American Journal of Agriculture and Forestry
2016; 4(6): 168-177
http://www.sciencepublishinggroup.com/j/ajaf
doi: 10.11648/j.ajaf.20160406.15
ISSN: 2330-8583 (Print); ISSN: 2330-8591 (Online)

Tidal Trends and Magnitude of Chwaka and Uzi Bays as a Proxy of Seawater Intrusion in Jozani Groundwater Forest, Zanzibar, Tanzania

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To cite this article:
Masoud Salum Said, Balthazar Michael Msanya, Johnson Mashambo Semoka, Salim Mohamed Salim Maliondo. 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.* Vol. 4, No. 6, 2016, pp. 168-177. doi: 10.11648/j.ajaf.20160406.15

Received: December 14, 2016; **Accepted**: January 4, 2017; **Published**: February 2, 2017

Abstract: Tidal characteristics, land 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 conditions 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 during rains and falls 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. Values of water TDS fell to a minimum of 0.7 x 10^3 and 4.9 x 10^3 ppm during rainfall and rose to a maximum of 25.5 x 10^3 and 34.1 x 10^3 ppm 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.

Keywords: Seawater Tide, Surface Level, Water Level, Total Dissolved Solids, Intrusion, Draining

1. Introduction

On coastal lands and aquifers, seawater intrusion is a natural phenomenon [1, 2]. 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 [3]. 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 [4, 5], is located on the lowest part of Zanzibar between Chwaka and Uzi bays [6, 7]. 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 increased climate variability.

Tanzania's coasts have semi-diurnal seawater tides with about 4.0 m as a Maximum Tidal Range (MTR) between Lower and Higher Water of Spring Tides, [8]. Chwaka bay has Neap Tidal Range (NTR) and Spring Tidal Range (STR) of about 0.9 and 3.6 m respectively [9]. Therefore, based on tidal figures by [10], 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 (*NS*) (*Kaskazi*) Monsoon winds [8, 9]. *SE* winds blow between May and October while *NE* winds blow between November and March [11]. When high water of spring tides (HWST) coincides with strong winds of *Kusi* or *Kaskazi*, seawater extends its reach to a bit higher elevated soil surfaces adjacent to the coast [9]. 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 [12]. 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 [13]. Together, position, ground altitude and water level in JGWF were thought as the factors influencing the said intrusion. The JGWF has close to ground surface freshwater aquifer which is recharged with about 1400 -1600 mm rainfall of *Masika* (March to May) and *Vuli* (October to December) seasons [5, 7]. In JGWF, temporary floods were observed during heavy rains within *Masika* or *Vuli* seasons [14]. 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 map out conditions of JGWF that affect tidal trends and magnitudes assumed to be the proxy of seawater intrusions into the forest.

2. Materials and Methods

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 coordinates of 9 305 880 to 9 317 855N and 539 100 to 549 000E (Fig. 1). Figure 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 Chwaka and Uzi bays through these creeks occasionally reaches soil surface on the North and South ends. In both ends, *Paspalum vaginatum* is one of the dominant plant species occupying the space area between JGWF and mangroves before the bays. The mangroves have plant density of about 7700 stands/ha and canopy cover of about 80 to 87% [5]. At the North-end JGWF makes sort of a diffused boundery consisting of *Paspalum vaginatum, Acrostichum aureum, Cyperus rotundus* and *Nephrolepis biserrata.* 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*, *Psidium guajava*, *Bridelia micrantha, Phoenix rectinata*, *Syzygium cumini*, *Cocos nucifera* before *Paspalum vaginatum* stands. The *Paspalum vaginatum* stands are mixed with *Acrostichum aureum, Cyperus rotundus* and *Nephrolepis biserrata* forming small scattered groups and patches before mangroves towards Uzi bay.

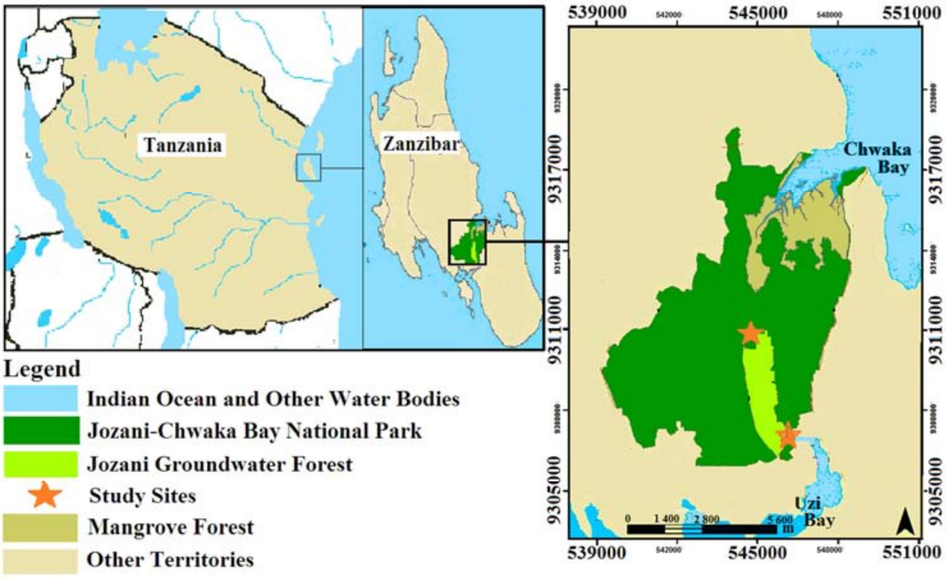

Figure 1. *Location map of Jozani groundwater forest. The map is based on Abass Mzee of Department of Forest and Non-renewable Natural Resources, Zanzibar, 2014.*

2.2. 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 [15] and [16]. Since, WL and TDS change spatially and temporally [12], 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 [17] 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* 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 ppm [18]. 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 into UTM 37S zone 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 [19]. Hand auger was used to open to depth estimated on basis of Equation (1).

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

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.

2.3. Elevation of the Study Sites

Reduced levels (RLs) of surface at OW were determined using Height of Instrument method [20], 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 [21].

$$HI = BS + RL \qquad (2)$$

$$RL = HI - SR \qquad (3)$$

$$Arithmetic\ Error = \sum Back - \sum Fore \qquad (4)$$

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.

2.4. Recording of Water Level Changes

Water level recorders (WLRs) were installed to capture the water level changes (WLC) which occurred in and/or on observation wells (OWs) (Fig. 2). 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. 3).

Figure 2. *Water level recorder at South-end observation well 3.*

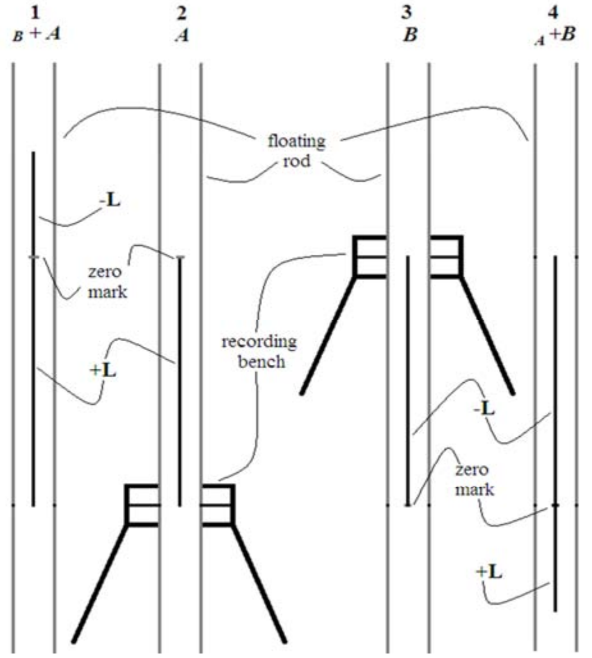

Figure 3. *Four variants of records, 1; $_{B}$+A (Fall and Rise) when B (-L (Fall)) of variant 3 joined by A (+L (Rise)) of variant 2, 2; A (+L (Rise)), 3; B (-L(Fall)) and 4; $_{A}$ + B (Fall and Rise) when A (+L (Rise)) of variant (2) is joined by B (-L (Fall) of variant 3.*

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. 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.

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 3 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)).

$$WL_{ZERO} = (1 + RL_{OW}) - D_WRB_{ZERO} \quad (5)$$

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

$$MRWL = ½(RWL_1 + RWL_2) \quad (7)$$

Where, WL_{ZERO} = initial water level, 1 = height from observation well (OW) surface to the recording bench (RB), RL_{OW} = 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.

2.6. Water Tests

Observation wells (OWs) gave an opportunity for spatial and temporal TDS tests which are primary data for sea water intrusion studies [22]. 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).

$$L_WS = (D_WRBcurrent + WSD) - DtRB \quad (8)$$

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 [17]. Distilled water with TDS values of about 2 - 5 ppm was used to dilute water samples reading higher values than the testers' readable range of about TDS 0 - 2000 ppm. 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 volume was mixed well before being transferred to 500 ml beaker for reading. Equations (9) and (10) were used to compute monthly total dissolved solids.

$$TDS = (TDS\ Reading * df) - TDS\ dil \quad (9)$$

$$MTDS = ½(TDS_1 + TDS_2) \quad (10)$$

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.

2.7. Collection of Data on Rainfall Patterns, TDS, 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 [8, 9] (Section 1) 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 1). The data were collected within 40 (±20) minutes of the indicated time.

Table 1. *Date and time of data collection for water levels and total dissolves solids in 2015.*

	January		February		March		April		May		June		July		August		September		October		November		December	
	FN	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**	**DN**	**DN**	**FN**	**DN**	**FN**	**DN**	**FN**	**DN**
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

FN: Full moon nights DN: Dark nights

2.8. Data Analysis

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

3. Results and Discussion

3.1. Proxy of Seawater Intrusion in Jozani Groundwater Forest

Link between elevation and intrusion in JGWF was described by relating elevations and conditions 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 [23], results in Table 2 showed that the surfaces of OWs ranged between 0.864 to 1.564 m. 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 [8]. 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 (0.9 and 3.6 m, respectively) reported by [9]. Therefore, the estimated maximum seawater levels for HWNT and HWST in 2015 were respectively about 0.495 and 1.980 m AMSL. 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 are prone to surface intrusion during HWST.

Table 2. *Position of observation well and its surface elevation.*

	South-end observation well (SOW)			North-end observation wells (NOW)		
	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		

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 [9]. 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 [9] has limited role which applies only on North-end.

3.3. Incidences of Seawater and Freshwater Reaching Soil Surfaces of Observation Wells

Incidences of seawater and freshwater reaching soil surface of OWs in study sites were captured by the WLCRs as variant 1 and 4 of Figure 3 (Section 2.4). The incidences occurred during rainy and dry seasons and were respectively brought by freshwater recharging, floods and flows (Figure 4) and seawater from the bays (Figure 5).

Figure 4. *Signs of freshwater temporary floods followed by rapid fall of water levels at observation well 2 (OW2) on the South-end.*

Figure 5. *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 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 3.1), 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.

3.4. Role of Mangroves and Paspalum Vaginatum Stands Against Seawater Intrusion

Upholding the findings from earlier discussion in Sections 3.1 to 3.3, the presence and condition of Mangroves and *Paspalum vaginatum* 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 and conditions of Mangroves and *Paspalum vaginatum* stands against intrusion in JGWF need further studies.

3.5. 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* and *Vuli* rains [7]. In the year 2015 the total rainfall recorded was 1506 mm. Figure 6 shows that *Masika* rains started from March and was much higher in May. *Vuli* rains fell in November and December. Table 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 3) and rainfall (Fig. 6). 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 7 and 8). The above conditions 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 7 and 8 coincided with the heavy rains within *Masika* and *Vuli* periods.

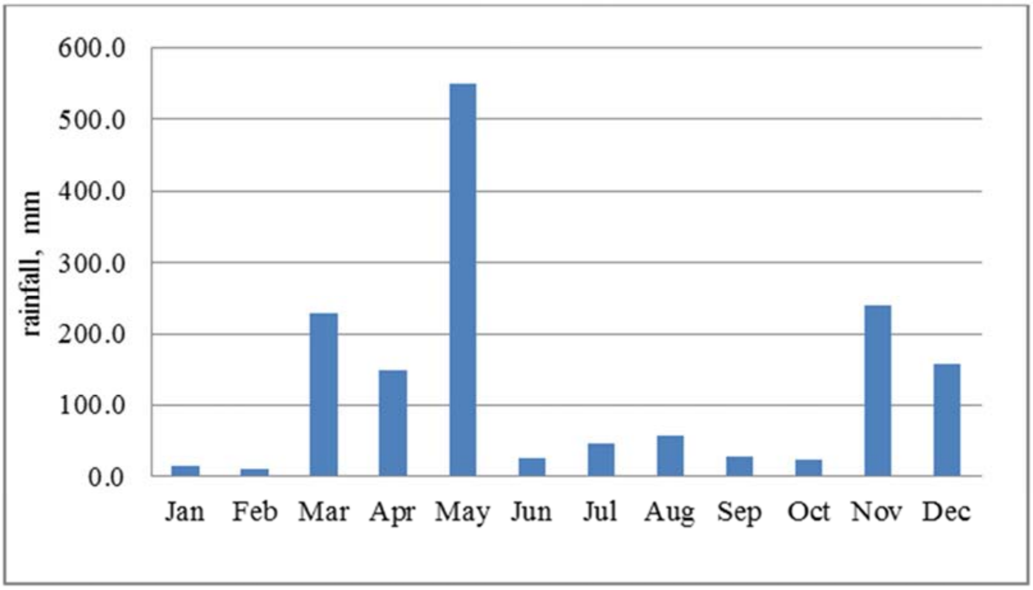

Figure 6. *Zanzibar monthly rainfalls in 2015. Source: Tanzania Meteorological Agency (TMA), Kisauni, Zanzibar.*

Table 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

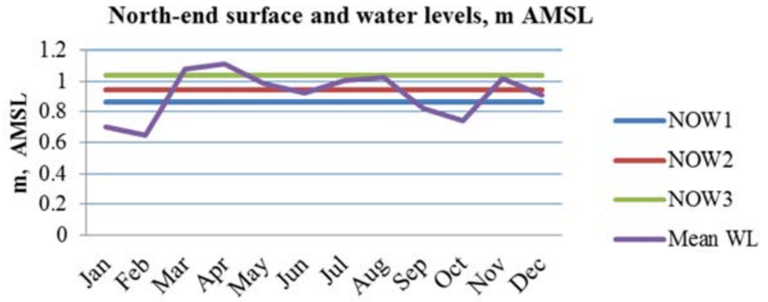

Figure 7. *Reduced levels of ground surface and mean month water levels in North-end observation wells. On the legend - NOW1, NOW2 and NOW3 refer to reduced levels (m, AMSL) of ground surface of North-end observation wells 1, 2 and 3 respectively, while Mean WL refer to mean water level (m, AMSL) at North-end in 2015.*

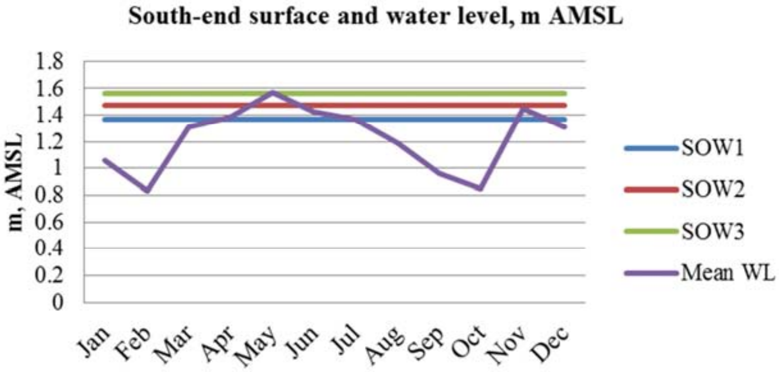

Figure 8. *Reduced levels of ground surface and mean month water levels in South-end observation wells. On the legend – SOW1, SOW2 and SOW3 refer to levels (m, AMSL) of ground surface of South-end observation wells 1, 2 and 3 respectively, while Mean WL refer to mean water level (m, AMSL) at South-end in 2015.*

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 frequently in North-end than in South-end. Such phenomenon in addition to the elevations and slope differences between the two ends discussed in Section 3.1 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.

3.6. Effects of Tidal Water on Study Sites

The monthly TDS changes in North-end and South-end are presented respectively in Table 4 and are graphically illustrated in Figures 9 and 10. Results from water test showed that TDS values ranged from 5 to 34 x 10^3 ppm at North-end and from 0.7 to 26 x 10^3 ppm 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 [13], 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. [24] 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 3.5), 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. *Average monthly total dissolved solids changes in observation wells in 2015.*

	TDS x1000 ppm											
	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

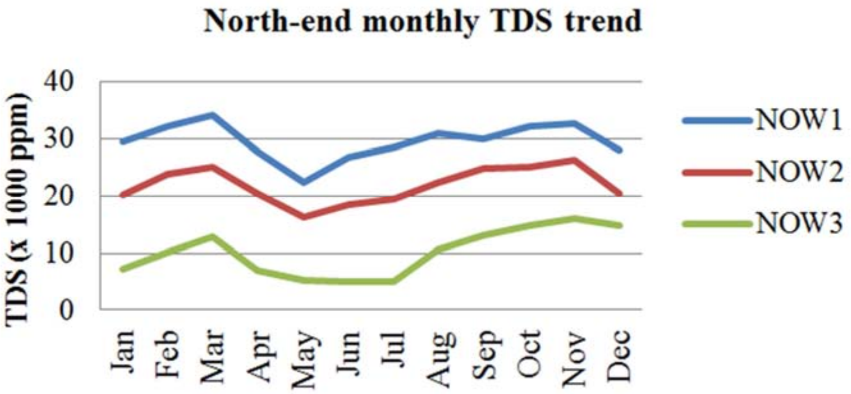

Figure 9. *Monthly total dissolved solids (TDS) in North-end observation wells in 2015. On the legend - NOW1, NOW2 and NOW3 refer to TDS trend lines of North-end observation wells 1, 2 and 3 respectively.*

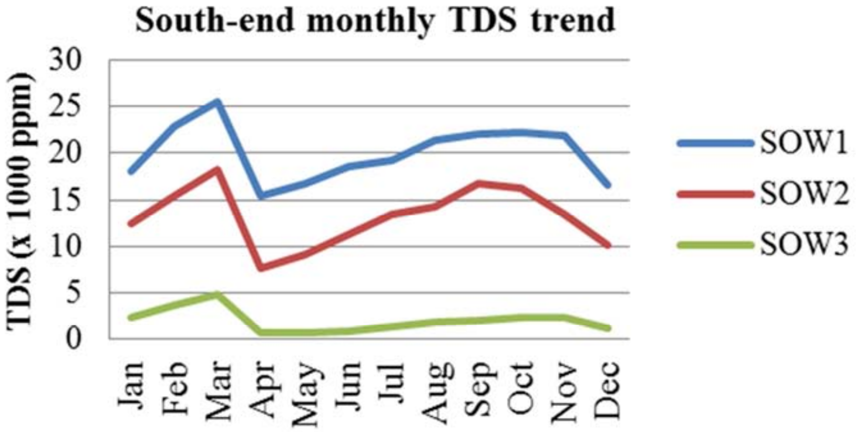

Figure 10. *Monthly total dissolved solids (TDS) in South-end observation wells in 2015. On the legend - SOW1, SOW2 and SOW3 refer to TDS trend lines of South-end observation wells 1, 2 and 3 respectively.*

3.7. Relationship Between Water Level and Total Dissolved Solids

Regression analyses (Fig. 11) of TDS and WLs in study sites showed that TDS values slightly decreased as WLs increased. This relationship was much 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 significant 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.

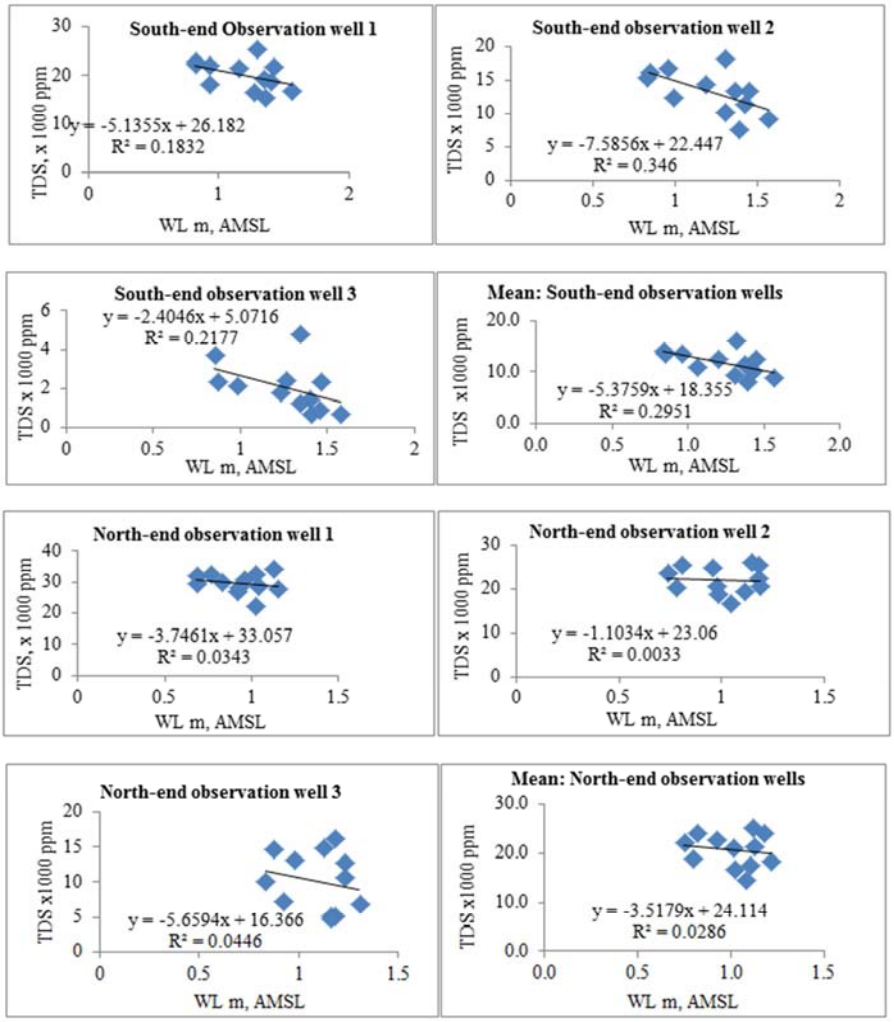

Figure 11. *Regression analyses - total dissolved solids (TDS) versus water level (WL) in the study sites in 2015.*

4. Conclusions

The results and discussion showed 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 respectively during dry and rainy seasons. Whereas seawater from Chwaka and Uzi bays reached the soil surfaces of North-end and south-end, it was concluded 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. It was further concluded 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 x10^3 and 4.9 x 10^3 ppm during rainfalls and rose to a maximum of 25.5 10^3 and 34.1 x 10^3 ppm 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. Furthermore, the results of this study indicated that high densities of mangroves and *Paspalum vaginatum* 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 (at about 7700 stands/ha) 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.

Recommendations

Based on the study results, the following recommendations were made:

1. Reforestation with the use of mangroves at plant density above 7700 stands/ha before the bays or creeks and plantation of *Paspalum vaginatum* at plant density of 15 - 20 stands/m^2 before the mangroves is an effective way of reducing surface seawater intrusion into low elevated

coastal agricultural and forest areas.

2. Long 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 study.

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