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Assessment of Soil Moisture through Climatic Variables Using Remote Sensing Data in Semi-Arid Sokoto State, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Soil moisture availability is an indispensable requirement for not only the growth of crops but also other living organisms in any ecological settings This study determined soil moisture condition in Sokoto State using climate-based water index. Satellite-based estimations of mean monthly rainfall data was obtained from the USGS/FEWS database for each of the local government areas. Also, approximations of monthly values of minimum and maximum air temperatures (AIRS) were downloaded from the NASA website. The latter variables were utilised in the computation of potential evapotranspiration using Hargreaves equation. It was very clear from the results that water surplus occurred in the months of July, August and September across almost all the locations. In addition, places lying in the southern part of the State such as Kebbe, Yabo, Tambuwal and Shagari recorded higher positive values of moisture availability in contrast to their counter parts in the

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extreme north bordering Niger republic. Thus, this study revealed slight spatio-temporal variation in soil moisture condition across the entire study area decreasing from the southern locations towards the north. Hence, the research could help improve agricultural planning and suggest irrigation during dry periods. Consequently, the findings could offer useful insights for managing water resources and improving farming in dry areas.

Keywords: Soil moisture; climate; water; ecosystems.

1. INTRODUCTION

Determining the Soil moisture Condition in Sokoto State using Climate-based water Index.

Soil moisture availability is an indispensable requirement for not only the growth of crops but also other living organisms in any ecological settings. It is defined by Kehinde & Umar (2021) as the quantity of water that is determined by prevailing climatic condition and the ability to hold water by the soil at a given location and period. The tendency of the soil to accumulates water surplus after precipitation depends on the values of potential evapotranspiration as well as the soil's capacity to hold moisture at any point in time. Thus, soil moisture acts as an interface that links all the spheres of the earth especially the biosphere, hydrosphere and atmosphere. According to Han et al., (2020) soil moisture regulates many activities on the earth including biogeochemical cycling and hence assists greatly in the study of the functioning of the ecosystems, human health and food security.

Soil moisture varies spatially on a global and micro scale (Guo, 2020). The factors such as climate, topography, pattern of land use/nature of vegetation and the soils characteristics at any particular location influence this spatial variation (Syed, et al., 2008). It is noteworthy to stress that climate exerts tremendous influence on the variation in soil moisture content of the soil at global scale while topography and land use factors modulate spatial differences at micro scales. The Sokoto State consists of 23 provinces lying within the same agroclimatic zone of Nigeria that are having relatively homogeneous climatic condition. However, some slight variations exist in terms of the pattern of land use and topography. Consequently, these differences as reported by Guo, et al., (2020) could influence differences in soil moisture content a (at relatively smaller scale across the globe).

An estimation of Soil moisture content of the soil across any given area can be of immense value to efficient agricultural practices for maximum yield of crops. Insufficient soil moisture storage is inimical to a healthy growth of crops which has been identified by many studies in Nigeria as greatly inhibiting crop growth and yield (Shiwachi, et al., 2008, Fasinmirin & Oguntuase, 2008, Kehinde & Umar 2021). In addition, a robust evaluation of soil moisture condition can necessitate the desire for the development of irrigation as an alternative and significant means of supplying water to raise crops during the dry season. This is because in most parts of Africa especially in the study area there is over reliance on rainfed agriculture which is being affected negatively by several challenges including rainfall variability, dry spell and climate change. It was further highlighted by Kehinde and Umar (2021). that awareness of moisture condition at any time of the year will enable the farmers to achieve sustainable agricultural practices. In this light, studies on soil moisture storage are of immense value in assessing the condition of drought and dry spell in the study area that has been described as one of the front-line states in terms of desertification.

A plethora of studies have been carried out in different parts of Nigeria on soil moisture storage using various climatic indices (Ayoade, J. O., 2004). However, no any known study has captured the spatio-temporal availability of water surplus using a water-based index approach in any semi-arid regions of Nigeria. In addition, this study has applied Hargreaves equation in the computation of potential evapotranspiration using the maximum and minimum temperature data from the National Aeronautics and Space Administration (NASA) website.

2. MATERIALS AND METHODS

2.1 The Study Area

Sokoto state (Fig. 1) is located between longitudes 4° 8′ and 6° 54′ East of Greenwich Meridian and latitudes 12° N and 13° 58′ North of the equator. It's bounded by Kebbi State in the east and Zamfara State in the west which formerly formed Sokoto State. The state consists of 23 local government headquarters that cover a landmass of 32,000 square kilometres. The duration of rainfall usually last for 4 to 5 months beginning from May to September and ranged between 500mm to 1300mm. Sokoto State being semi-arid is almost hot with an annual average temperature that reaches 34°C.

2.2 Climate Data

This study utilised satellite-based estimations of rainfall across the globe for each of the local government areas that constitute Sokoto State. In this regard, RFE 2.0 rainfall data was downloaded and is always accessible at http://earlywarning.usgs.gov/fews. According to (Xie, & Arkin, 1996) this source of rainfall data has the quality of reducing both random errors to the barest minimum as well as bias inherent in most rainfall approximations. The use of this satellite based approximations is necessitated by the dearth of weather satellite stations in the study area as is common in most parts of the developing countries (NOAA CPC., 2001). Rainfall estimates (RFE 2.0) have been proved to be very accurate when compared with many ground stations across various parts of Africa (Symeonakis, et al., 2009, Maidment, et al., 2013, Toté, et al., 2015).

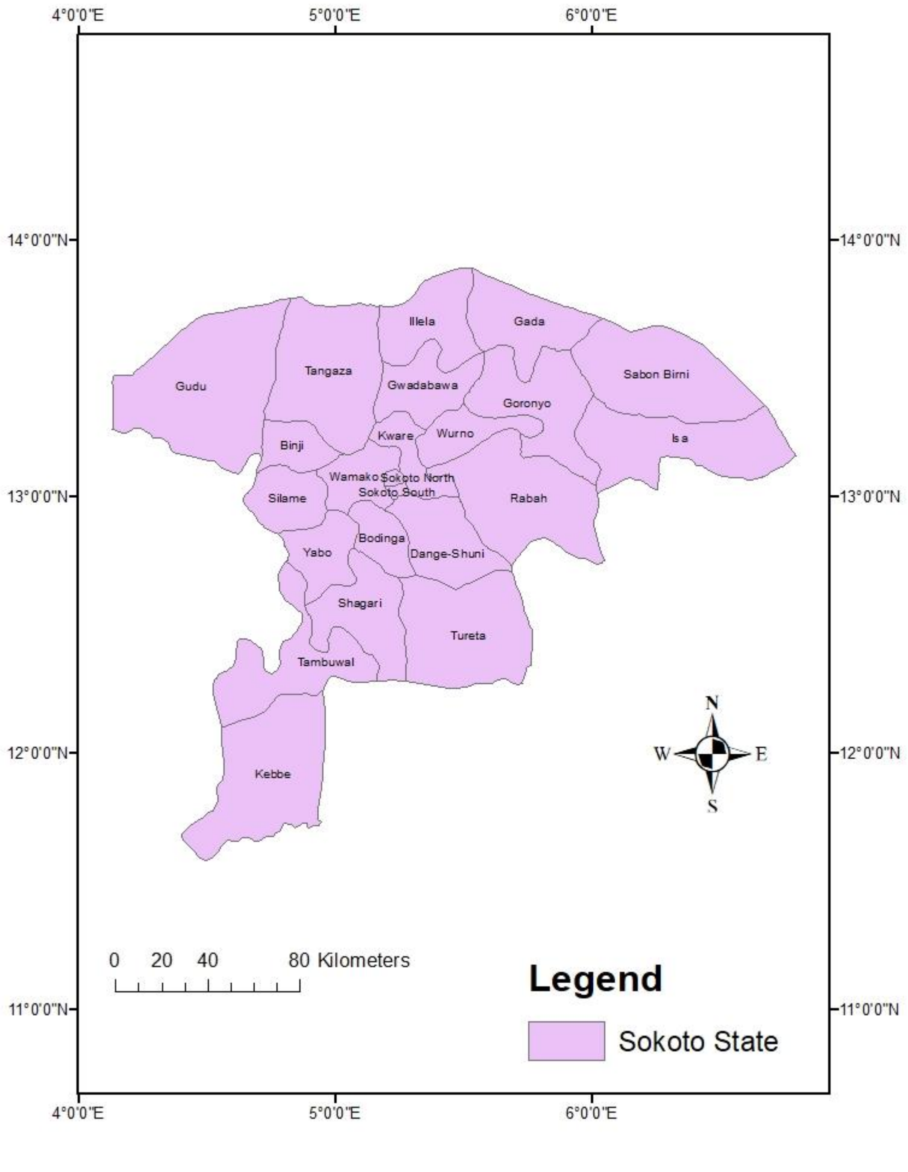

Fig. 1. The study area

On temporal scale, the rainfall approximations cover the entire Africa from 2000 to date at 8km spatial resolution available at 10-day composites. The data was subjected to GIS analysis through resampling of the spatial resolution to 1km prior to the extraction of the exact values for each unit that covers the area under study.

In addition to rainfall data, this study used minimum and maximum air temperature based on satellite approximations. Thus, near air surface temperature AIRS (AIRX3STM) of monthly time series values were extracted from https://disc.gsfc.nasa.gov/SSW/#keywords=AIRX3STM%20006. The database is based on AIRS/Aqua level 3 Standard Physical Retrieval version 6 (AIRS + AMSU) with a spatial resolution of 1^{o} by $1^{o.}$ The AIRS products have been used extensively in many studies in meteorology, hydrology and energy cycle (Le Marshall, et al., 2005, Tian, et al., 2013). This was due to the accuracy of the product that underwent cloud clearing of AIRS radiances through the utility of physical retrieval algorithm. This occurred according to (Chahine, et al., 2006) in all the participating AMSU footprints and encapsulating temperature and water vapour as affirmed by Susskind, et al., (2003).

2.3 Climate-Based Forecast Index

The index applied in this study was developed to account for the water availability based on the values of rainfall and potential evapotranspiration at any particular location in line with the concepts of Thorntwaite and growing degree days (GDD) for living organisms (Ruselle, 1984, Yilma, & Malone, 1998). It was reported by Afshan et al., 2014) that the index is referred to as a water-based due to incorporation of both thermal and moisture needs of plants and animals in the tropics. This empirical formula that was applied in the computation of the index employed the use of three basic components that include GDD, rainfall and potential evapotranspiration.

$$Index\ = GDD\ \times Days\ in\ month, if \quad (R - PET \times 0.8) > 0 \dots\dots\dots equation \qquad (1)$$

where GDD = Growing degree days
R= Rainfall (mm/month)
PET= Potential evapotranspiration (mm/month).

The GDD was based on the premise that living organisms composing of both plants and animals thrive under an optimal temperature (below which the survival may not be possible). It was calculated as the difference between monthly mean temperature and base development temperature at 16°C (Dinnik & Dinnik, 1963, Valentia-Lopez et al., 2012). In the study area the lowest minimal values of temperature annually do not fall below the threshold of base development temperature. Thus, the major constraint to the survival of living organisms in most of the semi-arid regions is moisture availability.

2.4 Computation of Potential Evapotranspiration

The satellite-based AIRS air temperature was used in the calculation of potential monthly evapotranspiration in line with the Hargreaves equation as follows

$$PE = 0.0023(T_{max} - T_{min})^{0.5}(T_a + 17.8)^{\frac{Ra}{\lambda}}\ \ equation \qquad (2)$$

Where
Ra = extra-terrestrial radiation (MJ, m^{-2} day^{-1})
T_{max} = the mean monthly values of the maximum daily air temperature (^{0}C)
T_{min} = the minimum mean monthly values of daily air temperature (^{0}C),
λ = the latent heat of vaporisation,
T_a = the average monthly air temperature

Based on the above equation 1, soil moisture would attain positive values if the amount of rainfall recorded at a particular time period is greater than the amount of potential evapotranspiration multiplied by 0.8 over the same period. This condition in line with the water budget model guarantees soil moisture storage at the surface of 2.5cm of soil (Malone, 1998, Valentia-Lopez, et al., 2012)

3. RESULTS

The values of rainfall and potential evapotranspiration are very essential in determining the soil moisture storage in the study area. Thus, the monthly average values of these parameters are presented in Tables 1 and 2. The Table 1 indicated the calculated monthly values of rainfall across the entire study area which vary temporally where higher amount of rainfall are recorded from the months of June to September. Furthermore, the complete dry months of the years under study were from November to March over all locations. Conversely, the months of April, May and October recorded moderate amount of rainfall.

Table 1. Mean monthly rainfall values

Provinces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Goronyo	0	0	0	2	29	163	208	136	124	64	0	0
Bodinga	0	0	0	4	53	145	185	179	124	13	0	0
Tangaza	0	0	0	3	46	158	273	140	107	20	0	0
Sokoto north	0	0	0	4	58	173	242	113	124	21	0	0
Tambuwal	0	0	0	10	50	196	257	242	163	29	0	0
Gada	0	0	0	1	34	124	299	149	110	11	0	0
Sabon birni	0	0	0	0	52	124	257	117	149	62	0	0
Binji	0	0	0	4	50	145	257	154	124	20	0	0
Gwadabawa	0	0	0	2	44	184	221	154	124	14	0	0
Rabah	2	0	0	4	66	158	169	242	208	19	2	0
Tureta	1	0	1	8	74	208	190	196	184	46	0	0
Isa	0	0	0	1	70	173	327	128	179	12	0	0
Gudu	0	0	0	2	64	179	348	149	89	16	0	0
Sokoto south	0	0	0	4	58	173	242	113	124	21	0	0
Silame	0	0	0	5	47	140	169	190	132	21	0	0
Shagari	0	0	0	5	62	132	185	227	128	24	0	0
Yabo	0	0	0	5	47	140	169	190	132	21	0	0
Dange shuni	3	0	0	4	104	140	190	234	173	15	0	0
Kware	0	0	0	3	70	128	202	128	149	21	0	0
Illela	0	0	0	1	60	202	282	149	117	11	0	0
Wurno	0	0	0	3	55	136	202	158	163	55	0	0
Wamakko	0	0	0	4	58	173	242	113	124	21	0	0
Kebbe	0	0	7	17	70	184	215	290	249	53	1	0

Table 2. Values of Potential Evapotranspiration in the study area

Provinces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Goronyo	174	216	227	222	237	191	213	206	207	210	182	167
Bodinga	174	207	225	222	227	213	215	198	195	201	183	174
Tangaza	171	230	227	222	248	221	220	202	204	220	185	167
Sokoto north	174	227	227	222	234	215	216	206	204	210	182	167
Tambuwa	170	182	226	275	265	247	213	202	213	207	181	176
Gada	174	227	227	231	231	214	216	187	204	210	182	167
Sabon birni	169	217	219	219	251	224	225	208	216	207	184	163
Binji	171	230	227	222	248	221	220	186	204	220	185	167
Gwadabawa	188	250	245	227	252	222	216	202	193	190	168	165
Rabah	174	207	225	222	227	213	215	198	195	201	183	174
Tureta	174	207	225	222	227	213	215	198	195	201	183	174
Isa	169	217	219	219	251	224	225	208	216	207	184	163
Gudu	171	230	227	222	226	236	220	202	204	220	185	167
Sokoto south	174	227	227	222	253	212	216	206	204	210	182	167
Silame	170	182	226	275	225	214	188	202	204	207	181	176
Shagari	170	180	227	257	226	214	213	202	196	207	182	175
Yabo	170	182	226	275	225	214	188	202	204	207	181	176
Dange shuni	174	207	225	222	227	213	215	198	204	201	183	174
Kware	174	227	227	222	253	221	216	206	180	210	182	167
Illela	174	227	227	222	253	221	216	206	204	210	182	167
Wurno	174	227	227	222	253	221	216	206	180	210	182	167
Wamakko	174	227	227	222	253	212	216	206	204	210	182	167
Kebbe	173	168	219	267	221	213	215	195	197	197	185	176

Table 3. Potential water loss in Sokoto State

Provinces	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Goronyo	-5.61	-7.41	-7.26	-4.75	1.65	-40	28	-6.1	18.	-113	-146	-134
Bodinga	-139	-166	-180	-173	-128	-25	11	20	-32	-147	-147	-139
Tangaza	-131	-166	-180	-17	-128	-25	11	20	-32	-147	-147	-139
Sokoto north	-139	-181	-182	-173	-129	1.4	68	-51	-39	-146	-146	-134
Tambuwa	-129	-170	-172	-173	-141	22	125	-0.60	-53	-157	-146	-134
Gada	-139.	-181	-182	-183	-151	12	90	-0.6	-53	-157	-146	-134
Sabon birni	-5.45	-7.75	-7.08	-7.32	43.8	11	24	11	-14	-15	-6.13	-5.2
Binji	-5.53	-8.24	-7.32	-2.89	42.4	13	25	16	-11	-13	-6.19	-5.4
Gwadabawa	-6.09	-8.93	-7.93	1.41	21.9	57	11	71	14	3.15	-5.69	-5.3
Rabah	-3.49	-7.41	-7.26	-2.90	58.8	15	16	13	-12	-13	-3.25	-5.6
Tureta	-4.5	-7.41	-5.87	0.83	67.3	11	15	18	17	39.6	-6.1	-5.6
Isa	-5.61	-7.41	-7.26	-4.75	1.65	14	34	49	3.4	2.83	-6.12	-5.6
Gudu	-137	-184	-181	-174	-117	-10	171	-12	-73	-160	-148	-134
Sokoto south	-139	-181	-182	-173	-143	3.7	68.	-51.0	-39.	-146	-146	-134
Silame	-136	-146	-181	-214	-132	-31	17	27.9	-30	-144	-145	-140
Shagari	-170	-180	-227	-251	-164	-82	28	25	67	-182	-182	-175
Yabo	-136	-146	-181	-214	-132	-31	17	27	-30	-144	-145	-140
Dange shuni	-136	-166	-180	-173	-78	-30	-2.4	76	9.7	-145	-147	-139
Kware	-139	-181	-182	-174	-132	-48	28	-36	4.7	-146	-146	-134
Illela	-139	-181	-182	-175	-142	-5.	108	-15	-46	-156	-146	-134
Wurno	-139	-181	-182	-174	-147	-40	28	-6.1	18.	-113	-146	-134
Wamakko	-139	-181	-182	-173	-143	3.7	68.	-51	-39	-146	-146	-134
Kebbe	-138	-134	-168	-197	-107	-5.8	42	133	91	-10	-147	-141

The values of the potential evapotranspiration are contained in Table 2. It was very clear from the table that the months of February to October experienced higher values of potential evapotranspiration over the period of the study. However, the months of November to January got lower values of between 167mm to 182mm across all the locations within the study area.

The computed values of accumulated water surplus are indicated in Table 3. It revealed that the water storage attained positive values in the months where the amounts of potential evapotranspiration were lower than that of the recorded rainfall. Thus, the temporal potential water loss indicated by the negative values over all the locations was a clear manifestation of the semi-arid nature of the study area. Given that, only the months of May to August recorded positive values over several localities in the study area. These units include Sabon Birni, Tureta, Binji and Gwadabawa. In terms of consistency, the months of July and August maintained higher values of rainfall over potential evapotranspiration in almost all the provinces in the study area throughout the year. This could be attributed to the nature of the agroecological characteristics of the study area where higher amounts of rainfall attain their peak in these two months all year round.

4. DISCUSSION

The soil moisture invariably modulates complex processes that have direct impacts on geomorphology, land management, food production and survival of micro-organisms living in the soil. According to Aina et al., (2007) insufficient moisture throughout the year in most parts of Nigeria has adversely affected agricultural activities as well as the survival of fauna. Furthermore, the reaction of the soil to the incident solar radiation depends to a large extent on moisture availability. In that light, it was stressed by Ayoade (2004). Ayoade that if there is moisture deficit in the soil then the outgoing radiation can cause discomfort through excessive warming of the environment. Conversely, presence of soil moisture in the soil aids convective activities of the incident solar radiation. Likewise, flooding can also be properly monitored through examining the temporal pattern of water or moisture availability

Sokoto State is characterized by high temperatures in most parts of the year coupled with the seasonal pattern of rainfall. Thus, determining the months of the year with the potential water surplus would invariably assist in the efficient agricultural planning in any semi-arid area (Kehinde, & Umar, 2021). In addition, effective control measures can be properly put in place to prevent the prevalence of pathogens that thrive during the periods of water surplus. This has revealed the significance of climate-based forecast model originally developed for agricultural production in monitoring the prevalence of climate sensitive parasites. In this light. Malone, J. B., & Yilma, J. M., (n.d.). applied the forecast model coupled with the geographic information system technique (GIS) in containing the prevalence of liver fluke in East Africa. Likewise, the method was employed efficiently by (Valentia-Lopez, 2012) in Columbia where the climate-sensitive pathogen constituted a serious threat to animal production. Afshan et al., (2014) also identified the use of the climatebased model in their study aimed at assessing the impact of climate and Man made irrigation systems on the transmission risk, long term trend and seasonality of human and animal fascioliasis in Pakistan. Similarly, as the soil moisture increases so also the concentration of fungal and bacterial populations as confirmed by Abubakar et al., (2013) based on their study in Upland and Lowland soils of Sokoto State.

In addition to the foregoing, determining the soil moisture storage can assist greatly as an indicator of soil profile pattern which mitigates the occurrence of flooding given the input of precipitation Ayoade (2004). It has also been explained by Han et al., (2020) that soil moisture exerts great influence on air temperature being the interface between all the spheres of the earth. However, the soil moisture in the area of study was generally concentrated in few months (July and August) that vary slightly across the study area due to the arid and semi-arid nature Sokoto State. This can also be attributed to climate change since the study area is described as one of the frontline states in terms of desertification in Nigeria.

5. CONCLUSION AND RECOMMENDATION

The study evaluated the spatio-temporal soil moisture condition using water-based index that was originally designed for the control of climate-sensitive species of both plants and animal’s pathogens. Although, the study area is homogeneous in terms of ecological condition, still slight spatial variation occurred in terms of temporal moisture availability across the 23 local government areas. And that the differences over various locations could be due to the function of rainfall and the values of potential evapotranspiration that was found to vary from the southern parts of the state towards the northern places. Furthermore, the months of July and August proved to be the months with the much-needed surplus water that appeared befitting for the growth of rice and other crops. In addition, these months can be targeted for the control of pathogens that require moisture for the continuity of their life cycle.

Based on the foregoing, the study recommends the development of irrigation scheme to make up for the water deficit especially in the dry months of the year. In addition, effective control measures against flooding can be put in place especially in the months of July and August owing to the perennial possibility of water surplus as identified in the study.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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