BIO-SHIELDS: WAVE ENERGY REDUCTION AND SEDIMENT STABILIZATION BY MANGROVES IN GAZI BAY, KENYA

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DECLARATION

This thesis is my original work and has not been submitted for award of a degree in any other university.

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LIST OF ABREVIATIONS

FAO	Food and Agriculture Organization
KMFRI	Kenya Marine and Fisheries Research Institute
UNEP	United Nation Environmental Program
NERC	National Environmental Research Council
UK	United Kingdom
IPCC	Intergovernmental panel for Climate Change
SLR	Sea level rise
NEMA	National Environmental Management Authority
GOK	Government of Kenya
ICZM	Integrated Coastal Zone Management

GLOSSARY

Hydrodynamics	The study of the motion of incompressible fluids and interaction of such fluids with their boundaries
Attenuation	A loss of intensity suffered by wave energy as it passes through a medium (forest). The loss may be caused by
Clod card	Blocks or spheres of calcium sulphate (plaster of Paris) prepared by standard ice- cube trays and are suited to marine
Biodiversity	The variability among living organism from all sources including inter alia terrestrial, and other aquatic ecosystems
Propagules	A dispersed unit in mangrove. It may also refer to a seed.
Sapling	Germinated propagules, a seedling or wildings.5
Anthropogenic	Relating to, or resulting from the influence of humans on nature.
Deforestation	The extensive cutting down of forests for the purpose of extracting wood fuel, mining or agriculture
Recruitment	The influx of new members into a population by reproduction or immigration
Resilience	The ability of a system to undergo, absorb, and respond to change and disturbance while maintaining its function

ABSTRACT

Mangrove forests provide natural coastal protection by attenuating wave energy and stabilizing sediments. Efficiency of coastal protection is likely to decline with increased losses and degradation of mangrove forests; but there are few empirical studies to test these hypotheses. The objective of the study was to investigate how wave energy and sediment stabilization vary with tree density in a monospecies stand of mangroves (*Sonneratia alba*) at Gazi Bay, Kenya. Seven, 80m long belt transects set perpendicularly to the shoreline were randomly selected along 900 m stretch of shoreline with homogenous emergent wave energy. Transects were positioned to give the widest possible range in remaining tree density, from transect without tree cover (control) to the one with highest tree density of 680 trees/ha. Structural parameters, including; tree density (stems/ hectare), pneumatophores density (ind./ m^2), and basal areas (m^2) were quantified using 2 quadrat measuring 25 m by 20 m along each transect. Three intertidal stations A, B and C were systematically positioned across each transect. Stations A's were 20 m before the mangroves on the seaward side while station B, and C were placed in the forest and were 30 m apart. Each station had 5 sampling points which were sampled for wave energy using uniform plaster of Paris clod cards. Sediment stability was measured at 10 points per station using improvised sinking metal disks made from bicycle spokes. Sediment accretion was monitored by Surface Elevation Tables (SETs), positioned at station B. The accretion rate was measured at 10 replicate point per transect once per month for 8 months using a standard ruler. All transects showed significant difference in pneumatophores density ($F_{(2, 39)}$ =25.15, p = 0.000), tree density ($F_{(2, 33)}$ =24.79, p = 0.000), and basal area ($F_{(2, 39)}$= 29.66,p = 0.01). One way analysis of variance (ANOVA) showed a significant difference in wave energy sampled by tree stems between stations A, B and C ($F_{(2, 18)}$ = 10.92, p = 0.001). Correlation of wave energy reduction against tree density/ha showed significant difference between stations (r^2 = -0.594, p = 0.000), where wave energy reduced with increase in tree cover. Similar test also showed significant difference in wave energy reduction against pneumatophores density/ m^2 (r^2 = -0.794, p = 0.000) and basal areas per m^2 (r^2 = -0.451, p = 0.000). Regression analysis showed a significant difference in sediment stability against tree density (R^2 = 61 %, P = 0.028) and basal areas (R^2 = 72.8 %, p = 0.015) whilst there was no significant difference between sediment stability and pneumatophores density (R^2= 47%, p = 0.089). Regression analysis between mean sediment accretion rates against tree density/ (R^2 = 7.2%, p = 0.608), basal areas (R^2 = 8.9 %, p = 0.566) and pneumatophores density/m^2 (R^2= 11.1, p= 0.415) were not significant. The study will help the managers and the government on the merit of using mangroves as bio-shields in protecting coastlines against erosion and stabilizing sediment in the wake of much anticipated global changing climate and sea-level rise.

CHAPTER ONE

1.0 INTRODUCTION AND LITERATURE REVIEW

1.1 Background to the Study

Mangrove forests are important ecosystem that stabilize coastlines and protect live and property (Keryn, *et al.,* 2011). The forests grow in the intertidal areas of sheltered tropical and subtropical coastlines. They are largely confined in the tropics; between latitude 30^0 north and 30^0south (Spalding, *et al.,* 1997). Globally, mangroves are estimated to cover 14-24 million ha; spread over 122 territories (Giri, *et al.,* 2010). The largest under mangrove forest is in South east Asia which occupies 34-42 % of global mangroves (Spalding, *et al*., 2010).

In African continent, Nigeria has the highest concentration of mangroves with 4.7 % followed by Mozambique and Madagascar with 2.3% and 2.0 % respectively (Spalding, *et al.,* 2010).

Given the multiple goods and services provided by mangrove ecosystem there is increased effort to restore degraded mangrove forests globally (Gilman, *et al.,* 2008). Efforts to replant degraded mangrove forests was started in Kenya in 1990's and is still on-going (Kairo, 1995).

In Kenya, there is some information on human induced mangrove deforestation and transformation (Abuodha & Kairo, 2001). However, little is known about the effects of degradation on ecosystem functions such as shoreline protection. At Gazi pilot area for instance, removal of the fringing mangroves has led to the erosion of adjacent coconut plantation (Dahdouh-Guebas, *et al.,* 2006). Some 30-40 % of near shore mangroves at Gazi comprises of *Sonneratia alba* forest which is mostly adapted to frequent inundation (Neukermans, *et al.,* 2008).

In the context of climate change, mangroves build new land by accreting sediment either *insitu* or exogenous (Krauss, *et al.,* 2013); thus balancing relative sea level rise (Bell & Lovelock, 2013). In the recent past mangrove forests have proved to provide shoreline protection (Bell & Lovelock, 2013). They attenuate wave energy and bind sediment by their roots (Mazda, *et al.*, 1997). Studies done in the Caribbean coast of Belize, Honduras and Panama (McKee, *et al.*, 2007) have shown sediment capture of 4.1 ± 2.2 cm by fringing mangrove forest which is likely to counter the global mean rates of eustatic sea level rise of 1.5–2 mm year^{-1} (Krauss, *et al.,* 2013).

This study measured wave attenuation by mangroves at Gazi Bay, Kenya; in a bid to establish baseline data on protective functions of mangroves in the area.

1.2 Literature Review

1.2.1 Mangroves of Kenya

In Kenya mangroves cover was approximately 45,590 ha by year 2010 and are distributed along 600 km of the coastline (Kirui, *et al.*, 2012). Largest concentration of mangroves in Kenya is found in Lamu, 33,500 ha, Kwale district: 8375 ha, Kilifi district: 5570ha, Tana River district: 3045 ha and Mombasa district: 2490 ha (Abuodha & Kairo, 2001) (Figure1).

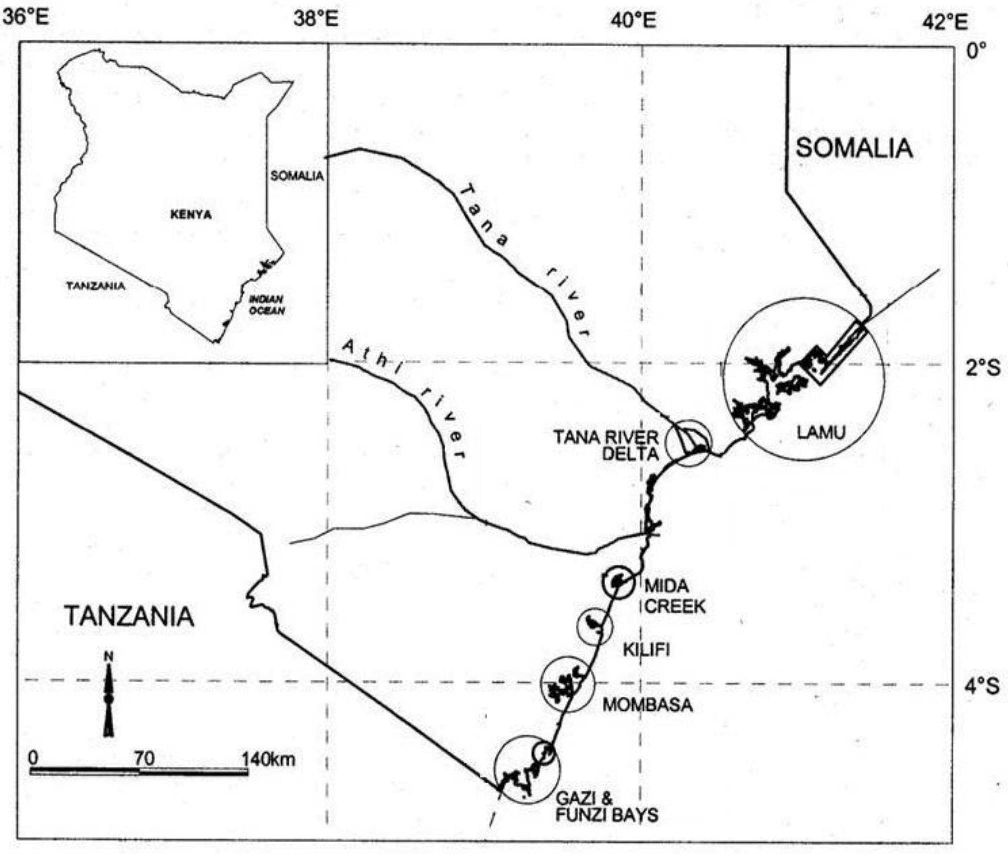


Fig 1; A map of Kenyan coast showing mangrove distribution (Bosire, *et al.*, 2003).

1.2.2 Attributes of mangrove environment

Environmental factors play a role in spatial distribution of mangrove forest at global, national and local scales (Lugo, 1974). These factors influence variations in terms of mangrove species richness, growth and productivity (Rabinowitz, 1978). The main environmental factors associated with variations in mangrove ecosystem include; climate, soil types, fresh water supply;(Alongi, 2009) tidal inundation, (Lugo, 1974) and geomorphology (Woodroffe, *et al.*,2005). Climatic conditions particularly temperature and precipitation is responsible for global distribution in mangroves (Spalding, *et al.*, 2010).

Maximum growth in mangroves occurs within the tropics where minimum temperature is about 20°C (Krauss, *et al.,* 2008). High rainfall minimizes salinity levels in the sediment especially in humid areas where evaporation is high accelerating growth performance of mangrove (Kathiresan & Qasim, 2005). Alluvial soils and muddy substrates support mangrove growth and also facilitate colonization of new areas due to improved physio-chemical characteristic (Alongi, 2009).

Physical compositions of the soil such as high levels of clay help sediment to be rich in nutrients unlike sandy substrates making the former to be conducive for mangrove growth (Alongi, 2009) In addition, high silt and clay levels in the sediment increase cohesion of particles as they attach to organic components from both living organisms such as algae, ciliates, zooplanktons and bacteria, and detritus from plants and animals (Crona, *et al.,* 2006). Silt and clay particles flocculates, creating mudflats that are more compact over time (Furukawa & Wolanski, 1996). More cohesive mudflats decrease fluidization and erosion by water currents interacting with mangrove forest structures (Furukawa & Wolanski, 1996).

Tides are important in determining the potential extent of mangrove species distribution through dispersal of viviparous propagules (Lugo & Snedake, 1974). In addition, tides facilitate nutrient distribution and sediment exchange between mangroves sea grasses and coral reef ecosystems (Kitheka, *et al.,* 2003).

1.2.3 Biology and adaptation of mangroves

Mangroves are adapted to the harsh environment in several ways which include: possession of pneumatophores for gaseous exchange, processes such as salt exclusion, and in some species, salt secretion and viviparous seed development (Tomlinson, 1994). Mangrove trees deal with salt stress by filtration of the soil water at root level and by secretion of salt crystals via salt glands on their leaves (Sobrado, 2005).

An often observed attribute of mangroves ecosystem is the horizontal distribution of species or zonation (Macnae, 1968). Certain species of mangroves are noted to fringe the seaward side where tidal inundations are frequent while others occur on the elevated side of the intertidal area (Kitaya, *et al.*, 2002). Multiple environmental gradients such as frequency of inundation, temperature, rainfall, salinity and oxygen concentration operate to control species association in mangroves (Saenger, 2002). Typical zonation patterns observed in the Indo-West Pacific region show *Sonneratia alba* and *Avicennia marina* occupying the lowest intertidal zones while *Rhizophora mucronata* and some species such as *Bruguiera gymnorrhiza* and *Ceriops tagal* occupy the mid-intertidal zones (Macnae, 1968). At lower intertidal elevations, low seedling survival for certain species such as *A. marina*, *B. gymnorrhiza* , and *C tagal* has been witnessed elsewhere in the world (Smith, 1987) whilst *S. Alba* has shown high survival rates at low elevation compared to other species (Kitaya, *et al.,* 2002) hence proving to be a suitable species that can be used as a bio-shield to minimize coastal erosion (Massel, *et al.,* 1999).

1.2.4 Threats to mangroves

Mangroves ecosystems in many areas of the world have experienced decline in area coverage mainly due to anthropogenic pressures (Valiela, *et al.,* 2001) which has left most mangrove forests degraded across the globe (Giri, *et al.*, 2010). In the last few decades, the anthropogenic pressures has increased due to rising demands for goods and services provided by mangrove forests that are of economic, ecological and environmental value to millions of people throughout the world (Barbier *et al.*, 2011). Economically, they are sources of wood fuel, charcoal, wild honey, herbal medicine and tannin for leather industries, and provide aesthetically pleasing ecosystems for ecotourists (Dahdouh-Guebas, *et al.*, 2000). Specifically, large-scale mangrove forests conversions were witnessed in the period before 1980's in Asia, Caribbean and Latin America primarily to create land for aquaculture and tourism infrastructure (FAO, 2007). In Asia approximately 25 percent of mangrove cover was lost from 1980-2005 mainly through over-exploitation and development of shrimp farming. Because of high economic returns, shrimp farming was promoted in Asia to boost national economies in the region (FAO, 2007). Other global causes of mangrove cover decline are salt extraction, pollution and wood fuel extraction among others (Kairo,*et al.,* 2001).

Despite offering critical regulatory service, mangrove forests have undergone significant reduction mostly arising from human induced pressure (IPCC, 2006). Up to 75% of tropical coastlines were once covered with mangroves (Williams, 2005). To date, less than 65% of mangroves exist (Alongi, 2002). Degradation of mangrove forests through over-exploitation, land use changes, and climate change related effects interfere with the stability and functioning of mangrove ecosystem (Friess, *et al.*, 2012).

Globally, mangrove forests declined by 23% since 1990 (Giri, *et al.*, 2010). In Kenya, the loss has been estimated at 18% since 1990; but accelerating (Kirui, *et al.*, 2012). Mangroves play an important role in shoreline protection against extreme weather events such as tsunami (Harinarayana & Hirata, 2005). Besides extreme events, mangroves perform their role of coastal protection continually, during 'average' wave conditions (Mazda, *et al*., 1997). Yet, there is little information on how much mangroves contribute to coastal protection in the long term (Bell & Lovelock, 2013). Such information is needed for integrated coastal zone management (ICZM), particularly as the risk of coastal erosion is likely to be exacerbated from emergent climate change and increased frequency of storminess. In addition, increased wave height is predicted to further threaten human lives and coastal infrastructure (Tanaka, *et al.*, 2006) through flooding, sedimentation and coastal erosion (IPCC, 2006).

In Kenya about 20% of mangrove forests have been lost at an average rate of 0.7% per annum varying between different areas and over time (Kirui, *et al.*, 2012). Major threats to mangrove forest in Kenya include: cutting mangroves for wood fuel, extraction of raw materials for construction industry and creating space for tourism infrastructure among others (Abuodha & Kairo, 2001).

Global climate change is emerging to be a unique threat to mangrove through changes in hydrodynamics regimes, sediment supply and increased sea level rise (Friess, *et al.*, 2012). The mean global sea level rise is approximated to 3.2± 0.4 mm y^{-1} with varying degree depending on location (Webb, *et al.*, 2013). Higher rates have been estimated in Indonesia; 7.5 mm y^{-1} and lower rates of 1.9 mm y^{-1} in the Caribbean as a result of regional variation in ocean warming and other factors (Krauss, *et al.,* 2013).

In Kenya, climate change is posing a big threat to the country's coastal strip which is characterized with rich flora and fauna including fish, coral reefs and mangroves (GOK, 2010) (GOK, 2010). With a projected sea level rise of between 0.17 and 0.59 mm over the next century, the Kenyan coastal ecosystems and infrastructural development will be exposed to a considerable risks (GOK, 2010). The 1997/98 El Nino weather pattern in Kenya for example, caused heavy rains that led to massive sedimentation and impounding of water leading to extensive mangrove die-back along the coast particularly in Mwache creek, Gazi Bay, Ngomeni, Tana River delta and Dodori (GOK, 2010). Exposed areas after degradation are left vulnerable to hydrological energy leading to shoreline erosion (Kitheka, *et al.,* 2003). In low laying coastal area a small increase in sea level will leave mangroves submerged unless they retreat further inland which is improbable due to human settlement (GOK, 2010).

1.2.5 Role of mangroves in shoreline protection

The role of mangroves in shoreline protection has been emphasized in earlier mangrove literature as makers of new land (Davis, 1938) and gardens of new mangrove forest (Curtis, 1888). To date the study has gained momentum (Barbier, *et al.,* 2011). Following the 26th December 2004 tsunami tragedy in the Indian ocean which killed thousands of humans and destroyed coastal infrastructure worth several billions of dollar, shorelines protection from such extreme weather events has been of great concern to many governments (Yalc, 2002). The tsunami event in the Indian Ocean confirmed important role played by mangroves in shoreline protection; as areas with intact mangroves suffered less from tsunami than areas without (Dahdouh-Guebas, *et al.,* 2005).

Wave attenuation by mangroves increases with forest depth (Mazda, *et al.,* 1997) and tree density (Alongi, 2009). Young mangrove tree of *Kandelia candel* are less effective in wave attenuation confirming that age of the forest is also major factor in coastal protection (Mazda, *et al.,* 1997). Forest degradation, which reduces the density above-ground biomass of trees and basal areas (Kairo, *et al.,* 2008) is very likely to impact on the capacity of mangroves to reduce hydrological energy (Alongi, 2009). However, there has been few studies on how wave attenuation relates to forest degradation (Furukawa, *et al.,* 1997).

Efforts have been turned to reviving coastal defences comprising of mangroves in many parts of South East Asia where over 30% of mangroves had been lost to human induced factors (Abuodha & Kairo, 2001). Scientific evidence now show that mangrove forest growing between human settlement and the sea could reduce the impacts of a tsunami thus shielding villages from severe destruction (Yalc, 2002). The major drawback from these studies was that conclusions were drawn from data collected after the event had taken place (Alongi, 2009).

Most empirical studies of physical processes in mangrove forests have been carried out in Asia (Furukawa, *et al.,* 1997; Mazda, *et al.,*1997), and Australia (Massel, *et al.,*1999). In Kenya most studies have been directed to ecology (Bosire, *et al.,* 2008), forestry (Kairo, *et al.,* 2008) and mangrove mapping studies (Kirui, *et al.,* 2012) among others. Literature available indicates no study that has been directed to physical processes in the mangrove forest in Kenya specifically in shoreline protection from average waves conditions.

Frictional interactions of waves with mangrove's trunks and roots, as well as bottom frictional drag caused by interaction between water flows (Mazda, *et al.*, 1997) and the substrate (Mazda, *et al., 2005)* are the two primary mechanisms that are responsible for hydrological energy dissipation within the mangrove forest. Energy dissipation by mangroves is likely to depend on the mangrove tree species, diameter and density of stems and roots (Phuoc & Massel, 2006). Some studies have focused on the interaction between the mangrove's tree trunks and roots and reports that mangrove trees attenuates hydrological energy to lower levels as the wave propagates across the forest of known width (Mazda, *et al.,* 1997; 2005; Alongi, 2009).

Forested sites tend to reduce sediment erosion and promote sediment accretion (Furukawa, *et al.,*1997). Movement of sediments that accompanies water flow modifies the swamp topography (Furukawa & Wolanski, 1996). Pneumatophores provide a physical barrier to suspended sediment thus stabilizing shorelines by reducing hydrological energy (Mazda, *et al.,*1997). Empirical field studies carried out elsewhere have shown that wave attenuation by mangroves is species specific due to morphological difference between tree species (Furukawa & Wolanski, 1996). For instance, *Sonneratia spp.* possess pneumatophores that reduce hydrological energy more efficiently than *Kendalia kendal* which has no aerial roots (Alongi, 2009). Hydrological energy may be reduced by 45% across 100 m wide *Sonneratia* forest (Mazda, *et al.,* 2005). Other than band width of mangrove forest, vegetation density and tidal elevation also influence the drag force (Mazda, *et al.*,1997). Models of the effectiveness of mangroves in protecting shoreline erosion therefore require being experimented in-situ due to sites specific characteristics such as tree species, density, micro topography and basin bathymetry (Dahdouh-Guebass, *et al.*, 2005).

In Kenya, however there is no empirical data to test the effectiveness of mangroves in shoreline protection.

1.2.6 Effects of mangrove trees density on sediment accretion

Higher plants increase the surface roughness of aquatic systems, thereby reducing hydrological energy and minimizing re-suspension of sediment after deposition, thus raising the chances of sediment accretion (Krauss, *et al.,* 2003). Mangrove trees play a major role in sediment trapping and stabilization (Tanaka, *et al.,* 2006). Empirical tests done elsewhere has shown that mangrove tree species with stilt roots are more effective in creating drag forces than those without as the former enhance sediment trapping and stabilization (Tanaka, *et al.*, 2006).

Degradation of mangrove forest results in loss of fine grained sediment as coastal protection measures diminishes (Dolch & Hass, 2008). Increase in hydrological energy through rising sea level is likely to contribute to the depletion of fine grained sediment (Dolch & Hass, 2008).Tidal basins devoid of fine grained sediment and mud reduces the chances of mangroves propagules and seedling colonizing the substrate. Loss of fine grained sediment becomes a major challenge to successful artificial or natural regeneration. Wave activity and tidal forces particularly result in erosion of seaward margin of fringing mangrove forest (Mazda, *et al.*, 1997). Removal of mud and accumulated peat from fringing mangroves may results in mangrove die-back regardless of their respective level of growth (Kitheka, *et al.,* 2003).

Most sediments in mangrove forest originates from the highlands and drains into the sea through river channels (Kitheka, *et al.*, 2003). Tidal wave redistributes sediment from one location to another within mangrove forests (Alongi, 2009). In Kenya, net import of sediment into the mangrove forest mostly occurs during the periods of high river discharge on both neap and spring tides (Kitheka, *et al.*, 2003). During the dry season, river discharge and sediment load is minimal but sediment movement and redistribution is mostly limited to spring tides (Kitheka, *et al.*, 2003). Where the mangrove forests are extensive, there are profound impacts of transport and deposition of fine particles (Furukawa ,*et al* .,1997) with minimal imports from both front and backwaters in the mangrove forest (Kitheka, *et al.*, 2003). Thus, major factors that affect sediment transport and flocculation include; mangrove tree density and coverage (Alongi, 2009) and the extent of mangrove degradation (Kitheka, *et al.*, 2003).

Sediment transport and flocculation in dense mangrove fringed coasts is generally high as clay particles are interwoven by fibers and threads of micro-organisms glues them by mucus membrane that withstands shear stress from turbulence without disaggregation (Wolanski, 1995). When tidal waters drain through a degraded mangrove forest the rate of sediment transport increases with distance from the sea, trapping efficiency declines from 65% to 27 % (Kitheka, *et al*,. 2003).

1.2.7 Measuring hydrological energy across mangrove forest

Wave attenuation refers to reduction of wave energy by lessening parameters such as wave height and wave length (Mazda, *et al.*, 1997). Reduction in wave energy through mangrove forest is a function of distance and density of the forest, water depth and incident wave conditions (Mazda, *et al.*, 2005). The rate of wave attenuation across a known distance has been defined by estimating the wave height in an arbitrary sea side station away from the mangrove influence and the second station placed in a known distance across mangrove forest (Mazda, *et al.*, 1997). The wave height decreased at an inshore station across mangrove forests (Mazda, *et al.*, 1997). Through this approach (Mazda, *et al.*, 1997) demonstrated that wave height could be reduced by 45% across two points in a mangrove forest while in an open mud flat without mangroves, wave height reduction was evident but minimal only due to frictional drag by the substrate (Mazda, *et al.*, 1997).

1.2.8 Estimation of Hydrological Energy Using Plaster of Paris Clod Cards

Clod cards made of plaster of Paris have been used to quantify hydrological energy (Thompson & Glenn, 1994). The technique was first used by (Glenn & Doty, 1992) and (Muus, 1968). The original principle to determine water motion involved calculating the ratio of weight loss of clod cards placed in the field to weight loss of clod cards from the same batch held under specific still-water conditions in the laboratory (Glenn & Doty, 1992). Improvements were done by attaching clod cards to a rotating arm in a tank of sea water and the dissolution rates found to be proportional to the rate at which they moved in sea water (Thompson & Glenn, 1994).

The relationship of weight loss versus velocity of the fluid is a linear function. Weight loss of clods versus water motion is expected to be decreasing rather than a linear function because the exposed area of clods diminishes as dissolution proceeds. Thus, the rate of loss of weight of clod cards is proportional to the hydrological energy exerted by flowing water. For clods, the approximation is useful until >50 % of clods has dissolved or longer depending on the velocity of the fluid (Thompson & Glenn, 1994).

1.2.9 Effects of mangrove degradation on shoreline erosion

Following degradation of the original fringing *S. alba* forest in Gazi Bay, site conditions were greatly changed (Nitto, *et al.,* 2008) leaving the area vulnerable to moderate wave exposure (Kirui, *et al.,* 2012). Wave energy has been eroding the shoreline washing coconut palms in the adjacent private agricultural farmland into the sea (Kirui, *et al.,* 2012). Previous attempts to control erosion along this shoreline involved use of gabions and barrier rocks which to date have either been washed in the sea or buried by sand. Effort to restock the site started in 1994 to date, with mixed success (Kairo, 1995). Dislodgement of seedlings remains a big challenge (Kairo, 1995; Kirui, *et al.,* 2012). In small parches where restocking has been successful, erosion and sedimentation is minimal with new recruitments of wildings being evident suggesting that reforestation remains the best option to diminish shoreline erosion.

1.3 Problem Statement

Losses and degradation of mangroves forest have left many sites along the coast exposed to strong wave and tidal energies resulting to shoreline erosion. Extreme weather events arising from climate change has further threatened human lives and many infrastructural facilities located at closer proximity to the coastline. However, little quantitative information exists on how mangrove forest could be used to protect shoreline erosion and stabilize sediment in Kenya and western Indian Ocean region.

1.4 Justification and Significance of the Study

This study was carried out to generate information on effects of mangrove stand density in wave energy reduction and sediment stabilization thus protecting shoreline from erosion in Gazi Bay, Kenya. Many studies done in the mangrove ecosystems in

Kenya has tended to concentrate on biological aspects particularly forestry (Kairo, *et al.,* 2001) community ecology (Kairo, *et al.,* 2008) natural regeneration (Kairo, *et al.,* 2002) and mapping (Kirui, *et al.,* 2012) with few studies directed to physical processes (Kitheka, *et al.,* 2003). Studies on physical processes in mangroves help to better understand environmental settings impacting on mangrove functions such as shoreline protection and sediment stabilization.

The results of this study will help the local community and the government to appreciate the provisional and regulatory roles of the mangroves forest. Specifically, the communities living in the near shore environments shall double their reforestation efforts by restocking degraded fringing mangroves forests with suitable mangrove species and claim carbon credits thus improving living standards. Restocking degraded areas of Gazi will increase stand density and therefore, enhance system ability to protect the shoreline. Such initiative could save millions of dollar that would otherwise been used to construct sea walls that with time succumb to hydrological energy from waves and tides.

1.5 Hypothesis

Mangrove tree density has no effect on wave energy reduction and sediment stability.

1.6 Main Objective

The broad objective of this study was to examine wave energy reduction strategies and sediment stabilization by fringing mangrove forest at Gazi Bay Kenya.

1.7 Specific Objectives

1 To determine the effect of trees and pneumatophores density on wave energy reduction.

2 To determine the effect of tree and pneumatophores density on sediment stability and accretion.

CHAPTER TWO

2.0 MATERIALS AND METHODS

2.1 Study Areas Description

The study was based at Gazi bay in the south coast of Kenya ($4^0$25'S and 4^0 27'S; $39^0$50'E and $39^{`}$$50^o$E). The Bay has a surface area of 18km^2 and an estimated mangrove cover of 615 ha (Kairo, *et al.,* 2001). Gazi bay is approximately 60 km from Mombasa Kenya. The bay is sheltered by Chale peninsula to the east and a fringing reef to the south, where a distance further on-shore a degraded and semi-pristine fringing mangrove forest occurs (Figure 2). The study site was severely degraded following deforestation in 1970's and early 1980's through unsustainable harvesting of industrial wood fuel. The width of the fringing mangrove forest ranges between 40-90 m width and 800 m long. The narrow stretch of fringing mangrove forest is inundated daily during spring and neap tide (Kairo, 1995).

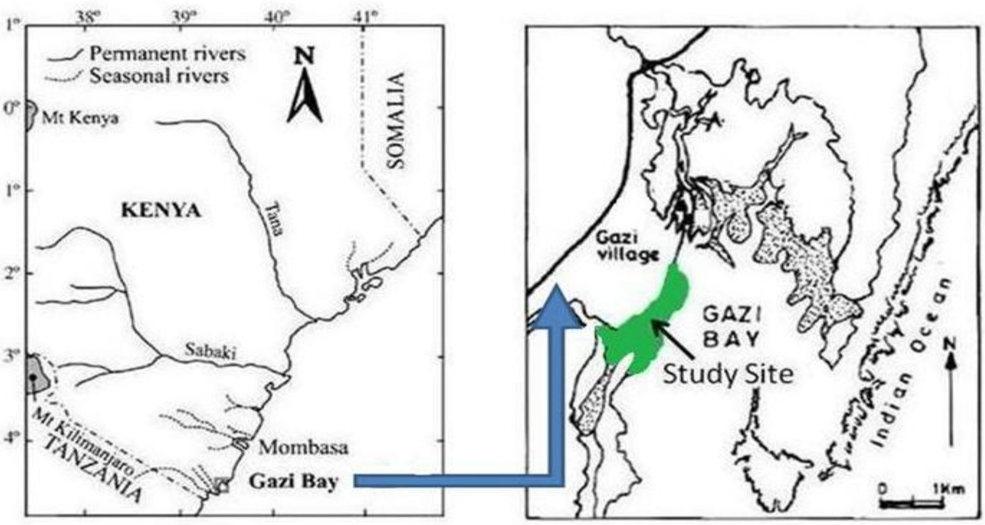


Figure 2: A map of Kenyan Coastline showing the study site comprising of fringing mangroves in Gazi Bay (Bosire, *et al.*, 2003).

2.1.1 Hydrology and rainfall

The climate of Gazi Bay is typically that of Kenyan coast. It is influenced by both south east and north east monsoons. Total annual precipitation ranges between 1000 mm to 1600 mm displaying bimodal pattern of precipitation (Kairo, 1995. The spring tidal range in Gazi bay is ~4.0 m (Kirui, *et al.*, 2012). Long rains are under the influence of south east monsoon, starts in April to August while north east monsoon influences the short rains starting from October to December. Average annual temperature is 26 degrees centigrade. Humidity is approximately 65-80 percent (Bosire, *et al.*, 2003).

Two seasonal rivers Kidogoweni and Mkurumuji drain into the Bay. Both Rivers are seasonal depending on rainfall experienced inland. River Mkurumuji is bigger with a catchment of $175km^2$ inland and has high flow rates; a maximum and minimum flow of $0.02m^3$/s and 5.90 m^3 respectively whilst ground water seepage is restricted to small parts (Kitheka, *et al.*, 2003). The hydrology of the bigger Mkurumuji river contribute positively in allochthonous nutrients together with the upcoming anthropogenic inputs from agricultural farms and mining industries during the rainy season (Kitheka, *et al.*,2003). Human activities particularly sugar plantations at Ramisi and Titanium mining both in Kwale County may affect allochthonous sediment input negatively due to damming upstream in both rivers.

2.1.2 Geology

Geologically, Kenyan coast comprises of rocks mostly marls and limestone, and are represented by sandstones, clays, conglomerates and gravels (GOK, 2009). These well-developed reef complex consisting of coral reefs, coral rubble and sandstones is extensively exploited by the building industry (GOK, 2009).

Fringing reef crests dominate the Kenyan coast forming a natural barrier to the wave energy from the ocean with a shoreline comprising of reef terraces and mangroves, with tidal flat in Gazi Bay fronting the mangroves (GOK, 2010). The study site is a low shore beach that receives daily inundation (Watson inundation class 1) and has moderate wave exposure and sandy sediments (Kitheka, *et al.,* 2003). The highest spring tide is approximately 4 m above datum (Kitheka, *et al*., 2003).

2.1.3 Mangroves of gazi

All the nine mangrove species described in the western Indian Ocean region occur in Gazi bay. The dominant species are *Ceriops tagal* (Perr) C.B Robinson and *Rhizophora mucronata* (Lam) that makes more than 70% of the formation (Kairo, *et al.,* 2008). A strong formation of species occurs, controlled by the large tidal regime, with a typical patter from the sea to the land being *S. alba, R. Mucronata, Bruguiera gymnorrhiza*,(L) Lam *C. tagal*, *Avicennia marina* (Forsk) Vierh, *Xylocarpus granatum*,(Koen), *Lumnitzera racemosa* (Willd), *Xylocarpus muluccensis* (Lam) Roem and *Heritiera Littoralis* (Dryand) (Dahdouh-Guebas, *et al.,* 2004). Animal species ranges from molluscs; sesarmids crabs which are keystone species due to their high rate of nutrient cycling (Bosire, *et al.,* 2008). Other common species of crabs include: *Uca annulipes* and *Uca inversa* (Skove, *et al*., 2002).

Epibiotic communities of algal species encountered in both sea ward and land ward zones include: *Enteromorpha ramulosa*, *Polysiphonia* sp., *Hypnea* sp. and *Caloglossa leprieuri* attached to pneumatophores of *S. alba* at different pneumatophores height and (Crona, *et al.,* 2006). Poriferans are found growing on the pneumatophores of *S. Alba* stands with common example being *Tedania digitata vulcanis* (Crona, *et al.,* 2006).

Gazi Mangrove forests are habitat for juvenile fish which are either planktivorous or benthic feeders (Kirui, *et al.,* 2012). Common juvenile species of fish found in the fringing mangrove forest are; *Gerres oyena* and *lutjanus fulviflamma* (Kirui, *et al.,* 2012). In addition, the forest form a good habitat for different species of snakes, resident and migratory birds that commonly feed in the near shore environments (Kairo, 1995).

2.1.4 Social economic activities

According to the national census of 2009, Gazi Bay has a resident population of approximately 4825 people, majority being women and children. About 90% of the men in Gazi are involved in artisanal fishing and mangrove cutting for sale to Mombasa and other coastal towns (Hamsa , 2013). It is estimated that 90% of mangroves harvested are used for building houses, provision of wood fuel, tannins, traditional medicine, ribs for boat manufacture and furniture (Dahdouh-Guebas, *et-al* 2000). Women are mostly engaged in weaving makuti (roof thatches made from coconut fronds) farming and small businesses (Dahdouh-Guebas, *et al.,* 2000). Mangroves in Gazi has been used extensively by both undergraduate and post graduate research student in different disciplines to address various research questions (Kairo, *et al.*, 2009).

Recently a community based mangrove conservation initiative, Mikoko Pamoja, in partnership with KMFRI and Universities in UK have started mangrove restoration and protection in the bay through sale of carbon credits in the voluntary carbon market (Hamsa, 2013).

2.2 Project Design

Change in wave energy was measured across seven belt transects selected randomly and perpendicular to the shoreline in a monospecies of fringing of *Sonneratia forest* (Figure 3). The seven transects had varying tree and pneumatophores densities and were denoted with letters K, L, M, N, O, and P. Among the seven transects, transect Q had no mangrove cover and was selected as a control. The belt transect were set a short distance from river Mkurumuji heading north towards the Bay. This selection was done in order to incorporate vegetation structural differences of fringing mangroves.

Positioning of transects was done in areas where the band width of the mangrove trees stretch was ≥ 80m. This was because the band width of the mangrove forest was not uniform at the study site and it was the widest stretch of mangrove cover that existed and allowed sufficient number of transects.

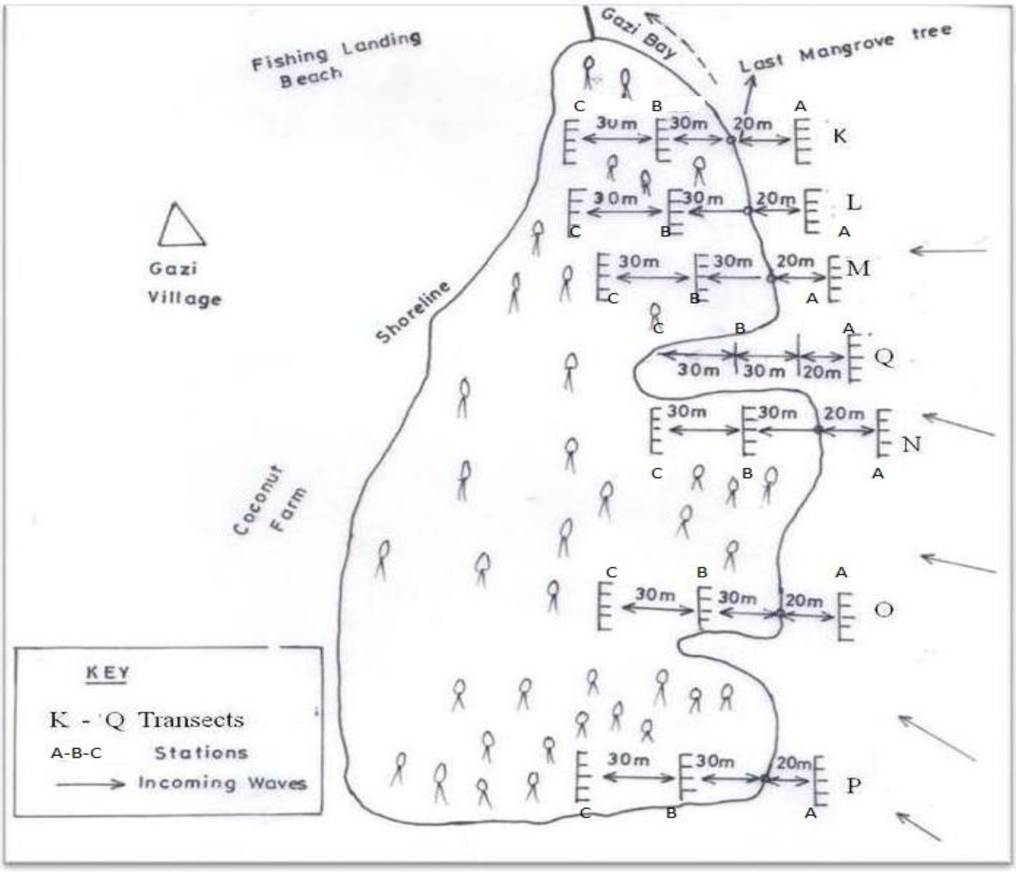


Figure 3: Schematic diagram showing relative position of stations in each transect at the study site (not drawn to scale).

2.3 Sampling Design

Mangrove tree density was quantified in seven; 80 m long belt transects using two plots each measuring 25 m long and 20 m width. The plots were systematically selected along each transect which were set perpendicular to the shoreline. The first plot was established 20 m from the lowest mangrove tree on the seaward side whilst the second plot was set 5 m from the first plot toward the landward side. Pneumatophores density was determined by systematically selecting 5 quadrats each measuring 1m by1 m nested in each of the bigger plots of 25 m by 20 m. The four plots of 1 m by 1 m were set at each corner and one at the middle of each of the two plots. A total of ten plots per transect were selected to estimate pneumatophore density per transect A total of 12 plots were selected to estimate mangrove trees and pneumatophores density respectively at the study site.

Wave energy was measured at three stations marked A B and C across seven transects set perpendicular to the shoreline. A total of 21 stations were marked in the study area. Station A was ~20 m from the last mangrove trees on the seaward side which measured incident wave energy before mangrove influence, station B was 50 m from station A whilst station C was 80 m from station A. Both station B and C measured incident wave energy passing through mangrove forest. Each station was marked with five wooden pole of 10cm girth, 1.5m high, driven 70 cm into the ground.

Wave energy was measured using plaster of Paris clods. The clods were prepared by mixing 11.4ml of fresh water with 14.3g plaster of Paris powder manufactured by LAFARGE PRESTIA (*www*.lafargeprestia.fr) (Figure 4). The powder was slowly added in water and stirred with a spoon. The slurry was poured in to a plastic ice cube trays. The trays were tapped vigorously several times to dislodge air bubbles. It was allowed to harden for between 20-30 minutes before removing them. After removal, the cards were oven dried for 48 hours at 40 degrees centigrade. The final weight of the clod after exposure to the field was determined by subtracting the total weight of the clod plus the plastic plate and the silicon cement before exposure. The basic assumption was that the weight of the plastic and that of the silicon cement remained constant and did not change due to corrosion by sea water.

Figure 4: Oven dried clod cards glued on plastic plates with silicon cement before exposure in the field (Photo by David Maina)

Clod cards were then sanded at the bottom to attain a uniform weight of 14 ± 1.5 g within a batch. They were glued to a plastic plate measuring 3 cm×8 cm with silicone cement (No Nonsense Ltd.BA 228RT). The clod cards were taken to the field and mounted on the poles at 15 cm and 50 cm from the substrate surface respectively (Figure 5). The clod cards mounted at 15 cm measured wave energy reduction by pneumatophores while the clod cards mounted at 50 cm measured wave energy reduction by mangrove tree stems.

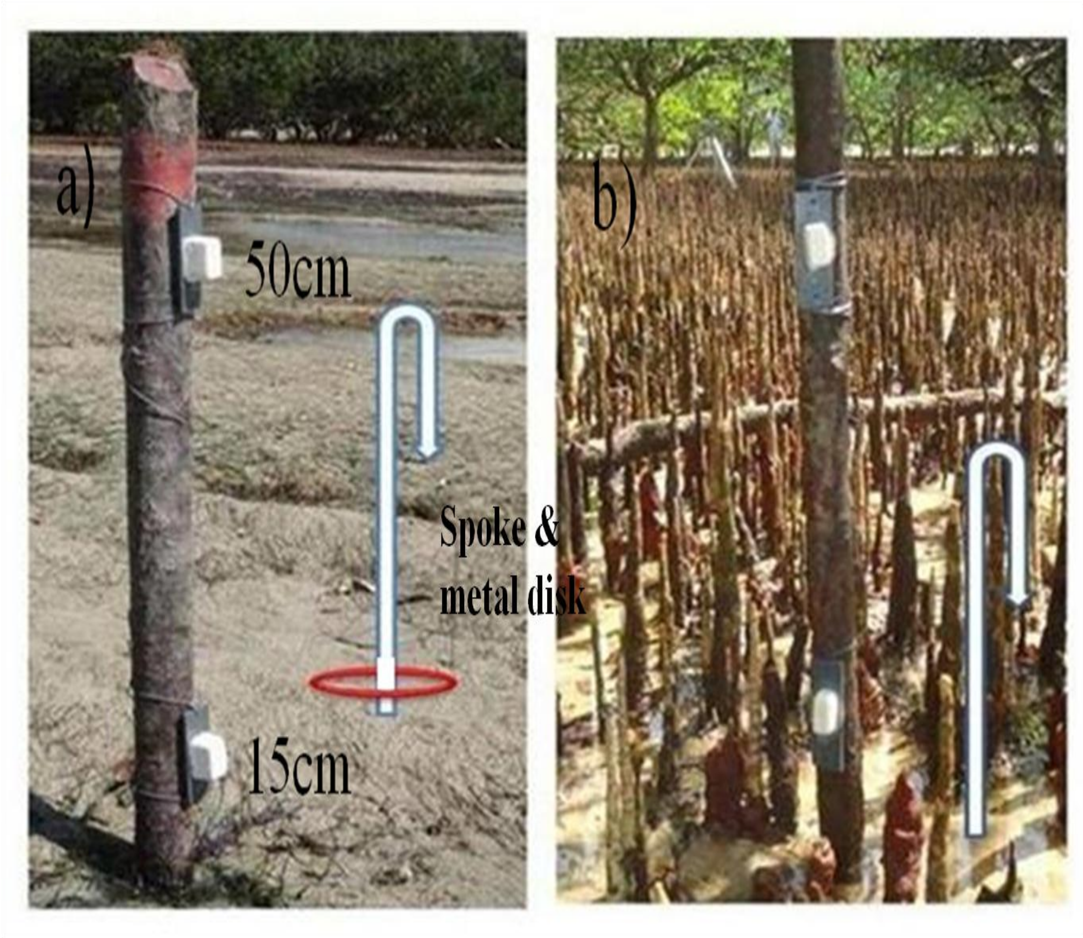


Figure 5: A setup showing (a) station A on the seaward side; (b) station B in the mangrove; with upper (50 cm) and lower (15 cm) clod card, a bicycle spoke and a metal disk (Photo by David Maina)

Soil samples were systematically collected at 10 points along the three stations for each transect namely; station A, on the seaward side, station B in the middle of mangrove forest and C on the landward side. The points at which the samples were collected were 5 m from each other thus covering a distance of 25 m along each station. The soil samples were taken using a corer at an approximate depth of 5 cm. The ten samples for each station were pooled in one labeled plastic bag and mixed thoroughly to make one composite.

Sediment stability was measured using cheap and inexpensive bicycle spokes fitted with metal disks at the three stations in the same transects set perpendicular to the shoreline where wave energy was determined. Ten replicate points which were 2.5 m apart were systematically selected covering a distance of 25 m along each station. The spokes were fitted with the metal disks weighing 2.8 g and 1.7 cm in diameter and inserted in the sediment approximately 5 cm Bicycle. The metal disks were held in position by the spokes and left at the substrate surface such that unstable sediment could cover them as sediment settles down during the alternating high and low tide regimes. A total of 30 spokes per transect were used in six transects with contrasting mangrove tree density. One transect without tree cover was established perpendicular to the shore as a control.

The use of bicycle spokes and metal disc was inexpensive for estimating sediment stability because the materials used were cheap and locally available. The assumptions were; first, the metal disk was denser than seawater and therefore sunk during high tide. Secondly, the dimension of the spoke such as thickness did not modify the site by reducing water velocity thus facilitating sediment to settle. In addition, all spokes and metal discs at station A before the mangroves on the seaward side were used as a control for all transects.

Sediment accretion was measured using stainless steel rods. The metal rods were 3 m long and 1cm in diameter. Two metal rods were set 50 cm apart and driven 280 cm into the sediment at station B which was almost in the middle of the transect. A portion of 20 cm ± 0.1 cm of each rod was left projecting perpendicular above the substrate surface. Leveling was done using spirit level to ensure both steel rods were at the same height. Thus, sediment accretion was estimated at six sites in six transects set perpendicular to the shoreline

Use of steel rods has an advantage of determining not only accretion and erosion but also gives information about subsurface processes down to the maximum level at which the pins are driven. Use of rods in surface elevation table (R-SET) is advantageous since it is cheap in terms of-cost, simple, high-precision and it is accessible to economically poor countries with coastal wetlands. In this experiment, wooden board 4.2 cm × 2.2 cm and 50 cm long smoothened flat and square was used to determine sediment accretion. Ten replicate points were marked along its entire length of the wooden board. The wooden board was placed on the two rods projecting above the substrate. To determine surface elevation changes at each transect the wooden board was placed on the two rods projecting on the substrate surface

2.4 Data Collection Methods

Within the two plots measuring 25 m by 20 m along each transect, diameter at breast height (DBH) of mangrove tree stem was measured at D_{130} or diameters at 1.3 m above the ground (Cintron & Schaeffer-Novelli, 1984). All mangrove tree stems with diameter $D_{130} \geq 2.5$ m were measured and recorded. Stand density per hectare for each transect was calculated using the relation. $\mathbf{D_i = n_i/A_i}$. *Where;* $\boldsymbol{Di}$ is the density for species **i,** ni is the total number of individuals counted for species $i$and $\boldsymbol{A}$ is the total area sampled (Brower & Carl., 1990). Basal areas was calculated using the formula; $BA = 0.00007854 \times DBH^2$ (where DBH is diameter at breast height)

Ten pneumatophores were selected randomly in ten quadrat per transect measuring 1m× 1 m. Their height and diameter at ½ heights were measured using a standard ruler and Vanier calipers respectively. The density of the pneumatophores was calculated per meter square in each transect and recorded.

Wave energy was sampled twice covering north east monsoon season by exposing clod cards to wave action in the field for 48 hours on the 8^{th} to10^{th} October 2012 during spring. A replicate sampling of wave energy was taken during neap tide on the 16^{th} -18^{th} of November 2012. During the south-east monsoon season, wave energy sampling was done by exposing clod cards for 48 hours on the 1^{st} to 3^{nd} March 2013 during spring tide. A replicate sampling of wave energy was taken again on the 25^{th} to 27^{th} May 2013. During the four sampling regimes, clod cards were mounted and retrieved during low water.

The basic assumptions were; First, station A, in all transects would be impacted more by high water velocity due to absence of mangrove forest structures thus experience high rates of dissolution of clod cards. Secondly, lower clod cards sampled the energy absorbed by pneumatophores while the upper clod card sampled the hydrological energy absorbed by the tree stems and pneumatophores. In addition, the magnitude of tide could not change within the same tide cycle during the period of clod card exposure

Data collection of the soil samples was done in the laboratory where the samples were weighed, oven dried at 80 ^{0}C for 24 hours. The samples were weighed after drying to determine the percentage moisture content. From the dried soil samples, a sub-sample of 25 g from each station was accurately weighed for grain size analysis. A second set of samples weighing 25 g were labeled and preserved for organic matter analysis.

The 25 g sediment was put in a labeled beaker and treated with (6.2g/1 dilution**)** of 250 ml water and 10 ml aqueous sodium hexametaphosphate ($(NaPO_3)_6$). The solutions were stirred for 10 minutes, and left for four hours then further stirred for 10 more minutes. The content of the beaker were flushed through 63 µm sieve with fresh water until no further silt was lost. The wet sediment was carefully flushed into a pre-weighed foil boat and oven dried at 80 ^{0} C for 12 hours. The dry content was weighed to determine the weight of silt. The dry sediment was then flushed through 500 µm sieve. The sediment grain size >500 µm were weighed and recorded and used to calculate the weight of the 63-500 µm fraction.

From the oven dried preserved sample of 25 g, a sub-sample of 10 g was weighed and put in pre-weighed aluminium crucibles and set in a muffle furnace for combustion at 440 ^{0} C for 6 hours after which they were cooled in a desiccator and weighed to determine the organic matter in the sediment.

Sediment stability was monitored by estimating the depth at which the metal disks sunk in the sediment. The depth of sinking metal disks was estimated every month using a standard ruler during low tide. New spokes and metal disks were reset for the presiding month to avoid confounding due to changes in mass of the disks as a result of corrosive nature of sea water.

Sediment accretion was estimated using a standard ruler by measuring the height from the substrate to the wooden board placed on the two rods. From the ten points marked on the wooden board, ten replicate measurements were taken and recorded once in each month for all the six transects (Figure. 6). The measurements were taken for 8 months covering a total of 240 days.

Figure 6: Surface elevation station measuring sediment accretion in a *Sonneratia alba* forest at Gazi Bay, Kenya (Photo by David Maina)

2.5 Data Analysis Methods

Data was analyzed using MINITAB 14.0 software package. One way analysis of variance (ANOVA) was carried out to test the variations in tree density, pneumatophores density and basal areas between transect. One way (ANOVA) was carried out to test how wave energy varied between the three stations in different transects with varying tree and pneumatophores density. Pearson's correlation analysis was carried out to test the significance of the forest structure namely; tree density, pneumatophores density and basal areas against wave energy.

Correlation analysis was carried to test for significant difference between silt, fine sand, coarse sand and organic matter against tree and pneumatophores density.

One way analysis of variance (ANOVA) was carried out to test for variation in sediment stability during the two sampling regimes and also variations between stations in different transects. Regression analysis was carried out to test for sediment stability and sediment accretion against tree density/ha and pneumatophores density m^2.

CHAPTER THREE

3.0 RESULTS

3.1 Forest Structure at the Study Site

Transect M had the highest pneumatophores density 174±21.1 Ind. /m^2. Tree density and basal areas were highest in transect L, 690±330 Ind/ha and 11.5±2.6/m^2 respectively; whereas transect O had the lowest structural attributes in the study site. All transects showed significant difference in pneumatophores density ($F_{(2, 39)}$ =25.15, p = 0.000), tree density (F ($_{2, 33)}$ =24.79, p = 0.000), and basal area ($F_{(2,39)}$= 29.66,p = 0.01). Structural parameters of mangrove forests in the study area are summarized in (Table 1).

Table 1: (Mean values ± SD) of Structural characteristics of the mangrove forest at Gazi Bay

Transect	Tree height (m)	Basal area (ha)	Tree Density (stems/ha)	Pneumatophores Density(m^2)
K	6.5±0.7	8.1±7.6	320±300	57.2±19.8
L	5.4±0.2	11.5±2.6	690±330	146.3±1.3
M	6.1±0.3	18.1±1.3	580±240	174.9±21.1
N	5.5±0.1	8±1.3	496±208	88.6±19.8
O	4.2±0.5	1.2±0.6	92±28	38.4±24.4
P	5.2±0.3	6.8±3.2	510±50	173.7±37.9
Mean	5.5±0.8	7.3±3.4	448±212.3	113.2±59.8

3.2 Effect of Tree and Pneumatophores Density on Wave Energy Reduction

Wave energy sampled by stems in all station A on the sea ward side before the mangrove influence had the highest mean in wave energy expressing 81.4 ± 5.1% (SE) reducing gradually from station B to C expressing 73.1 ± 4.9 and 65.5 ± 5.5 % (SE) respectively. Transect Q with no mangrove cover had the highest mean in wave energy sampled by tree stems expressing a mean of 84.3 ± 1.7 % (SE) in station A, 81.5± 1.4 % and 77.9 ± 2.0 % (SE) in station B and C respectively. The mean wave energy sampled by mangrove stems was 73.4 ± 4.8 while the mean of the control station Q had 81.2 ± 2.9. The mean wave energy expressed in the control denoted with letter Q without mangrove trees was higher by 7.8 % compared to the mean of wave energy reduction in the six transect with mangrove tree cover. Results for wave energy reduction along station A, B and C in all transects sampled at 50 cm by tree stems and the mean of the three stations per transect are shown in (Table 2).

Table 2: (Mean values ±SE) of wave energy reduction by mangrove stems (sampled at 50 cm in the three station; A (Open areas in the seaward side) and station B and C in the mangrove

	Weight loss of Clods cards (%); Wave energy reduction by mangrove tree stems			
Transect	Station A	Station B	Station C	Mean wave energy per transect
K	87.6±0.5	78.7±1.6	69.9±7.5	**78.7±8.2**
L	84.0±1.2	72.0±1.2	61.8±1.2	**72.6±10.3**
M	81.6±1.2	74.9±7.9	75.3±1.9	**77.3±3.5**
N	80.7±2	72.1±1.6	64.4±2.3	**72.4±7.5**
O	85.3±1.5	78.8±0.6	66.6±2.4	**76.9±8.7**
P	69.4±1.6	62.3±4.5	55.1±8.3	**62.3±6.6**
Mean wt. loss	**81.4±5.1**	**73.1±4.9**	**65.5±5.5**	**73.4±4.8**
Control (Q)	84.3±1.7	81.5±1.4	77.9±2.0	**81.2±2.9**

One way analysis of variance (ANOVA) showed a significant difference in wave energy sampled by tree stems between stations A, B and C ($F_{(2, 18)} = 10.92$, $p = 0.001$).

Wave energy sampled at 15 cm which expressed energy reduction by pneumatophores in all station A on the sea ward side before mangrove influence had highest mean of wave energy expressing 84.7 ± 2.7 % (SE). Results for wave energy reduction across station A, B and C in all transects sampled at 15 cm by pneumatophores and the mean of the three stations per transect are shown in (Table 3).

Table 3; (Mean values ±SE) of wave energy reduction by pneumatophores in the three station; A (Open areas in the seaward side) and station B and C in the mangrove

	Weight of Clods cards (%); Wave energy reduction by pneumatophores			
Transect	Station A	Station B	Station C	Mean wave energy reduction per transect
K	85.5±0.6	75.7±1.8	68.3±1.2	**76.5±9.8**
L	80.3±2	72.9±1.9	71.2±1.8	**74.8±5.5**
M	88.5±0.9	82.3±1.2	75.4±1.6	**82.1±7.4**
N	85.5±2	75.5±1.4	73.5±1.6	**78.2±7.3**
O	87.8±1.6	80.9±0.5	74.2±0.9	**80.9±7.7**
P	81.0±8.8	77.8±7.3	78.3±2.8	**79.0±1.9**
Mean wave energy	**84.7±2.7**	**77.5±2.8**	**73.5±2.8**	**78.6±2.3**
Control	86.4±2.5	84.3±1.5	81.3±1.6	**84.0±2.9**

The energy reduced gradually from station B to C which expressed a mean of 77.5 ± 2.8 and 73.5 ± 2.8 % (SE) respectively. Transect Q (Control) with no pneumatophores cover had the highest mean in wave energy in station A expressing 86.4 ± 2.5, whilst station B and C expressed 84.3 ± 1.5 and 81.3 ± 1.6 % (SE) respectively. The mean wave energy reduced by pneumatophores in the six transect with varying pneumatophore cover was 79.0 ± 1.9 while the mean wave energy measured at the three stations (A B and C) in transect without pneumatophore cover (control transect) had 84.0 ± 2.9. Therefore, the difference in wave energy reduction by areas covered by pneumatophores and the areas without (the control transect was 5%. One way Analysis of variance (ANOVA) showed a significant difference in wave energy reduction by pneumatophores between stations A, without pneumatophores cover and stations B and C with pneumatophores cover ($F_{(2, 18)}$ =17.05, p = 0.000).

Total energy reduced by mangrove trees was 7.8% while energy reduced by pneumatophores was 5.0 %. The total wave energy reduced by both tree density and pneumatophore density was 12.8%.

To get the relation between wave energy change across the mangrove forest, and to better understand the effect of tree density on the wave energy, a plot of wave energy on the Y-axis and transects with different tree density on the X-axis was plotted. Wave energy reduction measured at 50 cm above the substrate (energy reduction by mangrove tree stems) is shown by (Figure 7). The result showed wave energy decreasing with increasing tree density.

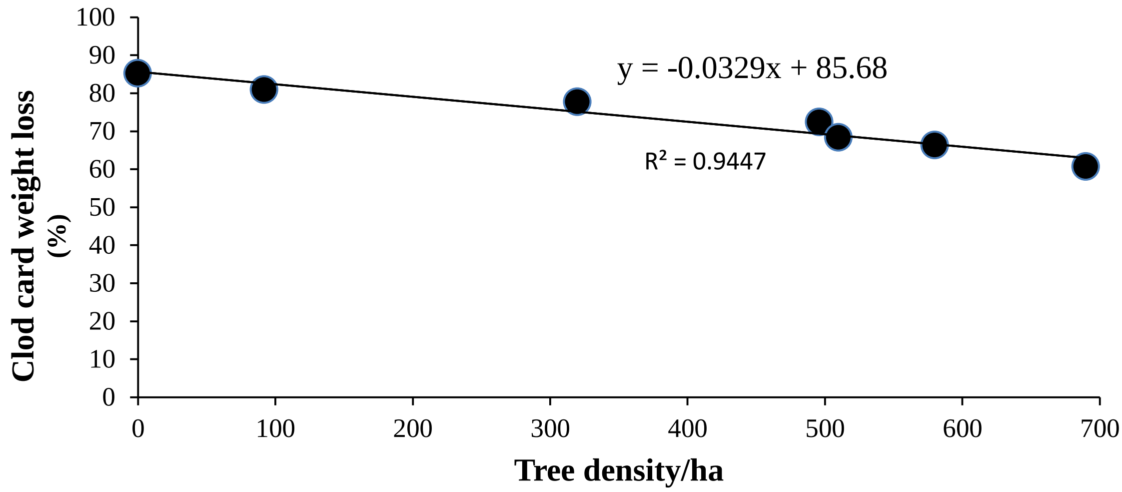


Figure 7: Linear relationship between wave energy against tree density/ha in seven transects.

The plot for hydrological energy sampled at 15 cm above (energy reduction by pneumatophores density) against pneumatophores density in the seven transect showed the same trend as the energy reduction sampled by tree density where wave energy reduced with increasing pneumatophore density (Figure 8)

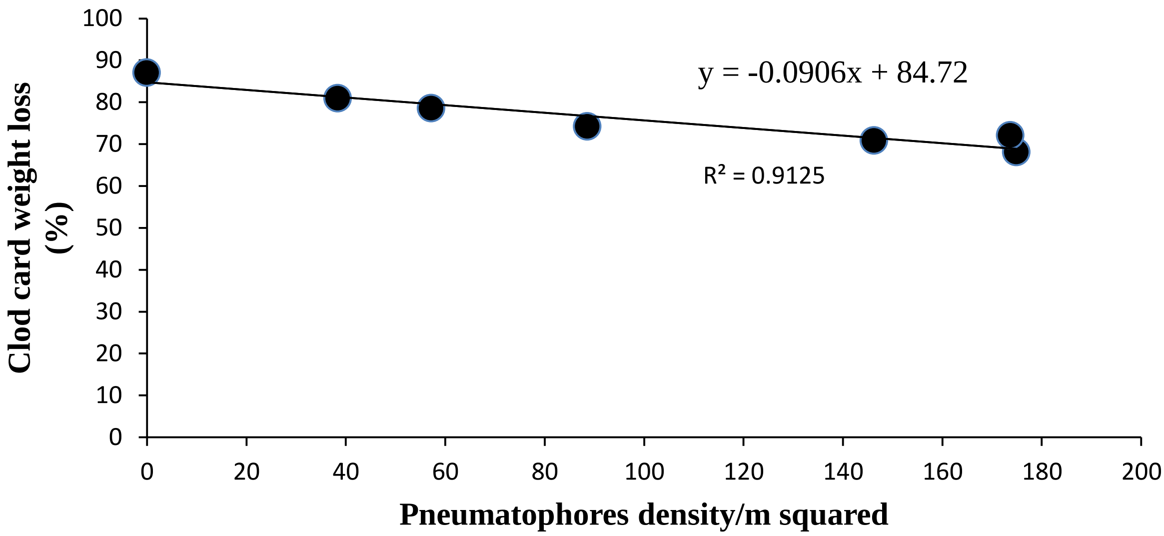


Figure 8: Linear relationship between wave energy against pneumatophore densities in seven transects

The results for Pearson's correlation of wave energy showed significant negative correlation coefficient for the three forest structures namely; Wave energy against tree density/ha (r^2 = -0.594, p = 0.000), wave energy against pneumatophores density/m^2, (r^2 = -0.794, p = 0.0000) and wave energy against Basal area (m^2) (r^2 = -0.451, p = 0.000).

3.3 Sediment Grain Size and Organic Matter Distribution

The grain size analysis showed a higher percentage of silt in transect M, K and L expressing 15.2 ± 5.8 %, 15.0 ± 2.2 % and 8.8 ±2 1.2 % (SE) whilst coarse sand was highest in transects P, O and N expressing 39.7 ± 0.1, 18.1 ± 0.5 and 12.8 ± 0.9 (SE) respectively. All transects expressed mean fine sand as the highest proportion of sediment 79.5±4.7 % (SE). Coarse sand was least frequent in all transect with exception of transect P which had a mean of 39.7 ± 0.1 % The highest percentage of fine sand was observed in transect Q with 93.1 ± 0.4 %. (SE)

Pearson product-moment correlation showed no significant difference between mean silt and tree density (r^2 = 0.530, p = 0.221), fine sand and tree density (r^2 = -0.307, p = 0.503) and coarse sand and tree density (r^2 = 0.083, p = 0.860) among transect in the study site. Correlation between mean silt and pneumatophores density ($r^{2\,=}$ 0.484, p = 0.271), fine sand and pneumatophores density (r^2 = -0.580, p = 0.171) and coarse sand (r^2 = 0.358, p = 0.431) was also not significant in all transect.

Organic matter distribution was highest in transect K, M and N expressing 2.1 ± 0.5, 1.9 ± 0.4 and 1.6 ± 0.5 (SE) respectively whilst the control transect (Q) with no mangrove cover expressed the lowest percentage of 0.8 ± 0.1 (SE). Organic matter showed no significant correlation between tree density/ha (r = 0.521, p = 0.230) and also in pneumatophores density/m^2 (r = 0.367, p = 0.419).

Results for sediment grain sizes and organic matter content during the study period are summarized in (Table 4).

Table 4: (Mean values ± SE) of Percentage of sediment grain sizes classes and organic matter content in the seven transects.

Transect	Silt (%)	Fine sand (%)	Coarse sand (%)	Organic matter (%)
K	15.0 ± 5.8	81.7 ± 4.7	3.3 ± 1.0	2.1 ± 0.5
L	8.8 ± 1.9	87.6 ± 0.9	3.5 ± 0.2	1.4 ± 0.2
M	15.2 ± 2.2	79.6 ± 2.9	5.3 ± 0.1	1.9 ± 0.4
Q(Control)	3.8 ±0.5	93.1 ± 0.4	3.5 ± 2.1	0.8 ± 0.1
N	5.6 ± 3.3	81.6 ± 2.3	12.8 ±0.9	1.6 ± 0.5
O	2.4 ± 1.4	79.5 ± 0.8	18.1 ± 0.5	1.1 ± 0.3
P	7.0 ± 2.3	53.4 ± 2.4	39.7 ± 0.1	1.2 ± 0.1

3.4 Effect of Tree and Pneumatophores Density on Sediment Stability and Accretion

Mean sinking depths of metal disks in the entire sampling period were pooled per station A, B and C covering both south east and north-east monsoon seasons. All stations before the mangrove influence on the sea ward side (station A) displayed the highest means of sinking depths of metal disks of 14.6 ± 3.1mm (SE). The depth reduced gradually from station B to C which attained a sinking depth of 8.2 ± 2.7 mm (SE) and 7.4 ± 3.5 mm (SE) respectively. However, transect P which was near river Mkurumuji recorded slightly high sinking depth in station C on the landward side with 7.35 ± 0.8 (SE) than station B and C which had similar values of 5.78 ±0.6 (SE). Transect Q with no mangrove cover registered the highest mean depth of 23.2 ± 2.3 mm (SE) in the three station. Unlike most station in other transect with varying tree cover, station A in the open area (control transect Q) had the least depth of 19.9 ± 2.4 (SE) compared with station B and C which recorded 21.9 ± 2.2 and 27.7 ± 2.9 (SE) respectively. Transect M had the least mean depth of 2.9 ± 1.1 1.6 (SE) in all transects.

One way analysis of variance (ANOVA) showed significant difference in sinking depth of metal disks between stations A B and C in transects with varying mangrove tree cover ($F_{(2, 15)} = 4.57$, $p = 0.028$). The results for sediment stability comparing different stations along seven transects are shown in (Figure 9).

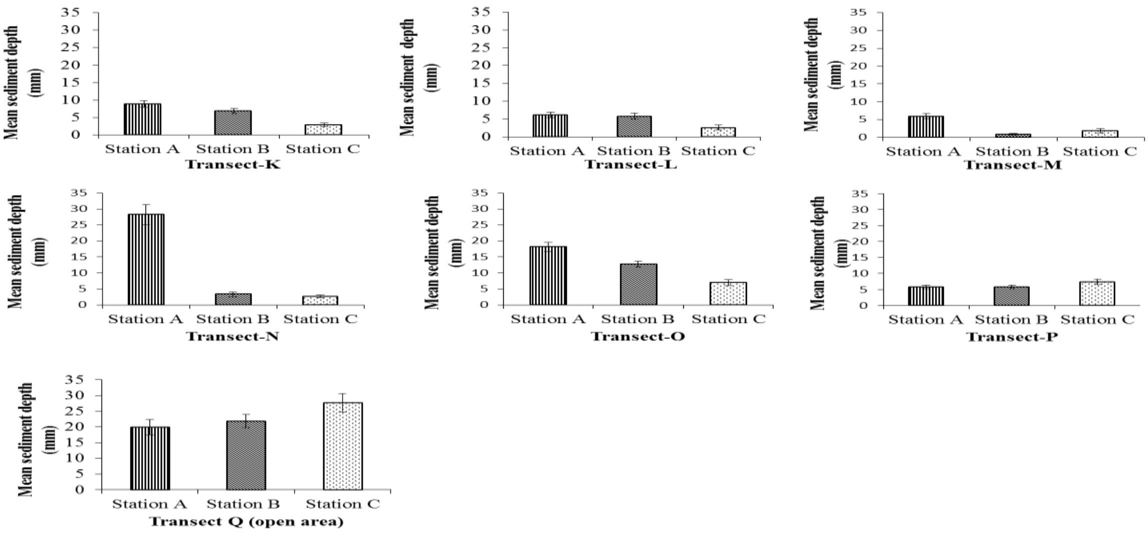
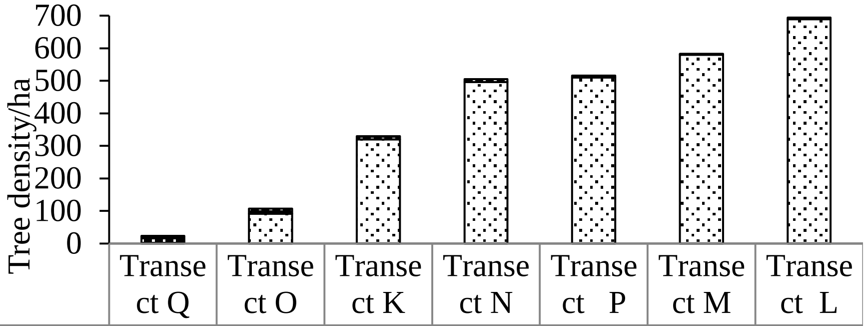


Figure 9: Mean values (± SE) of sinking depth of metal discs across station A, B and C along the seven transects

3.5 Effect of Tree and Pneumatophores Density on Sinking Metal Disks

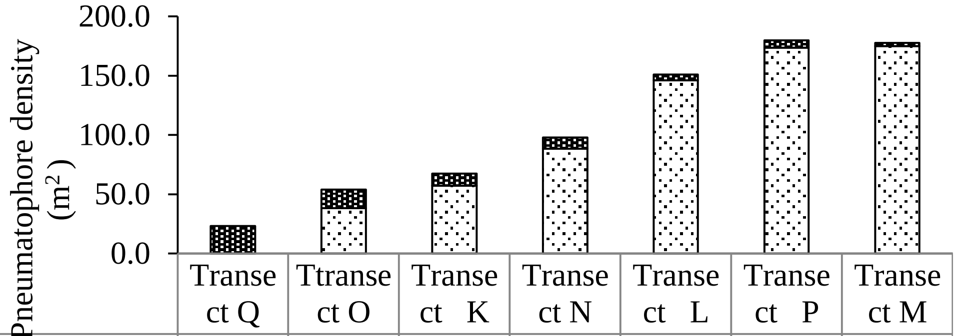
The means for sinking metal disks of different stations were determined and results compared with tree density/ha and pneumatophores density per m^2. The depth of metal disks decreased with increase in mangrove tree density (Figure 10).



	Transect Q	Transect O	Transect K	Transect N	Transect P	Transect M	Transect L
Mean sediment depth (mm)	23.18	15.63	10.21	9.43	6.30	2.91	4.83
tree density/ha	0	92	320	496	510	580	690

Figure 10: Mean of sinking depth of metal disks against; Tree density/ha across fringing mangrove forest

A plot of sinking metal disk against pneumatophores density per m^2 showed the similar treads with the one plotted against tree density/ha where the depth of metal disks decreased with increase in pneumatophores density per m^2 (Figure 11)



	Transect Q	Ttransect O	Transect K	Transect N	Transect L	Transect P	Transect M
Mean sediment depth (mm)	23.18	15.63	10.21	9.43	4.83	6.30	2.91
Pneu. Density/square meter	0.0	38.4	57.2	88.6	146.3	173.7	174.9

Figure 11: Means of sinking depth of metal disks against pneumatophores density/m^2 across fringing mangrove forest

Regression analysis showed a significant difference in sediment stability against tree density (R^2= 61%, P = 0.028) and basal areas (R^2 = 72.8%, p = 0.015) whilst there was no significant difference between sediment stability and pneumatophores density (R^2= 47%, p = 0.089).

Sediment accretion rates in six transects showned a net positive gain of 6.3±2.1mm (±SE). for a period of 330 days. When extraporated to annual rates, the transects showed values equal to a mean of of 5.4±1.7mm (±SE). The mean range between the highest and the lowest accreting transect was 12.2mm recorded between transect M and transect O respectivelly. Mean sediment accretion rates were highest in transects K 13.3 ± 1.8mm (±SE). followed by transect M with 11.5 ±2.1 (mm) (±SE). while the lowest mean accretion rates were recorded in transect P with 1.4±1.2mm (±SE). and transect O with 1.1±2.8mm (±SE). within the same period. Sediment accretion rates as shown in (Figure 12)

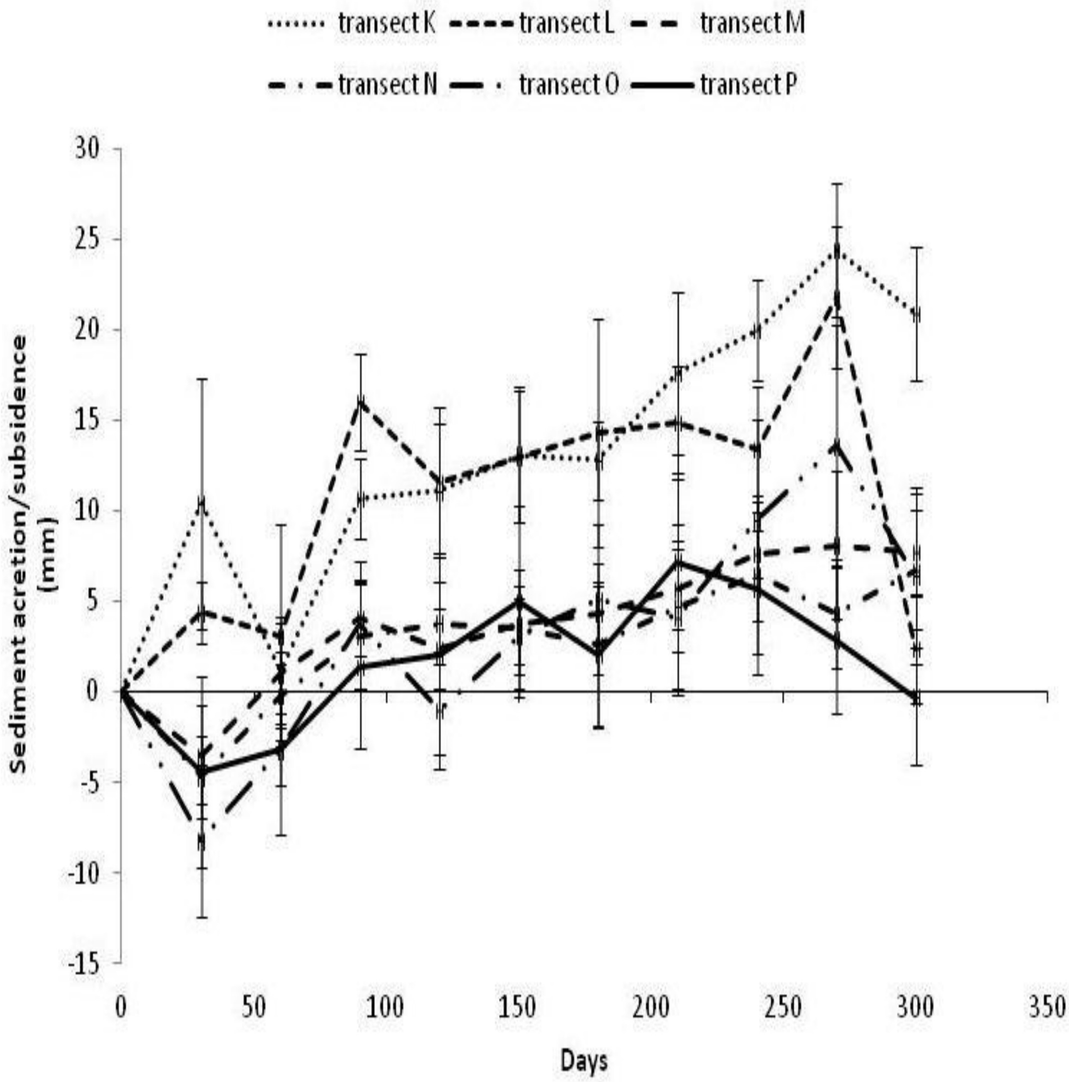


Figure 12: (Mean values ± SE) of sediment accretion rate in study area observed for 330 days

Regression analysis between mean sediment accretion rates against forest structures showed no significant difference namely; tree density/ ha showed no significant (R^2 = 7.2%, p = 0.608), basal areas (R^2 = 8.9 %, p = 0.566) and pneumatophores density/m^2 (R^2= 11.1%, p= 0.415) In addition, regression analysis between sediment accretion and wave energy reduction along transects was also not significant (R^2= 16.7, p = 0.489).

CHAPTER FOUR

4.0 DISCUSSION CONCLUSION AND RECOMMENDATIONS

Provision of natural defences by mangroves to both human and artificial structures along the coast has in the recent past been given a lot of attention following the lessons learnt during the 26th December tsunami in Asia. Many of the degraded mangroves sites along the Kenya coast has witnessed accelerated the rate of shoreline erosion prompting the government and local communities to put up artificial structures to mitigate the problem with little or no success. However, restoration efforts guided by scientific findings have proved to provide a lasting and sustainable solution by restocking the degraded sites with suitable species. Increasing the mangrove tree densities has led to stability and functioning of the ecosystem by reducing shoreline erosion and binding of sediment by mangrove forest structures.

4.1 Effect of Tree and Pneumatophores Density on Wave Energy

By comparing dissolution rates of percentage loss of clods card as a proxy to wave energy attenuation across the reforested mangrove forest, this study demonstrated that wave energy was gradually reduced along 80 m transects that had different tree and pneumatophore m densities. The energy reduction by tree stems alone was 7.8 % while the energy reduction by pneumatophores was 5 %. In total energy reduction by the two mangrove forest structures was 12.8%. Similar studies done in Vinh Quang village along Red River (Song Hong) Vietnam showed that 100 m of intact mangrove attenuates wave energy up to 45 % (Mazda, *et al.*, 1997). Hence, this study has proved that mangroves are suitable coastal vegetation defense that can protect shoreline erosion against average wave energy.

The clod cards exposed to water current in the sea were used to express loss of their weight as a function of water velocity since plaster of Paris objects erode with the friction with water. The higher the water velocity the higher the clod card weight loss. Therefore, the interest was to compare the relationship between weight losses of the clod cards versus tree and pneumatophores density along transects of known distance across the mangrove forest. Thus, change in wave energy was plotted as the weight loss of clods (in the y-axis) versus transects with varying tree density and pneumatophores density (in the x-axis). The slope of the regression was the change in wave energy as tree and pneumatophores density varied among transects.

High wave energy was experienced at 15 cm above the substrate as demonstrated by high clod card weight loss at this height with a mean of 78.3 ± 2.3% (SE) compared to the means of clod cards mounted at 50 cm which recorded 73.4 ± 2.4 in transect that had mangrove trees. Similarly, high wave energy was experienced at 15 cm above the substrate in the control transect without mangrove cover registering a mean of 84.0 ± 2.9 %) SE) whilst energy sampled at 50 cm was 81.2 ± 2.9 % (SE). The capacity to reduce wave energy however is known to dependent on forest width, tree density and tree species (Alongi, 2009). Mangrove reforestation initiatives at Gazi have seen increase in tree density of fringing *Sonneratia alba* from diminishing levels to 448 ± 212.3 (SD) at the time of the study. In this study the site comprised of one species (*Sonneratia alba*), the semi pristine nature of the forest stand coupled with narrow width limited the ability to reduce considerable wave energy contrary to Vinh Quang village along Red River (Song Hong) Vietnam with pristine fringing mangrove (Mazda, *et al.,* 1997)

The effect of tree and pneumatophores density on wave energy reduction among different transects demonstrated that increasing tree density enhances the frictional drag by the mangrove forest structures. Pneumatophores of *Sonneratia alba* taper off upwards thus reducing their efficiency to maintain high drag force explaining the reason why more wave energy was experienced at 15 cm due to pneumatophores influence as compared to energy sampled at 50 cm due to mangrove tree density (Mazda, *et al.*, 1997).

4.2 Effect of Tree and Pneumatophores Density on Sediment Stability and Accretion

Sinking depth of metal disks along transects with different tree densities demonstrated that sediment gains stability with increasing tree and pneumatophores density. The deeper the metal disks sunk in the sediment the more the unstable the sediment was. Therefore, this study showed sinking depth of metal disk reducing gradually with distance from the open areas on the seaward side towards the shoreline as tree and pneumatophores densities varied among transects The trends in sediment stability demonstrated in this study is similar to those reported in mangroves along Cairns boardwalk in wet tropical Australia within a fringing *Rhizophora sp.* (Furukawa & Wolanski, 1996). In both sites, the mechanisms of sediment transport are dominated by hydrodynamics from waves and sediment gained stability with increasing distance from the seaward side towards the shore. Sediment particles settled as wave energy reduced across the mangrove forest demonstrating the net effect of forest width and tree density on sediment stability as reported elsewhere in the world (Alongi, 2009).

Where mangrove tree stems and pneumatophores densities were high, the depth of sinking of metal disks in the sediments was less due to reduced wave energy thus facilitating trapping and holding of sediment. The trapping mechanism resulted from high micro-turbulence created by the flows around the trees structures such as tree stems and pneumatophores (Mazda, *et al.*, 1997; Wolanski, 1995) during flood tide and settled down at slake water when current flows are low during ebb tide.

The study showed station all A (before the mangroves) in all forested transect having the highest means of sinking depth of metal disks indicating high sediment instability which decreased with increasing distance across station B through station C. The observation witnessed in this study on sediment stability is true of studies done by (Balke *et al.*, 2013) who found sediment stability rates increasing with distance from the seaward side towards the shore. .In the control transect without mangrove there was less micro-turbulence due to absence of mangrove trees thus making the sinking depths of metal disks to increase with distance along the intertidal complex an indication of high sediment instability.

The study has revealed that degradation of fringing mangrove forest alters sediment stability by compromising their physical roles a condition that has been witnessed elsewhere in the world (Furukawa & Wolanski, 1996). Graphical relationship of sinking depth of metal disks against tree and pneumatophores density showed the mean depth sinking metal disks decreasing with increasing tree stems/ha and pneumatophores density/m^2 highlighting that the replanted fringing forest remains the best option to stabilizing the highly eroded study site at Gazi Bay.

The levels of sinking depth of metal disks improved with reduced exposure to strong wave energy with mangrove forest structures offering a bio-shield by creating frictional drag as reported elsewhere by (Furukawa & Wolanski, 1996). In this study, there was high wave energy observed from transect without mangrove cover (Control transect) and reduced gradually to fairly high forested transect. Reduced wave energy levels by mangrove forest structures (tree and pneumatophores density) improve sediment stability along the inter-tidal complex. In addition, transects with high organic matter content and fairly high levels of silt had low sinking depth of metal disk an indication of improving sediment physio-chemical characteristic (Macnae, 1968) a condition that make the mangrove forest a fully functional system (Bosire *et al.,* 2008).

The study showed sediment accretion rates of 5.4 ± 1.7 mm/ year^{-1} (SE) which is more or less similar to that reported in Kosrae, (FSM) at Yela and Utwe river basin of 4.5 ± 1.1 and 9.1 ± 2.1 (SE) mm respectively. Many studies on sediment dynamics in mangrove forests in many parts of the world has reported various levels of sediment accretion or subsindence due to the influence of mangrove forest structures such as tree and pneumatophores densties using sediment elevation tables (SETS) method.

The stems and pneumatophores create frictional drag reducing current flow from wave energy thereby creating eddies that encourage sedimentation when cohensive particals floculate particulary due to presence of clay particles (Furukawa, *et al.,*1997). This study has shown that reforestation efforts in this site has boosted the reguratory services offered by mangroves by modifying physical characteristics of the sediment. This has been observed in transects M, K and L which expressed the highest clay particles which bind sediment together thus supporting the sediment accretion. Tansect with lowest clay particles as witnessed at transect O and which had the lowest tree and pneumatophores density expressed least mean accretion rates. Therefore, the study shows that by increasing tree stems through reforstation, sediment are less prone to resuspension by waves thus reducing shoreline erosion as compared to other earlier efforts of mitigating shoreline protection through construction of gabions.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Through the use of inexpensive clod card dissolution method to quantify wave energy attenuation as a regulatory service, the study has established base line data to help monitor and quantitatively estimate the role of mangrove forests in shoreline protection, and how this change with tree density. Evidence of the study site regaining stability after replanting mangroves is a more sustainable and cost effective method as compared to putting up hard engineering structures and can easily be replicated elsewhere in many such sites along the Kenyan coast and western Indian Ocean region. Using the mangroves as a bio-shield shall provide other ecosystem benefits such as increased biodiversity, aesthetic beauty and will have potential application in disaster risk reduction in the long term. On average, mangroves at the study site in Gazi Bay proved to reduce 7.8 % of wave energy in transects with trees compared to open areas without trees whereas sediment stability correlated positively with increase in tree and pneumatophores density as wave energy reduces. Stable sediments have showed accretion rates improve as density of the forest increases over time through reforestation efforts and the shore line erosion gradually reduces and resist further coastline changes. The main challenge in the study was lack of baseline data and other comparative studies on the use of mangrove forests as bio-shields to provide coastal protection against average wave energy impacts along the Kenya coast and Western Indian Ocean region.

5.2 Recommendations

Based on results of this study, the following recommendations may be made:

1) Creating awareness among the stake-holder by educating them on importance of mangroves in offering regulatory service such as shoreline protection which is not clearly understood
2) Use of the baseline data obtained in this study to monitor wave energy changes and sediment dynamics in the study site as the tree density increases through reforestation and other improved forest management practices. Mikoko Pamoja is committed in replanting 4000 new mangrove trees per year on the shoreline of Gazi over the 20yrs contractual period with Plan Vivo.
3) Carrying out more studies of this nature in other fringing mangrove areas facing challenges of shoreline erosion along the Kenyan coast and Western Indian Ocean region.
4) The study will help the managers and the government on the merit of using mangroves as bio-shields in protecting coastlines against erosion and safe millions of dollars through construction of sea walls and gabions at the affected sites along the Kenyan coast and Western Indian Ocean region.

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