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Geospatial Assessment of Groundwater Potential Zones in Abuja, Nigeria, Using GIS-Based Weighted Overlay Analysis

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ABSTRACT

Sustainable development of groundwater is vital in meeting the increasing water demand in rapidly growing and rapidly urbanizing areas like Abuja, Nigeria. This study aimed at mapping and classifying areas with varying groundwater potential within Abuja for the purpose of strategic groundwater development planning. Using geospatial approaches, namely a weighted overlay technique, thematic maps for geology, elevation, land use/land cover, slope, drainage density, and precipitation were integrated based on their respective influences on groundwater availability. Each of the variables was given a weight depending on its importance in groundwater availability mapping. The final map delineated groundwater potential into three classes, namely low, moderate, and high. The results of the study show that about 79% (5,736.2 km^2) of Abuja has moderate groundwater potential, 7% (518.41 km^2) has high potential, and 14% (1,024.61 km^2) has low potential. The study concludes that although groundwater development is feasible for the vast area, there is a need for a focused approach for the high-potential area for the optimal use of this resource. These results provide critical guidance for policymakers and water resource managers for the purposes of facilitating sustainably managing groundwater in the scenario of the ongoing urbanization of Abuja.

Keywords: Groundwater Potential, Geographic Information System (GIS), Weighted Overlay Analysis, Abuja, Nigeria, Water Resource Management, Multi-Criteria Decision Analysis (MCDA)

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1. INTRODUCTION

1.1. Background and Review

The availability of sustainable water sources is a major challenge for rapidly growing urban centers in the Global South. In Abuja, Nigeria's capital city, the uncontrolled growth in population and urbanization has put great pressure on available water sources, thus making the sustainable management of groundwater an important priority (Adelana et al., 2006). Groundwater also tends to represent a more reliable and sustainable water supply than surface water due primarily to its lesser sensitivity to seasonal changes and pollutions. Nevertheless, the effective development of groundwater relies on a thorough understanding of its spatial distribution in order to avoid over-extraction and to correctly target investments in water infrastructure. In the event of no such understanding, uncontrolled extraction might bring about the depletion of aquifers, land subsidence, and long-term environmental degradation. In this light, a scientific characterization of groundwater distribution is paramount for sustainably utilizing and managing practices.

Traditionally, groundwater exploration has greatly depended on classical hydrogeological field surveys and drilling programs that have tended to be coupled with significant time commitments, costly outlays, and limitations in spatial coverages. Nevertheless, RS and GIS technologies have transformed groundwater research by providing the possibility for integrating and spatially interpreting multiple surface and subsurface variables that govern groundwater recharge and storage (Jha et al., 2010). By employing such technologies, multi-criteria decision analysis (MCDA) processes—such as the weighted overlay technique—enable the overall inclusion of vital parameters such as geology, topography, precipitation, and land use/land cover in comprehensive groundwater potential maps. This methodology has been systematically applied across a vast array of climatic and geological conditions and has emerged as effective and cost-effective for initial groundwater assessments (Murthy, 2000).

The overlay weighting technique, which is considered as one of the most used approaches within Multi-Criteria Decision Analysis (MCDA), has been successfully utilized within different hydrogeological environments around the world. For example, Murthy (2000) explained its application within semi-arid regions of India, highlighting the contribution of geological structures and drainage intensity in the identification of groundwater availability. Similarly, Oikonomidis et al. (2015) applied this method within Greece, again proving its success within the context of the Mediterranean climate. The underlying principle of the technique involves the allocation of weightings for each thematic map according to its corresponding contribution towards groundwater recharge and storage, a process that is strongly founded on conventional hydrogeological principles (Todd & Mays, 2005; **Adelana et al. 2008**).

The application of GIS-based multi-criteria analysis is extremely valuable on Basement Complex terrains, which dominate vast swaths of Africa, as well as Nigeria. Groundwater availability in the region is strongly influenced by basement complex geology and localized aquifer systems (Adelana et al., 2008). These Precambrian rocks have naturally weak primary porosity, and groundwater occurrence is almost entirely reliant on secondary porosity features that manifest due to fracturing and weathering activity. MacDonald et al. (2012) carried out a continent-scale examination of African groundwater stores, making reference to the normally weak-to-moderate yields that dominate these aquifers and once again making reference to the requirement for borehole site selection with careful consideration. Some studies carried out in Nigeria have utilized GIS and remote sensing approaches for groundwater mapping in similar environments.

For example, studies that were conducted in the Sokoto Basin and the crystalline basement terrains have reported a significant linkage between lineament density, soil permittivity, and borehole yield (Offodile, 2002). While there are global-scale hydrogeological assessments for Nigeria, spatially confined high-resolution appraisals are scarce, especially for the Federal Capital Territory (FCT) of Abuja. Earlier studies have mostly covered larger regional settings or other Nigerian states. Thus, there is a critical demand for a precise, site-oriented evaluation for the purposes of Abuja's urban water resource planning. In response, this study designs an exhaustive groundwater potential map specific to the city's specific geological and climatic features.

1.2. Novelty and Objectives

This research addresses an important knowledge gap by conducting a detailed Geospatial-based groundwater potential assessment for Abuja, Nigeria, through the application of GIS and Remote sensing technology. This research is new because it combines detailed satellite images, especially from Sentinel-2, to classify land use and cover. It also uses a structured method to analyze these images, tailored specifically for the geology of the Basement Complex area in Abuja.

The specific objectives of the study are to:

- Develop a groundwater potential map of Abuja by integrating thematic layers including geology, slope, drainage density, land use/land cover, soil type, and rainfall.
- Delineate the study area into zones of low, moderate, and high groundwater potential.
- Quantify the spatial extent of each potential zone and provide evidence-based recommendations for sustainable groundwater management and urban planning.

Through these objectives, the study provides a valuable decision-support tool for urban planners, hydrogeologists, and water resource managers, contributing to the scientific foundation for the sustainable development and management of groundwater resources in Abuja’s rapidly urbanizing environment.

2. MATERIALS AND METHODS

2.1. Study Area Description

Abuja, the Federal Capital Territory (FCT), Nigeria, is situated in the central part of Nigeria with coordinates 6°45'E to 7°45'E and 8°25'N to 9°25'N, The study area falls within the Guinea Savanna zone, while most of its subsoil formations are underlain by Precambrian Basement Complex rocks, which are characterized by having limited primary porosit. Aquifer systems are therefore mainly secondary, occurring within weathered regolith and fractured bedrock. Identification of groundwater potential in this geological context is relevant due to the fast-paced urbanization and increasing need for water in the region. Figure 1provides a detailed study area map (SAM) of Abuja, Nigeria.

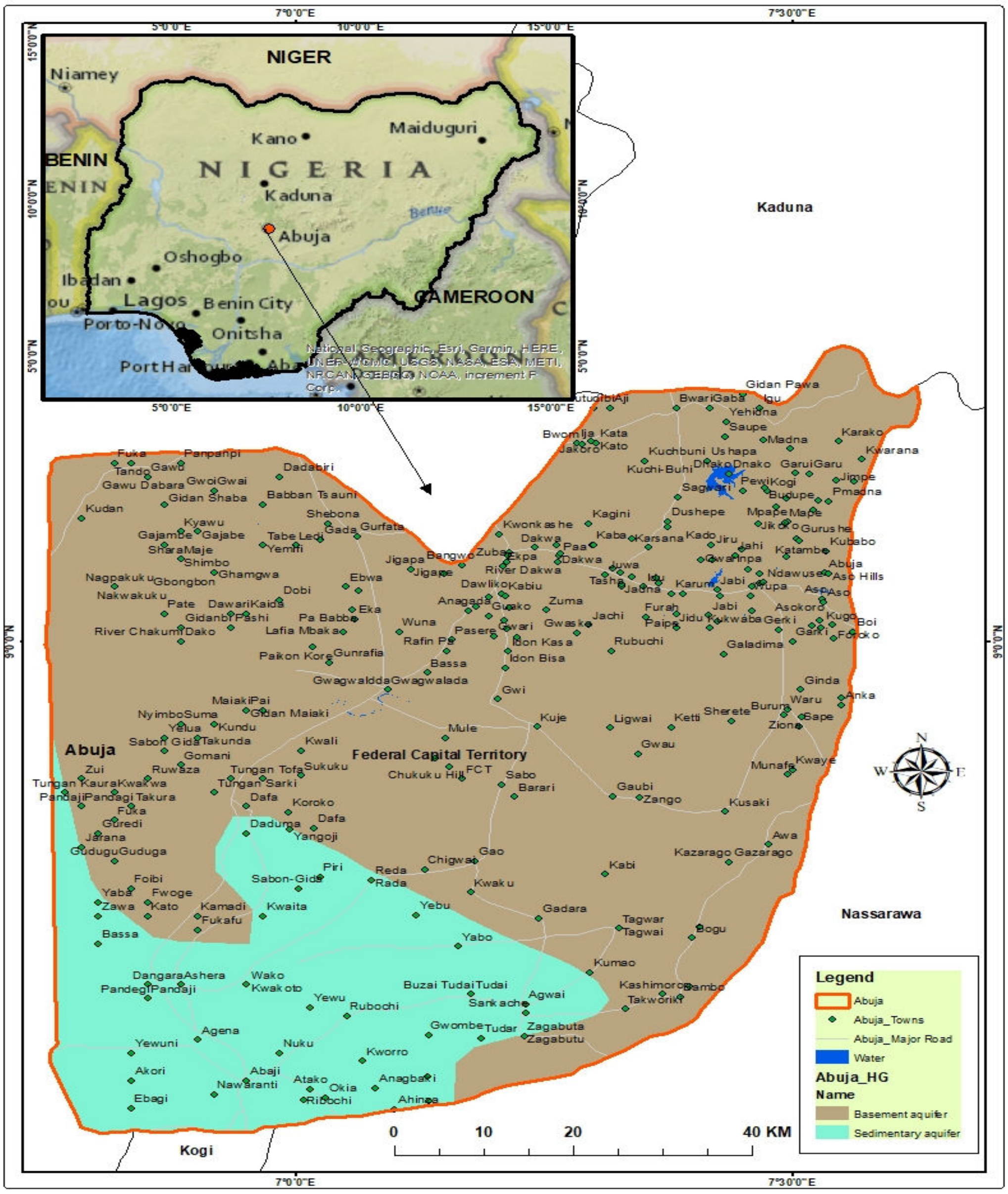

Figure 1. Detailed Study Area Map (SAM) of Abuja, Nigeria, showing major settlements and drainage networks.

2.2. Data Sources and Preparation

The study employed a **multi-thematic layer approach**, integrating spatial datasets obtained from publicly available global sources. All datasets were standardized to the **World Geodetic System 1984 (WGS 84), UTM Zone 32N,** ensuring consistent spatial reference and compatibility during analysis. The six key thematic layers utilized are presented schematically in Figure 2.

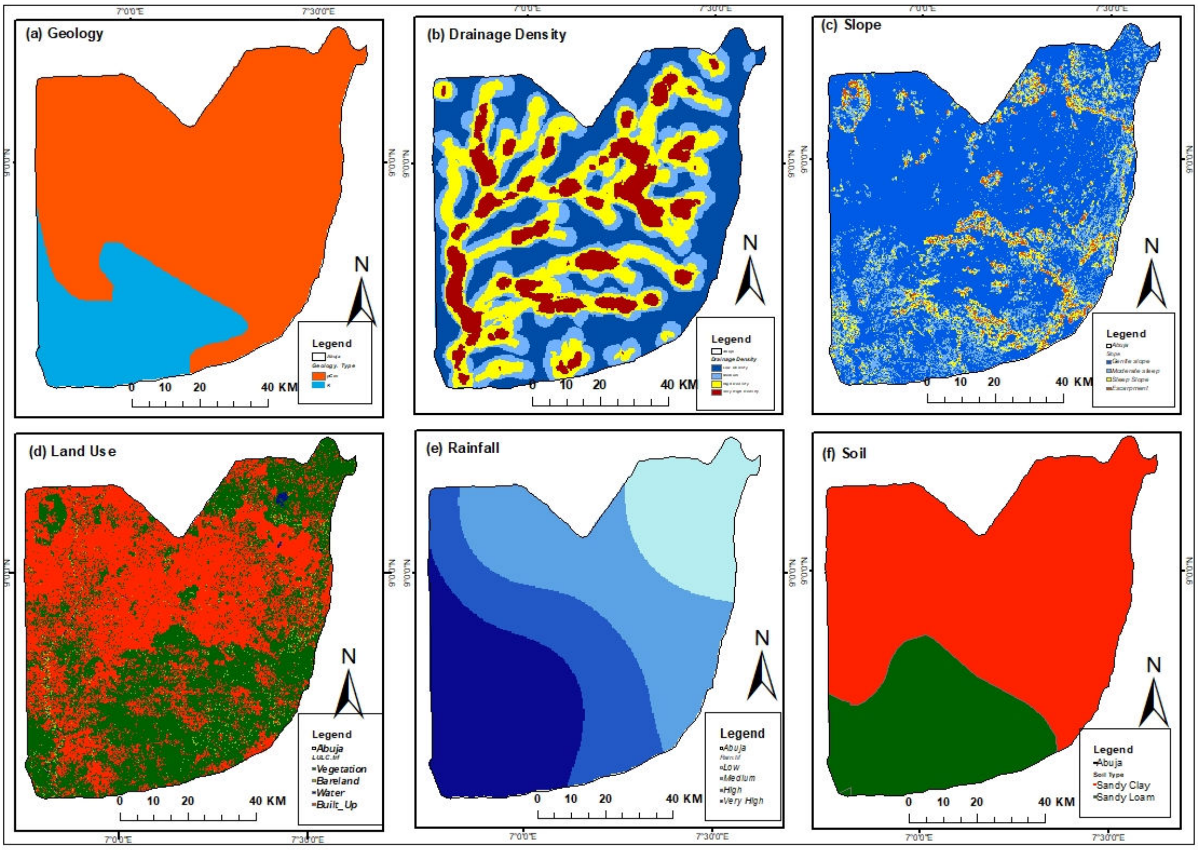

Figure 2. Thematic maps of the input parameters: (a) Geology, (b) Drainage Density, (c) Slope, (d) Land Use/Land Cover, (e) Rainfall, and (f), Soil.

2.2.1. Digital Elevation Model (DEM) and Derived Layers

A 30-meter resolution Digital Elevation Model (DEM) was obtained from the United States Geological Survey (USGS) EarthExplorer platform. Two critical hydrological parameters were derived using ArcGIS

Spatial Analyst tools:

- Slope: Generated from the DEM to quantify the gradient of the terrain, which influences surface runoff and groundwater infiltration.
- Drainage Density: Computed using the *Line Density* tool applied to a rasterized stream network extracted from the DEM. Drainage density reflects the degree of surface drainage dissection and inversely relates to infiltration potential.

2.2.2. Thematic Data Layers

The additional thematic datasets employed in this study include:

- Geology: Sourced from the USGS World Geology Database, providing information on lithological formations and their associated hydrogeological properties.
- Land Use/Land Cover (LULC): Derived from Sentinel-2 imagery available through the Esri online platform. The LULC was classified into four categories: *Built-up*, *Vegetation*, *Water bodies*, and *Barren land*.
- Soil Type: Land-use and soil characteristics play an important role in determining groundwater potential zones (FAO, 2015). Soil data was obtained from the Food and Agriculture Organization (FAO) global soil database, which includes data on soil texture, permeability, and infiltration capacity.
- Rainfall: Long-term mean annual precipitation data were extracted from the Climate Research Unit (CRU) database in point vector format, representing spatial rainfall variability across the FCT.

2.3. Methodology: GIS-Based Weighted Overlay Analysis

The main analytical technique applied in the study was the **Weighted Overlay Analysis**, which integrates multiple environmental and geological factors to delineate groundwater potential zones.

2.3.1. Data Reclassification

The entire thematic layers were reclassified to a unified scale of 1 to 4, in which 1 stands for least and 4 for the most suitable conditions for groundwater occurrence. Permeability potential was used for reclassification of the LULC map, assigning higher ratings to Water bodies and Vegetation owing to their infiltration nature. The IDW method was also used to interpolate the point rainfall data in preparation for the creation of a continuous raster surface, which was classified in terms of Low, Medium, High, and Very High rainfall regions. Similarly, slope, drainage density, soil, and geology layers have been reclassified in terms of their corresponding hydrogeologic significance.

2.3.2. Assigned weights for groundwater potential factors

The relative importance of the contribution of each factor in controlling groundwater occurrence was determined from established hydrogeological principles. The weights assigned, which add up to 100%, are listed in Table 1.

Table 1. Assigned weights for groundwater potential factors.

No.	Thematic Layer	Rationale	Assigned Weight (%)
1	Geology	Determines subsurface storage and flow characteristics.	25%
2	Drainage Density	High density reduces infiltration; low density promotes it.	20%
3	Slope	Steeper slopes increase runoff, reducing infiltration.	15%
4	Land Use/Land Cover	Impacts surface sealing and natural recharge.	15%
5	Soil Type	Controls infiltration rate into the subsurface.	10%
6	Rainfall	The primary source of groundwater recharge.	10%
7	Digital Elevation Model (DEM)	Base for deriving slope and drainage.	5%
Total	-	-	100%

2.3.3. Overlay Analysis and Zoning

The reclassified raster layers were all merged using the Weighted Sum Tool in ArcGIS 10.8. Each of the thematic layers was initially multiplied by its own weight, which is an expression of its relative significance, prior to summation; therefore, yielding a continuous Groundwater Potential Index (GPI). Thereafter, the resulting raster was grouped into three groundwater potential zones, that is, Low, Medium, and High, utilizing the Natural Breaks (Jenks) classification scheme. Area of each class was calculated in its entirety for the examination of its distribution within the study FCT. The final groundwater potential map is depicted in Figure 3 (Results section).

3. RESULTS

The weighted overlay analysis produced a detailed groundwater potential map for the Federal Capital Territory of Abuja (Figure 3). The delineated study area was clearly segmented into Low, Medium, and High groundwater potential zones. The quantitative assessment indicated that medium potential zones prevail, encompassing roughly 79% (5,736.2 km^2) of the entire region. High potential zones comprise approximately 7% (518.41 km^2), mainly situated in areas characterized by gentle slope gradients and diminished drainage density, whereas low potential zones represent the remaining 14% (1,024.61 km^2).

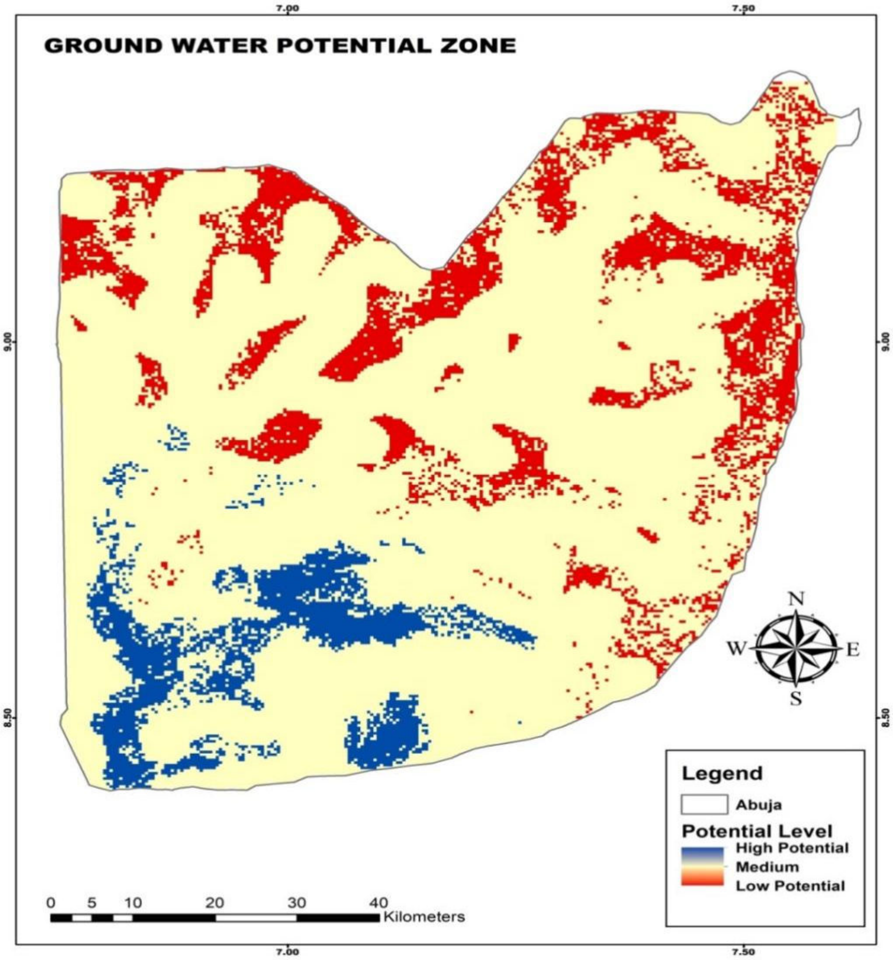

Figure 3. Groundwater Potential Map of Abuja showing the spatial distribution of Low, Medium, and High potential zones.

The quantitative analysis of the zonal areas is summarized in Table 2. The results indicate that most of Abuja land surface, amounting to approximately 5,736.20 km² (79%), falls under medium groundwater potential. High potential areas are predominantly limited, occupying 518.41 km² (7%) of the total area. Low potential areas occupy 1,024.61 km² (14%).

The spatial analysis revealed that the high potential zones were primarily linked to regions with mild slopes, reduced drainage densities, and particular geological formations that support groundwater storage. The majority class, represented by the medium potential zone, suggests that groundwater development is generally somewhat feasible throughout the region.

Table 2. Areal extent and percentage of groundwater potential zones in Abuja.

No.	Groundwater Potential Zone	Area (km²)	Area (%)
1	Low	1,024.61	14%
2	Medium	5,736.20	79%
3	High	518.41	7%
Total	-	7,279.22	100%

4. DISCUSSION

High groundwater potential (79%) in Abuja is typical for the hydrogeological conditions of Basement Complex terrains, wherein aquifer productivity is largely dictated by secondary porosity from fractures and weathering (MacDonald et al., 2012). Relatively small areas of high productivity (7%) indicate the spatial resolution typical for these second-order features. Lastly, high groundwater potential areas have close agreement with low relief and low drainage density areas, thus supporting the beneficial role of subdued slopes and low runoff in groundwater recharge (Jha et al., 2010).

However, the approach maintains certain deficiencies in its methodology. Trivariate weighted overlay method concludes subsurface conditions primarily from surface proxies, thus never experiencing direct verification of aquifer depth and continuity, for example. While geometric and slope serve as reliable proxy variables, verification in the field using borehole information or geophysical traverses is essential for more accurate characterization of subsurface components. Lastly, the process of assigning weights involves an element of expert subjectivity, which may in the future be minimized in subsequent studies using methods like the Analytic Hierarchy Process (AHP) in favor of more objectivity.

In spite of these liabilities, the analysis provides a low-cost, spatially bounded first-level groundwater potential evaluation, valuable in data-scarce environments. Synthesis of remote sensing and the GIS allows for a replicable model for groundwater regional analysis in other parts of West Africa, where similar hydrogeologic and data deficiencies predominate.

5. CONCLUSION

The research utilized a GIS-assisted weighted overlay method in the mapping of suitable groundwater locations in Abuja, Nigeria. By integrating seven key thematic layers, namely drainage density, geology, slope, land use/land cover, soil, rainfall, and elevation, an efficient, spatially inclusive groundwater zonation map was produced.

The result showed that roughly 79% of the study area is characterized by medium groundwater potential, 7% is of high potential, and 14% is low potential regions. From these findings, it is evident that, despite the fact that groundwater is developable in the bulk of Abuja, locations of high potential should be satisfactorily targeted for efficient resource exploitation.

Generally, the paper gives scientific justification for sustainable water management and urban water planning in the Federal Capital Territory. The groundwater potential map thus produced is used as decision support for water resource managers, policymakers, and planners who deal with the issues of fast urbanization and rising water demand. Ground-truth validation should be the focus in future studies using borehole logs, time-series monitoring, and the results of pumping test in order to characterize groundwater dynamics in response to changing climatic and land use conditions.

Statements and Declarations

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Competing Interests

"The authors have no relevant financial or non-financial interests to disclose."

Author Contributions

*"All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by **David Mkpanam Nyong,** Haulah Habeeb Muhammad, and Adaobi Thelma Onyemaobi. The first draft of the manuscript was written by **David Mkpanam Nyong,** and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript."*

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Declarations

Ethics approval**:** ***"****Not applicable."*

Consent to participate**:** ***"****Not applicable."*

Consent for publication**:** ***"****Not applicable."*

"Clinical trial number*: not applicable*."

Availability of data and materials

The datasets used in this study are publicly available from the United States Geological Survey (USGS), the Food and Agriculture Organization (FAO), and the Climate Research Unit (CRU). Processed data supporting the findings of this study are available from the corresponding author on reasonable request.

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