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Extent of Seawater Intrusion from Chwaka and Uzi bays into Jozani Groundwater Forest, Zanzibar, Tanzania

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Abstract— The rise in the 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 were collected from Tanzania Meteorological Agency (TMA). Spatial and temporal 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 98129 tester. Water tests were done in the middle of *Kiangazi, Masika, Kipupwe* and *Vuli* seasons. The area of JGWF was estimated based on JGWF elevation map. 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 about 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. In conclusion, it was found that about 77% of JGWF is free from intrusion effects, but there were some variations of TDS values between dry and rainy seasons that also in the long run cause TDS fluctuation between years.

Index Terms—Categories of affected areas, dilution, draining, dry and wet seasons, rainwater, seawater intrusion, total dissolved solids, Zanzibar.

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) [1], [2]. Jozani groundwater forest (JGWF) is a coastal forest located on the lowest point in Zanzibar between Uzi and Chwaka bays [3], [4], [5]. With such proximity and low terrain, JGWF is likely to be intruded by seawater from the bays. 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 flows and mixes with freshwater in the aquifer [2], [6], [7], [8]. Many studies have been made using TDS spatial tests to characterise the magnitude and spatial trend of seawater intrusion [9], [10], [11], [12]. Therefore, as reported by [13], [14], the extent and spatial trend of seawater intrusion from Chwaka and Uzi bays into JGWF can be determined by conducting spatial and temporal water tests on TDS levels in JGWF aquifer.

Grid system is often used for spatial pattern studies [15], [16]. Seawater intrusion spatial trend and the affected area by seawater intrusion are described by TDS measurements conducted on a known grid system [12], [17]. Water samples collected from wells are often used to assess water quality of aquifers [17]. Spatially distributed local and/or temporary wells therefore, were used as data collection points for this study which estimated areal extent affected by seawater intrusion.

Water sources and their interfaces influence water dynamics and quality in a forest [10], [11]. 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 [18] reported, Zanzibar receives precipitation of between 1400 and 2000 mm annually mainly during *Masika* and *Vuli* seasons. Thus, it is expected that TDS values and spatial trend in JGWF area are affected by amount and patterns of precipitation. Using TDS values and their spatial trends, rainwater, and rain patterns, this study intended to determine the extent to which JGWF has been affected by seawater intrusion from Chwaka and Uzi bays.

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2 Materials and Methods

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 Na-

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tional Park (JCBNP) located about 35 km from Stone Town, off the road to Makunduchi [18] (Fig. 1). As coastal forest, JGWF area is opened to Chwaka bay on the North and to Uzi bay on the South [3], [5], [18]. The study area is a tropical forest which receives precipitation of between 1000 and 2000 mm annually mainly during *Masika* and *Vuli* seasons [18], [19]. The ground water table in the forest is close to the surface and often emerges above the surface forming temporary marshes [4].

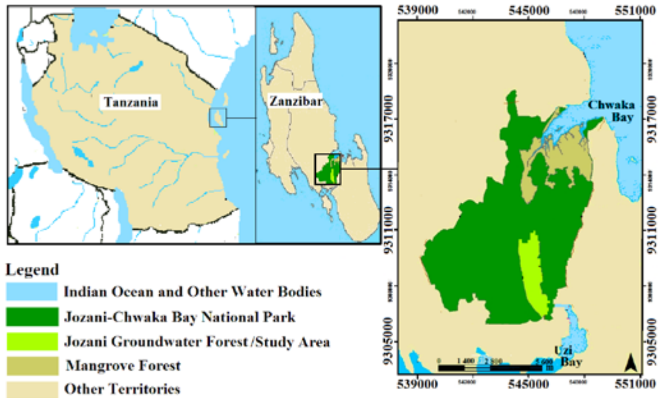


Fig. 1, Location map of Jozani groundwater forest. The map is based on Abass Mzee of Department of Forest and Non-renewable Natural Resources, Zanzibar, 2014

2.2 Spatial Distribution of Data Collection Points

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 in UTM 1960 zone 37S system due to irregular alignment of coral forest on the east and coral cliff on the west. Therefore, along northern gridlines only on three (out of four) grid points TWs were opened and used for data collection. Most of the TWs were not exactly drilled on grid points, but were within vicinity of less than 15 m from the gridpoints. Such alteration on one hand was due to plant density, complexity of plant species and coral outcrops in JGWF. On the other hand, alteration was made when it was found that the selected point was more convenient for the *in situ* water testing. The exception was on gridline N9 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 N9 306 800 TWs were between eastern coordinates 545 600 and 546 750. GARMIN ***e***trex 10 GPS set was used to indicate grid point geo-references.

Plate 1, Example of temporary wells in Jozani Groundwater Forest, 2015

2.3 Temporary and Local Wells

In the shallow aquifer, an auger-drilled bore hole was used as a temporary well for water sampling and testing [20], [17]. At a grid point (Section 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 1). Most of the TWs were not exactly drilled at grid points, but were within vicinity of less than 15 m from the grid points. Such alteration on one hand was due to plant density, complexity of plant species and uneven depth to the coral bedrock in JGWF. On the other hand, alteration was made when it was found that a nearby point was more convenient for the *in sit*u water testing. Some of TWs were replaced by local wells which were found adjacent to the grid points (Plate 2).

Plate 2, Example of local wells in Jozani Groundwater Forest, 2015

2.4 Data Collection Periods

According to [21], 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. Thus, based on [22] report about JGWF soil type, 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* and *Vuli* and two dry seasons, *Kiangazi* and *Kipupwe* [5]. 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.

2.5 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 [23]. 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.

$$TDS = (TDS\ Reading * df) - TDS\ dil \qquad (1)$$

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.

2.6 Data Analysis

Excel spread sheets were used for data computing and graphing. The proportion of areas with deferent TDS ranges (categories) was estimated with the help of ArcGIS 10.1 and JGWF elevation map sensu [24].

3 Results and Discussion

Figures 2, 3 and 4 were derived from 2011 to 2015 rainfall data which were collected from Tanzania Meteorological Agency (TMA), Kisauni, Zanzibar.

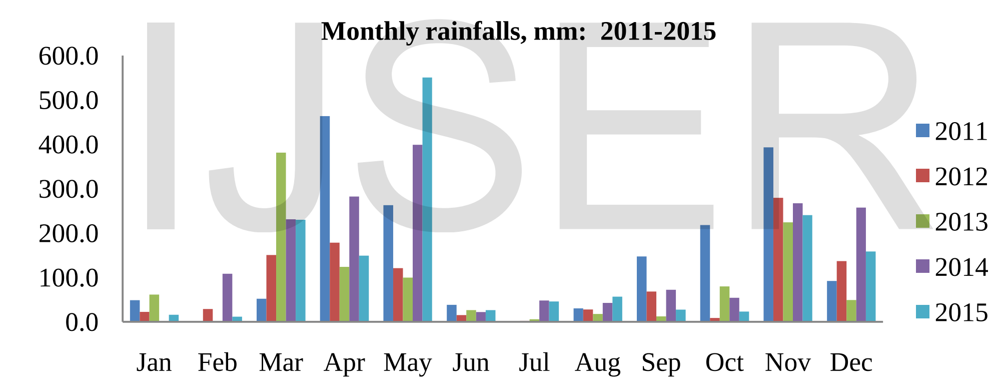


Fig. 2, Zanzibar monthly rainfalls (mm) of 2011 – 2015 period. Source: TMA, Zanzibar

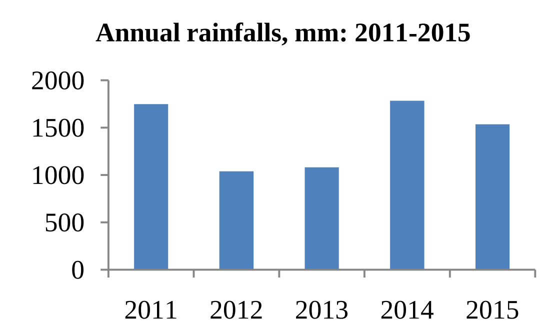


Fig.3, Average monthly rainfalls (mm) of 2011 - 2015 period. Source: TMA, Zanzibar

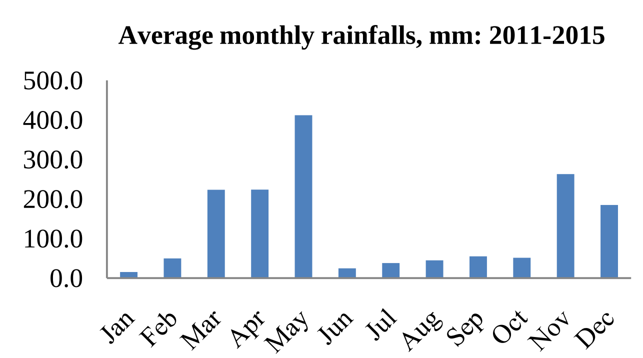


Fig. 4, Zanzibar annual rainfall (mm) of 2011 - 2015 period. Source: TMA, Zanzibar

Figures 2 and 3 show that in Zanzibar, amounts of precipitation fluctuate both monthly and annually while Fig. 4 shows that about 65 - 80% of precipitations occur during *Masika* and *Vuli* seasons. Based on TMA rainfall information and [25], *Masika* and *Vuli* rains are the only source of freshwater that replenishes JGWF aquifer since no other sources were ever recorded. Leonola [5], reported that JGWF needs less water to recharge its aquifer. Thus, temporary floods reported by [4] and as can be extrapolated from Plate 3, occurred when JGWF aquifer reaches its high level by receiving a large amount of water from *Masika* and/or *Vuli* rains. With reference to JGWF elevation map by [24], 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.

Plate 3. Central part of Jozani Groundwater Forest flooded by Masika rains, 2015

TABLE 1
TOTAL DISSOLVED SOLIDS (TDS) VALUES ALONG NORTHERNS GRIDLINES IN JOZANI GROUNDWATER FOREST (JGWF), 2015

	Thousands of Total dissolved solids (mg L^{-1})				
NC	**KGZ**	**MSK**	**KPP**	**VUL**	**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

NC = Northern coordinates, KGZ = Kiangazi, MSK = Masika, KPP= Kipupwe, VUL = Vuli seasons, SD = Standard deviation

TABLE 2
TOTAL DISSOLVED SOLIDS (TDS) VALUES ALONG NORTHERNS GRIDLINE 9 306 800 IN JOZANI GROUNDWATER FOREST (JGWF), 2015

	Thousands of Total dissolved solids (mg L^{-1})				
EC	**KGZ**	**MSK**	**KPP**	**VUL**	**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

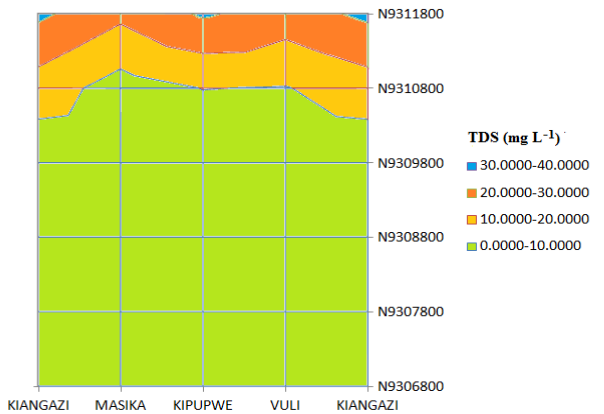
EC = Eastern coordinates, KGZ = Kiangazi, MSK = Masika, KPP= Kipupwe, VUL = Vuli seasons, SD = Standard deviation

3.1 Total dissolved solids values in Jozani groundwater forest

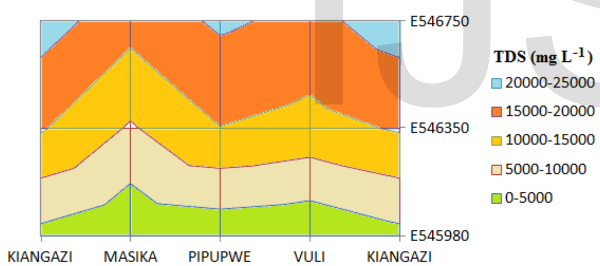
The average TDS values along northern gridlines for four seasons are presented in Table 1. The TDS values were significantly increasing northwards. However, there was different trend of increase of TDS values along northern gridline 9 306 800. The difference between the area around N9 306 800 and the rest of the northern gridlines was the direction of the increase and decrease of TDS values. Table 2 shows that TDS values along N9 306 800 were increasing eastwards. In some parts of JGWF high TDS values were recorded during dry seasons of *Kiangazi* followed by *Kipupwe*; and lesser values were recorded during rainy seasons of M*asika* followed by *Vuli*.

3.2 Spatial trend of dissolved solids in Jozani groundwater forest

Figures 5 and 6 are illustrating spatial trends of total dissolved solids (TDS) in Jozani Groundwater Forest (JGWF) in 2015. The Figures show that within the study period (January – December 2015), the TDS values in JGWF changed spatially and temporally. Figure 5 shows that the southern part of JGWF had less TDS values and the outmost northern part had the highest TDS values. However, Figure 6 shows that at outmost south-end of JGWF, TDS values were less on the west but increased towards the east. Therefore, Figure 6 implies that on the southern part of JGWF there were either fewer seawater intrusions from Uzi bay or significant dilutions and drains of dissolved solids towards Uzi bay during wet seasons. With exception of *Kiangazi* season, the TDS values were almost constant on the middle parts of the JGWF. Meanwhile on both outmost ends of JGWF, TDS values were increasing during dry seasons (*Kiangazi* and *Kipupwe*) and decreasing during wet seasons (*Masika* and *Vuli*). Such trend implies that during dry seasons, seawater spilled the dissolved solids on the north and south ends of JGWF, while during wet seasons rainwater flashed off the spilled dissolved solids. Additionally, Fig, 6 implies that spilling and dilution of the dissolved solids from and towards Uzi creek occurred mainly on the east of the transect N9 306 800.



Fig, 5, Seasonal and spatial trend of total dissolved solids (TDS) in Jozani Groundwater Forest, 2015



Fig, 6, Seasonal and spatial trend of total dissolved solids (TDS) values along northern gridline 9 306 800, Jozani Groundwater Forest, 2015

3.3 Fluctuation of Total Dissolved Solids in Jozani Groundwater Forest

According to [26], 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 [5], [25], rainfall patterns and rainwater are the ones influencing wetness and total dissolved solids trends (TDS) in JGWF area. During and a few days after *Masika* and/or *Vuli* rains, freshwater flows from JGWF area towards Chwaka and Uzi bays [24] [25]. Meanwhile during the dry (*Kiangazi* and/or *Kipupwe*) seasons, water flow stops as water level in the aquifer reaches its lowest level.

Figures 5 and 6 showed that in JGWF areas levels of TDS values augmented during dry seasons and dropped during rainy seasons. Tilting of TDS values from an area with higher into another area with lesser TDS values during dry seasons indicated that the seawater from the bays spilled salt compounds on the soil surfaces. Thereafter, the salts brought by seawater intrusion percolate into the aquifer. In contrast, TDS values on the said areas fell to a minimum when rain water saturates the soil and drains off some of the salt compounds from JGWF towards the bays.

3.4 Categories and distribution of JGWF area based on TDS values in the aquifer

According to [27], 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 [28], [29], [30] 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 [25], 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*. 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 [25], [27], [28], [30], this study adopted five categories of salt affected areas namely; none-, least-, slightly-, moderately- and severely-affected. Table 3 shows the spatial distribution and area covered by the five categories. 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 3
CATEGORIES AND DISTRIBUTION OF JOZANI GROUNDWATER FOREST AREA AFFECTED BY SEAWATER INTRUSION IN 2015

Northern coordinates	Seawater effects		Occupied area	
	TDS mg L^{-1}	Ranks	ha	%
9 306800-7300	2 – 5 x 10^3	Slightly-A	25.6	4.4
9307300- 7800	0.5 – 2 x 10^3	Least-A	37.3	6.3
9307800-9300	0 – 0.5 x 10^3	None-A	342.3	58.2
9309300-9800	0.5 – 2 x 10^3	Least-A	24.5	4.2
9309800-10300	2 – 5 x 10^3	Slightly-A	21.2	3.6
9310300-0800	5 – 10 x 10^3	Moderately	47.4	8.1
9310800-1800	>10 x 10^3	Severe-A	89.4	15.2
Total area			587.7	100

A =Affected area

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 (with the five categories) reflects the extent of seawater intrusion into JGWF. Finally, the area coverage and distribution trends of these categories show the extent, spatial trend and magnitude of seawater intrusion in JGWF.

4. Conclusions and Recommendations

It was concluded from this study that, since *Masika* and *Vuli* are the only sources of freshwater while 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 will fluctuate between wet and dry seasons and between years; but the level of the said fluctuations will remain constantly insignificant. The overall conclusion on extent of seawater intrusion was that, the northern part of JGWF was more affected by seawater intrusion than the southern part. In addition, this study concluded that, the TDS values of about 70% of JGWF area favor most of the plant species found in the JGWF.

This study concluded further that, rise and fall of TDS values will remain constant if JGWF biomass conditions remain intact, no water pumping from JGWF aquifer, and no extremely wet or extremely dry conditions. Further conclusion which was made here was that every outer part of JGWF is a protector of the adjacent inner part against the dissolved solids spilled by seawater intrusion. And the opposite is true; 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 recommended to Jozani-Chwaka Bay Bio-sphere Reserve Management installation of permanent TDS monitoring structures/systems that will capture TDS changes and that additional protection measures should be implemented if the current equilibrium is found deteriorating.

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