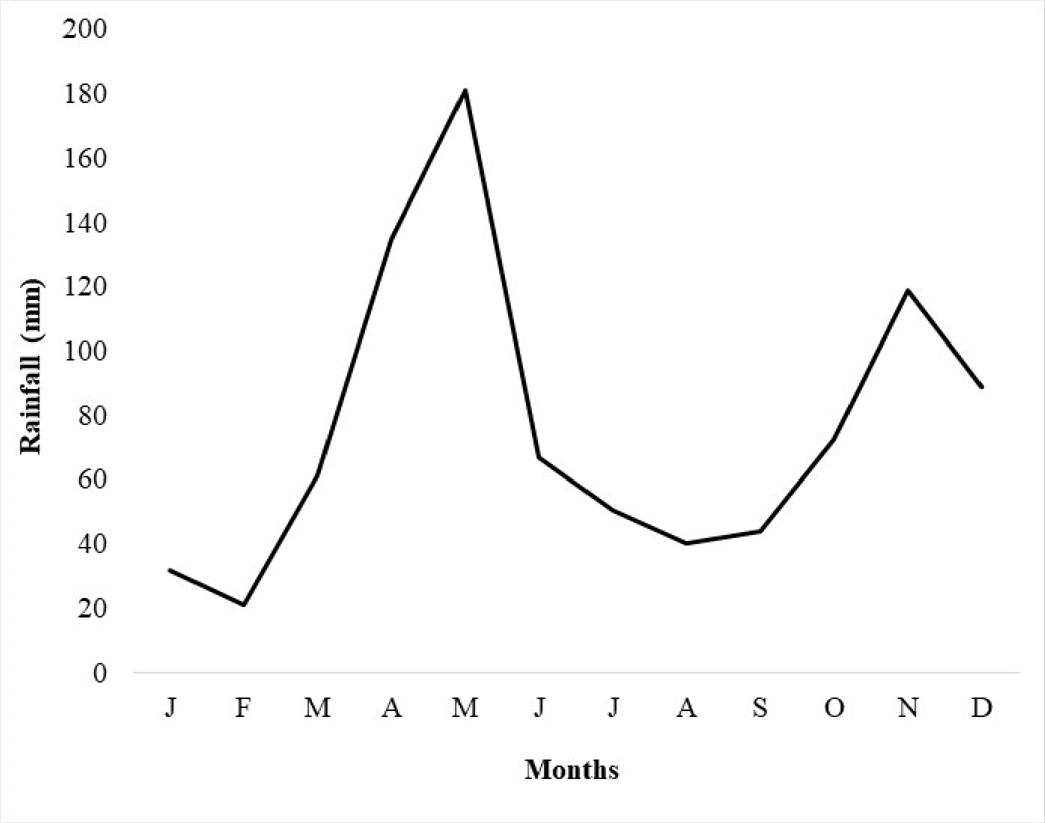

Figure 4: Annual rainfall pattern of Vanga (Lang'at and Kairo, 2008).

3.1.3 Geology and geomorphology

The variation in water discharge and sediment deposition of Umba River is majorly influenced by rainfall patterns, climatic changes, and land use activities. Vanga estuary is therefore susceptible to high deposition of terrigenous sediments from the river catchment area, which is estimated to be about 8070 km^2 (IUCN, 2003). The geological formation of Vanga area is of tectonic origin with quaternary deposits along the flood plains ranging from estuarine deposits to sand, clays, and residual coral limestone (NMEMP, 2017).

3.1.4 Soil

The soil in Vanga area varies in structure and texture. This is because of the influence of physicochemical parameters, climate, waves and tidal regime, sedimentation, and river discharge. The area has fine-grained nutrient-rich sediment, often associated with estuaries where fine-grained organic material settles along with mineral particles (NMEMP, 2017).

3.1.5 Biodiversity description

Vanga area consists of important ecosystems; a vast mangrove forest covering about 4,265 ha (the third largest in Kenya after Lamu (30,470 ha) and Ungwana Bay (6,325 ha)), 12 species of seagrass beds and 20 genera of coral reef. These ecosystems hosts a great number of associate biodiversity, fish, invertebrates, and other wildlife (KMFRI, 2015).

3.2 Study design

The riverine mangrove forest of Vanga was purposively divided into three blocks to capture variation in inundation influence across the tidal flat. Forest block A was positioned landward, block B- midstream, and block C- seaward. Plots of 10 m x 10 m as recommended by Kauffman and Donato (2012) were established at 10 m, 100 m, and 200 m along transects running perpendicular to the river channel at intervals of 300 m within each of the forest block (Fig 5). Approximately 21 plots were established in each block, bringing the total number of plots sampled to 63 plots within 22 transects.

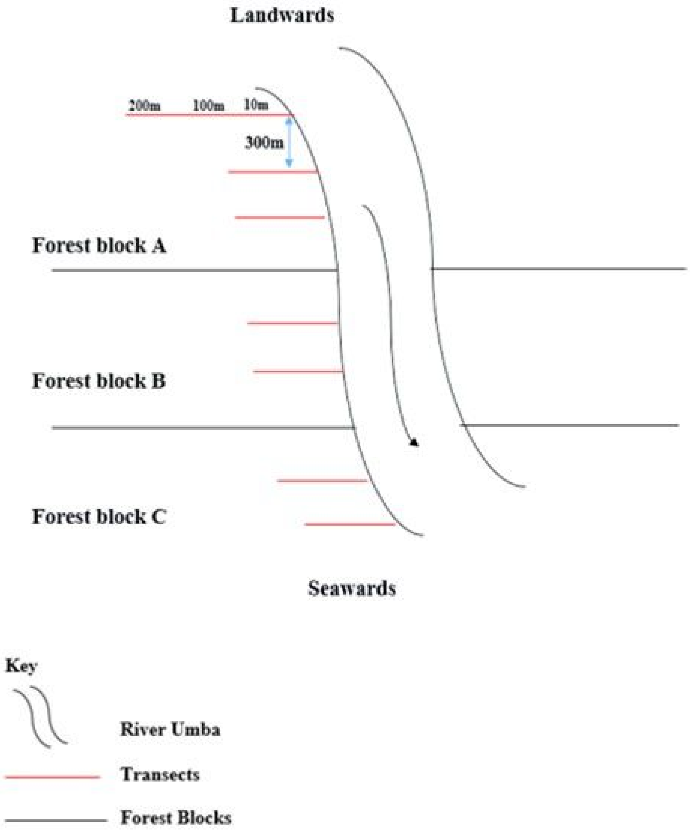

Figure 5: Diagrammatic representation of the sampling design used to collect data in the study area.

3.3 Field Sampling

3.3.1 Assessment of sediment surface elevation change

Fifteen (15) sediment elevation tables (SETs) were set up within the 10 m × 10 m plots in all the blocks. 4 m-long stainless-steel rods (6 mm in diameter) were driven into the ground until a hard ground (evidence from difficulty in driving it further). 3 m of the rods were sunk and the length above the surface were set at 25 cm above the ground level. Twelve height measurements from the mangrove surface to heights of the rods were made at twelve points along a wooden board placed across each set of rods. The

SETs were setup perpendicular to the river channel at 10 m and 200 m to cater and apportion the influence of distance away from the main channel. The 15 set ups were done in September 2017 and the initial reading were conducted. The initial reading was regarded as the initial elevation and referenced to the Lowest Astronomical Tide (L.A.T). Four subsequent readings were taken after deployment up until May 2019.

Plate 2: Sediment Elevation Tables (SET) installed to determine sediment elevation change.

3.3.2 Assessment of sediment physicochemical parameters

Using a 6.3 cm-diameter Polyvinyl chloride (PVC) coring tube, three sediment samples were cored at a depth of 30 cm — the zone most susceptible to deposition (Kauffman and Donato, 2012). The sediment cores were packed in zip lock bags and stored in a cooler box packed with ice for analysis in the laboratory. In the laboratory, nutrients (nitrogen, phosphorus and ammonia) were analyzed using Genesis^{TM}10 SEAL Vis spectrophotometer and QuAAtro^{TM}39 SEAL nutrient autoanalyzer. Water from the hole created after coring was collected and salinity determined in situ using ATAGO^{TM} handheld refractometer. In cases where there was no pore water, soil slurry was prepared by adding deionized water to the sediment sample at the ratio of 1: 2 (Marchand *et al.,* 2004).

3.3.3 Assessment of mangrove structural attributes

Within each 10 m x 10 m plots in all the blocks, mangrove tree species were identified, and the tree height and stem diameter recorded using the standard sampling techniques (Berlyn, 1986; Kauffman and Donato, 2012). Diameter measurements for all trees with diameters greater than 2.5 cm were taken at breast height (DBH; 130 cm) using a tree caliper. The point of DBH measurement for *R. mucronata* was 30 cm above the point of attachment of the highest prop root. For trees with stunted growth (height <150 cm) with a diameter greater than 2.5 cm, diameter measurements were not taken at the conventional breast height (130 cm) but rather at 30 cm from the ground.

3.3.4 Assessment of mangrove root morphology

Twenty-four plots on the established belt transects were systematically selected to assess mangrove root morphology for *A. marina* and *R. mucronata*. Distance from the bank of the river and the arrangement of the blocks were considered during selection to ensure a complete representation of the entire mangrove forest and to capture the influence of the river. In each plot, four trees were identified using the standard Systematic Point Sampling technique i.e., the first trees encountered while moving outwards in four different directions from the point center of the plot were sampled (Fig 6) (McRoberts *et al.*, 2015).

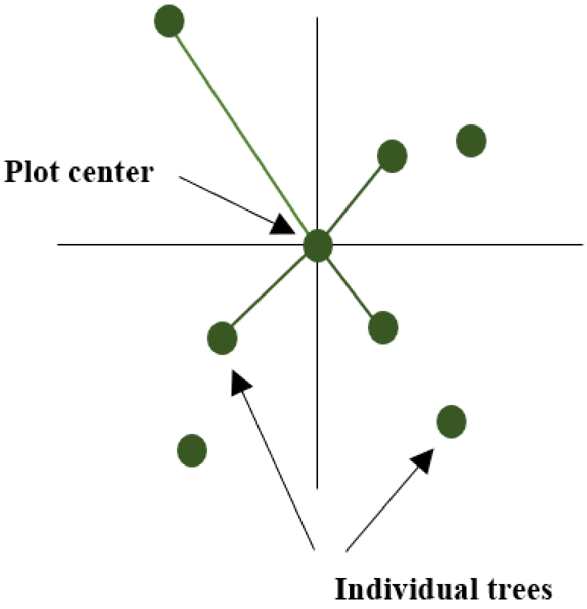

Figure 6: Systematic point sampling technique used to identify trees for assessment within a plot (McRoberts, 2015).

Two 1 m × 1 m quadrats; one facing the river and the other in the opposite direction were placed at approximately 0.5 m from the base of the target *A. marina* tree (Fig 7a).

For plots with only one *A. marina* encountered, four quadrats were positioned around the tree in opposite directions for consistency in the number of samples and to attain the targeted four samples in each plot. In each quadrat, pneumatophores were counted and their heights measured using a ruler and categorized as <5 cm, 5-10 cm, 10-15 cm and >15 cm. For *R. mucronata*, the prop root height on each target tree, from point of attachment to the base of the tree was taken using a tape measure (Fig 7b).

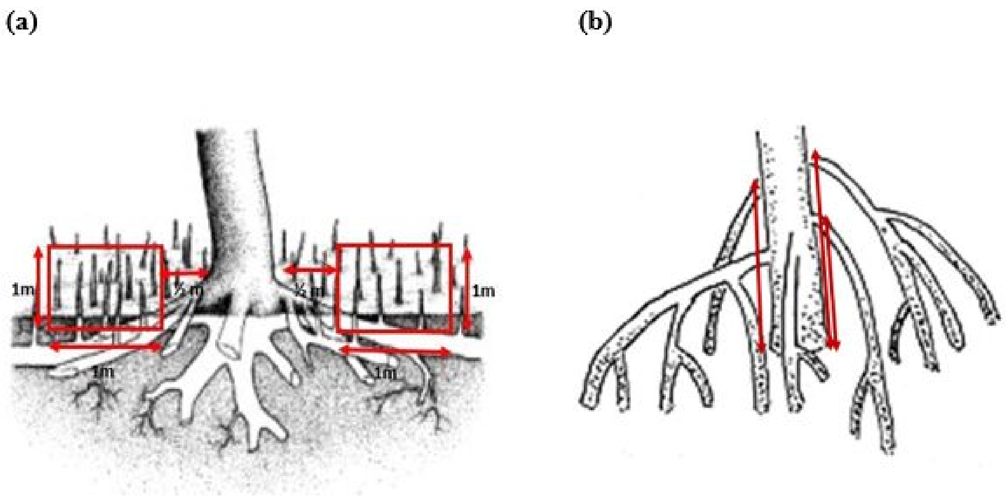

Figure 7: Diagrams showing (a) sampling of *A. marina* pneumatophores using 1 x 1 m quadrats (b) height measurement of *R. mucronata* prop roots.

3.3 Data Analysis

Data was analyzed in Ms Excel, XLSTAT, Minitab 17 and Statistica 7.0 software. Using Ms Excel, the Importance Value (IV), ranging from 0 to 300%, was used to determine the dominant species of mangrove based on the summation of the relative frequency, relative density, and relative dominance of the mangroves (Cintron and Schaeffer-Novelli, 1984). The difference in sediment surface elevation, sediment physicochemical parameters and mangrove species and root density and height across the sampling stations were determined using ANOVA followed by post hoc turkey test in Minitab 17 and STATISTICA 7. The correlation between mangrove species distribution and the environmental variables (chi-square for Canonical Correspondent) was analyzed in XLSTAT.

CHAPTER 4: RESULTS

4.1 Variation in sedimentation and related physicochemical parameters

4.1.1 Surface elevation change

Sedimentation was highest landwards (Table 4). The surface elevation change ranged from 2.69 to 2.97 cm. During the study period, change in sediment surface elevation did not differ significantly with distance from the river. However, this was not the case across the forest blocks as demonstrated by ANOVA (F (2,50) = 7.928, p = .001). A Tukey post hoc test revealed that highest mean was recorded in forest block A (2.97±0.74 cm, p = .599), but there was no significant difference between block B (2.61±0.56 cm, p = .001) and C (2.69±0.49 cm, p = .009).

Table 4: Sediment elevation change between mangrove forests blocks in Vanga estuary

Block	Sediment Elevation (cm)
A (Landward)	2.97±0.74^{a}
B (Midstream)	2.61±0.56^{b}
C (Seaward)	2.69±0.49^{b}

Means with different superscripts differ ($P < 0.05$) (mean± S.E.)

4.1.2 Sediment physicochemical parameters

The mean nutrient levels ranged between 0.11-0.23 mg/l, 0.01-0.32 mg/l and 0.0025-0.0037 mg/l for ammonia, phosphate and nitrate, respectively (Table 5). Generally, ammonia concentration dominated, accounting for 70% of the total nutrients while phosphate and nitrate contributed 29% and 1%, respectively. The nutrient concentration was however not significantly different (ANOVA, p>0.05) with distance from the river across the forest blocks.

There was an increasing trend in salinity from 10 m towards 200 m from the river bank in all forest blocks (Table 5). Statistically, the difference in salinity with distance from the river within each forest block as determined by ANOVA was significant (F (4,534) = 3.102, p = .015). Tukey post hoc test showed that highest salinity was consistently recorded at 200 m from the river bank among all the forest blocks.

Table 5: Sediment physicochemical parameters at 10 m, 100 m and 200 m from the riverbank within forest block A (landward), B (midstream) and C (seaward) in Vanga estuary

Block	DFR (m)	Salinity (ppt)	Nitrate (mg/l)	Phosphate (mg/l)	Ammonia (mg/l)
A (Landward)	10	20.03 ± 0.05^{c}	0.0025 ± 0.001^{a}	0.15 ± 0.35^{a}	0.14 ± 0.07^{a}
	100	29.62 ± 9.64^{b}	0.0027 ± 0.001^{a}	0.02 ± 0.02^{a}	0.16 ± 0.08^{a}
	200	40.35 ± 12.02^{a}	0.0025 ± 0.001^{a}	0.01 ± 0.00^{a}	0.15 ± 0.07^{a}
B (Midstream)	10	17.34 ± 2.53^{c}	0.0033 ± 0.002^{a}	0.02 ± 0.02^{a}	0.17 ± 0.10^{a}
	100	18.00 ± 0.00^{b}	0.0036 ± 0.001^{a}	0.32 ± 0.03^{a}	0.23 ± 0.06^{a}
	200	21.23 ± 3.21^{a}	0.0032 ± 0.002^{a}	0.01 ± 0.00^{a}	0.11 ± 0.02^{a}
C (Seaward)	10	24.95 ± 10.12^{c}	0.0033 ± 0.001^{a}	0.01 ± 0.01^{a}	0.15 ± 0.04^{a}
	100	29.12 ± 4.74^{b}	0.0026 ± 0.001^{a}	0.01 ± 0.01^{a}	0.13 ± 0.09^{a}
	200	33.63 ± 17.66^{a}	0.0037 ± 0.001^{a}	0.02 ± 0.02^{a}	0.14 ± 0.05^{a}

Means with different superscripts within each forest block differ ($P < 0.05$) (mean± S.E.)

4.2 Mangrove structural attributes

Seven mangrove tree species were recorded in the areas adjacent to Umba River. Based on the Importance Values (IV), *C. tagal* (107.99) is the most dominant species followed by *R. mucronata* (71.17) and *A. marina* (46.41) in that order. Similarly, *C. tagal* recorded the highest stem density (1108 stem/ha), followed by *R. mucronata* (675 stems/ha) and *A. marina* (322 stems/ha) in the same order. The tree height for all mangrove species ranged between 2.6 m to 8.6 m, while the basal area ranged from 12.72 m^2ha^{-1} to 24.69 m^2ha^{-1} (Table 6). Approximately 83% of the mangrove trees had a stem diameter of ≤9 cm, and 62% were of poor pole quality (form III; completely deformed and cannot be used for construction purposes).

Table 6: Stocking rate of mangroves of Vanga estuary. All trees were greater than 2.5 cm in diameter at breast height (DBH)

Species	Density (stems ha^{-1})	Mean height (m)	Basal area (m^2 ha^{-1})	Relative (%)			IV
				Density	Dominance	Frequency	
A. marina	322.22	8.57	23.88	13.15	20.11	13.15	46.41
B. gymnorhiza	119.05	4.95	24.69	4.86	20.79	4.86	30.50
C. tagal	1107.94	2.61	20.87	45.21	17.57	45.21	107.99
L. racemosa	1.59	3.5	0.00	0.06	0.00	0.06	0.13
R. mucronata	674.60	5.42	19.15	27.53	16.12	27.53	71.17
S. alba	17.46	8.36	12.72	0.71	10.71	0.71	12.13
X. granatum	207.94	5.72	17.45	8.48	14.69	8.48	31.66

Overall, the landward block recorded the lowest stem density (1879±370 stems/ha), while the seaward block recorded the highest stem density (3268±325 stems/ha) (Fig 8). Mangrove stem density was significantly different across the three forest blocks as well as with distance from the river (ANOVA, $p \leq 0.05$). However, Tukey post hoc test shows that stem density at midstream forest block was not significantly different from the other two blocks while means across seaward block were also similar.

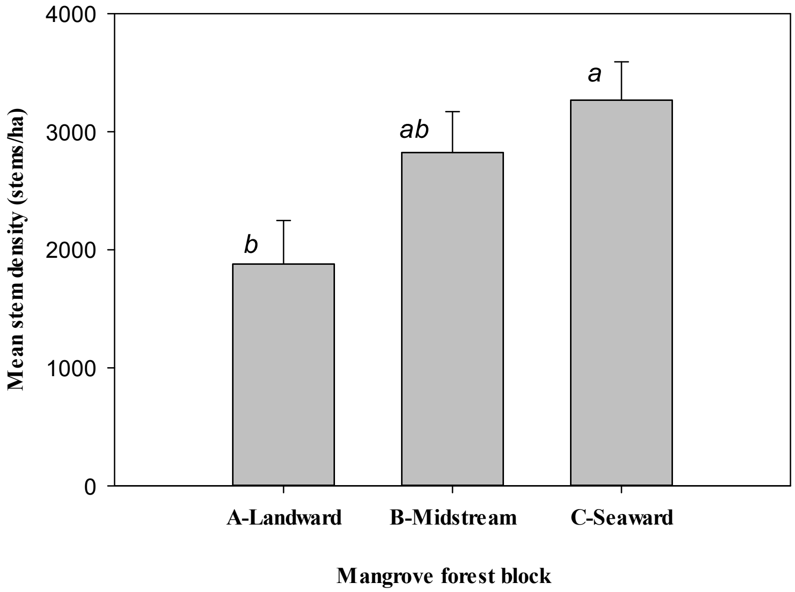

Figure 8: Vanga estuary mangrove stem density (stems/ha) in different forest blocks. Means with different letter differ ($P < 0.05$) (mean± S.E.)

Most mangrove species (*C. tagal*, *R. mucronata, B. gymnorhiza, X. granatum* and *S. alba)* had highest stem density at 200 m, but *A. marina* recorded highest stem density at 10 m. *L. racemosa* and *S. alba* were only recorded in the midstream and seaward block, respectively (Table 7).

Table 7: Stocking rate of mangroves at 10 m, 100 m and 200 m within different forest blocks

Block	Species	Mangrove stem density (Stems ha^{-1})			
		Distance from the river (m)			Mean stem density
		10	100	200	
A (Landward)	*A. Marina*	186±40	300±100	367±76	284±53
	B. gymnorhiza	100±0	267±67	200±58	189±49
	C. tagal	0	1125±342	2683±881	1269±778
	R. mucronata	0	250±29	400±0	217±117
	X. granatum	325±131	150±29	750±375	408±178
B (Midstream)	*A. Marina*	280±86	100±0	250±29	210±56
	B. gymnorhiza	100±0	150±29	800±115	350±225
	C .tagal	200±0	1900±906	1700±587	1267±536
	R. mucronata	840±328	1267±364	1867±1288	1325±298
	X. granatum	460±144	533±145	100±0	364±134
	L. racemosa	100±0	0	0	33±33
C (Seaward)	*A. Marina*	540±144	400±173	233±133	391±89
	B. gymnorhiza	233±88	200±58	400±0	278±62
	C .tagal	233±67	1733±689	4550±1150	2172±1265
	R. mucronata	1343±408	1220±434	1140±400	1234±59
	X. granatum	233±33	300±0	0	178±91
	S. alba	150±29	0	600±0	250±180

As illustrated in figure 9, *C. tagal* (CT) thrives in high saline areas, C200, B200 and A200. *A. marina* (AM) was dominant in areas experiencing relatively high accretion, it mostly occurred at A10. *X. granatum* (XG), *S. alba* (SA), *R. mucronata* (RM), and *B. gymnorhiza* (BG) thrived in areas with relatively low accretion and relatively lower salinity. Canonical correspondent analysis (CCA) indicated a correlation between mangrove species distribution and environmental variables (surface elevation change indicated as accretion, salinity, ammonia, phosphate and nitrate) within the study sites. Overall CCA analysis was significant, (chi-square, $p < 0.05$). The eigen values, indicating contribution of each variable to spatial distribution of sampled mangrove species from the most significant contributor to the least were, 0.121 for salinity, 0.108 for accretion, 0.001 for ammonia, 0.000 for nitrate and phosphate. Comparatively,

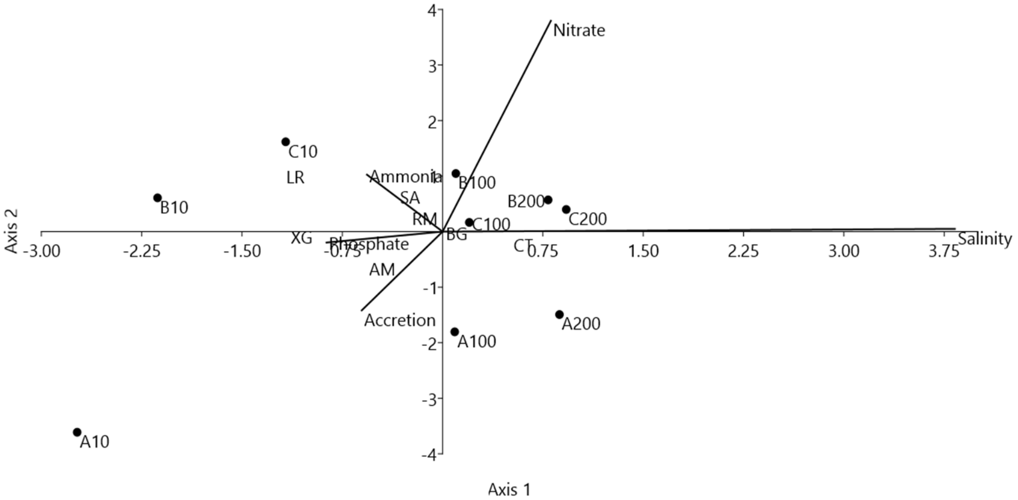

Figure 9: Canonical Correspondent Analysis (CCA) ordination diagram on Axis 1 (horizontal) and Axis 2 (vertical) of mangrove species (unique code), environmental variables (—) and site (•). The species are; AM = *A. marina*, CT = *C. tagal*, RM = *R. mucronata*, BG = *B. gymnorhiza*, XG = *X. granatum*, SA = *S. alba*, LR = *L. racemosa*. The environmental variables are; Nitrate, Phosphate, Ammonia, Salinity and Accretion.

The sampling locations (•) include; forest block = A, B, C and distance from the river = 10, 100, 200

4.3 Root morphology of *Avicennia marina* and *Rhizophora mucronata*

The pneumatophore density of *A. marina* ranged from 1 to 613 pneumatophores/m^2 with a mean of 121±17/m^2 (n=34). Pneumatophore root density showed significant variation with distance from the riverbank within the landward block (ANOVA, $p<0.05$), but did not exhibit significant variation in both midstream and seaward blocks (ANOVA, $p>0.05$) (Table 8). The pneumatophore density across the forest blocks was significantly different (ANOVA, $p <0.05$) with landward block recording the highest mean (242±45/m^2) while seaward block recorded the lowest density (45±10/m^2). Overall, pneumatophore roots of <5 cm in length dominated in all forest blocks accounting for 37-62 % of *A. marina* root density across the blocks. The longest pneumatophores (>15 cm) dominated the landward block (21±6 roots/m^2) (Table 9).

Table 8: *Avicennia marina* pneumatophore density at distance from the river across the forest block

	Pneumatophore density (roots/m^2)		
	Distance from the river (m)		
Block	10	100	200
A (landward)	60±12^b	316±57^a	459±85^a
B (midstream)	113±30^a	67±13^a	180±54^a
C (seaward)	30±9^a	82±29^a	30±8^a

Means within a row per forest block followed by different superscripts differ ($P < 0.05$) (mean± S.E.).

Table 9: *Avicennia marina* pneumatophore density of various heights across the forest blocks

	Pneumatophore density (roots/m^2)				
Block	<5 (cm)	5-10 (cm)	10-15 (cm)	>15 (cm)	Total Mean
A (landward)	90±18	68±18	63±18	21±6	242±45^a
B (midstream)	68±12	25±6	14±4	3±1	109±19^b
C (seaward)	19±4	12±4	8±3	7±2	45±10^b

Means with different superscripts differ ($P < 0.05$) (mean± S.E.)

The height of point of attachment of *R. mucronata* prop/stilt roots across to the ground ranged from 0.26 to 1.84 m with a mean of 0.62±0.02 m (n=622). Overall, the mean height of attachment of the prop/stilt roots across the forest blocks were not significantly different (ANOVA, $p>0.05$; Figure 10). *R. mucronata* species was absent at land ward forest block at both 10 m and 200 m from the river bank. The point of attachment of prop roots at the landward block ranged from 0.1-1.7 m with a mean of 0.74±0.1 m. Point of attachment of the prop roots at midstream block did not show significant variation with distance from the river (ANOVA, $p>0.5$), but those at forest block C (seaward) showed significant variation with distance from the river (ANOVA, $p<0.05$). Turkey post hoc test shows that the height at 200 m in the seaward block was significantly different from 10 m and 100 m (Table 10).

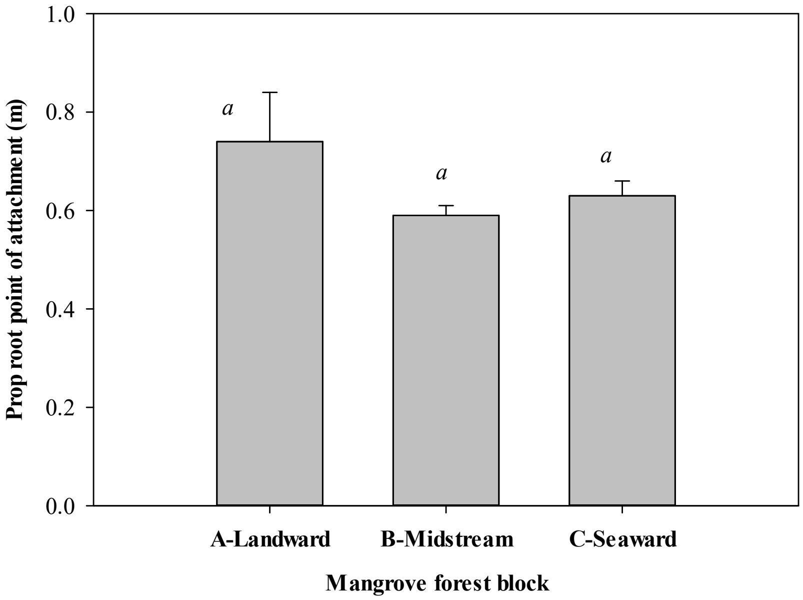

Figure 10: Vanga estuary mangrove prop root point of attachment in different forest blocks

Table 10: Mean height (m) of the point of attachment of prop roots on *R. mucronata* at different distance from the riverbank within forest blocks A, B and C

Forest block	Prop root point of attachment (m)			
	Distance from the river (m)			
	10	100	200	Mean
A (landward)	-	0.74±0.1	-	0.74±0.1
B (midstream)	0.59±0.04 ^{a}	0.56±0.04 ^{a}	0.61±0.04 ^{a}	0.59±0.02
C (seaward)	0.73±0.04 ^{a}	0.62±0.05 ^{a}	0.43±0.04^{b}	0.63±0.03

M-denotes *R. mucronata* not present; alphabetical superscripts indicate no/significant variation ($P < 0.05$) (mean± S.E.)

CHAPTER 5: DISCUSSION AND CONCLUSION

5.1 Discussion

5.1.1 Variation of sedimentation and its effects on physicochemical parameters

Anthropogenic and natural disturbances, coupled with climate change, are known to heighten the deposition of terrigenous sediments into the mangrove forest (Lerise, 2005; Chakrapani, 2005; Munga *et al.,* 2007; Caldeira, 2012; McGrane, 2016). A study by Chaudhuri *et al.,* (2019) established that sediment delivery into the Ganges-Brahmaputra mangroves is mainly sourced from overbank flooding of the rivers. A similar study in Tana Delta and Sabaki estuaries of Kenya attributed sediment input into the estuary's ecosystems; coral reef, seagrass and mangrove to land use change, damming and climatic variability (Kitheka and Mvuti, 2016). Similarly, this study established that Umba River deposits a significant amount of sediment into the mangroves. This was confirmed by the change in sediment surface elevation within the riverine mangroves of Vanga. The relatively high surface elevation change recorded landwards is attributed to a strong influence of the river.

Delivery of nutrients in sediment and water during tidal inundation and sporadic in floodwater provides a significant source of nutrients to the otherwise nutrient-poor mangrove substrate (Lugo and Snedaker, 1974). Given the increasing human population and unplanned settlement upstream coupled with the practice of unsuitable agricultural activities along the riparian land, riverine mangrove forests are destined to experience nutrient influx from sources such as; animal wastes, sewage, and detergent, fertilizer, delivered downstream by rivers (McGrane, 2016). Ultimately, the effects of land-use change and the resulting sedimentation and eutrophication will likely lead to changes in rates and pathways of nutrient transformation processes in mangroves (Alongi, 2018). Umba River catchment supports more than 1000 ha irrigation schemes in Kitivo, Mnazi, Kivingo-Mnazi, and Mwakijembe in Tanzania and 400 ha in Vanga, Kenya (Lerise, 2005). In addition to uncoordinated agricultural activities, population increase has led to an expansion of settlements along the stream particularly at the source of the river and as a result increased risks associated with anthropogenic activities such as pollution. Sediment along the riverine mangrove of Vanga recorded low concentration of all the nutrients measured (Table 5). Previous work in Caete estaury in Brazil and Gazi Bay in Kenya also recorded similar observation (Dittmar and Lara, 2001; Mwashote and Juma, 2002). These studies also noted that precipitation plays a significant role in the variation of physical and chemical environmental properties due to seasonal changes in river discharge, and surface runoff.

In Vanga estuary, nitrate and phosphorus (nutrient most likely to limit growth in mangroves) contributed the least (approximately 1% and 29% respectively). Ammonia, more toxic to aquatic life than nitrate, was the most abundant (70%). According to Alongi (2018), increased sedimentation mainly associated with hypoxia could result in biogeochemical processes that influence nutrient availability. A such, the anaerobic conditions could have created high rates of denitrification and/or ammonification depleting nitrate and nitrite pools and producing ammonia, making ammonia the most common form of nitrogen observed in Vanga. In addition, eutrophication often results in higher rates of nitrogen transformation in mangroves (Alongi, 2018). Weng *et al.,* (2013) found that ammonium and nitrate addition resulted in faster rates of ammonification and denitrification in mangrove soils. Compared with the control, nitrification intensity increased 200 - 1500% under ammonium addition and denitrification intensity increased more than 200% under nitrate addition.

Mangroves are thought to be more luxuriant in average salinity, approximately 35 ppt. In Vanga, the inflow of fresh water from Umba River lowered the level of salinity (28.6 ppt) within the riverine mangroves, lower than what was observed in Gazi Bay (31.5 ppt) by Mwashote and Jumba (2002). Though the effects of low salinity on mangrove stem density is not known we cannot demystify that low salinity resulted in relatively low stem density in the landward block. Besides, previous studies on how salinity influences mangroves in a dynamic developmental process are not well known. These studies only reveal significant differences in mangrove stem density, which can be attributed to salinity, tidal inundation and soil substrate differences that characterize the forest zones.

5.1.2 Effects of sedimentation on mangrove species distribution

Seven species that occur in Western Indian Ocean were observed in Vanga, but three species dominated: *C. tagal, R. mucronata* and *A. marina*. This agrees with a recent study by Mungai et al., (2019).

Sedimentation was negatively correlated with mangrove stem density as depicted by low stem density landwards. These observations were also comparable with that of similar work conducted in Tana Delta and Sabaki estuaries, which attributed degradation of mangroves to sedimentation. High sediment deposition in the landward block could have affected sediment oxidation state and nutrient availability necessary for plant growth. Similar observations have been reported in other studies where high sedimentation rate have been shown to disrupts the growth of some species (Ellison, 1998; Thampanya *et al.,* 2002; Sidik *et al.,* 2016; Okello *et al.,* 2019).

Also, the influence of the river and the associated effects of sedimentation on the physicochemical parameters will likely, in turn, affect rates of primary productivity and survival of specific mangrove species. *C. tagal,* which has a remarkably high degree of salinity tolerance linked to an adaptive regulation of hydration and ionic content (Patel *et al.,* 2010), was common in relatively highly saline areas. This explains their high occurrence in the seaward and landward blocks, in sites furthest from the river channel (200 m) (Table 7; Figure 9).

Other than highly saline, these sites were also subjected to high inundation (class III) with possible assumption of minimal influence from the river, that is, the closer the sea the lesser the river influence. *A. marina* had large population in the landward and seaward blocks. *A. marina* is known to displays a double zonation pattern, occurring on the coastal edge of mangroves, as well as on the inland side. It is often a pioneer in sandy habitats, but may also colonize mud flats and has a wide physiological tolerance to salinity; being able to survive in fresh stagnant water as well as in seasonally dry conditions with very high salinity (Clough, 1984). *S. alba* was better suited to inhabit sedimented areas with relatively high salinity. *S. alba* is known to inhabit areas with prolonged inundation for it does not tolerate wide fluctuations in salt concentration and high sedimentation (Thampanya, 2002). This explains their high population in the seaward block. The findings, on species distribution of mangrove of Vanga, portrayed a mangrove zonation pattern similar to that of the mangrove of Kenya (Langat and Kairo, 2008). Presence of a few species of terrestrial and freshwater plants

(*Acrostichum aureum*) among mangroves in the landward block indicated a decline in salinity over time.

5.1.3 Effects of sedimentation on root morphology of key mangrove species

Mangroves are adapted to flourish in sedimentary shorelines. Though sedimentation is beneficial to mangroves, there is a need to maintain the aerial roots above the sediments for continued respiration. The ability of mangrove species to cope with root burial varies between species. In this study, the landward block recorded the highest mean of *A. marina* pneumatophores density while seaward block recorded the lowest density. The highest number and longest *A. marina* pneumatophores were also recorded in the landward block. Studies elsewhere show that sedimentation triggers pneumatophores of *A. marina* to increase in number and extend upwards while those of *R. mucronata* develop higher root arches to enhance aeration. (Young and Harvey 1996; Ellison 1998; Okello *et al.,* 2019). These changes may take time but *A. marina* could adjust to sediment burial in this manner. Such modifications enhance functioning of biological processes, which facilitate mangrove growth. *R. mucronata*, however, did not show significant variation in the height of the prop/stilt roots from the river channel across the forest blocks. According to a study by Atmadja and Soerojo (1994), *R. mucronata* can tolerate much deeper root burial than *A. marina*. This suggests that, some mangrove species can survive high sedimentation to a given level as long as the threshold is not surpassed.

5.2 Conclusions

The mangroves of Vanga are subjected to fluvial disturbance of varying magnitude. Umba River discharge affects the amount of sediment deposited, especially landwards where the highest deposition was observed. Although we can’t decisively link Umba river to sedimentation, there is a general trend toward increased sediment deposition and related modifications on the physicochemical parameters.

The mangroves demonstrated a specific range of tolerance to the increasing sediment buildup and related sediment physicochemical changes. Findings suggest that sedimentation affects mangrove distribution and species zonation, with high stem density recorded at lower burial levels and species demonstrating a specific range of tolerance to environmental variables. This corresponds with a study by Okello (2019), which concluded that increased levels of sedimentation would affect different species distribution according to their threshold tolerance levels, with mortality being recorded at relatively lower burial levels in the more sensitive species.

The mangrove complex root system, depending on the species, may adjust to cope with increased sedimentation. These adjustments are likely to maintain oxygen diffusion from aerated root parts to the buried sections and facilitate elimination of by-products of anaerobic respiration, which could limit growth of mangroves.

5.3 Recommendations

This section presents some recommendations of this study:

i. The rate of sedimentation is above normal. This call for an urgent integrated management solution to curb further deposition and subsequent degradation of mangroves of Vanga.

ii. The study provides information on sedimentation and related physicochemical parameters, species composition and distribution, and root morphology that can be used to inform management and decision making for successful and efficient development of the proposed TBCA.

iii. Any future conservation measure and management program should consider using this study as a baseline to develop framework.

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