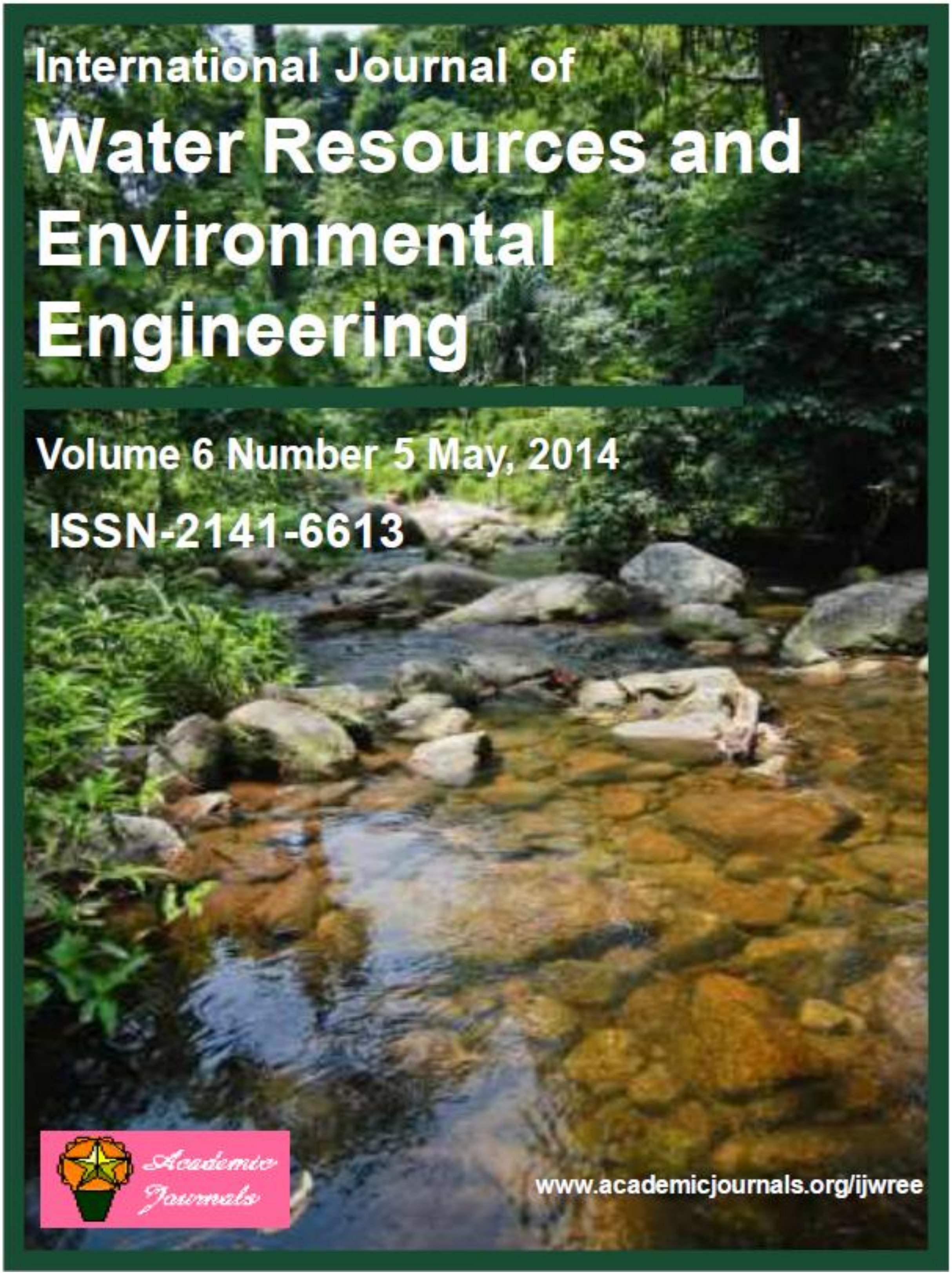

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Full Length Research Paper

Assessment of Silyaninov index for detecting climatic changes and droughts in the central Sudan

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Drought is a constraint upon development in Sudan. This paper attempts to understand drought and climate change in the central Sudan using the Silyaninov index (SI) because of its simplicity and its required datasets (monthly rainfall and temperature) are routinely collected in developing countries. Also, the ecoclimatological relationships for the natural vegetation cover were investigated using the normalized difference vegetation index (NDVI) and ancillary climatic data. The climate variability in the central Sudan is found to be highly generated by the variability in rainfall rather than temperature. Rainfall experienced a significant decreasing trend (≈ 3.5 mm per annum) coupled with a significant increasing trend in temperature (≈ 1.4°C per annum) during the period 1960 to 2010. Accordingly, the aridity increased significantly at 50% of the studied stations. SI is found to be more effective in detecting drought than using rainfall dataset alone. However, when the temperature dataset is anomalies-free it could explain effectively most of the historical meteorological droughts witnessed in central Sudan. Using SI, the majority of the drought events were observed in 1970 to 1990, with the exception of Damazine (1998 to 2002) and Ed Duim stations (2000 – 2005). The common wetted years outweighed the common drought years, revealing the localized behavior of the rainfall. The analysis of NDVI showed that the vegetation cover experiences a decreasing pattern under the semi dry (Ed Duim station) and semi humid (Damazine station) climatic zones during the period 2000 to 2010. The relationships of NDVI-SI and NDVI-rainfall were found better than the NDVI- temperature.

Key words: Central Sudan, drought, climate change, natural vegetation cover, Silyaninov index, normalized difference vegetation index (NDVI).

INTRODUCTION

According to the Intergovernmental Panel on Climate Change, IPCC (2007) climate change is defined as a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Thus, it refers to any change in climate over time, whether due to natural variability or as a result of human activity. These changes will likely lead to changes in rainfall, atmospheric moisture and regional climate variability, especially in the tropics and sub-tropic areas (Gitay, 2002). Most of the climate change studies have been

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done in large scales. This is necessitated downscaling studies, as the impacts of climate change will be different from one place to another (IPCC, 2007). For instance, it is expected that Africa will likely be the most vulnerable continent (Challinor et al., 2007).

Drought is an ordinary phenomenon in the eastern African countries, including Sudan. It has affected 100% of the land in Somalia, Eritrea and Djibouti, and 61 to 87% of the land in Ethiopia, Kenya and Sudan (Mati, 2005). The periods 1970s and 1980s were the most decades that have witnessed catastrophic results due to droughts that is, mass lost of souls, destroyed vegetation covers, failure in biomass production, displacement and social stability (Osman and Shamseldin, 2002; Sivakumar et al., 2005; Tilahun, 2006). In Sudan, drought has been related to famine, civil unrest, ill-health and desertification and in turns as a constraint upon development (Hulme, 1987). Ayoub (1999) has reported that the repeated droughts of the late 1960s to mid 1970s have resulted in destroying the whole of *Acacia tortilis* belt of north Kordofan, and in increasing the number of dust storms per year during the period of 1970 to 1980 in El Fasher area, Darfur region.

Climate change and drought pose great threats to human life, economic sectors and environments. Therefore, their quantitative monitoring is very important from many perspectives of views: risk management, assessing adaptive capacity, planning and decision making process. The better drought preparedness depends on monitoring drought's onset, progress and real extent (Morid et al., 2006). However, drought is very difficult to define. For example, Logan et al. (2010) cited more than 150 definitions for drought. This is because drought is not a distinct event, it is as a result of complex factors and it has neither a distinct start nor a finish; it is only after a period of time it can be recognizable (Oladipo, 1985). One of the definitions of drought that had been formulated was that "a sustained period of significantly below normal precipitation". This definition encounters two problems. Firstly, there was no universal agreement on the definition of "a sustained period". Secondly, due to the high variability of rainfall the term norm precipitation is questionable in the African Sahel (Hulme, 2001). In Sudan, Ayoub (1999) has called that there is a southward shifting of the desertification boundaries, which can be considered as a climatic change. It goes without saying that aridity is universally distinguished from the drought as the former is a permanent climate feature of a given region resulting from low precipitation.

Generally, there are four wide types of drought; viz: meteorological, agricultural, hydrological and socioeconomic droughts. The widely natural and human factors used to designate drought are climate, soil water, precipitation, soil type, water storage distribution, number of population and land use (Oladipo, 1985). In order to monitor drought, many indices have been devised, such as the ratio of precipitation and potential evapotranspiration, the standardized precipitation index (SPI), the evaporation ratio, the Palmer drought severity index (PDSI) and the soil moisture index (Arora, 2002; Ntale and Gan, 2003; Sivakumar et al., 2005; Bates et al., 2008; Mpelasoka et al., 2008; Logan et al., 2010). Ntale and Gan (2003) found that SPI is the most appropriate method for detecting the regional east African droughts, agrees with Morid et al. (2006) results for Tehran Province conditions in Iran. However, the preciseness of the SPI depends on the rainfall distribution and its length of record (Wu et al., 2005).

Recently, the drought indices have been used for detecting climate change. Mavromatis (2010) found that the self-calibrated version of PDSI has the potential to be used for climate change impacts assessment studies. In Sudan, climate change impacts are poorly documented. Rainfall remains the most studied climatic variable (Hulme, 1986, 1987; Eldredge et al., 1988; Ayoub, 1999; Fud Elmoula, 2004). Temperature datasets are commonly available but not so studied. Thus, from cost effective and data availability point of view both temperature and rainfall could be effectively used in studying climate change and drought in Sudan.

The Silyaninov index is historically used in classifying the climatic zone of Sudan, seven climatic zones (Table 1). By such mean, detecting any prolonged changes in SI values may indicate a climatic change. There are discernable reasons behind using of SI to detect climate change and drought for the central Sudan: (1) Adam (2002) designated the critical values for every climatic zones in Sudan, these values can be used as baselines, given that the persistent changes in those values can be considered as a climate change; (2) SI is very easy to estimate since its estimation depends on the most two reasonably available climatic variables in Sudan, viz. rainfall and temperature.

Agriculture and livestock breeding are the dominant livelihood generations in central Sudan. Thus, drought and climate change are expected to have detrimental impacts on communities stability. It is therefore, studying the relationship between climate and vegetation cover is very important. Recently, remote sensing techniques were widely used in monitoring vegetation cover, agriculture, natural resources, weather conditions, water balance and droughts (Bastiaanssen et al., 2003; Omuto and Shrestha, 2007; Tan, 2007; Elhag and Walker, 2009; Mavromatis, 2010). Also, remote sensing has been used recently to define aridity as Lioubimtseva et al. (2005) reported that a period with a natural difference vegetation index (NDVI) value of less than 0.07 (a unit less) is classified as arid. The huge advance in the remote sensing techniques makes them capable for studying precisely the climate changes impacts on vegetation cover dynamics in central Sudan. As yet the define of drought years in the central Sudan is depended on memories of local people (Abusin, 1986; Telku et al.,

Table 1. Sudan's climatic zones, on the basis of Silyaninov index (SI).

Climate type	Value of SI
Desert	< 0.1
Sem-desert	0.1-0.3
Dry	0.3-0.5
Semi-dry	0.5-0.7
Sub-humid	0.7-1.3
Humid	1.3-2.0
Super-humid	> 2.0

Source: Adam (2002)

1991), the objectives of this study were to detect climate change and drought using the Silyaninov index (SI) because of its simplicity and required datasets (monthly rainfall and temperature) are generally available in developing countries in the central Sudan. Also, the study examines the dynamic of the natural vegetation cover using the NDVI.

Description of the study area

The study area was located between 11.00 to 14.38 °N and 24.8 to 35.4 °E, which roughly represents the central Sudan with a total area of 434 000 km^2 (Figure 1). The climate is generally hot and dry, ranging from dry to sub humid zones. Rainfall and length of dry season are the most significant climatic variables (Food and Agriculture Organization of the United Nations, FAO, 2006). Rainfall extends for a short period (June to October) with a low magnitude, ranging from 100 in the northern part to 600 mm in the southern part. This is coupled with a high annual evapotranspiration of 2200 mm. Thus, the region suffers shortage in the water supply for a long period of time (8 months).

Central Sudan is distinguished as the main region of both animals and agricultural productions. It includes most of the Sudanese irrigated and rainfed agricultural projects. There is however, a delicate balance between man needs and natural resources as the vast majority of the livelihood generations, basically agriculture and rearing livestock are climate-land-based, especially in rural areas. Both climate and land however, have been deteriorated and in turns disturbed the region's socio-economic stability (Hulme, 1986; Ayoub, 1998). Add to this, the region belongs to the African Sahel belt where drought is a repeatable problem. Moreover, the evidence of the 1984/1985 famine states that drought is the main cause of famine in Sudan (Teklu et al., 1991).

MATERIALS AND METHODS

The first step for detecting climate change and droughts in the central Sudan is to choose the representative stations. To ensure the statistical validity, the station with a minimum record length of 25 years was chosen (Table 2). This restricted the number to only eight stations. Many stations have been found out of service since 1970s and 1980s (Figure 1), especially at the western part, that is, Kordufan and Darfur, due to drought episodes that is leading to instability and insecure situations. Therefore, each station is expected to cover about 54 000 km^2 from the total area, indicating poor spatial meteorological measurements in the central Sudan. Therefore, stationary data series are used instead of the regional ones.

Testing data quality

In order to detect trends in the time series, the following tests were applied in advance.

Test for homogeneity

The nonparametric Thom test was used to examine the homogeneity of the time series, following the procedure mentioned in Rodrigo et al. (1999), Modares and Silva (2007) and Nasri and Modares (2009). The null hypothesis (the time series is homogeneous) is verified at the 0.99 confidence level if $|Z| < 2.58$. The time series of rainfall were found homogeneous. However, temperature time series of 50% of the stations (namely Damazine, El Obied, Wadmedani and Gedarif stations) were found to be inhomogeneous. Consequently, the cumulative residuals method was used to apply the appropriate corrections as described in Allen et al. (1998).

Test for randomness

The presence of a positive correlation will increase the possibility of rejecting the null hypothesis (no trend) while it is actually true and the vice versa is correct for the negative correlation (Yue and Wang, 2004). The detection of trend in a time series entails that the datasets is serially independent (Yue and wang, 2004). Therefore, the Durbin-Watson test was used. It is found that all the stations, with the exception of Gedarif and Damazine, have shown significant positive serial correlations (P = 0.05). To eliminate such serial correlation, the pre-whitening approach was adopted, following the approach described in Burn and Hag Elnour (2002).

Test for trend

The non-parametric Mann-Kendall test was used to detect trends in time series as described in Burn and Hag Elnur (2002), Yue et al. (2002), Smith et al. (2004), Yue and Wang (2004), Modarres and Silva (2007), Luo et al. (2008), Basistha et al. (2009), Nasri and

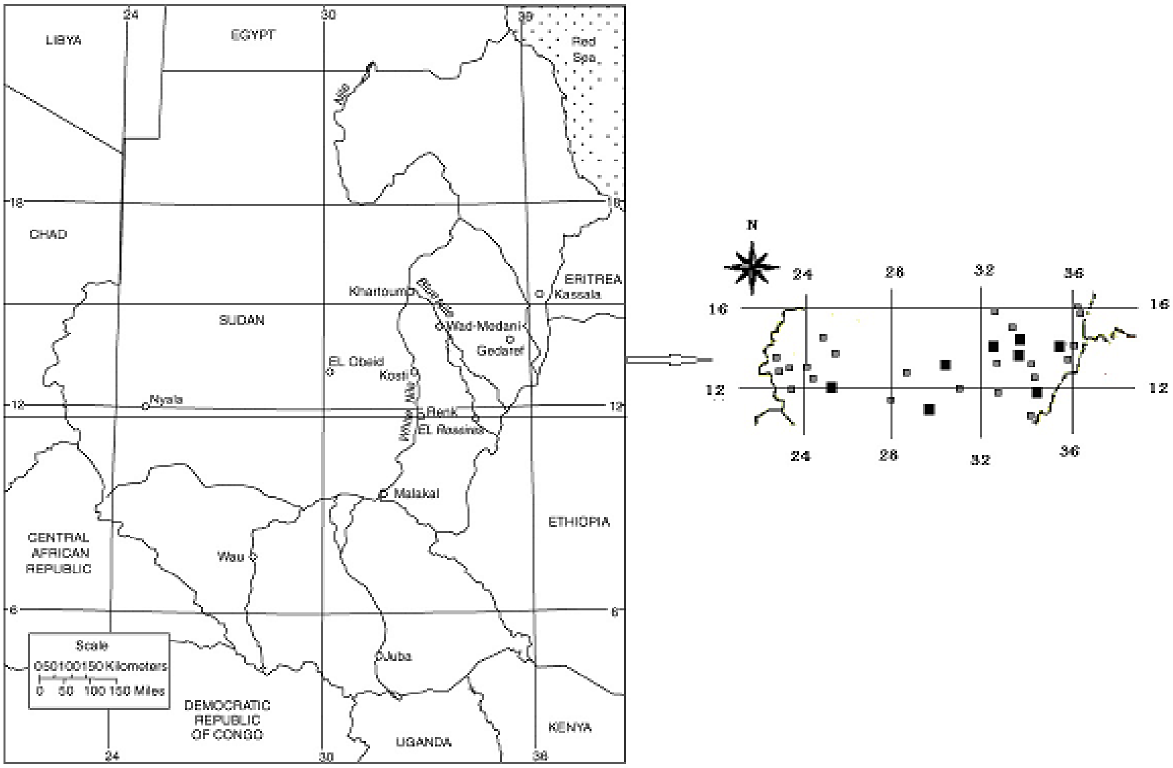

Figure 1. The studied stations (the black squares) in the central Sudan. The grey squares refer to the stations with problems in data availability

Table 2. The locations, altitudes and sample sizes of rainfall (R-N) and temperature (T-N) for the selected stations in the central Sudan.

No.	Station	Latitude (°N)	Longitude (°E)	Altitude (m)	R-N (year)	T-N (year)
1	Kadugli	11.00	29.72	500	47	41
2	Damazine	11.82	34.40	470	43	41
3	Nyala	12.00	24.80	675	36	39
4	El Obied	13.17	30.23	570	43	43
5	Sennar	13.55	33.56	420	36	40
6	Ed Duim	14.00	32.33	378	36	40
7	Gedarif	14.03	35.40	600	43	42
8	Wadmedani	14.38	33.48	405	47	41

Modarres (2009), and Xu et al. (2010). The magnitude of change, expressed as percentages of mean, is determined by the Theil and Sens's method (Burn and Hag Elnour, 2002; Basistha et al., 2009).

Detecting drought and climatic changes using Silyaninov index (SI)

Several methods have been used to classify Sudan's climate, among them Silyaninov index (SI) was found the best (Adam, 2002; Fud Elmoula, 2004; El Fadni, 1998). It's goodness is likely rose from the climatic variables used in its estimation, viz. rainfall and temperature, that is, moisture and thermal factor, which both play a vital role in the climate of the tropics (Fud Elmoula, 2004). For example, Tan (2007) points out that rainfall and temperature control most of the differences in the Earth's vegetation cover, affecting growth rate and plant reproduction. The SI is defined as a ratio between the annual rainfall and the cumulative annual temperature above 10°C as described below (Adam, 1995; Fud Elmoula 2004):

$$SI = \frac{R * 10}{C.T} \quad (1)$$

Where, R is the mean annual rainfall (mm) and $C.T$ is the cumulated annual temperature (°C). The stationary data lengths are shown in Table 2.

The preciseness of the SI in detecting drought is calibrated using the fragmentally documented historical drought events in Sudan, which have been well cited in Leku et al. (1996) and Abusin (1986). The recent drought events (1996 to 2010) were judged using the average crop yields of the period 1974-1982 as a baseline. Data of crop yields were obtained from the records of the ministry of agriculture and FAO reports. Type I errors i.e. the rate of rejecting the null hypothesis of no drought is computed by Clark and Schkade (1969)

$$\sigma p = \sqrt{\frac{\pi(1-\pi)}{n}} \quad (2)$$

$$z = \frac{pc - \pi}{\sigma p} \quad (3)$$

Where, P_c is the critical value of the sample percent, π is the value of the universe percent designated in the null hypothesis and σ_p is the standard error of the percent, z is taken as 1.96 which is corresponding to the value of 0.025 in one tail of the normal distribution and n is the random sample size. In this case, type I errors (rejecting the null hypothesis while in fact it is true) can be determined by management. The critical values were taken as the means of the upper and lower values designated to each climatic zone in Table 1.

NDVI estimation

This section deals with expected impacts of climate change and drought on the vegetation cover in central Sudan.Two Acacia Senegal forests (Perennial trees) were chosen through a surveying trip using a Global Positioning System (GPS). The first forest is located (11.56 °N and 34.23 °E) in the Damazine region (Blue Nile state, southern-eastern part of the study area) where the climate is sub humid. The second forest (13.24 °N and 35.85 °E) locates in the Gedarif region (Eastern part of the studied area) under semi dry climate conditions. The soil of both forests is heavy clay with a water holding capacity of 230 mm/ m depth. Thus, these forests are anticipated to reflect the long term impacts of climate change on the vegetation cover, soil moisture content and groundwater. The sizes of both forests (roughly 22 000 ha) are large enough to be compatible with the satellite images of coarse resolutions such as of the Moderate Resolution Imaging Spectroradiometer (MODIS). The MODIS-derived NDVI values were downloaded with a spatial resolution of 250 x 250 m and a temporal resolution of 15 days for eleven consecutive years (2000-2010). The ecoclimatological single variable relationships of NDVI, rainfall, temperature and aridity were examined on the basis of Pearson correlation (r). In order to eliminate seasonality impacts the standardized values were used by subtracting the mean and then dividing by the standard deviation.

RESULTS AND DISCUSSION

Trends in time series

The descriptive statistics of annual rainfall and temperature (mean, coefficient of variation (CV), skewness (CS) and kurtosis coefficient (CK)) are presented in Tables 3 and 4. The mean value of annual rainfall and temperature are found to be 219 to 662 mm and 25.5 to 29.3°C, respectively. The coefficient of variation of rainfall (30%) is higher than that of the temperature (2%), suggesting that rainfall controls the climate variability in the central Sudan.

The obtained mean SI value is ranged between 0.33 and 1.01, revealing that there were three distinct climatic zones in the central Sudan. These are dry, semi dry and sub humid. However, these climates are very variable since SI is associated with a high coefficient of variation of 29%. The coefficient of variations of both SI and rainfall are found equal, restating that rainfall is the determinant factor in the region's climate. This finding has been further tested as the relationship between the peaked-nesses of SI (wettest situation) and rainfall is higher (r ≈ 0.89) than that of the temperature (r ≈ 0.47). Trends in rainfall, temperature and SI are shown in Tables 5 and 6. At 55% of the cases, the annual rainfall shows a statistically significant decreasing trend of 3.5 mm per annum. This is coupled with a statistically significant increasing trend of 1.4°C per annum in temperature at 100% of the cases. Accordingly, SI showed a decreasing trend, suggesting that in the climatic conditions of central Sudan is deteriorated. This deterioration is found significant at 50% of the stations, that is, Kadugli (South Kordufan), Damazine (Blue Nile), Nyala (South Darfur) and Wadmedani (Gezira), which are very vital areas for the agricultural production in Sudan. For instance, Wadmedani station represents the Gezira climate where the world largest singly managed irrigated scheme (Gezira scheme) exists. Consequently, the increase of aridity in this region would result in increasing the crop water requirements, considering the limited water resource, that is, Sennar dam with a storage capacity of 0.5 km^3). On the other hand, Kadugli, Damazine and Nyala stations represent the traditional rainfed agricultural areas where most of the Sudanese people favored food (sorghum) is produced. It is therefore the resulted increase inaridity is basically jeopardized food security and socioeconomic stability in central Sudan confirming the results obtained by Hamid et al. (1995) and Farah et al. (1997). Consequently, the Sudan's government became more willing to increase sorghum cultivated area under irrigated conditions at the expensive of other cash crops such as cotton (Guvele, 2002).

Detecting climate change by SI

The climatic zones in Sudan have been ascribed by with specific SI ranging values. It is important to restate that the higher the SI value is the better, that is, good climatic conditions (Table 1). Therefore, any persistent changes on those SI values for an extended period may be indicated as climatic changes. According to Table 6, all the stations experienced a decreasing trend in SI values, that is, their aridity is increased. The investigated period is 50 years, which is a persistent period, that is, IPCC in

Table 3. Mean rainfall (Rm), coefficient of variation (CV), coefficients of skewness (CS), coefficients of kurtosis (CK) and time-series period for the stations in the central Sudan.

Station	Rm (mm)	CV	CS	CK	Time period
Kadugli	662.5	0.22	0.42	0.01	1962-2009
Damazine	647.5	0.21	-0.82	0.63	1962-2005
Nyala	355.7	0.36	-0.03	-0.01	1962-1998
El Obied	315.0	0.36	0.54	0.39	1962-2005
Sennar	418.0	0.22	-0.82	0.30	1970-2006
Ed Duim	219.0	0.43	0.70	2.35	1960-1996
Gedarif	589.3	0.22	-0.06	-0.36	1962-2005
Wadmedani	280.6	0.29	0.09	0.01	1960-2005

Table 4. Mean temperature (Tm), coefficient of variation (CV), coefficients of skewness (CS), coefficients of kurtosis (CK) and time-series period for the selected stations in the central Sudan

Station	Tm (^oC)	CV	CS	CK	Time period
Kadugli	28.4	0.02	0.34	-0.63	1960-2010
Damazine	27.9	0.03	-1.15	2.02	1960-2010
Nyala	27.6	0.02	-0.36	-0.92	1960-2010
El Obied	26.7	0.03	0.57	-0.23	1960-2010
Sennar	28.3	0.03	-0.53	0.10	1960-2010
Ed Duim	29.3	0.02	-0.35	0.41	1960-2010
Gedarif	28.9	0.01	-0.03	-0.39	1960-2010
Wadmedani	28.8	0.03	0.14	-0.82	1960-2010

Table 5. The time series trend by Man-Kendall test for rainfall (R-MK), temperature (T-MK) and Silyaninov index (SI-MK).

Station	R-MK	T-MK	SI-MK
Kadugli	decreasing*	increasing*	decreasing**
Damazine	decreasing**	increasing*	decreasing**
Nyala	decreasing**	increasing**	decreasing**
El Obied	decreasing	increasing**	decreasing
Sennar	decreasing	increasing*	decreasing
Ed Duim	decreasing	increasing**	decreasing
Gedarif	decreasing	increasing*	decreasing
Wadmedani	decreasing*	increasing**	decreasing*

* Statistically significant at $P < 0.05$ and ** statistically significant at $P < 0.01$.

2007 suggests a decade. Thus, on the basis of the SI the central Sudan climatic zones experienced climatic changes. The significant decreasing trend in SI values were found to be 37% for Wadmedani (dry), 76% for Nyala (semi dry), 31% for Kadugli (sub humid) and 37% for Damazine (sub humid). These values suggest that aridity is increased in the central Sudan during the period of 1960 to 2010, especially in the semi dry climate, which may be sooner converted to dry conditions.

Detecting drought by SI

In the central Sudan, during the period of 1960 to 2010 the SI showed successive runs of dry years (Figure 2), which can be ascribed to the below normal rainfall. At this point it is difficult to designate those periods as drought cycles as yet there is no wide applicable definition for the term drought. For example, Abusin (1986) mentioned that in the central Sudan a drought year implies one of the

Table 6. Average changes in rainfall (mm/year), temperature (^{o}C/year) and Silyaninov index (SI) by the Theil and Sens's method.

Station	Rainfall	Temperature	SI
Kadugli	4.8	1.1	1.00
Damazine	3.8	0.4	1.00
Nyala	3.8	1.6	0.62
El Obied	0.1	2.4	0.51
Sennar	1.8	1.2	0.64
Ed Duim	2.1	1.5	0.33
Gedarif	1.1	0.5	0.87
Wadmedani	2.1	2.1	0.45

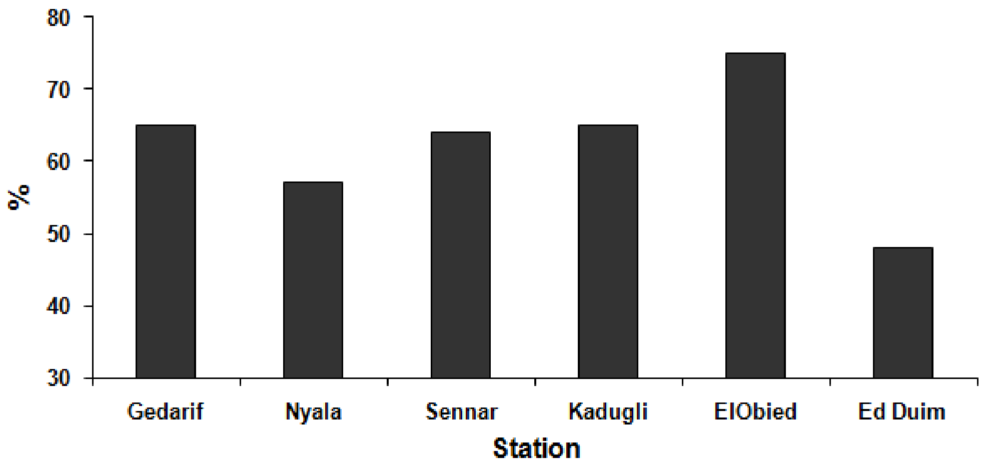

Figure 3. The performance of the Silyaninov index (SI) in detecting correctly the drought and wet years at selected stations in the central Sudan.

followings: lack of plant cover, crops failure and livestock losses, which in aggregate jeopardized the family's welfare. Thus, the drought definition will be different even between individuals of one society and from one society to another.

In this study, the power of SI in designation given year as drought or wet is evaluated using the confirmed historical events. This is firstly done without considering the drought's degree of intensity. The results suggest that generally SI is effective in detecting drought, with the exception of Gedarif and Ed Duim stations, as shown in Figure 3. The differences in detecting drought performance were largely attributed to the presence of anomalies in annual temperature. Hence, where the temperature data is anomalies-free the rainfall alone might explain much of the meteorological droughts in the central Sudan. This conclusion agrees with that of Ntale and Gan (2003) for the droughts in east African.

Hitherto, the comprehensive documentation of drought years in the central Sudan is poor. Consequently, SI is used to detect the stationary drought years. The obtained results were shown in Figure 4. It is obvious that Ed Duim and Damazine stations experienced the highest and lowest percentages of drought years of 59 and 38%, respectively. Based on the tested years, the region of central Sudan is dominated by wet conditions.

The common/regional wetted years were 1963, 1964, 1978 and 2007. The year 1984 is the only common drought year. This is revealed that rainfall of the central Sudan is characterized by its localized behavior.

According to the SPI approach, if the standardized precipitation index is continuously ≤ -1.0 there is drought event and vice versa. Therefore, each drought event has a well-defined duration (Ntale and Gan, 2003). Following the same procedure the stationary longest drought events in the central Sudan were determined (Table 7). It is clear that most of the drought events occurred during the periods of 1970 to 1990, with the exception of Damazine (1998 to 2002) and Ed Duim station (2000 to 2005). It is found also that the drought events with one year in length are dominant. Since that rainfall is found to be the dominant climatic variable in the SI estimation, the drought intensity classification scale of the SPI could be applicable to SI results. Consequently, the most detected stationary drought events in the central Sudan were classified (Table 7). It is clear that most of the drought

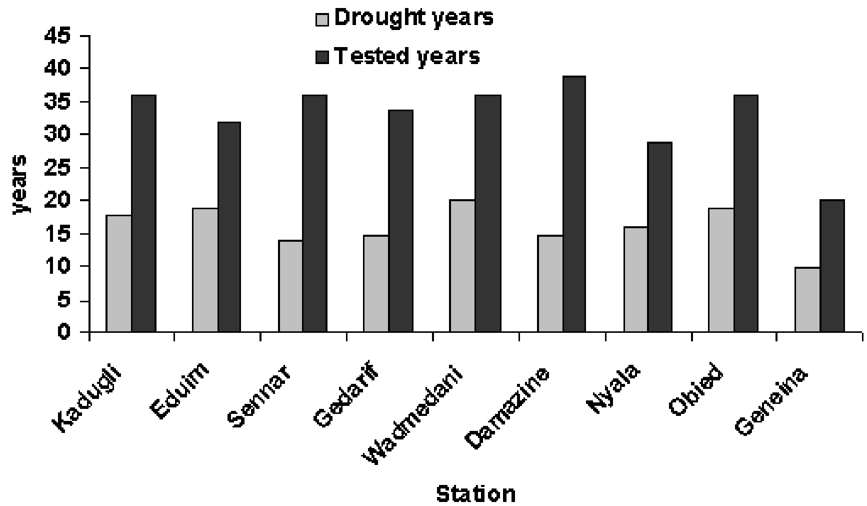

Figure 4. The drought years percentages at selected stations in the central Sudan. The trends of the standardized precipitation index, SPI (the smoothed line) and the Silyaninov index, SI (the dashed line) at selected stations in the central Sudan. The circles refer to years with different values of SPI and SI.

Table 7. The longest drought events, the driest years and their standardized Silyaninov index values (ZSI) and their drought scale at selected stations.

Station	Drought event time	Driest year	ZSI	Drought scale
Kadugli	1982-1987	2001	-1.61	Severe
Damazine	1998-2002	2004	-2.20	Extreme
Nyala	1982-1987	1984	-1.80	Severe
El Obied	1982-1985	1982	-1.95	Severe
Sennar	1965-1970	1981	-2.18	Extreme
Ed Duim	2000-2005	1984	-1.93	Severe
Gedarif	1970-1977	1984	-1.83	Severe
Wadmedani	1966-1970	2000	-1.50	Severe

cycles can be classified as severe ($-1.5 \geq SI \geq -1.99$), with the exception of Damazine and Sennar stations, which show extreme drought events ($SI \leq -2.0$). The use of regional mean in the central Sudan is found questionable and deceptive. For instance, on the basis of the regional rainfall average the central Sudan experienced a long-term drought cycle of 30 (1972 to 2002) as shown in Figure 5, which is unrealistic. Thus, the use of regional average in central sudan is not recommended.

Relationships of natural vegetation cover with rainfall, temperature and SI

Most of the obtained NDVI values were found to be below the general average for the period of 2000 – 2010 (Figures 6 and 7). This is attributed to the deterioration in the climatic conditions of the central Sudan, agreeing with the results of the Vicente et al. (2006) who found that aridity has caused a general decreasing of NDVI and increasing of coefficient of variation, in Spain. On the other hand, the result disagreed with results of Hermann et al. (2005) who indicated that there is a seasonal increasing trend in the greenness of the African Sahel region using the NDVI time series analysis (1982-2003).

Forestry system (90 million hectares, Mha) is the largest vegetation cover in Sudan (FAO, 2006). Its area however, is diminished by 3% during the period of 1976-1990 (Elbashir, 1994). Oldeman et al. (1991) stated that about 5 Mha of land in Africa as lost its original biotic functions due to degradation, to a level that their rehabilitation is economically been difficult. In Sudan, forestry system has an appreciated potential economic values that is, gum Arabic production, a sustainable timber industry, wildlife tourism, woods, etc (Glover, 2005). Thus, one of the steps that can be immediately taken regarding forest rehabilitation is the re-enforcement

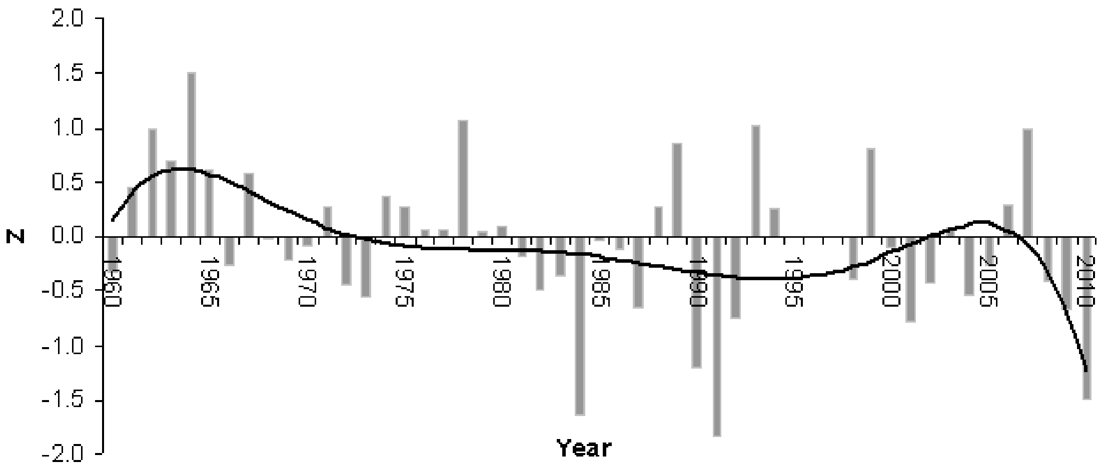

Figure 5. The standardized regional SI value.

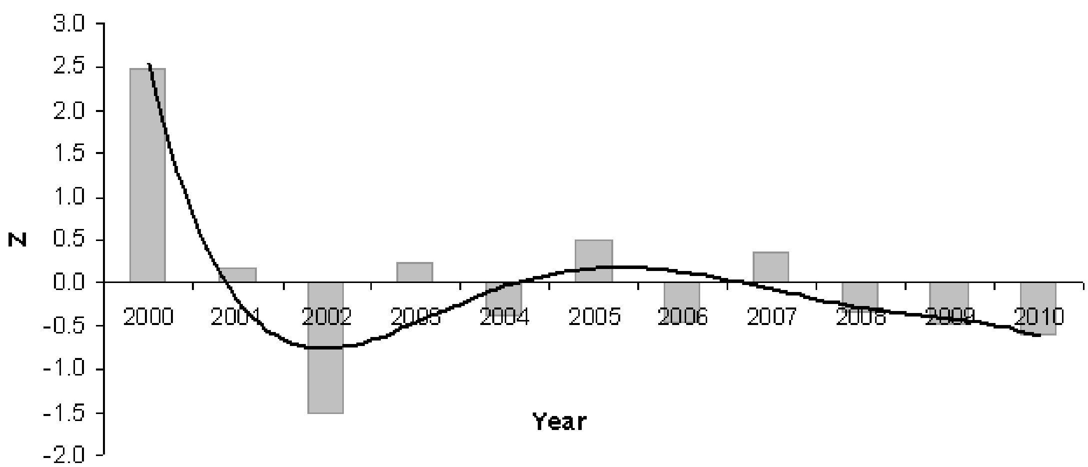

Figure 6. The standardized values of the NDVI for the forest, Damazine area. The smoothed line is the trend of NDVI

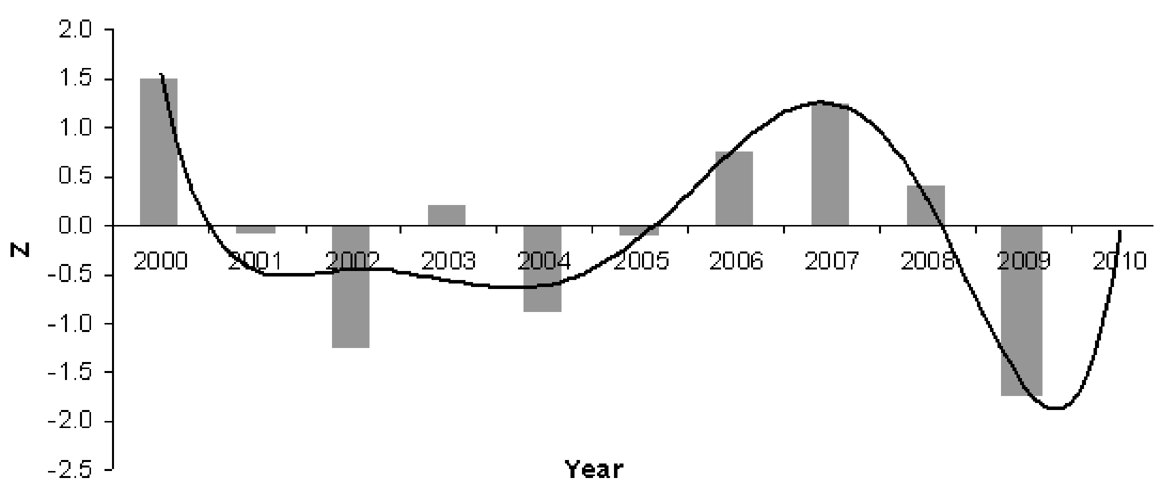

Figure 7. The standardized values of the NDVI for the forest, Gedarif area. The smoothed line is the trend of NDVI.

of the 10% law that is, set aside 10% of the farmer's land for forest production. Also, there is an urgent need for reforestation plans, which can be defined as the establishment of tree crops on deforested or cleared land, either on land previously degraded by agriculture, mining, or other activity, or on lands cleared of native vegetation specifically for the purpose of plantation establishment (Bowyer, 2001). However, care should be taken as some studies showed that improper forestation plans were lead to soil compaction, erosion and depletion of soil organic matter and thus degradation of physical and nutritional properties of soil (Bowyer, 2001). Thus, the good vegetation restoring plan needs the suitable vegetation to be re-stored in its right place. This required in-depth studies, e.g. studies on soil moisture variability are important since soil moisture is crucial to ecosystem restoration (Ma et al., 2004).

The detected vegetation-ecoclimatic relationships between NDVI-rainfall, NDVI-temperature and NDVI-SI were found nonlinear (exponential) under both the semi dry and sub humid climates. This is in conformity with the results of Vicente et al. (2006) who suggested a non-linear relationship between aridity and NDVI. Hermann et al. (2005) however reported a direct relationship between NDVI and rainfall at a threshold below 1000 mm per year, in the African Sahel zone.

Generally, the resulted Pearson correlations in the semi dry climate were observed higher than that of the sub humid. They were 0.88 for NDVI-temperature, 0.79 for NDVI-rainfall and 0.81 for NDVI-SI in the semi dry climate compared with 0.85, 0.62 and 0.61 for the semi dry climate, respectively. Because temperature is an indirect indicator for energy available for the plant development a strong relation between NDVI and temperature is anticipated (Tan, 2007). On the tested relations, NDVI-temperature was the highest; but it was statistically insignificant, which is attributed to the minimum variation in the annual temperature values (CV ≈ 3%). On the other hand, the relations NDVI- rainfall and NDVI- SI were found significant at 0.05 and 0.0005 levels of significance for sub humid and semi dry climates, respectively. It is worth mentioning that the slope of the relation NDVI-temperature is found negative and the opposite holds true for the relations NDVI-rainfall and NDVI-SI. This is indicated that the continued increasing in temperature may degrade the greenness of the forestry system in Sudan. Accordingly, rainfall is found to be the most significant climatic variable that affects the dynamics of the vegetation cover in the central Sudan.

Conclusion

Most of the livelihood generations are climate depended in the central Sudan. This study concerned on providing simple and cost effective approach for detecting climate change, drought and vegetation dynamics in the central Sudan using Silyaninov index (SI) and the normalized difference vegetation index (NDVI). Both indices showed good results. The most important result is that drought disturbed the climatic conditions of central Sudan, if the current trend of degradation is continued sooner the semi arid zone would experience arid conditions and the latter would change to desert conditions. Accordingly, the agricultural sector/food security will not sustain without irrigation, which is limited by water resources availability.

The accuracy of the SI results depends on two factors; the quality of inputs (rainfall and temperature) and availability of data (length of record). The former found to be poor since the homogeneity of the datasets were questionable. The length of record was disrupted mainly because of direct drought consequences (civil unrest) and fund issues as most of the meteorological stations in central Sudan were out of service since 1980s. This entails rehabilitation projects for the meteorological stations as well as capacity building programs.

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Full Length Research Paper

Groundwater resources of the Niger Delta: Quality implications and management considerations

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The Niger Delta region of Nigeria is of great socio-economic importance because of its huge and abundant reserves of crude oil and natural gas. The phenomenal increase in both industrial and social activities within the area in recent times has led to increase in groundwater abstraction rates. Groundwater development in the Niger Delta region has been carried out with little hydrogeological considerations. This is probably, due to strong political and other extraneous pressures. Consequently, borehole drilling has been indiscriminately and randomly sited and located, resulting to a myriad of problems. As a result, boreholes have failed where there are abundant groundwater storage, and many a time, have been drilled in, obviously, most unpromising locations. Salinity, bacteriological contamination, presence of undesirable iron and manganese as well as the high acidity of the groundwater and consequent corrosiveness pose serious distribution problems in the area. Efforts to solve the problems have been unsuccessful and supply of potable water remains grossly inadequate. Recent development plans proposed for the Niger Delta would call for high water demand. There is therefore an urgent need for a meaningful approach to the study of groundwater resources of the region. It is therefore hoped that many of the observations made in this paper will not only form a guideline for meaningful collection of data for quantitative analysis in future, but will also help in the understanding of the nature of groundwater resources of the region.

Key words: Groundwater resources, quality, aquifers, groundwater management, Niger Delta.

INTRODUCTION

The Niger Delta has an aerial extent of 75,000 km^2 and is located between latitude 4°30' and 5° 20' N and longitude 3° and 9°E. It is the second largest delta in the world with a coastline spanning about 450 km terminating at the Imo River entrance (Awosika, 1995). The region spans over 20,000 km^2 and it has been described as the largest wetland in Africa and consists mainly of freshwater swamps, mangrove swamps, beaches, bars and estuaries. This difficult terrain made it a region mostly forgotten by the rest of Nigeria, until the advent of petroleum in the area in the late fifties.

The pressure on water supplies and precious ecosystems in the coastal areas of the Niger Delta is very high and can increase in the future if urgent management

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measures are not put in place (Nwankwoala, 2011). Groundwater is the only source of water for water supply for both domestic and industrial uses in the Niger Delta and its demand will increase astronomically within the foreseeable future with increase in population, improved standard of living and more expansion and growth of the oil and gas industry (Oteri, 1983; Akpokodje, 2005; Nwankwoala and Udom, 2011).

Though the Niger Delta produces over 80% of Nigeria's petroleum, it is still very much a neglected part of the country. Beside efforts made by oil prospecting companies in the process of oil exploration and production, the region has not been studied in many areas and respects. Groundwater resources development of the Niger Delta is one such area where no serious effort has been made to investigate its nature, distribution and occurrence. Geologic considerations are rarely or inadequately incorporated into the design of boreholes (Amajor, 1989). Generally, groundwater has not attained a high level of development in the Niger Delta partly as a result of difficult environmental condition, low level of general underdevelopment of the region, inadequate finance; and partly perhaps as a result of deliberate neglect of the area by successive governments.

The Niger Delta is a large and ecologically sensitive region in which various water species (including surface and groundwater, saline and freshwaters) are in dynamic equilibrium (Abam, 1999). Because of the very nature of the region, groundwater constitutes the predominant, if not the only source of water supply in the area and unless a determined effort is made to understand the nature of the groundwater in the region, serious problems would be encountered in the area of water needs of the region, in future. Although, detailed stratigraphic analysis of the various geologic/geomorphic and aquifer systems (Etu-Efeotor and Akpokodje, 1990) have yielded a better understanding of the groundwater potentials of the Niger Delta region, they have not addressed the important and crucial question of over-abstraction and its associated consequences, particularly the possibility of large scale saltwater intrusion and general issue of sustainable supply of potable water in the region. This paper therefore appraises groundwater resources of the Niger Delta region, the quality impairments and management considerations.

GEOMORPHOLOGIC/GEOLOGIC SETTING

The geomorphology of the Niger Delta has been described by many researchers (NEDECO, 1954, 1959, 1961; Allen, 1965; Weber, 1971). The topography of the area is essentially flat, sloping very gently seawards. The area is low lying (usually does not exceed 20 m above sea-level) and is drained and criss-crossed by network of distributaries. The Niger Delta constitutes an extensive plain exposed to periodical inundation by flooding when the rivers and creeks overflow their banks. A prominent feature of the rivers and creeks is the occurrence of natural levees on both banks, behind which occur vast areas of backswamps and lagoons/lakes where surface flow is negligible.

Although various types of morphological units and depositional environments have been recognized in the area (coastal flats, ancient/modern sea, river and lagoonal beaches, sand bars, flood plains, seasonally flooded depressions, swamps, ancient creeks and river channels), the area can be sub-divided into five major geomorphological units (Figure 1) namely:

i) Active/abandoned coastal beaches
ii) Saltwater, mangrove swamps
iii) Freshwater swamps, back-swamps, deltaic plain alluvium and meander belt
iv) Dry deltaic plain with abundant freshwater swamps (Sombreiro-Warri deltaic plain) and
v) Dry flat land and plain.

Along the coastline lies a long coastal saline belt of active and abandoned beaches built by ocean currents and tides. This area is comparatively higher than the adjacent areas and its width varies from 1 to 10 km. Parallel to, and north of the coastal saline belt of the beaches, is a stretch of mangrove swamp with an approximate width of 10 to 25 km. North of the mangrove swamp is the freshwater swamp which is in turn succeeded inland by dry areas that are not prone to periodical flood inundation.

Consequently, the present knowledge of the geology of the Niger Delta was derived from the works of the following researchers (Reyment, 1965; Short and Stauble, 1967; Murat, 1970; Merki, 1970) as well as the exploration activities of the oil and gas companies in Nigeria. The formation of the so called proto-Niger Delta occurred during the second depositional cycle (Campanian Maastrichtian) of the southern Nigerian basin. However, the modern Niger Delta was formed during the third and last depositional cycle of the southern Nigerian basin which started in the Paleocene.

The geologic sequence of the Niger Delta consists of three main tertiary subsurface lithostratigraphic units (Short and Stauble, 1967) which are overlain by various types of Quaternary deposits. From bottom to top, the tertiary units are the Akata, the Agbada and the Benin Formations (Table 1).

Hydrologic factors in the Niger Delta

The hydrologic conditions in a region are important in understanding the groundwater situation, in that they determine the availability of water input into the basin for groundwater storage, the rate of groundwater recharge, and the movement of the water in the groundwater system, for extraction purposes. The factors of precipitation, runoff, evapo-transpiration and infiltration play major role. The process of water movement in the ground is more related to the factor of geology.

The amount of rainfall that takes place in a basin would determine the water input into the basin (Gobo, 1988). The annual rainfall in the Niger Delta is high and varies from 500 mm per annum at the coasts, to about 300 mm at the northern part of the delta (Etu-Efeotor and Odigi, 1983). Evapo-transpiration is 1000 mm, leaving an effective rainfall of 2000 mm. Of this effective rainfall, 37% or 750 mm is known to recharge the subsurface aquifers while the remaining 1250 mm flows directly into the streams (Akpokodje et al., 1996). This recharge which is 75% of the total precipitation is on the high side of the range commonly reported for unconsolidated sediments (Vecchioli and Miller, 1973; Legeette and Graham, 1994). This therefore ensures that the region is adequately supplied with water. Besides, rain may fall at any time of the year, even during the peak of the dry season, further ensuring an all year round water input into the region. Basically, the Niger Delta water resources are drawn from the Eastern littoral hydrological and the Niger South hydrological zones. Infiltration and percolation processes from these broad recharge networks flow southwards into the underlying aquifers of the Benin

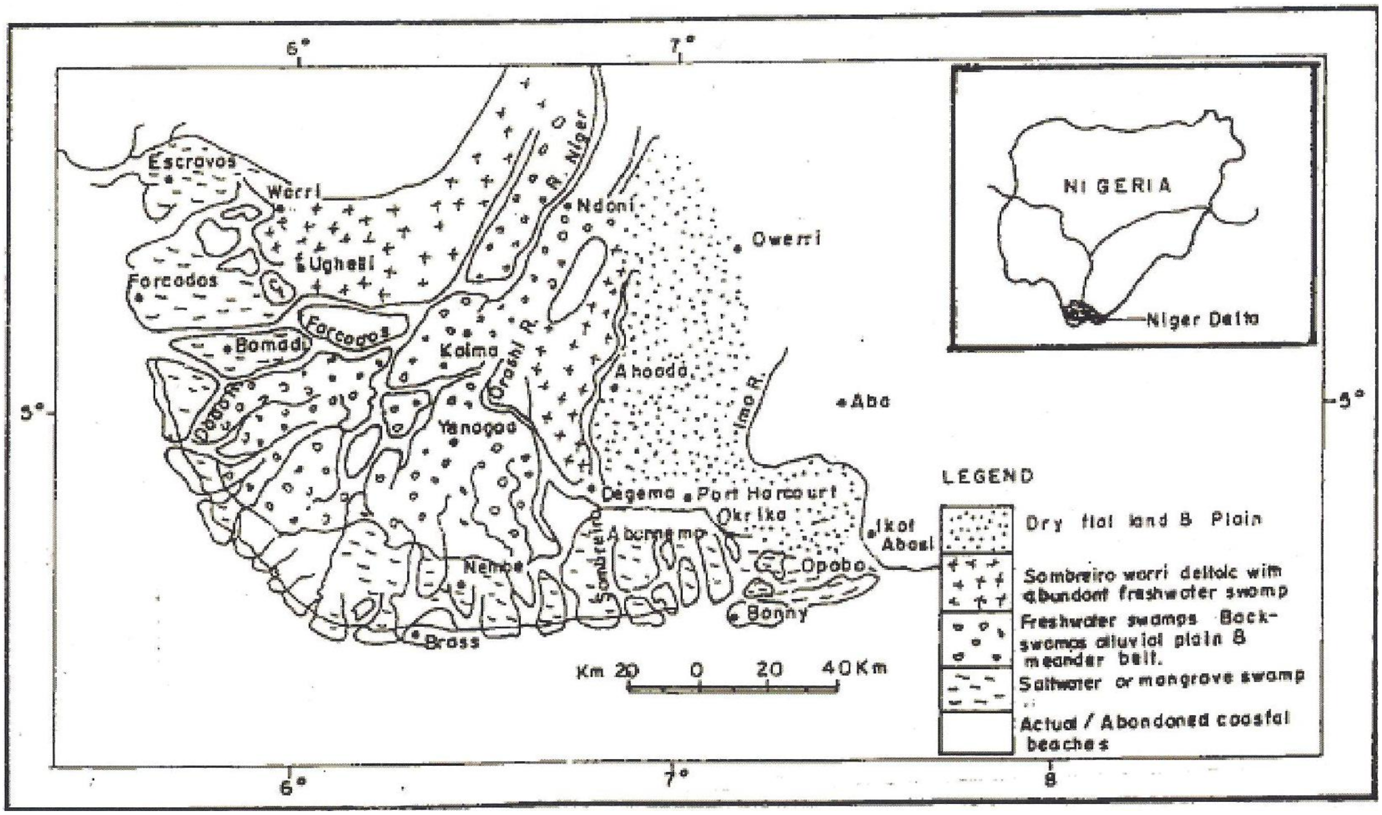

Figure 1. Major morphological units of the Niger Delta (modified after Akpokodje, 1987).

Table 1. Geological units of the Niger Delta (after Short and Stauble, 1967).

Age	Geological Unit	Lithology
Quaternary	- Alluvium (general) fresh water back swamp meander belt. - Mangrove and salt water. - Back Swamps - Active/Abandoned Beach ridges - Sombreiro Warri Delataic plain.	- Gravel, sand, clay, silt, sand, clay, some silt, gravel. - Medium-fine sands, - Clay and some silt.
Miocene	Benin Formation (coastal plain sand)	Coarse to medium grain sand with subordinate silt and clay lenses; Fluviatile marine
Eocene	Agbada Formation	Mixture of sand, clay and silt, fluviatile marine.

Formation beneath the Continental Shelf (Ngerebara and Nwankwoala, 2008). Both the structural and stratigraphic setting of the Niger Delta favour hydraulic gradient flow towards the coast, and hence into the Continental Shelf. This forms the basis of most freshwater aquifers located within the Continental Shelf. The general rainfall pattern in the Niger Delta ensures a permanent supply of water to the region.

The extent to which this rainfall reaches the ground to supplement the underground storage, greatly depend on the rate of infiltration, runoff pattern and the rate of evapo-transpiration. None of these factors had been studied quantitatively, but the following observations have been made (Ngerebara and Nwankwoala, 2008) in a more tentative way:

1) The rate of infiltration has generally been favoured by the prevailing flat nature of the Niger Delta which reduces runoff, by increasing retention time of rainwater on the land surface. Besides, the soil in most cases, except where surface clay and swamp prevail, is unconsolidated, porous and permeable, thus permitting quick infiltration of water underground.

2) The region is adequately drained by several streams and rivers. But more important is that these surface water bodies, flow through raised channels due to heavy load of sediments which settle within the channels. Consequently, the streams and rivers overlie most of the important aquifers in the area and feed them throughout the whole year. Most of the streams and rivers are therefore influent. The aquifers do not have to wait until flooding periods to be fed by

surface streams and rivers. The above prevailing conditions means that there is no period of the year when groundwater storage would have to be diminished by base flow but rather is ensured of a continuous discharge wherever the boundary with adjacent streams and rivers are continuous.

3) Evapo-transpiration measurements made on local scales by agricultural establishments indicate that water losses especially in areas of unconfined aquifers with water table near ground surface, may be high, due to high evapotranspiration during the dry season. This is in respect of the dense vegetation of the region and the dry condition that prevails during the dry season. But because of the huge reservoir prevailing under the Niger Delta, the more or less constant water supply in the region and the occurrence of clay lenses which often cut off aquifers from one another, the effect of evapotranspiration even where water is nearer the surface does not demand serious consideration in the Niger Delta.

Geological factors in the Niger Delta

The geology of the Niger Delta is well known and has been discussed by several authors (Reyment, 1965; Short and Stauble, 1967; Merki 1972; Weber and Daukoru, 1975; Avbovbo, 1978; Agagu, 1979; Whiteman, 1982; Doust and Omatsola, 1990; Owolabi et al., 1990; Koledoye et al., 2000, 2003). The influence of geology on the groundwater resources of the Niger Delta constitutes the most important factor besides that of climate in the region. Geology has been observed to be responsible for the complex groundwater distribution, extractability and quality in the Niger Delta. Unfortunately, the present knowledge of the true geological condition prevailing within the groundwater domain of the Niger Delta is limited.

Three major formations comprise the modern Niger Delta overlain by various types of Quaternary deposits (Table 1, Figure 1). These are the Akata Formation, which is predominantly shale and clay; the Agbada Formation which is generally fluviatile and fluviomarine, and the Benin Formation, constituting a continental deposit of sand and gravel (Murat, 1971). The depositional pattern which accompanied the accumulation of sediments during the formation of the delta, gave rise to structural traps (growth faults and roll-over anticlines) in the Agbada Formation. This constitutes the petroleum containing reservoirs in the Niger Delta. The Agbada Formation while suitable for petroleum accummulation, is too deep to be relevant to groundwater storage. There arises therefore, the major difference between the region where the petroleum geologist is prospecting for oil, that is, the Agbada Formation, and that, where the hydrogeologist is searching for water – the Benin Formation, in the Niger Delta.

Huge financial investments by oil companies have revealed the geology of the Agbada Formation in detail. Understandably, investigating the Agbada Formation, petroleum geologists had deliberately ignored the upper lying Benin Formation. Hence, the present knowledge of the Benin Formation is limited, compared with that of the Agbada Formation. An evaluation of the hydrogeology of the Niger Delta for petroleum exploration may appear to be ill-conceived. However, there is strong evidence that meteoric water from gravity-induced flow has recharged deep enough into the subsurface to possibly play a role in the distribution of hydrocarbons. According to Dickey et al. (1987) and Amajor and Gbadebo (1992), the extremely sandy nature of the upper Benin Formation and the abundant growth faults in the underlying Akata Formation have permitted meteoric water to penetrate very deep into the subsurface.

The controlling effect of geology on groundwater occurrence in the Niger Delta is no longer in doubt. The sedimentation pattern as well as stratification determines both the quality and quantity of water in the region. Its investigation is the first step towards a meaningful groundwater study of the region. The Benin Formation therefore needs detailed investigation.

Groundwater occurrence in the Niger Delta

The main body of groundwater in the Niger Delta is contained in mainly very thick and extensive sand and gravel aquifers. Three main zones have been differentiated. These are: a northern bordering zone consisting of shallow aquifers of predominantly continental deposit, a transition zone of intermixing marine and continental materials and a coastal zone of predominantly marine deposits (Etu-Efeotor and Odigi, 1983; Amajor, 1989; Etu-Efeotor and Akpokodje, 1990). A distinct trend in aquifer properties have been observed following this division. Akpokodje et al. (1996) have summarized the hydrostratigraphic units of the Benin Formation as four well defined aquifers in the upper 305 m that vary in thickness to over 120 m. The aquifers vary from unconfined conditions at the surface through semi-confined to confined conditions at depth. The aquifers are separated by highly discontinuous layers of shales, giving a picture of an interval that consists of a complex, non-uniform, discontinuous and heterogeneous aquifer system. Although, majority of groundwater supply wells abstract water from these aquifers, there is evidence that industrial and municipal groundwater supply wells produce water from deeper aquifers in the Benin Formation.

Aquifers at the northern border of the Niger Delta are more continental in character, being composed of river loads coming from the hinter land. They are also encountered at shallower depths, so that in most cases, an average depth of 60 m had been all that was required to be drilled, to obtain very pure freshwater and in huge quantity. Clay materials, except a few metres found within the top soil, do not occur at depth. The sand is coarse to very coarse generally, and gravel layers are commonly encountered. The borehole performance in this section has generally been so good and the water quality so excellent, that sinking of wells at the northern borders of the Niger Delta has always been taken for granted. Very good examples of such regions are Port Harcourt, Ogoni, and Elele areas of Rivers State, eastern Niger Delta.

Moving coastwards from the northern borders of the Niger Delta, one comes across a transitionary zone of swamp lands. Two types of swamp lands are observed – the mangrove swamp lands and the freshwater swamp lands. The mangrove swamp lands are associated with tidal inlets and they are therefore more prominent in those areas where estuaries penetrated farther inland, such as the western and eastern zones flanking the pro delta. On the other hand, fresh swamp land persists more within the front of the delta where the dense network of streams and rivers combine to empty into the sea.

A common feature of the transition zone is the presence of clay embodiments within the aquifers. These clay lenses are erratically distributed laterally and vertically within the region. In several cases, strata logs of wells drilled less than 200 m apart, have been known to vary, and under such prevailing circumstance, prediction of aquifer performance in the region is difficult. However, the freshwater swamp lands which constitute the front of the delta, continue to indicate many features of continental environments, until very close to the coast. The aquifers are still shallow, consisting of predominantly sand and gravel materials, but clay intercalations become more prominent, than within the northern zones. Lignitic materials are also present in the aquifer and the presence of vegetative matter strongly point to sedimentation under shallow water condition.

Within the mangrove swamp lands, very strong evidences of marine conditions are indicated. Thicker lenses of marine clay are encountered and saline conditions are still well noticed. There is no doubt that these areas are protected from the dynamic zones of the deltaic front. This makes it possible for marine conditions to penetrate further inland, creating a more complex transition zone.

This is the case in the freshwater swamp lands. There is an intermixing of continental and marine sediments resulting in a very complex aquifer system. Generally, it has been necessary to drill beyond the 200 m depth before a good water yielding aquifer could be obtained and saline water intrusion problem plague the region. It is here, however, that artisan conditions, due to the interbedment of sand aquifers within clay aquicludes occur. But such confined aquifers are generally too deep seated to result in flowing wells (Ngah, 2009; Nwankwoala, 2011).

Within the sand bars and beaches of the coastal lands, boreholes still need to go deeper to reach quality good water aquifers. Beneath the coastal sands that form the surface deposits of this last zone, marine conditions predominate, until at depth where deep seated aquifers empty into the sea. Aquifers within the Niger Delta generally produce and perform better during the rainy season. They dwindle in yield during the dry season. At the coastal lands, rains feed and maintain phreatic aquifers during the rainy season. But with the incoming of the dry season, such aquifers dry up, and wells sunk into them commonly go without water at that season.

RESULTS AND DISCUSSION

Groundwater quality status

Table 2 shows the groundwater quality in the Niger Delta. The quality of groundwater in the Niger Delta closely follows the sedimentation pattern. As a result, three distinct zones are recognized. The continental deposits of the Northern border produce the best quality water in the region – fresh, pure and commonly uncontaminated groundwater. Within the transition zones, however, the complex sedimentary environment greatly influences the water quality. Most remarkable are the freshwater swamp lands where quality degradation associated with the breakdown of organic matter derived from vegetation buried in the sediments, are encountered. These generally take the form of high carbonate acidity and introduced hydrogen sulphide, commonly identified by the bad smells of some water samples from the area.

Iron contamination is also another feature of groundwater quality within the transition zones. The intensity of its occurrence has been observed to be higher within the freshwater swamp zones (Etu-Efeotor, 1981; Etu-Efeotor and Odigi, 1983; Odigi, 1989). But in the mangrove swamp land areas, notably Buguma, Bonny and Abonnema in Rivers State, cases of iron contamination have been encountered. They are commonly in the form of ferrous iron which generally remains in solution when water samples are freshly collected. On standing the samples, the ferrous iron comes in contact with oxygen of the air and is oxidized into its ferric equivalent which is generally brownish in colour.

The source of the iron contamination is not quite known but it is suggested to have been emplaced by iron fixing bacteria associated with sedimentary environments of decaying vegetative matter. According to Allen (1965) and Oomkens (1974), the Quaternary glaciation was accompanied by eustatic lowering of the sea level such that the paleo- strandline was at the present edge of the continental shelf. This geologic event would have exposed the sediments and created paleo-soils rich in iron oxides. The subsequent rise in sea level would have incorporated the paleo-soils into the geologic record.

Salinity trends in the Niger Delta

Salinity problems are encountered in the Niger Delta. But this is a case prevalent within the mangrove swamp lands and the coastal aquifers. Because of the importance of saline problem in the groundwater development of the Niger Delta, it is necessary to know the main types of saline pollution and where they would be expected. Generally, two types of saline gradient are noticed. There is a vertical gradient which changes with respect to distance from the sea. Vertical salinity gradient develops within the estuarine areas. They arise from the penetration of saline water inland through creeks and estuaries. They are therefore saline conditions that originate from the infiltration of salt water from creeks into underlying sediments. Such saline pollution however, applies only where the aquifer is uninterrupted in depth. A thick or extensive aquiclude can and does exclude further penetration of salt water under such circumstances (Nwankwoala, 2011; Ngerebara and Nwankwoala, 2008).

The WHO (2008) appears to be silent on specifications of limit for this parameter. Salinity tends to increase in a southerly direction. Least values of salinity are more common in the hinterland. The salinity values of groundwater in the study area appear to be generally tolerable. The salinity depths in deep boreholes in Bonny Island suggest saltwater intrusion into submarine freshwater aquifers (Ngah and Nwankwoala, 2013b). Naturally, the coastal aquifers drain into the ocean and are in contact with the ocean at the coastline where under natural conditions fresh water is discharged into the ocean. Excessive abstraction of groundwater appears to have resulted in a decreased seaward flow of fresh groundwater causing saline water to enter and penetrate inland through submarine outcrops. This phenomenon will progressively displace the freshwater thereby increasing the salinity depth (Ngah, 2009). Figure 2 is the map of the Niger Delta showing salinity limits/vegetation of the coastal zones of the Niger Delta.

Human activities at times enhance such saline intrusion in the area. This was the case at Isaka near Port Harcourt where the dredging of the Port Harcourt harbor admitted saline water into the aquifer in the area. Also, influence of land reclamation in Borokiri area of Port Harcourt induced saline water (Nwankwoala and Udom, 2008). It requires further deep drilling beyond a thick lens of clay before an uncontaminated aquifer will be encountered. Within sands on islands and beach ridges at the coast, a unique condition of salinity prevails in which a cone of freshwater overlies a saline layer. Saline

Table 2. Groundwater quality data in parts of the Eastern Niger Delta (Ngah and Nwankwoala, 2013a).

S/No.	Borehole Location	Geomorphic zone	Depth (m)	Iron (mg/l)	Chloride (mg/l)	Salinity (mg/l)	Conductivity (us/cm)	pH	Alkalinity (mg/l)	Total hardness (mg/l)
1.	Kanana	SWS	186	0.0	34	500	125	6.7	0.12	38
2.	Kala Degema	"	40.96	0.0	18	150.0	-	7.3	0.38	6
3.	Krakrama	"	75	2.5	48	700	100	6.8	-	16
4.	Abalama	"	60.96	2.0	36	10.74	35	6.7	30	11
5.	Buguma	"	60.96	0.0	10.64	17.55	-	6.2	6.5	17.0
6.	Okrika Mainland	"	320	0.0	35.5	58.5	19	6.2	10.40	20
7.	Ibuluya-Dikibo	"	180	0.0	32.0	18.00	20.00	4.5	10	21
8.	Bolo I	"	91.44	0.0	99	14.00	16.00	7.0	0.12	31
9.	Bolo II	"	91.44	0.0	97	16.00	40	6.8	0.1	35
10.	Kalio-Ama	"	82.88	0.5	10	331	58.0	6.4	0.1	61
11.	Abam-Ama	"	128.02	0.0	6.38	100	23.0	5.9	21	Artesian
12.	Okujagu	"	30.0	0.8	62	100	-	4.5	2	30
13.	George-Ama	"	109.73	1.8	31.5	60.25	29	5.1	-	22
14.	Isiokpo	CPS	70.1	2.0	38.94	64.4	20	5.6	15	10
15.	Aluu	"	60.96	0.2	10	50	23.00	6.1	2	6
16.	Umuoji	"	81	10.0	32	80	-	8.2	-	68
17.	Ogbakiri	"	78.03	0.01	24.2	51.9	4.5	6.2	0.5	60
18.	Ndele	"	72.5	0	10.6	100	13.5	7.5	19.0	9
19.	Omerelu	"	70.1	0.4	20	20	20	6.5	0.6	8
20.	Ubima	"	70.1	0.0	18	50	18	5.2	2	4
21.	Elele	CPS	60.96	0.0	29.8	49	15	6.0	3.0	5.0
22.	Ibaa	"	60.96	0.0	40	68.25	12	6.2	-	2.0
23.	Obelle	"	81.0	0.0	48	63	6.7	6.1	-	0
24.	Rumuewho	"	54.86	0.3	10	50	-	6.2	-	38
25.	Egwi	"	61.28	0.15	3.4	65	-	6.5	-	28
26.	Rumuoyo	"	57.3	0.30	24	73	-	6.4	-	8
27.	Ulakwo	"	67.06	0.0	13	60.2	100	7.4	-	34
28.	Opiro	"	138	0.0	16	100	12.5	6.2	6.0	10
29.	Rumuokochi	"	91	10	12	60	100	6.2	-	20
30.	Umuechem	"	132	0.30	11	100	36	6.7	3.0	6.0
31.	Kalibiama	CBR	281	0.0	10	202.0	440.0	8.4	-	488
32.	Bonny	"	304	0.8	5	186	140	5.9	-	78
33.	Oloma I	"	91.46	0.8	810	210.0	600	6.5	90	72
34.	Oloma II	"	82.88	0.0	250	220.0	380.0	6.2	20	454
35.	Illoma Opobo	"	19.8	0.6	330	60	280	7.2	-	84
36.	Gbokokiri	"	176.8	0.40	300	192.0	-	6.6	-	18
37.	Ikuru	"	190	0.38	351	242.0	-	6.7	-	70
38.	G.R.A. P.H.	“	170	0.00	26	50	7	5.3	2	6
39.	Creek Road	"	170.0	0.02	390.5	643.5	150.0	5.8	35	135
40.	Potts Johnson	"	180.0	0.02	401	661	160.0	5.8	18	135

CPS = coastal plain sands, FWS = freshwater swamp, SWS = saltwater swamp, CBR = coastal beaches and ridges, SWP = sombreirowarri deltaic plain.

water pollution becomes imminent, if such pool of freshwater is not intelligently extracted.

Aquifer vulnerability to contamination

Groundwater contamination may be defined as the induced degradation of natural water quality by the introduction of inorganic and/or organic compounds. It is usually more serious than surface water contamination because it is more difficult to detect in a timely manner, moves more slowly and requires special expertise to predict the path and rate of contaminant movement. Aquifers can be polluted by a combination of the following factors: agricultural activities, petroleum leakage and

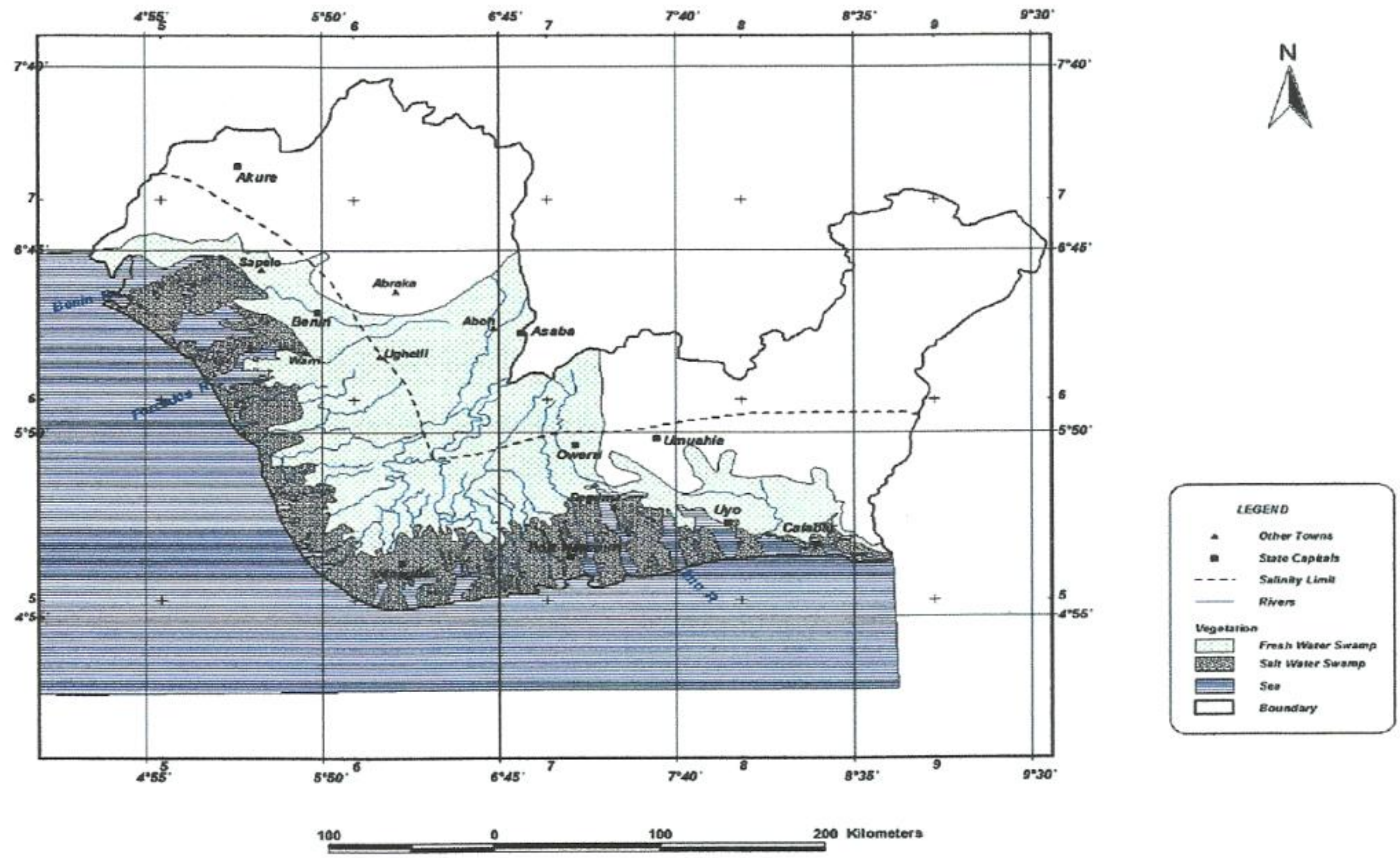

Figure 2. Map of the Niger Delta showing salinity limits/vegetation of the coastal zone (after Ogba and Utang, 2010).

spills, land disposal of solid wastes, sewage disposal on land, saltwater encroachment, deep well disposal of liquid wastes, mining activities, spread of urbanization to recharge areas, and seepage from industrial waste. Aquifers are vulnerable to pollution from these sources to the extent they are in proximity with such activities.

The first aquifer system is extremely vulnerable to pollution from surface sources. Consisting essentially of loose to poorly consolidated sandy materials, this aquifer is capped by laterized soil especially in the northern part of the study area. The laterite thins out in a southern direction and has become non-existent from the fresh water swamp to the coastline (Ngah, 2009). Where the laterite is thin or nonexistent, poor land use practices including use of fertilizers in farming and land disposal of solid wastes including refuse dump can result in the contamination of groundwater sources. For instance, the decomposition of refuse produces leachate, a highly polluting substance which can seriously degrade groundwater quality if allowed access to it. Moreover, the network of pipelines that convey petroleum products in the Niger Delta are buried in the first aquifer. Undetected leakage of hydrocarbon from the pipelines over a long period of time can pollute the aquifer.

Aquifer systems in the Niger Delta are separated by fairly thick clay/shale layer which by their nature, are impermeable, serving as a barrier to vertical (down-ward) percolation of contaminants from the first aquifer. The attenuation properties of clay also lead to an overall reduction of potency of contaminants and possible elimination through cation exchange. For this reason, it can be assumed that the aquifer systems below the first are shielded from pollution from surface sources.

Pollution of second aquifer system by surface sources can only be possible through vertical leakage if the overlying layer is an aquitard. Poor borehole completion practices may also lead to contamination of second aquifer system by the first if the well design does not exclude the first aquifer from contributing to the yield of the second.

In the coast, the shallow aquifer systems are unprotected from the dynamic coastal activities. Saltwater is likely to have mixed with shallow fresh water rendering it unfit for human use. Moreover, exploitation of the shallow freshwater aquifers will reduce the thickness and effective head of the freshwater wedge leading to saltwater intrusion into fresh water aquifers. The deeper aquifer systems are fed by recharge from distant (up-country) outcrops of the aquifers and through vertical leakage from the overlying aquitards. The deeper

Table 3. Activities that could contaminate groundwater aquifer and the likely aquifer to be affected in the Niger Delta (Ngah and Nwankwoala, 2013b).

S/No	Activity	Aquifer system				
		1	2	3	4	>4
1	Agricultural activities	x				
2	Petroleum leakage and spills	x				
3	Sewage disposal on land	x				
4	Saltwater encroachment	x	x	x	x	x
5	Deep well disposal of liquid wastes	x	x	x	x	
6	Mining activities	x				
7	Spread of urbanization to recharge areas	x				
8	Seepage from industrial waste lagoons	x				

aquifers are considered safe and free from pollution with zero vulnerability everywhere except in the coastal areas. Here, unplanned exploitation and/or over-pumping of groundwater could increase the already deep salinity depth thereby reducing the effective column of fresh water. Boreholes will therefore need to go even deeper to exploit freshwater. Table 3 outlines the activities and practices that could lead to the degradation of groundwater quality in the Niger Delta.

From the Table 3, it is evident that the first aquifer system is highly vulnerable to contamination and many activities of man impact directly on this aquifer. Where the lateritized soil cover or clayey overburden is thin or completely absent and the water table is shallow, the risk of contamination is much higher. Awareness of this situation amongst the stakeholders needs to be emphasized.

Groundwater management options in the Niger Delta

Groundwater deserves serious attention in the Niger Delta. This is because there are no alternative sources of water supply in many parts of the Niger Delta. This is particularly the case in those regions where estuaries penetrate very far inland, leaving many areas surrounded by saline creeks and inlets. Moreso, the network of deltaic tributaries create problem of isolation in the region. Such a condition has not favoured the growth of towns and cities. Little riverine communities scatter all over the delta and there is no likelihood that this situation would change in the very near future. The need therefore for the establishment of huge water development schemes would not arise for a very long time in the area. What would be needed would be water development projects tailored to expansion through increase in boreholes.

Furthermore, with particular reference to irrigation, waterlog problem prevalent in the Niger Delta, could be further aggravated through pumpage from the surface streams. Irrigation schemes, if planned in the area, would therefore be better served by boreholes through which groundwater levels are lowered, rather than raised in order to improve the waterlog condition in the area.

Whether for domestic, industrial or irrigational purposes, it appears evident that groundwater constitutes the most economical, practical and sensible source of water supply in the Niger Delta. It would have to be harnessed in order to meet the water needs of the several development projects now planned for the region. Important steps need to be taken in order to utilize the groundwater resources of the region more efficiently and usefully in future. Among the steps are:

(1) A deliberate effort to promote more understanding in the profession of hydrogeology. Several practicing Engineers today in Nigeria's water industry dismiss hydrogeology as irrelevant in the process of supplying the nation with more water. Consequently, wells are drilled haphazardly and are pumped without regard to the characteristics of the producing aquifer. While such a state of affair may constitute no problem under our present level of development, there is no doubt however that things might not continue in a similar way for long.
(2) The need for a Water Resources research body, specifically created to coordinate studies on both ground and surface water resources of the region. It is only such a body that can absorb the demand in money, material and men that such a complex region as the Niger Delta demands.
(3) There should be laws governing the abstraction of groundwater in the region. Today, no laws prohibiting individuals from drilling water wells anyhow, anywhere and at anytime exists. Over-pumpage in coastal aquifers can be dangerous where no regulation exists. This should be addressed with all seriousness.
(4) There is a need for accurate data collection, monitoring and on longer time scale to be able to detect and document effects of water degradation and conversely show the effects of remedial activities, despite the superimposition on natural climatic variability. Documentation, storage and dissemination of knowledge

are important. Through the development of awareness, knowledge and capacity at the national and local level, it is envisioned that the overall knowledge gap will diminish- a step towards sustainable development and management of water resources.

THE WAY FORWARD

Quite unfortunately, in spite of the fundamental role groundwater plays in human well being, as well as that of many ecosystems, groundwater basins are difficult to govern and manage, partly because of poor information, and also because of poor visibility of the resource, the need for reliable data and information in support of water resource planning is central to any strategy. Technology, knowledge transfer and sound research cooperation should receive sufficient attention at the regional scale for any meaningful solution of regional groundwater problems.

More importantly, any sustainable suggestion towards the improvement of water resources management in the Niger Delta must include but not limited to the following:

i) Re-introduction of long-term hydrological observations and investigation of new data collection on water use, irrigation and agriculture lands, water sediment deposits, industrial demands, urban development, recharge, hydraulic properties as well as groundwater/surface water interaction;

ii) Protection of groundwater resources to safeguard long-term use and balance the demands of economic development with ecosystem conservation;

iii) Regional studies of hydrogeology, hydraulic properties, regional flow system and water quality that cross state boundaries;

iv) Greater integration of the relevant information systems, e.g hydrology, hydrogeology, water quality, land use, sediment transport etc;

v) Since the responsibility of protecting our groundwater resources is a collective responsibility with everybody as a major stake holder, an aggressive public awareness programme comparable to that for HIV/AIDS is recommended for water users, planners and policy decision makers at all levels.

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Full Length Research Paper

Estimation and mapping of groundwater characteristics in Greater Wad-Medani Locality, Gezira State, Sudan

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Groundwater dominates the domestic water supply (85%) in the Gezira State, Central Sudan. Groundwater resources in Gezira are basically represented by two water-bearing geological formations: the Nubian Sandstone formation overlain by the Gezira formation and shallow quaternary to recent deposits in minor streams. This study aims at identifying the pattern distribution of selected aquifer characteristics of the Gezira geological formation. It applies empirical Driscoll's equation to generate the aquifer's transmissivity. Geospatial techniques in the Geographic Information System (GIS) accompanied with Digital Elevation Model (DEM) datasets were used in interpolation and map transmissivity. The obtained transmissivity of 7.44 to 875 m^2 a day were found to be conformable with those conventionally based values of 28 - 824 m^2 a day. The spatial variation in the water table was extracted using the DEM data, resulting in a reliable potentiometric map (water table map) for the Gezira formation as compared with that traditionally produced. Potentiometric map was used effectively for mapping trends in the water levels and flow directions. The study showed a powerful example of using GIS and DEM techniques in studying groundwater aquifer characteristics, specifically the geospatially dependent variables.

Key words: Groundwater, aquifer characteristics, spatial distribution, DEM.

INTRODUCTION

Geospatial sciences have become increasingly vital in managing natural resources, especially groundwater resources. With climatic changes and their detrimental impacts on all components of the hydrologic cycle, there is a persistent need to employ cost effective techniques in capturing, storing, processing, analyzing and displaying hydrologic and hydrogeologic data to assist decision making and planning to develop robust conservation and sustainable management practices. Integrating different themes of surface and groundwater in a geospatial context will provide an opportunity to understand the various processes pertaining to groundwater occurrence and development. For instance, the output of the geospatial analysis, whether it is aquifer parameters (that is, transmissivity) or water quality problems (saline zones, polluted zones, etc.) could be further utilized as inputs to develop groundwater flow conceptual and numerical models for deeply studying groundwater issues (Goodchild, 1992; Koch, 1997; Brodie, 2002; Gachet, 2006; Muley, 2008).

The number of functioning water wells is estimated at 2000m deep and shallow wells. Each of these formations has its own depositional characteristics, hydrogeological flow patterns, recharge and boundary conditions (GSWC,

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2011); thus they should be differently managed. A wide range of groundwater studies were carried out in the Gezira region, Central Sudan, especially on pollution of urban centers, saline zones, and water barren zones of the basement complex as well as the potential of the aquifers (Saeed, 1974; Magboul, 1992; Elzein, 2007). However, the lack of persistent data has greatly reduced sound management decisions, reflected on occasional failures of drilling successfully freshwater wells in some areas, total drawdown of yet some other wells and miss-pinpointing of well sites. The advance techniques of remote sensing and GIS could help a lot in managing groundwater resources in a low cost manner (Gachet, 2006; Muley, 2008).

The main objective of this study is to understand groundwater aquifer characteristics in the Gezira state, Sudan. The specific objectives were to estimate transmissivity and water table depth using geospatial analysis techniques in GIS with remote sensing technique. The study area, lies within the administrative boundaries of Greater Wad-Madani locality Gezira, Sudan (Figure 1). The area lies between 14° 24' 33.25 N, 33° 25' 47.07 E, 14° 07' 22.56 N and 33° 50' 31''.41 E, 14° 35' 21.09 N and 33° 24' 47.73 E and 14° 19' 59.82N and 33° 32' 51.57 E. The area occupies about 180 km^2.

The study area generally has flat slope of 10 cm per km. Some depressions represent relicts of proto-Blue Nile system spreading in the central part of the state. However, it was bounded by isolated hills in the eastern, western and southern direction. The Blue Nile River and its tributaries are the main surface water hydrological features in the area, reacting with groundwater within a distance of 2 to 4 km. The state is characterized by a short rainy season (July – September) and high rain fall variability (30%). The soil is vertisols where cracks developed due to change in soil moisture. The rock sequence in the study area is generally comprised of the Per- Cambrian basement complex rocks; the Cretaceous Nubian Sandstone; Quaternary Gezira Formation, Pleistocene buried channel deposits and recent alluvial and superficial deposits (Andrew, 1948; Whiteman, 1971; Vail, 1982). Groundwater in Gezira State is generally found in three aquifers, viz. Gezira, Nubian and Basement aquifers. (Ahmed, 2009) indicated that 90% of Gezira water supply is from the Gezira aquifer, while about 10% is from Nubian sandstone aquifers. Water in the Gezira aquifer occurs under the water table and semi confined conditions. The Blue Nile is the main sources of groundwater recharge for this aquifer The Vertisol soil has negative impact on groundwater recharge as it does not support percolation of water downwards because of its very low infiltration rate. Water hyacinths have demonstrated a great potential for purification of wastewater through physical, chemical and biological mechanisms. Artificial wetlands have been used for secondary treatment and for specific tertiary treatment such as removal of nitrogen and bacteria Successful case studies indicate that wetlands significantly reduce organic matter, suspended solids (SS), pathogens, heavy metals and excessive nutrients such as nitrogen, phosphorus and heavy metals from wastewater. The deviation in chemical, biological, and physical characteristics among wetland ecosystems and complications in understanding and predicting the efficiency of such systems, have motivated the development of artificial wetland systems (Barrie, 2002). As a result, for over 50 years, natural and artificial wetlands have been engineered for wastewater treatment particularly for small and medium sized communities and isolated areas in Europe and the USA where over 700 artificial wetlands have been constructed.

MATERIALS AND METHODS

The required wells and boreholes data were collected from the databases of the (GWC) and Water Management and Irrigation Institute (WMII), University of Gezira. The collected data included specific capacity (m^2/day), discharge (m^3/h), static water level (m), dynamic water level (m) and drawdown (m). The conventional fragmented available data were extracted from the documents of Gezira Water Corporation (GWC).

The transmissivity characteristics of the Gezira formation unconfined aquifer were estimated using specific capacity following the empirical formula of Driscoll (1986) as follows:

$$T=1.042\ (Q/Sw) \text{ for unconfined aquifer} \quad (1)$$

Where, T is transmissivity (m^2 day^{-1}), Q is constant discharge rate (m^3 day^{-1}) and Sw is drawdown in the pumped well after 1 day (m).

The inherent GIS capability in analyzing and interpolating vector and raster datasets was used to draw up aquifer characteristics maps, that is, transmissivity distribution, water table, directions of flow and drainage system. Survey data were collected using the Global Positioning System, (GPS), which were combined with the table attributes of boreholes data. DEM of Shuttle Radar Topography Mission (SRTM) with 90 m resolution was used.

Digital base map of Gezira State was prepared and compiled. The interpolation technique was used to infer distribution of the estimated transmissivity values. These inferred values were calibrated against calculated pumping test data by the analytical methods of Jacob and Theis's Recovery method:

$$\frac{Q}{s_w} = \frac{T}{0.183 \log\left(\frac{2.25Tt}{r_w^2 S}\right)} \quad (2)$$

where the term (Q/Sw) represents the specific capacity of a well, Q denotes the constant discharge rate (L3 T-1), rw is the radius of pumped well (L) and S denotes the storativity (unitless).

Well head elevations derived from the DEMs and water level elevations (static water level, SWL) were used to produce the potentiometric/water table map. The result is the z_value field (pot_surf) that is used to draw the potentiometric map:

$$\text{Pot\_surf} = \text{Raster value} - \text{SWL} \quad (3)$$

Where SWL is the static water level (m); Raster value is the elevation value extracted from the DEM grid (m) and Pot_surf is the elevation to the water table (m). Drainage systems are essential elements to construct the hydrogeologic potential of the renewable aquifers of the study area. The study results were validated using the previous studies mentioned above.

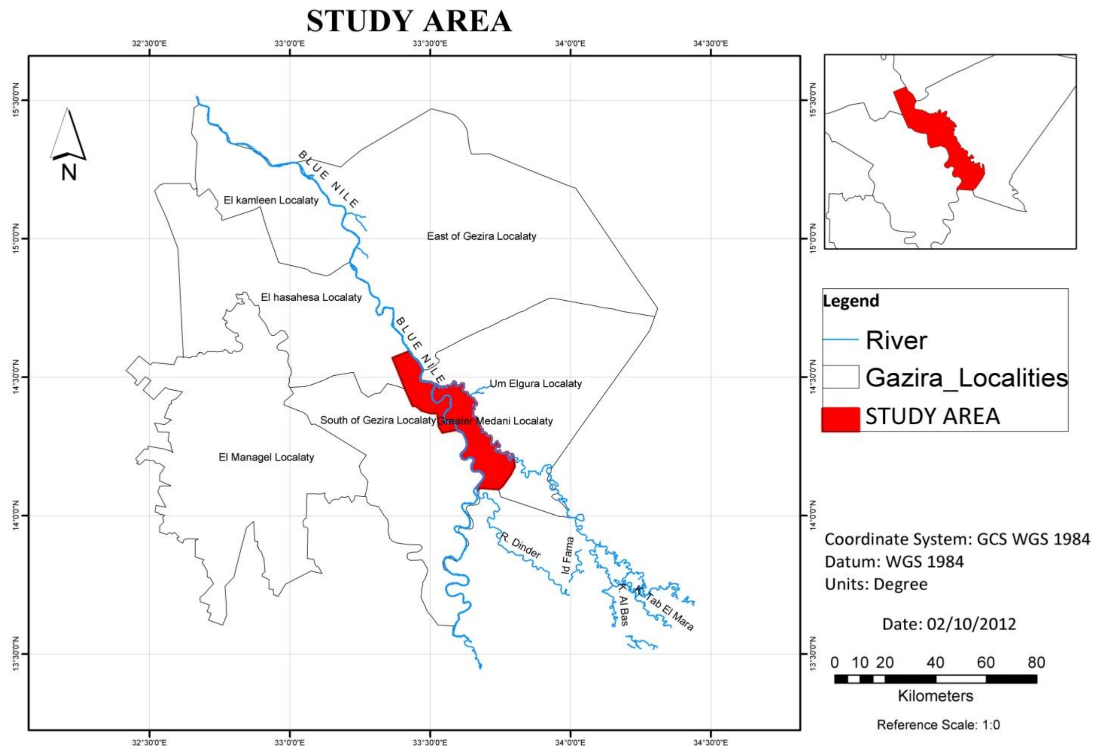

Figure 1. Study area location in Central Sudan.

RESULTS AND DISCUSSION

The data was collected from several wells distributed within and around the study area. Figure 2 shows the distribution of the wells. The transmissivity values for the Gezira aquifer estimated are shown in Figure 3. The average transmissivity was found to be 360.79 m^2/day. In the southern part transmissivity value was found to be as high as 2841 m^2/day. This odd value is attributed to problems in data quality since the drawdown was found to be inconsistent with the general gradations of drawdown values.

The transmissivity values based on the analytical solutions of Theis and Cooper-Jacob were 28 and 824 m^2/day minimum and maximum values respectively, and the average 368 m^2/day, as reported by Elkrai (2004) which is almost the same transmissivity values obtained from the empirical specific capacity calculations as shown in Table 1. The variation in transmissivity values in Gezira formation is attributed to the nature of the sediments depositional cycle of the geological formation. The intercalations of sediments in rapid changes may result in varied hydraulic conductivity and anisotropic conditions. The analysis of hydraulic conductivity of the Gezira formation resulted in values ranged between 34 and 95 m/day.

The aquifer's data were further analyzed using GIS techniques to detect the distribution of hydraulic parameters. The distribution of transmissivity values can be seen in Figure 3. The trend and pattern of the transmissivity distribution is conformant with the hydrogeological knowledge base of the area. Gezira formation has a rather moderate transmissivity values having higher values at the south and gradually getting flat and similar values at the middle area, Figure 4.

Digital Elevation Model of the study area is used to produce a potentiometric surface water table which defines the level to which water rises in a well under unconfined aquifer of the Gezira formation as seen in Figure 5. Potentiometric head data was used to map trends in the water levels, Figure 5 and directions of decreasing flow, Figure 5. The highest water table levels were found in the southern part of the study area gradually trending in the northern and north-western directions. This distribution is fairly conformable with the generally known hydrogeology of the area. Caution should be practiced as to the integrity of potentiometric maps drawn by interpolation methods which is subject to hypothesis in the first place and depends on the resolution of the DEM (90 m in this study). The trend and direction of flow of groundwater is safely indicated. The drainage pattern in Figure 5, was found conformant with the general observed hydrology of the area which reveals the potential of recharge to the unconfined aquifers from the Blue Nile River. A further comprehensive analysis based on the watershed scale to delineate net flow

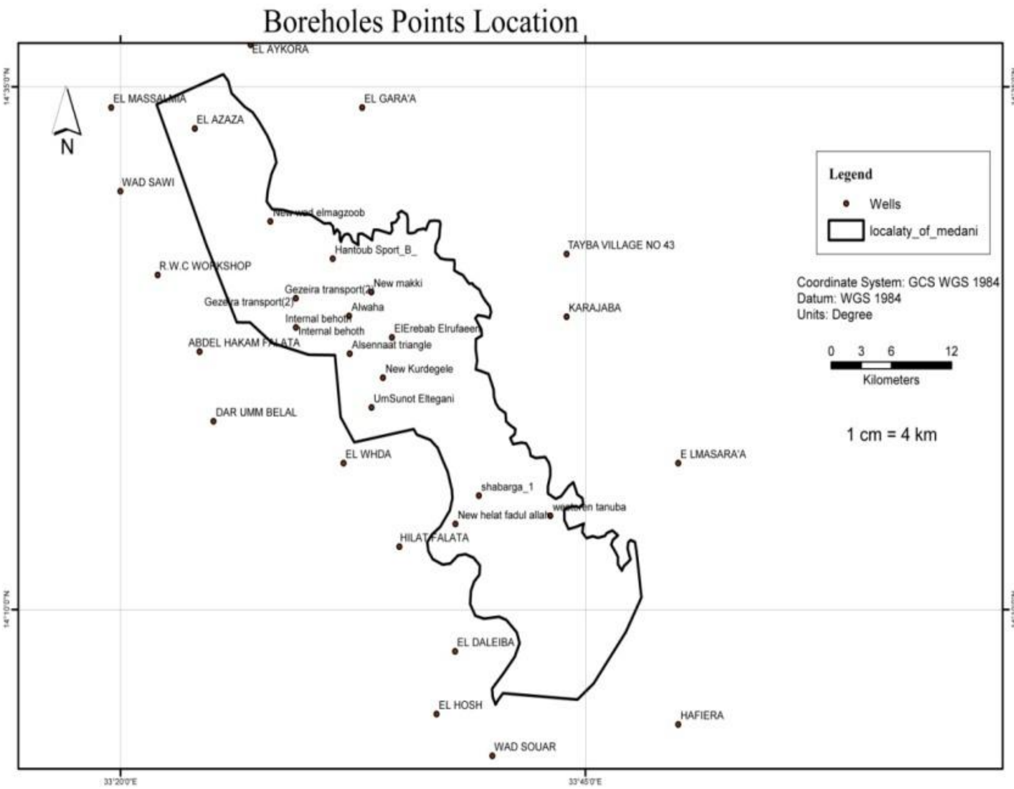

Figure 2. Location of the studied wells.

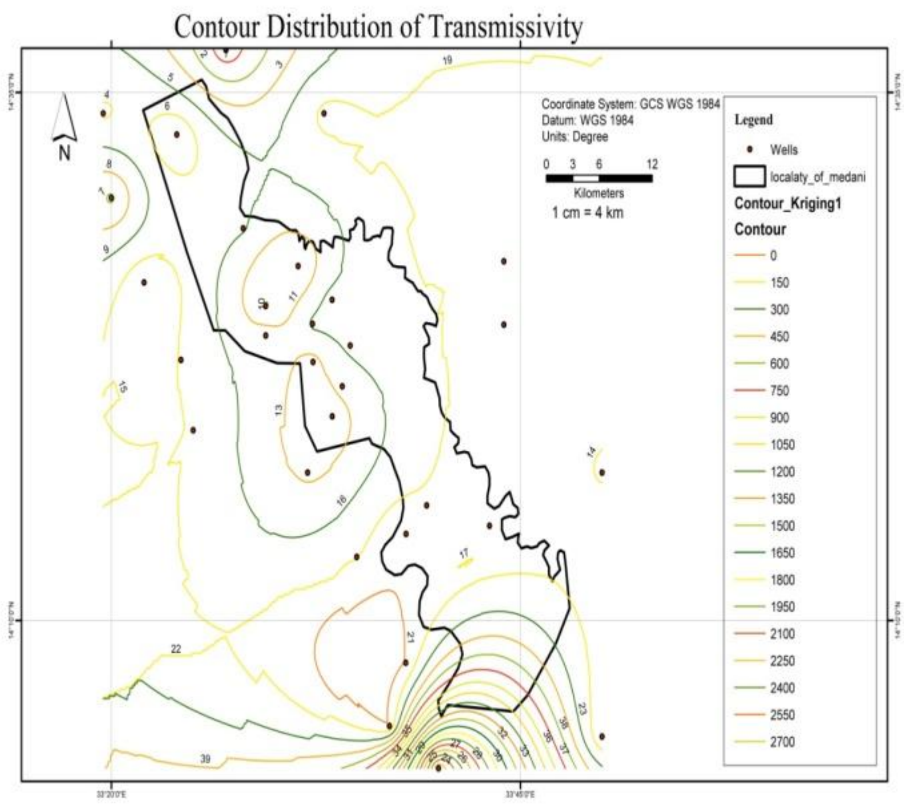

Figure 3. Transmissivity distribution.

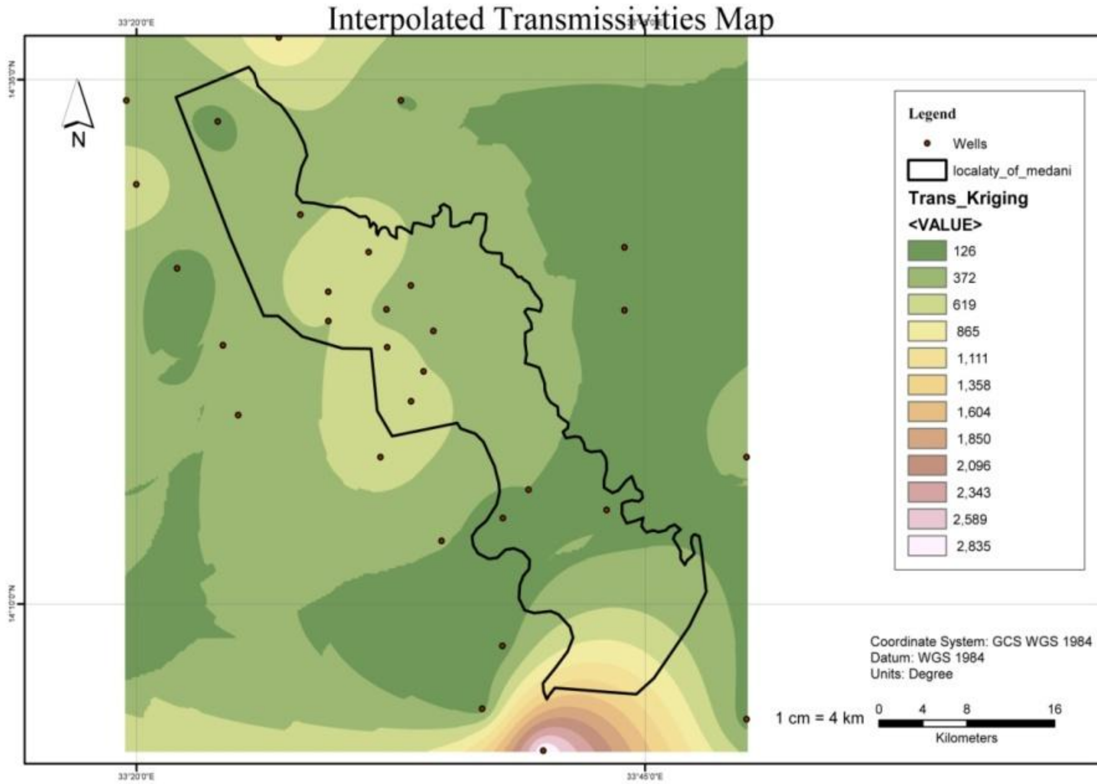

Figure 4. Spatial distribution of the transmissivity.

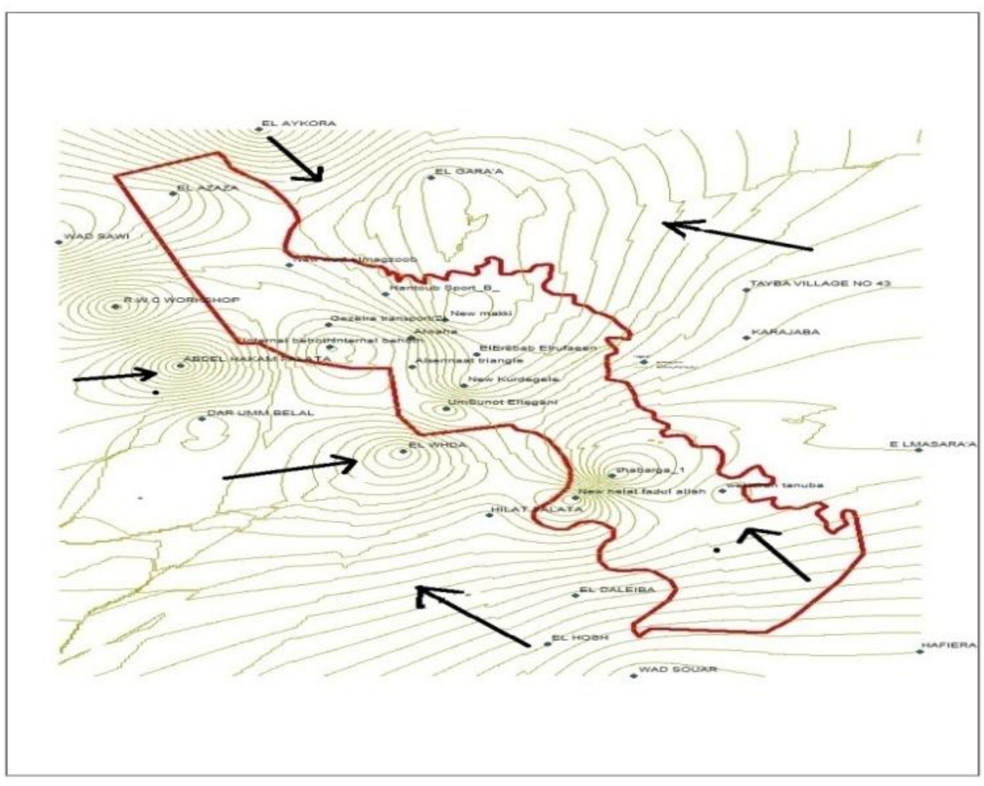

Figure 5. Directions of decreasing water table level depths.

Table 1. Transmissivity calculated from Pumping Test Data.

Method	Transmissivity (m^2/day)			Hydraulic Conductivity (m/day)		
	Min.	Max.	Mean	Min.	Max.	Mean
Jacob's	28	824	368.7	0.411	91.55	34.03
Theis's Recovery	66.5	643.2	355.2	0.977	71.47	26.56

*Source: Elkrai (2004).

Volumes and stream orders is needed.

Conclusion

Groundwater resources in Gezira State are basically represented by two water-bearing geological formations: the Nubian Sandstone formation overlain by the Gezira formation and shallow quaternary to recent deposits in minor streams. This study aims at identifying the pattern distribution of selected aquifer characteristics of the Gezira geological formation. The study applied empirical Driscoll's equation to generate the aquifer's transmissivity. Geospatial techniques in the Geographic Information System accompanied with Digital Elevation Model datasets were used in interpolation and map transmissivity. The obtained transmissivity of 7.44 to 875 m^2 a day were found to be conformable with those conventionally based values of 28 - 824 m^2 a day. The spatial variation in the water table was extracted using the DEM data, resulting in a reliable potentiometric map for the Gezira formation as compared with that traditionally produced. Potentiometric map was used effectively for mapping trends in the water levels and flow directions. The study showed a powerful example of using GIS and DEM techniques in studying groundwater aquifer characteristics, specifically the geospatially dependent variables. Further comprehensive analysis based on the watershed scale to delineate net flow volumes and stream orders is needed.

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