PATTERN OF RAINFALL ANOMALIES AND RURAL WATER SUPPLY IN THE SUDANO-SAHELIAN REGION OF NIGERIA

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ABSTRACT

The pattern of rainfall anomalies have been largely neglected in the literature on climatology in Nigeria in spite of their significance to rural water supply. This paper examined the pattern of rainfall anomalies from 1961-2010 with a view to understanding its causal factors and possible implications for rural water supply. Monthly rainfall data for five meteorological stations located in the Sudano-Sahelian region of Nigeria were obtained from the Nigerian Meteorological Agency. Other category of data used for the study included monthly Sea Surface Temperatures (SSTs) of the Atlantic and Pacific oceans and Southern Oscillation Index (SOI) obtained from the Climatic Prediction Center (CPC), U.S.A. Stepwise multiple regression model and simple linear regression analysis were used for data analyses. Simulations were run with Water Simulation Model (WaSim) for the stated period using daily rainfall and atmospheric temperature to predict the rate of recharge to groundwater table in response to rainfall anomalies in the region. The result showed that the El-Nino/Southern Oscillation (ENSO) and Sea Surface Temperature (SST) anomalies over the tropical oceans together deprive the Sudano-Sahelian region of Nigeria the copious moisture required for abundant rainfall in the region. It was also found that the annual and seasonal rainfall amounts in the region exhibited a downward trend over the period of study. Recharge to the groundwater table is found to be highly sensitive to annual rainfall anomalies in the region and this significantly affects the rural water supply. The paper recommends that the ENSO and SSTs factors should be considered for forecasting of rainfall anomalies in the region. The conjunctive use of surface and ground water sources should also be adopted in order to mitigate the adverse effects of rainfall anomalies on rural water supply in the region.

Key words: Rainfall anomalies, Sea surface temperatures, Sudano-Sahelian, Water simulation Model

INTRODUCTION

Rainfall is one of the most critical elements that determine the availability or otherwise of both surface and groundwater in semi-arid environments that are characterized by high rainfall variability. The term 'Anomalies' within the climatological context refers to the condition in which rainfall is either 'too high (positive anomalies)' or 'too low (negative anomalies) (Olaniran, 1991). This is responsible for the increasing concern particularly amongst hydrologists and climatologists on the potential implications of climate change and variability on the rural water supply in the Sudano-Sahelian region of Nigeria in particular and West Africa in general. Nyong and Kanaroglou (1997, 1999) argued that water availability is a major concern in the drought-prone semi-arid zone of Nigeria given the high rate of population growth in the region which contributes significantly to the increase in water consumption.

Hassan et al (2013) emphasized the need for massive rainwater harvesting as complementary measure of water supply as a way to reduce the effects of the frequent droughts experienced in some selected villages of Sahel Savannah Ecological Zone in Borno State of Northeastern Nigeria over the period 1980-2009. Brett et al (2007), on the other hand advocated for a *Platform* approach to rural water supply management that can mobilize the assets and insights of different social actors to influence decision making at all stages, including the design and choice-of-technology stages, in water supply interventions as against the community-based approach; which will not necessarily proffer sustainable rural water supply in semi-arid region.

Maaten and Jacek (2006) analyzed the changes in surface water supply across Africa with predicted climate change and argued that a decrease in perennial drainage due do climate change-induced precipitation changes would significantly affect present surface water access across 25% of Africa by the end of this century. One of the key uncertainties surrounding the impacts of a changing climate in Africa is the effect that it will have on the sustainability of rural water supplies. Alan et al (2009) examined the potential impact of climate change on rural groundwater supplies in Africa and concluded that the low yielding sources in poor aquifers are most at risk and that the predicted increased rainfall intensity might also increase the risk of contamination of very shallow ground water. Roger and Alan (2009) examined the question on '*what will climate change mean for groundwater supply in Africa*?' and reported that the occurrence of groundwater depends primarily on geology, geomorphology and rainfall and that climate change would superimpose itself by modifying rainfall and evaporation patterns, raising questions about how such changes might affect groundwater availability and, ultimately, rural water supplies.

Kumar (2012) reported a direct link between the groundwater resources and climate change through direct interaction with surface water resources such as lakes and rivers, and indirectly through the recharge process. Tarhule and Woo (1997) showed that the beginning of the rainy season presents a particularly precarious situation for water supply because runoff generated by the rainstorms renders the shallow wells unusable, but the deep wells are not yet recharged and the stream beds contain little more than several stagnant ponds of muddy, polluted water. Thus, there is heavy dependence on any deep groundwater wells that may still be viable, and on the highly variable rainfall.

From the foregoing, it is obvious that the major sources of rural water supplies – groundwater based sources such as hand-dug wells, hand-pumped boreholes, reservoirs, and surface water-based sources such as rivers, lakes, ponds and streams are climate-dependent. The rainfall in the Sahelian region is highly variable and therefore less reliable and as such, could affect the concentration and availability of the underground water within the aquifers. Concern for lack of access to quality water for drinking especially among rural dwellers in Sudano-Sahelian region of Nigeria had compelled government and some donor agencies to embark on massive rural water supply projects including creation of more dug-wells, hand-pumped bore-holes and some forms of water harvesting techniques in order to ease the suffering of their subjects by making more water available to the teeming population in the region. Though several studies have been carried out in different parts of Africa with the aim of understanding the impact of climate change on groundwater supplies, no attempt was made to examine the pattern of rainfall anomalies and its implications for rural water supplies in Sudano-Sahelian region of Nigeria over the period 1951-2000.

This paper is aimed at examining the pattern of rainfall anomalies and rural water supply in Sudano-Sahelian region of Nigeria. This was achieved through determination of annual and seasonal rainfall trends, identification of the causal factors and modelling the rate of groundwater recharge in response to rainfall anomalies using high and low rainfall years. The low and high rainfall years at each station were identified from the difference between the long-term annual mean and individual year total. The years with positive deviations from the long term mean are considered as anomalously high rainfall years, while those with negative deviations are regarded as anomalously low rainfall years.

THE STUDY AREA

The study area is the Sudano-Sahelian region of Nigeria located within the latitudinal band Lat. 11° - 14° N as shown in Figure 1. The five meteorological stations selected within the region include Sokoto, Kano, Katina, Maiduguri and Nguru.

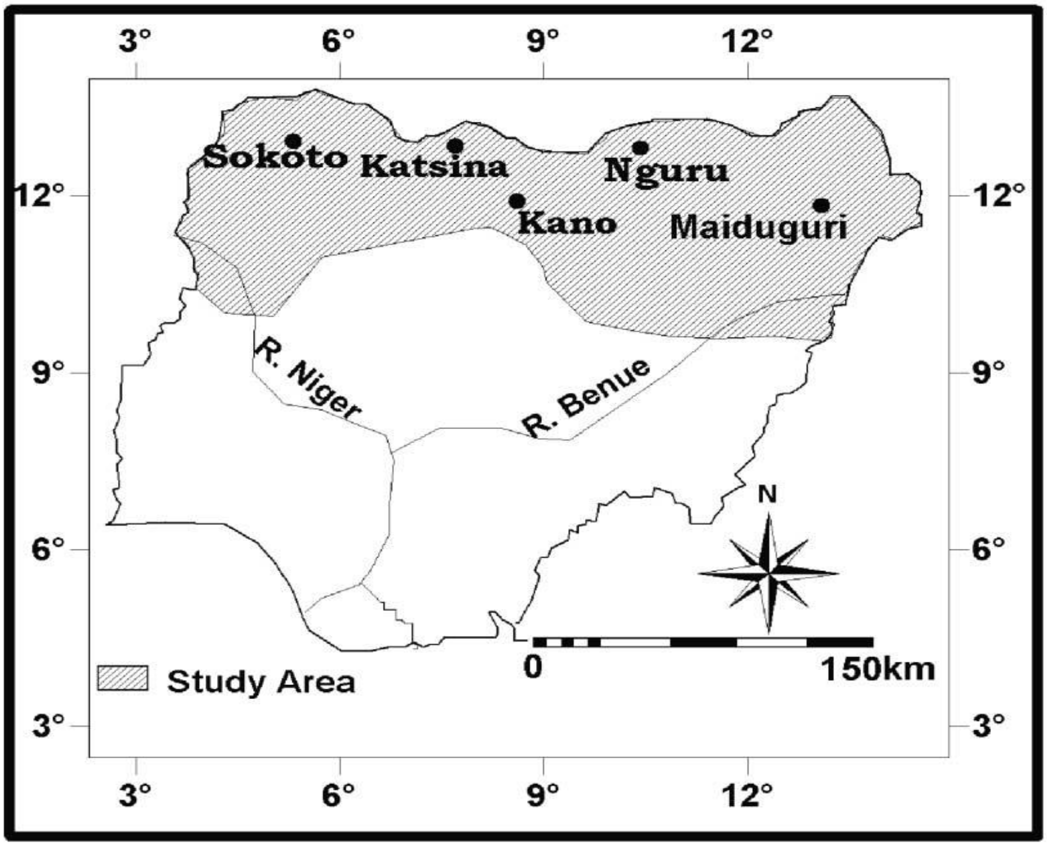

Fig. 1. Generalized map showing the areal entent of the Sudano-Sahelian region of Nigeria (After Odekunle et al, 2008)

The Sudano-Sahelian region of Nigeria like other parts of the country, enjoys a tropical continental climate characterized by two distinct seasons viz: the wet season and the dry season. The country receives rainfall from the south westerlies which invades the country from the Gulf of Guinea coast, i.e. the tropical Atlantic. This moist air stream is overlain by the northeast trades which originate from above the Sahara and therefore are dry and dust laden. The zone of contact of the two air masses at the surface is a zone of moisture discontinuity and it is known as the Inter-Tropical Discontinuity (ITD). The ITD advances inland as far as latitude 22-25^0 N in August at the margin of the Sahara i.e. considerably beyond Nigeria's northern border (Ayoade, 2011) while it does not retreat equatorward beyond latitude 4^{0}N during the 'Harmattan' dry season (Odekunle et al, 2008; Ayoade, 2011).

The five weather zones that are associated with the ITD over Nigeria are illustrated in Figure 2. Zone A lies to the north of the ITD and hence is rainless as well as zone B to the immediate south because they do not contain rain-producing clouds. Rainfall in the ITD occurs in zones C and D where conditions favour the development of clouds of great vertical extent. Thunderstorms and squall lines are associated with zone C weather and monsoon rains with zone D weather. Consequently, rainfall is spatially discontinuous when zone C weather prevails. On the other hand, the monsoon system gives continuous rains which may last 12 hours or more (Olaniran, 1986, 1991, 2005). Overall, rainfall occurs at a distance of about 500km south of the surface location of the ITD, 4-6 weeks behind it in its annual cycle. When the fifth weather type associated with the ITD i.e. zone E, prevails over an area, light rainfall usually occurs because Zone E weather is dominated by layered stratiform clouds. The amount, seasonal distribution, type of rainfall and the length of the rainy season as well as the general weather conditions experienced in the course of the year at any given location in the West African region depend primarily on its location relative to the position of the ITD and the associated weather zones (Ayoade, 2005).

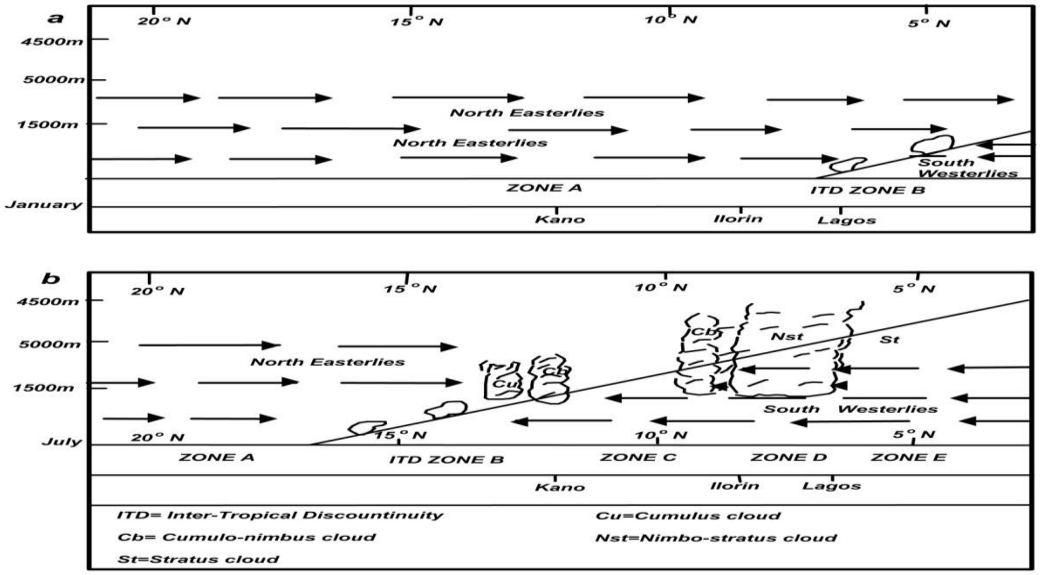

Fig. 2: The ITD and the weather zones in an idealized atmospheric cross-section from South to North over Nigeria (After Ojo, 1977)

MATERIALS AND METHODS

Monthly rainfall data for Katsina, Nguru, Maiduguri, Kano and Sokoto meteorological stations located in the Sudano-Sahelian region of Nigeria (see Figure 1) were collected from the Nigerian Meteorological Agency (NiMet), Oshodi, Lagos, Nigeria.

Other category of data collected are the monthly Sea Surface Temperatures (SSTs) and El nino/Southern Oscillation (ENSO) index over the tropical Atlantic and Pacific Oceans over the period 1951-2000. These data were sourced from the archives of the Climatic Prediction Centre (CPC), United States of America (USA). The annual and seasonal rainfall trends were analyzed using the simple linear regression model where by the values in the time series (*y*) were regressed on time (*x*). The equation of the line of best fit was then computed using the least square criterion by which the sum of squares of the deviation of each observation from the trend line is minimized. The equation is as follows: $Y = a + b\bar{x}$ +e Where $\boldsymbol{a}$ = intercept of the regression, $\boldsymbol{b}$ = regression coefficient and $\boldsymbol{e}$ = error term or residuals of the regression. The annual rainfall series for each of the stations was utilized for a 50-year period (1951-2000). A composite of (Jun + Jul + Aug) rainfall was also derived for each station within the same period (1951-2000). The Sudano-Sahelian stations considered in this study receive the bulk of their rainfall during these months in any given year. Both series were then subjected to stepwise multiple regression analysis in an attempt to determine the causal factors of rainfall anomalies in the region.

The independent variables used in the stepwise multiple regression model include: (1) The Southern Oscillation Index, (2) Global Tropics (10°South-10°North, 0-360^0) SST anomalies (3) Niño 1+2 (0-10°South)(90°West-80°West) SST anomalies (4) Niño 3 (5°North-5°South)(150°West-90°West) SST anomalies (5) Niño 3.4 (5°North-5°South)(170-120°West) SST anomalies (6) Niño 4 (5°North-5°South)(160°East-150°West) SST anomalies (7) South Atlantic (0-20°South, 30°West-10°East) SST anomalies (8) North Atlantic (5-20°North, 60-30°West) SST anomalies. The dependent variables are the annual and seasonal rainfall time series for each of the stations.

The WaSim model developed by Hess et al. (2000) was used for soil water balance simulation to estimate recharge into the sub-surface aquifer and to monitor the groundwater table movement in response to weather and irrigation where appropriate. Simulations of up to 30 years duration can be undertaken using WaSim and up to 3 crops can be specified in rotation. The model consists of several layers of soil with the upper boundary as the soil surface and the lower boundary as the impermeable layer and water is stored between these two boundaries in five stores. The first, compartment 0, is the surface layer compartment (0 – 0.15m), followed by the active root zone compartment 1 (0.15m – root depth), then, compartment 2 is the unsaturated compartment below the root zone (root depth – water table), then, compartment 3 is the saturated compartment above drain depth (water table – drain depth) and lastly, compartment 4 is the saturated compartment below drain depth (drain depth – impermeable layer). Soil water moves from upper layers to layers below only when the soil water content of the compartment exceeds field capacity. In this case, the drainage flow is a function of the amount of excess water. Calculation of water table depth was done using the formula below:

$$h_{\text{i}} = h_{\text{i}} - 1 - \frac{qd + Vs}{1000\mu}$$

where:
h_i height of the mid-drain water table position above drain depth on day i, m
q_d flow to drains, mm d^{-1}
Vs net flux from the water table to the root zone, mm d^{-1}
μ drainable porosity, dimensionless
and
$\mu = \Theta_{SAT} - \Theta$ *for a rising water table*
$\mu = \Theta_{SAT} - \Theta_{FC}$ *for a rising water table*

The data used for simulations includes daily rainfall and reference evapotranspiration (derived from daily air temperature) for Sokoto station. Three consecutive years were used to represent the wet (high) (1992-1994) and dry (low) (2003-2005) rainfall years in the model. This is to allow for normalization of the model during the simulation process and to observe the effects of high or low rainfall year on the groundwater table due to the influence of residual moisture in the soil storage. After careful examination of the rainfall trends for all the stations, the representative years selected are that of Sokoto station. Only those years are found to follow in sequential order to represent both the high and low rainfall progressions. In addition, unstructured questions were asked from the inhabitants about the water sources history, types and its viability as well as the lengths of the rainy season in the area.

RESULTS AND DISCUSSION

Rainfall trends in Sudano-Sahelian Region of Nigeria

The results of the annual and seasonal rainfall trends analysis are presented in Table 1.

Table 1. Rainfall Trends in Sudano-Sahelian Region of Nigeria (1951-2000)

Station	***R***		**Significance level %**	
	Annual	**Seasonal**	**Annual**	**Seasonal**
Katsina	-0.32	-0.38	0.05	0.05
Nguru	-0.24	-0.29	0.05	0.05
Maiduguri	-.0.51	-0.57	0.01	0.01
Kano	0.00	0.00	-	-
Sokoto	-0.72	-0.78	0.01	0.01

The results showed that annual rainfall series at Katsina, Nguru, Maiduguri and Sokoto stations exhibited a significant downward trend over the period 1951-2000 while Kano annual rainfall did not show any discernible trend over the period of the study. The seasonal rainfall pattern in the region also showed similar rainfall trends (Table 1).

Similar results were obtained by Umar (2010) using annual rainfall series for the period 1941-2000 at Katsina, Maiduguri and Sokoto stations as presented in Figure 3.

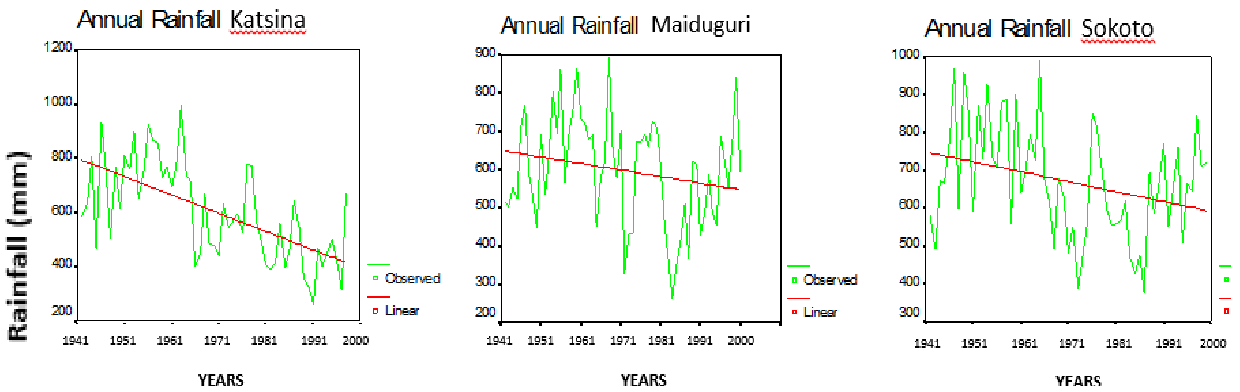

Fig. 3: Annual Rainfall Series for the Period 1941-2000 at Katsina, Maiduguri and Sokoto Stations

The implication of this rainfall pattern is that if persisted, it will further put more stress on rural water sources and undermine the efforts at providing water for domestic use in the rural communities located in the region.

Rainfall Anomalies in Sudano-Sahelian Region of Nigeria

The results of the stepwise multiple regression model for annual rainfall series at each of the stations considered in this study are presented in Table 2.

Table 2. Summary of the Regression of Annual Rainfall on SSTs and ENSO Indices at the selected Sudano-Sahelian Stations of Nigeria

Station	Critical Variable (s)	*R*	r^2	Significance
Katsina	Global SST	0.45	0.198	0.00
	North Atlantic SST	0.60	0.359	0.00
	NINO 3.4 SST	0.67	0.442	0.00
Nguru	South Atlantic SST	0.52	0.274	0.00
	Global SST	0.61	0.366	0.00
Maiduguri	Global SST	0.36	0.129	0.01
	North Atlantic SST	0.54	0.288	0.00
Kano	North Atlantic SST	0.46	0.207	0.00
Sokoto	South Atlantic SST	0.40	0.160	0.00

It could be observed from Table 2 that the most critical variable that dominates the inter-annual variability of rainfall at Katsina is NINO 3.4 SSTs which accounts for 44.2% of the explained variance. Table 2 further shows that the Global SSTs exercises greater control on inter-annual variability of rainfall at Nguru and accounts for 36.6% of the explained variance. It could also be observed from Table 2 that the most critical variable that controls annual rainfall variability at Maiduguri is North Atlantic SSTs and accounts for 28.8% of the explained variance. It could also be observed that the only critical variable that modulates annual rainfall variability at Kano is North Atlantic SSTs which accounts for 20.7% of the explained variance in inter-annual variability in rainfall at Kano. However, at Sokoto, South Atlantic SSTs accounts for only 16.0% of the explained variance in inter-annual variability of rainfall.

Table 3 provides a summary of the result of the Step-Wise Multiple regression of wet season rainfall of selected stations in the Sudano-Sahelian region of Nigeria on indices of SSTs and ENSO.

Table 3. Summary of the Regression of Wet Season Rainfall on SSTs and ENSO Indices at the Selected Stations in the Sudano-Sahelian Zone of Nigeria

Station	Critical Variable (s)	*R*	r^2	Significance
Katsina	Global SST	0.44	0.189	0.00
	North Atlantic SST	0.54	0.290	0.00
	NINO 3.4 SST	0.64	0.408	0.00
Nguru	South Atlantic SST	0.54	0.294	0.00
	Global SST	0.61	0.377	0.00
Maiduguri	South Atlantic SST	0.35	0.121	0.01
	ENSO Index	0.47	0.218	0.00
Kano	North Atlantic SST	0.46	0.207	0.00
Sokoto	South Atlantic SST	0.39	0.151	0.01

It could be observed from Table 3 that sea surface temperature variations in the East-Central Pacific region (NINO 3.4 SSTs) dominate the intra-seasonal variations in rainfall at Katsina and it accounts for 40.8% of the explained variance. Table 3 further shows that Global SSTs has the highest level of explanation as it accounts for 37.7% of the explained variance in intra-seasonal variability of rainfall at Nguru. The ENSO represented by the SOI dominates the intra-seasonal variability of rainfall at Maiduguri as it accounts for 21.8% of the explained variance. The North Atlantic SSTs accounts for 20.7% of the explained variance in intra-seasonal variability of rainfall at Kano while at Sokoto, the South Atlantic SSTs is the only critical variable recognised and accounts for only 15.1% of the explained variance in intra-seasonal variability of rainfall.

The results presented in Tables 2 and 3 confirm the links between the Sea Surface Temperatures (SSTs) anomalies over the tropical Atlantic and Pacific Oceans and rainfall anomalies in the Sudano-Sahelian region of Nigeria. Such extra ordinary warming was found to significantly reduce the meridional gradient of SST south of the Inter-Tropical Discontinuity (ITD), and as a result, leads to a weakened Hadley meridional circulation. The weakened circulation reduces the intensity of the south-west monsoon flow into West and central Africa and consequently reduce rainfall in the region as demonstrated by Folland et al. (1986).

Implications for Rural Water Supply in Sudano-Sahelian Region of Nigeria.

Population increase and demand for more water in the Sudano-Sahelian region of Nigeria is putting more pressure on the already stressed available water resource. The frequent failure of boreholes and dryness of hand dug wells reported by many researchers in the region (Oteze, 1979; JICA, 1990; Offodile, 2002; Oduvie, 2006; Gada, 2016) is not only associated with decrease in rainfall but also due to over abstraction. During the fieldwork interview, the local people confirmed that 10 – 20 years back, some of the hand dug wells that dry up in the dry season used to have water throughout the year. When the current population (2013) of the area was compared with that of 15 years back (1991), it shows that the population almost tripled, implying triple increases in water demand.

A soil moisture balance was carried out from which recharge was estimated. This recharge enters an aquifer system which is exploited for domestic purposes, for livestock and for irrigation. The WaSim model represents both the soil moisture zone and the aquifer with its storage as a single unit.

It has been found in this study that the larger parts of the anomalies in rainfall in Sudano-Sahelian region of Nigeria over the period 1951-2000 were caused by the air-sea interaction phenomena of the Sea Surface Temperatures (SSTs) and the El-Nino/Southern Oscillation (ENSO) over the tropical Atlantic and Pacific Oceans. The anomalies in rainfall are aspects of the variability in rainfall which could be too high, leading to floods, or too low, leading to droughts of various magnitudes. Thus, the most notable indicator is the reduction in recharge as indicated in the response of water table to rainfall input in Figure 4 (See materials and methods section).

Note that the three years selected each to represent the wet or high rainfall (1992-1994) and dry or low rainfall (2003-2005) years are in sequence. This is to allow for normalization of the model during the simulation process and to observe the effects of high or low rainfall year on the groundwater table.

In Figure 4, the groundwater table usually responds to rainfall infiltration and subsequent recharge whenever there is heavy downpour or continuous rainfall for few days consecutively. During the high rainfall years, the water table rises higher close to the surface as shown in the first part of Figure 4 for the years 1992 and 1994. During the low rainfall years (2003 – 2005) however, the water table always remains at shallow level indicating low or complete absence of water table movement in response to rainfall. The response of groundwater table movement is not dependent on only rainfall occurrence, but also the intensity by which it occurs. This behavior generally controls the distribution and availability or otherwise of groundwater within the study area.

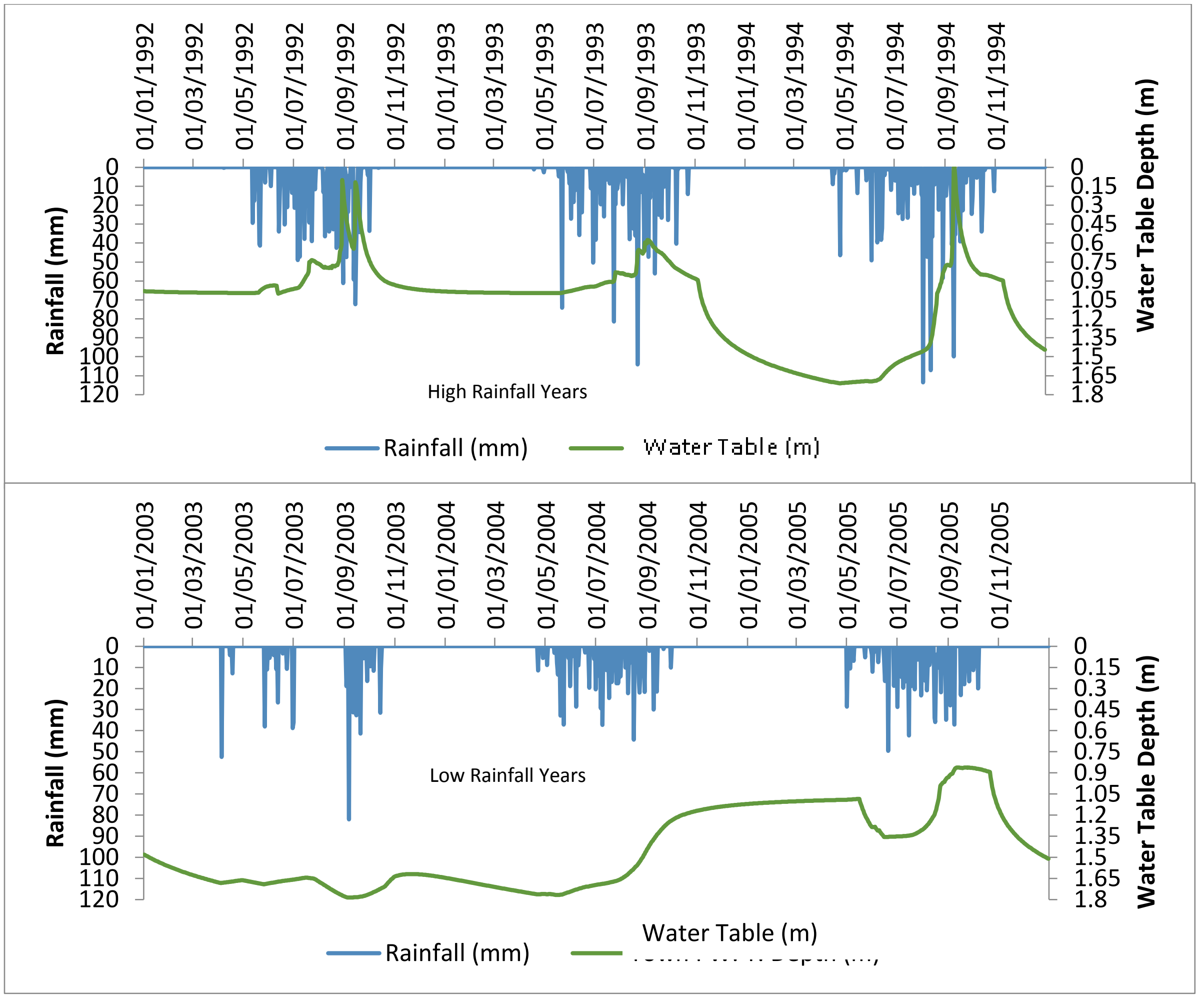

Figure 4: Daily Rainfall and Water Table Depth in the Wet (High) and Low (Dry) Rainfall Years for Sokoto Station

Since the major sources of rural water supply (e.g. hand-dug wells, hand-pumped boreholes, rain harvesting, ponds, streams, lakes, and rivers) are climate dependent as noted in the previous studies in the African Sahel, it is obvious that perturbations in climate as symbolized in the occurrence of rainfall anomalies, could have some implications on the availability and reliability of both the ground and surface water supplies in the rural communities in the Sudano-Sahelian region of Nigeria. These implications may include the following:

1. In the event of anomalously low rainfall in the region, the already poor yield aquifers will be badly affected in form of natural water recharge which is mainly rain-fed, and consequently pose serious water stress in the region.
2. The contamination of the groundwater may occur due to excessive rainfall in the region in any given year. When rainfall is anomalously high, there will be huge run-off in the region and this could lead to infiltration of various industrial toxic wastes and other pollutants into the groundwater. This may impair the groundwater quality and pose health threat to people when such water is extracted and used for domestic purposes.

3. Acute water shortage in the event of anomalously low rainfall in the region could trigger communal crises that may arise from stiff competition among the population for limited water in the region. The cattle rearers for example, may clash with farmers under such conditions, since the former has to feed his animals and provide water for them even in the face of serious water scarcity in the region. He may want to continuously extract the limited water from the hand-dug wells around to give his animals while the farmer at the same time may want to extract this limited water for irrigating his crops. Hence, the clash is inevitable.
4. The rural population who rely on the flow of water in rivers and streams for fishing activities may suffer serious economic losses in the event of anomalously low rainfall in the region. Low water level in streams and rivers may worsen if rainfall amounts continue to decline far below the long term mean in the region. The water vendors in the region are likely to suffer similar fate if rainfall anomalies in the region persist, especially in the case of anomalously low rainfall.

CONCLUSION

The paper examined the pattern of rainfall anomalies and trend over the period 1951-2000 and highlights its possible implications for rural water supply in the Sudano-Sahelian region of Nigeria. Both annual and seasonal rainfall series were found to exhibit a significant downward trend over the period of the study at four out of the five stations considered. Evidence of atmospheric teleconnections between rainfall in the region and anomalous Sea Surface Temperatures (SSTs) over the tropical Atlantic and Pacific Oceans were also found. The paper concludes that major sources of rural water supply in the region are at the mercy of climate. It is recommended that the ENSO and SSTs factors should be considered for forecasting of rainfall anomalies in the region. The conjunctive use of surface and ground water sources should also be adopted in order to mitigate the adverse effects of rainfall anomalies on rural water supply in the region.

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