INFLUENCE OF TERRAIN, SOIL AND WATER INTER-RELATIONSHIPS ON THE DISTRIBUTION OF PLANT COMMUNITIES IN JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

MASOUD SALUM SAID

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EXTENDED ABSTRACT

On a coastline, tidal water and air constantly reach land surface and/or aquifer. Tropical forests before or adjacent to this line are usually having a wide range of habitats. Jozani Groundwater Forest (JGWF) is one of the tropical coastal forests with a wide range of floral and faunal habitats. The forest (JGWF) has a significant role in biodiversity conservation and ecotourism. International bodies including UNESCO recognize JGWF as the most important part of Jozani-Chwaka Bay Bio-Sphere Reserve (formerly Jozani-Chwaka Bay National Park). The Zanzibar Wood Biomass Survey found that JGWF area has a biomass of above 50 tonnes ha^{-1} compared to the surrounding areas having a biomass of about 10 tonnes ha^{-1}. Plant species found within JGWF area exceed 300 counts and vary in their assemblages. Thus, there was a need of ditermining the underlying conditions that made JGWF to be so rich in biomass and biodiversity. Plant growth is favoured by soil and water characteristics, so those characteristics favoured JGWF area over its surroundings were to be revealed. Again, it is known that plant species existence, richness, assemblage and spatial distribution are influenced by biotic and abiotic factors. So, it was important to determine environmental factors influencing plant species assemblage and distribution in JGWF. The aim of the current study therefore, was to determine the underlying soil and water inter-relationships influencing plant species communities' distribution in Jozani Groundwater Forest area.

Specifically, this study aimed to i) determine the elevation of Jozani Groundwater Forest (JGWF), ii) characterize soil depth to coral bedrock and bedrock roughness in JGWF, iii) determine seawater tidal trends and magnitude at Uzi and Chwaka bays as

a proxy of the sea water intrusion into JGWF, iv) determine the extent of seawater intrusion, v) characterize the effects and implication of rainwater - seawater interaction on physical and chemical soil properties in JGWF and vi) map-out distribution of plant species assemblages in relation to abiotic environmental variables including elevation, salinity, soil and water characteristics. The study was conducted in Jozani Groundwater Forest area of about 590 km^2 located between Chwaka and Uzi bays within the Jozani-Chwaka Biosphere Reserve (former Jozani-Chwaka Bay National Park), Zanzibar, Tanzania.

Generally, seawater intrusion occurs along low elevated coastal lands and/or aquifer. As JGWF is a low elevated coastal forest, it is likely being intruded by seawater from Chwaka and Uzi bays. Hence, it was hypothesized that if there was seawater intrusion into JGWF land and aquifer, such intrusion has direct relation to tidal characteristics on the two bays. *Masika* (long rain season) and *Vuli* (short rain season) are a good source of freshwater into JGWF aquifer. The aquifer continuously interacting with seawater and to some extent reduces the effects of intrusion. The water interaction and its spatial trends is therefore influenced by tidal trends and wet (*Masika* and *Vuli*) and dry (*Kiangazi* and *Kipupwe*) seasons. Seawater intrusion processes are also affected by land elevation, soil type and vegetation conditions.

Effects caused and/or brought by abiotic factors such as terrain, soil and water conditions significantly affect forest plant assemblage and distribution. Plant communities' assemblage and spatial distribution often imply the species response to the abiotic factors. This study therefore, intended to determine terrain, soil and water characterictics of JGWF, examine tidal trends and magnitude as proxy of intrusion

into JGWF, reveal the extent of the intrusion, and how far these conditions influenced plant communities' distribution in JGWF.

With the help Height of Instrument/Collimation method of reduction in levelling survey, the reduced levels (RLs) of the north-end and south-end of JGWF were identified. Two benchmarks (no. 205 and 210) of the Zanzibar Department of Survey (DOS) were used for RLs determination at and inbetween the north and south ends of JGWF. During the survey, the level of water table in local (shallow) wells was measured. Water table was used as a wide benchmark to produce Digital Elevation Model (DEM). Thereafter, with the help Height of Instrument/Collimation method, benchmark no. 205 was used to validate elevation of ten points in the southern part of JGWF. ArcGIS 10.1 was used to produce DEM, soil depth to the coral bedrock (SDCB) and bedrock roughness (BR) maps for JGWF. Data were collected from soil auger boreholes in a 320 grid system made from 32 northern and 10 eastern gridlines.The data were depths of water table and coral bedrock from the ground surface. To determine tidal trends and magnitude (elevation of reach) of seawater from Chwaka and Uzi bays into JGWF, two sets of three observation wells (OW) were drilled at the north and south ends of JGWF. The OWs were the data collection points. At OW, a water level change recorder was installed from which levels of water table (above mean sea level (AMSL)) were measured during low water of spring tides. Water from OWs was tested *in situ* to determine salinity level (total dissolved solids (TDS)) round OWs. The data of water and salinity levels were computed and used to describe the seawater tidal trends and magnitude of seawater intrusion into JGWF. Data on water salinity to determine the extent of seawater intrusion, soil characteristics and plant species composition were collected from second grid system.

The second grid system had a total of 44 gridpoints made from 11 northern and 4 eastern gridlines. Data on soil characteristics were collected from soil auger probing. Soil profile description and sampling were done in two profile pits based on auger probing results. From auger bore holes (temporary wells) water salinity was tested in the middle of *Kiangazi* (hot, dry), *Masika* (long rainy), *Kipupwe* (cold, shower) and *Vuli* (short rainy) seasons, respectively arranged from January to December. For vegetation characterization, plant species with diameter at breast height (DBH) ≤ 5 cm were measured in a quadrat of 4 m^2, > 5 but < 10 cm in quadrat of 100 m^2, > 10 but < 25 cm in quadrat of 400 m^2, and > 25 cm in quadrat of 900 m^2 respectively.

This study found that the elevation of JGWF ranges from 0.7 to 2.5 m AMSL. Level of water table in North and South fluctuated between 0.586 and 1.206 m AMSL and between 0.820 and 1.586 m AMSL, respectively, during dry and rainy seasons and during high and low water of spring tides. Soil depth to coral bedrock and bedrock roughness varied from 0.3 to >1.4 and 0.1 to > 0.4 m, respectively. The levels of TDS in water ranged between 0. 5 and 2 x 10^3 mg L^{-1} in central part of JGWF and exceed 14 x 10^3 mg L^{-1} in areas close to Chwaka and Uzi bays. The soil was covered by 0.10 to 0.23 m thick layer of moist decomposing plant residues. Beneath this layer, found a humic horizon of about 0 – 0.12 m which consisted of moist, slightly compact, dark well decomposed material mixed with topmost soil mass of greyish brown (10 YR 3/2) colour. Soil horizons beneath the humic horizon comprised a brown (10 YR 4/3), slightly compact horizon of about 0.1 to 0.15 m overlying a thick water saturated olive gray (5 YR 4/2) clay-paste like loose horizon resting on an unevenly undulating coral bedrock. The thickness of all the horizons increased as the probing points approached south-eastern of JGWF. The soil had a considerably high percentage of available moisture (AM) that increased with depth and ranged from 28 to 36%. The soil had low bulk density (BD) which increased with depth from 0.23 - 0.54 g cm^{-3}. The values of AM and BD in JGWF were mainly contributed by a thick layer of plant residues and paste-like clay material. More than 69 plant species were found in probed areas. Five plant communities were identified from Redundancy Analysis (RDA) analysis and more than 3 specific communities were observed as patches during survey. About 60% of the plant species community assemblages consisted of about 19 ± 5 plant species of 15 ± 3 *Genera*. However, the community assamblages were in complex distribution making less distinct and smoothly diffusing ecotones in between. A clear ecotone of about 40 m wide dominated by *Acrostichum aureum* (Mangrove fern) stands was inbetween the area of pure *Paspalum vaginatum* (Seashore couch) stands (with TDS > 20 x 10^3 mg L^{-1}) and the area of mixed plant species dominated by *Nephrolepis biserrata* (Tropical fern), *Terminalia boivinii* (Terminalia) and *Guettarda speciosa* (Beach gardenia) (with TDS of about 15 x 10^3 mg L^{-1}).

Based on the findings, this study concludes that: i) in multi-storey high canopy groundwater forest, the method of using water table for levelling is feasible, applicable and an alternative method, ii) Jozani Groundwater Forest (JGWF) has shallow water table that seasonally fluctuates and slightly sloping from the south towards the north, iii) JGWF area has elevation ranges between 0.75 and 2.5 m above the mean sea level (AMSL), iv) Chwaka and Uzi bays are the only sources of seawater and rainwater apparently is the only source of freshwater which dilutes and partially drains out seawater that intruded into JGWF, v) seawater intrusion caused by surface movement through Chwaka and Uzi creeks takes place frequently and on large area at and beyond North-end towards JGWF during high water of spring tides, vi) the values of TDS fell to a minimum range of 0.7 x 10^3 to 4.9 x 10^3 mg L^{-1} during the rainy seasons and rose to a maximum range of 25.5 x 10^3 to 34.1 x 10^3 mg L^{-1} during dry seasons at South-end and North-end, respectively, vii) high densities of mangroves and *Paspalum vaginatum* (Seashore couch) stands pulled down seawater elevation of reach into JGWF soil surface by 0.9 and 0.5 m for Chwaka bay and Uzi bay respectively, viii) seawater abrasion forces acted on JGWF area resulted into the formation of Jozani trough like terrain, ix) so long as *Masika* and *Vuli* are the only sources of freshwater, seasonal trend of the rise and fall of water table in JGWF remains constant and the northern part of JGWF shall be more affected by seawater intrusion than the southern part, x) water salinity levels in about 70% of JGWF area favour most of the plant species found in the JGWF xi) water salinity fluctuations will remain constant if JGWF biomass conditions remain intact, no water pumping off JGWF aquifer, no extremely wet or extremely dry conditions, xii) soils of JGWF are peat soils overlying gluey clays which were formed under partially anaerobic conditions and were classified as *Limnic Histosols* (*Gleyic)* (FAO WRB) and *Haplosaprists* (USDA Taxonomy) and rainwater and marine water appeared to be involved in the formation of the soil, xiii) plant species in JGWF enjoy soil wetness throughout the year and their spatial distribution is influenced much by salinity.

This study recommending the following: i) levelling with the use of water table method, ii) reforestation with mangroves to reduce surface seawater intrusion, iii) proper utilize of information from this study and iv) further studies on spatial-environmental factors affecting JGWF plant species.

DECLARATION

I, Masoud Salum Said, hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

______________________________ ____________________

Masoud Salum Said Date

(PhD Soil Science Candidate)

The above declaration is confirmed by supervisors:

______________________________ ____________________

Prof. Balthazar M. Msanya Date

______________________________ ____________________

Prof. Salim M. S. Maliondo Date

______________________________ ____________________

Prof. Johnson M. Semoka Date

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DEDICATION

This work is dedicated to my mother Mwatima Idd Ame and to the memory of my beloved father the late Sheikh Salum Said, may Allah rest his Soul in Eternal Peace, Amen. I also dedicate this work to my wife Asha M. Dai and our children Laila, Ibrahim, Husna, Sharifa and Abdillah because with them I have achieved this goal.

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LIST OF ABBREVIATIONS AND SYMBOLS

ARI	Agricultural Research Institute, Mlingano
ASCLIME	Agulhas and Somali Current Large Marine Ecosystems
BM	Benchmark
BR	Bedrock roughness
COSTECH	Commission of Science and Technology of Tanzania
DEM	Digital elevation model
DFNNR	Department of Forest Non-renewable Natural Resources, Zanzibar
DOS	Department of Survey of Zanzibar
E&I	Effects and Implications
FH	Floating heights
FP	Floating point
GIS	Geographic information system
HWNT	High water of neap tides
HWST	High water of spring tides
JCBNP	Jozani-Chwaka Bay National Park
JFR	Jozani Forest Reserve
JGWF	Jozani Groundwater Forest
LIDAR	Light Detection and Ranging
LWNT	Low water of neap
LWST	Low water of spring tides
MTL	Monthly Tidal Level
MTR	Maximum Tidal Range
NT	Neap Tides

NTR	Neap Tidal Range
OB	Observation well
PSCA	Plant species community assemblage
RDA	Redundancy Analysis
RL	Reduced Level
RSI	Rainwater-seawater interaction
RW	Reference well
SDCD	Soil depth to coral bedrock
SMOLE II	Sustainable Management of Land and Environment II
SPCC	Soil physical and chemical characteristics
ST	Spring Tides
STR	Spring Tidal Range
SUA	Sokoine University of Agriculture
TMA	Tanzania Meteorological Agency
URT	United Republic of Tanzania
UTM	Universal Transverse Mercator
VPO	Vice President's Office
WFL	Water floating level
WLC	Water level changes
WLR	Water level recorders
WRB	World Reference Base for Soil Resources
ZARI	Zanzibar Agricultural Research Institute
ZGR	Zanzibar Revolutionary Government

CHAPTER ONE

1.0 INTRODUCTION

1.1 General Characteristics of Tropical Coastal Forests

1.1.1 The tropical coastal forests

On coastal lines, tidal water and air meet land surface and/or aquifer (Pajak and Leatherman, 2002; Boak and Turner, 2005; Carter, 2013). As tides keep on changing, there is no exactly and/or fixed data for the length of the coastal line(s) on the earth surface (Boak and Turner, 2005; Cui and Xiao-Yan, 2011). Tropical and/or sub-tropical forests before or adjacent to this line usually have some common biotic and abiotic conditions (Malhi *et al*., 2014; Viles and Spencer, 2014). Some of the common conditions include a range of plant species diversity, factors affecting plant growth, plant species assemblage, communities, richness and spatial distribution, seawater intrusion, and seawater freshwater interactions (Suc, 1984; Barbier *et al*., 2011; Viles and Spencer, 2014). Mangrove forests are one of the coastal forests occupying a surface area which is normally within the range of reach by seawater (Mukherjee *et al.,* 2014). Most of the freshwater coastal forests are separated from tidal zone of a bay by mangroves (Bouillon *et al*., 2007; Hamad *et al*., 2014). This study is therefore, focusing on environmental conditions of the coastal forest known as Jozani Groundwater Forest. This forest is of its kind because it has shallow freshwater aquifer although located inbetween two mangrove forests before two separate bays.

1.1.2 Jozani Groundwater Forest

Based on Burgess *et al*. (1992), in Tanzania there are about 39 coastal forests reserves of various size, shape and distance from the coastal line including Pangani, Saadani and Jozani Forest Reserve (JFR). Actually, JFR area was the one currently refered to as Jozani Groundwater Forest (JGWF) area which is found between Uzi and Chwaka bays. The area has a shallow (close to the ground surface) water table the condition contributed on naming of the forest. The JGWF as “The Coastal Forest inbetween the Two Bays” has been the major component of the Jozani based forest reserve that has changed its status from time to time. For example, from 1950s to 1992 JGWF area had a status of Jozani Protected Area and from 1992 to 2004 period, the area had a Jozani Forest Reserve (JFR) status the one reported by Burgess *et al.* (1992) (Sustainable Management of Land and Environment II (SMOLE II), 2013). From 2004 to 2016 the JFR and its surroundings of about 62 km^2 area had status of Jozani-Chwaka Bay National Park (JCBNP) (SMOLE II, 2013). The gain of status of JGWF area nationally and internationally, implies that the area is unique and important ecologically and economically. The location of JGWF is shown in Fig. 1.1.

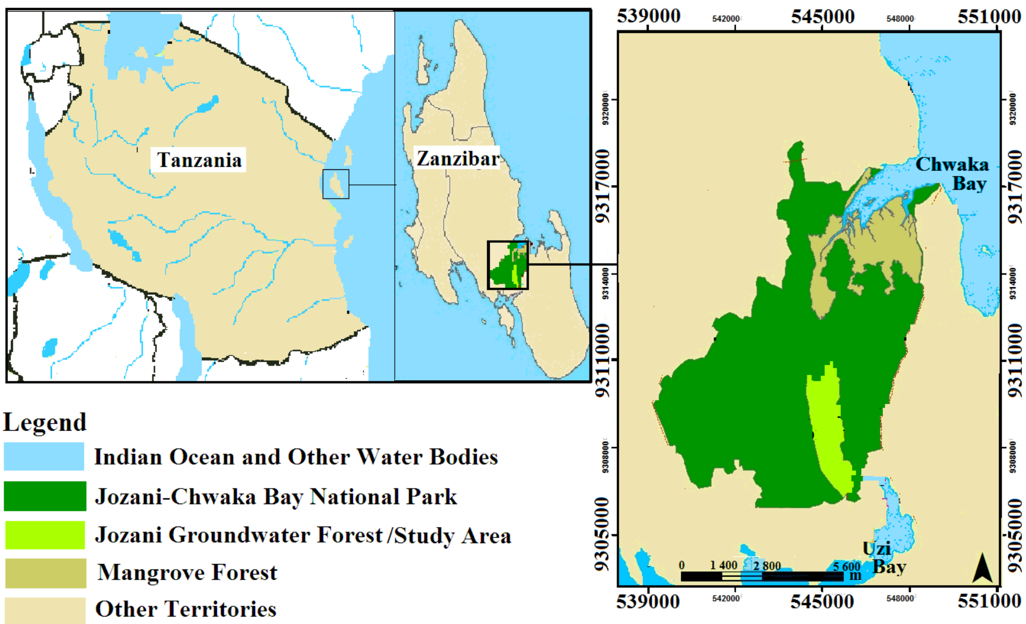


Figure 1.1: Location of Jozani-Chwaka Bay National Park and Jozani Groundwater Forest. Source: Department of Forest Non-renewable Natural Resources (DFNNR), Zanzibar

From March 2016 the area of JCBNP was expanded and the status was upgraded and included into World Network of Biosphere Reserve by UNESCO and Man and the Biosphere Programme. Among the conditions which made JGWF area to be of its kind include 1) a shallow water table (Nahonyo *et al*., 2002; Salum, 2009), 2) more than 50 tonnes ha^{-1} biomass (Zanzibar Revolutionary Government (ZRG), 2013), 3) low elevation (Klein, 2008; Mchenga and Ali, 2014), 4) found between two bays, and 5) found before mangrove forest (Liang, 2014). However, the most valuable characteristic of JGWF is that, it is the habitat that is hosting a high count of Biosphere Reserve flora and fauna. By 2014 the plant species counts exceeded 320. The count of flora and fauna in the Reserve keeps on changing from time to time.

1.2 Factors Affecting Vegetation in Coastal Forests

1.2.1 Elevation

Plant growth is affected by a number of genetic and environmental factors (Sollins, 1998; Clark *et al*., 1999; Casazza *et al*., 2008). In many cases elevation is among abiotic factors affecting assemblage of a number of tropical plant species (Casazza *et al*., 2008; Li *et al*, 2009; Read *et al*., 2014). Generally, distribution of plant species makes a difference when there is a significant change of elevation. Gentry (1988) and Bodin *et al*. (2013) reported that species distribution changes when elevation changes by at least 15 m height. From this point of view, less significant effects on plant species distribution are expected once JGWF is a coastal forest located in low elevated trough running between Chwaka and Uzi bays. However, even at such low elevation, water table changes to the extent that it makes dry surface (during dry seasons) and wet to temporary floods (during rainy seasons) (Salum, 2009). Such conditions likely implying that the level of dryness and/or wetness is influenced by elevation of a particular area within JGWF. Therefore, moisture level in JGWF is likely differs between places and fluctuates seasonally. Since JGWF is located between Chwaka and Uzi bays but free from seawater and levels of fresh water wetness vary locationally, the conditions imply that, 1) JGWF is elevated higher than the two bays and 2) JGWF has some sort of slopes, depressions, and other topographic characteristics. Therefore, there are questions that need answers; (1) What is a relative elevation of JGWF to the bays? (2) What elevation trend does JGWF have? (3) To what extent does elevation trend affect plant species distribution in JGWF?

1.2.2 Coral terrains of Zanzibar

Marine terraces of Zanzibar consist of coral limestones which indicate that the coral terrains are of marine and tectonic origin (Agulhas and Somali Current Large Marine Ecosystems (ASCLIME), 2012). Most of the coral terrains are consistent of protrudes from the coral bedrocks. These protrudes are found above and/or below the soil surface in low altitude, flat, slightly undulating terrains or cliffs of about 3 to 10 m height that creates sharp terrace separating two flat lands (Hettige, 1990; Klein, 2008). The polymorphic morphology, physical and chemical properties of soils found in Zanzibar coral areas (about 50% of Zanzibar territory) indicate that the soils were formed *in-situ* (Hettige, 1990). On the other hand, about 44.5% of Zanzibar territory is forest cover, 83.3% of which is occupied by coral forests and the rest 16.7% by mangroves (SMOLE II, 2013). Jozani Groundwater Forest (JGWF) is one of the coral forests developed less than 2 million years ago (Nahonyo *et al.,* 2002), during which there was a gradual fall in sea level and rise of corals (Klein, 2008). The coral forests are on flat land with *Lithic Leptosols* (Hettige, 1990) having low water retaining capacity. The forests are dominated by *dry bush land thickets* community (Nahonyo *et* *al*., 2002) that makes a biomass of about 10 tonnes ha^{-1} (Zanzibar Revolutionary Government (ZRG), 2013). As there are specific relationships that exist between soil (properties) and vegetation cover, and JGWF area has biomass that exceeded 50 tonnes ha^{-1} (ZRG, 2013), the soil in JGWF is therefore, likely to be different from its surrounding coral areas.

1.2.3 Tidal trends and magnitude

Study of trends in mean sea levels in Tanzania indicates a fall in sea level (Mahongo, 2009). According to Mahongo (2009), Zanzibar sea level was declining at a rate of 3.6 mm/year for the period between 1985 and 2004. Mahongo and Francis (2010) reported that during the period there were seasonal variations of sea level at the island of Zanzibar, revealing three major cycles of sea level i.e. semi-annual, annual and four-year oscillations. However, there are few studies about sea level changes along the coast of Tanzania that have been undertaken so far, and some of them contradict each other. Muzuka *et al*. (2004) found that the oldest Palaeo-shoreline is approximately 5 m above the present sea level. This extends landward to more than 1 km and in case of Zanzibar islands, specific localities where Pleistocene/Holocene sea level changes occurred have been preserved in the form of marine terraces and/or beach ridges. These are found in Chwaka, Uroa, Jambiani, Paje and Nungwi in Unguja Island, and Vumawimbi and Kiuyu in Pemba Island (Muzuka *et al*., 2004). Projections of future mean sea level trends in Tanzania are currently not feasible due to insufficient data occasioned by limited duration of monitoring. The longest sea level record is only 25 years at Zanzibar Harbour. However, model simulation of long-term sea level trends (1955-2003) using a combination of tide gauge records and satellite altimetry, show a general rising trend in Tanzania ranging from 0.4 to 2.0

mm/yr (Bindoff *et al.*, 2007). The global average rise within this period is about 0.4 to 3.6 mm/yr (Bindoff *et al.*, 2007).

1.2.4 Seawater-freshwater interactions effecting coastal forests

In coastal aquifer, high and low tides, saltwater and freshwater density, water table and soil hydraulic conductivity characterize a seawater-freshwater interaction (Guo, 2007). Eddy *et al.* (2009) concluded that a change of sodium concentration through space has direct relation with the source and magnitude of the sea water intrusion into freshwater aquifer. Based on Ghyben – Hezberg principle (Van Camp *et al*., 2014) there is an interaction between saltwater and freshwater in Jozani Groundwater Forest (JGWF). For the case of JGWF such interaction is influenced by elevation of the water table and soil clay content, amount of seawater from tidal trends and magnitude and amount of freshwater from rain fall and condition of the Jozani aquifer. Such interaction has significant effects on assemblage, richness and spatial distribution of plant communities. The main effect from the said interaction is on salinity spatial trend into JGWF. Monge-Nájera (2008) reported salinity is key element for climate change in the ecological biogeography of many species. In addition Bui (2013) reported that soil salinity even at low levels, is an abiotic stress factor that influences vegetation patterns and diversification.

1.3 Factors Affecting Plant Species Community Spatial Distribution

1.3.1 Environmental variables

Jozani Groundwater Forest (JGWF) has a wide range of plant species (Andersen, 2012; Kukkonen and Käyhkö, 2014). According to Zanzibar Wood Biomass Survey (ZRG) (2013) report, JGWF has a high count of forest plant species which makes a biomass above 50 tonnes ha^{-1}. Plants spatial distribution is always influenced by environmental (several biotic and abiotic) factors (Crain *et al*., 2004). Plant species in a forest make a certain assemblage based on favorable environmental conditions within the forest (Frank *et al*., 2010; Ahmad *et al.*, 2013). In addition, Munishi e*t al.* (2011) and Schmitt *et al.* (2013) reported that distribution of forest plants is strongly influenced by environmental variables. According to Nahonyo *et al*. (2002) and ZRG (2013), plant species found within Jozani Chwaka Bay National Park (JCBNP) area exceed 200 counts. As JGWF was within JCBNP, obviously plant species in JGWF are in certain spatial patterns which in the long run act as their assemblages and distribution.

1.3.2 Spatial effects of environmental variables to forest plants

Plant spatial distribution is significantly affected by biotic and abiotic factors such as plant density, canopy and water availabity (Meier *et al.*, 2010; Pellissier *et al*., 2013; Wisz *et al*., 2013). Le-Maitre *et al.* (1999) reported on the interactions occurred between vegetation and groundwater. Monge-Nájera (2008) reported that temperature, humidity and salinity are key abiotic elements affecting ecological biogeography of many species. Based on these abiotic elements, Blaser and Gregersen (2013) reported that, salinity plays a great role in communities' distribution in tropical coastal forests. Ribeiro *et al.* (2011) was more specific, in reporting that salinity and flooding cycles are the major determinant factors for plant assemblage. Blaser and Gregersen (2013) concluded that salinity is the determinant of plant assemblage in tropical coastal forests. Furthermore, Bui (2013) concluded that soil salinity even at low levels, is an abiotic stress factor for vegetation patterns and diversification. As JGWF is a natural (Kukkonen and Käyhkö, 2014) tropical coastal forest (Mchenga and Ali, 2014) located in the lowest point of Zanzibar (Klein, 2009; Leonila, 2011), the main factors of spatial distribution of plant communities shall include elevation, seawater-freshwater interaction and soil characteristics. Based on Balley-Serres and Timothy (2014), among factors of spatial distribution of plant community in JGWF include fluctuation of water table between dry and wet seasons that have direct relation with elevation of a point within JGWF. General plant communities' spatial distribution in JGWF is subjected to change with time through the changes of the mentioned abiotic factors (Ahmad *et al.*, 2013).

1.4 Justification of the Current Study

A good number of studies have been conducted by local and international researchers to explore, and characterize conditions and habitats found in Jozani-Chwaka Forest Reserve (ZRG, 2013). Based upon those studies, reports, ecotourism, workshops, international bodies including UNESCO recognized the importance of Jozani based Forest to mankind. For decades, many of the conducted studies were inclined on inventory and biotic factors for the flora and fauna found in the Reserve. To that direction there is a good progress of disclosure of a number of flora and fauna species and related information in the Reserve. Among valuable works for the Reserve include inventory carried out by Nahonyo *et al.* (2002) and biomass report of ZRG (2013). On the contrary there are none or very few noticeable studies on the underlying abiotic factors influencing the habitats in JGWF. This study is therefore, focused on conducting research to fill the gap of information on abiotic factors affecting JGWF habitats.

The Vice President's Office (VPO) (2012) predicted that, so far, due to climate change in Tanzania, there will be a rise of sea level and proportional increase of sea water intrusion into coastal land and/or aquifer. According to Guo and Jiao (2007) however, sea water intrusion depends on the level of ground water table; if the ground water table is above the sea water level, the intrusion is at a minimum while the opposite causes water to flow inland. Again, long term and continuing sea water intrusion on a flat land accumulates more sodium compounds in the soil (Gole, 2006). The rise of sodium compound affects soil properties and plant growth (Eddy *et al*., 2009). Since JGWF has a close to the ground surface water table, conditions such as rise of sea level are therefore, strongly threatening flora and fauna in JGWF. The threats directed to JGWF shall have irreversible negative impact to the Reserve, biodiversity and ecotourism of Zanzibar and Tanzania as a whole. Therefore, the findings from this study are expected to be a strong foundation against salinity threats and be valuable information for conservation and managerial practices of the Bio-sphere Reserve.

Biomass variations between coral lands (10 tonnes ha^{-1}) and JGWF (> 50 tonnes ha^{-1}) which were reported by ZRG (2013) indicate that the variations are the outcomes of abiotic factors affecting plant growth, species composition and gradient distribution in the areas. Hettige (1990) blanketed JGWF soil into *Lithic Leptosols*, the soil type which is commonly found in coral areas of Zanzibar. Characteristics of shallow water table in JGWF are among research areas needed for better understanding of the key issues for good management of JGWF as well as the Reserve as a whole. Soil and water characteristics and their interrelationships are among primary environmental factors affecting forest habitats (Soil Survey Staff, 2014). As JGWF aquifer is shallow and found between two bays, relationships between soil and seawater-freshwater interaction are also among worthy information for proper management of JGWF.

For sustainable management and conservation of the Jozani-Chwaka Bay Biosphere Reserve as well as JGWF, there is a need for scientific information on conditions, environmental facotrs and their interrelationships that influence the existence, assemblage, and spatial distribution of the plant species found in Reserve. Mustelin *et al*. (2009) gave highlights on management of coastal forest of Zanzibar, while ZRG (2015) has included specific issues of management and conservation of Reserve. Among the highlights given by Mustelin *et al*. (2009) include mangrove plantation along coastalline. The issues focused on biodiversity, environment and coastal land conservation and eco-system. Zanzibar forest policy SMOLE II (2013) developed a number of laws and bylaws in managerial practices for forest territories in Zanzibar. Findings from this study therefore, will act as a guiding tool for developing soil, water, biodiversity conservation and management programmes for the JGWF and the Bio-sphere Reserve. This study will develop comprehensive information on the JGWF soils and water inter-relationships and distribution of plant communities and other areas with similar ecological settings in Zanzibar, Tanzania.

1.5 Objectives

1.5.1 Overall objective

To characterize inter-relationships between terrain characteristics, sea water intrusions, soil characteristics and plant communities' distribution in Jozani Groundwater Forest, Zanzibar, Tanzania.

1.5.2 Specific objectives

Specific objectives were to:

i. To determine the elevation of Jozani Groundwater Forest.

ii. To characterize soil depth to coral bedrock and bedrock roughness in Jozani Groundwater Forest.

iii. To determine tidal trends and magnitude of Chwaka and Uzi bays as a proxy of the sea water intrusions in Jozani Groundwater Forest.

iv. To determine the extent of seawater intrusion from Chwaka and Uzi bays into the Jozani Groundwater Forest.

v. To characterize the effects and implication of rainwater-seawater interactions on physical and chemical characteristics of Jozani Groundwater Forest soils.

vi. To characterize influence of spatial environmental gradient on plant species communities' assemblage in Jozani Groundwater Forest.

1.6 Conceptual Framework of the Study

The conceptual framework adopted in the current study is presented in Fig. 1.2.

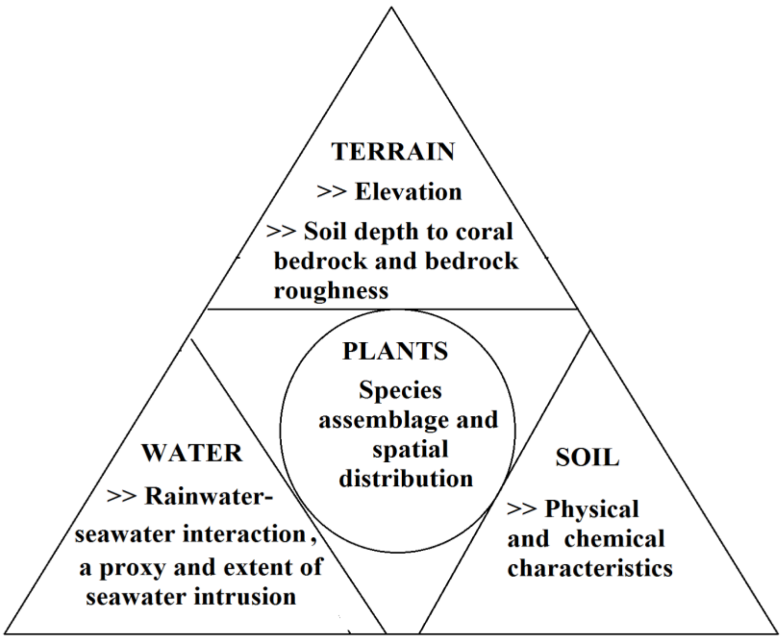


Figure 1.2: Three environmental variable components. The components include terrain, soil and water which are interrelated to each other and together have an influence to plant communities' distribution

1.7 References

Ahmad, P., Azooz, M. and Prasad, M. (Eds.) (2013). *Ecophysiology and Responses of Plants under Salt Stress.* Springer Science + Business Media. New York. 497pp.

Andersen, I. (2012). REDD in Zanzibar: Ethnography of Stakeholders. Thesis submitted for Master of Arts Department of Social Anthropology University of Oslo, Norway. 138pp.

ASCLME (2012). National Marine Ecosystem Diagnostic Analysis, Tanzania. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant). Unpublished report. 92pp.

Balley-Serres, J.A. and Timothy, D.C. (2014). Plant tolerance of flooding stress–recent advances. *Plant, cell and Environment* 37(10): 2211-2215.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C. and Silliman, B.R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81(2): 169-193.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. (2007). Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D. Manning, M., Chen, Z. Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA. 429pp.

Blaser, J. and Gregersen, H. (2013). Forest Come and Go: 300 Years of Sustainable

Forest. *FAO Unasylva* 64(1): 61-73.

Boak, E.H. and Turner, I.L. (2005). Shoreline definition and detection: *A Review Journal of Coastal Research* 21(4): 688–703.

Bodin, J., Badeau, V., Bruno, E., Cluzeau, C., Moisselin, J.M., Walther, G.R. and Dupouey, J.L. (2013). Shifts of forest species along an elevational gradient in Southeast France: climate change or stand maturation? *Journal of Vegetation Science* 24(2): 269-283.

Bouillon, S., Dehairs, F., Velimirov, B., Abril, G. and Borges, A.V. (2007). Dynamics of organic and inorganic carbon across contiguous mangrove and seagrass systems (Gazi Bay, Kenya). *Journal of Geophysical Research: Biogeosciences* 112(2): 1-14.

Bui, E.N. (2013). Soil salinity: a neglected factor in plant ecology and biogeography. *Journal of Arid Environments* 92: 14-25.

Burgess, N.D., Mwasumbi, L.B., Hawthorne, W.J., Dickinson, A. and Doggett, R.A. (1992). Preliminary assessment of the distribution, status and biological importance of coastal forests in Tanzania. *Biological Conservation* 62(3): 205-218.

Carter, R.W.G. (2013). *Coastal environments: an introduction to the physical, ecological, and cultural systems of coastlines*. Elsevier. 617pp.

Casazza, G., Zappa, E., Mariotti, M.G., Médail, F. and Minuto, L. (2008). Ecological and historical factors affecting distribution pattern and richness of endemic plant species: the case of the Maritime and Ligurian Alps hotspot. *Diversity and Distributions* 14(1): 47-58.

Clark, D.B., Palmer, M.W. and Clark, D.A. (1999). Edaphic factors and the landscape-scale distributions of tropical rain forest trees. *Ecology* 80(8):

2662-2675.

Crain, C.M., Silliman, B.R., Bertness, S.L. and Bertness, M.D. (2004). Physical and biotic drivers of plant distribution across estuarine salinity gradients. *Ecology* 85(9): 2539-49.

Cui, B., and Xiao-Yan, L. (2011). Coastline change of the Yellow River estuary and its response to the sediment and runoff (1976–2005). *Geomorphology* 127(1): 32-40.

Eddy-Miller, C.A., Wheeler, J.D. and Essaid, H.I. (2009). Characterization of interactions between surface water and near-stream groundwater along Fish Creek, Teton County, Wyoming, by using heat as a tracer: U.S. Geological Survey Scientific Investigations Report 2009–5160. 53pp.

Frank, D.A., Pontes, A.W., Maine, E.M., Caruana, J., Raina, R., Raina, S. and Fridley J.D. (2010). Grassland root communities: species distributions and how they are linked to aboveground abundance. *Ecology* 91(11): 3201-3209.

Gentry, A.H. (1988). Changes in plant community diversity and floristic composition on environmental and geographical gradients. *Annals of the Missouri Botanical Garden* 1-34.

Gole, C. (2006). Jewel of the Australian Continent. *Southwest Australia Ecoregion Initiative. WWF-Australia* 1: 32.

Guebas, F. and Koedam, N. (2014). Using expert knowledge and modeling to define mangrove composition, functioning, and threats and estimate time frame for recovery. *Ecology and Evolution* 4(11): 2247-2262.

Guo, H. and Jiao, J.J. (2007). Impact of coastal land reclamation on ground water level and the sea water interface. *Groundwater* 45(3): 362-367.

Hamad, H.M., Mchenga, I.S. and Hamisi, M.I. (2014). Status of exploitation and regeneration of mangrove forests in Pemba Island, Tanzania. *Global Journal* *of Bio-Science and Biotechnology* 3(1): 12-18.

Hettige, M.L. (1990). Land evaluation and land sustainability classification. Unguja and Pemba Islands. *Food and Agriculture Organization of the United Nations*. FAO TCP/URT/6759 (A), Zanzibar. 156pp.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Dissertation for Award MSc Degree at Turku University Dept. of Geography, Finland. 85pp.

Kukkonen, M. and Käyhkö, N. (2014). Spatio-temporal analysis of forest changes in contrasting land use regimes of Zanzibar, Tanzania. *Applied Geography* 55: 193-202.

Le-Maitre, D., David, F. and Colvin, C. (1999). A review of information on interaction between vegetation and groundwater. *Water South Africa* 25(2): 132-152.

Leonila, Z. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award MSc Degree at University of Twente Netherland. 43pp.

Li, L., Huang, Z., Ye, W., Cao, H., Wei, S., Wang, Z., Lian, J., Sun, I.F., Ma, K. and He, F. (2009). Spatial distributions of tree species in a subtropical forest of China. *Oikos* 118(4): 495-502.

Liang, J. (2014). Feasibility of a Mangrove-Based Carbon Business in Makoba Bay, Unguja, Zanzibar. Independent Study Project (ISP) Collection. Paper 1917. [http://digitalcollections.sit.edu/isp_collection/1917] site visited on 21042015.

Mahongo, S.B. (2009). The changing global climate and its implication on sea level trends in Tanzania and the Western Indian Ocean Region. *Western Indian Ocean Journal of Marine Science* 8(2): 147-159.

Mahongo, S.B. and Francis, J. (2010). Monthly variations in sea level at the Island of Zanzibar. *Western Indian Ocean Journal of Marine Science* 1: 1-16.

Malhi, Y., Gardner, T.A., Goldsmith, G.R., Silman, M.R. and Zelazowski, P. (2014). Tropical forests in the Anthropocene. *Annual Review of Environment and Resources* 39: 125-159.

Mchenga, I.S. and Ali, A.I. (2014). A review of status of mangrove forest in Zanzibar Island, Tanzania. *Int. J. Res. Rev*. 2(8): 518-526.

Meier, E.S., Kienast, F., Pearman, P.B., Svenning, J.C., Thuiller, W., Araújo, M.B., Guisan, A. and Zimmermann, N.E. (2010). Biotic and abiotic variables show little redundancy in explaining tree species distributions. *Ecography* 33(6): 1038-1048.

Monge-Nájera, J. (2008). Ecological biogeography. A review with emphasis on conservation and the neutral model. *Tropical Biology, Gayana* 72(1): 102-112.

Mukherjee, N., Sutherland, W.J., Khan, M.N.I., Berger, U., Schmitz, N., Dahdouh-Munishi, P.K., Temu, P.R. and Soka, G. (2011). Plant communities and tree species associations in a Miombo ecosystem in the Lake Rukwa basin: Implications for conservation. *Journal of Ecology and Natural Environment* 3(2): 63-71.

Mustelin, J., Klein, R., Asseid, B., Sitari, T., Khamis, M., Mzee, A. and Haji, T. (2009). Practical measures to tackle climate change: coastal forest buffer zones and shoreline change in Zanzibar, Tanzania. *Turku University Department of Geography Publications B* 13: 106.

Muzuka, A.N., Nyandwi, N. and Shaghude, Y. W. (2004). Preliminary investigation on the Pleistocene/Holocene sea-level changes along the coastline of

Tanzania, with reference to Unguja and Pemba Islands. *Boletim Geologico* 43: 8–13.

Nahonyo, C.L., Mwasumbi, L.B., Eliapenda, S., Msuya, C., Mwansasu, C., Suya, T. M. and Kihaule, P. (2002). *Jozani-Chwaka Bay proposed National Park biodiversity inventory report*. Department of Forest Non-renewable Natural Resources (DCCFF). The Revolutionary Government of Zanzibar. 184pp.

Pajak, M.J. and Leatherman, S. (2002). The high water line as shoreline indicator. *Journal of Coastal Research* 18(2) 329-337.

Pellissier, L., Pinto-Figueroa, E. and Niculita-Hirzel, H. (2013). Plant species distributions along environmental gradients: do belowground interactions with fungi matter? *Frontiers in Plant Science.* 4:500. doi:10.3389/fpls.2013.00500.

Read, Q.D., Moorhead, L.C., Swenson, N.G., Bailey, J.K. and Sanders, N.J. (2014). Convergent effects of elevation on functional leaf traits within and among species. *Functional Ecology* 28(1): 37-45.

Ribeiro, J.P.N., Matsumoto, R.S., Takao, L.K., Peret, A.C. and Lima, M.I. (2011). Spatial distribution of Crinum americanum L. in tropical blind estuary. Hydrologic, edaphic and biotic drivers. *Environmental and Experimental Botany* 71(2): 287-291.

Salum, L.M. (2009). Ecotourism and biodiversity Conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47:166-170.

Schmitt, C.B, Senbeta, F., Woldemariam, T., Rudner, M. and Denich, M. (2013). Importance of regional climates for plant species distribution patterns in moist Afromontane forest. *Journal of Vegetation Science* 24(3): 553-68.

SMOLE II (2013). Zanzibar Sustainable Management of Land and Environment II, Zanzibar National Forest Policy Analysis. Zanzibar. 25pp.

Soil Survey Staff (2014). *Keys to Soil Taxonomy*. 12th Edition. United States Department of Agriculture, Natural Resources Conservation Service. 359 pp.

Sollins, P. (1998). Factors influencing species composition in tropical lowland rain forest: does soil matter? *Ecology* 79(1): 23-30.

Suc, J.P. (1984). Origin and evolution of Mediterranean vegetation and climate in Europe. *Nature Publishing Group* 307(2): 429-433.

Van Camp, M., Mtoni, Y., Mjemah, I.C., Bakundukize, C. and Walraevens, K. (2014). Investigating seawater intrusion due to groundwater pumping with schematic model simulations: the example of the Dar es Salaam coastal aquifer in Tanzania. *Journal of African Earth Sciences* 96: 71-78.

Vice President Office (2012). *National Climate Change Strategy*. Division of Environment. United Republic of Tanzania. 92pp.

Viles, H. and Spencer, T. (2014). *Coastal problems: geomorphology, ecology and society at the coast*. Routledge. 350pp.

Wisz, M.S., Pottier, J., Kissling, W.D., Pellissier, L., Lenoir, J., Damgaard, C.F., Dormann, C.F., Forchhammer, M.C., Grytnes, J.A., Guisan, A. and Heikkinen, R.K., (2013). The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. *Biological Reviews* 88(1): 15-30.

Zanzibar Revolutionary Government (2013). Zanzibar Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report. Indufor (Forest Intelligence) and Norwegian Embassy, Zanzibar, Tanzania. 139pp.

Zanzibar Revolutionary Government (2015). Zanzibar Reasearch Agenda (ZRA) 2015-2020, Zanzibar, Tanzania. 124pp.

CHAPTER TWO

2.0 ELEVATION OF JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

ABSTRACT

Levelling techniques, including the use of levels, theodolites and GPS are less applicable under forest canopies. On the other hand "Light Detection and Ranging" (LIDAR) technique which could perform the levelling is sophisticated, expensive and not readily available in developing countries. The current study therefore attempted the use of water table as an alternative method for levelling the Jozani Groundwater Forest (JGWF) of Zanzibar, Tanzania. The "Height of Instrument" method was used to determine reduced level (RL) of the water table (RL_{WT}) of JGWF from local wells. Then, through temporary wells (TWs), RL_{WT} was used as a wide benchmark to determine other RLs on the ground surface along 32 transect lines. The height from the water table to the ground surface (floating height (FH)) was then measured. Benchmark number 205 and SOKKIA C.3.2 level were used to determine the RL_{WT}. Soil auger was used to open TWs, and cellphone timer and floating rod tape were used respectively to determine time of water settlement, and FH in a TW. GARMIN GPS Model *e*trex 10 and ArcGIS 10.1 were used for geo-referencing and mapping. Elevations of ground surfaces were computed by summing the RL_{WT} and FH at a particular point. These elevations were then used to produce Digital Elevation Model (DEM) of JGWF. The DEM (the main result) showed that JGWF is a coastal forest with low elevation ranged between 0.75 and 2.5 m, AMSL. It is concluded that, use of water table for levelling the groundwater forest is feasible and an alternative method.

Key words: Benchmark, groundwater forest, leveling, reduced level, water table, Zanzibar

2.1 Introduction

2.1.1 Importance of topographic map of Jozani Groundwater Forest

Topographic maps show a wide range of land information, and for decades, they have been used broadly for land use planning, management and development (Pradhan *et al.*, 2010). Information on the terrain conditions and topography beneath trees canopy is important to the forestry industry and natural resources management (Peterson *et al*., 2005). The Jozani groundwater forest (JGWF) which is characterized by dense canopy's multi-storey forest (Nahonyo *et al*., 2002), needed such information not only for what Pradhan *et al.* (2010) and Peterson *et al*. (2005) listed uses, but as a tool for studying soil, water, flora and fauna conditions and their distributions within the forest.

Jozani Groundwater forest (JGWF) is located within the 62 km^2 of Jozani-Chwaka Bay National Park (JCBNP) (Zanzibar Sustainable Management of Land and Environment II, 2013). The forest is on a trough lying between Uzi and Chwaka bays and is the lowest inland point in Zanzibar (Klein, 2008; Leonila, 2011). The trough can be observed in the Zanzibar topographic maps of Department of Survey (DOS). The maps were among the series of DOS 208 of 1980s sheets no. 10/4404 and 10/4410 of Pete and Charawe, respectively. In the said area, there were few randomly spotted points with less than 5 m elevation above mean sea level (AMSL). Since there were a number of features and conditions that differ within the JGWF and with its surrounding areas, the DOS maps were of little use in revealing the underlying factors affecting soils and water, and their interrelationships which influence the distribution of plant species and communities in the forest. Therefore, a study of generating digital elevation model (DEM) and related features of JGWF is a key to a number of pressuring agendas related to research and management in the forest.

The use of levels, theodolites and related surveying techniques for production of contours and DEM requires a series of instruments' setups along the surveying route using sensitive levels and geo-referencing systems (Brinker and Minnick, 2012; SaMeh, 2014). Surveys with the use of levels are valid only if the instruments' setups were linked to each other and all of them were referred to a datum (SaMeh, 2014). On unstable grounds of multi-storey high canopy forests, levelling with the said instruments and GPS receivers were obstructed and poorly signalled (Punmia, 2005; Ceylan *et al.*, 2005; Duggal, 2013). Such scenarios were experienced during surveying operations along Jozani-Wangwa (the grassland) trail to characterize the water table of the JGWF. Surveying operations were tedious as they were carried out while upholding the "Zanzibar Forest Policy" cautions (SMOLE II, 2013; Zanzibar Revolutionary Government (ZRG), 2013a) insisting that any activity in the JGWF shall be carried out in a manner that ensures intact maintenance of environment of the flora and fauna. Therefore, surveying with such technologies for levelling JGWF was impossible.

LIDAR (Light Detection and Ranging) technique is most useful for mapping-out heights of vegetation and elevation of ground surfaces under forest canopies (Peterson *et al.*, 2005; Staats, 2015). Therefore, the use of LIDAR outweighs the use of levels and theodolites (Wulder *et al.*, 2008). However, LIDAR requires sophisticated equipment and highly qualified expertise; it is expensive and yet has limitations

(Mandla and Kamal, 2008). Hence, in developing countries even with the need of the use of LIDAR, it is yet economically unsuitable and unaffordable. When such conditions are in place, as it is the case for JGWF and low economic potential of Zanzibar Revolutionary Government; an alternative way of making the topographic information available is inevitable.

A number of survey technologies are used to prepare maps of water tables and static water levels from measurements obtained from well-log records of private wells (Ridder, 1994; Rowley *et al.*, 2003). Such measurements result in a production of depth-to-water table maps, such as isobaths (Ridder, 1994). For decades, many, if not all publications used the word “water table” (WT) to express the top/upper surface/level beneath in-land earth surface saturated by water; and “static water level” (SWL) to express the water level in a well before water has been pumped out.

According to The *Columbia Electronic* Encyclopaedia (2013), “The Great Soviet Encyclopaedia of 1970s” went further on the term water table as referring also to the water surface of rivers and lakes. However, the word “float/floating” was often used when it was referring to specific use of the water bodies rather than the WT alone. Again, the SWL was used to refer to a WT, but was confined to its uses in engineering and water pumping studies and applications. With such context, the terms poorly expressed the water surface when it acts as a line/level floating the mass/objects above it. Therefore, in this study “water floating level (WFL)” has been used instead of “water table”. The term was defined as an imaginary reference line/level horizontally laid on the upper surface of an in-land water body above which all masses/objects were floating and it was used as a wide floating benchmark.

2.1.2 Basic principle on the use of water floating level

When a water floating level (WFL) acts as a benchmark (BM), heights from it to soil surface (floating heights (FHs)) can be measured from every point (floating point (FP)) of the surveyed area. In this case a FP was a geographic point of the measured FH. Since WFL as BM was referred to the mean sea level (MSL), all reduced levels (RLs) of FPs were also referred to the MSL (Fig. 2.1).

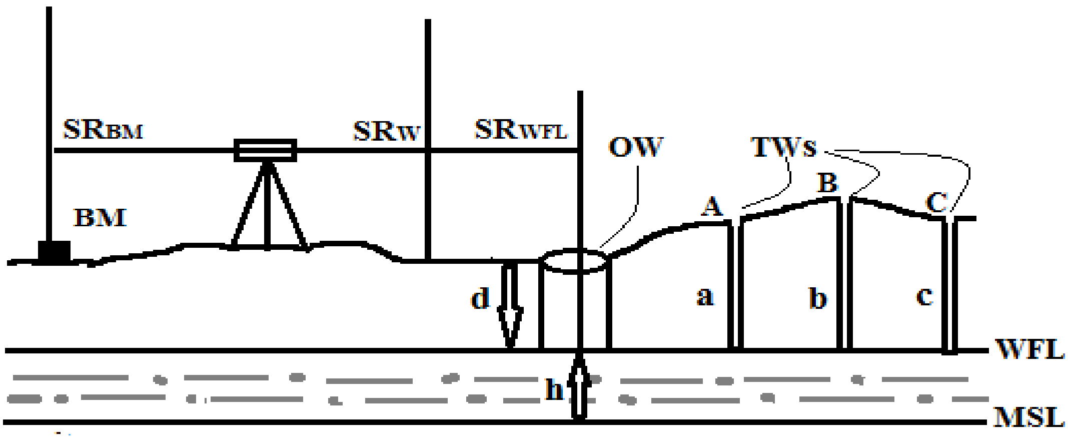


Figure 2.1: A **basic principle of levelling with the use of water floating level**

Fig. 2.1 illustrates that the reduced level (RL) of the water floating level (WFL) (RL_{WFL}) in observation well (OW) was determined from (differential) surveying by the "Height of Instrument (HI)" method from a nearby benchmark (BM), Formulae 1, 2 and 3 apply as per Brinker and Minnick (2012). The RL of floating points ($FP_{A, B, C}$) were then obtained by summing the RL_{WFL} and FH $_{a, b, c}$, Formulae 4 and 5.

$HI = BS + RL_{BM}$ ……………………………………………………………(1)

$RL = HI - SR$ ……………………………………………………………(2)

$RL_{WFL} = HI - SR_{WFL} = h$ ……………………………………………………(3)

$RL_W = HI - SR_W = RL_{WFL} + d$ …………………………………………………(4)

$RL_{A, B, C} = RL_{WFL} + a, b, c = h + a, b, c$ ……………………………………(5)

Where HI; height of the instrument, BS; back sight, RL; reduced level, SR; staff reading, BM; benchmark, SR_{BM}; SR at BM, WFL; water floating level, RL_{WFL}; RL of WFL, SR_{WFL}; SR on WFL, RL_W; RL of soil surface at the OW, SR_W; SR on the soil surface at the OW, MSL; mean sea level, h; height of WFL AMSL, d; depth from soil surface to WFL, a, b, c; measured depths from soil surface to WFL at point A, B, C, and $RL_{A, B, C}$; are RL at $FP_{A, B, C}$.

Elevation of soil surface at a particular floating point (Elv_{FP}) was therefore, identified by summing the RL_{WFL} of the area in a particular day of surveying and measured FH. A floating metric tape was used to measure the FH through a geo-referenced temporary well (TW). If FPs were many enough and were obtained from transects covering the studied area, they are the inputs for DEM production with the use of a digital mapping tool such as ArcGIS.

The current study explored the possibility of using a shallow (close to soil surface) WT referred to as WFL for the JGWF DEM production. The WFL acted as a wide benchmark and was used to determine elevation of several points within the JGWF. A close to soil surface WT was a unique opportunity in this method. The method cuts down the costs of levelling under forest canopies using modern technologies. The map produced can be used in a number of academic and management programmes such as soil and water inter-relationships, plant species distributions, biodiversity and ecotourism conservation.

2.2 Materials and Methods

2.2.1 Description of the study area

The study was conducted in about 8 km^2 area of JGWF located between the Chwaka and Uzi bays and was within the Jozani-Chwaka Bay National Park (JCBNP) area, Zanzibar, Tanzania. The Park of about 62 km^2 lies within Universal Transverse Mercator (UTM) Zone 37S coordinates between N 9 305 880 to 9 317 855 and E 539 100 to 549 000 (SMOLE II, 2013) (Fig. 2.2). The Park has a tropical sub-humid climate and receives about 1400 mm annual average rainfall from long rainy season (*Masika*); March to May and the short rainy season (*Vuli)*; October to November (Leonila, 2011). The JGWF has a closed to the soil surface WT (Nahonyo *et al*., 2002; Zanzibar Revolutionary Government (ZRG) 2013b). During the rains, the WT often emerged above the soil surface and form temporary marshes (Salum, 2009).

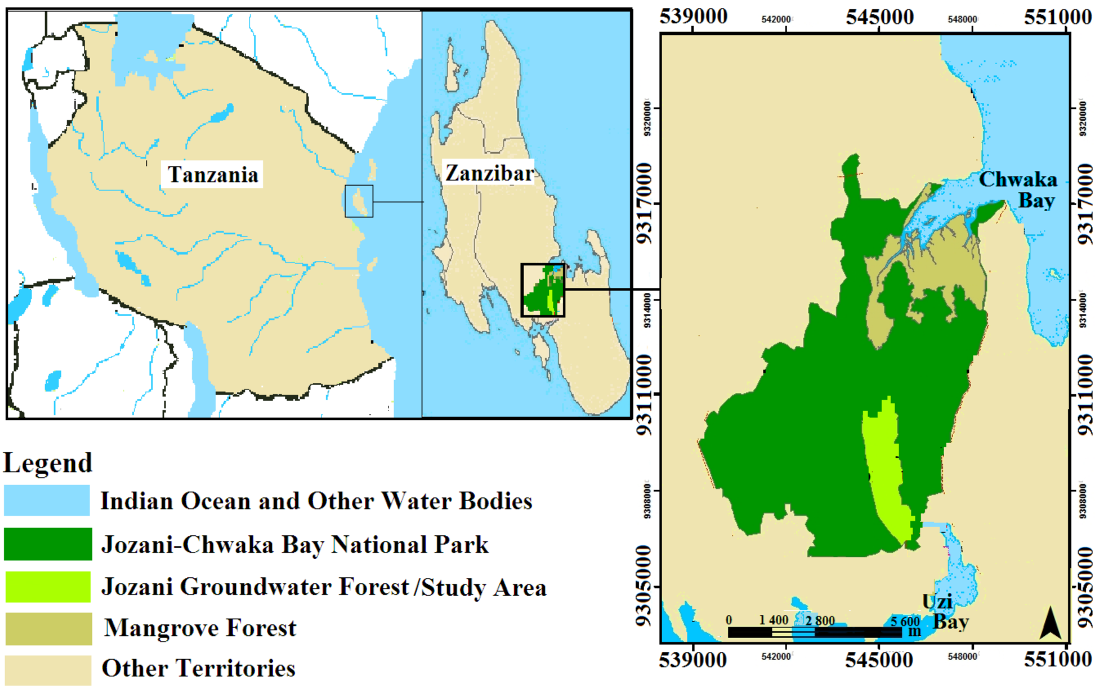


Figure 2.2: **Location map of Jozani Groundwater Forest. Source: Department of Forest Non-Renewable Resources Zanzibar, Tanzania**

2.2.2 Survey to characterize water floating level of Jozani Groundwater Forest

As cited in Ridder (1994), a water level in a well has a height of the WT of a particular water body. Hence existing wells offer ready-made sites for water level observations. During the reconnaissance survey, a total of eight wells; two on the southern end (Jozani) close to datum no. 205, four along the Jozani-Wangwa trail, and two on the northern end (Wangwa) were identified. These wells were used as OWs for WFL characterization. The survey to characterize the WFL was done for two consecutive days in October 2014 as suggested by Ridder (1994). He suggested that, measurement for WT determination should be done within a short period of time. The HI/Collimation method (NIWA, 2004) with the aid of SOKKIA C.3.2 level was used to determine the WFLs through the OWs.

During the survey, temperature ranged between 30 and 32^{o}C as recorded from Tanzania Meteorological Agency (TMA) stations at Kisauni, Zanzibar. Such temperature range would results into systematic errors if aluminium reading staff was used. According to Ceylan *et al*. (2005), aluminium reading staffs are affected by temperature above 27^{o} C. Therefore, to minimize errors associated with the aluminium reading staff, wooden reading staff was used. Datums numbers 205 and 210 with RL of 2.134 and 5.621 m, AMSL located respectively at Northern (N) 9 306 943, Eastern (E) 546 217 and N 9 310 846, E547 685 were used during the survey. These datums were installed in 1976 and revisited in 2013 by the DOS office.

GARMIN **e**trex 10 GPS receivers were used for geo-referencing of OWs. From datum no. 205 at Jozani, the levelling process continued to Wangwa and then from Wangwa to datum no. 210 at Mapandani along Charawe road. The RLs were computed in Excel spread sheets by Formulae 1 and 2, Section 2.1.2. Arithmetic error and slope of WFL (between Jozani and Wangwa) were calculated as proposed by SaMeh (2014) and Cavanagh (2008), using Formulae 6 and 7, respectively.

Arithmetic Error = Σ Back - Σ Fore…………………….………..……………..….(6)

Slope (gradient) = Rise/Run x 100……………………………………………..…….(7)

Where Σ Back is sum of all back sights, Σ Fore is sum of all fore sights, Rise is vertical height, Run is horizontal distance between the two points and 100 is factor of expression in per cent.

2.2.3 Transecting and water floating level slope determination

In areas where water table (WT) is smoothly sloped, observation wells (OWs) can be spaced further apart than 200 m (Ridder, 1994). With this regard, it was estimated that, in JGWF the height of WFL m, AMSL was the same within a radius of about 200 m from the OW. Therefore, transects were spaced at 200 m apart aimed at evenly distributing the slope of the WFL. The transecting was done with expectation that, through transects across the forest length the RL_{FP} will be properly captured. These transects were running east-westwards. Along transect line; TWs were opened for FH measurements. One of the OWs at 545 987 E, 9 306 659 N was used as reference well (RW), and for the convenience of transecting, its northern coordinate was rounded to 9 306 600 N. Hence, the area of the first three southern transects (9 306 400, 9 306 600 and 9 306 800 N) had the same RL_{WFL} as recorded at RW and was indicated as T_0. Therefore, the first transect affected by WFL slope was 9 307 000 N indicated as T_{200} (200 m from T_0) and the last transect was 9 312 600 N, indicated as T_{5800} (5800 m from T_0). Therefore, the run (length) of about 6 km was subdivided into 32 transects.

The primary references at water level recording stations are the sets of datum (Ridder, 1994; NIWA, 2004). So, WFL on a particular day of transect walks was determined by surveying from datum no. 205 to the RW (about 372 m apart) using HI method with SOKKIA C.3.2 level. The identified level of water table above the mean sea level(AMSL) (WFL) was used as benchmark (BM) for floating height (FH) probing during transect walks. Equation 8 was used to nullify the WFL slope (S) along T_X aimed at obtaining FHs that were free from the S effects.

$WFL_{TX} = WFL_{RW} \pm (S \times T_X)$, m…………………………………………………….(8)

Where WFL_{TX}; was WFL (m) at a given transect (T) with X distance (m) from T_0, WFL_{RW}; WFL at RW in a day of transect walk, S; slope in per cent (%) a constant. The sign was negative when the T_X runs down the slope and positive when T_X runs up the slope.

2.2.4 Transect walks

GARMIN ***e***trex 10 (GPS) receivers were used to navigate the teams along transect lines during the walks. The transect walks for probing involved four teams of four people, each consisting of two villagers with at least secondary school education, a skilled park attendant, and a diploma-holder surveyor. Each of the team walked on two transects per day and the walks were for four consecutive days. The task of each of the teams was to identify the FPs on a T_X where the measured FH coincided with the one indicated in the field book for a given elevation (Elv). Thereafter, the eastern coordinates (E) of the identified FPs were recorded. It was experienced that in JGWF it was impossible to walk on a straight line along indicated T_X (Northern coordinate (N)), so an alteration of about 5 m from a given T_X was allowed.

2.2.5 Determination of floating heights at selected points

From observations made on DOS maps, it was decided that, JWGF could be surveyed at 0.25 m vertical interval as that would give more detailed elevation map. So the elevations (Elv) comprised: 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00 and 2.25 m, AMSL. The FH_{TX} were calculated and recorded in the field book with their respective Elv before the transect walks. A field book consisted of partial pre-printed separate sheets with a table indicating N coordinates, Elv and their respective FH for the T_X. Value of FH for a given Elv on T_X was calculated by Formula 9.

FH_{TX} = Elv– WFL_{TX}, m…………………………………………………………..(9)

Where, FH_{TX}; was FH along T_X, Elv; elevation and WFL_{TX}; WFL along T_X at a given distance from RW.

2.2.6 Probing

To minimize the number of probes while maximizing the time use efficiency during transect walks, the survey team members were trained on how to perform the task. The probing was performed for 4 days in late November, 2014. Transect probing was carried out when a team found a sort of sharp or gradual slope, depression or rise along transect. Drilling, depth measurements and data recording were done as suggested by Ridder (1994). Soil auger of about 0.08 m diameter and up to 2.0 m long was used to open the TWs to reachable depths. The floating measuring rod was inserted down the TW just 2 minutes after drilling. The cell phones were used as timers. Following several observations made on JGWF, it was recommended that measurement should be done in 5-6 minutes time after drilling. Data for FH were observed from the metric rod at the cap slot at soil surface. The E coordinates of given FP were recorded in field book. However, it was difficult to obtain FP with exact metric figures of FHs as given in the field book for a given Elv. Therefore, alteration of ±0.05 m from a given FH value was allowed. On the selected point about 3-4 probes for a particular FH were recommended. However, an FP was recorded when its measured FH fall upon Elv range indicated in the field book for a particular T_X.

2.2.7 Validation of the method of using a shallow water table as a benchmark

With the help of SOKKIA C 3.2 level, Height of Instrument (HI) method of reduction in survey, benchmark no. 205 was used to determine reduced levels (RLs) of ten selected points which were earlier used as floating points (FPs). Similar procedures explained in Sections 2.2.2, 2.2.3, 2.2.5 and 2.2.6 were adopted. Thereafter, the RLs obtained by HI method were used to avalidate the RLs (floating heights (FHs)) obtained during probing with the use of water table as a benchmark.

2.2.8 Mapping

The FPs with their respective FHs were used to produce DEM of JGWF with a height range 0.75 to 2.25 m. ArcGIS 10.1 was used for mapping as per Schaeffer (2012).

2.3 Results and Discussion

2.3.1 Status of water floating level

The water floating level (WFL) was at varying depths from the soil surface and no rains were recorded during the surveying and probing time. A summary of the performed instrumental levelling process from Jozani to Wangwa (grassland) to characterize the WFL in the forest is presented in Table 2.1. Table 2.2 shows the recorded WFL_{TX} for a T_X after having nullified slope based on the WFL_{RW} obtained from surveys carried out from datum no. 205 to the RW on the day of transect walk.

Table 2.1: Levelling characterizing the water floating level (WFL) in Jozani Groundwater Forest, October 2014

OW and Datum IDs	Coordinates UTM 1960 37 S		RL		Arithmetic error	Slope	
			Surface	WFL		Surface	WFL
	Eastern	Northern	m	m	m	%	%
OW at JCBNP office	545 732	9 306 309	4.721	0.780			
Reference well (RW)	545 987	9 306 659	1.477	0.781			
Datum no. 205	546 217	9 306 943	1.967	-			
First OW along trail	546 176	9 307 148	2.330	0.699			
Second OW	545 892	9 307 545	1.275	0.660			
Third OW	545 808	9 307 848	1.106	0.643			
Fourth OW	545 519	9 312 091	4.642	0.637			
OW at Wangwa (E)	545 000	9 312 000	0.765	0.635			
OW at Wangwa (W)	544 459	9 312 174	0.770	0.635			
Mean				**0.688**	**0.063**	**0.023**	**0.0028**

Table 2.2: Water floating levels for various transects

Day1		Day2		Day3		Day4	
T_X	WFL_{TX}	T_X	WFL_{TX}	T_X	WFL_{TX}	T_X	WFL_{TX}
RW	0.732	RW	0.732	RW	0.730	RW	0.728
T_0	0.732	T_{1600}	0.687	T_{3200}	0.641	T_{4800}	0.594
T_{200}	0.726	T_{1800}	0.682	T_{3400}	0.635	T_{5000}	0.589
T_{400}	0.721	T_{2000}	0.676	T_{3600}	0.630	T_{5200}	0.583
T_{600}	0.715	T_{2200}	0.671	T_{3800}	0.624	T_{5400}	0.577
T_{800}	0.710	T_{2400}	0.665	T_{4000}	0.618	T_{5600}	0.572
T_{1000}	0.704	T_{2600}	0.660	T_{4200}	0.613	T_{5800}	0.566
T_{1200}	0.699	T_{2800}	0.654	T_{4400}	0.607		
T_{1400}	0.693	T_{3000}	0.648	T_{4600}	0.602		

A total of 453 FPs on Elv ranging from 0.75 to 2.25 m, AMSL were recorded in the field books. The FPs were geo-referenced with E and N coordinates from 544 430 to 546 400 and from 9 306 600 to 9 312 400, respectively.

2.3.2 Geographical setting of the Jozani Groundwater Forest

From digital elevation model (DEM) it was determined that JGWF occupies the area between 544 400 to 546 400 and 545 000 to 544 459E on South and North-ends, respectively, and extends from 9 306 400 to 9 312 400N. The forest is located beneath and confined within coral ridges and cliffs on the west that gently up-ridging on the JGWF and narrowly opens towards Uzi creek and widely opens towards Chwaka bay. The DEM of the JGWF is presented in Fig. 2.3.

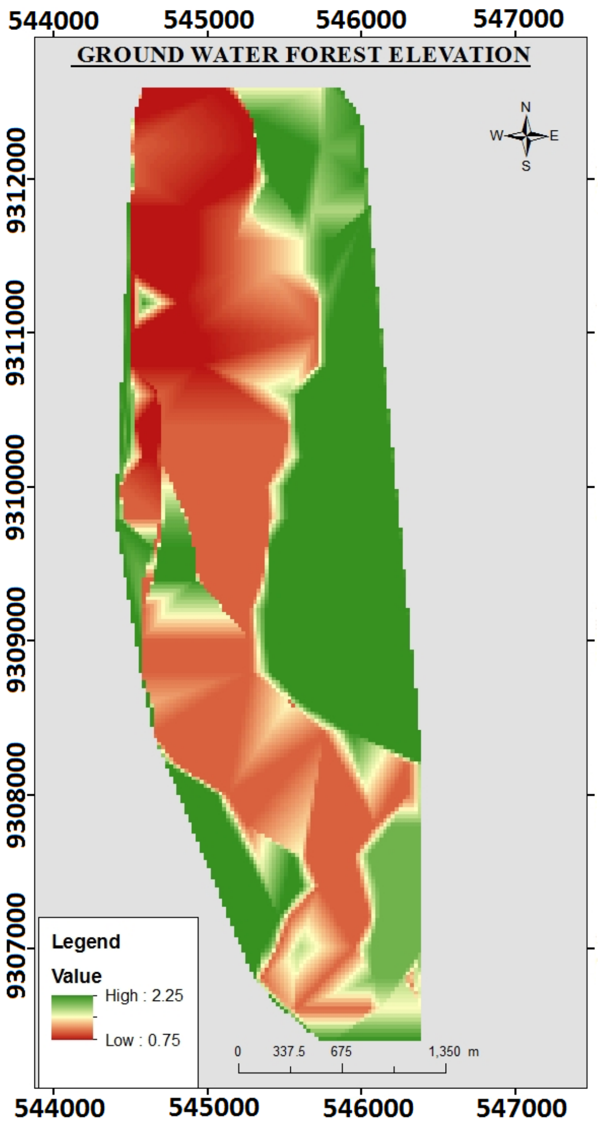


Figure 2.3: Digital elevation model (DEM) of Jozani Groundwater forest

2.3.3 Characteristics of surface elevation of the Jozani Groundwter Forest

Datum no. 205 was at the height of 2.134 m AMSL (data from DOS, 2013), but the RL of the soil surface where the datum is located is about 2 m AMSL only. The heights (AMSL) of the area close to the benchmark no. 205 were proved confirmed based on the results of validation of floating heights (FHs) of floating points (FPs) around the benchmark. Results from Chi Square Tests (Appendix 1) showed that there is a significant association of *P-value* of 0.003 between two methods, 1) a survey with the help of Height of Instrument (HI) and 2) a survey by which a Water Table (WT) was used as benchmark. Again, the difference between Jozani and Wangwa soil surfaces (about 6 km run) was about 1.12 m, giving an average slope of about 0.023%. The surface elevations and slopes indicated that although JGWF has an altitude of about 2.25 m AMSL and less, yet slope of the soil surface is decreasing from Jozani towards Wangwa.

2.3.4 Characteristics of water table in Jozani Groundwater Forest area

For good results of levelling with the use of WFL, time and duration of survey was crucial. Based on suggestion on WT recording period by Dalton *et al*. (2006), the surveying was done on appropriate time as there was no rain two weeks before and during the survey period. As reported by Ridder (1994) and Rowley *et al.* (2003), the water table changes due to precipitation and in JGWF case, its rises and falls were related to a number of processes occurring in the forest including evapo-transpiration and drainage. Within the 4 days of transect walks, the WFL had an insignificant change of its level as recorded drop of 0.004 m (0.001 m/day) indicated that JGWF never gets dry. During the dry period, the WT falls by few centimetres and rises during the rains. Hence, the forest is favoured by close to surface wetness throughout the year. Many scholars including Ridder (1994); Appelo and Postma (2005), and Zhu *et al.* (2014), reported that like streams and rivers, in coastal areas, groundwater flows down slope in seaward direction. The recorded difference of 1.477 and 0.780 m of soil surface and 0.765 and 0.635 m of WFL between Jozani and Wangwa respectively, indicated that, although JGWF is located between the Uzi and Chwaka bays, ground water sloped and flowed towards Chwaka bay. Again, based on Ridder (1994), the recorded 0.144 m difference between the WFLs of the two ends also indicated that, the water aquifer in the area was a single segment. Although Sophocleous (2002) reported that, a WT is subjected to change seasonally, annually or after a period of time, according to Rowley *et al.* (2003), the slope of the WT will remain constant unless factors influencing abrupt change are in place. Since the slope was of about 0.0028% and was constant and smooth, the subsurface geology of JGWF is fairly uniform and this suggests that only seasonal rain was the major factor behind the changes of WFL in the forest.

2.4 Conclusions and Recommendations

This study concludes that Jozani Groundwater Forest (JGWF) is a coastal forest on low altitude terrain with general elevation ranged between 0.75 and 2.5 m, AMSL The forest (JGWF) has shallow (close to the ground surface) water table that seasonally fluctuates. The water table has constant gradient that is slightly sloping from Jozani towards Wangwa (the north-end). The aquifer of JGWF is on fairly uniform geological subsurface. In the case of JGWF, this study concluding that the digital elevation model (DEM) produced is a key tool for studies on soil, water, plant species distribution and the inter-relationships between them.

This study rcommending a utilization of this method as it is feasible, applicable, an alternative and nullifies the challenges of levelling under forest canopy and high costs of levelling with modern technologies. The recommendations were made based on the following: The method was a reverse process of surveying where the water table was used to identify the surface levels instead of surfaces being used to identify the water levels. With the DEM produced, it was confirmed that, the method was feasible. One of the advantages is that in areas where the WT is not segmented, few OW and/or TW can be used to characterize the WFL and DEM production, respectively. The method can be performed in areas with many surveying obstacles. Again, the method is less time consuming and less costly. Furthermore, this method needs less data inventory and calculations, allows the use of less personnel and the surveying processes can be done by separate groups working at a time.

2.5 References

Appelo, C.A.J. and Postma, D. (Eds.) (2005). *Geochemistry, Groundwater and Pollution*. A. A. Balkema Publishers, Amsterdam, Nertherland. 649pp.

Brinker, R.C. and Roy, M. (Eds.) (2012). *The Surveying Handbook*. Springer Science and Business Media. 970pp.

Cavanagh, M. (2008). Trigonometry from a Different Angle. *Australian Mathematics Teacher* 64(1): 25-30.

Ceylan, A., Cevat, I. and Ismail, S. (2005). *Modern Height Determination Techniques and Comparison of Accuracies.* From Pharaohs to Geoinformatics, Cairo, Egypt TS33.5. 14pp.

Dalton, M.G., Brent, E.H and Ken, B. (2006). *Acquisition and Interpretation of Water-Level Data*. The Essential. 173pp.

Duggal, S.K. (2013). *Surveying* (Vol 2). Tata McGraw-Hill Education, New Delhi India. 625pp.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Exploratory study on the relation between soil variability and landscape. Dissertation for Award of MSc Degree at Turku University, Department of Geography Publications. B 11. 85pp.

Leonila, Z. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award of MSc Degree at University of Twente, Netherland. 46pp.

Mandla, V.R. and Kamal, J. (2008). Digital Elevation Model Accuracy Aspects. *Journal of Applied Sciences* 8: 134-139.

Nahonyo, C.L., Mwasumbi, L.B., Eliapenda, S., Msuya, C., Mwansasu, C., Suya, T.M., Mponda, B.O. and Kihaule, P. (2002). *Jozani – Chwaka Bay proposed National Park Biodiversity inventory report*, CARE Tanzania and department of Commecial Crops, Fruits and Forestry, Zanzibar. 184pp.

National Institute of Water Atmospheric Research (2004). Leveling and Surveying. Pacific Island Hydrology Course, Fiji: pp. 7. [http://www.whycos.org/fck_editor/ upload/File/Pacific-HYCOS/Surface_ Waters/ Levelling_ and_surveying.pdf] site visited on 12/08/2015.

Peterson, B., Dubayah, R., Hyde, P., Hofton, M., Blair, J.B. and Fites-Kaufman, J. (2005). Use of LIDAR for forest inventory and forest management application. In: *Seventh Annual Forest Inventory and Analysis Symposium* 19: 193 – 202.

Pradhan, R., Kumar, S., Agarwal, R., Pradhan, M.P. and Ghose, M.K. (2010). Contour line tracing algorithm for digital topographic maps. *International Journal of Image Processing (IJIP)* 4(2): 156-163.

Punmia, B.C. (2005). *Surveying* (Vol. 1). Firewall Media. LAXMI Publication (P) Ltd. 537pp.

Richard Hill, R., Thomas, M. and Matthew, M. (2003). Static water level mapping in East Central Michigan. *Journal of the American Water Resources Management Association (JAWRA)* 39(1): 99–111.

Ridder, N.A. (1994). Groundwater Investigations. In: *Drainage Principles and Application*. *(Edited by Ritzema H. P., 2nd Edition completely revised*), International Institute of Land Reclamation and Improvement ILRI Wageningen, The Netherlands. pp 33-75.

Salum, L.M. (2009). Ecotourism and biodiversity Conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47: 166-170.

SaMeh (2014). A precise methodology integrates low-cost GPS data and GIS for monitoring groundwater quality parameters in Majmaah region, KSA. *Intern. Journal of Environmental Monitoring and Analysis* 2(5): 279-288.

Schaeffer, J.M. (2012). *Working with ArcGIS for Environmental Analysis: Core GIS skills and analysis*. Juniper GIS services Inc. Tanzania. 248 pp.

Sophocleous, M. (2002). Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal* 10(1): 52-67.

Staats, W.A. (2015). Use of LIDAR–Derived terrain and vegetation information in a deciduous forest in Kentucky. Dissertations for Award of MSc Degree at University of Kentucky UK. 98pp.

The Columbia Electronic Encyclopedia® (2013). Water table. [**Error! Hyperlink reference not valid.**] site visited on 31/08/2015.

Welch, R. and Homsey, A. (1997). Datum shifts for UTM coordinates. *Photogrammetric Engineering and Remote Sensing* 63(4): 371-375.

Wulder, M.A., Bater, C.W., Coops, N.C., Hilker, T. and White, J.C. (2008). The role of LiDAR in sustainable forest management. *The Forestry Chronicle* 84(6): 807-826.

Zanzibar Revolutionary Government (2013a). Zanzibar *Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report*. *Using Zanzibar Woody Biomass Survey in Policy and Planning Processes, Working Paper.* Indofood and Norwegian Embassy, Zanzibar. 24pp.

Zanzibar Revolutionary Government (2013b). Zanzibar *Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report*. Indofood and Norwegian Embassy, Zanzibar. 139pp.

Zanzibar Sustainable Management of Land and Environment II (SMOLE II) (2013). Zanzibar National Forest Policy Analysis. Zanzibar. 25pp.

Zhu, J.T., Yu, J., Wang, P., Yu, Q. and Eamus, D. (2014). Variability in groundwater depth and composition and their impacts on vegetation succession in the lower Heihe River Basin, north-western China. *Marine and Freshwater Research CSIRO Publishing* 65: 206-217.

CHAPTER THREE

3.0 CHARACTERIZATION OF SOIL DEPTH TO CORAL BEDROCK AND BEDROCK ROUGHNESS IN JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

ABSTRACT

Soils formed on coral terrain have a wide range of depths to coral bedrock and percentage of coral outcrops. Cliffs and other features of seawater abrasion, limited root zone, habitation and distribution of specific plant species are among the common characteristics of Zanzibar coral landscapes. The current study was intended to characterize the relationship between soil depth to coral bedrock (SDCB) and bedrock roughness (BR) and determine features which are related to seawater abrasion at Jozani Groundwater Forest (JGWF). Such conditions and features have varying spatial distribution and magnitude which are likely to affect plant growth and species distribution in JGWF. The study area was divided into 320 grid points that were used as probing points for determining SDCB and BR. Global positioning system (GPS) model GARMIN *e*trex 10 was used to locate pre-selected grid points, while a long graduated stick was used to measure depths from soil surface to coral bedrock at each point. SDCB was calculated as an arithmetic mean of measured depths and BR as standard deviation of measured depths. ArcGIS 10.1 was used to map SDCB and BR of JGWF. Kichangani in Tumbatu Islet was visited to gather information related to abrasion that took place on coastal coral bedrock. Minimum values of SDCB and BR obtained from JGWF grassland were used to rank and categorize SDCB and BR in JGWF. Results from probes on the 302 grid points showed that JGWF has range of

SDCB of about 0.35 to > 1.4 m, and BR of 0.1 to ≥ 0.4 m. Trends of SDCB and BR values in JGWF were complex, decreasing towards the cliff on the West and towards North-end, but increased in the opposite direction. This study concludes that that there are complex relationships between SDCB and BR on coral land. However, the relationships can be captured, ranked, and mapped. The relationships affect plant growth and species distribution as they have direct effects to plant rooting system, feeding area and stability. This study concludes futher, that flat platform which was found at Kichangani and grassland of JGWF is an evidence of seawater abrasion on coral bedrocks.

Key words: Bedrock roughness, seawater abrasion, soil depth to coral bedrock, spatial distribution of plant species, Zanzibar

3.1 Introduction

About 50% of Zanzibar territory is occupied by coral terrain (Hettige, 1990; Zanzibar Sustainable Management of Land and Environment II (SMOLE II), 2013). Jozani Groundwater Forest (JGWF) which is within Jozani-Chwaka Bay National Park (JCBNP) is one of the coral forests possibly generate less than 2 million years ago (SMOLE II, 2013; Nahonyo *et al*., 2002). The terrain of JGWF was exposed from seawater during gradual fall of sea level and the rise of corals (Klein, 2009). According to Agulhas and Somali Current Large Marine Ecosystem (ASCLIME), (2012), some parts of Tumbatu islet of Zanzibar Island is a raised Pleistocene reef platform similar to that of JGWF. Thus, the conditions in the JGWF are similar to those in some parts of Tumbatu Islet. Coral terrains of Zanzibar are characterized by a wide range of coral outcrops and soil patches in between, and most of the soils which were developed on such terrain are usually shallow amd polymorphic (Hettige, 1990) (Plates 3.1 and 2).

Plate 3.1: Rocky coral terrain at Unguja Ukuu, Zanzibar

Plate 3.2: Coral terrain covered with polymorphic coral soil at Unguja Ukuu, Zanzibar

For decades, scholars including Hettige (1990), Käyhkö *et al*. (2011), Nowak and Lee (2011), Mchenga and Ali (2014) used the term "coral rag" to express the irregularities of the terrain. Basically, the term “coral rag” meant that the coral terrains of Zanzibar are irregular rocky (coral) surfaces, with uneven soil depths and irregular coral protrusions from unaligned bedrock and the terrains cannot be properly characterized morphologically.

Soil depth and condition of the parent materials are among morphological characteristics which are used to describe soil formation, development, and classification (Retallack, 2008; Jones *et al*., 2013). These characteristics are among physical properties that affect plant rooting zone, plant growth and distribution (Gregory, 2008; Buol *et al*., 2011; Munishi *et al*., 2011). Therefore, from these conditions it was assumed that in JGWF, plant species distribution and stability of plants of similar species depend on the depth of the coral bedrock and conditions of coral protrusions from the bedrock. Tropical forests on coral terrains of Zanzibar (Hettige, 1990) are usually consist of plant communities of dry bushland thickets (Kukkonen and Käyhkö, 2014) that constitute biomass of about 10 tonnes ha^{-1} (Zanzibar Revolutionary Government (ZRG), 2013). Although JGWF is among the coral terrains and/or surrounded by coral terrains, it has a wide diversity of plant species and biomass exceeding 50 ton ha^{-1} (Nahonyo *et al*., 2002; ZRG, 2013). Presence and stability of forest tree species are influenced by biotic and abiotic factors (Blaser and Gregersen, 2013). Vigorous growth of plant species (Plate 3.3) and natural tree falls of the same species (Plate 3.4) are occurring in JGWF, something that has never been reported in other coral terrains. The assumptions for this anomaly include: (1) plant species growth trend and spatial distribution are likely associated with conditions of coral outcrops, soil depth, and coral protrusions from the base of the coral bedrock, and (2) the conditions resulted from specific geological and biological processes (habitation of plant species) that happened before the emergence and during the early stages of JGWF development.

Plate 3.3

Plate 3.4

Plate 3.3: ***Calophyllum inophyllum*** **(Red mahogany) big (woody) tree aged above 100 years in Jozani Groundwater Forest**

Plate 3.4: **Wide base with radius of about 1.6 m of** ***Calophyllum inophyllum*** **(Red mahogany) plant which naturally fell before age of 50 years at Jozani Groundwater Forest**

This study was therefore intended to characterize the soil depth to coral bedrock and roughness of the coral bedrock that influence plant roots' zoning and species distribution and to some extent, give a clue on geological processes that occurred on the coral bedrock of JGWF.

3.2 Materials and Methods

3.2.1 Description of the study area

The study was conducted in Jozani Groundwater Forest (JGWF) area which is located between Chwaka and Uzi bays (Fig. 3.1). The study area occupies the central part enclosed by coral forests and bushland within Jozani-Chwaka National Park (JCBNP) (SMOLE II, 2013). The forest is found on the lowest part of Zanzibar Island that mainly comprises of Quaternary geologic formations predominantly limestone (Nahonyo *et al*., 2002; Klein, 2009). According to Klein (2009), Leonila (2011), JGWF is on a stream-like terrain running between Chwaka and Uzi bays. The forest has shallow water table which often emerges above the surface forming temporary marshes (Salum, 2009). Tumbatu Islet of Zanzibar Island is located about two kilometres off the Mkokotoni area (Liang, 2014). Tumbatu-Kichangani has E524 550 and N 9 354 860 coordinates in UTM Zone 37S.

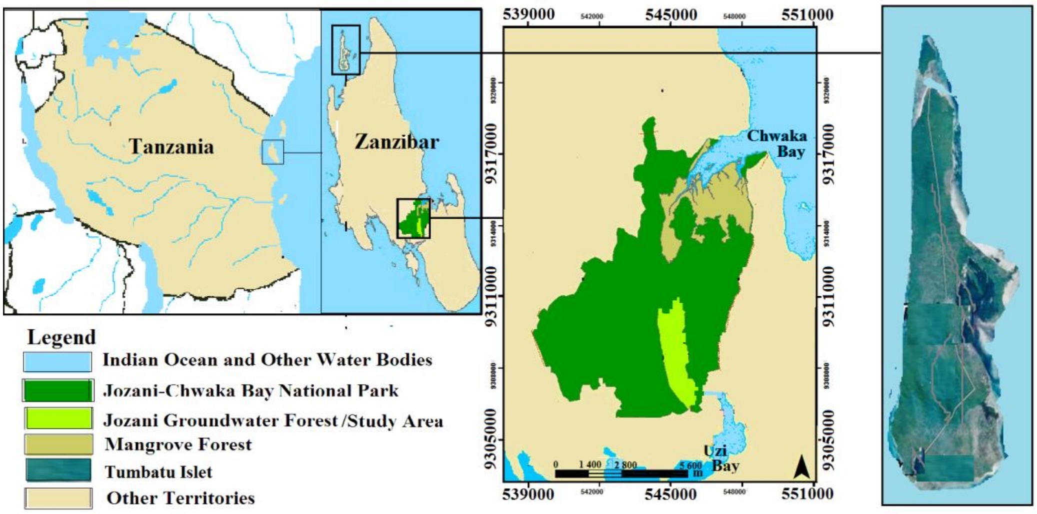


Figure 3.1: Location map of Jozani Groundwater Forest and Tumbatu Islet. Source: Department of Forest Non-renewable Natural Resources, Zanzibar

3.2.2 Probing for characterization of soil depth to coral bedrock

Spatial patterns and geo-statistical studies use transect and/or grid system/designs for geographical data collection (Irvine *et al*., 2013; Zhu *et al*., 2014). The study area was divided into 32 northern and 10 eastern gridlines making a system of 320 grid points. Global Positioning System (GPS) GARMIN ***e***trex 10 was used to direct the study teams to the grid points for probing. The probe teams measured the depths from the soil surface to the coral bedrock. On the grid points along the northern grid lines, five long stick probes were done at an interval of one metre between the probes. The collected data were recorded in a field book with their respective grid points.

3.2.3 Estimating the mean depth to the bedrock and protrudes from the bedrock

The data from five deep stick probes at a grid point were used to estimate the soil depth to coral bedrock (SDCB) and the mean height of protrusion from the bedrock (bedrock rough-ness (BR)). From the data, SDCB and BR were computed as an arithmetic mean and standard deviation of measured depths by Formulae (1) and (2), respectively.

$$\text{SDCB} = \overline{X} = \frac{1}{n}\sum_{i=1}^{n} Xi \ldots\ldots\ldots\ldots 1$$

$$\text{BR} = \text{SD} = \sqrt{v} \ \text{ where } v = \frac{1}{n}\sum X_i^2 - \left(\overline{X}\right)^2 \ldots\ldots\ldots\ldots 2$$

Where, Xi; is measured depths (m) from the soils surface to the bedrock, n; is number of probes.

3.2.4 Soil depth to coral bedrock and bedrock roughness

Minimum values of SDCB and BR in the study area were used as the units for SDCB and BR ranking. The SDCB and BR values were ranked in two sets of five ranks with corresponding attributes for SDCB as: too shallow (1), shallow (2), moderately deep (3), deep (4), and very deep (5); while BR attributes were: smooth (1), a bit smooth (2), moderately rough (3), rough (4), very rough (5).

3.2.5 Study visit to Tumbatu Islet for seawater abrasion on coral bedrock

During reconnaissance in the study area, the effects of seawater abrasion were clearly observed on the Western border and the Northern end of JGWF. The main indicators of seawater abrasion were the presence of a cliff on the Western border and a flat platform and the remaining protruded coral rocks on the North-end. Therefore, a visit to Tumbatu Islet was made to capture detailed information on the effect of seawater abrasion from which the condition that occurred on the JGWF could be properly inferred and described.

3.2.6 Data analysis

Excel software was used to compute mean soil depth to bedrock (SDCB) as an arithmetic mean of measured depths. Standard deviations of measured depths were used to estimate the length of protrusions from the base of the coral bedrock (bedrock roughness (BR)). Descriptive analysis was used to characterize the general existence and trends of percentage of counts of soil depth to bedrock (SDCB) and roughness of the bedrock (BR) of Jozani Groundwater Forest (JGWF). Arc-GIS 10.1 was used to map SDCB and BR of JGWF. The analysis was also used to relate SDCB and BR characteristics and condition of JGWF trough.

3.3 Results and Discussions

3.3.1 Results

A total of 302 (94%) grid points were probed, soil depth to coral bedrock (SDCB) and bedrock roughness (BR) were captured. The rest 18 (6%) grid points were not accessible and hence omitted. Lowest values for SDCB (0.35 m) and BR (0.1 m) were recorded from the grassland which occupied the space between North-end of JGWF and Mangrove forest at Chwaka bay. These values represented the shallowest depth and the least roughness. Hence, 0.35 m (SDCB) and 0.1 m (BR) were used as the unit values for ranking SDCB and BR (Table 3.1) in Jozani Groundwater Forest (JGWF). Table 3.2 shows the data collected from probing along northern gridline 9 309 800 as an example of data obtained during the probing. The data were then computed to obtain ranks of SDCB and BR. Table 3.3 shows the assessment of SDCB and BR ranks in JGWF. Fig. 3.2 shows the rationale of soil SDCB and BR in JGWF, and Fig. 3.3 shows the variation of SDCB and BR of JGWF.

Table 3.1: Ranks of depth to coral bedrock (SDCB) and bedrock roughness (BR) in Jozani Groundwater Forest

	Ranks				
	1	**2**	**3**	**4**	**5**
SDCB, m	0.0 - 0.35	0.35 - 0.7	0.70 - 1.05	1.05 - 1.4	>1.4
SDCB, rank	Very shallow	Shallow	Moderately deep	Deep	Very deep
BR, m	0.0 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	>0.4
BR rank	Smooth	A bit smooth	Moderately rough	Rough	Very rough

Table 3.2: Coral out-cropping, soil depth to coral bedrock and bedrock roughness along Northern 9 309 800 in Jozani Groundwater Forest

Eastern coordinates	Out-crops	Measured depths from soil surface to coral bedrock, m					Ranking	
		Probes	**Min**	**Max**	**SDCB**	**RB**	**SDCB**	**BR**
544 400	10	0.86, 1.48, 1.04, 0.98, 1.60	0.86	1.60	1.19	0.23	4	3
544 600	0	1.26, 1.35, 1.50, 1.22, 1.63	1.22	1.63	1.39	0.15	4	2
544 800	0	1.40, 1.00, 1.60, 1.23, 1.42	1.00	1.60	1.33	0.20	4	2
545 000	0	1.85, 2.38, 2.02, 1.95, 2.30	1.85	2.38	2.10	0.20	5	2
545 200	0	2.40, 2.02, 1.98, 2.54, 2.42	1.98	2.54	2.27	0.23	5	3
545 400	0	1.92, 2.24, 1.76, 1.69, 2.33	1.69	2.33	1.99	0.26	5	3
545 600	0	1.53, 1.02, 1.73, 1.30, 1.36	1.02	1.53	1.39	0.24	4	3
545 800	0	1.22, 1.06, 0.98, 0.63, 1.02	0.63	1.22	0.98	0.19	3	3
546 000	20	0.44, 1.15, 1.42, 0.93, 1.32	0.44	1.32	1.05	0.35	3	4
546 200	> 20	1.34, 0.65, 0.92, 0.68, 1.42	0,65	1.42	1.00	0.32	3	4

SDCB = Soil depth to coral bedrock; BR = bedrock roughness

Table 3.3: Assessment of soil depth to coral bedrock (SDCB) and bedrock roughness (BR) in Jozani Groundwater Forest

	Number of Probes and Percentages of SDCB and BR											
SDCB/BR	**S**	**%**	**A bit S**	**%**	**Mode-rately R**	**%**	**R**	**%**	**Very R**	**%**	**T**	**%**
Too shallow	26	8.6	3	1.0	0	0	0	0	0	0	29	9.6
Shallow	8	2.6	8	2.6	5	1.7	0	0	0	0	21	7.0
Moderately deep	6	2.0	35	11.6	34	11.3	25	8.3	0	0	100	33.1
Deep	4	1.3	45	14.9	22	7.3	16	5.3	13	4.3	100	33.1
Too deep	0	0	23	7.6	20	6.6	4	1.3	5	1.6	52	17.1
Total	**44**	**14.5**	**114**	**37.7**	**81**	**26.9**	**45**	**14.9**	**18**	**5.9**	**302**	**100**

S = smooth, R = rough, T = total

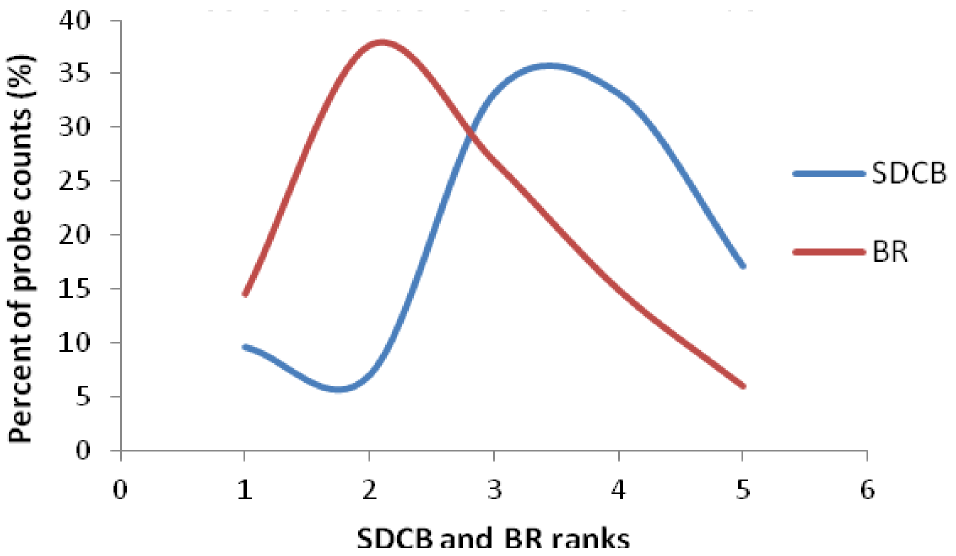


Figure 3.2: General existence and trends of percentages of counts of soil depth to coral bedrock (SDCB) and bedrock roughness (BR) of Jozani Groundwater Forest

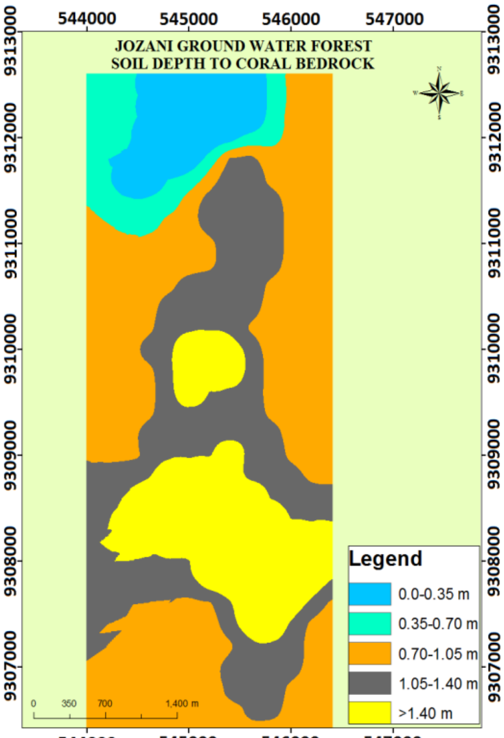


Figure 3.3a.

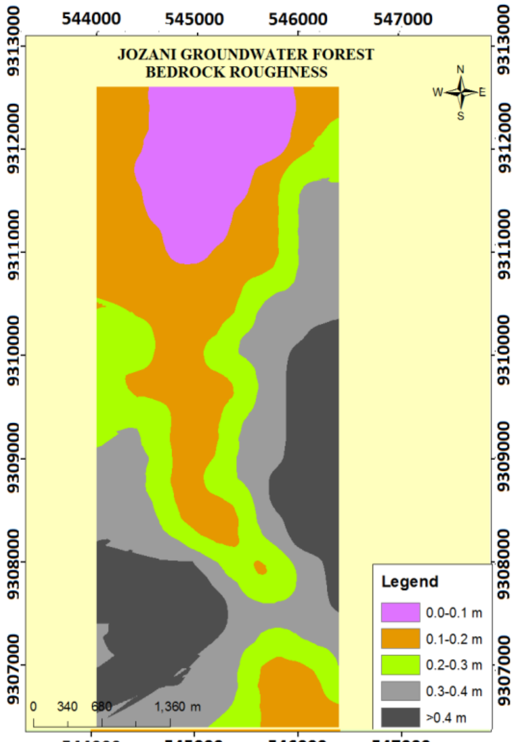


Figure 3.3b.

Figure 3.3: a) Variation of soil depth to coral bedrock (SDCB) and b) bedrock roughness (BR) of Jozani Groundwater Forest

3.3.2 Discussion

3.3.2.1 Rationale and geographic distribution of soil depth to coral bedrock and bedrock roughness in Jozani Groundwater Forest

Fig. 3.2 shows that JGWF terrain has complex trend of SDCB and BR. The terrain mainly consists of moderately deep to deep SDCB and smooth to moderately rough BR. Figures 3.3a and b show that the North-end of JGWF is dominated with shallow and smooth SDCB and BR ranks, respectively. Such spatial distribution of the ranks implies that the area favors grasses and small plant species only. The rest of the areas with complex distribution of a mixture of SDCB and BR towards the South-end and East of JGWF favour more plant species including bigger plants. The protrusions that were above the soil surface (outcrops) were found mainly in the Eastern borderline of JGWF and the outcropping increased as the area approached the coral forest East of

JGWF. However, this study did not relate values and ranks of SDCB and BR to coral out-cropping. Shallow soil depths were also found in areas where the outcrops exceeded 20%. Patches which were too deep were not recorded during the probing but were observed in some areas close to the Southern end of JGWF. Shallow depth to coral bedrock (SDCB) and smooth (BR) were also found as patches in several points especially where bigger plants fell down before reaching maturity/old age. This condition implies that such combination of SDCB and BR tended to destabilize bigger plants when they grow beyond the stable height or when the branches incline beyond stability zone. However, the extent of the incidents and conditions that led to the falling of trees needs further studies.

3.3.2.2 Seawater abrasion on protrusions off the coral bedrock

Marine terraces of Zanzibar consist of coral limestone and are indicative of marine and tectonic origin (ASCLIME, 2012). The conditions of SDCB and BR in JGWF were found to be related to seawater abrasion before the emergence of Jozani Groundwater Forest (JGWF). Information from the study site (JGWF) and the study visit to Tumbatu Islet revealed evidence of seawater on the protrusions of coral bedrock in JGWF. This study found that during the early stages of sea water level fall, and rise of coral terrain, the western part (before the cliff) of JGWF lay along the coastal line and was affected by seawater movements from the east, north (Chwaka), and south (Uzi). The coral bedrock had more protrusions of different sizes and the protrusions were subjected to strong sea water abrasion. Abrasion in JGWF terrain occurred in several stages, but the magnitude of abrasion declined with time. Such abrasion resulted in cliff formation which currently acts as west borderline running in North-South direction and separating the JGWF from the higher elevated coral terrain above it. As the fall of sea water level and the rise of coral land continued periodic abrasion processes led to the formation of Jozani trough with small irregular terraces on the east of JGWF (Fig. 3.4).

Figure 3.4: Sketch of coral bedrock of Jozani Groundwater Forest (JGWF) in North-South (bottom-up) direction. This sketch shows a trough-like terrain of JGWF in relation to digital elevation model (DEM) of JGWF

According to Storlazz *et al*. (2011), a sort of cliff adjacent to the sea shore platform limits the movement of sea water across the cliff. Similarly, seawater abrasion forces remained active and abraded the coral protrusions between the cliff on the West and terraces on the East.

3.3.2.3 Effects of abrasion on Jozani Groundwater Forest coral bedrock

According to Ershov *et al.* (1988), the rate and mode of abrasion are highly dependent upon the position of the rock and the forces that worked on it. In the case of JGWF terrain, the abrasion process led to the formation of various BR values which increased towards the South-East and decreased towards the North-West of JGWF. Terrain conditions as shown in Fig. 3.3a and 3.3b (Section 3.3.4) indicate that abrasion took place much longer and were stronger in JGWF areas with a minimum value of RB. Such abrasion on coral bedrocks results in the formation of flat coral platform (Ershov *et al.*, 1988; Latypov, 2006). As evidence of the effects of abrasion on JGWF coral bedrock, Plate 3.5 shows flat coral bedrock at Kichangani seashore in Tumbatu Islet. Plate 3.6 confirms that similar magnitude of abrasion took place at JGWF grassland.

Figure 3.5: Flat area with coral bedrock used as football play ground during low tides at Kichangani, Tumbatu Islet

Figure 3.6: Flatland covered by *Paspalum vaginatum* (Seashore couch) at North-end of Jozani Groundwater Forest. The whitish materials are the remains of almost flat corals being an evidence of coral bedrock underneath and sea water abrasion

3.3.2.4 Relation between soil depth, bedrock roughness and vegetation

From the above relations of SDCB, BR and the trend and magnitude of abrasion on coral bedrock, this study found that abrasion in JGWF area stopped when sea water run between terraces (on the east) and cliff (on the west) attained its minimum velocity. Meanwhile, pioneer plants which were dominated by *Paspalum vaginatum* (Seashore couch) (Buol *et al*., 2011; Lonard *et al*., 2015) by then were regenerating from seashore edges (Plate 3.7a). Furthermore, Plate 3.7b upholds the fact that JGWF areas with moderate and above ranges of RB are exposed to either less force or shorter periods of abrasion.

Plate 3.7a

Plate 3.7b

Figure 3.7: a) Grassland at North-end of Jozani Groundwater Forest (JGWF) covered by *Paspalum vaginatum* (Seashore couch) and few erected coral remains (stand still as coral outcrops) beside strong abrasion on the surrounding area, b) Gradual increase of coral outcropping with gradual change of plant species towards inner parts (the South) of JGWF

Plant inhabitation (after land rise) was accelerating from the South-Eastern area of JGWF towards the North-West. The accumulation of plant residues filled pot-like spaces between several partially abraded protrusions that rose from the coral bedrocks. Thereafter, other plant species including salt tolerant and non-salt tolerant higher plants were growing, following a similar trend of pioneer species. The conditions on one hand have a direct relation on soil depth that affects root growth, plant stability and species distribution; and on the other hand contributing to the elevation trend of JGWF.

3.4 Conclusions and Recommendations

This study found that Jozani Groundwater Forest (JGWF) has a coral terrain with various soil depths to the coral bedrock and bedrock roughness. On the north (flat grassland platform) JGWF has a shallow soil depth to coral bedrock (SDCB) of about 0 -0.35 m and minimum bedrock roughness (BR) of about 0.1 m. The SDCB and BR increases respectively to about 1.4 and 0.4 m as the area the the terrain approaches the south-east. As there were no abrupt falls in sea water level and/or rise of corals, for a long time seawater movement was thus limited towards the West and the East, but moved freely between the North and the South (Chwaka and Uzi) bays. A continued seawater abrasion led to the formation of Jozani trough between the East and the West cliffs. When seawater velocity on the trough was at its minimum, this condition was conducive for pioneer plant species habitation, from which organic sediments were the basic soil components. The process led to soil formation with various ranges of SDCB and BR values. Thus, this study concludes that the condition of SDCB and BR affects root growth, stability of bigger plants and plant species distribution in the JGWF. Furthermore, the study concludes that the flatlands which were found at Kichangani in Tumbatu Islet and that on the grassland are the evidence of the prevalence of severe seawater abrasion on coral bedrocks in the sites. This study concludes further, that the values of soil depth to bedrock (SDCB) and bedrock roughness (RB) are always differ locationaly. This study recommends characterization and utilization of SDCB and BR for detail soil volume calculations, characterization of plant root zone conditions and describing the productive capacity of coral lands. This study recommends further on utilization of the SDCB and BR values as good indicators and/or inputs for planning and implementing agronomic, engineering and environmental projects and related works or studies.

3.5 References

ASCLIME (2012). National vMarine Ecosystem Diagnosis Analysis. Contribution to the Agulhas and Somali Current Large Marine Ecosystem Project (supported by UNDP with GEF grant financing) Unpublished report. 121pp.

Blaser, J. and Gregersen, H. (2013). Forest Come and Go, in 300 Years of Sustainable Forest, FAO. *Unasylva* 64(1): 61 – 73.

Buol, S.W., Southard, R.J., Graham, R.C. and McDaniel, P.A. (Eds.) (2011). *Soil Genesis and Classification*. 6th Edition. John Wiley and Sons. 543pp.

Ershov, V.V., Novikov, A.A. and Popova, G.B. (1988). *Fundamentals of Geology*. Mir Publishers, Moscow. 358pp.

Gregory, P.J. (2008). *Plant Roots: Growth, Activity and Interactions with the Soil*. John Wiley and Sons. 329pp.

Hettige, M.L. (1990). Land evaluation and land sustainability classification. Unguja and Pemba Islands. *Food and Agriculture Organization of the United Nations*. FAO TCP/URT/6759 (A), Zanzibar. 156pp.

Irvine, K.M., Thornton, J., Backus, V.M., Hohmann, M.G., Lehnhoff, E.A., Maxwell, B.D., Michels, K. and Rew, L.J. (2013). A comparison of adaptive sampling designs and binary spatial models: a simulation s tudy using a census of

Bromus Inermis. *Environmetrics* 24(6): 407-417.

Jones, A., Breuming-Madsen, H., Brossard, M., Drampha, A., Deckers, J., Dewitle, O., Gallali, T., Hallert, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Yemefack, M. and Zougmore, R. (Eds.) (2013). *Soil Atlas of Africa*. Europian Commission Publication office of the European Uniun, Luxembourg. 176pp.

Käyhkö, N., Nora, F., Bakari, S.A. and Abbas, J.M. (2011). Dynamic land use and land cover changes and their effect on forest resources in a coastal village of Matemwe, Zanzibar, Tanzania. *Land Use Policy* 28(1): 26-37.

Klein, R. (2008). *An* E*daphic landscape of Unguja Island, Zanzibar*. *Exploratory Study on the Relation between Soil Variability and Landscape*. Turku University Department of Geography Publications B. 11. 85pp.

Kukkonen, M. (2013). Forest cover and its change in Unguja Island, Zanzibar. Dissertation for Award MSc Degree at University of Turku Faculty of Mathematics and Natural Sciences Department of Geography and Geology. 174pp.

Kukkonen, M. and Käyhkö, N. (2014). Spatio-temporal analysis of forest changes in contrasting land use regimes of Zanzibar, Tanzania. *Applied Geography* 55: 193-202.

Latypov, Y.Y. (2006). Changes in the Composition and Structure of Coral Communities of Mju and Moon Islands, Nha Trang Bay, South China Sea. *Russian Journal of Marine Biology, Pleiades Publishing* 32(5): 269–275.

Leonila, Z. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award MSc Degree at University of Twente Netherland. 46pp.

Liang, J. (2014). Feasibility of a Mangrove-Based Carbon Business in Makoba Bay, Unguja, Zanzibar. Independent Study Project (ISP) Collection. Paper 1917. [http://digitalcollections.sit.edu/isp_collection/1917] site visited on 21/04/2015.

Lonard, R.I., Judd, F.W. and Stalter, R. (2015). Biological flora of coastal dunes and wetlands: Paspalum vaginatum Sw. *Journal of Coastal Research (JCR)* 31(1): 213–223.

Masoud, S.S., Msanya, B.M., Semoka, J.M.R. and Maliondo, S.M.S. (2016). Use of water table as a benchmark for levelling groundwater forest: The case of Jozani Groundwater Forest, Zanzibar, Tanzania. *International Journal of Scientific and Technical Research in Engineering (IJSTRE)* 1(5): 49-57.

Mchenga, I.S. and Ali, A.I. (2014). Natural regeneration of mangroves in a degraded and non-degraded tropical forest of Zanzibar Island. *Journal of Global Biosciences ISSN* 3(1): 334-344.

Munishi, P. K., Temu, P.R.A. and Soka, G. (2011). Plant communities and tree species associations in a Miombo ecosystem in the Lake Rukwa basin, Southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* 3(2): 63-71.

Nahonyo, C.L., Mwasumbi, L.B., Eliapenda, S., Msuya, C., Mwansasu, C., Suya, T.M., Mponda, B.O. and Kihaule, P. (2002). *Jozani – Chwaka Bay proposed National Park Biodiversity inventory report*, CARE Tanzania and department of Commecial Crops, Fruits and Forestry, Zanzibar. 184pp.

Nowak, K. and Lee, P.C. (2011). Demographic structure of Zanzibar red colobus populations in unprotected coral rag and mangrove forests. *International Journal of Primatology* 32(1): 24-45.

Retallack, G.J. (2008). *Soils of the Past: An Introduction to Paleopedology*. John Wiley and Sons. 403pp.

Salum, L.M. (2009). Ecotourism and biodiversity Conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47: 166-170.

Storlazzi, C.D. Elias, E., Field M.E. and Presto, M.K. (2011). Numerical modeling of the impact of sea-level rise on fringing coral reef hydrodynamics and sediment transport. Coral Reefs. *Springerlink.com* 30: 83–96.

Sustainable Management of Land and Environment II (2010). The Zanzibar National Forest Policy Analysis (2010 - 2013). Final Report. 88pp.

Zanzibar Revolutionary Government (2013). Zanzibar Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report. Indufor and Norwegian Embassy, Zanzibar, Tanzania. 139pp.

Zhu, J.T., Yu, J. Wang, P., Yu, Q. and Derek, E. (2013). Variability in groundwater depth and composition and their impacts on vegetation in Heihe River Basin, China. *Marine and Freshwater Research CSIRO* 65: 206-217.

CHAPTER FOUR

4.0 TIDAL TRENDS AND MAGNITUDE OF CHWAKA AND UZI BAYS AS A PROXY OF SEAWATER INTRUSION IN JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

ABSTRACT

Tidal characteristics, altitude, level of groundwater, and rainfall patterns are among the main factors determining seawater intrusions in coastal areas. As Jozani Groundwater Forest (JGWF) is a coastal forest of low altitude found between Chwaka and Uzi bays, it was assumed the forest is increasingly being intruded by seawater. This study was therefore intended to discern status of tidal trends and magnitude in relation to seawater intrusion into JGWF. Tidal data and rainfall patterns were collected from Tanzania Meteorological Agency, Kisauni Zanzibar. Two sets of three observation wells (OWs) were opened at two forest ends towards Chwaka and Uzi bays. The OWs were used as data collection points while Height of Instrument method with the help of SOKKIA C.3.2 level and benchmarks number 205 and 210 were used to determine elevation of ground surfaces of the OWs. GPS receiver model GARMIN etrex 10 was used for geo-referencing the OWs. Water level recorders were installed above the wells to record changes in water level (WL) around the wells. Total dissolved solids (TDS) in water samples from the OWs were measured in situ using Hanna Combo tester HI 98129. Results showed that WL in South-end OWs rises to 1.586 m AMSL during rains and falls to 0.820 m AMSL during dry seasons, and occasionally also rises during high water of spring tide (HWST) associated with South Easterly monsoon winds. Similar results were obtained at North-end OWs, but more frequently even during HWST that were not associated with Monsoon winds.

Levels of water TDS fell to a minimum of 0.7 x 103 and 4.9 x 103 mg L^{-1} during rainfall and rose to a maximum of 25.5 x 103 and 34.1 x 103 mg L^{-1} during dry season at South-end and North-end, respectively. It was concluded that intrusion takes place during dry seasons when seawater of HWST from Chwaka and Uzi bays through creeks reached the soil surfaces at North-end and South-end of JGWF. The water accumulated salts which were then diluted and drained off the areas by rain water.

Key words: Seawater tide, surface level, water Level, total dissolved solids, intrusion, draining

4.1 Introduction

On coastal lands and aquifers, seawater intrusion is a natural phenomenon (Werner and Simmons, 2009; Kuan *et al*., 2012). Climate change is also considered responsible for hastening intrusions and there is a likely increase in sea level, and intrusion in low-lying coastal areas of Tanzania (Vice President's Office (VPO), 2012; Werner *et al*., 2013). Jozani Groundwater Forest (JGWF) which is an important habitat biodiversity hot spot and is one of the intact stretches of coastal forests of Eastern Africa (Nowak and Phyllis, 2011; Zanzibar Revolutionary Government (ZRG), 2013), is located on the lowest part of Zanzibar between Chwaka and Uzi bays (Klein, 2008; Leonola, 2011). Given its low elevation, it was assumed that JGWF is being intruded by seawater and there is a high possibility that such intrusion will increase further in the near future due to increased climate variability.

Tanzania coasts have semi-diurnal seawater tides with about 4.0 m as a Maximum Tidal Range (MTR) between the Lower and Higher Water of Spring Tides (LWST and HWST) (Nhnyete and Mahongo, 2007). Chwaka bay has Neap Tidal Range

(NTR) and Spring Tidal Range (STR) of about 0.9 and 3.6 m respectively (Agulhas and Somali Current Large Marine Ecosystems (ASCLME), 2012). Therefore, based on tidal figures by Robinson *et al.* (2007), at Chwaka bay and likewise at Uzi bay, the level of seawater above mean sea level (AMSL) is about 0.45 m for Neap Tides (NT) and 1.8 m for Spring Tides (ST). In Tanzania, waves of seawater are normally higher during South-East (SE) (Kusi) Monsoon winds and less during North-East (NE) (Kaskazi) Monsoon winds (Nhnyete and Mahongo, 2007; ASCLME, 2012). SE winds blow between May and October while NE winds blow between November and March (Semesi, 2013). When high water of spring tides (HWST) coincides with strong winds of Kusi (SE) or Kaskazi (NE), seawater extends its level of reach to a bit higher elevated soil surfaces adjacent to the coast (ASCLME, 2012). Thus, in addition to the earlier assumption that JGWF is intruded by seawater, the notion that followed after was that such intrusion is influenced by tidal trends and magnitude associated with Monsoon winds.

Distances from the tidal coast, level of freshwater aquifer and land altitude are the determinants of sea-freshwater interface and intrusion following Ghyben-Hezberg's principle (Van Camp *et al.,* 2014). Intrusion is at minimum when the level of the aquifer is above the level of HWST, but it increases with the lowering of the aquifer level (Guo and Jiao, 2007). Together, position, ground level and water level in JGWF were thought as the factors influencing the said intrusion. The JGWF has shallow freshwater aquifer which is recharged with about 1400 -1600 mm rainfall of *Masika* (long rains within March to May) and *Vuli* (short rains within October to December) seasons (ZRG, 2013; Leonila, 2011). In JGWF, temporary floods were observed during heavy rains within *Masika* or *Vuli* seasons (Salum, 2009). Hence, there was a perception that rainwater and rain patterns play a role on freshwater aquifer level, salt water dilution and draining. From the above mentioned assumptions and perceptions of the researchers, this study was therefore, intended to determine influence of tidal trends and magnitudes assumed to affect and be the proxy of seawater intrusions into JGWF.

4.2 Materials and Methods

4.2.1 Description of the study area

Study sites were the North-end and South-end of JGWF. The forest is located about 35 km from Stone Town, off the road to Makunduchi within the Jozani-Chwaka Bay National Park (JCBNP) area. The area lies within UTM Zone 37S encomprised by coordinates of 9 305 880 to 9 317 855N and 539 100 to 549 000E (Fig. 4.1). Fig. 4.1 shows a narrow prolonged bent seawater creek from Uzi bay towards the South-end of JGWF and a wide base and slanted end seawater creek from Chwaka bay towards the North-end of JGWF. Sea water from the bays through these creeks occasionally reaches soil surface on the North and South ends. In both ends, *Paspalum vaginatum* (Seashore couch) is one of the dominant plant species occupying the space area between JGWF and mangroves before Chwaka (at the North-end) and Uzi (at the South-end) bays. The mangroves have plant density of about 7 700 stands/ha and canopy cover of about 80 to 87% (Semesi, 2013). At the North-end JGWF makes sort of a diffuse boundery consisting of *Paspalum vaginatum* (Seashore couch), *Acrostichum aureum* (Mangrove fern), *Cyperus rotundus* (Nut grass) and *Nephrolepis biserrata* (Giant swordfern). After this border, a pure stand of *Paspalum vaginatum* occupies and covers soil surface of about 95 ha before the mangroves towards Chwaka bay. At the South-end, JGWF has an irregular border consisting of *Brexia madagascariensis* (Mfukufuku), *Psidium guajava* (Guajava), *Bridelia micrantha* (Coastal golden-leaf), *Phoenix rectinata* (Wild date palm), *Syzygium cumini* (Jambolan), *Cocos nucifera* (coconut tree) before *Paspalum vaginatum* stands. The *Paspalum vaginatum* stands are mixed with *Acrostichum aureum* (Mangrove fern), *Cyperus rotundus* (Nut grass) and *Nephrolepis biserrata* (Giant sworfern) forming small scattered groups and patches before mangroves towards Uzi bay.

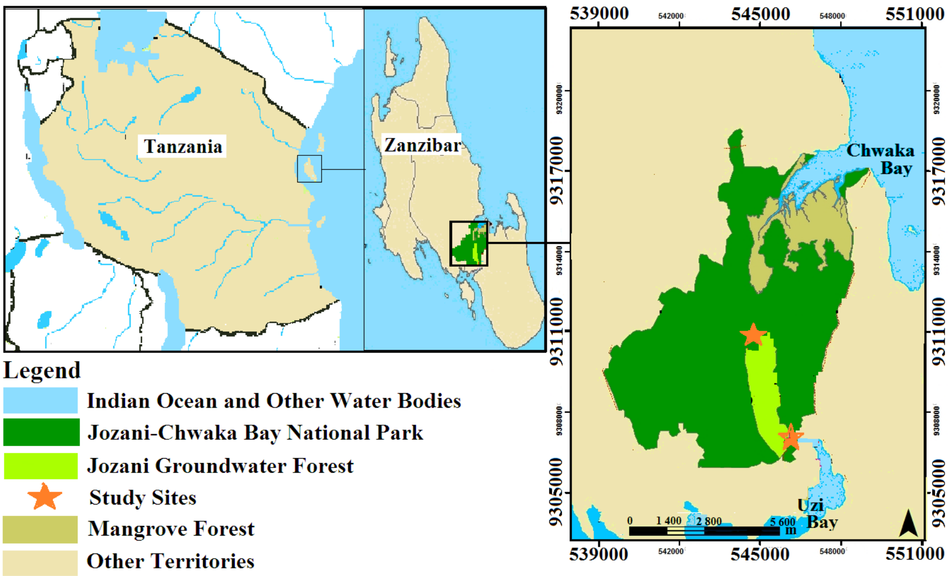


Figure 4.1: Location map of Jozani Groundwater Forest. Source: Department of Forest and Non-renewable Natural Resources, Zanzibar

4.2.2 Installation of observation wells

Observation wells (OWs) were used as the points to collect data on water level changes (WLCs) and total dissolved solids (TDS) as suggested by Humphrey *et al*. (2012); Majolagbe *et al*. (2014). Since, WL and TDS change spatially and temporally (Van Camp *et al*., 2014), positions, depths, number of OWs and observation periods were used to obtain spatially and temporally distributed data. Installation of OWs was done on the North-end and South-end of JGWF based on Emmanuel and Chukwu (2010) who suggested that for salinity studies in stream like areas, the opposite end points are useful for data collection. The positions of OWs were decided upon, based on the presence of

Paspalum vaginatum (Seashore couch) in the JGWF ends. The species was used as a surface indicator of the point of reach by seawater from the bays. *Paspalum vaginatum* is capable of growing on soil surface or water bodies with a minimum water velocity with TDS values above 22 x 10^3 mg L^{-1} (Shahba *et al*., 2012). Therefore, on both ends of the forest, study sites were the areas on which *Paspalum vaginatum* stands were found. The study involved three OWs on each of the study sites; named after the North-end and South-end and were respectively numbered from the bays inwards to JGWF as NOW 1, 2, and 3 and SOW 1, 2 and 3. At the study sites, OW2 (the middle) was at about 5 m towards the inner parts of the forest from the beginning of the *Paspalum vaginatum* stands (the border). Global Positioning System (GPS) receiver model GARMIN etrex 10 was used for geo-referencing the position of OW2 and from OW2 the receiver was used to point out the positions where OW1 and OW3 were to be located on a straight line at about 400 m from OW2. The spacing was adopted from Philippa *et al*. (2003). Hand auger was used to open to depth estimated on the basis of Equation (1).

$$DOW = RL + \frac{1}{2}STR \qquad (1)$$

Where; DOW; is the depth of observation well, RL; is reduced level of the ground surface at the observation well and STR; is spring tidal range.

4.2.3 Determination of elevation of the observation wells

Reduced levels (RLs) of surface at OW were determined using Height of Instrument method (SaMeH, 2014), SOKKIA C.32 level and Zanzibar Department of Survey (DOS) benchmarks (BMs). From BM No. 205 (RL = 2.134) at the South-end the levelling progressed to the North-end and ended at BM no. 210 (RL = 5.621). Equations (2), (3) and (4) were used to determine RLs and arithmetic error (Brinker and Minnick, 2012).

HI = BS + RL …………………..……………………………………………………….. (2)

RL = HI – SR ……………………………………………………………………………(3)

Arithmetic Error = ∑Back - ∑Fore ………………………………………………….. (4)

Where HI is height of the instrument, BS; back sight, RL; reduced level, SR; stuff reading of back/fore sight, Σ Back is sum of all back sights, Σ Fore is sum of all fore sights.

4.2.4 Installation of water level recorder

Water level recorders (WLRs) were installed to capture the water level changes (WLC) which occurred in and/or on observation wells (OWs) (Plate 4.1).

Plate 4.1: Water level recorder at South-end observation well 3

The concept on the use of WLR was meant to establish, if there are links between WLCs at the bays, study sites and JGWF, since such links would be captured by WLR installed on top of each OW. The WLRs were set to record WLCs occurring in the OWs and about 0.5 m above ground surface of OWs (Fig. 4.2). Each WLR consisted of a perforated polyethylene tube, polyethylene Floating Rod (FR), a wooden Recording Bench (RB) and a galvanized tripod stand. The tube of about 3 m long and 0.125 m in diameter was installed down into OW with part of it (about 0.85 m) protruded above the ground surface. The tube was used as floating line for the FR, preventing it from damage or from being removed off the well during floods. The FR is made of an air tight, flat base, rounded plastic bottle of about 1500 ml, fixed on the lower end of a 3 m long rod of about 0.05 m diameter.

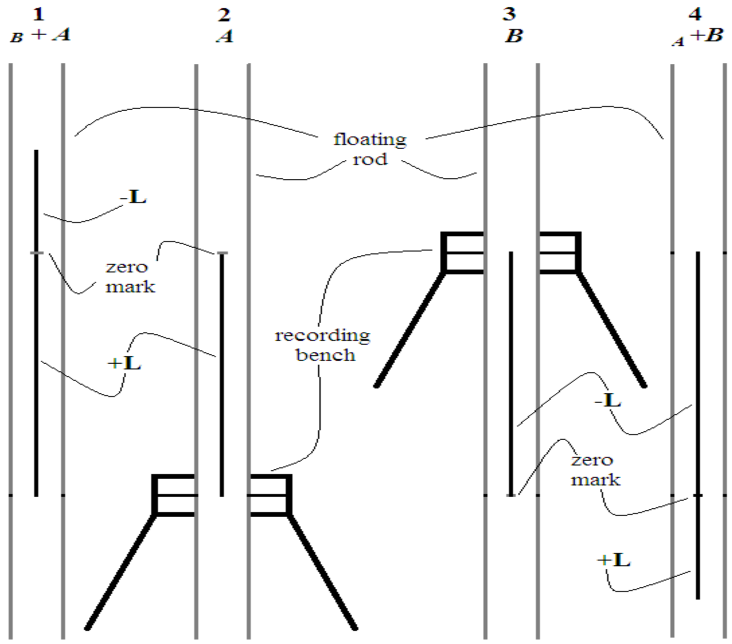


Figure 4.2: Four variants of records, 1; $_B$+A (Fall and Rise) when B (-L (Fall)) of variant 3 joined by A (+L (Rise)) of variant 2, 2; A (+L (Rise)), 3; B (-L(Fall)) and 4; $_A$ + B (Fall and Rise) when A (+L (Rise)) of variant (2) is joined by B (-L (Fall) of variant 3

The FR passed through a vertical hole made at the centre of the RB and was floating as the water level (WL) in and/or on the OWs' surface moved up and down. With the help of tripod stand, the RB was horizontally laid at about 1.0 m above ground surface. Through horizontal holes in the RB, a 2HB pencil and a ball pen were installed on opposite side to each other. As WL moved up and down, the pencil and pen were traced lines on a smooth-whitish mask tape wrapped on the FR.

4.2.5 Determination of a month reduced water level

After installation of WLR, the floating rod (FR) was manually rotated across the line markers to trace first horizontal *zero* line. Line markers were marking on FR vertical lines indicating *rise* and/or *fall* of WL which occurred in or on the OWs. At the time of data collection, the FR was again manually rotated half circle to mark the second horizontally laid *current* line which was used to determine length of water sampler. Then, the line markers were removed from the RB and the FR together with the tripod stand was uninstalled by lifting them up from the OW. From the *zero* line on the FR, depth from the center of the recording bench to the water level (DwRB) and the length of *rise* and/or *fall* lines were measured using a measuring tape with 0.001 m graduation.

Figure 4.2 shows that in relation to the *zero* line, a *rise* of WL was indicated by a vertical line fall into variant 2 (A), and a *fall* of WL was indicated by a vertical line fell into variants 3 (B). In the first case, *zero* line was a lower level and in second case it was an upper level. When WLR through a given time marked *rise* and *fall* lines, the WL was considered as *rise* if the *rise* line is longer than the *fall* line (variant 1 = *B* + A) and the opposite means *fall* (variant 4 = A + B). These data were recorded in a field book from which an initial water level (WL_{ZERO}), a reduced water level (RWL) and a month reduced water level (MRWL) above mean sea level (AMSL) were then respectively determined (Equations (5), (6) and (7)).

$WL_{ZERO} = (1 + RL_{OW}) - D_WRB_{ZERO}$ ……………………………………………...(5)

$RWL = WL_{ZERO} \pm ½(+L + -L)$ ……………………………………………………(6)

$MRWL = ½(RWL_1+RWL_2)$ ……………………………………………………...(7)

Where, WL_{ZERO} = initial water level, 1 = height from observation well (OW) surface to the recording bench (RB), RLOW = reduced level of ground surface at OW, DwRBzero = depth of WL from the RB measured from zero line, RWL= reduced water level, +L = rise, -L = fall, MRWL = month RWL, RWL1 and RWL2 = first and second RWL.

4.2.6 Determination of water total dissolved solids

Observation wells (OWs) gave an opportunity for spatial and temporal TDS tests which are primary data for sea water intrusion studies (Slama, 2010). The TDS test was done after the uninstallation of water level recorder (WLR). In this study water samples were collected at 0.01 m depth from the surface of WL using flat bottom borosilicate flask of about 100 ml attached to the wooden rod to form a kind of canister. Before sampling, the length of the sampler (LwS) from the tube top was determined by Equation (8).

LWS = (DWRBcurrent + WSD) – DtRB……………………………...…….……(8)

Where, LwS is length of water sampler, DwRB; depth water surface from recording bench measured from current line, WSD; water sampling depth and DtRB; distance from tube top to the recording bench.

The water samples were tested for TDS in situ using a portable Hanna Combo Tester HI 98129 as per Emmanuel and Chukwu (2010). Distilled water with TDS values of about 2 - 5 mg L^{-1} was used to dilute water samples reading higher values than the testers' readable range of about TDS 0 – 2000 mg L^{-1}. A Dragon Lab single top pipette (100 - 1000 µml) was used to transfer water sample into a volumetric flask of 200 ml. Then, the sample was diluted by adding distilled water to the 200 ml mark. The dilution was mixed well before being transferred to 500 ml beaker for reading. Equations (9) and (10) were used to compute monthly total dissolved solids.

TDS = (TDS Reading * df) – TDS dil……………………………………………(9)

MTDS = ½(TDS1 +TDS2) ……………………………………………………..(10)

Where; TDS = total dissolved solids, TDS reading = TDS values from the instrument, df = dilution factor, TDS dil = TDS of water used to dilute water sample, MTDS = month total dissolved solids and TDS1 and TDS2 = TDS values recorded in first and second water tests.

4.2.7 Collection of data on rainfall patterns, total dissolved solids, tidal and groundwater levels

Data of rainfall and tidal levels at Zanzibar harbour for the year 2015 were collected from Tanzania Meteorological Agency (TMA), Kisauni, Zanzibar. The tidal data from TMA together with the ones cited from Nhnyete and Mahongo (2007); ASCLME (2012) were used to estimate seawater tidal heights in the year 2015 at Chwaka and Uzi bays. Elevations at OWs were obtained from instrumental survey. Data on monthly water levels and TDS were collected from WLCRs and water tests, respectively. The data were collected twice per month during day time on low water of spring tides (LWST), but not during or shortly after rains. Date and time of data collection were selected based on online monthly tides prognoses of University of Hawaii Sea Level Centre (UHSLC) (Table 4.1). The data were collected within 40 (±20) minutes of the indicated time.

Table 4.1: Date and time of data collection for water levels and total dissolved solids in 2015

	Jan		**Feb**		**Mar**		**Apr**		**May**		**Jun**		**Jul**		**Aug**		**Sep**		**Oct**		**Nov**		**Dec**	
	1	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Date	7	22	5	21	7	22	5	19	5	19	4	17	4	18	2	16	1	15	28	14	26	12	26	13
Hour	11	11	11	11	11	11	10	10	10	10	11	10	11	11	11	11	11	11	10	10	10	10	10	11
Minute	37	26	19	45	19	23	50	23	50	43	05	29	33	33	20	14	43	20	29	56	16	34	47	23

1 = data collected during full moon nights; 2 = data collected during dark nights

4.2.8 Data analysis

Excel spread sheets were used to compute reduced levels, arithmetic error, means, standard deviations, slopes and regression analysis and graphing.

4.3 Results and Discussion

4.3.1 Proxy of seawater intrusion in Jozani Groundwater Forest

Link between tidal trends and magnitude (elevation of reach) and intrusion in JGWF was described by relating elevations of study sites, incidents of reach and drain of seawater into and from the forest. Although JGWF itself is the lowest part of Zanzibar with elevation of about 0.75 to 2.50 m AMSL (Masoud *et al*., 2016), results in Table 4.2 showed that the surfaces of OWs ranged between 0.864 to 1.564 m.

Table 4.2: Position of observation wells and their surface elevations

	South-end observation well			**North-end observation wells**		
	SOW1	**SOW2**	**SOW3**	**NOW1**	**NOW2**	**NOW3**
Northern coordinates	9 306 800	9 306 820	9 306 660	9 311 600	9 311 200	9 310 800
Eastern coordinates	546 750	546 350	545 980	544 700	544 700	544 700
Elevation (m, AMSL)	1.368	1.477	1.564	0.864	0.946	1.037
Mean slope (%)	0.025			0.022		

The South-end was higher than the North-end by about 0.521 m. The slope towards Uzi bay made by the OWs' surfaces at South-end was relatively higher than the one on OWs' surfaces at North-end which declined towards Chwaka bay.

Based on TMA, a maximum Monthly Tidal Level (MTL) at Zanzibar harbour in the year 2015 was 2.2 m AMSL, twice (4.4 m) what was considered as a Maximum Tidal Range (MTR). The MTR was higher by 0.4 m (10%) than the one (2.0 m) reported by Nhnyete and Mahongo (2007). Heights of high water of neap tides (HWNT) and high water of spring tides (HWST) at Chwaka and Uzi bays were therefore, obtained by adding 10% to the ones reported by ASCLME (2012) which were 0.9 and 3.6 m, respectively. Therefore, the estimated maximum seawater levels for HWNT and HWST in 2015 were about 0.495 and 1.980 m AMSL, respectively. Hence, relations between land and tidal levels were: first; all surfaces at OWs were out of reach by seawater of low water of spring tides (LWST), low water of neap tides (LWNT) and HWNT because the surfaces were at a higher elevation, and second; the surfaces were within the range of reach by seawater of HWSTs because they were a bit lower than 1.98 m AMSL. Thus, the bays were the sources of seawater and OWs surfaces were prone to surface intrusion during HWST.

4.3.2 Monsoon winds as a proxy of seawater intrusion

Monsoon winds act differently in the bays and likewise in the study sites. *Kusi*, with velocity of above 6 m/s blows towards the South-end and outwards from the North-end (ASCLME, 2012). The role of *Kusi* on South-end is therefore, pushing and accelerating seawater of HWST from Uzi bay to reach soil surfaces of OW within or above the reachable range of 1.98 m AMSL. *Kaskazi*, with velocity of less than 6 m/s blows towards the North-end and outwards from the South-end (ASCLME, 2012) has limited role which applies only on North-end.

4.3.4 Incidences of seawater and freshwater reaching soil surfaces of observation wells

Incidences of seawater or freshwater reaching soil surface of OWs in study sites were captured by the WLCRs as variant 1 and 4 of Fig.4.2 (Section 4.2.4). The incidences occurred during rainy and dry seasons and were respectively brought by freshwater recharging, floods and flows (Plate 4.2) and seawater from the bays (Plate 4.3).


Plate 4.2 **Plate 4.3**

Plate 4.2: Signs of freshwater temporary floods on the South-end of Jozani Groundwater Forest. Several small marks/lines made of tiny pieces of plant residues on the plastic tube of observation well are the signs of temporary water levels above soil surface (floods and rapid fall)

Plate 4.3: Presence of saline tolerant algae and high turbidy water are the signs of persistent saltwater around OW3 on North-end

The data from WLCRs indicated that seawater never reached soil surface at South-end observation well 3 (SOW3), in July-August 2015 period reached SOW1 and SOW2 twice, reached North-end observation well 3 (NOW3) six times and frequently reached NOW1 and NOW2. Incidences of seawater reaching study sites partially supported the proxy of seawater intrusion based on land and tidal level and trend. As indicated earlier (Section 4.2.1), all OWs were within the range of reach by seawater of HWSTs because they were lower than 1.98 m AMSL. In this case elevation of HWST was 1.98 m AMSL at the bays whereas that of seawater reach differed within the study sites and OWs. The situation was such that elevation of seawater at the bays was always higher than elevation of reach (ER). On the South-end, ER was higher by about 0.4 m than that on the North-end. However, the North-end was more susceptible to intrusion because of lowness of the altitude. Again, ER decreased with increase of distance from the bay. The phenomenon of uneven distribution and frequency of seawater reach on the study sites indicates the presence of other factors affecting ER as proxy of intrusion.

4.3.5 Role of mangroves and *Paspalum vaginatum* (Seashore couch) stands against intrusion

Upholding the findings from earlier discussion in Sections 4.2.1 to 4.2.3, the presence and condition of Mangroves and *Paspalum vaginatum* (Seashore couch) stands in front of the study sites were additional factors affecting distribution, frequency and elevation of seawater reach. These plant stands slowed down seawater velocity towards JGWF, extending the time of reach and thereby pulling down elevation of reach (ER). At the North-end, the estimated ER down-pull was about 0.6 - 0.9 m while at the South-end it was about 0.4 - 0.5 m. However, the role of Mangroves and *Paspalum vaginatum* stands against intrusion in JGWF need further studies.

4.3.6 Relationship between rains and water levels in the study sites

Jozani Groundwater Forest has a tropical sub-humid climate and receives about 1400 - 1600 mm mean annual rainfall from *Masika* (long) and *Vuli* (short) rains (Leonila, 2011). In the year 2015 the total rainfall recorded was 1506 mm. Figure 6 shows that *Masika* rains started from March and were much higher in May. *Vuli* rains fell in November and December.

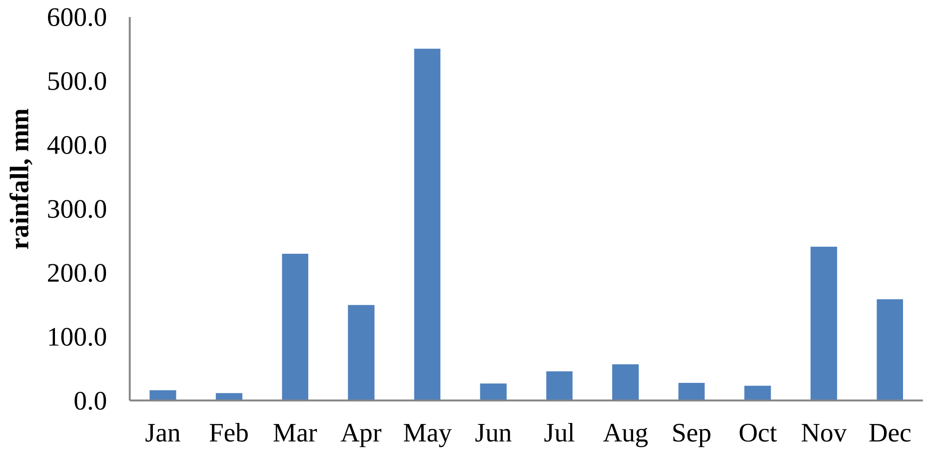


Figure 4.3: Zanzibar monthly rainfall in 2015. Source: Tanzania Meteorological Agency (TMA), Kisauni, Zanzibar

Table 4.3 shows the WLCs captured by WLCRs in North-end and South-end. There was a strong relationship between rise and fall of WL (Table 4.3) and rainfall (Fig. 4.3). Rainfall patterns and water volume play a great role on trends of WLs in the study sites. The WLs in OWs were fluctuating following the wet and dry periods of the year (Figures 4.4 and 4.5).

Table 4.3: Monthly water level changes in observation wells in 2015

	Water level changes (WLCs), m AMSL											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
NOW1	0.586	0.582	1.025	1.056	0.922	0.823	0.94	0.864	0.736	0.685	0.926	0.828
NOW2	0.681	0.635	1.076	1.088	0.944	0.88	1.007	1.082	0.852	0.754	1.046	0.878
NOW3	0.826	0.732	1.134	1.206	1.082	1.064	1.064	1.134	0.886	0.786	1.088	1.024
Mean	0.698	0.650	1.078	1.117	0.983	0.922	1.004	1.027	0.825	0.742	1.020	0.910
SD	0.121	0.076	0.055	0.079	0.087	0.126	0.062	0.143	0.079	0.052	0.084	0.102
Slope%	0.030	0.019	0.014	0.019	0.020	0.030	0.016	0.034	0.019	0.013	0.020	0.025
SOW1	0.936	0.82	1.292	1.356	1.562	1.402	1.348	1.164	0.936	0.825	1.427	1.280
SOW2	0.982	0.835	1.302	1.388	1.565	1.422	1.367	1.18	0.954	0.843	1.448	1.302
SOW3	1.262	0.852	1.344	1.406	1.576	1.462	1.4	1.232	0.988	0.872	1.464	1.346
Mean	1.060	0.836	1.313	1.383	1.568	1.429	1.372	1.192	0.959	0.847	1.446	1.309
SD	0.176	0.016	0.028	0.025	0.007	0.031	0.026	0.036	0.026	0.024	0.019	0.034
Slope %	0.041	0.004	0.007	0.006	0.002	0.008	0.007	0.009	0.007	0.006	0.004	0.008

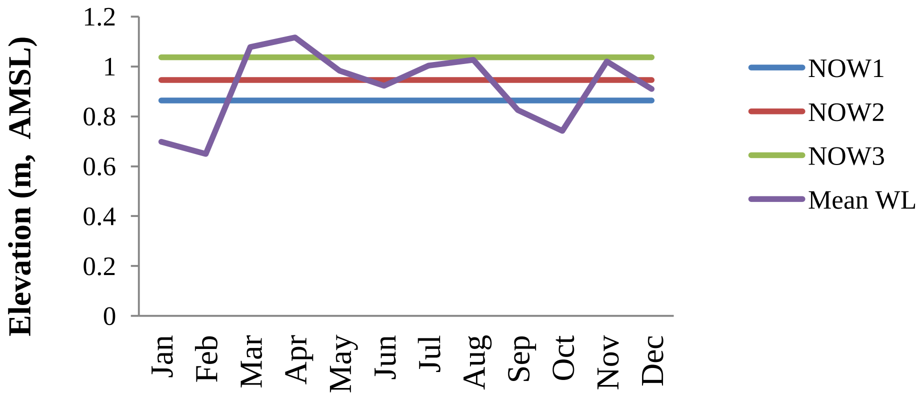


Figure 4.4: Reduced levels of ground surface and mean month water levels in North-end observation wells. Whereby (on the legend): NOW1, NOW2 and NOW3 refer to reduced levels (m, AMSL) of ground surface of North-end observation wells 1, 2 and 3, while Mean WL refer to mean water level (m, AMSL) at North-end in 2015

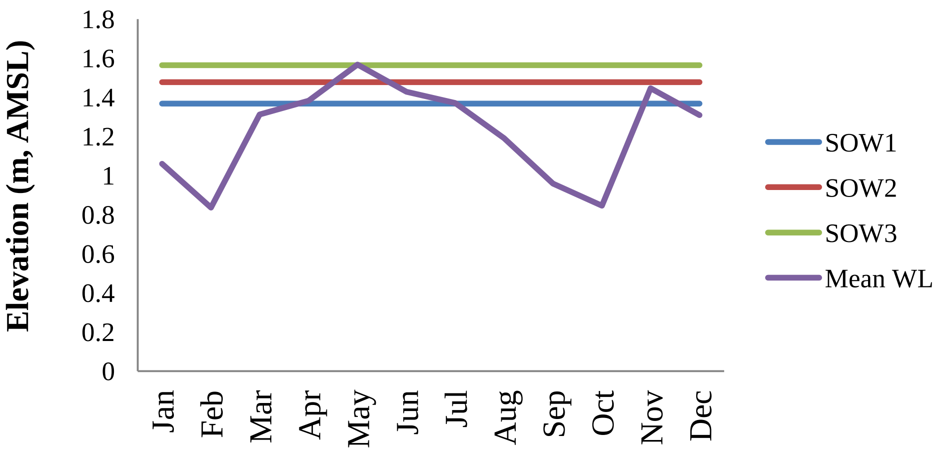


Figure 4.5: Reduced levels of ground surface and mean month water levels in South-end observation wells. Whereby (on the legend): SOW1, SOW2 and SOW3 refer to levels (m, AMSL) of ground surface of South-end observation wells 1, 2 and 3, while Mean WL refer to mean water level (m, AMSL) at South-end in 2015

The above phenomenons indicate that rainwater is the only source of fresh water in JGWF. The rise of WLs to the ground surfaces and above (temporary floods) shown in Figures 4.4 and 4.5 coincided with the heavy rains within *Masika* and *Vuli* periods. Moreover, during dry periods WLs were gradually falling to minimum level. WLs in South-end were higher than in North-end, while temporary floods were more frequent in North-end than in South-end. Such phenomenon in addition to the elevations and slope differences between the two ends discussed in Section 4.1 implied that considerably large amount of rain water slowly and through a long period of time drained from the forest towards Chwaka bay. On the other hand, less rain water drained towards Uzi bay during and after heavy rains within a short period.

4.3.7 Effects of tidal water on study sites

The monthly TDS changes in North-end and South-end are presented respectively in Table 4.4. Results from water test showed that TDS values ranged from 5 to 34 x 10^3 mg L^{-1} at North-end and from 0.7 to 26 x 10^3 mg L^{-1} at South-end. These ranges on one hand, varied due to sites, distance from the bay and wet and dry seasons and on the other hand, amount of salts accumulated during HWST and amount of salts drained off during the rainy seasons. During dry seasons there were few freshwater drains to dilute the accumulating salts reaching the OWs surface. Under such conditions, as reported by Guo and Jiao (2007), there would be seawater intrusion and accumulation of salts. When weather factors including rains and tidal pattern do not change abruptly, these values and trends are not subjected to abrupt changes. Heiss and Michael (2014) reported that, as salt water is denser than freshwater; these values were therefore, subjected to change if sampling was done deeper than 0.10 m from the water surface. As noted earlier that JGWF has a single source of freshwater which is rain (Section 4.5), and a single source of saltwater which is seawater. Thus, the increase and decrease in values of TDS are directly related to the tidal conditions at the bays.

Therefore the main effect of the sea tides is the spilling of saltwater into the soil surface of the forest ends.

Table 4.4: Average monthly total dissolved solids changes in observation wells in 2015

	TDS x1000 mg L^{-1}											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
NOW1	29.4	32.1	34.1	27.8	22.3	26.8	28.4	31	30.1	32.3	32.6	28.0
NOW2	20.3	23.8	25.2	20.5	16.4	18.6	19.4	22.4	24.9	25.2	26.2	20.5
NOW3	7.2	10.1	12.8	6.9	5.2	5.1	4.9	10.6	13.1	14.7	16.1	14.9
Mean	20.0	23.3	25.4	18.7	15.3	16.8	18.0	21.3	22.7	24.1	25.0	21.1
SD	11.2	11.1	10.7	10.6	8.7	11.0	11.9	10.2	8.7	8.9	8.3	6.6
SOW1	18.1	22.8	25.5	15.4	16.7	18.6	19.3	21.4	22.1	22.2	21.8	16.6
SOW2	12.5	15.4	18.3	7.6	9.1	11.3	13.5	14.3	16.8	16.2	13.5	10.2
SOW3	2.4	3.7	4.8	0.7	0.7	0.9	1.4	1.8	2.1	2.3	2.3	1.2
Mean	11.0	14.0	16.2	6.9	7.9	9.3	11.4	12.2	13.7	13.6	12.5	9.3
SD	8.0	9.6	10.5	5.9	6.3	7.3	8.9	9.2	10.4	10.2	9.8	7.7

4.3.8 Relationship between water level and total dissolved solids

Regression analyses (Fig. 4.6) of TDS and WLs in study sites showed that TDS values slightly decreased as WLs increased. This relationship was a bit stronger in South-end (R^2 = 0.295) than in North-end (R^2 = 0.029). The relationship suggests that at South-end, there was a dilution and draining of the occasionally accumulated salts off the forest towards the bay during rainy seasons. Rain water thus flushes salts accumulated during dry season and keeps the area free from high salt concentration for a long period. The low decline of TDS values in the North-end suggested that seawater from Chwaka bay contributed much to water level rise which is generally maintained for a longer time.

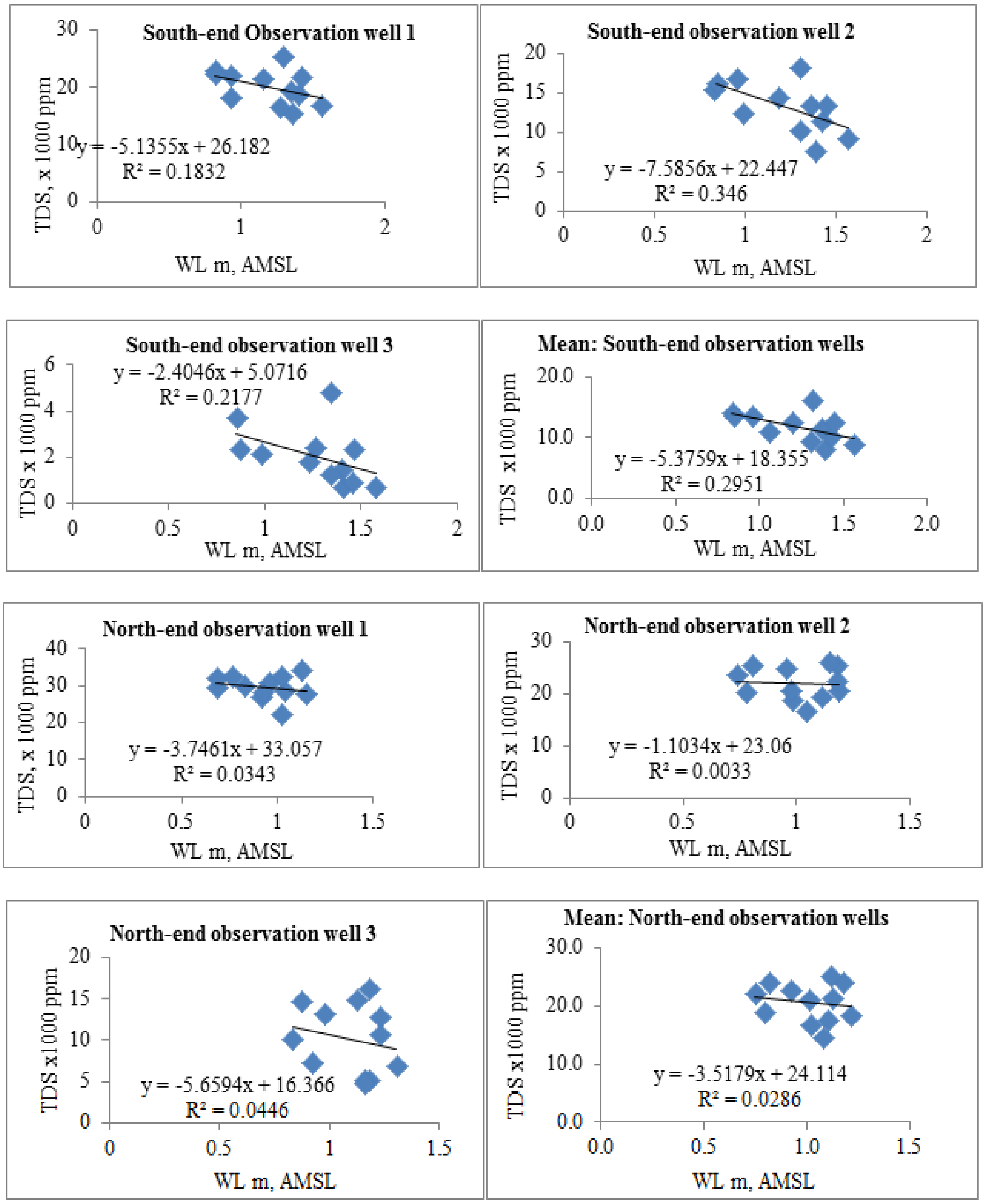


Figure 4.6: Regression analyses total dissolved solids (TDS) versus water level (WL) in the study sites in 2015

4.4 Conclusions and Recommendations

The results and discussion showing that water level in North-end and South-end fluctuates between 0.586 and 1.206 m AMSL and between 0.820 and 1.586 m AMSL during dry and rainy seasons, respectively. As seawater from Chwaka and Uzi bays reached the soil surfaces of North-end and South-end, this study concludes that Chwaka and Uzi bays are the only sources of seawater that intrudes Jozani Groundwater Forest (JGWF). Rainfall apparently is the only source of freshwater which dilutes and partially drains out seawater that intruded JGWF. This study further concludes that seawater intrusion caused by surface movement of seawater through Chwaka and Uzi creeks takes place frequently and on large area at and beyond North-end towards JGWF during high water of spring tides (HWST). On the contrary, seawater intrusion takes place occasionally and in a small area on the South-end during HWST which is associated with strong South-east (*Kusi*) Monsoon winds. The values of water total dissolved solids (TDS) fell to a minimum of 0.7 x 10^3 and 4.9 x 10^3 mg L^{-1} during rainfalls and rose to a maximum of 25.5 x 10^3 and 34.1 x 10^3 mg L^{-1} during dry seasons at South-end and North-end respectively, implying that the magnitude of TDS values as a measure of seawater intrusion varied spatially and temporally in both ends. In addition, this study conclude that high densities of mangroves and *Paspalum vaginatum* (Seashore couch) stands pulled down seawater elevation of reach into JGWF soil surface by 0.9 and 0.5 m for Chwaka bay and Uzi bay respectively. This implies that the mangroves and the dense *Paspalum vaginatum* stands do not affect seawater tidal trends and its magnitude but reduce seawater reach area, frequency and area of intrusion.

Based on the study results, recommendations are as follows:

1. Making reforestation with the use of mangroves before the bays or creeks as an effective way of reducing surface seawater intrusion into low elevated coastal agricultural and forest areas.

2. Conducting lond term studies on frequency, spatial distribution of seawater reach and effect of sampling at different water depths are recommended to fill the gap of information on total dissolved solids changes.
3. Use of digital portable water geo-logger and related equipment will simplify and upgrade data collection in this kind of studies.

4.5 References

ASCLME (2012). National Marine Ecosystem Diagnostic Analysis, Tanzania. Contribution to the Agulhas and Somali Current Large Marine Ecosystems Project (supported by UNDP with GEF grant financing). Unpublished report. 92pp.

Brinker, R.C. and Minnick, R. (Eds.) (2012). *The Surveying Handbook.* Springer Science and Business Media. 971pp.

Emmanuel, B.E. and Chukwu, L.O. (2010). Spatial distribution of saline water and possible sources of intrusion into a tropical freshwater lagoon and the transitional effects on the lacustrine ichthyofaunal diversity. *African Journal of Environmental Science and Technology* 4(7): 480-491.

Guo, H. and Jiao, J.J. (2007). Impact of coastal land reclamation on ground water level and the sea water interface. *Ground Water* 45(3): 362-367.

Heiss, J.W. and Michael, H.A. (2014). Saltwater-freshwater mixing dynamics in a sandy beach aquifer over tidal, spring-neap, and seasonal cycles. *Water Resources Research* 50(8): 6747-6766.

Humphrey, C.P., Harris, J. and O'Driscoll, M.A. (2012). Evaluation of Water Table Dynamics in Relation to Soil Morphological Indicators of Seasonal Wetness. *Universal Journal of Environmental Research and Technology* 2(4): 286-292.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Exploratory study on the relation between soil variability and landscape. Dissertation for Award of MSc Degree Turku University, Finland. 85 pp.

Kuan, W.K., Jin, G., Xin, P., Robinson, C., Gibbes, B. and Li, L. (2012). Tidal influence on seawater intrusion in unconfined coastal aquifers. *Water Resources Research* 48 (2): W02502, doi:10.1029/2011WR010678. Site visited on 25/08/2014.

Leonila, B.S. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award of MSc. Degree at University of Twente, Enschede, Netherland. 46pp.

Majolagbe, A.O., Adeyi, A. and Osibanjo, O. (2014). Hydrochemical characterization and quality assessment of groundwater in the vicinities of a major active dumpsite in Lagos, Nigeria: the use of multivariate analytical technique water quality indices. *Europe Water* 48: 29-42.

Masoud, S.S., Msanya, B.M., Semoka, J.M.R. and Maliondo, S.M.S. (2016). Use of water table as a benchmark for levelling groundwater forest: The case of Jozani Groundwater Forest, Zanzibar, Tanzania. *International Journal of Scientific and Technical Research in Engineering (IJSTRE)* 1(5): 49-57.

Nhnyete, I.K. and Mahongo, S.B. (2007). National Report of the United Republic of Tanzania on sea level measurements. [http://www.gloss-sealevel.org/publications/documents/tanzania_gex2007.pdf] site visited on 25/07/2014.

Nowak, K. and Phyllis, C.L. (2011). Demographic structure of Zanzibar red colobus populations in unprotected coral rag and mangrove forests. *International Journal of Primatology* 32(1): 24-45.

Philippa, A., Marc, E., Carl, H., Shirley, H., Rebecca, L., Russel, S., David, S. and Anna, V. (2003). Coastal aquifer saltwater intrusion assessment guidelines. Environment Canterbury Technical Report No. R04/18. 47pp.

Robinson, C., Gibbes, B., Carrey, H. and Li, L. (2007). Salt-freshwater dynamics in a subterranean estuary over a spring-neap tidal cycle. *Journal of Geophysical Research: Oceans* 112(9): 1-15.

Salum, L.M. (2009). Ecotourism and biodiversity conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47: 166-170.

SaMeH (2014). A precise methodology integrates low-cost GPS data and GIS for monitoring groundwater quality parameters in Majmaah region, KSA. *International Journal of Environmental Monitoring and Analysis* 2(5): 279-288.

Semesi, A.K. (2013). Developing management plans for the mangrove forest reserves: The Ecology of Mangrove and Related Ecosystems: In: Proceedings of the International Symposium. Edited by Springer Science & Business Media 80. 24–30 September 1990 Mombasa, Kenya. 1-10pp.

Shahba, M.A., Alshammary, S.F. and Abbas, M.S. (2012). Effects of salinity on seashore *Paspalum* cultivars at different mowing heights. *Crop Science* 52(3): 1358-1370.

Slama, F. (2010). Field experimentation and modelling of salt transfer in Korba coastal plain: Impact of seawater intrusion and irrigation practices. Doctoral dissertation for Award MSc degree of University of Neuchâtel. 138pp.

Van Camp, M., Mtoni, Y., Mjemah, I.C., Bakundukize, C. and Walraevens, K. (2014). Investigating seawater intrusion due to groundwater pumping with schematic model simulations. The example of the Dar es Salaam coastal aquifer in Tanzania. *Journal of African Earth Sciences* 96: 71-78.

Vice President's Office (2012). *National Climate Change Strategy.* Division of Environment, United Republic of Tanzania. 92pp.

Werner, A.D. and Simmons, C.T. (2009). Impact of sea-level rise on sea water intrusion in coastal aquifers. *Ground Water* 47(2): 197-204.

Werner, A.D., Bakker, M., Post, V.E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T. and Barry, D.A. (2013). Seawater intrusion processes, investigation and management: recent advances and future challenges. *Advances in Water Resources* 51: 3-26.

Zanzibar Revolutionary Government (2013). Zanzibar Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report. Using Zanzibar Woody Biomass Survey in Policy and Planning Processes, Working Paper. Indofood and Norwegian Embassy, Zanzibar. 24pp.

CHAPTER FIVE

5.0 EXTENT OF SEAWATER INTRUSION FROM CHWAKA AND UZI BAYS INTO JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

ABSTRACT

The rise in total dissolved solids (TDS) in a coastal land is among the signs of seawater intrusion into the land. In many cases, the magnitude of the effects of seawater intrusion depends upon the proximity of the land to the coast, amount, and patterns of freshwater recharging the aquifer underneath. The intention of this study was to determine the extent to which Jozani Groundwater Forest (JGWF) has been affected by seawater intrusion from Chwaka and Uzi bays. Rainfall data was collected from Tanzania Meteorological Agency (TMA). Spatial and temporal total dissolved solids (TDS) values were collected from temporary wells (TWs) and local wells. Desk work divided JGWF length into 11 northern and 4 eastern gridlines. Along northern gridlines, three grid points were selected on which TWs were drilled for data collection. GARMIN *e*trex 10 GPS was used for geo-referencing the wells. Water samples were collected at about 0.1 m depth from water surface and were tested *in situ* using Hanna Combo HI 98 129 tester. Water tests were done in the middle of *Kiangazi* (hot, dry), *Masika* (long rains), *Kipupwe* (cold, showers) and *Vuli* (short rains) seasons. The area of study was estimated based on JGWF digital elevation model (DEM). The results showed that the average TDS values in JGWF ranged from 0.4 - 25 x 10^3 mg L^{-1}. The least TDS values were recorded from the inner parts of JGWF while highest TDS values were recorded from the outmost parts. It was found that rainfall patterns: rainy and dry seasons affected TDS values and their spatial trends. The TDS severity in JGWF area was assigned five categories namely none: least-, slightly-, moderately- and severely-affected areas. The range of TDS values for these categories were 0 - 0.5, 0.5 - 2, 2 - 5, 5 - 10 and >10 x 10^3 mg L^{-1} and the areas of occupation were 342.3 ha (58.2%), 61.8 ha (10.5%), 46.8 ha (8.0%), 47.4 ha (8.1%) and 89.4 ha (15.2%), respectively. It was concluded that 77% of JGWF is free from seawater intrusion effects, but there were variations of TDS values between dry and rainy seasons that also in the long run cause TDS fluctuation between years.

Key words: Total dissolved solids, rainwater, and seawater intrusion, dry and wet seasons, dilution, draining, and category of affected area

5.1 Introduction

The best evidence of seawater intrusion into aquifer is the proximity of the aquifer to the coast and a distinct rise in the total dissolved solids (TDS) (Philippa *et al*., 2003; Zhu *et al*., 2014). Various scholars concluded that a change of sodium concentration through space has a direct relation with the source and trend of intrusion into aquifer. In this sense, seawater, which is always concentrated with sodium salts (Eddy-Miller *et al*., 2009; Zhu *et al*., 2014), flows and mixes with freshwater in the aquifer (Praveena *et al.*, 2010; Naderi *et al*., 2013). Water sources and their interfaces influence water dynamics and quality in a forest (Elewa *et al*., 2013; El-Fadel *et al*., 2014). Jozani Groundwater Forest (JGWF) is a coastal forest located on the lowest point in Zanzibar between Uzi and Chwaka bays (Leonila, 2001; Klein, 2008; Salum, 2009). With such proximity and low terrain, JGWF is likely to be intruded by seawater from the bays. Therefore, there was an information gap to what extent

JGWF has been affected by seawater from Chwaka bay on the North and Uzi bay on the south. Therefore, this study intended to determine the extent to which JGWF has been affected by seawater intrusion from Chwaka and Uzi bays.

5.2 Material and Methods

5.2.1 Description of the study area

The study was conducted in Jozani Groundwater Forest (JGWF) area. The area is within the Jozani-Chwaka Bay National Park (JCBNP) located about 35 km from Stone Town, off the road to Makunduchi (Mchenga and Ali, 2014) (Fig. 5.1). As coastal forest, JGWF area is opened to Chwaka bay on the North and to Uzi bay on the South (Klein, 2008; Leonila, 2011; Mchenga and Ali, 2014).

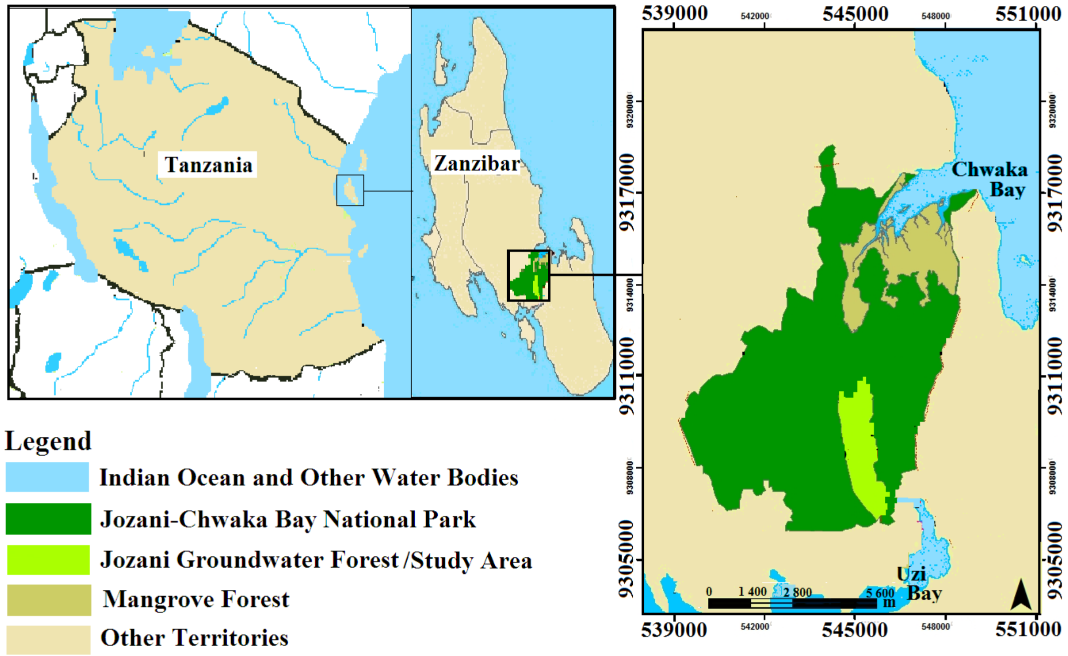


Figure 5.1: Location of Jozani-Chwaka Bay National Park and Jozani Groundwater Forest. Source: Department of Forest Non-renewable Natural Resources (DFNNR), Zanzibar

5.2.2 Rainwater and rainfall patterns in the study area

Mchenga and Ali (2014) reported, Zanzibar receives precipitation of between 1400 and 2000 mm annually, mainly during Masika (long rainy) and Vuli (short rainy) seasons. However, based on Kukkonen (2013) the study area which is a tropical forest is likely receives annual precipitation of between 1600 and 2000 mm annually. Figures 5.2 and 5.3 were derived from 2011 to 2015 rainfall data collected from Tanzania Meteorological Agency (TMA), Kisauni Zanzibar. Jozani Groundwater forest has shallow water table which during rainy seasons often emerges above the surface forming temporary marshes (Salum, 2009). In this case, rain water as the main source of fresh water is expected to play a major role in regulating TDS values and their spatial trend in JGWF. As Thus, it is expected that TDS values and spatial trend in JGWF area are affected by amount and patterns of precipitation.

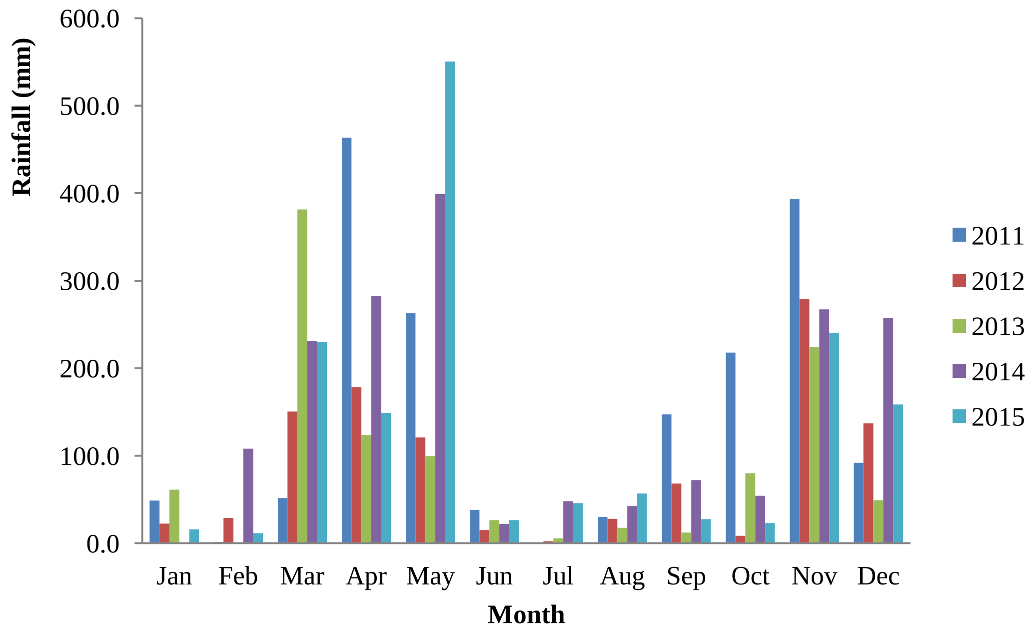


Figure 5.2: Monthly rainfall distribution in Zanzibar between 2011 and 2015. Data source: TMA, Zanzibar

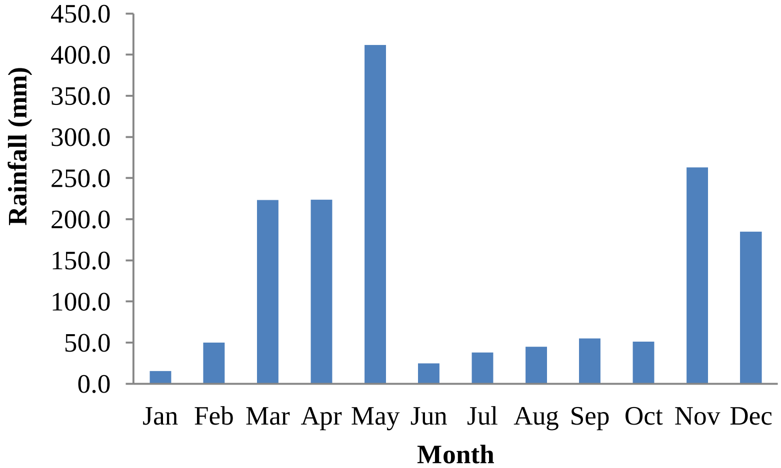


Figure 5.3: Zanzibar average monthly rainfall (mm) in 2011 - 2015 periods. Source: TMA, Zanzibar

5.2.2 Spatial distribution of data collection points

Grid system is often used for spatial pattern studies (Adhikari *et al*., 2014; Hu and Si, 2014). Seawater intrusion spatial trend and the affected area by seawater intrusion are described by TDS measurements conducted on a known grid system (Taha, 2014; Beaujean *et al*., 2014). In this regards, the study area was divided into 11 (northern) x 4 (eastern) grids lines which were spaced at 500 m in between northern coordinates 9 306 800 and 9 311 800. All eastern gridlines were bounded between 544 700 and 546 200 due to irregular alignment of coral forest on the east and coral cliff on the west. Therefore, along Northern gridlines only three (out of four) grid points were used as data collection. During data collection an alteration from the exactly GPS indicated grid point was made when there was poor accessibility to the point due to either high plant density, complex plant assemblage and/or coral outcrops. In addition to that an alteration was made purposely when it was found that a nearby point was more convenient for the *in sit*u water testing. However, the data were collected within vicinity of less than 15 m from the selected grid point. The data collection process was exceptional on northern gridline 9 306 800, which was limited by a cliff on the West but was shifted eastwards and slightly opened to seawater creek from Uzi. Therefore, on northern gridline 9 306 800 data were between Eastern coordinates 545 600 and 546 750. GARMIN *e*trex 10 GPS set was used for georeferencing.

5.2.3 Estimation of total dissolved solids levels

Scholars including Alongi (2007), Elewa *et al*. (2013), El-Fadel *et al*. (2014) and Taha (2014) used TDS spatial tests to characterize the magnitude and spatial trend of seawater intrusion. Again, Aitchison-Earl *et al*. (2003) and Naderi *et al*. (2013) reported that aquifer can be used to test a level seawater intrusion. Therefore, as reported by Aitchison-Earl *et al*. (2003) and Naderi *et al*. (2013), the extent and spatial trend of seawater intrusion from the bays into JGWF can be determined by conducting spatial and temporal tests on TDS levels in JGWF aquifer. Spatially distributed local and/or temporary wells therefore, were used as data collection points for this study which estimated level and areal extent affected by seawater intrusion.

5.2.4 Local and temporary wells

Water samples collected from wells are often used to assess water quality of aquifers (Beaujean *et al*., 2014). In the shallow aquifer, an auger-drilled bore hole was used as a temporary well for water sampling and testing (Beaujean *et al*., 2014; Kohne and Mohanty, 2014). At a grid point (Section 5.2.2), soil auger was used to drill down to about 1.5 m depth to make a bore hole that served as a temporary well (TW). A perforated plastic pipe of about 2 m long was installed into bore hole and about 0.5 m of the pipe was left protruding off the well surface (Plate 5.1). Most of the TWs were drilled at GPS selected grid points; however, some of them were replaced by local wells which were found adjacent to the selected grid points (Plate 5.2).

Plate 5.1 **Plate 5.2**

Plate 5.1: Example of temporary wells at selected grid point in Jozani Groundwater Forest (JGWF)

Plate 5.2: Example of local wells in JGWF used as data collection point

5.2.5 Data collection periods

According to Burk and Delgliesh (2008), a certain amount of water is drained from coarse textured (sandy) soils for a couple of days. Similar amount of water is drained for approximately two weeks from medium textured (loamy) soils and for over several months from fine textured (clayey) soils. According to Hettige (1990) JGWF soil has clayey loamy textured. Hence, for this study sampling for TDS value changes was prolonged to four months interval. The time for data collection was also related to wet and dry seasons. Zanzibar has two wet seasons namely *Masika* (long rainy) and *Vuli* (short rainy) and two dry seasons, *Kiangazi* (hot, dry) and *Kipupwe* (cool with showers) (Leonila, 2001). To obtain representative TDS values and trends in JGWF, data were collected in the middle of each of the four seasons, with the exception of data collection during floods.

5.2.6 Water sampling and testing

A canister was used to sample water from temporary wells (TWs). Water sampling depth was 0.1 m from the water surface. Floating ruler was used to measure the depth of the water surface from the top of the plastic tube. The length of canister therefore, was equal to the measured depth plus the sampling depth. The water sample was analyzed *in situ* for total dissolved solids (TDS) using a Hanna Combo Tester HI 98129 (Emmanuel and Chukwu, 2010). To obtain TDS values from the water samples with TDS exceeding the instrumental upper limit (2000 mg L^{-1}), the samples were diluted to readable dilution. The TDS values from diluted samples were calculated by Equation 1.

TDS = (TDS Reading * df) – TDS dil………………………………………………(1)

Where; TDS = total dissolved solids, TDS reading = TDS values from the instrument, df = dilution factor, TDS dil = TDS of water used to dilute water sample.

5.2.7 Data analysis

Excel software was used for data analysis and presentation of results. The proportion of areas with different TDS ranges (categories) was estimated with the help of ArcGIS 10.1 and JGWF elevation map by Masoud *et al.* (2016a).

5.3 Results and Discussion

Based on TMA rainfall information, Figures 5.2 and 5.3 showed a likely rainfall distribution in the study area in the year 2011 to 2015. The amount of precipitation fluctuate both monthly and annually, and about 65 - 80% of precipitations occur during *Masika* (long) and *Vuli* (short) rain seasons. Again, according to Masoud *et al.*

(2016b), *Masika* and *Vuli* rains are the only source of freshwater that replenishes JGWF aquifer since no other sources were ever recorded. Leonola (2011) reported that JGWF needs less water to recharge its aquifer. Thus, temporary floods reported by Salum (2009) and as can be extrapolated from Plate 5.3, occurred when JGWF aquifer reaches its high level by receiving a large amount of water from *Masika* and/or *Vuli* rains.

Plate 5.3: Central part of Jozani Groundwater Forest flooded by *Masika* rains

With reference to JGWF elevation map by Masoud *et al.* (2016a), usually such flooding occurs in areas with an elevation of less than 1.75 m above mean sea level (AMSL). In JGWF, flooding condition lasts for 1 to 5 days or more depending upon the elevation of the flooded area, amount and duration of precipitation.

5.3.1 Levels of dissolved solids in Jozani Groundwater Forest

The average levels of dissolved solids in Jozani Groundwater Forest (JGWF) for four seasons are presented in Table 5.1. The dissolved solids were significantly increasing northwards. However, there was a different trend of increasing dissolved solids on the south-end of JGWF. The difference between the south-end (area around and south of northing (N) 9 306 800) and the rest of JGWF area was the direction of the increase and decrease of dissolved solids. Table 5.2 shows that dissolved solids at south-end were increasing eastwards.

Table 5.1: Total dissolved solids (TDS) values along northern gridlines in Jozani Groundwater Forest in 2015

	Thousands of total dissolved solids (mg L^{-1})				
Northings	Kiangazi (Hot, dry)	Masika (Long rains)	Kipupwe (Cool, showers)	Vuli (Short rains)	Mean ± SD
9306800	3.678	0.762	1.736	0.928	1.776±1.34
9307300	2.575	0.595	1.071	0.871	1.278±0.89
9307800	1.472	0.428	0.406	0.814	0.780±0.50
9308300	1.359	0.400	0.406	0.696	0.715±0.45
9308800	1.245	0.372	0.405	0.578	0.650±0.41
9309300	1.954	0.650	1.320	1.036	1.240±0.55
9309800	2.662	0.928	2.234	1.493	1.829±0.77
9310300	8.961	3.329	6.217	5.517	6.006±2.32
9310800	15.260	5.730	10.200	9.540	10.183±3.92
9311300	23.700	14.035	20.740	17.571	19.012±4.16
9311800	32.140	22.340	31.280	25.602	27.841±4.68

Table 5.2: Total dissolved solids (TDS) values along Northern 9 306 800 in Jozani Groundwater Forest

	Thousands of total dissolved solids (mg L^{-1})				
Easterns	Kiangazi (Hot, dry)	Masika (Long rains)	Kipupwe (Cool, showers)	Vuli (Short rains)	Mean ± SD
E545500	3.678	0.762	1.736	0.928	1.78±1.158
E546000	15.48	9.48	14.9	13.35	13.30±2.34
E546500	22.38	16.9	20.8	18.68	19.69±2.08

5.3.2 Spatial variability of total dissolved solids in Jozani Groundwater Forest

Figures 5.4 and 5.5 illustrate seasonal spatial variation of dissolved solids (TDS) in Jozani Groundwater Forest between January and December, 2015.

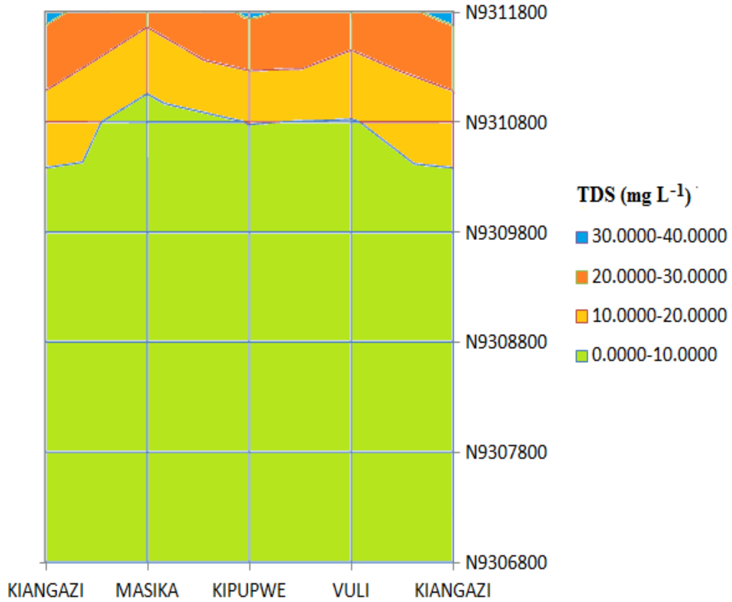


Figure 5.4: Seasonal and spatial variation of dissolved solids in Jozani Groundwater Forest, 2015

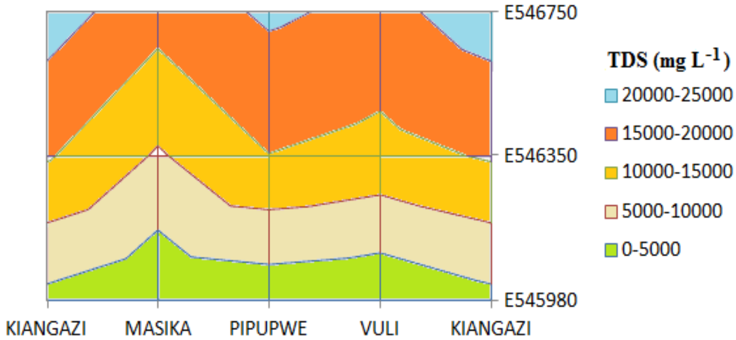


Figure 5.5: Seasonal and spatial variation of dissolved solids in Jozani Groundwater Forest along Northern 9 306 800, 2015

In northern and south-eastern parts of JGWF high TDS values were recorded during dry season followed by *Kipupwe*; and lesser values were recorded during long rain season followed by short rain season. Figure 5.4 shows that the middle and southern part of Jozani Groundwater forest (JGWF) had less TDS values, while Fig. 5.5 shows that at south-end of JGWF, the TDS values were increased towards the East. Therefore, the condition illustrated in Fig. 5.4 implies that on the southern part of JGWF there were either fewer seawater intrusions from Uzi bay or there were significant dilutions and drainage of dissolved solids towards Uzi bay during the wet seasons. Meanwhile on both ends of JGWF there was an increase of dissolved solids during the dry seasons and a decrease TDS values during the wet seasons. Such variability implies that during the dry seasons, seawater spilled the dissolved solids on the north and south ends of JGWF, while during the wet seasons, rainwater flashed out the spilled dissolved solids. Additionally, the condition illustrated in Fig. 5.5 implies that spilling and dilution of the dissolved solids from and towards Uzi creek occurred mainly on the eastern part of the south-end of JGWF.

5.3.3 Fluctuation of total dissolved solids in Jozani Groundwater Forest

According to Callaghan (2014), sodium salts are diluted and drained from soils by rainfall and/or irrigation water. Since, rainfall is the only but adequate source of freshwater for JGWF (Leonila, 2011; Masoud *et al*., 2016b), rainfall patterns and rainwater are solely influencing wetness and dissolved solids variations in JGWF area. During and a few days after *Masika* and/or *Vuli* rains, freshwater flows from JGWF area towards Chwaka and Uzi bays (Masoud *et al*., 2016a, b). Meanwhile during the dry (*Kiangazi* and/or *Kipupwe*) seasons, water flow stops as water level in the aquifer reaches its lowest level.

Tables 5.1 and 5.2 showed that in JGWF area, levels of TDS values increased during the dry seasons and dropped during rainy seasons. Tilting of TDS values from an area with higher TDS values into another area with less value during dry seasons (Figures 5.4 and 5.5) indicate that the seawater from the bays spilled salt compounds on the soil surface. Thereafter, the salts brought by seawater intrusion percolate into the aquifer. In contrast, TDS values on the same areas fell to a minimum when rain water saturates the soil and drains off some of the salt compounds from JGWF towards the bays. Above results supports the importance of freshwater budget imbalance during low rainfall periods beween adjacent areas as reported by Lambs *et al*. (2015) that: 'Sustained and/or delayed dry seasons cause soil salinity to rise at the mangrove/swamp forest ecotone'.

5.3.4 Classification and distribution of Jozani Groundwater Forest area based on TDS values in the aquifer

According to Mato (2015), the average TDS values of pumped water from Zanzibar Municipality bore holes range from 0.2 - 1.1 x 10^3 mg L^{-1}. The values increased to about 5 x 10^3 ppm in the water pumped from the bore holes adjacent to the coastal line of Zanzibar. As Bui (2013), Colón-Rivera (2014) and Mirck and Zalesny (2015) noted, water with TDS values ranging from 0.5 - 2.0 x 10^3 mg L^{-1} has slight to moderate levels of salinity for irrigation purposes and is less harmful to a number of plant species. According to (Masoud *et al.*, 2016b), the south-east part of grid line N9 306 800 on the south-end of JGWF and around and beyond transect N9 310 800 on the north-end of JGWF were covered with salt-tolerant species including *Paspalum vaginatum* (Seashore couch). Therefore, these areas were considered as severely-affected by seawater intrusion from Chwaka and Uzi bays. Meanwhile, areas which were between the low-affected and the severely-affected were considered as moderately affected. Therefore, based on information gathered from Bui (2013), Callaghan (2014), Mato (2015), and Mirck and Zalesny (2015), this study adopted five classes of salt affected areas namely; none-, least-, slightly-, moderately- and severely-affected. Table 5.3 shows the geographic distribution and area covered by the five classes. The TDS values ranged from none-, least-, slightly-, moderately- to severely- affected categories and were 0 - 0.5, 0.5 – 2, 2 - 5, 5 - 10 and > 10 x 10^3 mg L^{-1}, respectively.

Table 5.3: Classes and distribution of Jozani Groundwater Forest area affected by seawater intrusion

Northern coordinates		**TDS Range**	**Seawater effect**	**Occupied area**	
From	**To**	**mg L^{-1}**	**Rank**	**ha**	**%**
9 306 800	9 307 300	2000 - 5000	Slightly-affected	25.6	4.4
9 307 300	9 307 800	500 - 2000	Least-affected	37.3	6.3
9 307 800	9 309 300	0.0 - 500	None-affected	342.3	58.2
9 309 300	9 309 800	500 - 2000	Least-affected	24.5	4.2
9 309 800	9 310 300	2000 - 5000	Slightly-affected	21.2	3.6
9 310 300	9 310 800	5000 - 10000	Moderate-affected	47.4	8.1
9 310 800	9 311 800	>10000	Severe-affected	89.4	15.2
Total area				**587.7**	**100.0**

Accordingly, salt affected areas under the five categories were; 342.3 ha (58.2%), 61.8 ha (10.5%), 46.8 ha (8.0%), 47.4 ha (8.1%) and 89.4 ha (15.2%), respectively. The distribution of TDS values in respective areas within the five categories reflects the extent of seawater intrusion into JGWF. Finally, the area coverage and distribution trends of these categories show the extent, geographic variation and magnitude of seawater intrusion in JGWF with the most severely affected area (89.4 ha) having TDS exceeding 10^3 mg L^{-1}.

5.4 Conclusions and Recommendations

This study concludes that, since *Masika* and *Vuli* are the only sources of freshwater and Chwaka and Uzi bays are the sources of seawater intrusion, the seasonal trend of rise and fall of total dissolved solids (TDS) in Jozani Groundwater Forest (JGWF) is expected to remain constant. Fluctuations of TDS values in JGWF depend on the amount of rainwater received in wet (*Masika* and *Vuli)* seasons against dry seasons of *Kiangazi* and *Kipupwe.* The TDS values in the least- and low-affected areas fluctuate between wet and dry seasons and between years; but the level of fluctuations remain constantly insignificant. The overall conclusion on extent of seawater intrusion is that, the northern part of JGWF is much affected by seawater intrusion than the southern part. In addition, this study concludes that, the TDS values of about 70% of JGWF area favor most of the plant species found in the JGWF.

This study further concludes that, rise and fall of TDS values will remain constant if JGWF biomass status remains intact, no water pumping from JGWF aquifer, and no extremely wet or extremely dry conditions. And that every outer part of JGWF is a protector of the adjacent inner part against the dissolved solids spilled by seawater intrusion, in contrast; every inner part of the JGWF is a protector of the adjacent outer part against further increase of TDS values as freshwater from inner part drains off the dissolved solids towards the bays.

This study recommendes to Jozani-Chwaka Bay Bio-sphere Reserve Management to install permanent TDS monitoring systems that will capture TDS changes and that additional protection measures should be implemented if the current equilibrium is found deteriorating.

5.5 References

Adhikari, K., Minasny, B., Greve, M.B. and Greve, M.H. (2014). Constructing a soil class map of Denmark based on the FAO legend using digital techniques. *Geoderma* 214: 101-113.

Alongi, D.M. (2007). The Energetics of the Mangrove Forest. *Springer Sciences + Business Media B. V.* pp 47-64.

Beaujean, J., Nguyen, F., Kemna, A., Antonsson, A. and Engesgaard, P. (2014). Calibration of seawater intrusion models: Inverse parameter estimation using surface electrical resistivity tomography and borehole data. *Water Resources Research* 50(8): 6828-6849.

Bui, E.N. (2013). Soil salinity: a neglected factor in plant ecology and biogeography. *Journal of Arid Environments* 92: 14-25.

Burk, L. and Dalgliesh, N. (2008). *Estimating Plant Available Water Capacity-A Methodology.* Canberra: CSIRO Sustainable Ecosystems. 40pp.

Eddy-Miller, C.A., Wheeler, J.D., and Essaid, H.I. (2009). Characterization of interactions between surface water and near-stream groundwater along Fish Creek, Teton County, Wyoming, by using heat as a tracer: U.S. Geological Survey Scientific Investigations Report 2009–5160. 53pp.

Elewa, H.H., Shohaib, R.E., Qaddah, A.A. and Nousir, A.M. (2013). Determining groundwater protection zones for the Quaternary aquifer of northeastern Nile Delta using GIS-based vulnerability mapping. *Environmental Earth Sciences* 68(2): 313-331.

El-Fadel, M., Tomaszkiewicz, M., Adra, Y., Sadek, S. and Najm, M.A. (2014). GIS-based assessment for the development of a groundwater quality index towards sustainable aquifer management. *Water Resources Management* 28(11): 3471-3487.

Emmanuel, B.E. and Chukwu, L.O. (2010). Spatial distribution of saline water and possible sources of intrusion into a tropical freshwater lagoon and the transitional effects on the lacustrine ichthyofaunal diversity. *African Journal of Environmental Science and Technology* 4 (7): 480-491.

Hettige, M.L. (1990). Land evaluation and land sustainability classification. Unguja and Pemba Islands. *Food and Agriculture Organization of the United Nations*. FAO TCP/URT/6759 (A), Zanzibar. 156pp.

Hu, W. and Si, B.C. (2014). Can soil water measurements at a certain depth be used to estimate mean soil water content of a soil profile at a point or at a hill slope scale?. *Journal of Hydrology* 516: 67-75.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Exploratory study on the relation between soil variability and landscape. Dissertation for Award MSc Degree at Turku University Department of Geography Publications B, 11. 85pp.

Kohne, M.J. and Mohanty, B.P. (2005). Water flow process in a soil column with cylindrical micropores. Water Resources Research 41. W03010, doi:1029. site visited on 25/12/2014.

Lambs, L., Bumpy, F., Imbert, D., Corenblit, D. and Dulormne, M.B. (2015). Seawater and freshwater water circulations through Coastal Forested Wetlands on a Caribbean Island. *Water* 7: 4108-4128.

Leonila, B.S. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award of MSc. Degree at University of Twente, Enschede, Netherland. 46pp.

Masoud, S.S., Msanya, B.M., Semoka, J.M.R. and Maliondo, S.M.S. (2016a). Use of water table as a benchmark for levelling groundwater forest: The case of

Jozani Groundwater Forest, Zanzibar, Tanzania. *International Journal of Scientific and Technical Research in Engineering (IJSTRE)* 1(5): 49-57.

Masoud, S.S., Msanya, B.M., Semoka, J.M. and Maliondo, S.M.S. (2016b). Tidal Trends and Magnitude of Chwaka and Uzi Bays as a Proxy of Seawater Intrusion in Jozani Groundwater Forest, Zanzibar, Tanzania. *American Journal of Agriculture and Forestry (AJAF)* 4(6): 168-177.

Mato, R.A. (2015). Groundwater quality degradation due to salt water intrusion in Zanzibar Municipality. *African Journal of Environmental Science and Technology* 9(9): 734-740.

Mirck, J. and Zalesny, R.S. (2015). Mini-review of knowledge gaps in salt tolerance of plants applied to willows and poplars. *International Journal of Phytoremediation* 17(7): 640-650.

Naderi, M.N., Kermani, M.R.H. and Barani, G.A. (2013). Seawater intrusion and groundwater resources management in coastal aquifers. *European Journal of Experimental Biology* 3(3): 80-94.

Philippa, A., Marc, E., Carl, H., Shirley, H., Rebecca, L., Russel, S., David, S. and Anna, V. (2003). Coastal aquifer saltwater intrusion assessment guidelines. Environment Canterbury Unpublished Technical Report No. R04/18. ISBN 1- 86937-543-2. Revised version of U02/35. 46pp.

Praveena, S.M., Aris, A.Z., Harun, M. and Bidin, K. (2010). Ground water studies in tropical islands. *Malaysian Perspective Episode* 33(3): 200 – 204.

Salum, L.M. (2009). Ecotourism and biodiversity Conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47: 166-170.

Taha, R.A. (2014). Effect of growth regulators and salinity levels on in vitro cultures of jojoba plants. *World App. Sci. J.* 31(5): 751-758.

Zhu, J.T, Yu, J., Wang, P., Yu, Q. and Eamus, D. (2014). Variability in groundwater depth and composition and their impacts on vegetation succession in the lower Heihe River Basin, north-western China. *Marine and Freshwater Research CSIRO Publishing* 65: 206-217.

CHAPTER SIX

6.0 EFFECTS AND IMPLICATIONS OF RAINWATER - SEAWATER INTERACTION ON PHYSICAL AND CHEMICAL CHARACTERISTICS OF JOZANI GROUNDWATER FOREST SOIL, ZANZIBAR, TANZANIA

ABSTRACT

Soil physical and chemical characteristics (SPCC) are indicators of effects of different soil forming factors. These characteristics are influenced by the factors of soil formation. This study assessed the role of rainwater-seawater interaction (RSI) on SPCC of Jozani Groundwater Forest (JGWF). The study area was divided into six transects along which three points were set for probing soil and water characteristics.The study area was divided into 44 grid points which were spaced at 500 m apart. Data collected *in situ* from auger profiles included arrangement and width of soil horizons, soil depth to coral bedrock, soil texture and colour. Other data collected include water depth from the soil surface, pH and total dissolved solids (TDS). Two soil profiles were opened at selected points within JGWF. The points were selected based on transect probing outcomes. Standard soil profile description and sampling procedures were used. Soil samples were analyzed for physical and chemical characteristics. The results showed that JGWF has alkaline soil covered with a thick layer of decomposing plant residues. The soil had few smooth and diffuse horizons overlying the coral bedrock. Olive grey colour (5YR4/2), water saturation, low bulk density (0.23 - 0.54 g cm^{-3}) of gluey clayey-paste like horizons and increasing TDS values towards Chwaka and Uzi bays were identified as basic SPCC, implying that RSI affected in the formation and development of JGWF soil. The study concluded that JGWF area has polymorphic Limnic Histosols (Gleyic)

(Haplosaprists), a soil formed under partially anaerobic conditions on coral bedrock whereby RSI was responsible for its formation and development.

Key words: Transect probing, water tests, profiling and sampling, analysis, soil physical and chemical characteristics, rainwater-seawater interaction, soil formation

6.1 Introduction

Soil physical and chemical characteristics (SPCC) are indicators of the effects and contributions of each of the soil forming factors (Buol *et al.*, 2011; Bockheim *et al*., 2014). These characteristics (as indicators) directly and/or indirectly show the conditions and development processes through which a given soil has undergone during its formation (Quesada *et al.*, 2010; Landon, 2014).

Formation of Jozani Groundwater Forest (JGWF) soil likely started about 2 million years ago following a gradual fall of sea water level and the rise of coral terrain (Nahonyo *et al.*, 2002; Klein, 2008). In this respect, this study considered that the soil which was formed on such a rise of coral land and fall in seawater level was continuously and significantly affected by rainwater-seawater interactions (RSI). Although there is no scientific records describing the intensity of rains that fell onto JGWF by then, it is assumed that the rains were sufficient and influenced JGWF soil formation. According to Nahonyo *et al.* (2002) and Leonila (2011), for decades, JGWF had been receiving an annual average rainfall of about 1400 mm. Also, reports by Werner *et al*. (2013) and Colón-Rivera *et al*. (2014) indicated that rainwater and seawater did interact and influenced the formation of JGWF soil.

Most of the JGWF plant species described by Nahonyo *et al*. (2002) and the Zanzibar

Woody Biomass Survey, ZRG (2013) thrive in the freshwater aquifer. This implies that for centuries JWGF received high amount of rainwater which interacted with seawater and resulted in today's status of JGWF aquifer. It is likely that the vegetation of JGWF consists of plant species which thrive and/or tolerate high concentration of dissolved solids. This scenario implies that both, seawater and freshwater were (and still are) the key components of JGWF soil formation and its development. Landon (2014) and Jones *et al.* (2013) noted that the RSI has an effect and implication on primary SPCC. This study was therefore, aimed to assess physical and chemical characteristics of Jozani Groundwater Forest (JGWF) assuming the overriding effects of rainwater-seawater interaction on JGWF soil formation and development.

6.2 Materials and Methods

6.2.1 Description of the study area

The study was conducted in Jozani Groundwater Forest (JGWF) located between Chwaka and Uzi bays (Fig. 6.1). According to Sustainable Management of Land and Environment II (SMOLE II) (2010), the area lies within the Jozani-Chwaka National Park (JCBNP) and has an areal extent of about 62 km^2, having coordinates between N 9 305 880 to 9 317 855 and E 539 100 to 549 000 in UTM Zone 37S. The Park has a tropical sub-humid climate and receives about 1 400 mm annual average rainfall from long rain season (*Masika*) (April to May) and short rain season (*Vuli*) (October to November) (Leonila, 2011). The bimodal rains has influenced and maintained water table close to the surface (Salum, 2009).

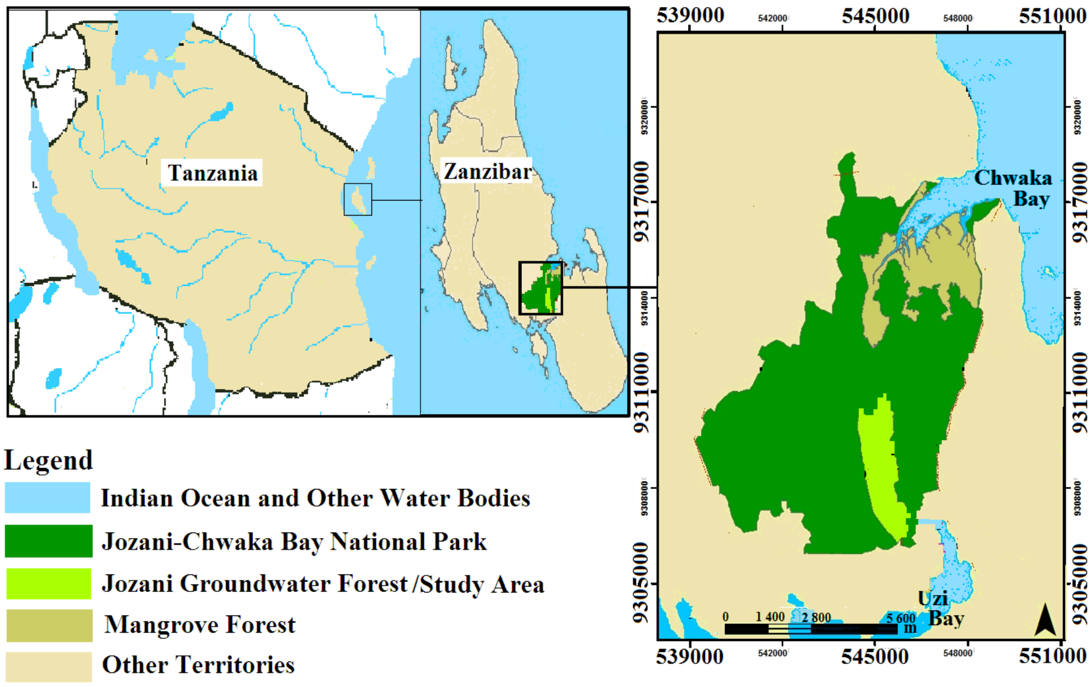


Figure 6.1: Location map of Jozani Groundwater Forest. Source: Department of Forest Non-renewable Natural Resources (DFNNR), Zanzibar

6.2.2 Distribution of auger probing points

Spatial pattern auger probing and *in situ* tests on pH and total dissolved solids (TDS) values were used for rapid capture of soil and water characteristics (He *et al.*, 2014; Tippler *et al.*, 2014). The study area was divided into 11 x 4 gridlines, Northings 9 306 800 and 9 311 800 and Easterns 544700 and 546 200 in UTM grid zone 37S. A total of 44 grid points spaced at 500 m apart were delineated and their coordinates uploaded on a Geographical Positioning System (GPS) receiver model GARMIN ***e***trex 10 set, which was later used to navigate to the location.

6.2.3 Auger probing

Auger probing along a selected transect is widely used for soil studies which involve spatial data collection (Zhu *et al.*, 2013). The gathered information from such probing includes changes of vegetation, elevation, slopes, and soil physical and chemical characteristics (Landon, 2014; Jones *et al.*, 2013). Global Positioning System (GPS) model GARMIN *e*trex 10 was used to navigate the study teams to the probing points. On each grid point a soil auger was used to collect soil samples at 0.1 m interval down the profile depth to the bedrock. For each soil sample, the following information was collected: condition and width of organic matter, number of soil horizons, soil colour, and soil texture and moisture conditions. Texture and moisture conditions were estimated by '*Feel'* method.

6.2.4 Testing of total dissolved solids

Water samples were collected from auger bore-holes after the soil mass had been collected leaving the bore-hole saturated with water. Canister was used to sample water from the bore- holes. Water sampling was done, two to three minutes after the water in the bore-hole attained its level. Floating ruler was used to measure the depth of water surface from the soil surface. The length of canister was therefore equal to the measured depth plus the sampling depth which was about 0.1 m from the water surface. Each water sample was analysed *in situ* for pH and total dissolved solids (TDS) using a Hanna Combo Tester HI 98129 (Emmanuel and Chukwu, 2010). Water samples with TDS value readings higher than instrumental upper limit (2 000 mg L^{-1}) were diluted to a readable dilution and Equation 1 was used for calculation.

TDS = (TDS Reading * df) – TDS dil……………………………………………(1)

Where; TDS = total dissolved solids, TDS reading = TDS values from the instrument, df = dilution factor, TDS dil = TDS of water used to dilute water sample.

6.2.5 Soil description and sampling

The selection of the points for soil profiling for JGWF soil classification was done using the information gathered from auger probing (Section 6.2.3) and water TDS testing (Section 6.2.4). Soil profiling, description and sampling were done as per FAO (2006) Guidelines for Soil Description. The United Republic of Tanzania (URT), Zanzibar topographic maps of the Department of Survey (DOS) series of 1980s were used for site orientation. Tanzania National Soil Service soil profile description form was used as guide for *in situ* soil profile descriptions and recording on transfer sheets. Generally, in JGWF profile depth was about 60 cm deep, beyond which there were saturated by groundwater. Therefore, from each profile, decomposing plant residues and soil samples before 60 cm were sequentially collected, while soil samples from 60 to 150 cm were collected by a soil auger. Soil samples were collected from each identified horizons in the profile. Core samplers (of 100 cm^3) were used to collect undisturbed soil samples at 0 - 0.05, 0.45 - 0.50 and 0.95 - 1.00 m depths. The decomposing plant residues and soil materials were sequentially collected, evenly spread on a flat wooden board to form a sort of JGWF soil profile model. The GARMIN *e*trex 10 GPS was used for geo-referencing the profiling points.

6.2.6 Physical and chemical analysis

Laboratory analyses included particles size distribution and textural classes, bulk density, moisture characteristics, organic carbon (OC), pH, total nitrogen (TN%), cation exchange capacity (CEC), available phosphorus (P) and exchangeable cations (K, Na, Mg and Ca) and total elemental composition. The analysis on particles size distribution was done by hydrometer method (Day, 1965) while textural classes were determined using the USDA textural triangle and bulk density by gravimetric method. At Zanzibar Agriculture Research Institute (ZARI), soil pH in H_2O and in KCl in 1:2.5 soil to water ratios were done potentiometrically; OC by Walkey and Black, then multiplied by 1.724 to get organic matter; TN% and CEC (distillation) by Kjeldahl method and available P by Bray 1 (for samples with pH $<$ 7) and Olsen (for samples with pH $>$ 7). Analysis of exchangeable cations and CEC was done by neutral Ammonium acetate extraction and determined by AAS. Undisturbed soil samples were used for determination of soil bulk density and moisture retention characteristics was determined by pressure plate/membrane at Mlingano Agricultural Research Institute, Tanga. Analysis for total elemental composition was done at Geological Survey of Tanzania (GST) laboratories, Dodoma. At GST analysis, total Aluminum was determined by Inductively Coupled Plasma ICP-OES Progidy 7, silicon by Utraspec 2000 UV/Visible spectrophotometer. The remaining elements were analysed by EDXRF, MiniPal 4 X-Ray fluorescence (XRF).

6.2.7 Data analysis

Excel software was used for statistical analysis of collected data. Descriptive statistics was used to discern effects and implications (E&I) of rainwater-seawater interaction (RSI) on JGWF soil physical and chemical characteristics (SPCC).

6.3 Results and Discussion

6.3.1 Transect probing outcomes

Summarized information gathered from auger probing on grid points are presented in Appendix 2. The probing results indicate that Jozani Groundwater Forest (JGWF) has one type of soil. However, soil depth, width of layer of decomposing plant residues, coral outcropping and total dissolved solids are among the parameters which varied from one point to another within JGWF. Soil depth, thickness of decomposing plant residues, and coral outcrops increased in the south-east direction while TDS increased in the north-west direction towards Chwaka bay.

Results from auger probing showed that, JGWF soil *solum* was covered by 0.10 to 0.23 m thick layer of moist decomposing plant residues. The thickness of the organic layer increased as the probed points approached south and eastern parts of the forest. Beneath this layer, there was a humic horizon of about 0 - 0.12 m which consisted of moist, slightly compacted, very dark well decomposed material mixed with top soil mass of grayish brown (10YR3/2) colour. This was then followed by a brown (10YR4/3) colored, moist or wet, slightly compacted horizon. This horizon of about 0.1 to 0.15 m was followed by a thick water saturated olive gray (5YR4/2) clay-paste like loose horizon overlying the unevenly undulant coral bedrock. The thickness of soil horizons increased towards the south and east of the forest.

6.3.2 Physical and chemical characteristics of Jozani Groundwater Forest

Table 6.1 shows water characteristics and low bulky density of soil which are among the distinctive physical properties of JGWF. The soil has a considerable high percentage of the available moisture (AM) that increased with depth and ranged from 28 to 36%. The soil has low bulky density (BD) which increased with depth from 0.23 to 0.54g cm^{-3}. The values of BD and AM of JGWF were mainly contributed to a thick layer of plant residues and paste-like clay material.

Table 6.1: Moisture retention characteristics and bulk density of Jozani Groundwater Forest soil

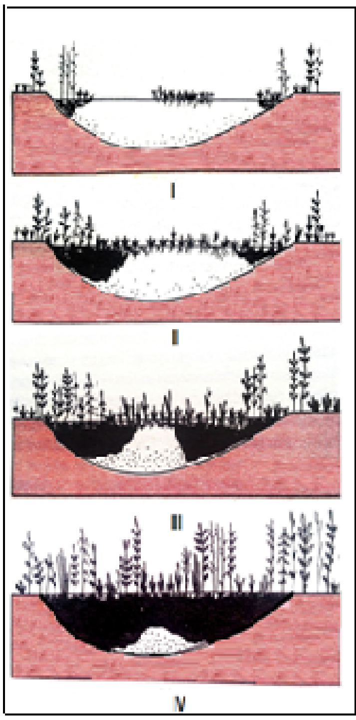
Depth	**Moisture, %**						**BD**
	0.02 Bar	**0.06 Bar**	**0.3 Bar**	**6.1 Bar**	**15.0 Bar**		
cm	**0.3 PSI**	**0.9 PSI**	**4.4 PSI**	**87 PSI**	**218 PSI**	**Available**	**g cm^{-3}**
0-5	59.9	56.5	52.7	35.1	25.1	27.60	0.23
45-50	72.0	70.8	69.6	46.4	33.8	35.80	0.58
95-100	67.3	65.5	62.3	41.5	29.9	32.45	0.54

BD = bulk density

Information on primary soil physical and chemical characteristics (SPCC) obtained during soil profiling and from soil laboratory analysis is shown in Appendix 3. The SPCCs were used to classify JGWF soil to Tier 2 of the World Reference Base (WRB) for Soil Resources (FAO, 2014) and up to Subgroup level of the USDA Soil Taxonomy (Soil Survey Staff, 2014). Generally, JGWF has peat soil overlying gluey clays which were formed under partially anaerobic conditions on semi-permeable coral bedrock. The soil was classified as *Limnic Histosols* (*Gleyic*) at Teir II of WRB and Haplosaprists for USDA classification, respectively. Results of the total analysis of JGWF soil are shown in Appendix 4. Among the distinctive chemical properties of JGWF were: the low percentage of silica (SiO_2) which ranged from 18 to 29 %, and a wide range of sulphur (S) content (280 - 5500 mg kg^{-1}). The concentrations of other selected elements were as follows: a short range but significant concentration of chloride (Cl) (2 300 – 3 000 mg kg^{-1}) and significant amounts of chromium (Cr) ranging from about 300 to 320 mg kg^{-1}.

6.3.3 Effects and implication of seawater-rainwater interaction

The current study used the physical and chemical characteristics (SPCC) of JGWF soil to describe how far rainwater-seawater interaction (RSI) influenced soil formation and development of the forest (JGWF). The probing results imply that soil formation in JGWF started and developed more on the south-east areas. This was based on soil depth and layers of plant residues which were much higher in those areas of JGWF. Each of the SPCC highlighted one or more effects and implication (E&I) of RSI, but most of the SPCC of JGWF showed certain phenomena of E&I of close to the surface groundwater aquifer. In addition to that, spatial and wide ranges of TDS values were indicators of E&I associated with RSI. From such implications, this study found that soil formation in JGWF followed by the processes suggested by Ershov *et al*. (1988) as shown in Fig. 6.2a and described in Fig. 6.2b.



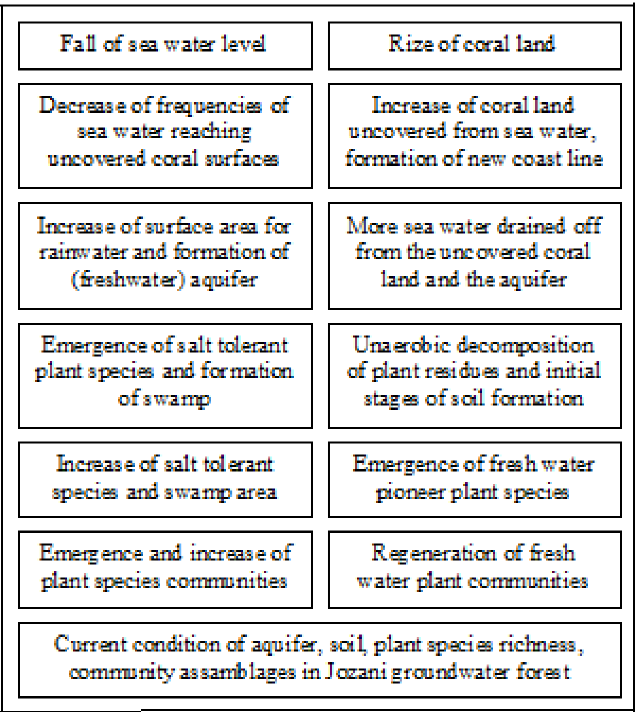


Figure 6.2a **Figure 6.2b**

Figure 6.2: a) Soil formation and development under water saturation/swampy condition, stages of plant species habituation and b) Schematic stages of soil formation and development in Jozani Groundwater Forest.

In Fig. 6. 2a, stages I to IV indicate that soil formation started with decomposition of plant residues from pioneer low plant species to soil organic matter accumulated from other higher plant species. Rainwater-seawater interaction in JGWF was related to Ershov et al. (1988) stages of soil formation under swampy condition. Information obtained from Figures 6.2a and b imply that after the fall of sea water level and the rise of corals, JGWF aquifer was simultaneously changed from seawater to freshwater aquifer. The expansion of freshwater aquifer happened together with soil formation and development. Generally, the formation of JGWF soil took place under water saturation on every part of today's JGWF which by then acted as seawater trough (passage) running between Chwaka and Uzi bays while separating the east and west coral terrains. Seawater passage and movement across the trough were gradually shrinking and then split into two halves by encroachment and development of pioneer plants and expansion of soil. During heavy rainfall, seawater was gradually diluted and drained off from the soil mass which was formed on low elevated flattened coral bedrocks. The soil coverage trend was similar to the freshwater-seawater interface trends were gradually shifted towards the bays. The condition implies that the rainwater and marine water were part and parcel of soil formation and development of JGWF soils. Salt tolerant species mentioned in Fig. 6.2 were considered as among the non-forest plant species but were the primary pioneer species for JGWF soil formation and development. This trend implies that *Paspalum vaginatum* (Seashore couch) was among the earliest plant species to habituate in the JGWF and continued its presence in the North-end of JGWF.

6.3.4 Effects and implication of shallow water table on Jozani Groundwater Forest soil

Many of JGWF soil physical properties, separately and in combination show certain phenomena of the effects and implication of being close to the surface aquifer (groundwater). On the other hand, the spatial and wide range of TDS values in JGWF area indicate that in the past and currently, the two types of water have always interacted with each other. Morphology of JGWF soil (Plate 6.1) and other soil physical and chemical characteristics (SPCC) imply that rainwater and seawater have been interacting on stream-like coral terrains. Plate 6.2 shows a general view of

JGWF soil profile which is covered by a thick layer of decomposing organic matter. The thickness of the organic layer differed from place to place. Beneath this layer, was a humic soil horizon of about 0.8 to 0.12 m, which was moist, slightly compact, with very dark grayish brown colour, followed by a brown coloured, moist or wet, slightly compact horizon of about 0.1 to 0.15 m, followed by a thick (> 0.5 m) water saturated olive gray horizon resting on an unevenly undulant coral bedrock.

Plate 6.1: A general view of Jozani Groundwater Forest soil profile

6.3.5 Existence of Jozani Groundwater Forest in future

Tongkul *et al*. (2013) reported that, natural forests are self managed, so do the vegetative condition in JGWF which implies that JGWF has for centuries been expanding resulting from favourable ecosystem with rainwater-seawater interaction (RSI) equilibrium. According to Vice President Office (VPO) (2012) and Naderi *et al*. (2013), JGWF is subjected to intrusion. Meanwhile, Masoud *et al*. (2016) reported that seawater intrusion took place from Chwaka and Uzi bays. Furthermore, Bindoff *et al.* (2007) noted that sea level rises at rate of 0.4 to 2.0 mm/yr. From the above citations and RSI conditions in JGWF, the implication is that currently, JGWF is either on the edge of its expansion or at a turning point and is been gradually reduced by seawater intrusion from the bays. However, the expansion or turning point situation of JWGF needs further studies.

6.4 Conclusions and Recommendations

This study concludes that soils of JGWF are peat soils overlying gluey clays which were formed under partially anaerobic conditions. The soils are Limnic Histosols (Gleyic) refred to FAO, WRB and/or Haplosaprists refered to USDA, Taxonomy. The soils vary in depth to the bedrocks, and in salinity towards Uzi and Chwaka bays. This study also concluded that rainwater and marine water appeared to influence soil formation of JGWF on low elevated flattened coral bedrocks which were formed in marine creek running between the two bays. The formation and development of JGWF involved a gradual pushing of seawater out of the present JGWF area by bimodal rainwater. This study concludes futher that the low TDS values in the inner part of JGWF implies that seawater intrusion in the area has ended several centuries but are slow pace and it is still active in the outer parts of JGWF before grassland and mangroves towards Chwaka and Uzi bays. In addition, this study concludes that the rise of sea level will favour seawater intrusion into JGWF territory which changing the soil and water characteristics and may negatively affect forest biodiversity.

6.5 References

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D. and Unnikrishnan, A. (2007). Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D. Manning, M., Chen, Z. Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 429pp.

Bockheim, J.G., Gennadiyev, A.N., Hartemink, A.E. and Brevik, E.C. (2014). Soil-forming factors and Soil Taxonomy. *Geoderma* 226*:* 231-237.

Buol, S.W., Randal, J.S., Robert, C.G. and Paul, A.M. (2011). *Soil Genesis and Classification*. John Wiley and Sons. 560pp.

Colón-Rivera, R.J., Feagin, R.A., West, J.B., López, N.B. and Benítez-Joubert, R.J. (2014). Hydrological modification, saltwater intrusion, and tree water use of a Pterocarpus officinalis swamp in Puerto Rico. *Estuarine, Coastal and Shelf Science* 147: 156-167.

Emmanuel, B.E. and Chukwu, L.O. (2010). Spatial distribution of saline water and possible sources of intrusion into a tropical freshwater lagoon and the transitional effects on the lacustrine ichthyofaunal diversity. *African Journal of Environmental Science and Technology* 4(7): 480-491.

Ershov, V.V., Novikov, A.A. and Popova, G.B. (1988). *Fundamentals of Geology*. Mir Publishers, Moscow. 358pp.

FAO (2006). *Guidelines for soil description.* Fourth Edition. FAO Rome. 97pp.

FAO (2014). *World Reference Base for Soil Resources.* International soil classification system for naming soils and creating legends for soil maps.

World Soil Resources Reports IUSS Working Group WRB, No. 106, Rome. Italy 181pp.

He, B., Cai, Y., Ran, W. and Jiang, H. (2014). Spatial and seasonal variations of soil salinity following vegetation restoration in coastal saline land in eastern China. *Catena* 118: 147-153.

Jones, A., Breuming-Madsen, H., Brossard, M., Drmpha, A., Deckers, J., Dewitle, O., Gallali, T., Hallert, S., Jones, R., Kilasara, M., Le Roux, P., Micheli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Yemefack, M. and Zougmore, R. (Eds.) (2013). *Soil Atlas of Africa*. Europian Commission Publication office of the European Uniun, Luxembourg. 176pp.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Exploratory study on the relation between soil variability and landscape. Dissertation for Award MSc Degree at Turku University Department of Geography Publications B 11. 85pp.

Landon, J.R. (2014). *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. Routledge. 465pp.

Leonila, B.S. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award of MSc. Degree at University of Twente, Enschede, Netherland. 46pp.

Masoud, S.S, Msanya, B.M., Semoka, J.M. and Maliondo, S.M.S. (2016). Tidal Trends and Magnitude of Chwaka and Uzi Bays as a Proxy of Seawater Intrusion in Jozani Groundwater Forest, Zanzibar, Tanzania. *American Journal of Agriculture and Forestry* (*AJAF)* 4(6): 168-177.

Naderi, M.N., Kermani, M.R.H. and Barani, G.A. (2013). Seawater intrusion and groundwater resources management in coastal aquifers. *European Journal of Experimental Biology* 3(3): 80-94.

Nahonyo, C.L., Mwasumbi, L.B., Eliapenda, S., Msuya, C., Mwansasu, C., Suya, T.M. and Kihaule, P. (2002). *Jozani-Chwaka Bay proposed National Park biodiversity inventory report.* Submitted to Care Tanzania and Department of Commercial Crops, Fruits and Forestry, Serikali ya Mapinduzi, Zanzibar. 184pp.

Quesada, C.A., Lloyd, J., Schwarz, M., PatiÃo, S., Baker, T.R., Czimczik, C., Fyllas, N.M., Martinelli, L., Nardoto, G.B., Schmerler, J. and Santos, A.J. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences* 7(5): 1515-1541.

Salum, L.M. (2009). Ecotourism and biodiversity conservation in Jozani-Chwaka Bay National Park, Zanzibar. *Africa Journal of Ecology* 47: 166-170.

Soil Survey Staff (2014). *Keys to Soil Taxonomy*. Twelfth Edition. United States Department of Agriculture, Natural Resources Conservation Service. 359 pp.

Tippler, C., Wright, I.A., Davies, P.J. and Hanlon, A. (2014). The influence of concrete on the geochemical qualities of urban streams. *Marine and Freshwater Research* 65(11): 1009-1017.

Tongkul, F., Lasimbang, C., Lasimbang, A. and Chin, P. (2013). Traditional knowledge and sustainable forest management (SFM) experience from Malaysia, FAO *Unasylva* 64(240): 41 – 49.

Vice President Office (2012). *National Climate Change Strategy.* Division of Environment. United Republic of Tanzania. 92pp.

Werner, A.D., Bakker, M., Post, V.E., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T. and Barry, D.A. (2013). Seawater intrusion processes, investigation and management: recent advances and future challenges. *Advances in Water Resources* 51: 3-26.

Zanzibar Revolutionary Government (2013). Zanzibar Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report. Using Zanzibar Woody Biomass Survey in Policy and Planning Processes, Working Paper. Indufor (Forest Intelligence) and Norwegian Embassy, Zanzibar, Tanzania.139pp.

Zanzibar Sustainable Management of Land and Environment II (2010). The Zanzibar National Forest Policy Analysis (2010 - 2013). Final Report. 88pp.

Zhu, J.T., Yu, J., Wang, P., Yu, Q. and Derek, E. (2013). Variability in groundwater depth and composition and their impacts on vegetation in Heihe River Basin, China. *Marine and Freshwater Research CSIRO* 65: 206-217.

CHAPTER SEVEN

7.0 INFLUENCE OF SPATIAL ENVIRONMENTAL GRADIENT ON ASSEMBLAGE OF PLANT SPECIES COMMUNITIES IN JOZANI GROUNDWATER FOREST, ZANZIBAR, TANZANIA

ABSTRACT

In a natural forest, plant species richness and assemblage follow a certain gradient which is retained or change as a result of the interaction of spatial-environmental are temporal factors affecting the species within the plant communities. Jozani Groundwater Forest (JGWF) has high plant species diversity, and this study was intended to reveal the underlying spatial-environmental factors affecting plant species assemblage and distribution. Data collected from 34 grid points included: soil depth to coral bedrock, total dissolved solids (TDS), and plant species were identified counted and measured for diameter at breast height (DBH). GARMIN ***e***trex 10 set was used to georeference location of four quadrat plots and also used to establish the quadrats. Tree species with DBH ≤5 cm were measured in quadrats of 4 m^2; those with DBH > and <10 cm in quadrats of 100 m^2.˙ Trees with with DBH ≥ 10 ≤ 25 cm were measured in quadrats of 400 m^2, and > 25 cm in quadrats of 900 m^2. The plant species abundance matrix data were analysed by unconstrained ordination using Redundancy Analysis (RDA). The results showed that there were about 69 plant species from 45 familes and 53 genera. Species composition was substantially affected by salinity and spatial gradients. Five plant communities were identified from the survey and during analysis. There were two clear and sharp ecotones of 40 to 50 m wide dominated by *Acrostichum aureum* (Mangrove fern) found between the area of pure stands of *Paspalum vaginatum* (with TDS > 20 000 mg L^{-1}) and the area of mixed plant species dominated by *Nephrolepis biserrata* (Giant swordfern), *Terminalia boivinii* (Terminalia) and *Guettarda speciosa* (Beach gardenia) (with TDS of about 15 000 mg L^{-1}). Thus, salinity and spatial gradient are the factors influencing plant species assemblage in JGWF. Management intervention for plant species protection and restoration of JGWF should therefore take into account the existing salinity and spatial distribution of ecotones.

Key words: Assemblage, environmental factors, plant communities, plant species, spatial distribution

7.1 Introduction

Plant species distribution is strongly influenced by environmental factors, causing non-random distribution of species community assemblage in a landscape (Pellissier *et al.*, 2013). Plant species often display non-random distribution patterns on the ecosystem in response to species-specific limiting environmental factors (Kikvidze *et al.*, 2005). Plant distribution along spatial gradient is significantly affected by both biotic and abiotic factors (Meier *et al*., 2010; Pellissier *et al*., 2013; Wisz *et al*., 2013). Key abiotic elements affecting plant species distribution in marine wetland ecosystems include soil nutrients and salinity (Monge-Nájera, 2008). According to Blaser and Gregersen (2013), salinity is one of the main determinants of plant assemblage in tropical coastal forests. Apart from abiotic factors climate influenced functions such as flooding cycles and tides have a large influence on plant species community assemblage (Ribeiro *et al*., 2011). However, plant community distributions in forests are not static and can change over time due to changes in abiotic factors (Crain *et al*., 2004; Ahmad *et al*., 2013). Surface water table in marshy forests like JGWF (Salum, 2009) has a significant impact on vegetation succession (Praveena *et al*., 2011; Zhu *et al*., 2013) depending on seasonal fluctuation of water table between dry and wet seasons (Balley-Serres and Timothy, 2014).

Plant ecotones are common in coastal forests and represent gradients from marine water-tidal zones to freshwater and inland (Martin *et al*., 2007; Ribeiro *et al*., 2011; Gonçalves and Souza, 2014). Multiple plant species assemblages in a forest are separated by ecotones of various vegetation and spatial trends (Davis *et al*., 1999; Gonçalves and Souza, 2014). In tropical forests, spatial distribution of plant species and their associated ecotones tend to increase with increased variations of soil properties, water availability, topography, and number of plant genera and species (Greenwood *et al*., 2014; Gonçalves and Souza, 2014; Zhang *et al*., 2014). Other factors include genetic properties of individual species that are favoured or hampered by environmental conditions brought about by other species around or within the plant assemblage (Martin *et al*., 2007; Zhang *et al*., 2014).

Forests cover about 44.5% of Zanzibar territory, 83.3% of which is occupied by coral forest (Sustainable Management of Land and Environment II (SMOLE II), 2013). Jozani Groundwater Forest (JGWF) is surrounded by coral terrain with Lithic Leptosols (Hettige, 1990) which are characterized by a wide range of coral outcrops and varying soil depth to coral bedrock (SDCB) that makes various bedrock roughnesses (BR). The coral terrain is dominated by dry bushland thickets community that makes biomass of about 10 tonnes ha^{-1} (Nahonyo *et al*., 2002 and Zanzibar Revolutionary Government (ZRG) (2013)). There is high plant species diversity and biomass (>50 tonnes ha^{-1}) in JGWF (ZRG, 2013) presumably due to favorable plant growth conditions such as high soil nutrients and depth of rooting zone (Frank *et al*., 2010).

Thus, the overall objective of tthis study was to assess plant community assemblage patterns along spatial and environmental gradients in the Jozani Groundwater Forest (JGWF). The study hypothesis was that plant community assemblages in JGWF are influenced by environmental factors associated with water salinity, because of the complex distribution of water tides along relatively flat coastal belt terrain. Specifically, the study focused on the following questions: (1) What are the overall plant species composition in the JGWF?, (2) How does distances and environmental (land elevation, soil depth to coral bedrock, bedrock roughness, and total dissolved solids) factors influence species community assemblage in the JGWF?, (3) What are the indicator plant species along the salininity gradient in JGWF? and (4) Based on these results, suggest management recommendations for the JGWF.

7.2 Materials and Methods

7.2.1 Description of the study area

The study was conducted in Jozani Groundwater Forest (JGWF) area located between the Chwaka and Uzi bays (Fig. 7.1). The JGWF of about 590 ha is located within the Jozani-Chwaka Bay National Park (JCBNP) area of about 62 km^2, lies between Northerns 9 305 880 to 9 317 855 and Easterns 539 100 to 549 000 in UTM zone 37S (SMOLE II, 2013). This area of the park has a shallow water table (Salum, 2009) which during rains seasons often emerges above the ground surface forming temporary marshes. The park has a tropical sub-humid climate and receives about 1400 mm annual average rainfall from *Masika* (long rains) during April to May and *Vuli* (short rains) between October and November (Leonila, 2011; Kukkonen, 2013).

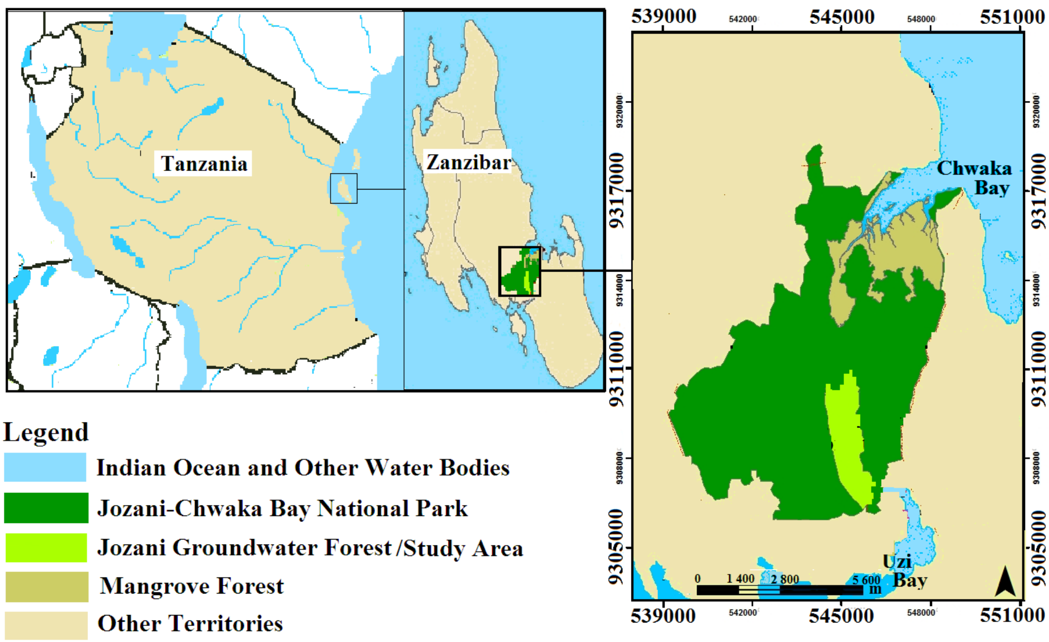
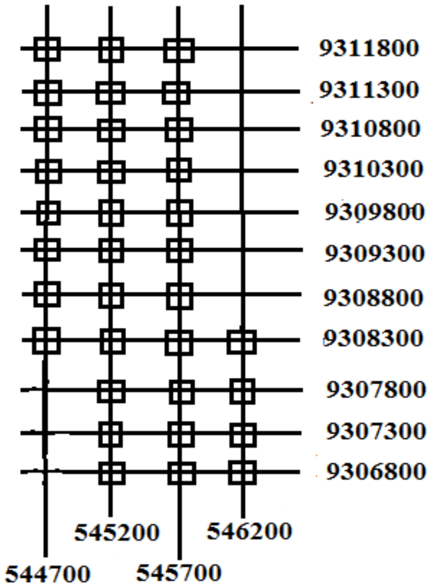


Figure 7.1: Location of Jozani Groundwater Forest. Source: Department of Forest Non-renewable Natural Resources (DFNNR), Zanzibar

7.2.2 Sampling design and plot sizes

The study area was divided into 11 x 4 gridlines between Northings 9 306 800 and 9 311 800 and Easterns 544 700 and 546 200 in UTM Zone 37S (Fig. 7.2a). A total of 44 grid points spaced 500 m apart were delineated and their coordinates uploaded on a Geographical Positioning System (GPS) receiver model GARMIN ***e***trex 10 set, which was later used to navigate study team to the grid points. In each grid point four plant species scoring quadrates were established. A quadrat of 900 m^2 nested the rest three quadrates of 4, 100 and 400 m^2 (Fig. 7.2b). The quadrates were marked using ranging poles and wide yellow coloured thread tapes.



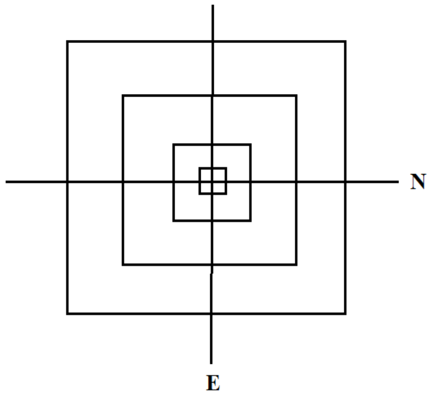


Figure 7.2a **Figure 7.2b**

Figure 7.2: a) Schematic diagram of plot layout in the study area: a) Grid system used for data collection and b) Plant species scoring quadrates at grid points in Jozani Groundwater Forest

7.2.3 Data collection

All plants in a quadrat were measured for plant diameter at breast height (DBH) using aluminum caliper (Model Hagl of Mantax). Plant species with DBH less than or equal to 5 cm (≤ 5 cm) were measured in the smaller quadrat of 4 m^2, those greater than 5 but less than 10 cm (> 5 < 10 cm) were measured in quadrat of 100 m^2, those equal and greater than 10 but less than 25 cm (≥ 10 < 25 cm) were measured in quadrat of 400 m^2, and those above 25 cm (> 25 cm) were measured in quadrat of 900 m^2, respectively. All measured tree species were identified in the field, for species that were not identified in the field specimens were taken to a Botanist in Jozani-Chwaka Bays Biosphere Reserve for further identification. The check list of the identified species was further validated with existing check list from the study areas (Nahonyo *et al.*, 2002; ZRG, 2013). Plant canopy density of plots was estimated with the help of

Forest Spherical Concave Densiometer (MPN: 43888 - Forestry Suppliers). To obtain water total dissolved solids (TDS), a floating ruler was used to measure the depth of water surface from soil surface when water in the hole made by soil auger in the smaller quadrat (4 m^2) attained its level. The measured depth was used to determine the length of canister that was supposed to sample water at 0.1 m from the water surface. The TDS values of water samples were obtained *in situ* with the help of Hanna Combo Tester HI 98 129. In case of water samples with TDS exceeding the instrumental upper limit (2 000 mg L^{-1}), the samples were diluted to readable dilution and the TDS values were calculated by Equation 1.

TDS = (TDS Reading * df) – TDS dil……………………………………………(1)

Where; TDS = total dissolved solids, TDS reading = TDS values from the instrument, df = dilution factor, TDS dil = TDS of water used to dilute water sample.

At a grid point, within the length of plot 2 (Quadrate with 100 m^2) along northern grid lines, five long stick probes were done at one-meter long interval. The data from the stick probes were used to estimate the soil depth to coral bedrock (SDCB) as an arithmetic mean and were used to estimate the bedrock roughness (BR) as standard deviation of the measured depths by Equations (2) and (3), respectively.

$$\mathrm{SDCB} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad \ldots\ldots (2)$$

$$\mathrm{BR} = \sqrt{v} \ \text{ where } v = \frac{1}{n}\sum X_i^2 - \left(\overline{X}\right)^2 \quad \ldots\ldots (3)$$

Where, Xi; is measured depths (m) from the soils surface to the bedrock, n; is number of probes.

7.2.4 Data analysis

Elevation of the grid points were estimated from Digital Elevation Model (DEM) developed by Masoud *et al*. (2016). Plant species composition was given as all plant species encountered in the study area. Unconstrained ordination using Detrended Correspondence Analysis (DCA) of plant species abundance matrix indicated a gradient length of 3.9 standard deviation units (SD Units). Since SD Units above 4 suggest a unimodal response to underlying gradient (Ter Braak, 1987), gradient length between 3 and 4 standard units suggest intermediate gradient. Thus Redundancy Analysis (RDA) was chosen over Canonical Correspondence Analysis (CCA) since both approaches would lead to more less similar results (Legendre and Gallagher, 2001).

Sample-plot of tree species abundance matrices was constrained by sets of environmental and spatial variables using RDA, respectively (Økland and Eilertsen 1994; Borcard *et al.*, 1992). The enivornmental variables included soil depth to coral bedrock (SDCB), bedrock roughness (BR), elevation, and total dissolved solids (TDS). The spatial variables were obtained through decomposition of a truncated geographical distance matrix among plot locations in their respective groups from Moran’s Eigenvector Maps (MEMs), which accounted for the spatial correlations using function “dbMEM” in R-software (Dray *et al.*, 2006). The connectivity of multiple spatial patterns obtained from the MEMs represents a wide range of spatial scales that can be used as complex patterns of spatial variations in plant community composition (Borcard *et al.*, 2011). The MEMs was calculated from best linear combinations of eigenvectors based on maximum spanning tree and weighed algorithms (significant Moran I’s coefficients, Monte Carlo-permutation test (α =

0.05, 999) using forward selection double stopping criteria (Borcard *et al*., 2011; Blanchet *et al*., 2008). The study interest was on broad scale spatial patterns, thus MEMs with minimum truncation distances and positive significant Moran I's coefficients were retained for subsequent analysis (Borcard *et al*., 2011; Dray *et al*., 2012).

The species response matrix was transformed using Hellinger transformation (Borcard *et al*., 2011) and all explanatory variables were corrected for skwedness, standardized and checked for colinearity. Multicolinearity of all environmental variables prior using RDA was checked using VIFs and all variables with VIF ≤ 8.0 (Zuur *et al*., 2010) and Pearson correlation (r ≤ 70%) were retained for the subsequent analysis (Dormann *et al*., 2013).

For each set of explanatory variables, an automatic stepwise forward selection was used to select the significant variables that explain variations in species composition by RDA regression using function "forward.sel ()" procedure in the package "packfor" in R-software (Blanchet *et al*., 2008). Significant variables were tested using Monte Carlo-permutation test (α = 0.05, 999) with unrestricted RDA axis model (Borcard *et al*., 2011; Legendre and Gallagher, 2001). In addition, to determine indicator species for each salinety category, indicator species analyses was conducted from vascular plant community using the function 'indval' from the 'indicspecies' library of the R package (Cáceres, 2013).

7.3 Results and Discussion

7.3.1 Results

Environmental variables and species composition along Northings captured from this study are shown in Table 7.1 and Appendix 5. Plant species spatial-environmental variations Moran's Eigenvector Map (MEM) and plant species assemblage in Jozani Groundwater Forest are shown in Figures 7.3 and 7.4, respectively.

Table 7.1: The environmental variables measured in Jozani Groundwater Forest

Variables, unit	Categories/Groups					Range	
	1	2	3	4	5	Min	Max
Elevation, m, AMSL	< 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	> 2.5	0.75	2.5
Salinity, x 10^3 mg L^{-1}	0 – 0.5	0.5 – 2	2 – 5	5 – 10	> 1 0	0.2	> 10
Soil depth, m	0.0 - 0.35	0.35 - 0.7	0.70 - 1.05	1.05 - 1.4	> 1.4	0.1	> 1.4
Roughness, m	0.0 - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	> 0.4	0.1	> 0.4
Canopy density, %	< 80	80 - 85	85 - 90	90 - 95	95	80	97

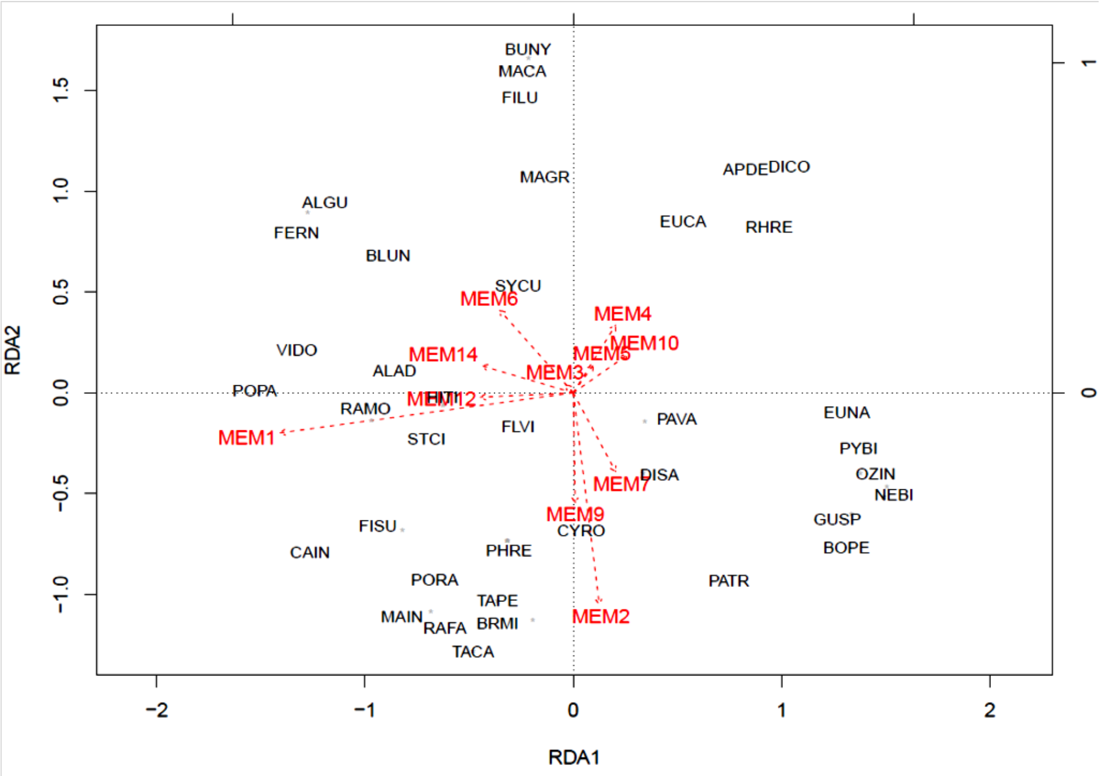


Figure 7.3: Plant species spatial-environmental variations Moran's Eigenvector Map (MEM) for Jozani Groundwater Forest

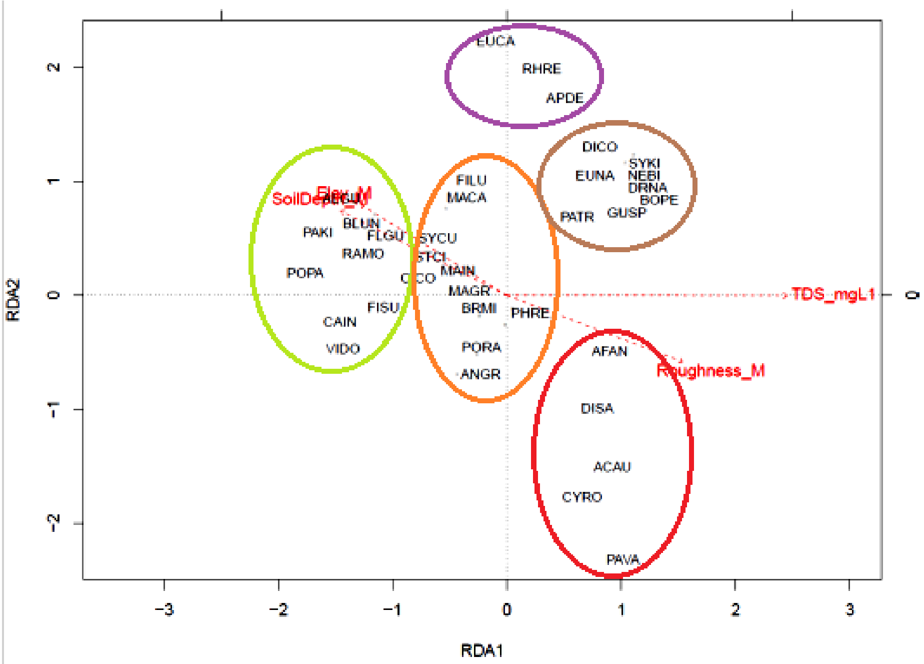


Figure 7.4: Species community assemblage correlated to environmental variables

Variable sets selected (at $p < 0.05$ with 999 Monte Carlo permutation test) to represent the three sets of environmental variable (EV) and spatial heterogeneity (SV) used in the redundancy analysis (RDA) variance partitioning of the plant species composition in JGWF (n = 34) in Jozani Groundwater Forest (JGWF), 2015 are shown in Table 7.2. Table 7.3 shows RDA variation partition used to determine the influence of environmental factors and spatial variation variables on plant species composition in JGWF, 2015. The *F-value* and *p-values* obtained from 999 permutations test showing the significance ($\alpha = 0.05$) of the environmental fractions in the reduced model (total variance) explained is given by the adjusted R^2, due to bias associated with R^2. Fig. 7.5 shows Venn diagram of variation of plant species composition that explained by sets of environmental and spatial variables. Indicator species along salinity gradient of JGWF are shown in Table 7.4 and species richness and dominance along northern grid lines are shown in Appendix 5.

Table 7.2: Spatial-environmental variations along northern gridlines

Variables subsets	**Variables**	***F-value***	***p-value***
Environmental (EV)	**TDS_mg L^{-1}**	7.328	0.001
	Spatial Trend [MEM1]	8.026	0.001
Spatial Variables (SV)	Spatial Trend [MEM2]	6.806	0.001
	Spatial Trend [MEM3]	4.121	0.002
	Spatial Trend [MEM4]	4.031	0.002
	Spatial Trend [MEM5]	2.643	0.009
	Spatial Trend [MEM6]	2.550	0.009
	Spatial Trend [MEM7]	2.617	0.006
	Spatial Trend [MEM81]	2.178	0.025
	Spatial Trend [MEM91]	2.259	0.022
	Spatial Trend [MEM10]	2.290	0.017
	Spatial Trend [MEM11]	1.930	0.042

Table 7.3: Spatial-environmental effects

Source of variation	**Covariable**	**DF**	**Variance**	**Adj. R^2 (%)**	***F-Value***	***p-Values***
Total effect: Environmental (EV) and Spatial (SV		12	0.655	59.5		
Spatial (SV)		11		59.4		
Environ. (EV)		1		0.1		
Spatial (SV)		11		43.2		
Partial Effects						
Environmental (EV)	Spatial (SV)	1	0.008		0.9414	0.489
Spatial (SV)	Environmental (EV)	11	0.364		4.106	0.001
Joint Effect						
Environmental Intersects Spatial		12		16.2		
Enviroment Given Spatial				2		
Spatial given Environmental				10		
Union				14		
Residuals				40.5		

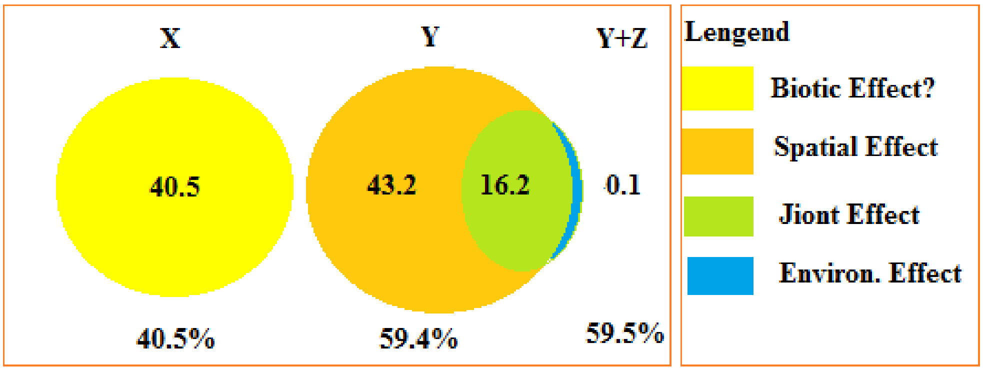


Figure 7.5: Venn diagram, showing variation of plant species composition explained by sets of environmental and spatial variables of Jozani Groundwater Forest

Table 7.4: Indicator species along saline gradient

Saline Group	Indicator Species	A	B	Statistics	P-value
500	*Anthocleista grandiflora*	0.64	1.00	0.80	0.015
500	*Pandanus kirkii*	0.41	1.00	0.64	0.029
1000	*Elaeis guineensis*	0.58	1.00	0.76	0.000
1000	*Rauvolfia mombassiana*	1.00	0.57	0.76	0.023
1000	*Asplenium spp*	0.57	0.93	0.73	0.001
1000	*Albizia glaberrina*	1.00	0.50	0.71	0.039
1000	*Blighia unigujata*	0.77	0.64	0.71	0.036
5000	*Macaranga capensis*	0.77	0.80	0.78	0.009
5000	*Brexia madagascariensis*	0.74	0.80	0.77	0.014
5000	*Mimusops obtusifolia*	0.67	0.80	0.73	0.025
5000	*Burttavya nyasica*	0.62	0.80	0.70	0.039
5000	*Ficus lutea*	0.59	0.80	0.69	0.049
5000	*Syzygium cumini*	0.41	1.00	0.64	0.041
10000	*Bourreria petiolaris*	0.57	1.00	0.75	0.024
10000	*Macphersonia gracilis*	0.60	0.75	0.67	0.045
15000	*Drypetes natalensis*	0.52	1.00	0.72	0.035
15000	*Guettarda speciosa*	0.51	1.00	0.71	0.040
15000	*Terminalia boivini*	0.50	1.00	0.71	0.040
15000	*Nephrolepis biserrata*	0.49	1.00	0.70	0.044
20000	*Paspalum vaginatum*	0.84	0.83	0.84	0.008

7.3.2 Discussion

7.3.2.1 Enfluence of spatial and environmental gradients to plant species

With exception of salinity that varied alot from 0.5 to 10 x 10^3 mg L^{-1} and above, the rest of the environmental variables (Table 7.1) had a small difference between the lowest and the highest values. Elevation of soil surface in Jozani Groundwater Forest (JGWF) varied between the lowest (0.75 m AMSL) and the highest (2.50 m AMSL) point by 1.75 m only. However, even with such small difference, in JGWF elevation it affects soil moisture status at plant root zones. Soil moisture on the soil surface simultaneously decreased with increase in elevation. Nevertheless, as shown in Fig. 7.4 the increase of elevation correlate significantly with the increase of soil depth to the coral bedrock (SDCB) and bedrock roughness (BR). Again, SDCB and BR have significant effects on plant nutrision and sability of the big plants. Thus, these environmental variables were effective collectively and localized, and together favoured assemblages of the most of the plant species in JGWF. On contrary the increase of salinity correlates with the decrease of the rest of variables. Therefore, salinity had significant spatial effect on species assembleges (Table 7.3). Coefficient of correlation/association (R^2) for the tested environment variables was 59.5 % (Table 7.3) indicating that there were other conditions and/or variables which decreased not accounted by R^2. However, irregular trends of soil depth and bedrock roughness were considered as source of reduction of R^2. Since, all tested environmental variables (except salinity) were locally effective, so they had less effect on community gradients. Meanwhile, salinity ranges and their spatial trends were the determinants of the community composition, assemblage, and spatial distribution (Table 7.3 and Fig. 7.5). High (80 - 95%) forest canopy density indicated that all plant species found in JGWF are favoured by the ranges of environmental variables throughout the year.

7.3.2.2 Plant species composition

A total of 69 plant species encountered during survey represents about 23.7% of the plant species listed in Nahonyo *et al*. (2002) inventory report for Jozani-Chwaka Bay National Park area. Average number of plant species along the northern grid lines was about 20.7 ± 8.4, whereby southern gridlines had higher species composition than the northern gridlines. The range of predominant plant species within the four quadrats and the communities varied a lot. In addition to that during the survey it was observed that in between the grid points, there were several patches of different communities of different vegetation lifeforms. For example; Plate 7.1a shows plant species composition predominant (over 70% with species with DBH >10 cm) *Elaeis guineensis* (African oil palm), while Plate 7.1b shows patches with mainly *Pandanus rabaiensis* (Srew palm, pandan).

Plate 7.1a

Plate 7.1b

Plate 7.1: a) Plant species assemblage dominated by *Elaeis guineensis* (African oil palm) and b) Plant species assemblage dominated by *Pandanus rabaiensis* (Pandan), Jozani Groundwater Forest

The difference between plant species compositions obtained at grid points and the ones observed in between the grid points implies that there are a large number of small and/or localized plant species compositions that can be captured by a survey that will involve less than 500 m interval between grid points. Either, this study found Jozani Groundwater Forest (JGWF) missing a huge amount of plant species for Jozani-Chwaka Biosphere Reserve. In this case, besides salinity trend, high moisture content at root zone and temporal floods were considered as among major factors affecting gradient in species composition. However, the amount and variations in plant species compositions are common phenomena of natural forests with wide plant species diversity such as JGWF and/or the Reserve in particular. Simultaneously, this study found that plant species compositions in JGWF have a complex multi-storey assemblages enriched with plant species varying in age, DBH and other vegetative trend parameters (Plate 7.2a). In addition Plate 7.2b shows the JGWF area is predominate by *Calophyllum inophyllum* (Red mahogany) which is a mixture of the ones existed before and after reforestation of the destroyed natural forest in 1950s.

Plate 7.2a

Plate 7.2b

Plate 7.2: a) Natural pre-coral forest in Jozani Groundwater Forest (JGWF), b) Area predominated with 1950s planted *Calophyllum inophyllum* (Red mahogany) within JGWF area adjacent to natural pre-coral forest

7.3.2.3 Species community assemblage

There were variations in plant species composition between grid points along Northings and/or Eastings gridlines. This study found futher that there were several plant species community assemblages (PSCAs) within JGWF. Based on the results however, JGWF has five major PSCAs (Fig. 7.4) with about 19±5 plant species in 15±3 *Genera* were plant species constituting most of the PSCA in JGWF. Maximum species counts made PSCAs were recorded in south-east grid points, while the minimum were recorded as grid points approached north-west of JGWF. Based on such PSCA variation, this study found that there were direct relations between the increase of plant species in PSCA and the increase in land elevation of the JGWF. Digital elevation model (DEM) of JGWF showed that elevation increased from 0.75 to 2.5 m above the mean sea level (AMSL) from the north-west towards south-east of JGWF. Elevation increase in the south east areas of JGWF has direct relation with soil moisture at root zones that was found to simultaneously decrease as a soil depth to water table increasing. Generally, this study found that elevation variation affects soil moisture trends which also affect PSCA variation.

7.3.2.4 Gradient in species community

This study found that although Jozani Groundwater Forest (JGWF) has wide plant species diversity, it has gradient of species communities that increased towards south east of the forest. Plant species counts increased by 10 to 17% as the grid point approached the south-east of JGWF. Results on Table 7.2 imply that in JGWF species communities are spatially distributed in a complex slanted gradient pattern, on one hand is due to the mixed effects of abiotic factors (environmental variables), and on the other hand is due to biotic factors which were not tested in this study. Moreover, this study found that salinity had significant effects on plant species growth and geographical distribution, and thus had a significant influence on plant community gradient in JGWF. In this case all other environment variables tested in this study had comparatively less effects on community gradients.

7.3.2.5 Ecotones and indicator species along saline gradient

Based on Appendix 5 and analysis presented in Table 7.4 (*p-values* < 0.05) Jozani Groundwater Forest (JGWF) has about 20 indicator species which are in six saline gradient groups. In natural forest such as JGWF, the large number of plant species communities indicates a presence of a large number of ecotones and indicators species. As there are six saline gradient groups, the lines between these groups were considered in this study as the ecotone lines. However, as the plant communities found in JGWF exist in complex assemblage and geographical distribution, most of the ecotones within it are less distinct and have smoothly diffusing trend. There was one clear sharp ecotone of about 40 to 50 m wide dominated by *Acrostichum aureum* found between pure stands of *Paspalum vaginatum* (Seashore couch) (with TDS >20 000 mg L^{-1}) area and the mixed plant species dominated by *Nephrolepis biserrata* (Giant swordfern), *Terminalia boivinii* (Terminalia) and *Guettarda speciosa* (Beach gardenia) (with TDS of about 15 000 mg L^{-1}) area. There were patches of plants species communities which acted as ecotones between common plant community assemblages. These ecotones with irregular variations were associated with elevation and soil depth to the coral bedrock at each particular line/zone between two plant communities.

7.4 Conclusions and Recommendations

This study concludes that all plant species in Jozani Groundwater Forest (JGWF) are influenced by salinity. Other factors such as soil depth to coral bedrock and bedrock roughness and have the less significant affects on JGWF plant species community assemblages. Thus, salinity and spatial gradient are the most significant factors influencing plant species assemblage in JGWF.

This study recommendes a management intervention for plant species protection and restoration of JGWF should take into account the existing salinity and geographical distribution of ecotones.

7.5 References

Ahmad, P., Azooz, M. and Prasad, M. (Eds.) (2013). *Ecophysiology and Responses of Plants under Salt Stress.* Springer Science + Business Media. New York. 497pp.

Andersen, I. (2012). REDD in Zanzibar: Ethnography of Stakeholders. Thesis submitted for Master of Arts Department of Social Anthropology University of Oslo, Norway. 138pp.

Bailey-Serres, J. and Timothy, D.C. (2014). Plant tolerance of flooding stress–recent advances. *Plant, Cell and Environment* 37(10): 2211-2215.

Blanchet, F.G., Legendre, P. and Borcard, D. (2008). Forward selection of explanatory variables. *Ecology* 89(9): 2623-2632.

Blaser, J. and Gregersen, H. (2013). Forest in the next 300 Years. *Unasylva* 64(1): 61-73.

Borcard, D., Gillet, F. and Legendre, P. (2011). Unconstrained ordination. In: *Numerical Ecology with R*. Springer New York. pp. 115-151.

Borcard, D., Legendre, P. and Drapeau, P. (1992). Partialling out the spatial component of ecological variation. *Ecology* 73(3): 1045-1055.

Bui, E.N. (2013). Soil salinity: a neglected factor in plant ecology and biogeography. *Journal of Arid Environments* 92: 14-25.

Cáceres, M. (2013). How to use the indicspecies package (ver. 17.1). 29pp. [https://cran.r-project.org/web/packages/indicspecies/vignettes/indicspeciesTutorial.pd] site visited on 05/05/2016.

Crain, C.M., Silliman, BR., Bertness, S.L. and Bertness, M.D. (2004). Physical and biotic drivers of plant distribution across estuarine salinity gradients. *Ecology* 85(9): 2539-49.

Daramola, T.M. (2012). Opportunities for Climate Change Mitigation through Afforestation and Reforestation of degraded lands in the Sub-Saharan Africa.

Davis, A.L., Scholtz, C.H. and Chown, S.L. (1999). Species turnover, community boundaries and biogeographical composition of dung beetle assemblages across an altitudinal gradient in South Africa. *Journal of Biogeography* 26(5): 1039-1055.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J. and Münkemüller, T. (2013). Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* 36(1): 27-46.

Dray, S., Legendre, P. and Peres-Neto, P.R. (2006). Spatial modelling: a comprehensive framework for principal coordinate analysis of neighbour matrices (PCNM). *Ecological Modeling* 196(3): 483-493.

Dray, S., Pélissier, R., Couteron, P., Fortin, M.J., Legendre, P., Peres-Neto, P.R., Bellier, E., Bivand, R., Blanchet, F.G., De Cáceres, M. and Dufour, A.B.

(2012). Community ecology in the age of multivariate multiscale spatial analysis. *Ecological Monographs* 82(3): 257-275.

Frank, D.A, Pontes, A.W, Maine, E.M, Caruana, J., Raina, R., Raina, S. and Fridley, J.D. (2010). Grassland root communities: species distributions and how they are linked to aboveground abundance. *Ecology* 91(11): 3201-9.

Gonçalves, E.T. and Souza, A.F. (2014). Floristic variation in ecotonal areas: patterns, determinants and biogeographic origins of subtropical forests in South America. *Australian Ecology* 39(1): 122-134.

Greenwood, S., Chen, J.C., Chen, C.T. and Jump, A.S. (2014). Strong topographic sheltering effects lead to spatially complex treeline advance and increased forest density in a subtropical mountain region. *Global Change Biology* 20(12): 3756-3766.

Gregory, P.J. (2008). Plant roots: growth, activity and interactions with the soil, John Wiley and Sons. 329pp.

Hettige, M.L. (1990). Land evaluation and land sustainability classification. Unguja and Pemba Islands. Food and Agriculture Organization of the United Nations. FAO TCP/URT/6759 (A), Zanzibar, 1990.

Kikvidze, Z., Pugnaire, F.I., Brooker, R.W., Choler, P., Lortie, C.J. and Michalet R. (2005). Linking patterns and processes in alpine plant communities: a global study. *Ecology* 86: 1395–1400.

Klein, R. (2008). An edaphic landscape of Unguja Island, Zanzibar. Exploratory study on the relation between soil variability and landscape, Turku University Department of Geography Publications B, 11. pp. 85.

Kukkonen, M. (2013). Forest cover and its change in Unguja Island, Zanzibar.

Dissertation for Award MSc Degree at University of Turku Faculty of Mathematics and Natural Sciences Department of Geography and Geology. 174pp.

Kukkonen, M. and Käyhkö, N. (2014). Spatio-temporal analysis of forest changes in contrasting land use regimes of Zanzibar Tanzania. *Applied Geography* 55: 193-202.

Legendre, P. and Gallagher, E.D. (2001). Ecologically meaningful transformations for ordination of species data. *Oecologia* 129(2): 271-280.

Legendre, P. and Legendre, L. (1998). *Numerical Ecology: Second English* edition. Developments in environmental modeling. 20pp.

Leonila, B.S. (2011). Assessing the spatial and temporal characteristics of ground water recharge in Zanzibar. Dissertation for Award of MSc. Degree at University of Twente, Enschede, Netherland. 46pp.

Love, D., Hallbauer, D., Amos, A. and Hranova, R. (2004). Factor analysis as tool of ground water quality management: *Physics and Chemistry of the Earth Part A/B/C* 29(15): 1135 - 1143.

Martin, P.H., Sherman, R.E. and Fahey, T.J. (2007). Tropical montane forest ecotones: climate gradients, natural disturbance, and vegetation zonation in the Cordillera Central, Dominican Republic. *Journal of Biogeography* 34(10): 1792-1806.

Masoud, S.S., Msanya, B.M., Semoka, J.M.R. and Maliondo, S.M.S. (2016a). Use of water table as a benchmark for levelling groundwater forest: The case of Jozani Groundwater Forest, Zanzibar, Tanzania. *International Journal of Scientific and Technical Research in Engineering (IJSTRE)* 1(5): 49-57.

Masoud, S.S., Msanya, B.M., Semoka, J.M.R. and Maliondo, S.M.S. (2016b). Tidal trends and magnitude of Chwaka and Uzi Bays as a proxy of seawater intrusion in Jozani Groundwater Forest, Zanzibar, Tanzania. *American Journal of Agriculture and Forestry (AJAF)* 4(6): 168-177.

Mchenga, I.S. and Ali, A.I. (2014). natural regeneration of mangroves in a degraded and non-degraded tropical forest of Zanzibar Island. *Journal of Global Biosciences* 3(1): 334-344.

Meier, E.S., Kienast, F., Pearman, P.B., Svenning, J.C., Thuiller, W., Araújo, M.B., Guisan, A. and Zimmermann, N.E. (2010). Biotic and abiotic variables show little redundancy in explaining tree species distributions. *Ecography* 33(6): 1038-1048.

Monge-Nájera, J. (2008). Ecological biogeography: A review with emphasis on conservation and the neutral model. *Tropical Biology, Gayana* 72(1): 102-112.

Munishi, P.K., Temu, P.R.A. and Soka, G. (2011). Plant communities and tree species associations in a Miombo ecosystem in the Lake Rukwa basin, Southern Tanzania: Implications for conservation. *Journal of Ecology and the Natural Environment* 3(2): 63-71.

Nahonyo, C.L., Mwasumbi, L.B., Eliapenda, S., Msuya, C., Mwansasu, C., Suya, T.M., Mponda, B.O. and Kihaule, P. (2002). *Jozani – Chwaka Bay proposed National Park Biodiversity inventory report*, CARE Tanzania and department of Commecial Crops, Fruits and Forestry, Zanzibar. 184pp.

Nowak, K. and Lee, P.C. (2011). Demographic structure of Zanzibar red colobus populations in unprotected coral rag and mangrove forests. *International*

Journal of Primatology 32(1): 24-45.

Økland, R.H. and Eilertsen, O. (1994). Canonical correspondence analysis with variation partitioning: some comments and an application. *Journal of Vegetation Science* 5(1): 117-126.

Oommen, M.A. and Shanker, K. (2005). Elevational species richness patterns emerge from multiple local mechanisms in Himalayan woody plants. *Ecology* 86(11): 3039-3047.

Pellissier, L., Pinto-Figueroa, E. and Niculita-Hirzel, H. (2013). Plant species distributions along environmental gradients: do belowground interactions with fungi matter? *Frontiers in Plant Science*. 4:500. doi:10.3389/fpls.2013.00500.

Peres-Neto, P.R., Legendre, P., Dray, S. and Borcard, D. (2006). Variation partitioning of species data matrices: estimation and comparison of fractions. *Ecology* 87(10): 2614-2625.

Praveena, S.M., Aris, A.Z., Harun, M. and Bidin, K. (2010). Ground water studies in tropical islands. *Malaysian Perspective Episode* 33(3): 200 – 204.

Ribeiro, J.P.N., Matsumoto, R.S., Takao, L.K., Peret, A.C. and Lima, M.I. (2011). Spatial distribution of Crinum americanum L. in tropical blind estuary. Hydrologic, edaphic and biotic drivers. *Environmental and Experimental Botany* 71(2): 287-291.

Salum, L.M. (2009). Ecotourism and biodiversity Conservation in Jozani-Chwaka Bay National Park, Zanzibar, *Africa Journal of Ecology* 47(1): 166-170.

Schmitt, C.B., Senbeta, F., Woldemariam, T., Rudner, M. and Denich, M. (2013). Importance of regional climates for plant species distribution patterns in moist Afromontane forest. *Journal of Vegetation Science* 24(3): 553-68.

Susan, W., Wilson, J.B., John, B.S., Rapson, G.L., Benjamin, S., Warren, M.K. and Yvette, H.C. (2003). Properties of Ecotones: Evidence from Five Ecotones Objectively Determined from aCoastal Vegetation Gradient. *Journal of Vegetation Science* 14(4): 579-590.

Ter Braak, C.J. (1987). The analysis of vegetation-environment relationships by canonical correspondence analysis. In: *Theory and Models in Vegetation Science.* Springer Netherlands. pp. 69-77.

Thompson, I. (2011). Biodiversity ecosystem thresholds resilience and forest degradation. Measuring Forest Degradation. *Unasylva* 62(238): 25 – 30.

Vice President's Office (2012). *National Climate Change Strategy*. Division of Environment United Republic of Tanzania. 92pp.

Wisz, M.S., Pottier, J., Kissling, W.D., Pellissier, L., Lenoir, J., Damgaard, C.F., Dormann, C.F., Forchhammer, M.C., Grytnes, J.A., Guisan, A. and Heikkinen, R.K. (2013). The role of biotic interactions in shaping distributions and realised assemblages of species: implications for species distribution modelling. *Biological Reviews* 88(1): 15-30.

Zanzibar Revolutionary Government (2013). Zanzibar Woody Biomass Survey Preparedness for REDD+ Phase: Biophysical Inventory Report. Using Zanzibar Woody Biomass Survey in Policy and Planning Processes, Working Paper. Indofood (Forest Intelligence) and Norwegian Embassy, Zanzibar, Tanzania. 24pp.

Zanzibar Sustainable Management of Land and Environment II (2013). The Zanzibar National Forest Policy Analysis. Final Report. 88pp.

Zhang, J., Cheng, K., Zang, R. and Ding, Y. (2014). Environmental filtering of species with different functional traits into plant assemblages across a tropical coniferous-broadleaved forest ecotone. *Plant and Soil* 380(1-2): 361-374.

Zhu, J.T., Yu, J., Wang, P., Yu, Q. and Derek, E. (2014). Variability in groundwater depth and composition and their impacts on vegetation in Heihe River Basin, China. *Marine and Freshwater Research* CSIRO 65(3): 206-217.

Zuur, A.F., Ieno, E.N. and Elphick, C.S. (2010). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1(1): 3-14.

CHAPTER EIGHT

8.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In Jozani Groundwater Forest, the underlying factors influencing existence, richness, assemblage and spatial distribution of high diversity of plant species into plant communities include elevation, level of groundwater table, soil depth to the coral bedrock and bedrock roughness. In some parts of this forest, high water salinity and temporary floods significantly affected non-saline and flooding non-resistance species. However, most of the plant species enjoy a wide range of soil moisture from shallow aquifer which is recharged by bimodal rainfalls. Vigor growth of the plant species is influenced by a good supply of plant nutrients from Jozani groundwater peat soil. Areas with low elevation and shallow soil above the impermeable coral bedrock tend to reduce root growth zone, increase seasonal wetness and hamper normal growth of big plants. Plant species in the forest exist in natural assemblage, coexisting and diverse based on the biotic and abiotic factor that may be favouring or stress the species. The findings of this study have generated empirical (practical) inputs which contribute to do better management of the environment, ecology and biodiversity assessment and conservation.

Based on the findings from this study the following conclusions were pertinent:

a) The use of water table for levelling a multi-storey and high canopy groundwater forest is an alternative and low cost method.

b) Jozani Groundwater Forest occupies the low elevatation range (0.75 – 2.50 m above the mean sea level), almost flat coal terrain with few coral outcrops and low to medium range bedrock roughness. The terrain has been under abrasion for a long period during and after the fall of seawater in level and rise of coral land.

c) The ranking of soil depth to the coral bedrock and bedrock roughness provides opportunities for evaluation of coral terrains for multiple purposes which include agronomic, environmental, engineering and social-economic aspects.

d) The extent of seawater intrusion (salinity level and affected areas) in Jozani Groundwater Forest can be categorized into five salinity zones which are free, least, low, and medium and highly affected areas. However, the salinity condition is non-static and influenced by dry or wet seasons and distance from bays.

e) Bimodal rainfalls of *Masika* and *Vuli* are useful and adequate sources of fresh water which significantly recharge Jozani Groundwater Forest aquifer, dilute and drain off the accumulated salts back to Chwaka and Uzi bays.

f) The formation and development of Jozani Groundwater Forest soil involved marine-freshwater interactions which occurred in the low elevation coral trough-like terrain running between Chwaka and Uzi bays. The soil is moist (above 75% moisture content) throughout the soil profile (excluding the litter), shallow to medium (0.3 – 1.4 m) soil depth to the coral bedrock with a peat soil which supports and favours the existence and vigour growth of a wide range of plant species. Soil horizons with gleyic, paste-like clay material with low density that smoothly defusing above the low/impermeable coral bedrock implying that the Jozani Groundwater Forest soil was formed under anaerobic conditions whereby plant residues and organic sediments were gradually fermented and accumulated.

g) In Jozani Groundwater Forest co-existence, assemblage and spatial distribution of plant species communities are influenced by localized effects resulting from a complex interaction between biotic and abiotic factors.

8.2 Recommendations

In the light of the above achievements, findings of gaps revealed by this study the following recommendations are made:

a) The wider application of water table as a benchmark for levelling a multi-storey forestry as among the appropriate alternative methods based on the cost effectiveness and low expertise requirements.

b) The use of soil depth to coral bedrock and bedrock roughness to evaluated usefulness of coral terrains should be promoted.

c) The findings of this study should be utilized by academicians, researchers in environment, ecology, biodiversity assessment and conservation.

d) Further studies should be carried out to fill the gaps of information not covered by this study.

APPENDICES

Appendix 1: Validation of the method of using a shallow water table as a benchmark

	Coordinates	RL, m AMSL		
Method	**Northern (N), Eastern (S)**	**HI**	**WT as a BM**	**Mean ± SD**
Benchmark	-	(No. 205)	Water table	-
Benchmark	N: 9 306 943, E: 546 217	2.124	0. 788	-
SP 1	N: 9 306 820, E: 546 360	1.436	1.440	1.438±0.002
SP 2	N: 9306840, E: 546 360	1.378	1.380	1.379±0.001
SP 3	N: 9306840, E: 546 480	1.356	1.355	1.356±0.001
SP 4	N: 9306840, E: 546 660	1.422	1.425	1.424±0.002
SP 5	N: 9306860, E: 545 980	1.560	1.560	1.560±0.000
SP 6	N: 9306880, E: 545980	1.748	1.750	1.749±0.001
SP 7	N: 9306880, E: 545960	1.698	1.700	1.699±0.001
SP 8	N: 9306900, E: 545960	1.850	1.850	1.850±0.000
SP 9	N: 9306900, E: 545980	1.895	1.900	1.898±0.002
SP 10	N: 9306920, E: 545960	2.057	2.060	2.059±0.002

BM = Benchmark, HI= Height of Instrument, RL = Reduced level, SD = Standard deviation; SP = Selected point, WT = water table

Chi Square Tests

	Value	df	Asymp. Sig. (2 sided)
Peason Chi Square	90.000	81	0.231
Likelihood ratio	46.052	81	0.999
Linear by Linear association	90.000	1	0.003
Number of valid cases	10	-	-

Appendix 2: Summary of results from auger probing

Parameter	Conditions observed during auger probing	Learnt effects and implication
Decomposing Plant residues	Soil is covered by a thick layer (10 – 20 cm or more) of decomposing plant residues	A thick layer of decomposing plant residues indicates high biomass and peat soil condition
Number and conditions of horizons	Soil has three to four horizons which are smoothly defusing to each other	Effects of continuously nutrient leaching under continuous moist to saturate condition
Moisture	The profiles were with dry plant residues on the surface, followed by moist to wet plant residues underneath. The remained lower part of the profiles were saturated by water	Jozani groundwater forest (JGWF) has close to the surface water table. Wetness increase with depth
Soil density	Drilling with soil auger needed a little more force to drill down soil horizon which was just below a thick layer of a mixed decomposing organic matter. Then after drilling needed least force to pass soil masses down to the coral bed rock	Soil horizon under organic layer was a denser one. The rest horizons were paste like soil material which are easy penetrated by a little forced soil auger. Implication was: soil formation happened under unarobic condition
Colour	The humic mass have very dark colour. Denser soil horizon has grayish brown (10YR3/2), followed by horizon with brown (10YR4/3). The rest soil mass were of olive grey (5YR4/2)	Ranges of YR chroma are common in coral soils of Zanzibar. Grayish colour is among distinctive indicator of effects and implication continuous partial or total water saturation of the soil mass by groundwater (aquifer)
Texture	The texture of soil material was sticky, soft, leak through fingers when squeezed, no ball formation	Soil of JGWF is clayey-paste like material. Implication was: the soil mass were derived from *in situ* sedimentation of decomposed materials
Total dissolved solids (TDS)	Increased from 1 to 25 x 10^3 ppm as transect approached North- and South-end of JGWF	Presence and effects of seawater increased towards the ends as well as towards the bays

Appendix 3: General characteristics of Jozani Groundwater Forest profile

Profile ID: JOZ-P1 Mapping unit: DOS 208 (19820. Natural forest zone
Region: South Unguja District: South
Map sheet no. : 10/4404 Coordinates: E545903/N9307243
Location: Jozani-Chwaka Bay National Park, about 300 west of park offices
Elevation: about 2 m asl. Parent material: complex of *in situ* weathering of corals, marine deposits and decomposing organic matter. Land form Site characteristics: marine plain; flat. Slope: <0.3 %; straight, more than 100 m length, upper part, ground water at 9-10 cm depth. Surface characteristics: coral rock out crops 2%.Flooding/ponding: during rain seasons mainly during Masika and Vuli rains, sustain up to 15days, 30cm depth. Erosion: mild sheet erosion. Deposition: marine deposits. Natural drainage class: imperfect, rapid infiltration. STR: hyperthermic. SMR: ustic: Land use: Natural ground water forest.

Authors: B.M. Msanya, S. Mwango and M. S. Said

O >15 cm: Partial and intermediate decomposing organic matter (Fibric + Hemic)

OA 0-9 cm: Well decomposed organic matter mixed with surface soil horizon (epipoden).

Ah 9-26 cm: very dark greyish brown (10YR 3/2),wet, loam; friable wet, slightly sticky and plastic wet; moderate fine and medium crumble; moderate medium and common fine pores; common fine, many fine, moderate medium and many coarse roots; crotovina present, gradually smooth boundary to

C1 26-100 cm: brown (10YR4/3), wet; clay; sticky and plastic wet; weak medium crumble; common fine pores; common fine, moderate medium, common coarse roots; gradually smooth boundary to

C2 100 – 120+ cm: Olive gray (5Y4/2) wet; clay; very friable wet, sticky and plastic wet; many fine pores; very few fine, few medium and common coarse roots.

Analytical data for profile JOZ-P1

Horizon Depth (cm)	**Oa 0 -9**	**Ah 9- 26**	**C1 26-100**	**C2 100-120+**
Clay %	ND	45	67	73
Silt %	ND	40	25	20
Sand %	ND	15	8	7
Texture class	-	SiC	HC	CH
Silt/clay ratio	-	0.89	0.37	0.27
Bulk density g/cc	0.23	ND	0.56	ND
pH H_2O	7.4	7.2	7.0	6.8
pH KCl	6.7	6.6	6.4	6.3
Organic C %	13.82	6.74	0.65	0.22
Total N %	0.44	0.23	0.04	0.02
C/N	31.41	29.30	16.25	11.00
Avail. P mg/kg	8.1	6.3	3.4	2.5
CEC NH_4OAc cmol(+)/kg	18.7	17..9	17.2	17.1
Exch. Ca cmol(+)/kg	3.29	5.59	6.07	6.39
Exch. Mg cmol(+)/kg	0.79	0.78	0.69	0.99
Exch. K cmol(+)/kg	0.06	0.09	0.05	0.06
Exch. Na cmol(+)/kg	0.32	0.39	0.20	0.33
TEB cmol(+)/kg	4.46	6.85	6.91	7.77
Base saturation %	24	38	40	45
CEC clay cmol(+)/kg	-	21	13	13

Soil classification:
World Reference Base for Soil Resources (WRB) (FAO, 2010) Tier II:
Limic Histosols (Gleyic)
USDA Soil Taxonomy (Soil Survey Staff, 2014):
Order/Suborder: Histosols/Saprists
Great group: Haplosaprists

Appendix 4: Results of total element analysis of Jozani Groundwater Forest soil

Depth cm	SiO_2	Al_2O_3	Fe_2O_3	K2O	CaO	TiO_2 %	V_2O_5	MnO	P_2O_5	MgO	Na_2O
0-5	17.72	22.35	18.29	0.71	11.90	3.48	0.11	0.06	1.00	0.030	0.023
45-50	21.81	22.77	27.25	0.41	6.34	2.96	0.10	0.09	0.94	0.012	0.014
95-100	28.62	12.15	27.08	0.86	4.82	3.55	0.12	0.11	0.52	0.023	0.023

Depth cm	S	Cl	Zr	Cr	W	Rb mg L^{-1}	Zn	Ni	As	Y	Sr	V
0-5	5443	2887	351	297	78	55	68	136	41	102	498	235
45-50	281	2286	456	313	98	19	88	139	98	125	278	251
95-100	2279	2334	391	322	162	32	108	145	84	123	352	345

Appendix 5: Species richness and dominance along northern grid lines, 2015

	Species counts					Dominants species, per cent of dominance			
NGL	**A**	**B**	**C**	**D**	**Total**	**A**	**B**	**C**	**D**
1	13	23	21	10	42	PATR,44 POPH, 30 CYRO,26	FIEX, 14 BRMI, 10 CAIN, 10	PAKI,19 TAPE, 18 TACA,8	TACA, 21 TAPE, 17 PAKI, 13
2	9	5	6	9	16	CYRO, 24 ALGU, 16 POPA, 16	POPA, 48 CAIN, 15 ALGU, 13	PAKI, 78 ANGR, 9 RAMO, 6	PAKI, 35 ALGU, 20 VIDO, 13
3	6	9	7	3	14	FERN, 48 ALGU, 20 FISU, 10	RAMO, 29 POPA, 21 VIDO, 12	PAKI, 35 CAIN, 30 ALGU, 19	CAIN, 92
4	5	9	16	6	22	FERN, 49 ALGU, 26	CICO, 17 BRMI, 17	PAKI, 13 ALGU, 11 VIDO, 11	PHRE, 52 VIDO, 28 SYCU, 12
5	4	13	17	10	20	FERN, 75 ALGU, 9 CAIN, 9	PAKI, 19 ALGU, 15 POPA, 13	PAKI, 28 BUNY, 9	PAKI, 23 ALGU, 21 FILU, 13
6	5	12	10	9	17	FERN, 40 MARG, 28 MACA, 26	PAKI, 25 MAGR, 15 POPA, 12	PAKI, 47 BEMA, 10 MACA, 10	PAKI, 25 ALGU, 20
7	4	10	9	9	16	FERN, 52 MACA, 22 DICO, 17	PAKI, 37 MACA, 14 POPA, 14	PAKI, 65 MACA, 6 BEMA, 6	ALGU, 20 SYCU, 18 PAKI, 18
8	6	14	13	3	24	NEBI, 24 AFAN, 24 DICO, 17	TIBO, 14 DICO, 11 BOPE, 10	TIBO, 19 OZIN, 12	GUSP, 40 PHRE, 33 VIDO, 27
9	8	16	12	4	28	PAVA, 18 DICO, 18 EUCA, 15	TIBO, 16 ACAU, 16 DICO, 11	TIBO, 14 EUCA, 9	GUSP, 33 VIDO, 33 PHRE, 29
10	3	6	7	2	13	PAVA, 53 CYRO, 32	ACAU, 75	VIDO, 24 PHRE, 18 PORA, 18	PHRE,80 ALGU,20
11	5	9	5	1	16	PAVA, 78 DICO, 14	DICO, 33 TIBO, 13 SYKI, 13	TIBO, 38 EUCA, 29	GUSP,100

Where, NGL= Northern gridline; 1st = (9 306 800) to 11th (9 311 800), A, B, C and D = scoring plots for plant species with BDH less than or equal to 5 cm, greater than 5 but less than 10 cm, greater than 10 but less than 25 cm and above 25 cm, respectively, ACAU = *Acrostichum aureum* (Mangrove fern), AFAN = *Afromomum angustifolium* (Afromomum), ANGR = *Anthocleista grandiflora*, BOPE = *Bourreria petiolaris*, BEMA = *Brexia madagascariensis* (mfurugudu), BRMI = *Bridelia micrantha*, BUNY = *Burttavya nyasica*,, CAIN = *Calophyllum inophyllum*, CYRO =

Cyperus rotundus, DICO = *Diospyros consolatae,* ALGU = *Elaeis guineensis*, EUCA = *Eugenia capensis*, FERN = Ferns, FISY = *Ficus cycomorus*, FIEX = *Ficus exasperate*, FILU = *Ficus lutea*, FISU = *Ficus sur*, FLGU = *Flagellaria guineensis*, GUSP = *Guettarda speciosa*, MACA = *Macaranga capensis*, MAGR = *Macphersonia gracilis*, MIOB = *Mimusops obtusifolia*, NEBI = *Nephrolepis biserrata*, OZIN = *Ozoroa obovata*, PAKI = *Pandanus kirkii*, PORA = *Pandanus rabaiensis*, PATR = *Panicum trichocladium*, PAVA = *Paspalum vaginatum*, PHRE = *Phoenix rectinata*, POPH = *Polypodium phymtodes,* POPA = *Polysphaeria parvifolia*, RAMO = *Rauvolfia mombassiana*, RHRE = *Rhoicissus revoilli*, SYKI = *Synaptolepis kirkii*, CICO = *Syzygium cordatum*, SYCU = *Syzygium cumini*, TAPE = *Tabebuia pentaphylla*, TIBO = *Terminalia boivinii*, TACA = *Terminalia catappa* and VIDO = *Vitex domiana*.