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The Influence of Weather and Climate Variability on Groundwater Quality in Zanzibar

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Abstract

Climate change and variability have been inducing a broad spectrum of impacts on the environment and natural resources including groundwater resources. The study aimed at assessing the influence of weather, climate variability, and changes on the quality of groundwater resources in Zanzibar. The study used the climate datasets including rainfall (RF), Maximum and Minimum Temperature (T_{max} and T_{min}), the records acquired from Tanzania Meteorological Authority (TMA) Zanzibar office for 30 (1989-2019) and 10 (2010-2019) years periods. Also, the Zanzibar Water Authority (ZAWA) monthly records of Total Dissolved Solids (TDS), Electrical Conductivity (EC), and Ground Water Temperature (GWT) were used. Interpolation techniques were used for controlling outliers and missing datasets. Indeed, correlation, trend, and time series analyses were used to show the relationship between climate and water quality parameters. However, simple statistical analyses including mean, percentage changes, and contributions to the annual and seasonal mean were calculated. Moreover, t and paired t-tests were used to show the significant changes in the mean of the variables for two defined periods of 2011-2015 and 2016-2020 at $p \leq 0.05$. Results revealed that seasonal variability of groundwater quality from March to May (MAM) has shown a significant change in trends ranging from 0.1 to 2.8 mm/L/yr, 0.1 to 2.8 μS/cm/yr, and 0.1 to 2.0˚C/yr for TDS, EC, and GWT, respectively. The changes in climate parameters were 0.1 to 2.4 mm/yr, 0.2 to 1.3˚C/yr and 0.1 to 2.5˚C/yr in RF, T_{max}, and T_{min}, respectively. From October to December (OND) changes in groundwater parameters ranged from 0.2 to 2.5 mm/L/yr 0.1 to 2.9 μS/cm/yr, and 0.1 to 2.1˚C/yr for TDS, EC, and GWT, whereas RF, T_{max}, and T_{min} changed from 0.3 to 1.8 mm/yr, 0.2 to 1.9˚C/yr and 0.2 to 2.0˚C/yr, respectively. Moreover, the study has shown strong correlations between climate and water quality parameters in MAM and OND. Besides, the paired correlation has shown significant changes in all parameters except the rainfall. Conclusively, the study has shown a strong influence of climate variability on the quality of groundwater in Zanzibar, and calls for more studies to extrapolate these results throughout Tanzania.

Keywords

Quality of Groundwater Parameters, Climate Variability, Mean Changes of Climate and Water Quality Parameters

1. Introduction

The quality of groundwater sources is essential as long as chemical, physical, and biological characteristics play a vital role in providing suitable conditions for domestic, agricultural, and industrial uses amongst others [1] [2]. Apart from biological and chemical contaminants water quality is also affected by extreme weather events [3] including drought and floods, which may affect the quality and quantity of both underground and surface water [4]. For example, during severe to moderate droughts groundwater recharge is highly affected, and aquifers are declined, and this decline, may result in either increase or decrease of electrical conductivity (EC) and dry dissolved solids (TDS) [5].

Moreover, natural and anthropogenic climate variability and changes may degrade water quality by deposing contaminants on freshwater sources and hence exploit both pure and freshwater availability [6] [7] [8]. Indeed, reference [9] has shown how the changes and variability in weather and climate can result in the variability of physical characteristics of freshwater for example elevation of water temperature, water discharge, water level as well as retention time, also groundwater temperatures are highly variable due to increased air temperature [10].

The continual abstraction of the groundwater and its unregulated drilling in Zanzibar have been challenging the sea and freshwater balance in aquifers leading to seawater intrusion, along with the events of tourism expansion and population increase in Zanzibar are likely to lead to the total aquifer exploitation if not monitored [11]. Climate change is also well-thought-out to speeding up intrusions and there is a likely increase in sea level and intrusion in low-lying coastal areas of Tanzania. For instance, reference [12] has noted that the Jozani groundwater forest has been affected by the saltwater intrusion and the salinization level is probable to increase under enhanced sea-level rise.

Furthermore, the amount of TDS seems to be increasing due to the introduction of different contaminants including salts that later tend to dissolve into positively and negatively ions, inducing the transfer of electrons to the groundwater source. However, TDS varies concerning time and space, therefore, changes into space and time influence the TDS as the geology and amount of seasonal rainfall contribute to the transfer and dissociation of the salt. Electrical conductivities (ECs) (μS/cm/yr) are described as the ability of the water to conduct an electrical current, where the electrons are responsible for carrying the charges [13]. Therefore, it is important for determining groundwater salinity in parts per thousand, or gram per liter. Though the previous research results including [14] have found that there is a correlation between TDS and EC but not always linear, and the associations between EC and TDS are given by

$$\mathrm{TDS} = k \times \mathrm{EC} \tag{1}$$

In natural waters, the relationship between EC and temperature tends to be nonlinear [15], although, the degree of nonlinearity is not significant in ambient environmental temperature range of (0˚C - 30˚C), and a linear equation expressed by [16] is given by Equation (2)

$$\mathrm{EC_t} = \mathrm{EC_{25}}\left[1 + a\left(t - 25\right)\right] \tag{2}$$

where: $\mathrm{EC_t}$ = electrical conductivity at a given temperature,

t = temperature (˚C),

$\mathrm{EC_{50}}$ = is electrical conductivity at 25˚C, and

a = (˚C^{-1}) = (0.0187) is a temperature compensation factor [16].

Additionally, the root-mean-squared (RMS) percentage error of the equation is defined by the following equation:

$$e = \frac{100}{\mathrm{EC_{25}}}\sqrt{\frac{1}{m}\sum_{i-1}^{m}\left(\mathrm{EC_{mes}} - \mathrm{EC_{eqn}}\right)^2} \tag{3}$$

where: e = RMS percentage error,

m = the number of data points,

$\mathrm{EC_{mes}}$ = measured EC, and

$\mathrm{EC_{eqn}}$ = the predicted EC (Lynne, 2014).

Globally, groundwater is estimated to supply some 36% of all potable water supply, whereby 43% of the water is used for irrigated agriculture, and 24% of direct industrial water supply [17]. However, one of the impacts of the most noticeable climate change could be variation in both surface and groundwater levels and quality, the greatest concern of stakeholders is the decline of quantity and quality of groundwater supplies as the main potable water supply source for environmental and human consumption [18]. However, recently the volume and quality of water have changed resulting in decreasing in groundwater reserves due to extensive overconsumption of water sources and ongoing reduction of precipitation trends and intensity, especially through the past decade [14]. As for recharging the groundwater sources including aquifers, two factors are crucially responsible for the groundwater recharging system. These include precipitation, controlling evapotranspiration as well as controlling irrigation water, or other artificial recharge [19].

Though Zanzibar lies in a tropical climate with two rainfall regimes and significant seasonal and annual rainfall amounts (1500 - 1700 mm/yr), Zanzibar people living in both urban and rural areas to a large extent rely on groundwater as a sole source of water supplies. The public organization which is responsible for the extraction and distribution of water in ZAWA meets only about 62% (45,000 m^3/day) of water demand and the rest is sourced/extracted from private boreholes and shallow wells [11]. Though studies including [11] have shown that 97% of boreholes in Zanzibar municipality have been observed to have a positive trend in EC, salinity, TDS, and chloride levels, indicating the increased salinity due to saltwater intrusion, as well as the change in chloride which is estimated to range from 110 mg/L in 1993 to 284 mg/L in 2004 (*i.e.* 60% increase).

Apart from extraction and distribution of groundwater in Zanzibar, ZAWA plays a role to supervise water management systems and water quality and standards under the World Health Organization (WHO) guidelines. For instance, based on WHO guidelines the recommended maximum temperature limit at the tap, and for drinking water is 25˚C and below 25˚C [20], respectively. As for TDS, EC, and pH the desired WHO limits for drinking water are 500 - 100 mg/l, less or equal to 400 μS/cm and 6.5 to 8.5 [21], respectively. Studies to examine water quality levels based on different environmental and oceanographic parameters had been conducted in Zanzibar. For example, the studies by [11] [12] [22] have been tried to examine the influence of seawater intrusion on water quality in various areas of Zanzibar, but either limited or no study has been conducted to assess the impacts of weather and climate variability on water quality in Zanzibar, Tanzania and East Africa (EA) at large. This indicates that the extent to which extreme weather events affect the groundwater quality is poorly understood in most EA countries including Tanzania, Zanzibar being particular.

Thus, this study is generally aimed at understanding the influence or impacts of climate and weather on the quality of the groundwater resources in Zanzibar. Specifically, the study aimed at (i) Assessing the seasonal influence of the variability of rainfall, Maximum and Minimum Temperatures on the water quality parameter including TDS, EC, and GWT (ii) Examining the extent to which weather/climate parameters affect the underground freshwater quality in Zanzibar (iii) Examining the influence of wet and dry rainfall seasons on EC, TDS, and water temperature. Academically and socio-economical study will be of much importance to the water-related stakeholders in Zanzibar including ZAWA, Zanzibar Utilities Regulatory Authority (ZURA), owners of dig and borehole wells and the community at large (*i.e.* Universities including water resource departments). Indeed, the study will provide the baseline information for the responsible authorities to plan, design, and project about water quality in response to the economics of resource management in the projected climate change environment

2. Data and Methods

2.1. Study Area

Zanzibar is composed of two Islands of Unguja and Pemba roughly defined by grid point 5˚7'S, 39˚3'E to 6˚5'S, 39˚5'E for Unguja and 4˚1'S, 39˚7'E to 4˚1'S, 39˚7'E for Pemba. These two sister Islands are located at 35 km and 56 km off the east coast of Tanzania's mainland [23]. These islands are formed by different types of limestone; raised sands, sandstones together with different residual deposits related to alluvial strata and different soil types including deep red earth, clays among others, are found as a result of limestone weathering and erosion [24].

2.2. Geological Structure of Rocks and Soil in Unguja

Being the best-documented island in the region in terms of geology, contemporary flora and fauna, this makes Zanzibar (Unguja and Pemba) to be an excellent case study for exploring the effects of island formation [25]. Unguja Island is underlain by Miocene sandy clay marl, alluvial deposits and laterites which are found on the northwest part of the Ubguja up to 130 m above sea level [26]. This area supports a small number of perennial rivers and numerous seasonally active streams, which tend to divert into the ground once they intercept the porous [26]. The rest of the Island is dominated by quaternary coralline limestone reef terraces [26]. Over these lime stones, the landscape is typical of karst (limestone) environments with the development of sink holes, caves, and doline features. These subterranean features which are not controlled by surface topography supports water flow, especially in the dry season. This is due to the high permeability of limestone rock enabling water to infiltrate into the bedrock to form cave systems, rather than converging in topographic depressions or river channels, resulting in a variable relationship between terrain and water table depth. Through dissolution widening of fractures, preferential flow paths and conduits develop in a positive feedback loop eventually leading to the development of sinkholes and cave systems.

2.3. Climate of Zanzibar

Climatically, Zanzibar lies under the bimodal rainfall regime of March to May (MAM) or *Masika* and October to December (OND) or *Vuli*. *Masika* is characterized by abundant rainfall with low temporal and spatial variability [23] [27] [28] [29], while *Vuli* is characterized by low rainfall with high temporal and spatial variability [29] [30] [31] [32]. *Masika* and *Vuli* are characterized by good and poor temporal and spatial coverage [33] [34]. Unguja receives between 1000 and 2250 mm of rainfall per year (Siexs and [35]). Rainfall is strongly seasonal, typically with dry and hot weather during January and February, heavy rains from March to May, a dry season during June to September and light rains during October to December [23] [28] [29] [35]. The long term average maximum temperature during January for Zanzibar ranged from 32.4˚C for Unguja and 31.6˚C for Pemba, while for February is 33.0˚C for Unguja and 32.0˚C for Pemba. As for the minimum temperature the values ranges from 24.3˚C to 23.7˚C during January and 23.9˚C to 23.4˚C for February in Unguja and Pemba (Kai *et al.* 2021), respectively. As for November, the long-term average maximum and minimum temperature is 31.0˚C and 22.7˚C for Unguja and 30.9˚C and 23.1˚C for Pemba, while the average total rainfall is about 202.5 mm at Unguja and 169.29 mm at Pemba [23] [29] [36].

2.4. Study Sites, Data Sets and Data Processing

The study took place on purposively sampled ZAWA groundwater wells located in three regions of Unguja namely, Urban West (for the ground water station of Hali ya Hewa), Southern (for the ground water station of Makunduchi), and North (for the ground water stations of Bumbwini and Makoba), respectively. These stations were selected based on data availability (*i.e.* most groundwater wells had no well-organized datasets with a lot of missing information), The selected stations had datasets characterized by minimum number of gaps and missing as well as outliers. The study used two periods for climate data acquired from TMA Zanzibar office and ZAWA 1) the 30 years (1989-2019) observed records of RF, T_{max} and T_{min} acquired from and 2) 10 years (2010-2019) datasets of water quality parameters involving TDS, EC and GWT over the purposively selected ground water stations. The data quality control was conducted using the interpolation methods where the missed data during a specific month on annual records were handled by taking the mean of the nearby stations or mean of the long term data of that station for the specific month. This process was conducted under the assumption that there was a small spatial variability of the water quality parameters over nearby stations as well as the mean long term will not highly differ from the specific month [37]. The scarce data values were first identified through a sorting datasheet and graphed so that the extreme value (outlier) was spotted. The fate of the outlier was decided based on its statistical significance.

2.5. Analytical Methods

2.5.1. Correlations, t and Paired t Tests and Simple Statistics

The Pearson double moment correlation analysis was used to show the extent and direction to which climate/weather is likely to relate with water quality parameters. Hence, the strength between the associations of variables has been calculated using Equation (4)

$$r_{xy} = \frac{\sum\left(X_i - \overline{X}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum\left(X_i - \overline{X}\right)^2 \sum\left(y_i - \overline{y}\right)^2}} \tag{4}$$

where, r_{xy} is a correlation coefficient of the linear relationship between the variable *x* and *y*,

X_i Value of *x*-variable in sample,

$\overline{X}$ Mean of the values of *x*-variables,

y_i Value of *y*-variable in a sample,

$\overline{y}$ Mean of the value of *y*-variables (CFI, 2020).

Trend analysis was used to examine the changes of selected water quality parameters using long term time series plots and trends of rainfall and temperature. Also, simple statistical analysis included the mean percentage change was used for calculating seasonal means and percentage contributions to those changes over time. However, T-test (t) was used to show the significance of the association between the climate and water parameters at the most significant level ($p \le 0.05$).

2.5.2. Palmers Drought Severity Index

Palmers Drought Severity Index has been used to calculate or estimate the wetness and dryness thresholds where its standardized index spans from ≤−1 (for dry conditions) to ≥+1 (for wet conditions) [38]. The Precipitation Index (PI) equation presented in Equation (5) was used to mark the wet and dry seasons or years,

$$\text{PI} = \left(X - \bar{X}\right)/\sigma \tag{5}$$

where X is the monthly rainfall total, $\bar{X}$ is the long term mean rainfall and σ is the standard deviation. The wet and dry conditions are defined as

1) If PI ≥ 1, it was defined as a wet season or year.

2) PI ≤ −1 it was defined as dry season or year, otherwise normal wet/dry month (*i.e.* −0.9 ≤ PI ≤ 0.9). As for the wetness thresholds.

PI ranges from 1 ≤ PI ≤ 1.49 or moderate wet; while 1.5 ≤ PI ≤ 1.99 defines very wet; and PI ≥ 2 is defined as extremely wet. Similar negative PI ranges hold for the dryness conditions.

Also, the Paired T-test (t) was used for mark the significant change between the two means of climate and water parameters for the two five years' periods of 2011-2015 and 2016-2020, and its significance was decided by the p value of ≤ 0.05 as an influence as noted by [39]. Also, the paired T test was conducted under the assumption (Null hypothesis) that there was no significant change between the mean of climate and water quality parameters for the two defined periods, and its calculation was based on Equation (6)

$$t = \frac{m}{s/\sqrt{n}} \tag{6}$$

where m = mean differences,

n = Sample size,

s = Standard deviation [40].

3. Results

3.1. Long Term Seasonal Variability Rainfall and Temperature

The results of the long term rainfall variability for the two seasons of MAM (*Masika*) and OND (*Vuli*) for data observed at Zanzibar airport, Mahonda and Makunduchi meteorological stations presented in **Figure 1** revelas that the ten years (2009-2019) MAM seasonal RF had positive trends of 0.25 and 0.17, and 0.23 mm/yr, for Zanzibar airport, Mahonda, and Makunduchi (**Figure 1(a)**), respectively. Moreover, results in Figure 1(a) revealed a directional change on RF pattern (anomalies) during 2017, where backwards of 2017 the investigated stations had negative anomalies, while from 2017 onwards these stations have shown strong positive anomalies of more than 1.5σ indicating a climate shift from negative anomalies to positive ones.

Unlike *Masika* (*MAM*), the results for the *Vuli* (OND) RF variability Figure 1(b) shows an inconsistent trend for all investigated stations. For instance, Mahonda and Makunduchi had an increasing trend of 0.17 and 0.18 mm/yr while Zanzibar Airport has shown a decreasing trend of about −0.06 mm/yr. This inconstancy could be explained by the fact that the *Vuli* RF is weaker with poor spatial and temporal distribution except during extreme dipole events such as El Nino, La Nina positive phases of Indian Ocean Dipole (ID), Madden Julian Oscillations (MJO) among others as supported by [23] [29] [33]. Further results in Figure 1(b) shows that OND 2019 was exceptional by having higher RF of more than 0.5 σ in all investigated stations, this could be attributed by the influence of extreme positive IOD and strong phase of westerly propagating cloud clusters or Madden Julian Oscillation (MJO) as agreed by [29].

As for the Maximum (T_{max}) and Minimum (T_{min}) Temperature, the results of the seasonal variability of T_{max} and T_{min} for the last ten years presented in Figure 4.2 reveals that during *Masika* both T_{max} and T_{min} have shown fluctuations in temperature trends (Figure 2(a)),such that T_{min} has shown a decreasing trend of 0.05˚C/yr; mainly in 2017 with a peak of −2.0α below the normal range, while the T_{max} has shown an increasing trend of about 0.004˚C/yr, where during *Masika* of 2016 the T_{max} variability, was higher by at least 2.0α (Figure 2(a)) indicating a hot *Masika* season due to a temperature increase.

More results in Figure 2 revealed that both T_{max} and T_{min} during 2019 (Figure 2(a)) had very low anomalies (cold conditions) the phenomenon which could be attributed by high RF occurred during both seasons of MAM and OND as supported by Figure 1. Also, results in Figure 2(b) revealed that though the climate of Zanzibar is warm during OND 2019, but Zanzibar was characterized by very cold days because T_{max} was very low with strong weak anomalies, while the T_{min} anomalies were high indicating warm nights. This condition could be attributed

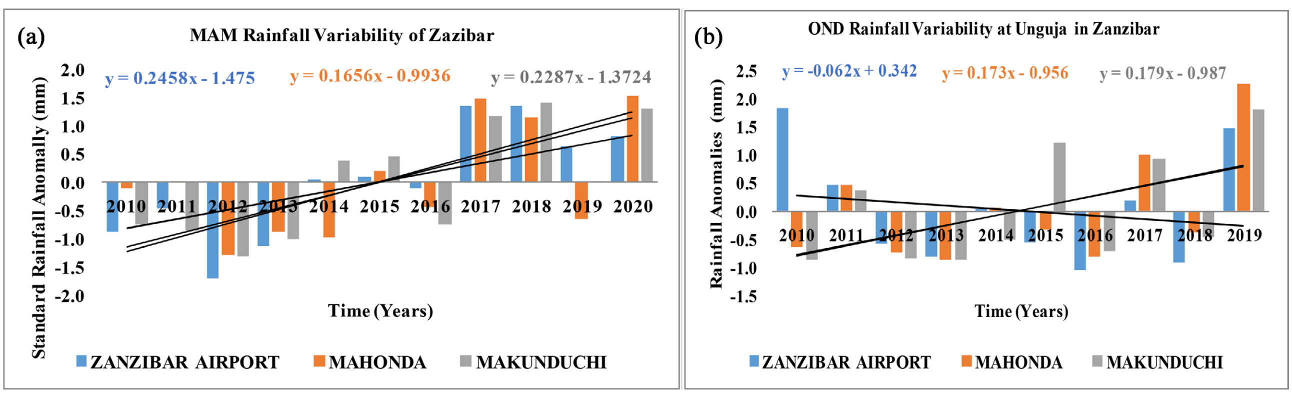

Figure 1. The seasonal variability of RF for (a) MAM and (b) OND in Zanzibar.

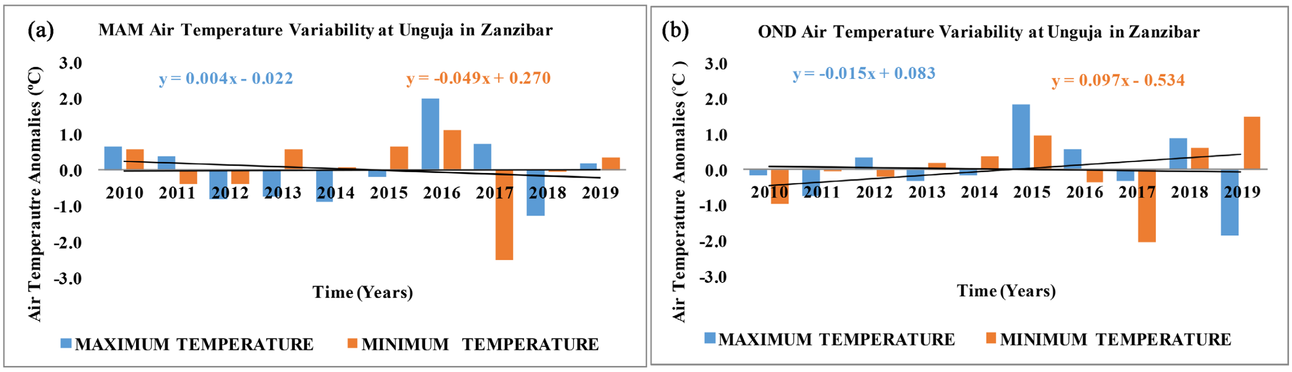

Figure 2. MAM (a) and OND (b) T_{max} and T_{min} variability at Zanzibar airport.

to the fact that in 2019 both MAM and OND seasons had higher RF which led earth to be concentrated and lose its absorption capacity as agreed by [41]. Similar situation of an extreme low anomaly of T_{min} as shown in Figure 2 during 2017 during both seasons; this could be attributed by the occurrence of strong El Nino condition in (2016-2017).

The T_{max}, during OND, has shown a decreasing trend in temperature for about −0.02˚C/yr, whereby in 2019 the temperature seemed to reach a peak of at least −1.9˚C/yr below the normal range while T_{min} has shown an increasing trend for 0.9˚C/yr, similarly from the Figure 2(b), the T_{min} has shown to be higher in 2019 for about ≥1.5˚C/yr; indicating strong cold days due to heavy downpours.

3.2. Seasonal Variability of Water Quality Parameters

The results of the long term variability of TDS, EC, and GWT during MAM and OND seasons are presented in Figure 3 to Figure 5. The variability of TDS, Figure 3(a) showed that during MAM, TDS had a decreasing trends of 0.12 and −0.01 mm/L/yr at Hali ya Hewa and Bumbwini groundwater stations indicating improvement of water quality due to low TDS and this may apply to EC as well, while TDS at Makunduchi has shown an increasing trend of about 0.004 mm/L/yr, with the highest peak of at least 2.0σ above normal during 2016, with increased MAM T_{max} which reached 2.0σ above normal range and low MAM RF of above −0.7 in that particular year presented in Figure 2(a) and Figure 1(a) respectively; this indicates one to one relationship between temperature and TDS as shown from Figure 2(a) and Figure 3(a) at Makunduchi, while Figure 1(a) has shown an opposite relationship between TDS and MAM RF during 2016.

As for OND season Figure 3(b) shows a decreasing trend of −0.1 mm/L/yr and −0.01 mm/L/yr at Hali ya Hewa and Makunduchi groundwater wells signifying that there has been a decreasing trend in TDS with time, and an increasing trend of 0.03 mm/L/yr Bumbwini Makoba. However, while Hali ya Hewa and Makunduchi have shown a decreasing trend in TDS, during OND, but the OND RF at Zanzibar airport and Makunduchi have a similar decreasing trend in RF (−0.1 mm/yr) and an increasing trend of 0.2 mm/yr (Figure 1(b)). This indicates

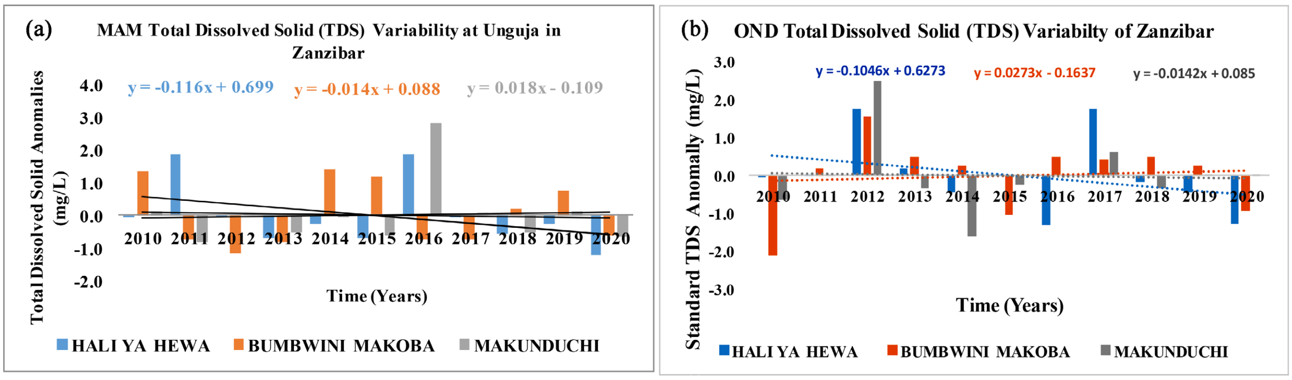

Figure 3. Variability of TDS during (a) MAM and (b) OND at groundwater stations.

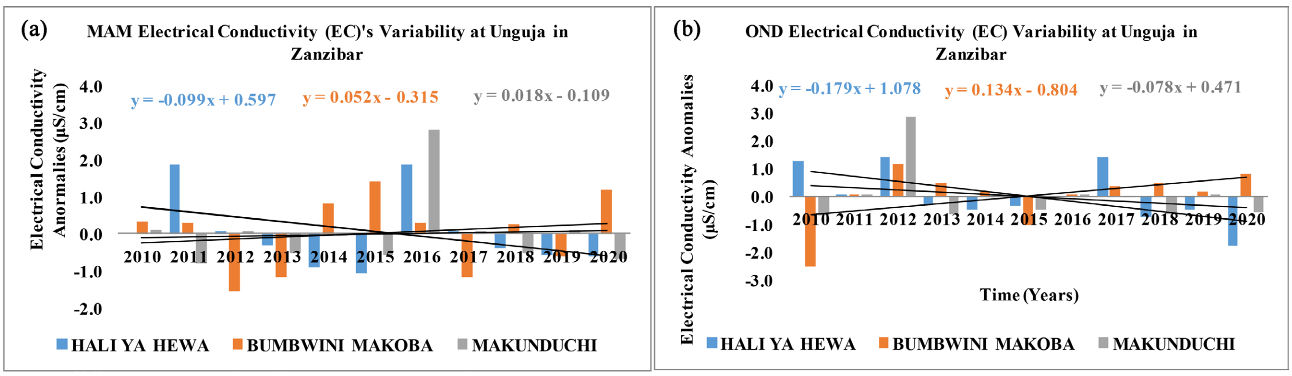

Figure 4. The seasonal variability of EC during (a) MAM and (b) OND over investigated groundwater stations.

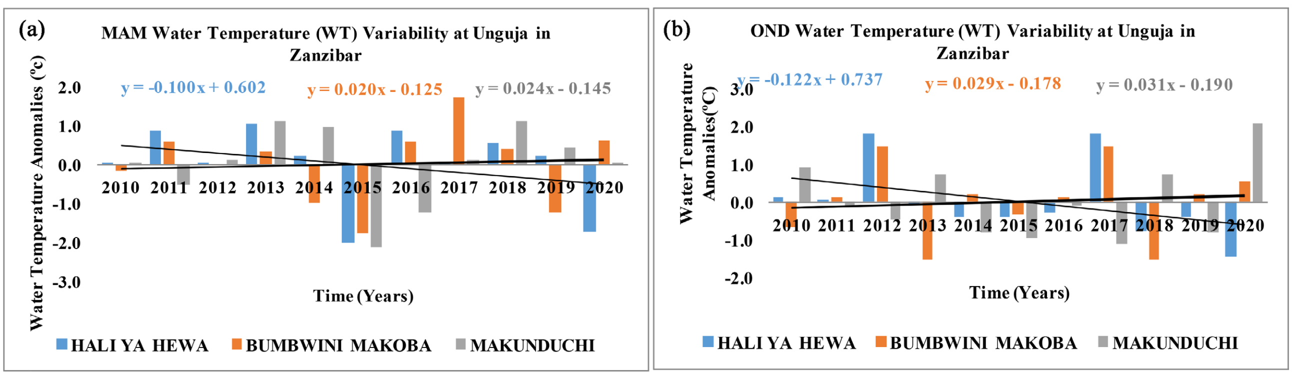

Figure 5. The variability of WT during MAM (a) and OND (b) Hali ya Hewa, Bumbwini and Makunduchi.

that higher RF increases the number of soluble ions in the water sources our results are in agreement with [42] who noted that rainwater has an aggressive behavior with a high ability to dissolve soil salts, and that the amounts of TDS increase with infiltration process *i.e.* rainwater increases in salinity during infiltration with increasing depth. Thus the periods with more rainfall (wet seasons) have more influence of TDS and dry seasons have less influence. A similar situation holds for air temperature seems to behave like RF variability with TDS since T_{min} has shown an increasing trend by 0.01˚C/yr Figure 2(b). The observed increases in GWT can be associated with preceding positive shifts in regional surface air temperatures (Figure 2 bottom panel), which are in turn linked to global air temperature changes as noted by [43]. Indeed, [44] noted groundwater natural quality is more affected by climatic variations than anthropogenic contamination. This indicates that conductivity of ions in water depends on the water temperature *i.e.* ions move faster when the water is warm. Hence, the apparent conductivity is increased when the water has a higher temperature Indeed, similar results holds for the EC variability on the groundwater wells of Hali ya Hewa, Bumbwini, Makoba and Makunduchi during the MAM **Figure 4(a)**, showing a slight increase in EC at Bumbwini Makoba and Makunduchi (0.05 and 0.02 μS/cm/yr) and negative decrease at that Hali ya Hewa −0.01 μS/cm/yr with significant increase of at least 2.5σ at Makunduchi during 2016 **Figure 4(a)**. The presented results of the EC fluctuation can be explained by the fact that EC depends on chemicals that has been dissolved at a particular areas and amount of rainfall at a particular time indicating that EC amount can be manipulated by a factor more than climate. For instance, during MAM RF of Mahonda (**Figure 1(a)**) and MAM EC (**Figure 4(a)**) of Bumbwini Makoba had shown very strong relationship where all parameters were at the peak in the year 2019, and vice versa. However, the increasing/decreasing in EC could also be associated with the underlying environmental conditions including geological characteristics in which some soil minerals interfere with the water permeability or salt contents, this may be account for the decreasing of EC amount, though RF in MAM 2017 and 2018 was high as shown on **Figure 1(a)**.

The results of the variability of the EC during OND presented in **Figure 4(b)** shows that EC at Hali ya Hewa and Makunduchi groundwater stations were decreasing with time (*i.e.* shows a negative trend) of about −0.18 and −0.08 μS/cm/yr, respectively. Indeed, the increasing trend of about 0.13 μS/cm/yr was noticed at Bumbwini Makoba. Further results revealed that during OND 2012 all three groundwater stations had high EC of up to 3.0 μS/cm/yr, while during MAM RF and T_{max} has shown to be increased. Moreover, the OND 2019 which was characterized by higher RF (**Figure 1(b)**) has shown to have negative EC for Hali ya Hewa and Makunduchi groundwater station; indicating that EC amount can be manipulated by a factor more than climates such as environmental and geological composition.

As for the variability of GWT results showed a negative trend of >−0.1˚C/yr below the normal range for Hali ya Hewa station during MAM, and a weak positive increasing trend of greater than 0.01 and 0.02˚C/yr for Bumbwini Makoba and Makunduchi, respectively. This variability in GWT trend (positive to negative) could be explained by the fact that RF activities are likely contributing to the cooling effects of groundwater as shown in **Figure 1(a)** and **Figure 2(a)** and as in the year 2016. This study finding is well supported by [45] who noted that shifting in precipitation from warmer to colder months could be supported with an increased groundwater recharge during cool seasons which then cool groundwater sources.

The GWT during OND has shown a positive trend of 0.03˚C/yr within the groundwater stations of Bumbwini Makoba and Makunduchi, while negative trend of about −0.12˚C/yr was found at Hali ya Hewa station, the results which can be traced as due to the possible reduction in T_{max} as shown on **Figure 5(b)** and **Figure 2(b)**. These finding strongly agrees with [10] who noted that both minimum and maximum air temperature are showing positive correlation with the corresponding groundwater temperatures.

3.3. Extent to Which Climate Parameters Affect Groundwater Quality

The percentage changes in TDS for the five years (2011-2015) presented in **Table 1** shows that TDS in the Bumbwini Makoba has changed by 33.2% while its inter annual variability is in decreasing trend at a rate of −0.3%/yr. As for the Hali ya Hewa groundwater station the percentage change in TDS for the periods of 2011-2015 and 2016-2020 was 33.2% and 33.2%, respectively. These changes indicate an increasing trend rated by 0.4%/yr (between 2010 and 2015) with no significant difference in percentage changes of TDS for 2011-2015 and 2016-2020 (**Table 1**). TDS percentage changes at Makunduchi was 32.8%, 29.7% and 37.5%, with a decreasing trend rated at −3.1%/yr (during 2010-2015) and the sharp increasing trend of 7.7%/yr (during 2015-2020). EC had percentage changes of 32.8%, with decreasing trend rated at −1.5%/yr for 2011-2015 at Bumbwini Makoba, and no significant differences in EC percentage changes for 2016-2020 periods. Similar results of 33.4% and 33.4%, holds for changes in EC at Hali ya Hewa (**Table 1**). Also, results show a 0.1% as a difference in percentage changes for five and ten years' intervals indicating a positive increasing trend over time. EC Makunduchi revealed a percentage change of 28.8%, and 36.9% (**Table 1**), with a decreasing/increasing trends of −5.5% and 8.2% for the periods of 2010 to 2015 and 2016-2020, respectively. The percentage changes in GWT at Bumbwini Makoba for the 2010-2014 and 2016-2020 periods (**Table 1**) was 33.3%, while the differences in percentages changes for this station were indicating a decline of −1.1%/yr and −0.1%/yr, respectively.

As for the change of water quality parameters during ONDs of the two mentioned periods (*i.e.* 2011-2015 and 2016-2020) the results shows a TDS percentage

Table 1. Percentage changes in water quality parameters during MAM.

Station	Period	% C TDS	D % TDS	% CEC	D% EC	% CWT	D% WT
Bumbwini Makoba	11 - 15	33.2	−0.3	32.8	−1.5	33.3	−0.2
	16 - 20	33.2	0.0	32.8	0.0	33.3	0.0
Hali ya Hewa	11 - 15	33.2	0.4	33.4	0.1	33.3	0.0
	16 - 20	33.2	0.0	33.4	0.0	33.3	0.0
Makunduchi	11 - 15	29.7	−3.1	28.8	−5.5	33.0	−1.1
	16 - 20	37.5	7.7	36.9	8.2	32.9	−0.1

Note that in **Table 1**, the numbers 11 - 15 and 16 - 20 refer to the years 2011-2015 and 2016 to 2020, respectively. Also, % C refers to percentage changes TDS, EC andTW, while D%TDS, D%EC and D%WT refer to the differences in the percentage changes in TDS (mm/L/yr), EC (μS/cm/yr) and WT (˚C/yr), respectively.

changes ranged from 32.8% to 35% in TDS the investigates station of Bumbwini Makoba, Hali ya Hewa with no significant changes in Makunduchi. These results indicated an increase and decreased changes in TDS of about 5% and −1.7% for Bumbwini Makoba and Haliya Hewa, respectively. As for percentage changes in EC, Table 3 revealed that Bumbwini Makoba, Hali ya Hewa, and Makunduchi ground water stations has shown percentage changes in EC ranged from 23.4% to 38.3% with an increasing rates ranged from −14.8% to 0.6%, respectively. As for GWT the changes were 33.4% at Bumbwini Makoba an increase rate of the changes by of 0.3% for the period of 2010 to 2020

As for the percentage changes in climate parameters (RF, T_{max} and T_{min}) during MAM and OND for the aforementioned periods presented in Table 2 revealed that the long term RF variability during the MAM season has changed by 33.9% for the period of 2011-2015 with an increasing RF trend of about 1.8%/yr with no significant percentage changes during 2016-2020, However, the MAM T_{max}, had changed for 30.4%, 35.5% and 34.1% (Table 2), these results indicate an increase of 5.0%/yr for 2010-2014 and a slight decrease in −1.4%/year during MAM of 2016-2020, while T_{min} had changed for 30.0%, 36.5% and 33.5%, respectively, indicating an increase of 6.5% for the period of 2010-2014 and a decrease of −2.9% during 2016-2020.

The percentage changes of the climate parameters (RF, T_{max}, and T_{min}) for the two mentioned periods of 2011-2015 and 2016-2020 during OND presented in Table 4.4 revealed that RF changed by 39.1% and 32.6% resulting in RF increase and decline of about 10.8%, and −6.5% respectively. However, T_{max} changed by 35.5% and 34.1% (Table 4), resulting in an increase of 5.1% during 2011-2015 period, while the T_{min} changed by 35.9% and 33.8% resulting an increase and decline of chance of 5.5% and −2.1%, respectively.

3.4. Correlation between Weather and Water Quality Parameters during MAM and OND

The results of the correlation between weather and groundwater quality parameters at Hali ya Hewa during MAM show that the two were significantly correlated. For instance, TDS has shown a strong negative correlation with T_{min} ($r = -0.72$, at $p \leq 0.02$) while no significant association with T_{max}. Also, TDS and RF had high negative correlation but not significant, indicating that decreased

Table 2. The percentage changes in weather/climate parameters for two given periods.

Station	Period	% CRF	D% RF	% CT_{max}	D% T_{max}	% CTim	% CT_{min}
Zanzibar airport	11 - 15	33.9	1.8	35.5	5,0	36.5	6.5
	16 - 20	33.9	0.0	34.1	1.4	33.5	2.9

Note that in Table 1, the numbers 11 - 15 and 16 - 20 refer to the years 2011-2015 and 2016 to 2020, respectively. Also, % C refers to percentage changes RF, T_{max} and T_{min}, while D%RF, D%T_{max} and D%T_{min} refer to the differences in the percentage changes in TDS (mm/L/yr), EC (μS/cm/yr) and WT (˚C/yr), respectively.

groundwater recharge, reduces the organization of underground salt as noted by [46]. EC has shown a strong positive correlation with T_{max} (at r = 0.67 and $p \leq 0.05$) indicating that like the TDS also EC is affected by higher temperature during MAM season, while GWT has shown a strong negative relationship with the minimum temperature of r = −0.7 ($p \leq 0.05$), indicating that lower minimum temperatures affects the groundwater temperatures.

As for OND results revealed a negative correlation −0.5 (not significant) between TDS and T_{min}. However, EC has shown a high negative relationship r = −0.80 ($p \leq 0.01$) and r = −0.6 (at $p \leq 0.01$) with both T_{min} and T_{max}, while RF has shown a positive relationship of r = 0.3 with EC as supported by (Mohammad *et al.*, (2017), and GWT had a strong negative correlation (r = −0.69 at $p \leq 0.02$) with T_{min}. The results of the correlation analysis for weather and groundwater quality parameters for Bumbwini Makoba during MAM shows that RF and T_{min} are strongly correlated (r = −0.6), also EC and GWT are strongly positive and negative correlated with T_{min} at 0.5 and −0.6, respectively. As for OND season, similar result holds for the correlation between air temperature (T_{max} and T_{min}) TDS and GWT, but with r not being significant indicating no significant relationship between T_{max} and T_{min} and TDS as agreed by (Thomas, 2021) who noted that there is no direct correlation between TDS and air temperature. The results of the association between the weather and water quality parameters during MAM at Makunduchi has shown a strong correlation (r = 0.7 at $p \leq 0.02$) between TDS and T_{max}, while insignificant correlation with T_{min}. However, EC and T_{max} had high and insignificant correlation (r = 0.7 at $p \leq 0.01$), with T_{min}. As for GWT T_{min} and T_{max}) results revealed positive and negative correlation (r = ±0.4). As for the OND season, all correlations were either weak positive or negative but not significant, except for RF and GWT which had a strong significant negative correlation (*i.e.* r = −0.7 at ($p \leq 0.02$).

3.5. Paired t-Test

Results of the paired t-test between the means of the groups of weather and water quality parameters at all station under investigation, under the null hypothesis that; "there are no significant changes in means of weather/climate and water quality parameters for periods of 2011-2015 and 2016-2020" presented in **Table 3** shows that apart from RF which had accepted the stated null hypothesis (*i.e.* have $p \leq 0.02$) otherwise all other parameters rejected the stated null hypothesis (*i.e.* $p \geq 0.05$) indicating that there was a significant change between the means of water and climate parameters for the two stated periods. These results indicate that significant mean changes of the weather parameters (T_{max} and T_{min}) for the stated periods has resulted to significant mean changes of the mean water quality parameters for all investigated station, indicating that the variability of the climate parameters has significant influence to the variability of the groundwater quality parameters in most ground water station of Zanzibar.

Table 3. Correlation between weather and water quality parameters at $p \leq 0.05$.

Parameters	Correlation (r)	P-value ($p \leq 0.05$)
RF	−0.6	0.02**
T_{max}	0.8	0.07
T_{min}	0.44	0.5
TDS	0.4	0.3
EC	0.4	0.3
GWT	0.98	0.4

Note that ** indicates significant correlation resulting to accept the null hypothesis.

3.6. Influence of Dry MAM and OND and Seasons on Water Quality Parameters

The Precipitation Index (PI) calculations used to separate the wet and dry seasons based on the Palmers Severity Index revealed that 2012 and 2013 have been marked as dry years, while 2017, 2019 and 2020 were categorized as wet years. The results of analysis of the average groundwater quality parameters based on the dry MAM and OND season of 2012 revealed a decreasing trends of −0.4 mm/L/yr and −0.5 μS/cm/yr for TDS and EC, while no changes in GWT, meaning that the low RF also influence decreasing in TDS and EC values (Table 4(a)). As for the climate parameters of T_{max} and T_{min}, results showed a negative trend of −0.4˚C/yr, while T_{max} experienced a positive trend of 0.6˚C/yr. Likewise, for dry MAM seasons of 2013, results have shown that TDS and EC have the same negative trend of −0.7 since the two have a linear relationship while GWT showed an increasing trend of 0.8˚C/yr (Table 4(a)) while T_{min} had a positive trend of 0.6˚C/yr.

The correlation between weather and water quality parameters during dry years was seen to have a strong positive r = 0.8 between RF and T_{max} showing a significant relationship at $p \leq 0.01$ (Table 4(b)). Also, TDS and EC have both showed a positive relationship of r = 0.7 (Table 4(b)) with RF indicating that rainfall had a positive effect on TDS and EC.

3.7. Influence Wet MAM and OND Seasons on Groundwater Quality

The results of the variability of groundwater parameters during the wet MAM 2017 season shows that TDS, EC and GWT had positive trends of 0.9 mm/L/yr, 2.0 μS/cm/year and 0.7˚C respectively, while the T_{min} has been decreased by −2.5˚C and T_{max} has shown a positive trend of 0.7˚C/yr. As for the wet year of 2017 the wet MAM of 1.3 mm/yr in RF showed a negative trend and for the wet OND, the RF was 1.4 mm/yr, while both T_{min} and T_{max} had shown a negative trend of −2.0˚C and −0.3˚C/yr (Table 5(a)), respectively. As for wet MAM 2019 season all groundwater parameters were showing a decreasing trend of about −0.1 mm/L/yr, −0.6 μS/cm/yr and −0.2˚C for the TDS, EC and GWT, while the T_{min} and T_{max} were at 0.4˚C and 0.2˚C (Table 5(a)), respectively. The results of

Table 4. (a)The trends of weather and water quality parameters during dry MAM and OND season, and (b) Correlation between climate and water quality during dry years.

(a)

Parameters	**2012 (Trends)**		**2013 (Trends)**	
	MAM	**OND**	**MAM**	**OND**
RF	−1.4	−0.7	−1.0	−0.9
T_{min}	−0.4	−0.2	0.6	0.2
T_{max}	−0.8	0.3	−0.8	−0.3
TDS	−0.4	1.9	−0.7	0.1
EC	−0.5	1.8	−0.7	−0.2
GWT	0.0	0.9	0.8	−0.3

(b)

	RF	**T_{min}**	**T_{max}**	**TDS**	**EC**	**GWT**
RF	1.0					
T_{min}	0.3	1.0				
T_{max}	**0.8**	−0.3	1.0			
TDS	**0.7**	−0.4	−0.2	1.0		
EC	**0.7**	−0.4	**1.0**	**1.0**	1.0	
GWT	**0.5**	0.2	0.3	0.4	0.5	1.0

Table 5. (a)The trends of weather and water quality parameters during wet MAM and OND season, and (b) Correlation between climate and water quality during wet years.

(a)

Parameters	**2017**		**2019**		**2020**	
	MAM	**OND**	**MAM**	**OND**	**MAM**	**OND**
RF	1.3	1.4	1.8	0.9	1.2	
T_{min}	−2.5	−2.0	0.4	1.5	0	0.4
T_{max}	0.7	−0.3	0.2	−1.9	0	0
TDS	−0.2	0.9	−0.1	0.1	0.4	−0.4
EC	−0.4	2.0	−0.4	−0.6	0.0	−2.3
GWT	0.6	0.7	−0.2	−0.3	−0.4	−0.4

(b)

	RF	T_{min}	T_{max}	TDS	EC	GWT
RF	1.0					
T_{min}	−0.2	1.0				
T_{max}	0.7	−0.6	1.0			
TDS	−0.1	−0.3	−0.2	1.0		
EC	0.2	−0.5	0.0	**0.9**	1.0	
GWT	0.2	**−0.9**	0.3	0.4	0.7	1.0

the groundwater parameters for the wet season of MAM and OND 2020 areas are presented in **Table 5(a)**.

The results of the correlation between groundwater and climate parameters during wet years presented in **Table 5(b)** shows a strong negative correlation between T_{min} and GWT at r = −0.9 (p ≤ 0.01) otherwise all the results were either weak positive or negative and not significant. Indeed, **Table 5(b)** shows a strong relationship between parameters of the same type.

4. Discussion

The variability of weather and climate have numerous impacts on human life and his environments including the natural resources such as surface and groundwater sources. The decline in rainfall may affect the aquifers to recharge the groundwater and excess rainfall may pollute the groundwater through impurities penetrated either direct or indirect to groundwater sources. Thus, this study was aimed to determine the influence of weather and climate variability in groundwater quality in Zanzibar, where the long-term and seasonal variability of water quality parameters including TDS. EC GWT, subject to the changes of RF, T_{max} and T_{min}. The presented results have shown that RF during MAM had a positive trend ranging 0.17 to 0.25 mm/yr in most stations while in OND a positive trend ranged from 0.17 - 0.18 mm/yr and few stations had a negative trend (−0.06 mm/yr). As for specific years, most stations in 2017 had a higher RF of more than 0.5σ. As for T_{max}, the trend was positive of 0.04˚C/yr during MAM and a negative trend of −0.015˚C/year during-0.049 during OND, while T_{min} had the negative trend of 0.049˚C/yr during MAM and a positive trend of 0.097˚C/yr during OND. This has influenced TDS to have an average negative trend on 0.12 mm/L/yr most stations except Makunduchi which had a positive trend of 0.018 mm/L/yr indicating that decreased TDS due to increased rainfall had ejected higher level of impurities to groundwater and affected its quality as supported by [45] and [42] who noted that that higher rainfall with increase the amount of TDS with infiltration process. Also, the presented results have shown a negative trend (0.0014 - 0.104 mm/L/yr) in TDS during OND. The presented results in seasonal variability EC has shown a positive increasing trend ranging from 0.01 - 0.052 (μS/cm/yr) except at Hali ya Hewa which had a negative trend of −0.099 (μS/cm/yr) during OND the ranges from −0.078 - 0.179 (μS/cm/yr) at Hali ya Hewa and Makunduchi indicating that the EC is affected by the declined rainfall resulting to limited infiltration rates. The GWT had a positive trend in MAM and OND at two stations and negative both in MAM and OND at Hali ya Hewa indicating that rainfall variability has an impact on GWT as noted by [45] who noted that shifting in precipitation from warmer to colder months will increase ground research and results in cooling of groundwater sources. Also, the presented results have shown that the percentage changes in seasonal variability in climate parameters were 14.3%, 18.8% and 11.1% for RF, T_{max}, and T_{min}, respectively. While for the groundwater parameters the changes were 5.6% for TDS, 1.75% for EC and 2.4% in GWT. These percentage changes indicate that the variability among weather and climate parameters is noticeable between seasons and how they impact the water quality parameters as noted by [47] that irregularities in-season rainfall and warming can influence annual precipitation and daily temperature over time, and this can influence the variability of groundwater parameters though they show gradual changes as agreed by [9] who noted that weather variability also influences physical variability of water.

Indeed, the presented result in pared t-test has shown that the mean changes in climate and water quality parameters in two times periods (2011-2015 and 2016-2020) were significant except for the RF (**Table 3**) indicating that the increasing climate variability has posed the changes in ground ware quality. Furthermore, the presented correlation results for the climate parameters and water quality parameters have been varying from the station and with time as well as in direction. For instance, RF had a positive and linear relationship with TDS and EC as agreed by [45] who noted that higher rainfall results in higher TDS and EC amounts since water recharge is responsible for the dissolving of salts into ions.

5. Conclusions

Based on the presented results and a foregoing discussion the study concludes the following:

1) The variability and changes of climate/weather parameters had to a great extent affected groundwater quality parameters.

2) Seasonal variability of the weather parameters has been shown to affect both direction and strengths of the seasonal groundwater parameters.

3) The variability of the wet and dry seasons has both positively and negatively affects the groundwater parameters.

6. Recommendations

Based on the foregone discussion and presented conclusion the study recommends the following:

1) Well recording of groundwater data to facilitate further research work.

2) Updating the results with detailed data from Ungula and Pemba ground water stations wells.

3) Extensive monitoring of groundwater data should be taken into account for having a continuous flow of data records.

4) Each groundwater station should be equipped with thermometers.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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