Groundwater Water Potential Mapping in Calabar, Cross River State Nigeria Using Remote Sensing and Geospatial Technique

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Abstract

Nearly two-thirds of people on Earth suffer from water scarcity, with 55.6% of those without access to sanitary facilities also lacking clean water. 60 million Nigerians do not have access to safe water, despite multiple government initiatives. Due to increasing population density, industrialization, and forest loss, groundwater—a vital resource for residential, agricultural, and industrial uses—is becoming more and more scarce. Using weighted overlay analysis and GIS technology, this study attempts to map groundwater potential zones (GWPZs) in Calabar Municipality, Cross River State, Nigeria. Data were gathered from NASA, USGS, and FAO sources on rainfall (2012–2022), digital elevation models (DEMs), Landsat imagery, and soil vector data. Layers were normalized and weighted according to effect levels: slope (20%), rainfall (15%), soil (15%), stream density (15%), NDWI (15%), NDVI (15%), and NDBI (5%). Important indices, such as NDWI, NDVI, and NDBI, were obtained using ArcGIS 10.8. The study area was divided into low and high GWPZs using a weighted overlay technique. The findings showed that there was a considerable potential for groundwater in flat areas with sandy soils, moderate vegetation, and substantial rainfall. Because of their impervious surfaces, urbanized areas demonstrated poor potential. The effectiveness of GIS and remote sensing in defining GWPZs is demonstrated by this work, which provides an affordable substitute for conventional techniques. In order to improve groundwater recharge and lessen scarcity, policymakers should concentrate on sustainable water management techniques, such as urban design and soil conservation.

Keywords: Foreign Direct Investment, Economic Growth, Cameroon

1. Introduction

Water scarcity affects almost two-thirds of the world's population for at least some part of the year (Mekonnen and Hoekstra, 2016) [20]. Statistics show that approximately 55.6% of the 3.6 billion people who lack access to sufficient sanitation facilities do not have access to clean and wholesome water to drink (United Nations World Water Development Report (UNWWDR), 2023) [42]. For example, despite numerous government and River Basin Authority efforts, 60 million people in Nigeria do not have access to safe water at home (The World Bank, 2021) [40].

In heavily populated and developed nations like China, India, and several African countries, the increasing demand for water for home, agricultural, and industrial uses has become a critical concern (Ojo *et al*., 2024) [32]. The amount and quality of groundwater are greatly impacted by factors such as urbanization, industrialization, and deforestation (Olusola *et al*. 2017; Ijioma 2021) [34, 17]. Groundwater is widely used worldwide; 36, 42, and 27% of groundwater resources are used by the residential, agricultural, and industrial sectors, respectively (Ojo *et al*., 2024) [32]. More than half of the agricultural fields in densely populated nations including the US, China, and India are irrigated by groundwater (Sharma *et al*. 2021) [39]. Finding groundwater potential zones (GWPZs) is crucial since groundwater resources are being used more and more to supply the growing water demands of the population. Delineating GWPZs has historically relied heavily on fields like geology, hydrogeology, and geophysics (Nair *et al*. 2017) [27].

Since the beginning of time, humans have managed and used water, a crucial natural resource, to sustain life. Only a small portion of the world's water supply, nevertheless, is fit for human use as fresh water. More than half of the fresh water needed for daily activities including drinking, cooking, and personal hygiene comes from groundwater (Sikakwe, 2019) [15]. According to Lerner (2002), groundwater in urban settings displays unusual characteristics that are somewhat unrelated to the natural water cycle. Cities' impermeable surfaces, like parking lots, paved roads, buildings, and other infrastructure, increase runoff while obstructing aquifer recharge (Uchenna *et al*., 2023) [41]. Rainfall causes urban rivers and streams to collect more water, which frequently finds its way into sewers. When urban streams merge into sewers, wastewater treatment plants must treat a larger amount of water, which raises expenses (Broadhead *et al*., 2013) [7]. Concurrently, aquifer recharge takes place beneath permeable surfaces like parks, golf courses, and lawns; excessive irrigation and water pipe leaks also contribute to a constant recharge, particularly during the dry season (Nguyen *et al*., 2021) [28]. Depending on how water infrastructure and water levels are spatially related, exfiltration from pipelines and tanks to aquifers may happen seasonally (Lancia *et al*., 2020) [19].

Traditional techniques for identifying, defining, and mapping the groundwater potential zones rely heavily on ground surveys using geophysical, geological, and hydrogeological tools, which are usually expensive and time-consuming (Echogdali *et al*., 2022a; Mondal *et al*., 2022a; Echogdali *et al*., 2022b; Mondal *et al*., 2022b) [10, 24, 25]. According to Moghaddam *et al*. (2015) [21] and Russo *et al*. (2015) [38], geospatial technologies, on the other hand, may swiftly and economically collect and model meaningful data in a range of geoscience domains. The groundwater potential zones have been identified and mapped using a variety of methods based on published research. For example, probability models such as Shannon's entropy, logistic regression, weights of evidence, and the frequency ratio have been employed by several researchers (Razandi *et al*., 2015; Pourghasemi & Beheshtirad, 2015; Echogdali *et al*., 2023; Naghibi *et al*., 2015) [37, 21, 8, 26]. All things considered, GIS and remote sensing are effective instruments for rapidly estimating natural resources. Before employing more complex and costly surveying techniques, the methods are practical and can be used to effectively investigate groundwater (Benjmel *et al*., 2022) [5]. The current study is aimed to map out the groundwater potential zones in Calabar Municipal, Cross River State Nigeria.

2.0 Literature Review

2.0.1 Advantage of Groundwater and Methods of Measuring Groundwater

A vital buffer against the unpredictability of surface water sources is groundwater. It promotes farming, which is especially important in areas that endure protracted droughts or dry seasons (Ogungbade *et al*., 2022) [31]. Groundwater is a vital supply of drinking water in many developing nations, and it is frequently cleaner and more dependable than surface water. Groundwater resources are under more stress due to the expanding world population and rising agricultural needs, thus appropriate management techniques are required to guarantee their sustainability (Ewuzie *et al*., 2021) [12].

2.0.1.1 Geophysical Methods

Because geophysical techniques are non-invasive and can yield useful subsurface data, they have been widely employed in groundwater exploration. The Vertical Electrical Sounding (VES) methodology has shown itself to be the most successful of these approaches. By measuring the earth's resistivity at different depths, VES makes it possible to identify distinct geological layers and their water-bearing characteristics (Odoh *et al*., 2024) [29]. This method offers a cost-effective way to gather vital hydrogeological information and is especially useful in areas with little to no drilling data (Mohammed & Taofiq, 2021) [22]. The foundation of the VES approach is the idea that the electrical resistivity of various subsurface materials varies (Okoli *et al*., 2024) [33]. The resistivity of the underlying layers can be deduced by running an electrical current through the ground and measuring the potential variations that result. The existence of aquifers, impermeable layers, and other geological features is subsequently determined by interpreting these resistivity results. A detailed vertical profile of the subsurface can be obtained by adjusting the distance between the current electrodes, which controls the depth of study (Ezema *et al*., 2020) [13].

2.0.1.2 Remote Sensing Techniques

Geographic Information Systems (GIS) and remote sensing are effective methods for examining changes in land use and how they affect groundwater supplies. To track changes across time, remote sensing offers historical and current information on land use and cover (Adewumi *et al*., 2023) [2]. VES data, land use maps, and hydrological information are only a few of the datasets that may be integrated and spatially analyzed using GIS (Odoh *et al*., 2024) [29]. This combination makes it easier to comprehend how groundwater and land use interact thoroughly, which helps with the creation of efficient management plans (Falebita *et al*., 2020) [14]. Notwithstanding the benefits, there are certain difficulties in integrating VES data with land use dynamics.

Several factors, such as the existence of resistive or conductive surface materials, cultural noise, and the constraints of the interpretation models, can affect the accuracy of VES data (Odoh *et al*., 2024) [29]. In groundwater exploration, researchers are increasingly using Geographic Information Systems (GIS) to improve geological interpretations (Mensah *et al*., 2024) [43]. GIS methods facilitate the creation of models for forecasting groundwater potential by revealing geographical distribution and provide a platform for the integration of geophysical and other hydrogeological elements (Mensah *et al*., 2024) [43]. In estimating groundwater potential locations, GIS and remote sensing approaches have shown themselves to be both efficient and economical (Al-Bahrani *et al*., 2022; Epuh *et al*., 2022; Yusuf *et al*., 2022) [3, 11, 44]. Additionally, GIS provides a basis for incorporating machine learning techniques into groundwater forecasting (Mensah *et al*., 2024) [43].

2.0.1.3 Parameters of influence for the Evaluation of Groundwater Potential Zones

Choosing appropriate parameters that significantly impact groundwater occurrence, flow, storage, and any other adequate indication of groundwater availability is usually the first step in evaluating an area's subsurface potential. While precipitation, land use, land cover type, and rate of infiltration/percolation generally control groundwater recharge, the underlying lithology, soil properties, landforms, lineament, and drainage/spring densities primarily control groundwater storage and movement (Shao *et al*., 2020, Ifediegwu, 2021, Amos-Uhegbu *et al*., 2023) [16]. Other crucial elements in groundwater replenishment are the amount and intensity of rainfall. According to Nasir *et al*. (2018), modest amounts of low-intensity rainfall will have a long-term positive impact on groundwater. Additionally, slope directly affects the surface runoff mechanism in a region, which in turn affects the recharge of groundwater (Zghibi *et al*., 2020). Because precipitation has an extended period of time before it penetrates the subsurface, initial investigations have found that low-slope areas have a good potential for groundwater storage. High steepness terrains have limited groundwater potential due to their reduced recharge capacity, increased erosion, and faster water flow (Nistor 2019; Igwe *et al*., 2020) [16]. Furthermore, according to Magesh *et al*. (2012), drainage density is the length of the stream channel per drainage watershed area. The density of drainage systems can also affect how quickly water percolates into the ground, especially after precipitation when a dense network of drainage allows water molecules to exit the system more quickly. According to Ghosh *et al*. (2020) [24], the processes of pore saturation and desaturation determine the type of soil, which in turn affects the rise in water entry into the soil. The amount of water that circulates into the subsurface is influenced by the porosity of the different types of soil because coarse-grained matrices have a higher groundwater potential than fine-grained matrices (Amos-Uhegbu *et al*., 2024).

2.1 Empirical Review

The use of GIS and remote sensing to locate groundwater potential zones was illustrated by Kumar *et al*. (2017) [18]. The study included thematic maps of slope, soil, lineaments, drainage, boundary, drainage density, DEM, rainfall, and land use and land cover. The maps were superimposed using ArcGIS 9.3's spatial analyst tool and the weighted overlay technique. With weights assigned according to their influence, the weighted overlays provided a ranking for every parameter. The generated map displays the groundwater potential zones, which include very good, good, fair, moderate, and fair.

A comparable study of groundwater potential assessment in Iran was conducted by Zeinolabedini and Esmaeily (2015) [45] utilizing the Analytical Hierarchical Process approach and GIS. Four zones were identified by the created model: high, average, low, and no groundwater potential. In the Rift Valley Lake Basins Weito Sub Basin, Ethiopia, Bashe (2017) [4] tried mapping groundwater potential using remote sensing and GIS. In order to analyze the data, the researcher employed theme layers of rainfall, land use, slope, soil, lithology, drainage, lineaments, and geomorphology. The groundwater potential map was created using ArcGIS overlay analysis and weights provided to the layers using AHP. 1.15 and 23% of the watershed, respectively, are classified as excellent, very good, or good, according to the results. The groundwater potential of the remaining 60% of the land area was either low or extremely poor.

Danso & Ma (2023) mapped groundwater potential zones (GWPZ) in Ghana's Komenda-Edina-Eguafo-Abrem (KEEA) Municipality using geospatial approaches. Lineament density, slope, drainage density, topographic wetness index (TWI), land use/land cover (LULC), normalized difference vegetation index (NDVI), geology, and soil type were the eight predictors taken into account. ASTER GDEM and Landsat 8 imagery were among the sources from which raster and vector data were gathered. GIS was used to process and standardize the data. The groundwater potential zones were divided into five groups by the study: extremely poor, poor, good, very good, and excellent. While 27% of the research area was found to be very favorable for groundwater prospecting, the majority (36%) was found to be in poor groundwater zones. The majority of coastal areas were located in impoverished areas.

Odoh *et al*. (2024) [29] assessed the groundwater potential and offered guidance for sustainable groundwater management by analyzing the apparent resistivity, depth, and thickness of aquifers in Arochukwu. In order to capture the regional heterogeneity of aquifer features, eight VES locations were carefully chosen throughout Arochukwu. A Schlumberger setup was used to acquire apparent resistivity measurements, which were then evaluated using computer-aided tools to ascertain the aquifers' depth and thickness. Following that, the geoelectric characteristics were compared to established land use patterns and geological formations. Significant differences in apparent resistivity, depth, and thickness were found throughout the study area using the VES data. In the northern and central regions, such as Amokwu, Etiti-Ulo, Ndinya, Idima, and Ndi-Ebe, low apparent resistivity values (0.20 to 3.63 Ωm) suggested highly conductive, water-saturated aquifers. The southern areas around VES 7 and VES 8, on the other hand, showed higher resistivity values (7.07 to 17.39 Ωm), indicating less conductive materials, most likely as a result of lower water saturation or a higher clay content. The aquifer's thickness varied from 14.20 meters to 59.30 meters, while its depths ranged from 15.70 meters in the south to 80.90 meters in the north. Aquifer characteristics' spatial distribution identifies regions with ideal groundwater extraction conditions. Because of their thicker aquifers and lower resistivity, the northern and central regions are more suited for sustainable groundwater development. On the other hand, because of their thinner aquifers and higher resistivity, the southern regions could need more thorough research to guarantee feasible groundwater extraction. There was a clear correlation between land use and aquifer features; areas covered by trees had deeper aquifers and lower resistivity, whereas areas that were built up had shallower aquifers and higher resistivity.

In a study carried out in Nigeria by Amos-Uhegbu *et al*. (2024), a multi-criteria decision-making tool known as the analytical hierarchical process was used to rank various characteristics, including geology, rainfall, slope, drainage density, lineament density, soil type, and land use and land cover. After integrating the elements into a geographic information system (GIS), ArcGIS software was used to perform weighted overlay analysis. According to the findings, there were 31.5% of high to very high groundwater occurrence zones in the southern region and 41.6% of poor to very poor zones in the northern region. 26.8% of the research region was made up of the moderate zones. The study revealed the reasons for the frequent random borehole failures in the moderate zones by demonstrating that the groundwater occurrence in the study area is principally governed by the interactive impact of geology, rainfall, and slope factors.

3.0 Methods

3.0.1 Study Area

In Calabar Municipality, the study was carried out (Fig. 1). Situated at an elevation of 27 to 36 meters above sea level, the region lies between Latitudes 04^0 50´ and 50^0 10´ North of the Equator and Longitudes 08^0 18´ and 08^0 37´ East of the Greenwich Meridian. Two different tropical moist climates—the rainy and dry seasons—define the region. From November to February is the dry season, and from March to October is the wet season. The region has a typical humid tropical climate, with around eight months of the year having more rainfall than evapotranspiration. The region's parent material is made up of Coastal Plain Sands, according to geology (Bulk-trade, 1989). The region is gently sloping, highly porous, well-drained, and primarily eroded by sheets and rills. The soil depth can reach two meters. According to USDA soil taxonomy, the region's soils were categorized as Typic Paleudults in the Ultisols order (Esu, 2005). Evergreen trees, herbs, shrubs, and creepers make up the flora features. The region is mostly utilized for the production of arable and horticultural crops, including yam, cassava, watermelon, fluted pumpkin, and maize.

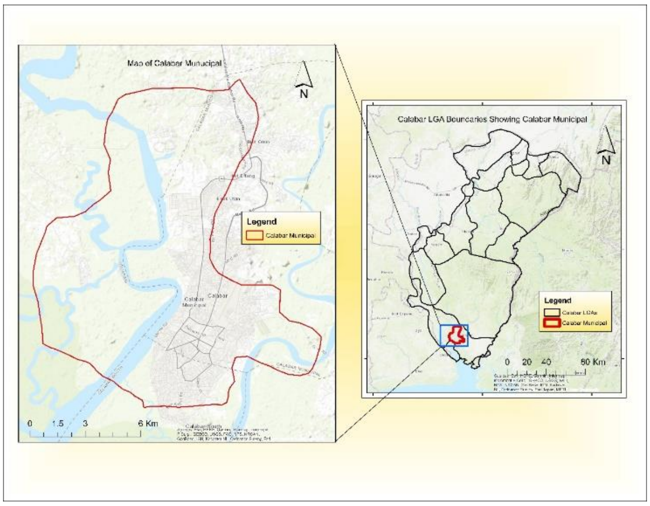

Fig 1: Showing map of the study area

3.0.2 Data Collection

3.0.2.1 Rainfall

Average rainfall data over the study area for a period of 10 years (2012 to 2022) were collected form NASA website.

3.0.2.2 Digital Elevation Model

SRTM DEM over the study area was downloaded from the USGS official website. DEMs provided elevation data crucial for calculating the slope and stream density, for the study. DEMs with high resolution from sources like USGS Earth Explorer were downloaded.

3.0.2.3 Landsat Imagery

Landsat 9 image (OLI) of the study area was downloaded from the USGS official website for the month of May 2024

3.0.2.4 Soil Data

Soil vector data was downloaded from the official website of FAO

3.0.3 Data Processing

Data processing was achieved using ArcGIS 10.8. The DEM was imported and clipped to match the study area. This ensures accurate elevation data by eliminating irrelevant areas. the Landsat images were also imported, radiometric corrections were performed to standardize reflectance values, and the images clipped to the study area to maintain spatial alignment. The Normalized Difference Water Index (NDWI) was carried out to allow for water identification. Band 5 (Green) and Band 6 (SWIR 1) were used with the formula:
NDWI = (Green Band (Band 5) - SWIR 1 Band (Band 6)) / (Green Band (Band 5) + SWIR 1 Band (Band 6)).
NDWI = ("Band6" - "Band5") / ("Band6" + "Band5")
NDVI = ("Band5" - "Band4") / ("Band5" + "Band4")
Band 4 (Red): 0.64–0.67 µm
Band 5 (NIR): 0.85–0.88 µm
Band 6 (SWIR1): 1.57–1.65 µm

This calculation was done in ArcGIS 10.8 using the Raster Calculator tool.

3.0.3.1 Reclassifying the Rasters

The raster values of each layer (NDVI, NDWI, NDBI, slope, DEM, stream density, LULC, soil) was normalized using the Reclassify tool in ArcGIS Spatial Analyst Tools. A consistent scale (1-3) to the values of each raster based on their suitability for groundwater recharge. All raster layers have the same spatial resolution and extent. The Clip tool was used to match the extent to the area of interest using Data Management Tools in ArcGIS 10.8. Weights were assigned to the factors based on their relative importance in groundwater recharge potential.

Table 1: Weighted Overlay Table created in ArcGIS 10.8

S/N	Parameters	Influence level	Scale
1	Rainfall	15	1-3
2	Slope	20	1-3
3	Soil	15	1-2
4	Stream Density	15	1-3
5	NDWI	15	1-3
6	NDVI	15	1-3
7	NDBI	5	1-3

The variables and their corresponding influence levels utilized in a weighted overlay analysis to identify groundwater potential zones in ArcGIS 10.8 are described in the table 1. On a scale of 1 to 3, each variable's relative significance in groundwater recharge was given a percentage influence to categorize its eligibility for recharging. With higher values signifying more favorable conditions for groundwater recharge, this classification guarantees a consistent comparison of the characteristics.
rainfall was assigned an influence level of 15%. locations with various rainfall intensities are represented on the suitability scale of 1 to 3, where locations with higher rainfall are more advantageous. With a 20% contribution to the study, slope is the most important element. Because gentle slopes allow water to seep into the ground instead of contributing to runoff, they are essential for groundwater recharge. Additionally, the slope appropriateness scale goes from 1 to 3, with flatter regions receiving higher scores. Because it

controls infiltration rates, soil texture—which has a 15% influence—is another crucial component of groundwater recharge. A suitability rating of 2 is given to sandy soils because they are more conducive to infiltration, whilst clay and other less permeable soils are given lower values. Additionally, stream density has a 15% effect level. Moderate stream density levels, which are ranked from 1 to 3 according to appropriateness, can suggest the possibility of localized recharge even while regions with high stream densities may sustain runoff.

Both the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) have a 15% impact on the analysis. While vegetation density can improve infiltration and decrease runoff, NDVI measures surface water availability, which promotes recharging in particular areas. Depending on how much they contribute to the possibility for recharging, both are ranked from 1 to 3. Lastly, the Normalized Difference Built-up Index (NDBI) had the least impact at 5% since impermeable surfaces in built-up areas usually prevent penetration. Variations in urban intensity were still taken into account, though, and permeability was used to award ratings ranging from 1 to 3.

3.0.4 Data Analysis

Using the Weighted Overlay Tool in ArcGIS 10.8, each raster layer was added and weights were assigned to each layer based on the determined table the scale of values for all layers was consistent. The output cell size and processing extent were defined while the Weighted Overlay analysis was executed to generate a composite raster that represents the potential groundwater zones. The raster map was classified into low and high groundwater potential zones. Layout view in ArcGIS was used to prepare a comprehensive map of groundwater zones in the study area.

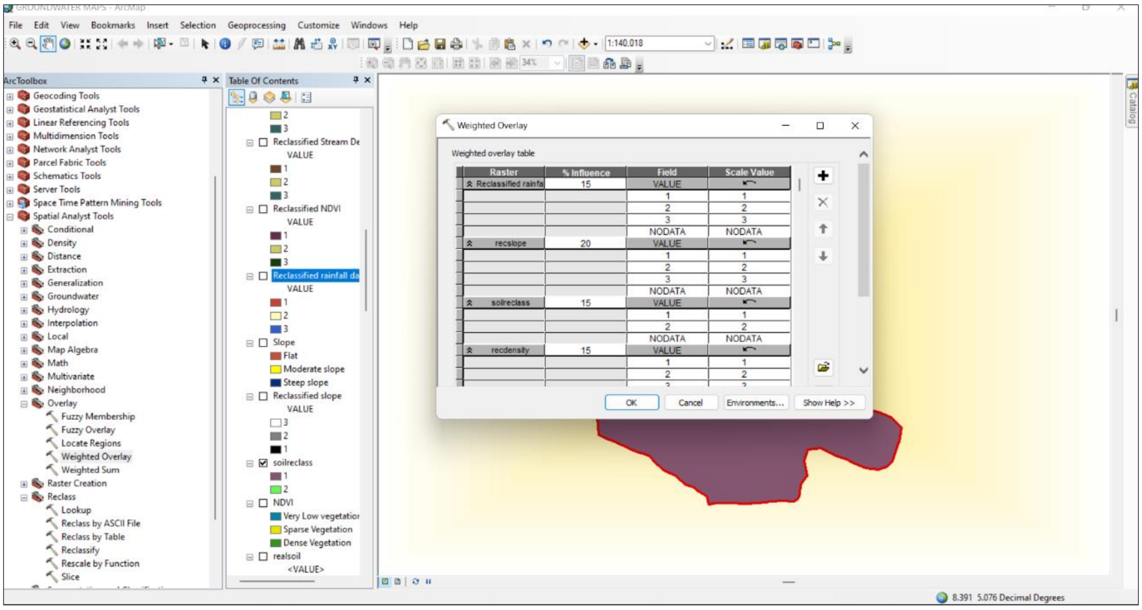

Fig 2: Showing the Data Analysis Process in ArcGIS 10.8 Environment

4.0 Results and Discussion

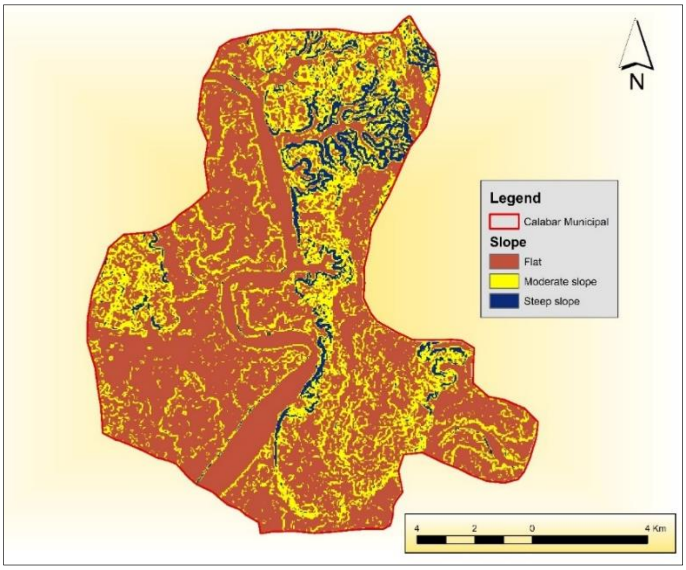

Fig 3: Showing slope map of the study area

The terrain of Calabar Municipal is divided into three classifications on the slope chart above: flat (brown), moderate slope (yellow), and steep slope (blue). Important information about the terrain and hydrological patterns of the research area is provided by this classification. Generally speaking, high stream density regions (brown/green areas on the stream density map) correlate with steep slope areas and high/very high stream density. Because of their steep gradients, these regions conduct significant runoff from the surface, which makes them crucial for hydrological and drains management. They are areas for erosion, nevertheless, particularly during times of heavy precipitation. In locations with few drainage channels, brown zones on the slope map correspond to grey areas on the stream density map. Flat surfaces frequently retain water, which could lead to flooding and waterlogging if drainage infrastructure is not in place. The slope map's yellow areas match the stream density map's yellow areas (Figure 3), indicating a balanced topography with modest runoff and a comparatively significant possibility for infiltration. Both surface water management and replenishment of groundwater may use these locations as transitory zones. The places with steep slopes (blue) are primarily found along ridges and natural drainage channels, which frequently coincide with regions with dense streams. The municipality's moderate (yellow) slopes provide a balanced terrain that accommodates a variety of land uses while lowering the risks related to steep slopes.

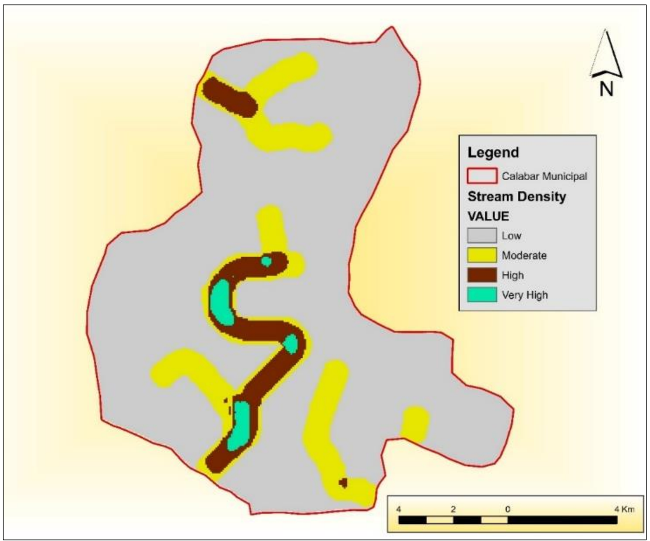

Fig 4: Showing the stream density map of the study area

Four categories—low (grey), moderate (yellow), high (brown), and very high (green) stream densities—were used to illustrate the geographical diversity of Calabar Municipal's stream networks in the stream density map above (figure 3). Important information about drainage features, surface water availability, and the hydrological dynamics of the region are found on this map. Stream networks in Low Stream Density Areas (Grey) are either very small or nonexistent. A low stream density indicates a higher chance of water penetration into the subsurface and less surface runoff. Although these regions are less likely to flood, there may not be as much surface water available for household and agricultural use. Areas of Modest Stream Density (Yellow) allow moderate surface runoff due to their well-balanced stream network. These places have sufficient drainage and the potential to recharge groundwater through infiltration. The municipality's center areas are dominated by high stream density zones (brown), which represent important drainage networks that help control surface runoff. Transitional areas are formed by moderate stream density zones (yellow), which balance surface and subterranean water flows. Potential regions for groundwater recharge are low stream density zones (grey), which are common in outlying areas and suggest scant surface drainage.

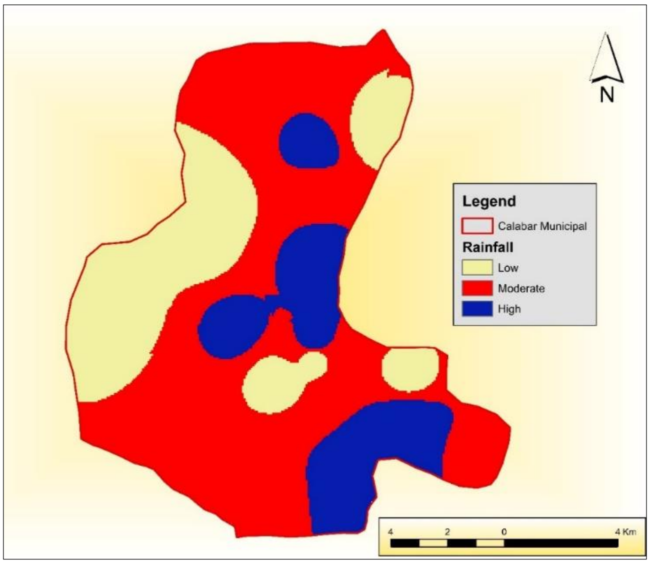

Fig 5: Showing rainfall map of the study area

Three classes—low rainfall (yellow), moderate rainfall (red), and high rainfall (blue)—are used to depict the pattern of the degree of rainfall throughout Calabar Municipality in the rainfall map above (Figure 4). This classification sheds light on the research area's geographic disparity in rainfall, which has a major impact on vegetative health, groundwater replenishment, and overall water resource management. Yellow zones, or low rainfall areas, are areas with little precipitation. Rainfall in most of Calabar Municipality is classified as moderate. Both moderate groundwater recharge and moderate vegetation cover are maintained in these locations. High Rainfall Areas (Blue) get a lot of precipitation, usually along rivers or in depressions. Zones of high groundwater potential (shown on the groundwater potential map). This is due to the fact that heavy rains encourage surface water infiltration and accumulation, which in turn encourages groundwater recharging. High rainfall regions (blue) are concentrated around bodies of water and correspond with areas of thick vegetation and substantial groundwater recharge. This emphasizes how important precipitation is to maintaining subsurface and surface water systems. The municipal territory is dominated by moderate rainfall zones (red), underscoring the necessity of effective water resource management to balance groundwater recharge and extraction. In conclusion, the rainfall map shows that one of the main factors influencing groundwater potential and vegetation health in Calabar Municipality is precipitation patterns. Planning for sustainable water resources is aided by the comprehensive understanding of the hydrological dynamics in the area provided by the combined use of the rainfall map with NDWI and NDVI maps.

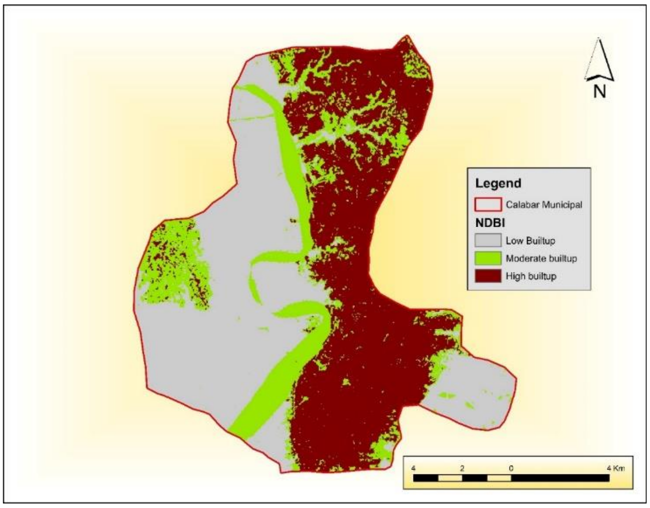

Fig 6: Showing NDBI map of the study area

Built-up regions are identified and mapped using the NDBI, a remote sensing index. It determines how much a satellite image's shortwave infrared (SWIR) and near-infrared (NIR) bands differ from one another. Areas having higher proportions of built-up surfaces, such as roads, buildings, and concrete, are generally indicated by higher NDBI values. High NDBI values are represented by the reddish area, which denotes densely populated or urban areas. Areas with intermediate NDBI values are indicated by orange, which may indicate peri-urban or suburban areas with a mix of natural and built-up surfaces. Green denotes regions with low NDBI values, which reflect landscapes that are primarily natural or agricultural.

The map shows that the region's middle and eastern regions include the majority of the built-up areas. As one moves toward the northern and western areas, the built-up concentration appears to be gradually decreasing. Orange and red areas indicate that the area is still experiencing urban growth and development. The green spaces suggest the existence of natural landscapes, which could include fields, meadows, or forests.

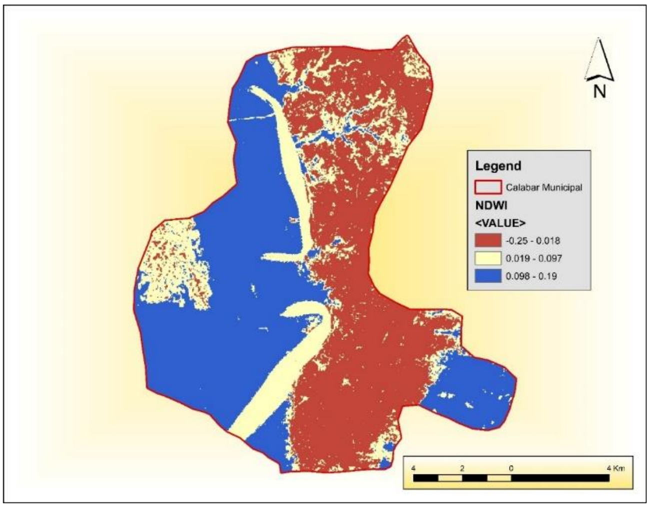

Fig 7: Showing NDWI of the study area

Water presence in Calabar Municipality is represented spatially by the NDWI (Normalized Difference Water Index) map, which is divided into three ranges: low (-0.25 to 0.018, red), moderate (0.019 to 0.097, yellow), and high (0.098 to 0.19, blue). For locating water bodies, evaluating water resources, and tracking surface moisture, this map is a vital resource. Areas with little to no water content are shown by the red zones, which usually denote arid surfaces, populated areas, or plants with little to no moisture. The municipality is dominated by these regions, which correspond to areas used for urbanization where water retention is lower. Wetlands, floodplains, and partially irrigated zones are examples of transitional habitats that are represented by the yellow zones, which have a moderate water content. These spots are suggestive of locations that may have tiny water channels or soil wetness, which could support natural vegetation or agriculture that needs moderate hydration.

Streams, rivers, ponds, and other bodies of water are represented by the blue zones, which indicate high water content. Situated along streams and river networks, these sites attest to the existence of surface water resources that are essential to the municipality's hydrological balance and ecosystem health. A distinct spatial relationship between the groundwater potential zones map and the NDWI map is evident. In Calabar Municipality, areas with high groundwater potential on the groundwater map typically correspond to blue zones on the NDWI map, indicating a close link between surface water characteristics and subsurface water availability. According to this correlation, areas with high levels of surface water are either suggestive of shallow groundwater tables or are likely to contribute to groundwater recharge.

On the other hand, areas designated as having low groundwater potential on the groundwater map correspond to the low NDWI areas (red zones). The results in Calabar Municipal show that areas of high groundwater potential overlap with locations along large rivers, wetlands, or other waterlogged areas (shown in blue on the NDWI map). These findings highlight how crucial water bodies and the surrounding vegetation are to the processes of groundwater recharge in this particular research area. A more thorough knowledge of the hydrological processes at work in Calabar Municipality is made possible by the combination of NDWI and groundwater mapping.

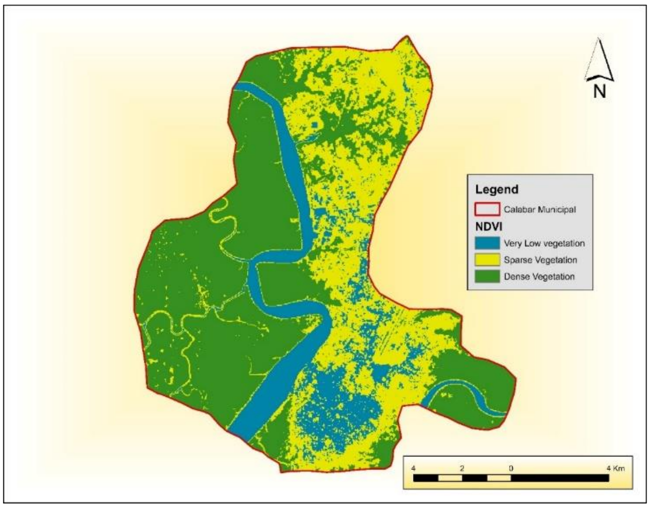

Fig 8: Showing NDWI map of the study area

The Calabar Municipal Normalized Difference Vegetation Index (NDVI), which shows the spatial variation in vegetation density throughout the research region, is displayed on the accompanying map (Figure 7). Three categories are used to classify NDVI values: "Very Low Vegetation," which is shown in blue, "Sparse Vegetation," which is shown in yellow, and "Dense Vegetation," which is shown in green. For geographical perspective, the Calabar Municipal boundary is indicated in red. Areas with dense vegetation, mostly found in green, correspond to areas of wetlands, natural forests, or areas with little human impact. Yellow-marked areas with sparse vegetation are grasslands, agricultural lands, and places where natural flora is giving way to more man-made landscapes. Urbanized regions, bodies of water, or bare fields with little vegetation cover are examples of very low vegetation zones, which are shown in blue.

There is an intriguing similarity between this map and the groundwater potential zones map. Dense vegetation areas and places with high groundwater potential frequently overlap, indicating that areas with more water availability promote the growth of denser and healthier vegetation. This is to be expected since plant grows best in places that receive enough moisture, which groundwater supplies may provide. On the other hand, locations with low groundwater potential are more strongly correlated with areas with sparse or extremely low vegetation, suggesting that there is less water available for plant growth.

The connection between groundwater availability and vegetation cover is highlighted by this relationship.

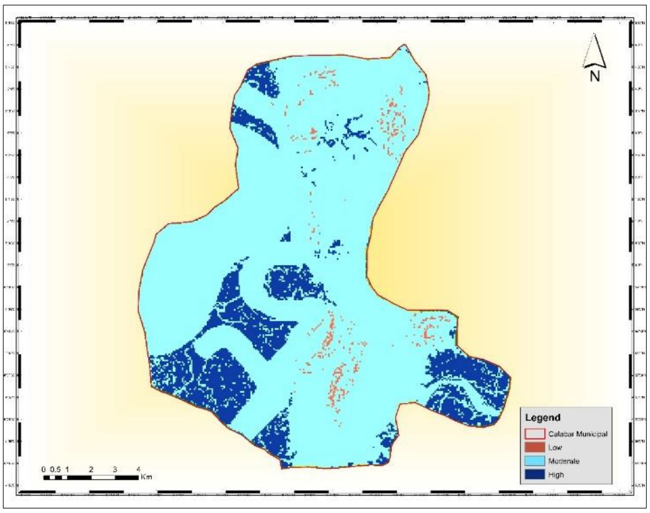

Fig 9: Showing groundwater potential zones

The groundwater potential zones in Calabar Municipality are depicted on the map. The associated legend designates the three categories into which the spatial distribution of groundwater potential is divided: low, moderate, and high. Different colors are used to indicate these zones: light blue for places with moderate potential, dark blue for areas with great potential, and red for areas with poor potential. The dark blue zones with high groundwater potential are concentrated in areas with favorable underlying geological and hydrological features, including aquifer permeability, water retention, and recharge potential. These regions are linked to elements that improve groundwater recharge and storage capacity, such as lower altitudes, porous soil types, concentrated vegetation, and closeness to surface water bodies. The majority of the mapped region is covered by the light blue zones of modest groundwater potential. These zones are areas where less obvious recharge conditions or moderate aquifer features affect groundwater supply.

The map's red-highlighted poor groundwater potential zones are sporadically spaced. Unfavorable hydrogeological features, such low porosity or permeability, steep slopes that prevent infiltration, or geological obstacles that restrict groundwater flow, are usually what define these areas. Without sophisticated methods or outside recharging systems, these regions might not be able to sustain substantial groundwater extraction.

4.0.1 Major Findings

The study found that rainfall, soil, slope, Vegetation index and water bodies are the main elements determining groundwater potentials in the studied area. The findings of this study are consistent with those of Opoku *et al*. (2024), who discovered that rainfall directly affects groundwater accumulation through percolation and infiltration of precipitation into the underground, with greater permeability occurring with longer duration and less intense rain. This is also consistent with studies conducted by Biswas *et al*. (2023). Furthermore, rainfall is an important source of groundwater recharge and has a considerable impact on groundwater potential (Abijith *et al*., 2020). Additionally, rainfall is the main source in the hydrological cycle and a significant determinant of a region's groundwater, claim Chauhan and Negi (2023). In this study, rainfall data from 2022 is used. Rainfall in their study ranged from 916 to 1190 millimeters annually. The amount of infiltration depends on the rainfall and when it occurs.

Furthermore, this study supports earlier research that found low slope areas had a good potential for groundwater storage because of the longer residence time for precipitation to seep into the subsurface. However, because of the quick water flow from the landscape, steep slope zones have weak groundwater potential (Igwe *et al*. 2020) [16]. Additionally, along with the assertion made by Ashaolu *et al*. (2019), vegetation and water bodies both contribute significantly to groundwater recharge. This is also in alignment with Mohan *et al* (2018) who found that meteorological factors (precipitation and potential evapotranspiration) and vegetation factors (land use and land cover) had the most predictive power for recharge.

5.0 Conclusion

This study used a geospatial technique that integrates rainfall, slope, soil type, stream density, NDWI, and NDBI data to successfully delineate the groundwater potential zones (GWPZs) in Calabar Municipality, Cross River State, Nigeria. The results showed that the best places for groundwater recharge are those with high vegetation density, moderate stream density, sandy soils, and gentle slopes. In order to effectively and economically identify GWPZs and meet the region's increasing water demands, this spatial mapping emphasizes the vital role that GIS and remote sensing play. In order to address the more general issues of water shortage and guarantee water security in urban and peri-urban regions, the findings offer a framework for sustainable groundwater management.

6.0 Recommendation

Based on findings from this study, the following recommendations were made:

1. To guarantee efficient planning and management of water resources, local and state governments should regularly map groundwater using geospatial technology.

2. In order to avoid contamination and overexploitation, locations with high groundwater potential should be safeguarded.
3. In regions with high groundwater potential, investments in artificial recharge facilities such recharge basins and infiltration wells should be given priority.
4. Residents should be taught the value of preserving groundwater recharge zones and sustainable water use practices through public awareness programs.
5. The effects of climate change on the potential for groundwater recharge as well as temporal fluctuations in groundwater levels should be included in future research.

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