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Integrated Analysis Of Satellite Gravity And Geospatial Techniques For The Evaluation Of Groundwater Potential Zones In Nasarawa State, Nigeria.

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ABSTRACT

The evaluation of groundwater potential zones in Nasarawa State was carried out using remote sensing, Geographic Information Systems (GIS) and satellite gravity techniques. Thirteen thematic maps obtained from remote sensing and satellite gravity data were used in this study. The Eight thematic maps from remote sensing include: Drainage density, Land use/ Land cover, lineament density, geological, rainfall, soil, elevation, slope maps derived from Landsat 8 and Shuttle Radar Topographic Mission (SRTM)/Digital Elevation Model (DEM). The five thematic maps from Satellite gravity include: Bouguer gravity anomaly, residual gravity anomaly, degree of regionality (mechanical stiffness), second horizontal derivative and basement depth maps obtained from satellite gravity derivative filters; were integrated to determine the structural morphometry and groundwater potential zones of the state. The remote sensing and gravity thematic maps were integrated using the GIS based multi-criteria analysis techniques; the Analytic Hierarchy Process (AHP) to produce the groundwater potential zone (GWPZ) maps. The research region was classified into five groundwater potential zones: very low, low, moderate, high, and very high, a classification was achieved by implementing the Analytical Hierarchical Process (AHP) approache, in conjunction with satellite gravity data. The findings indicated that the moderate potential zone encompasses the most extensive region, accounting for 75.3% (AHP) and 47.7% (AHP and Gravity) of the total land area respectively. This is followed by the high potential zone, which covers 16.6% (AHP) and 28.5% (AHP and Gravity) of the area, and the very high potential zone, which covers 0.003%, and 10.7% of the total land area. The area is comprised of 8.19%, and 12.81% low potential zones and 0.004% (AHP) and 0.3% (AHP and Gravity) very low potential zones respectively. The findings emphasize areas that have optimal characteristics for replenishing and storing groundwater, making them well-suited for digging new wells and constructing water infrastructure. By integrating geospatial and satellite gravity techniques, this study will improve the identification of the very-high and high-potential groundwater zones, thereby reducing the costs and risks associated with borehole drilling. This study will provide an accurate, scientific evaluation of groundwater potential zones in Nasarawa State; this will be of benefit to a wide range of stakeholders for sustainable water resource management.The study suggest that further studies such as the impact of climate change on groundwater distribution should be done to ascertain the effect of climate change on goundwater distribution in the study area.

Keywords: *Groundwater Potential, Remote sensing, GIS, and Gravity.*

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I. INTRODUCTION

Water, the elixir of life, stands as an indispensable component for the survival and prosperity of all known forms of life on Earth (Hayashi, 2006). Amongst the various sources of water, groundwater is the most appropriate because, it often meets the criteria of the quality of water required for human consumption. It is the most widely used source of water in Nigeria and most of the African countries (Fasunwon et al., 2010). Groundwater is defined as that water that lies under ground and the world depends on its freshwater availability as the best quality source of water. It is the water held in the sub-surface within the saturated zone under hydrostatic pressure below water table. Groundwater occurs in pockets restricted by fractures and weathered zones in Basement Complex rocks (Abdullahi et al., 2016; Oladunjoye and Jekanyinfa, 2016). Unlike surface water sources such as rivers and lakes, groundwater is concealed from view, making it challenging to quantify accurately (Epuh et al., 2020). It is accessed through wells, springs, and other boreholes, providing a reliable and often high-quality source of water for various purposes (Fenicia et al., 2006). Groundwater, as a crucial component of the hydrological cycle, plays a fundamental role in sustaining various ecosystems and meeting the water demands of human societies worldwide (Gleeson et al., 2012).

About half of the population of Nigeria, that is 70 Million, live in rural communities, half live in small communities of less than 1, 500 persons where hand pumps are likely to be the most suitable technology, making it possible for women and children to trek not more than 500m walking distance, to get potable water, while the other half live in larger communities between 1, 500 and 5000 persons where small pipes systems are Likely to be appropriate (RADWQ, 2005).Nigeria has adequate surface and groundwater resources to meet the current demands for potable water of its citizens. The pattern for water demand differs from time to time and from place to place. As the uneven distribution in space has turned areas of surplus into areas of scarcity, water shortages are experienced for various needs, particularly during the dry season when the biggest part of the year is spent without rain (Ifatimehin and Musa, 2008). Regardless of the abundant natural water resources, the proliferation of waterworks in the country coupled with a robust policy that spells out strategies and attainable targets mean that the water situation in Nigeria could best be described as precarious, and over the years, improvement in domestic water supply has not been impressive (Olajuyigbe, 2010). Water scarcity forces people to rely on unsafe sources of drinking water. It also means they cannot bathe or clean their clothes or homes properly (FAO, 2007). Residents of Nasarawa State have resorted to wells as alternative sources of water, following scarcity of water in the state in recent times. The situation has forced many into buying water from water vendors who walk long distances before getting the supply from the few wells in parts of the state. Places like Nasarawa Local Government Area, Keffi and Lafia now get water from the Water Board at three-day intervals, as opposed to one-day intervals before (Ahmed, 2010).

One of the main issues influencing the supply of water in Nassarawa State is the unending bore- hole that keeps drying up, especially during the dry season and the drilling of unproductive boreholes which has been a source of concern for people in most rural communities in Nassarawa State. This caused the majority of communities to revert to old methods of getting drinking water from water vendors, and domestic wells. Besides, the study area’s lack of water sources has made contemporary irrigation farming incredibly challenging.This is because there is no comprehensive and detailed Groundwater potential zone map of the state to guide people on where to site wells and boreholes to avoid unproductive drilling and wasting of resources that comes with such unproductive drilling.

Over the years, researchers have employed various methodologies to investigate groundwater resources in the region and similar geological settings (Abdulahi et al.,2019, Stanley Ikena I (2021). These methodologies encompass a wide range of techniques, including hydrogeological surveys, geophysical methods such as electrical resistivity imaging and seismic refraction, and the application of remote sensing and GIS techniques.

None of previous groundwater studies in Nassarawa state has incorporated the integration of geospatial based techniques (remote sensing and multi criteria decisions analysis) and Satellite gravity data methods for groundwater mapping in Nssarawa State. This integration is with the purpose of improving the accuracy and getting and optimum Ground water potential zones. Hence, an attempt has been made in this study to delineate groundwater potential zones in Nassarawa state using the integration of geospatial-based techniques considering eight groundwater potential contributing factors which are land cover, drainage density, soil texture, geology, elevation, slope, rainfall, and lineament density) and satellite gravity data(satellite gravity derivative filters such as bouguer anormaly,residual anormaly, degree of regionality, lineament depth and second horizontal derivatives Maps).These factors will be evaluated to prepare the groundwater potential maps from the analytic hierarchical process(AHP) and the combined techniques which will be useful in the management and conservation of groundwater resources in Nassarawa state, Nigeria.

2.1 DESCRIPTION OF STUDY AREA

Nasarawa State (see figure 2.1) is centrally located in the Middle Belt region of Nigeria. The state lies between latitude 8° 32′N and longitude 8° 18’ E . It shares boundary with Kaduna state in the North, Plateau State in the East, Taraba and Benue states in the south while Kogi and the Federal Capital Territory flanks it in the West. The state occupy a land area of about 27, 117 Km2 with total population of 20, 40097 with density of 75/km2 (Yari et al, 2001).

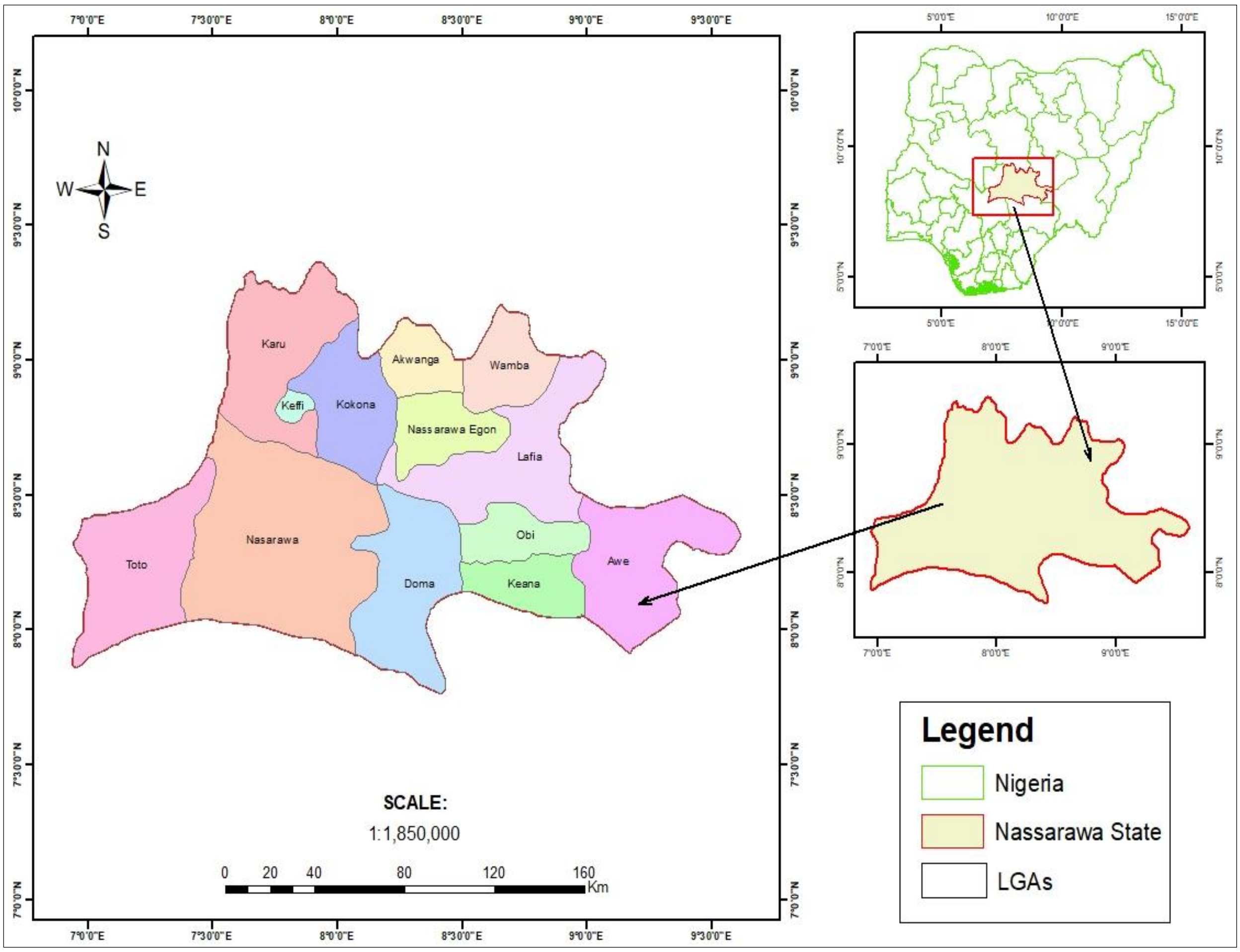

Figure 2.1: Map of Nasarawa state (Insert Map of Nigeria).

Located in the North Central Geo-political zone of Nigeria, Nasarawa State is blessed with abundant mineral resources and for this reason it is appropriately tagged the “Home of Solid minerals” In Nigeria. The state is endowed with abundant solid mineral resources with also the possibility of petroleum occurrence in parts of her sedimentary basin (Obaje et al, 2007). Prominent among the mineral deposits of the State are coal, barytes, salt, limestone, clays, glass sands, tantalite, columbite, cassiterite, marble, iron ore and gold. The state has a tropical humid climate characterized by two distinct seasons is experienced in the study area and occurs as intense thunderstorms. The wet (rainy) season last from the ending of March and ends in October while the dry season is experienced between November and February, Monthly total can vary widely, and so the annual total (Yari et al, 2001).Temperature is generally high in the area during the day between the month of March and April partly because of its location in the tropical sub-humid climatic belt.The major soil units of the area as observed by Samaila and Ezeaku, (2007) belong to the category of the tropical ferruginous soils. The soils are derived mainly from the basement complex formation and older sedimentary rocks.

2.2 THEORY AND APPLICATION

2.2.1 Gravity Computation

The gravitational effect, F of the earth can be defined as:

$$F = \frac{GmM}{\mathrm{R}^2} \qquad (1)$$

$R\ GmM\ F =$ Where M and R are the mass and radius of the earth respectively, G is the universal gravitational constant, and m is the mass of the rock. The higher the mass of a rock, the higher the gravity effect of the body. Unconsolidated rocks are potential aquifers for groundwater because of their high porosity and permeability. They usually have lower density and hence possess lower gravity values compared to denser Precambrian rocks (Raji, 2014).

i. First and second vertical derivatives vertical derivative (FVD and SVD)

The first and second orders of vertical derivative (FVD, SVD) filtering are effective tools for mapping intra-sedimentary volcanic rocks and geological structures (Anudu et al. 2014). Vertical derivatives generally highlight the borders of anomalies and improve the physical representation of shallow causative geological formations. It is used in this study to delineate geological structures that might serve as migratory paths/traps for hydrocarbon accumulation within the study area Adewum et al (2022). This enhancement filter calculates the vertical rate of change in the gravity signal (Blackey, 1996). It emphasises short-wavelength anomalies associated with shallow geological structures. Mathematically, the first and second vertical derivatives is given by the equation Prihadi Sumintadireja, *et al* (2018) and Blackley (1986)

$$FVD = \frac{\partial g}{\partial z} \qquad (1)$$

$$SVD = \frac{\partial^2 g}{\partial z^2} \qquad (2)$$

ii. First and Second horizontal derivative (FHD and SHD)

The first and second horizontal derivative (FHD, SHD are well-known filtering method, the measure the change rate of the gravity field in two horizontal directions (x and y), Zakariah et al, 2021, as shown in equation 3 and 3

$$.FHD = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \qquad (3)$$

Where $\frac{\partial g}{\partial x}$ and $\frac{\partial g}{\partial y}$ are the two horizontal derivatives of the observed gravity field. The second horizontal derivative is given as

$$SHD = \sqrt{\left(\frac{\partial^2 g}{\partial x^2}\right)^2 + \left(\frac{\partial^2 g}{\partial y^2}\right)^2} \qquad (4)$$

The second horizontal derive equation used is as applied according to Epuh and Joshua (2018).As a rule, the complete even subordinate inconsistency created by a plain body will in general overlie the edges of the bizarre body, whether vertical or level and isolated from one another (Cordell and Grauch 1985 and Okoro et al, 2021). According to Epuh and Joshua (2018), the second horizontal derivative using the modified truncated Horizontal Plate Model (THPM) is given as

$$\Delta g_{xx} = 2\pi G\rho_0\left[1 - e^{-k\sqrt{ks}}\right]e^{-k\sqrt{ks}}\Delta g \qquad (5)$$

$\Delta g_{xx} =$ Second horizontal derivative using the modified Truncated Horizontal Plate Model (THPM)
$\rho_0 =$ Weathered tertiary density obtained from well log or Parasnis method
$z =$ mean depth pertubated by the interfaces
$s =$ shot point distance

$$k = \sqrt{k_x^2 + k_y^2} \qquad (6)$$

$k_x k_y =$ Nyquist wavenumber in the x, y direction

$$k_x = \frac{p}{x_m}, k_x = \frac{p}{y_m}$$

k_x, k_y = wave numbers, we choose x and y axes which lie in the directions of maximum and minimum horizontal gradient in Δg. x_m and $y_m =$ measured distances between points at which g_{obs} takes the value $\frac{1}{2}\Delta g$ in these two directions. $\Delta g_{\max} =$ amplitude of the Bouguer anomaly on the surface

iii. Depth Estimation Methods

Estimation of depths to basement was carried out using the Source Parameter Imaging method (Reid et al. 1990; Zhang et al. 2000). (Avbovbo, 1980; Whiteman 1982; Brownfield and Charpentier 2006; Osinowo and Olayinka 2012; Kaki et al. 2013; Osinowo et al. 2014; Oladele et al, 2016, **Ayuba and Nur (2018)** Ola and Olabode

2018, Okoro et al, 2021). Depths to causative anomalous bodies were determined using 2D forward modelling of some selected profiles using the Grav2DC software which gave insights on the structural morphometry and the basement architecture.

The depth estimation using the Source parameter imaging (SPI) methods described by: Thurston et al. 2002; Thurston and Smith 1997,Thurston and Smith 1997; Thurston et al. 1999, Smith et al. 1998, is based on the principle of complex analytic signal which computes source parameters from gridded gravity data. The analytic signal was calculated from the x, y and z derivatives. The analytic signal amplitude, as used in this work is the vector sum of the horizontal (x and y) and vertical (z) derivatives for the first and second order derivatives (Nabighian, 1972; Hsu et al., 1996, Smith and Salem, 2005) defined by equation 7:

$$|A_1(x)| = \sqrt{\left(\frac{\partial g}{\partial z}\right)^2 + \left(\sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}\right)^2} \tag{7a}$$

$$|A_2(x)| = \sqrt{\left(\left(\frac{\partial^2 g}{\partial z^2}\right)^2 + \left(\sqrt{\left(\frac{\partial^2 g}{\partial x^2}\right)^2 + \left(\frac{\partial^2 g}{\partial y^2}\right)^2}\right)^2\right)} \tag{7b}$$

$|A_1(x)| = First$ derivative analytical signal, $|A_2(x)| = Second$ derivative analytical signal

The results are used for structural and geologic discrimination (Falufosi and Osinowo, 2021).The SPI method was used in this study to determine the depth to anomalous causative bodies and to map the basement topography source parameters from gridded gravity data. This method requires computation of the first- and second order derivatives, making it susceptible to noise and interference effects (Nabighian et al. 2005). The rudiments is that for vertical contacts, the pinnacles of the neighborhood wavenumber characterize the opposite of profundity. Hence, the local wave number is calculated using the formula (Nabighian, 1972; Hsu et al., 1996 Smith and Salem, 2005) as shown in equation 3.8 a, b

$$K_x = \frac{-1\left[\frac{\partial}{\partial z}|A_1(x)|\right]}{[A_1(x)]} \tag{8a}$$

$$K_z = \frac{-1\left[\frac{\partial}{\partial x}|A_2(x)|\right]}{[A_2(x)]} \tag{8b}$$

The depth to the basement structure can be estimated using the formulas (Smith and Salem, 2005) as shown in equation 3.8

$$D_{basement} = \frac{1}{\frac{d}{dx}\left(\frac{k_z}{k_z}\right)} \tag{9}$$

$D_{basement} =$ basement depth.

Thusly, SPI map all the more intently looks like the geography, giving a superior picture of the storm cellar silt interface than either the first gravity information or its subordinates (Okoro et al, 2021).

iv. Vening Meinesz Rigidity Model

The degree of regionality (mechanical stiffness) of the sedimentary rock were determined using the relations (Kuhn, 2003)

$$l = \sqrt[4]{\frac{D}{g\mathrm{D}r}}, \qquad (10)$$

$l =$ is the degree of Regionality which describes the mechanical stiffness of the plate, D=flexural rigidity, $g =$ gravity anomaly, $\mathrm{D}r =$ Density contrast

$$D = \frac{ET^3}{12(1- c^2)} \qquad (11)$$

$T = \mathit{Effective}$ elastic plate thickness $= 70,000m$ ($\mathit{Djomani}$ et al.,1999)

$E = \mathit{Young's}$ Modulus, $6.5x10^{10}Pa,\ c^2 = \mathit{Poisson's}$ Ratio=0.25

III. MATERIALS AND METHODS

3.1 Data Acquisition

3.1.1 Remote Sensing, and Satellite Gravity Data

This primary imagery used in this study was the Landsat 8 Operational Land Imager (OLI) acquired from the United States Geological Surveys (USGS) Earth Explorer. The Landsat mission is a joint drive between the USGS and the Public Flying and Space Organization (NASA). It addresses the world's longest constantly obtained assortment of room based medium-goal land remote sensing data. Software packages such as ArcGIS 10.8 was used in the processing and analysis of the data.

Table 3.1: *summarizes the characteristics of the Landsat data and other datasets used*

SECONDARY DATA	RESOLUTION	SOURCE	USE
Landsat 8 Operational Land Imager (OLI)	30m x 30m	U.S. Geological Surveys (USGS) Earth Explorer.	To classify the land cover and land use, as well as identifying surface of water bodies and lineaments within the study area
Shuttle Radar Topography Mission - SRTM DEM (1 Arc-second Global) or Topographic maps.	30m x 30m	U.S. Geological Surveys (USGS) Earth Explorer.	To understand the terrain and elevation variations, extract slope and drainage density patterns in Nasarawa State.
Rainfall data	0.25° x 0.25°	CRU data https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.07/	To obtain the historical rainfall records to understand recharge patterns and temperature records in Nasarawa state.
Geological Map		Nigerian Geological Survey Agency (NGSA).	To show rock types, formations, and structures of the study area.
Soil Map		Nigerian Geological Survey Agency (NGSA).	To extract the Soil maps and soil properties data, including soil texture, permeability, and porosity of the study area.
Digitized Administrative Map of Nigeria		DIVA-GIS.	To get the administrative boundary data for Nasarawa administrative subdivisions, such as local government areas and wards, data on roads, highways, and transportation infrastructure, further information about rivers, streams, lakes, and other water bodies.
Gravity Map data		Gravity Recovery and Climate experiment (Grace) Satellite	Use in determination of satellite gravity derivative filters such as Bouguer anormaly, Residual anormaly, Degree of regionality, Lineament depth and Second horizontal Derivatives Maps

Figure 3.1 shows the flow chart for the project execution.To process and analyze the data, software packages such as ArcGIS 10.8.2, Global Mapper 13, ENVI 5.3 Classic, Surfer 13, and PCI Geomatica 2018 was used. The imagery was acquired under the projection and datum;

i. Projection: Transverse Mercator
ii. Datum: WGS 1984

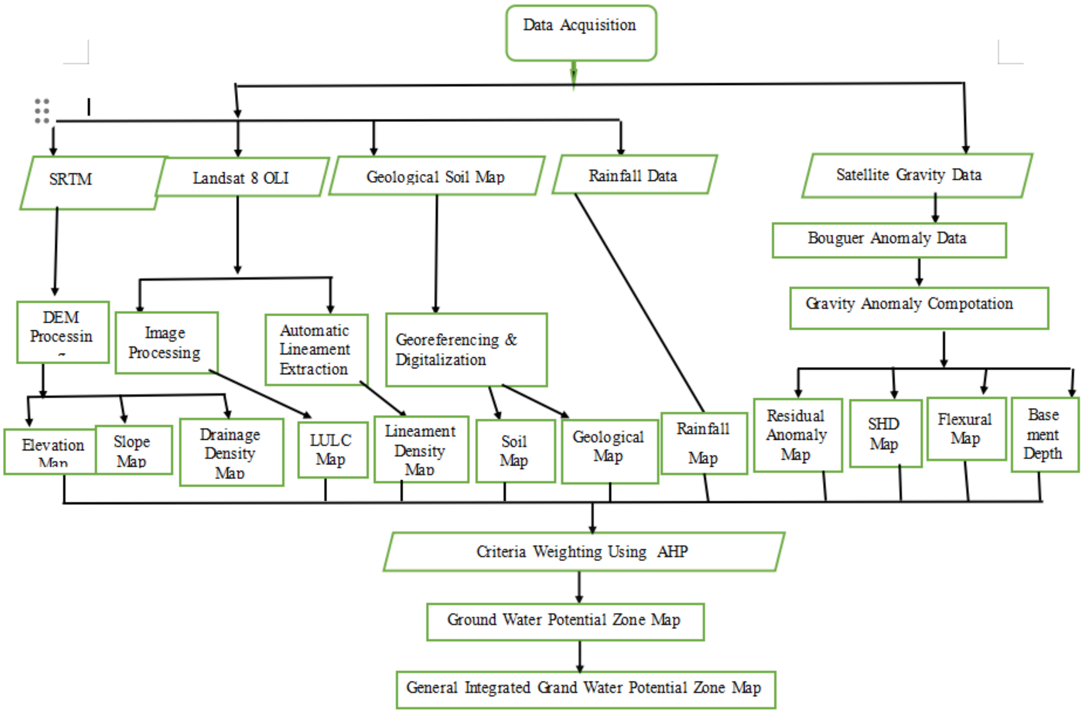

Figure 3.1: Methodology flowchart

3.2. Generation of the Remote sensing thematic layers for the groundwater potential zonation

From remotely sensed and GIS tecniques, eight thematic layers:—land cover, drainage density, lineament density, soil texture, geology, elevation, slope, and rainfall—were taken into consideration using GIS techniques. Five land cover classes: built-up, bare land, vegetation, agricultural land, and waterbody were identified from Landsat OLI scenes of Nasarawa State using the maximum likelihood image classification algorithm in the ArcGIS enviroment.The watershed generation function in the Global Mapper 13 software was used to extract the drainage lines from the ALOS DEM, from which the drainage density map was created. A stream count of 5000 was used to ensure that drainage lines could be extracted sufficiently. To create the drainage density raster, the ArcGIS 10.4 software environment's line density tool was utilised. The slope map was prepared by extracting the DEM from the SRTM data. The slope was then extracted from the digital elevation model in ArcGIS software using slope function under the spatial analyst tool.The lineament map was prepared from the SRTM DEM. This was done by extraction techniques with the aid of ArcMap. It involves transforming each of the shape points into a straight line in parameter space. ArcGIS 10.8 was used for result analysis.The geological map for the study area was digitized from an existing geology map of Nasarawa state and then digitized and rasterized using the polygon to raster tool in ArcToolbox. The rasterized data was then converted from a continuous data to a discrete data for further analysis.The Soil map for the study area was also extracted from an existing Soil map of Nigeria using the intersect tool in ArcMap.Downloaded in Tiff format from https://crudata.uea.ac.uk, the high-resolution gridded datasets covering Africa were converted to NetCDF format using Multidemension tools in Toolbox. Nasarawa State boundary shapefile was utilised to cut the necessary precipitation raster segment. The data was converted from raster to point using a toolbox conversion tool, and the total was computed for the state boundary's annual rainfall using the cell statistics tool. The precipitation raster's study area was clipped using the boundary shapefile of the study area after the state boundary points were interpolated using IDW, and the precipitation raster was then reclassified.

3.3. Weighting of thematic layers using the Analytical Hierarchical (AHP) technique

AHP was used to evaluate each student's class weights and map scores in accordance with Saaty and Vargas (1991). It helped to arrange the criteria in a hierarchical order through a pair-wise comparison matrix, so it was utilized to identify the themes with their rank and priority. Because pairwise comparisons of matrices of the selected criteria make judgements and calculations simple, AHP also illustrates the compatibility and incompatibility of decisions, which is the benefit of multi-criteria decision making (Lee, 2007). Literature (Saaty, 1988; Brunelli, 2015; Reisi et al., 2018; Hamid-Mosaku et al., 2020) has established and applied the principle of AHP. Eight probable groundwater contributing elements were discovered and taken from the literature for this investigation. They consist of slope, land cover, soil texture, yearly rainfall, drainage density, lineament density, elevation, and geology. Vinogradova et al. (2018) claim that selections for the individual theme and class weight were made based on the experts' rankings after they completed a questionnaire and provided ten responses.Groundwater potential were identified using AHP. AHP is a decision-making method that uses pairwise comparisons of factors to determine their relative importance. In this case, the factors that were considered were geology, slope, rainfall, drainage density, soil, land use/land cover, and lineament density. The weightages of each factor were determined using AHP pairwise matrix shown in Table 3. The AHP extension on ArcMap was activated and the values computed were imported into the environment and the weights of the criteria were generated.

Table 3: *The pairwise matrix and weights distribution*

	GE	LD	EL	LC	DD	ST	AR	SL
GE	1	1	1	3	3	1	5	5
LD	1	1	1	1	3	3	1	5
EL	1	1	1	1	1	3	3	1
LC	1/3	1	1	1	1	1	3	3
DD	1/3	1/3	1	1	1	1	1	3
ST	1	1/3	1/3	1	1	1	1	1
AR	1/5	1	1/3	1/3	1	1	1	1
SL	1/5	1/5	1	1/3	1/3	1	1	1

GL- Geology, LD- Lineament density, EL-- Elevation, LC--Landcover, DD--Drainage density, ST--Soil type, AR--Annual rainfall, SL--Slope

Table 3.2: The assigned weights and scores to different thematic layers and features respectively (AHP)

Thematic layer	Priority weight (%)	Class	Assigned weight	Normalized weight
Drainage density (km^2)	13	28.01 – 142.1	5	0.1333
		142.2 – 194.7	4	0.2667
		194.8 – 241.8	3	0.2000
		241.9 – 301.5	2	0.1333
		301.6 – 489.9	1	0.0667
Elevation (m)	7	36 – 151	5	0.1333
		151.1 – 251	4	0.2667
		251.1 – 374	3	0.2000
		374.1 – 571	2	0.1333

		571.1 – 1,307	1	0.0667
Geology	28	Undifferentiated Basement Complex	1	0.0476
		Migmatite	1	0.0476
		Nupe Sandstone	3	0.1429
		Shales	2	0.0952
		Sandstone, Mudstones and Shales	3	0.1429
		Sandy Materials	4	0.1905
		Sandstone and Shales	5	0.2381
		Recent Alluvium	2	0.0952
Landcover	10	Water body	5	0.1333
		Vegetation	4	0.2667
		Agricultural land	3	0.2000
		Built-up Area	2	0.1333
		Bare land	1	0.0667
Lineament density (km^2)	9	0 – 0.0729	1	0.0667
		0.073 – 0.139	2	0.1333
		0.14 – 0.199	3	0.2000
		0.2 – 0.267	4	0.2667
		0.268 – 0.454	5	0.1333
Rainfall (mm)	10	1,119 – 1,162	1	0.0667
		1,163 – 1,180	2	0.1333
		1,181 – 1,194	3	0.2000
		1,195 – 1,212	4	0.2667
		1,213 – 1,261	5	0.1333
Slope (degree)	15	0 – 2.336	5	0.1333
		2.337 – 5.839	4	0.2667
		5.84 – 12.55	3	0.2000
		12.56 – 22.77	2	0.1333
		22.78 – 74.45	1	0.0667
Soil	8	Sandy Clay	3	0.2500
		Clay Loam	4	0.3333
		Sandy Loam	5	0.4167

Table 3.3: *Weighing criteria and ranking of the sub-criteria for AHP and Satellite Gravity*

Thematic layer	Priority weight (%)	Priority weight (60%)	Class	Assigned weight	Normalized weight
Drainage density (km^2)	13	8	28.01 – 142.1	5	0.1333
			142.2 – 194.7	4	0.2667
			194.8 – 241.8	3	0.2000
			241.9 – 301.5	2	0.1333
			301.6 – 489.9	1	0.0667
Elevation (m)	7	4	36 – 151	5	0.1333
			151.1 – 251	4	0.2667
			251.1 – 374	3	0.2000
			374.1 – 571	2	0.1333
			571.1 – 1,307	1	0.0667
Geology	28	17	Undifferentiated Basement Complex	1	0.0476
			Migmatite	1	0.0476
			Nupe Sandstone	3	0.1429
			Shales	2	0.0952
			Sandstone, Mudstones and Shales	3	0.1429
			Sandy Materials	4	0.1905
			Sandstone and Shales	5	0.2381
			Recent Alluvium	2	0.0952
Landcover	10	6	Water body	5	0.1333
			Vegetation	4	0.2667
			Agricultural land	3	0.2000
			Built-up Area	2	0.1333
			Bare land	1	0.0667
Lineament density (km^2)	9	5	0 – 0.0729	1	0.0667
			0.073 – 0.139	2	0.1333
			0.14 – 0.199	3	0.2000
			0.2 – 0.267	4	0.2667

			0.268 – 0.454	5	0.1333
Rainfall (mm)	10	6	1,119 – 1,162	1	0.0667
			1,163 – 1,180	2	0.1333
			1,181 – 1,194	3	0.2000
			1,195 – 1,212	4	0.2667
			1,213 – 1,261	5	0.1333
Slope (degree)	15	9	0 – 2.336	5	0.1333
			2.337 – 5.839	4	0.2667
			5.84 – 12.55	3	0.2000
			12.56 – 22.77	2	0.1333
			22.78 – 74.45	1	0.0667
Soil	8	5	Sandy Clay	3	0.2500
			Clay Loam	4	0.3333
			Sandy Loam	5	0.4167
Residual Anomaly		10	-15.03 – 5.249	5	0.1333
			5.25 – 25.52	4	0.2667
			25.53 – 45.8	3	0.2000
			45.81 – 66.07	2	0.1333
			66.08 – 86.35	1	0.0667
SHD		10	-0.08976 - -0.03755	5	0.1333
			-0.03754 – 0.01467	4	0.2667
			0.01468 – 0.06688	3	0.2000
			0.06689 – 0.1191	2	0.1333
			0.1192 – 0.1713	1	0.0667
Basement depth		10	0.003538 – 0.6207	1	0.0667
			0.6208 – 1.238	2	0.1333
			1.239 – 1.855	3	0.2000
			1.856 – 2.472	4	0.2667
			2.473 – 3.09	5	0.1333
Degree of regionality		10	1,018,000 – 2,472,000	5	0.1333
			2,473,000 – 3,925,000	4	0.2667
			3,926,000 – 5,378,000	3	0.2000

			3,379,000 – 6,831,000	2	0.1333
			6,832,000 – 8,285,000	1	0.0667

3.4 Groundwater Potential Index (GWPI) Map

The appropriateness analysis of the Weighted Overlay Index (WOI) is used to vector integrate all of the thematic layers into a single Groundwater Potential Zone (GWPZ) map. As indicated in Table 3, the weights for the various themes were allocated according to their impact on the ground water potential. The final Groundwater Potential Zone map is obtained by adding the weights and themes, as indicated in Equation (8).

$GWPI = Gl_wGl_r + Ld_wLd_r + E_wE_r + S_wS_r + ST_wST_r + Dd_wDd_r + LC_wLC_r + AR_wAR_r$ (Eq 12)

In this context, geology is denoted by Gl, lineament density by Ld, slope by S, soil texture by ST, drainage density by Dd, land cover by LC, annual rainfall by AR, and elevation by E. The subscripts 'w' and 'r' stand for a feature's weight and that of each of its subclasses according to how important it is in terms of groundwater potentiality. The subclasses were scored from 1 to 5, with 1 being very poor, 2 representing poor, 3 representing moderate, 4 represent good, and 5 representing very good groundwater storage potential. The AHP-weighted layers' groundwater potential zonation maps was blended.

In the integration of the remote sensing thematic maps with the four (4) gravity thematic maps: residual gravity anomaly, SHD, degree of regionality and basement depth is shown in equation 13.

$$GWPI = [(G_w)x(G_T)] + [(LULC_w)xLULC_T] + [(ST_w)x(ST_T] + [(RD_w)x(RD_T)] + [(SL_w)x(SL_T)]$$
$$+ [DD_w)x(DW_T)] + [GR_w)x(GR_T)] + [GL_w)x(GL_T)] + [GF_w)x(GF_T)] + [GB_w)x(GB_T)]$$

Where GWPI= Groudwater Potential Index, G= Geology, LULC= Land Use Land Cover,
ST= Soil,SL= Slope, RD= Rainfall Distribution, DD= Drainage Distribution,
$GL =$ *Gravity* Lineament, $GR =$ *gravity* Residual, $GF =$ *grvity* flexural regidity, $GB =$ *gravity* basement
$w =$ *weighting Coefficient*, $T =$ *Thematic* Layers

IV. RESULTS AND DISCUSSION

The groundwater potential maps are presented and discussed in this section, along with the contributing variables to the groundwater potential as thematic layers.

4. 1. 1 Drainage Density Map And its effect on Groundwater Potential Distribution

According to Abdullateef et al (2021) and (Magesh et al., 2012), drainage density refers to the proximity of stream channels and a measure of the overall length of the stream segments per unit area. Drainage density refers to the total length of streams per unit area (Avtar *et al.*, 2011; Das and Pardeshi, 2018). Understanding the relationship between drainage density and Groundwater potential distribution in Nasarawa State is crucial for effective water resource management. Drainage density, indicating the extent of surface water flow patterns, significantly influences groundwater recharge, discharge, and storage. Figure 4.1 shows the drainage density pattern of Nasarawa State. The drainage map shows that the study area has five zones of drainage patterns which are: very low, low, moderate, high and very high. The very low ranges from 28.01-142.1km^2, the low ranges from 142.2-194.7km^2, the moderate ranges from 194.8-241.8km^2, the high ranges from 241.9-301.5km^2, and the very high ranges from 301.6-489.9km^2. Areas with high drainage density often experience rapid surface water runoff, limiting groundwater recharge opportunities and potentially leading to lower groundwater potential. However, dense drainage networks can enhance hydrological connectivity between surface water bodies and aquifers, promoting groundwater recharge and sustaining higher potential in regions with abundant surface water resources.

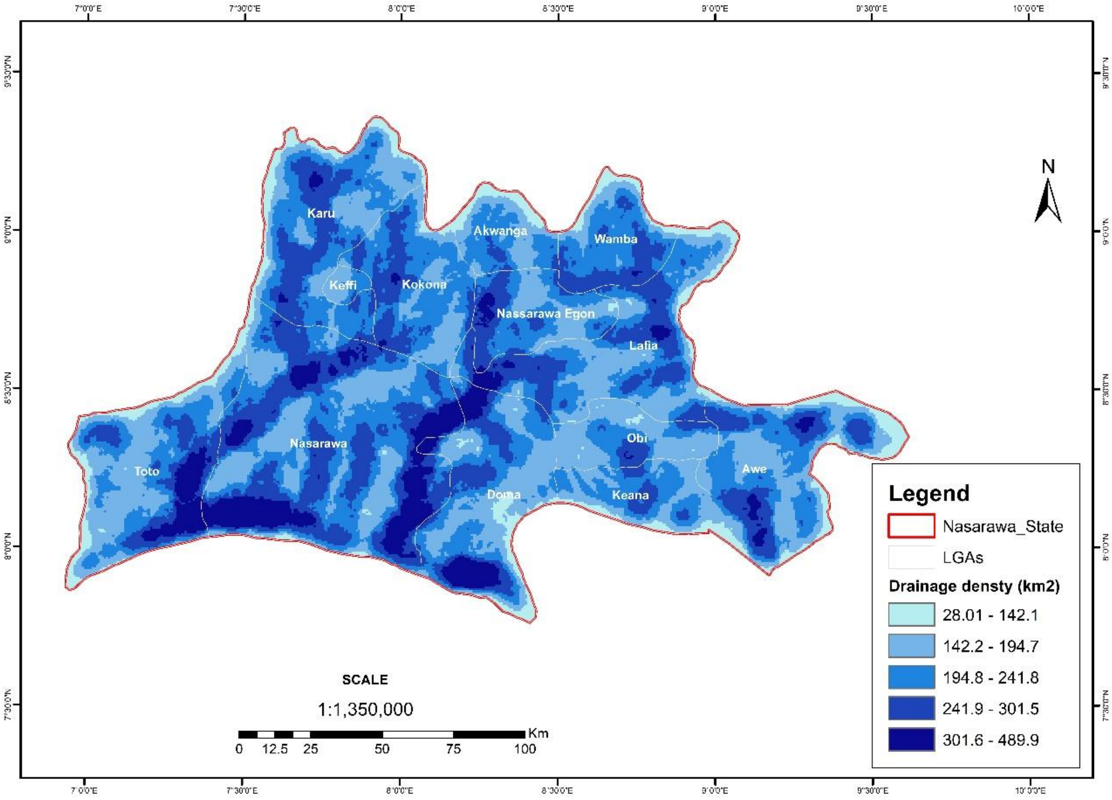

Figure 4. 1: Drainage density.

4.1.2 Lineament Density Map

Lineament features are the criteria that ultimately determines permeability. Water circulation is greater in regions with high lineament density; therefore, groundwater potential is as well greater in these regions (Lentswe and Molwalefhe 2020). Lineament act as a conduit for groundwater flow and hence, are hydrogeologically significant. Lineaments are indicators of sub-surface faults and fractures that influence the occurrence of ground water act as reservoirs and canals. High lineament density areas typically have high levels of porosity and permeability, which allows for more water percolation and may indicate a respectable ground water potential (Mogaji *et al.* (2011). According to Mogaji et al. (2011), the zones of high lineament intersection density are feasible zones for groundwater prospecting in the study area.

The result presented in Figure 4.2 shows that regions with high lineament density tend to have a higher potential for groundwater while regions with lesser density have reduced potential regarding groundwater.From figure 4.2 the lineament density of of Nasarawa Sate can be grouped into five categories with value ranging from 0 – 0.0729km^2 , 0.073 – 0.139km^2, 0.14 – 0.199km^2, 0.2 – 0.267km^2, and 0.268 – 0.454km^2 which indicates very low, low, moderate, high and very high lineament densities respectively. High lineament density areas typically exhibit enhanced groundwater potential by facilitating aquifer recharge and connectivity, while low-density areas may experience reduced potential due to isolated groundwater pockets. Structural features within lineament zones, such as faults, further influence groundwater distribution.

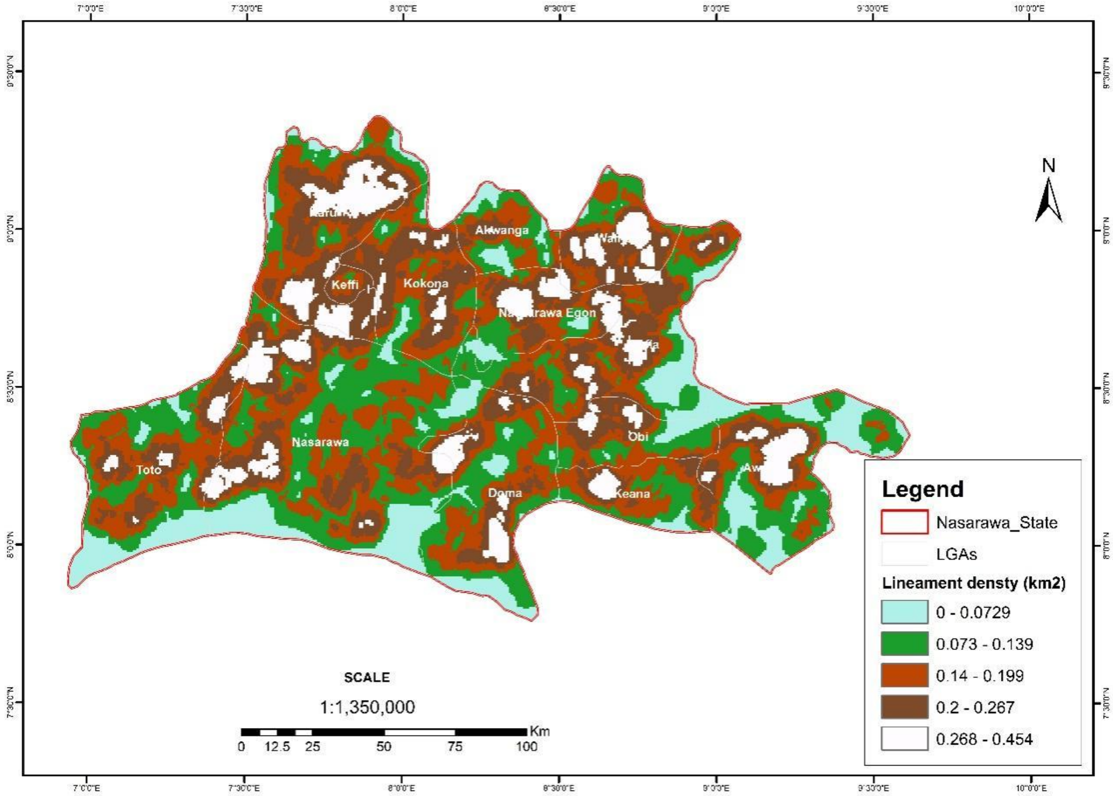

Figure 4. 2: Lineament density.

4.1.3 Rainfall Map

The amount of rainfall is one of the major factors that contribute to groundwater recharge. Rainfall distribution alongside slope gradient primarily affects the infiltration rate of runoff water which in turn increases the possibility of groundwater occurrence.It is important to note that not only the quantity of rainfall in the area is important, but also the period and intensity of rainfall as well plays a major role in recharging the groundwater. Small amounts of low intensity rainfall will make a good impact to the groundwater over a prolonged period of time (Nasir et al. 2018).

Rainfall is a major source of recharge to the groundwater. Intensity and duration of rainfall highly have significance on infiltration and runoff volume (Abuzied et al. 2015). It is reasonable to say that rainfall has a significant impact on the groundwater potential in a particular area. In hydrogeology, the relationship between groundwater potential and rainfall is essential. Since some precipitation seeps into the earth and joins the groundwater system, more rainfall often results in higher groundwater recharge. On the other hand, less rainfall may lead to less recharge, which may affect groundwater levels. The mean annual rainfall, as presented in Figure 4.3, ranges between 1,119 – 1,261mm; the rainfall distribution was classified into five (5) classes, and higher weight was assigned to higher rainfall amount, which suggests good groundwater potential and lower rainfall amount contribute to low groundwater potential in the study area.

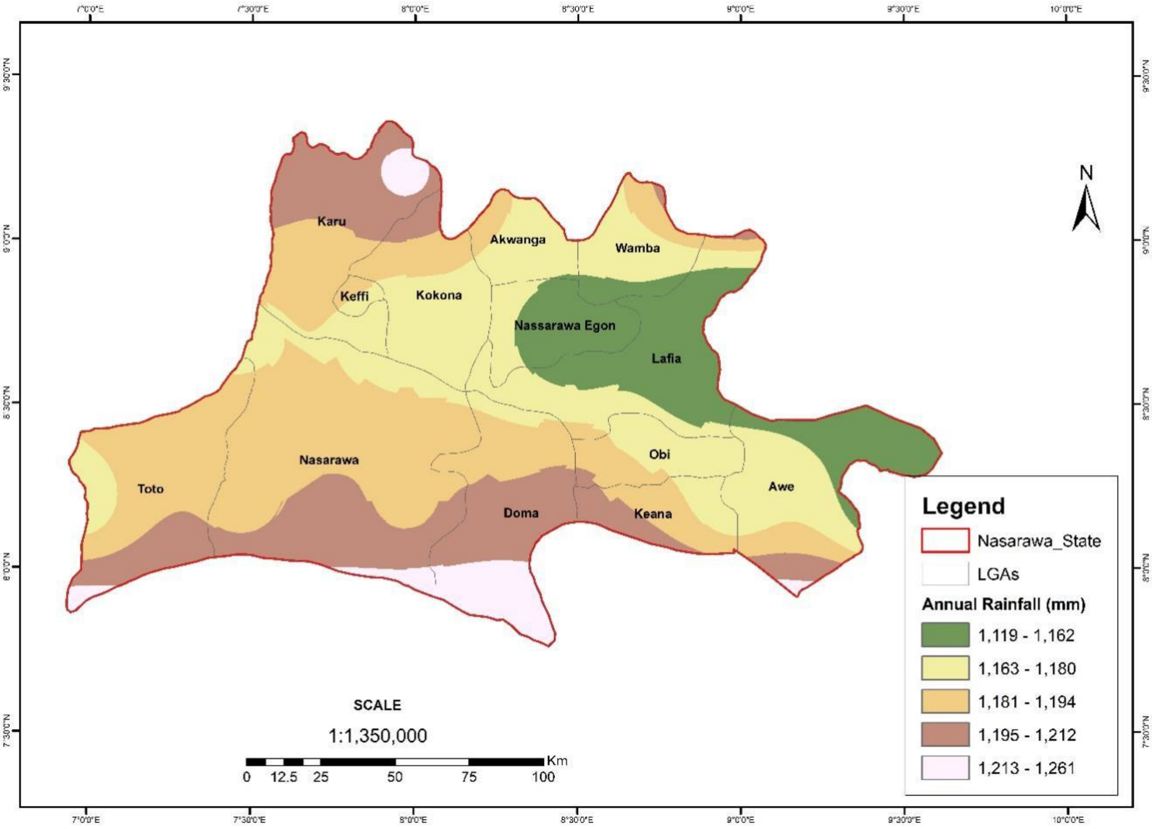

Figure 4. 3: Annual rainfall.

4.1.4 Geology Map

Geology completely determines the penetration and percolation of groundwater. As a result, it is a crucial criterion for assessing groundwater potential (Aju et al. 2021). The high permeability and porosity of the geologic units boost groundwater storage and yields (Yıldırım 2021).Groundwater behaviour is largely determined by an area's geology, with porosity and permeability being two important factors. Important variables are permeability, which shows a material's capacity to transfer fluids, and porosity, which shows the amount of open spaces in rocks or sediments. High porosity and permeability geological formations, such as some aquifers, allow groundwater to travel and store more easily. There is significant groundwater storage and release possible because of these porous rocks' reservoir-like function.

Figure 4.4 depicts the geological formation of Nassarawa state, which has varying effects on the potential of groundwater; the sandstone and shales exhibit the greatest potential owing to their elevated levels of porosity and permeability. The potential of Sandy materials and Nupe Sandstone is moderate, whereas Shales and Recent Alluvium have lesser permeability and hence contribute less. The Undifferentiated Basement Complex and Migmatite have the lowest potential due to their low porosity and limited ability to allow groundwater to flow. From the map, the geology of the state is not uniform as one town could exhibit more than one geological formation.The distribution of groundwater potential in Nasarawa State is intricately tied to its geological features. Various factors, including aquifer characteristics, structural controls, hydrogeological units, and recharge mechanisms, collectively influence the availability and movement of groundwater within the region. Aquifers, such as sandstone and shales exhibit high porosity and permeability, promoting groundwater storage and transmission. Conversely, impermeable formations like clay hinder groundwater movement, leading to lower groundwater potential. Geological structures such as faults and fractures play a significant role in directing groundwater flow paths and storage capacities. Fault zones may act as pathways for groundwater movement, enhancing potential in areas conducive to aquifer recharge and discharge. Mapping distinct hydrogeological units helps identify regions with high groundwater potential, such as those underlain by alluvial deposits or fractured basement rocks. Recharge processes, influenced by the permeability of geological formations, affect groundwater availability. Areas with permeable lithologies experience rapid infiltration of precipitation, sustaining higher groundwater potential, while regions dominated by impermeable lithologies may have limited recharge rates and lower potential.

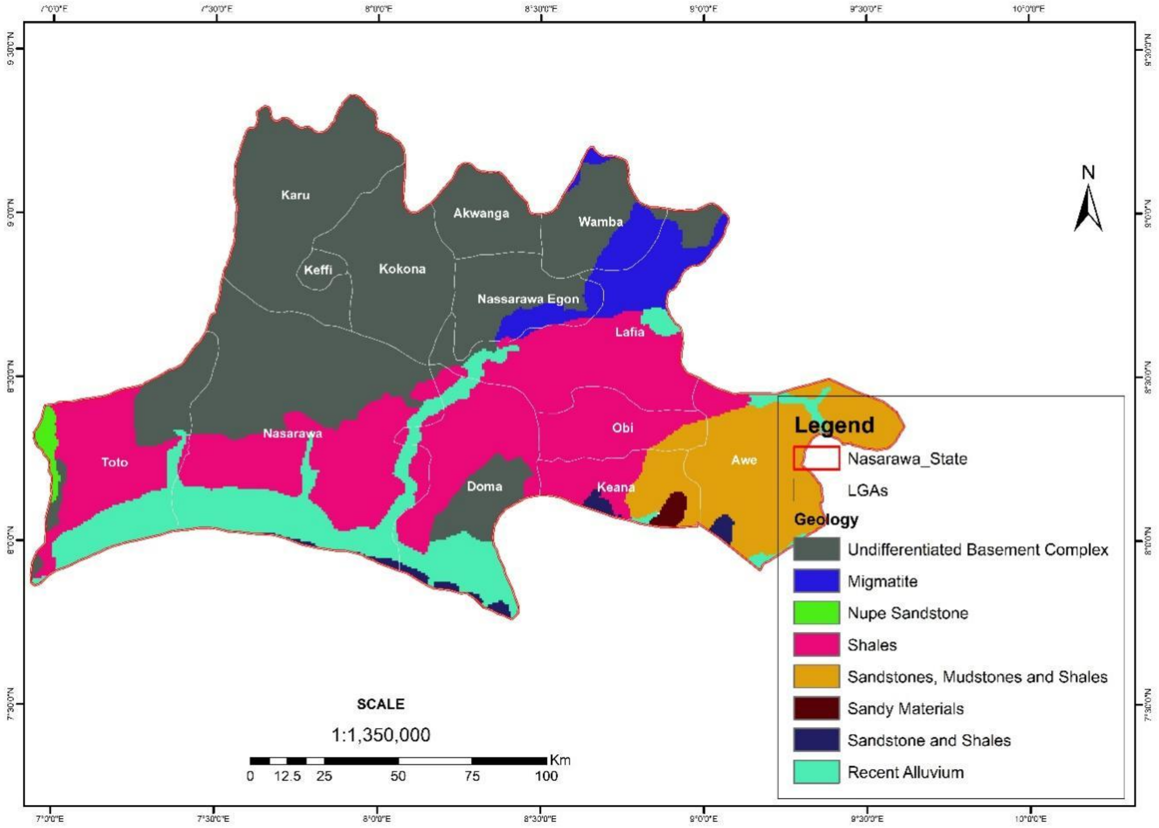

Figure 4.4: Geology

4.1.5 Soil texture Map

The increase in water entry into the soil is afected by soil type, which is determined by the activities of pore saturation or desaturation (Gbosh et al. 2020).Water transport into the ground is controlled by the porosity of the soil categories. Soil type with coarse-grained matrix (e.g., lithosols) has good groundwater potential, whereas soil type with fnegrained matrix (ferralsols) has poor groundwater potential (Ifediegwu et al. 2019).

Soil texture is a significant element in the delineation of groundwater potential zones in any region. Soil Porosity and permeability are direct function of soil texture. The nature of soil texture determines its infiltration intensity. The movement and infiltration of water in fine-grained soil is low compared to coarse-grained soil because these types of soils are not the same (Das and Pardeshi, 2018).The study area is mainly characterized by sandy clay, clay loam and sandy loam.The kind of soil influences the increase in water entry into the soil, which is controlled by pore saturation or desaturation processes. The amount of water absorbed by the various soil types is determined by their porosity.The soil composition in Nassarawa State is displayed in Figure 4.5. Each soil class has a distinct impact on groundwater recharge. Sandy loam, characterized by its high permeability, contributes the most to groundwater recharge, Clay loam, with moderate permeability, provides a balanced contribution. In contrast, Sandy clay, which has a higher clay content and is less porous, contributes the least to groundwater recharge and hinders water movement.

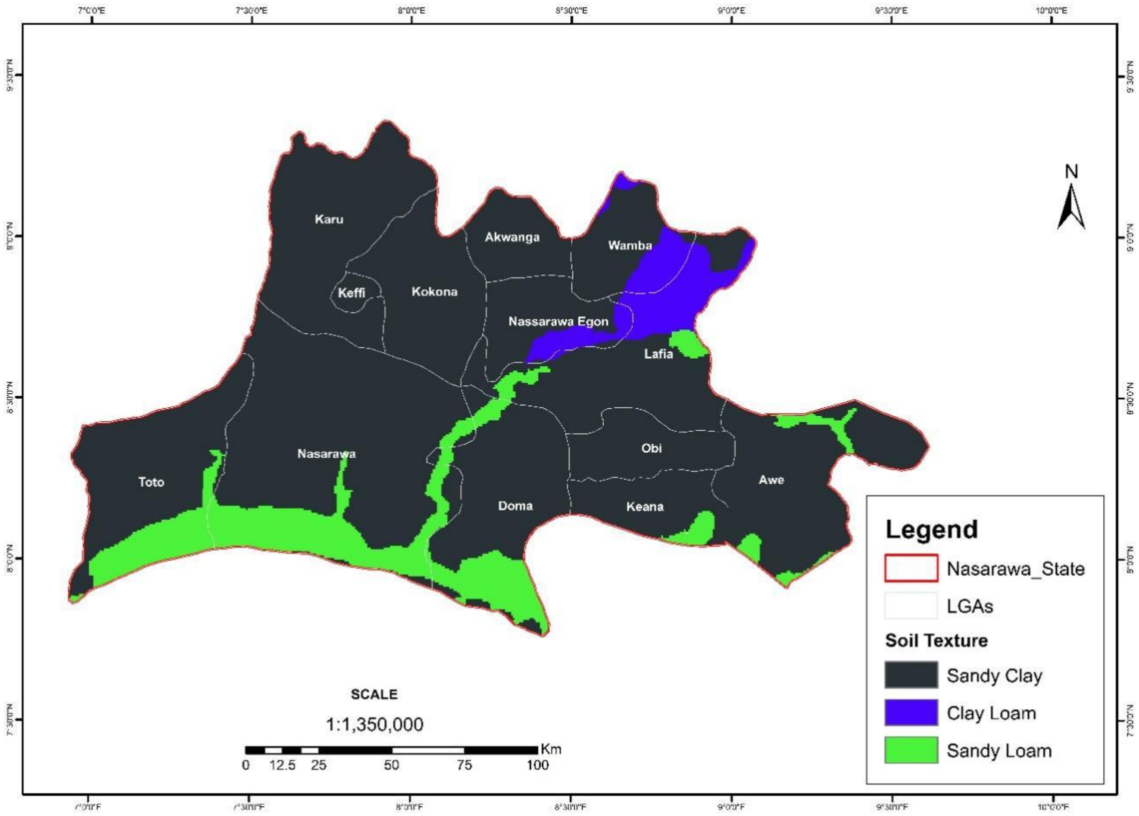

Figure 4.5: Soil texture

4.1.6 Slope Map

Slope is one of the most essential terrain derivatives used in expressing the steepness from ground surface, providing information on the nature of geologic and geodynamic processes operating at the regional scale (Epuh *et al.,* 2020).Slope directly affects the mechanism of surface runoff and is essential for groundwater recharging. The increased residence time for rainwater to permeate the subsurface in low slope areas has prompted preliminary analyses to conclude that these areas have a good potential for groundwater storage. On the other hand, steep slope zones have weak groundwater potential because of the quick water drainage from the surroundings.Preliminary investigations have revealed that the low slope regions have a good potential for groundwater storage due to the extended residence time for rainwater to infiltrate the subsurface. Steep slope regions, on the other hand, possess poor groundwater potential due to rapid water runoff from the landscape (Igwe et al. 2020).

The slope of the study area has been calculated in degrees (o) based on the Digital Elevation Model (DEM) which was extracted from the ALOS DEM data. The slope has been classified into five categories varying from 0 – 74.45 degrees.

Results presented on Figure 4.6, shows the five distinct slope value ranges for the study area which is between 0 to 74.45degrees; value between 0 – 2.336 degrees has a very high contribution to groundwater and values between 2.337 – 5.839 degrees have a high contributing power indicating favourable conditions for groundwater recharge. In terms of moderate to low potential its has a range of 5.84 – 12.55 and 12.56 – 2.77 degrees respectively while the elevation between 22.78 degrees and above indicated a very low potential contribution in terms of groundwater potentiality and recharge. According to Chowdhury *et al.* (2009), in relation to groundwater, flat areas in the Nasarawa state slope map that depict low slope percentage are most capable of containing rainfall, which in turn enhances recharge. However, elevated regions depicting very high slope (22.78 degrees – 74.45 degrees) will experience high run-off and low infiltration will be observed.

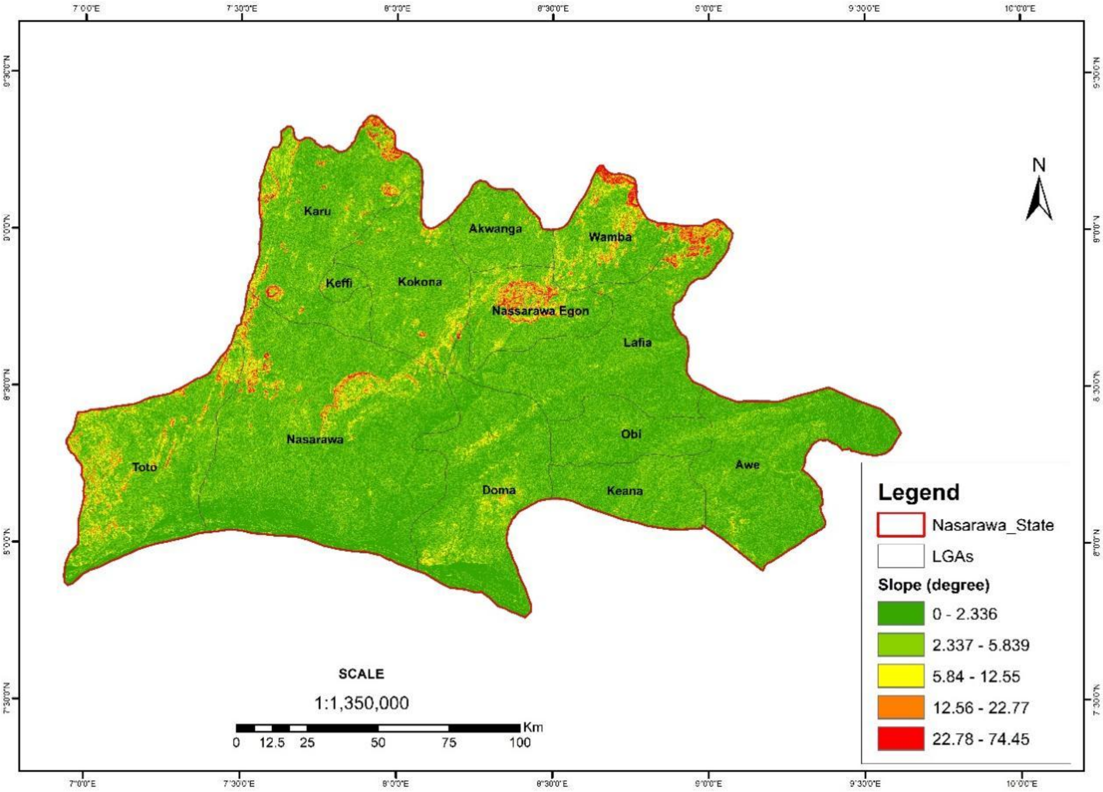

Figure 4.6: Slope

4.1.7 Elevation Map

The elevation class of Nasarawa state was categorized into five distinct classes, signifying the various ranges of elevation with their contributing power to groundwater potential as presented in Figure 4.7; elevation range from 36.22 to 265 meters has a very high potential for groundwater because lower elevation often indicates potential groundwater recharge areas, 265.1 to 490.8 meters elevation range according to the result of the analysis has a high contributing potential, the moderate groundwater contributing potential has an elevation range between 490.9 to 716.6 meters. High and very high elevations tend to lower influence and limit the impact of groundwater potential in the state, with the range of 716.7 to 942.4 meters and 942.5 to 1,168 meters, respectively.

Elevation maps play a crucial role in groundwater potential zone mapping by offering vital insights into the topography and relief of an area. They aid in identifying recharge areas, often located at higher elevations, where rainwater percolates into the ground, replenishing aquifers. These maps also assist in delineating watershed boundaries, allowing for an understanding of surface water and groundwater interactions.The findings in this study is similar to that of Das (2018), who concluded in his study that locations of low elevation have a significant impact on groundwater potentiality because surface water has more time to permeate into the subsurface, boosting groundwater rechargeability, and vice versa.

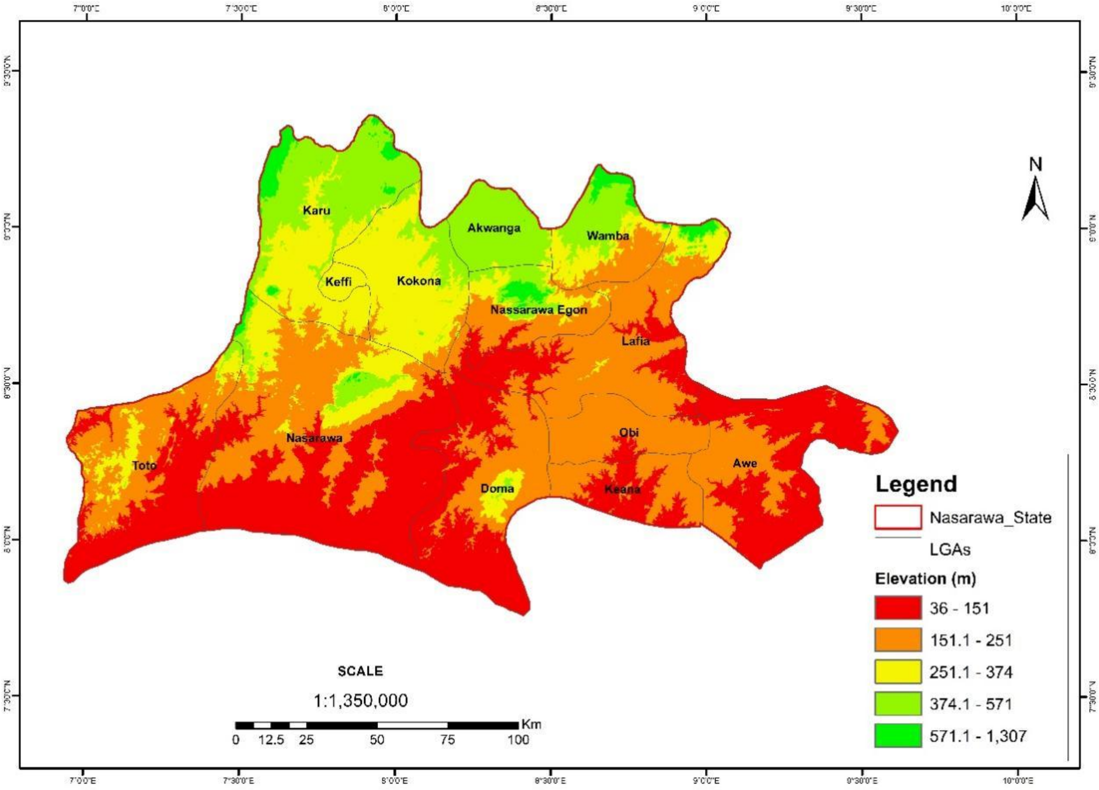

Figure 4.7: Elevation

4.1.8 Landcover Map

One of the most crucial aspects controlling surface runoff is the pattern of land use and land cover since evapotranspiration, penetration, and condensation are all influenced by things like vegetation type and soil moisture. Therefore, it significantly affects groundwater recharge. For this research work, Figure 4.8 shows the landcover classification result which is classified into five (5) classes, namely: Bare land, Built-up area, Farmland, Vegetation and Water body with each having a significant important as regards contributing to groundwater in Nasarawa State. Water bodies and vegetation have very high and high contributions, respectively, fostering groundwater recharge (Ashaolu *et al.*(2019). At the same time, Built-up areas may pose challenges due to impervious surfaces having a low contribution in terms of groundwater potential. Farmland has a moderate impact, and Bare land exhibits a low contribution to groundwater potential.

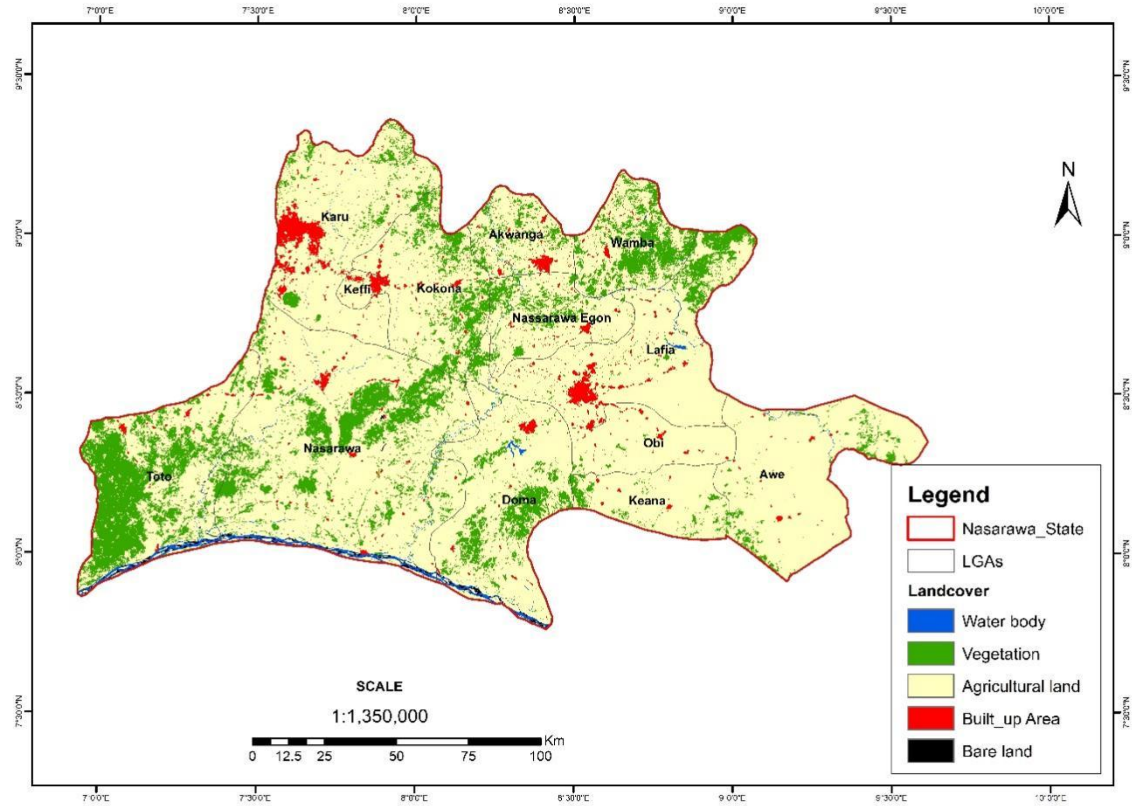

Figure 4.8: Landcover

4.1.9 Bouguer Anomaly

The Bouguer anomaly map represents gravity anomalies corrected for the effects of elevation, terrain, and crustal density variations. It provides a regional-scale view of gravity variations associated with subsurface geological features, such as sedimentary basins, igneous intrusions, and fault systems. Bouguer anomaly maps assist in delineating broad-scale trends in gravity anomalies and identifying areas with potential groundwater resources.The linearity in the Bouguer gravity anomaly map as shown in Figures 4.9 is indicative of strike features in the sate. In most cases, linearity shows the presence of block faulting and a structural alignment which indicates that the region is tectonically active (Okiwelu et al., 2010, Epuh and Joshua (2018)). A gravity low of between -20.12mGal and -8.415mGal was observed within places like Doma,Kaena,Obi Tand some other region of the state. High gravity between 15mGal to 26.69mGal was observed within places like Wamba and Toto.

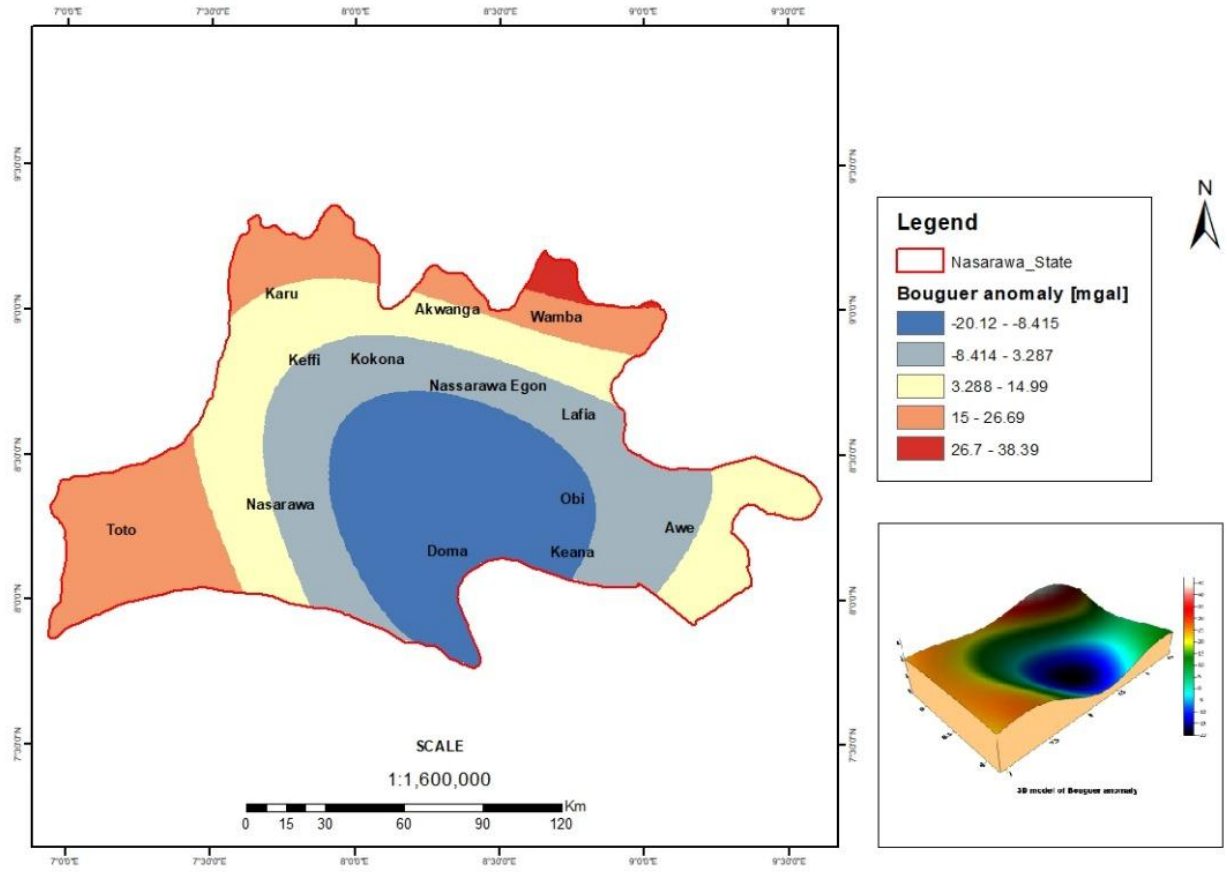

Figure 4. 4: Bouguer Anomaly.

4.1.10 Residual Anomaly Map

The AH residual gravity anomaly map represents residual gravity anomalies after removing the effects of regional trends and known geological features. It highlights local-scale gravity anomalies associated with subsurface geological structures and density variations, including buried faults, igneous intrusions, and sedimentary formations. AH residual gravity anomaly maps assist in identifying potential groundwater-bearing formations and structural controls on groundwater flow within the study area.The residual gravity anomalies in Nassarawa state range from -15.03 to 5.249mgal, indicating the presence of highly promising groundwater resources as a result of favourable subsurface features. Anomalies ranging from 5.25 to 25.52mgal indicate a high potential, whilst larger anomalies indicate a lesser potential, with values between 66.08 and 86.35mgal being the least favourable due to the presence of dense, impermeable materials.

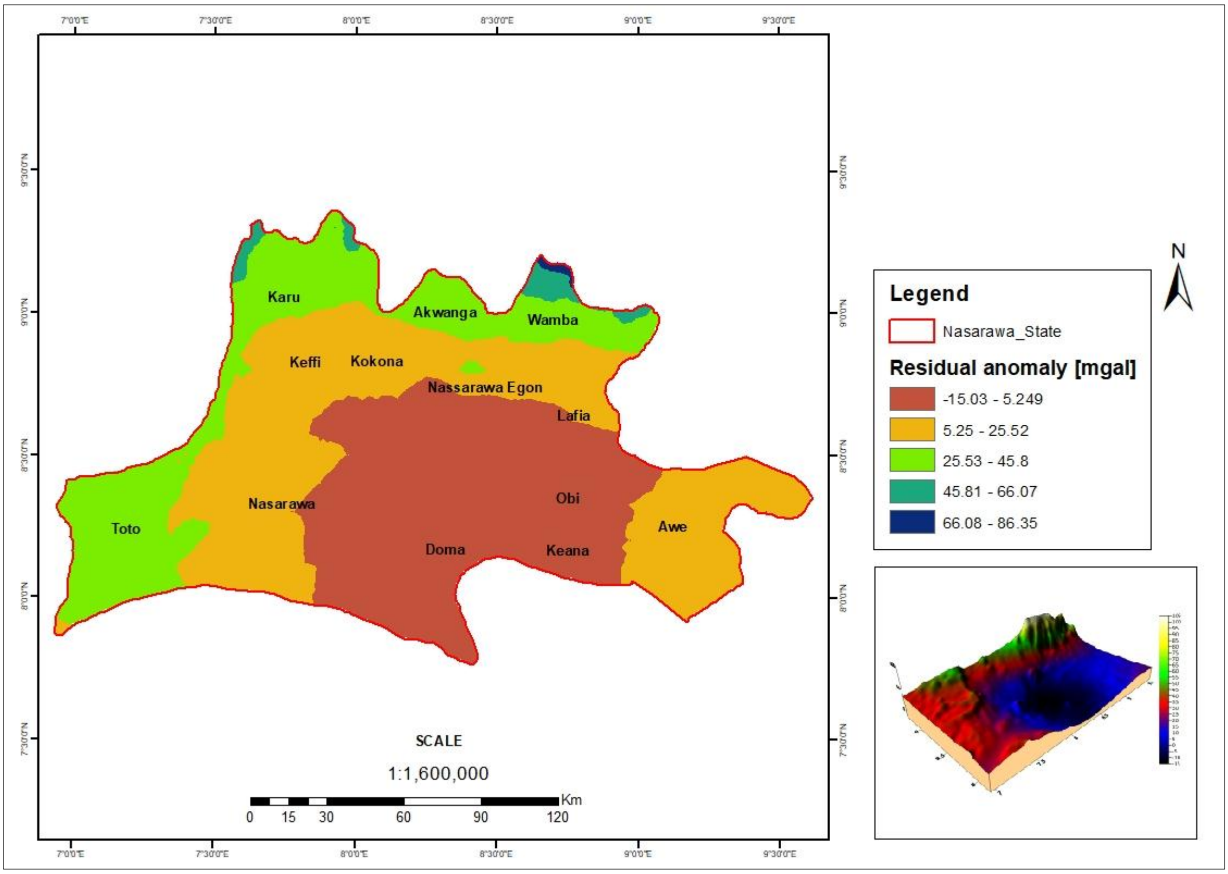

Figure 4. 5: Residual anomaly.

4.1.11 Degree of Regionality Map

The degree of regional or mechanical stiffness variation in Nassarawa state shown in figure 4.11, ranging from 1,018,000 pa.m^4 to 2,472,000pa.m^4 , indicates the maximum level of groundwater potential as a result of favourable regional conditions. Values ranging from 2,473,000pa.m^4 to 3,925,000pa.m^4 indicate a high level of potential, and higher values indicate a lesser level of potential, with 6,832,000pa.m^4 to 8,285,000pa.m^4 being the least favourable.The degree of regionality map quantifies the degree to which gravity anomalies exhibit regional or local characteristics within the study area. It helps distinguish between regional-scale gravity trends associated with broad geological features and local-scale anomalies related to specific subsurface structures. Degree of regionality maps aid in interpreting gravity data and identifying areas with significant local anomalies that may influence groundwater potential.

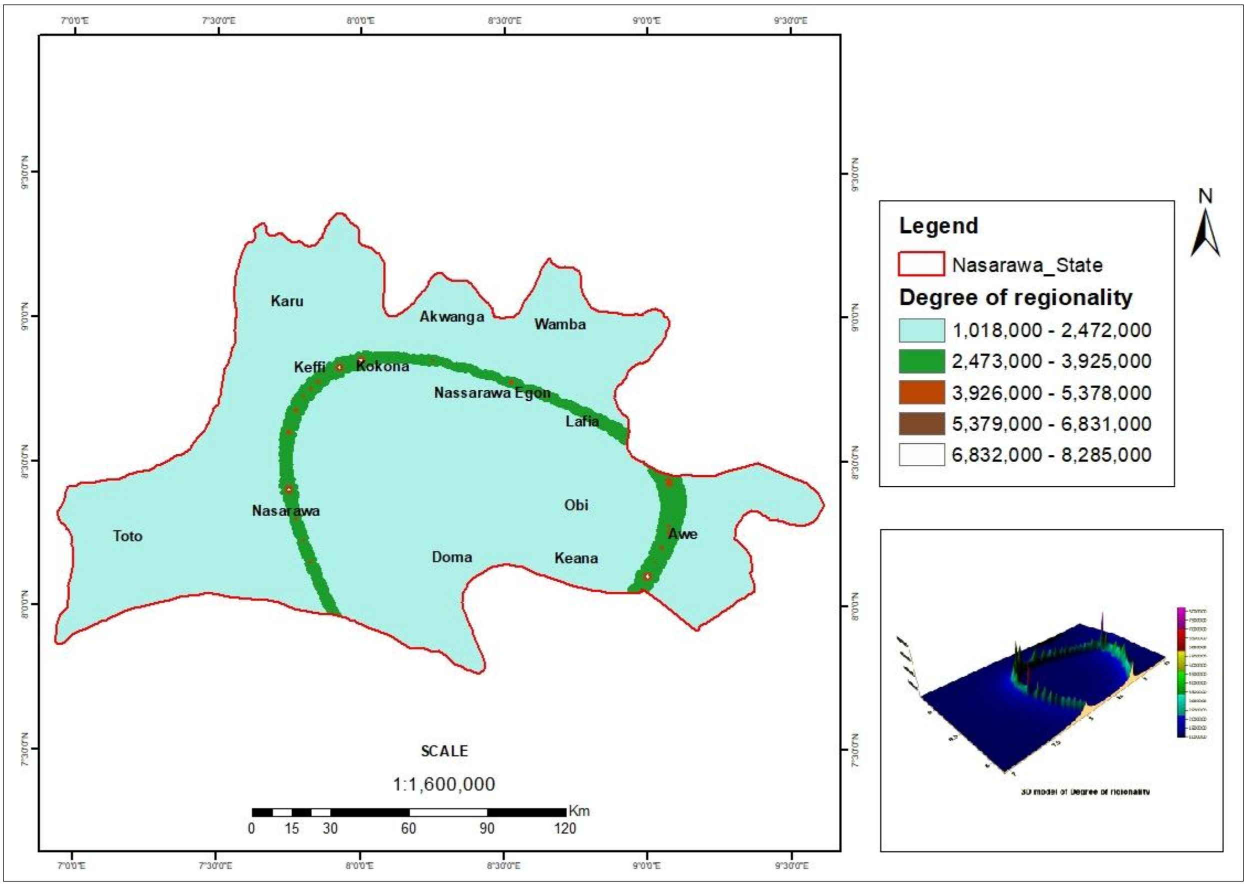

Figure 4. 6: Degree of Regionality.

4.1.12 Second Horizontal Derivatives (SHD)

The SHD map highlights lateral variations in gravity gradients, emphasizing abrupt changes in gravity anomalies along horizontal directions. It helps identify linear features such as faults, shear zones, and lithological contacts that may serve as preferential pathways for groundwater flow and influence groundwater potential distribution. SHD maps assist in delineating structural controls on groundwater flow and storage within the study area.Figure 4.12 shows the SHD map, it depicts the structural trend of the study area. The general trends of the lineaments delineated revealed, linear features show variations in strike and become parallel to the dominant strike in the basement with sinistral strike-slip sense of movement (Ajakaiye et al., 1986, Epuh et al, 2020 and Abdullateef et al. 2021).The SHD values ranging from -0.08976 to -0.03755mgal/m^2 in Nassarawa state indicate the highest groundwater potential, which is attributed to notable variations in the subsurface. Values ranging from -0.03754 to 0.01467mgal/m^2 indicate a significant level of potential, while higher values indicate a lesser level of groundwater potential, with a range of 0.1192 to 0.1713 mgal/m^2 being the least favourable due to negligible change beneath the surface.

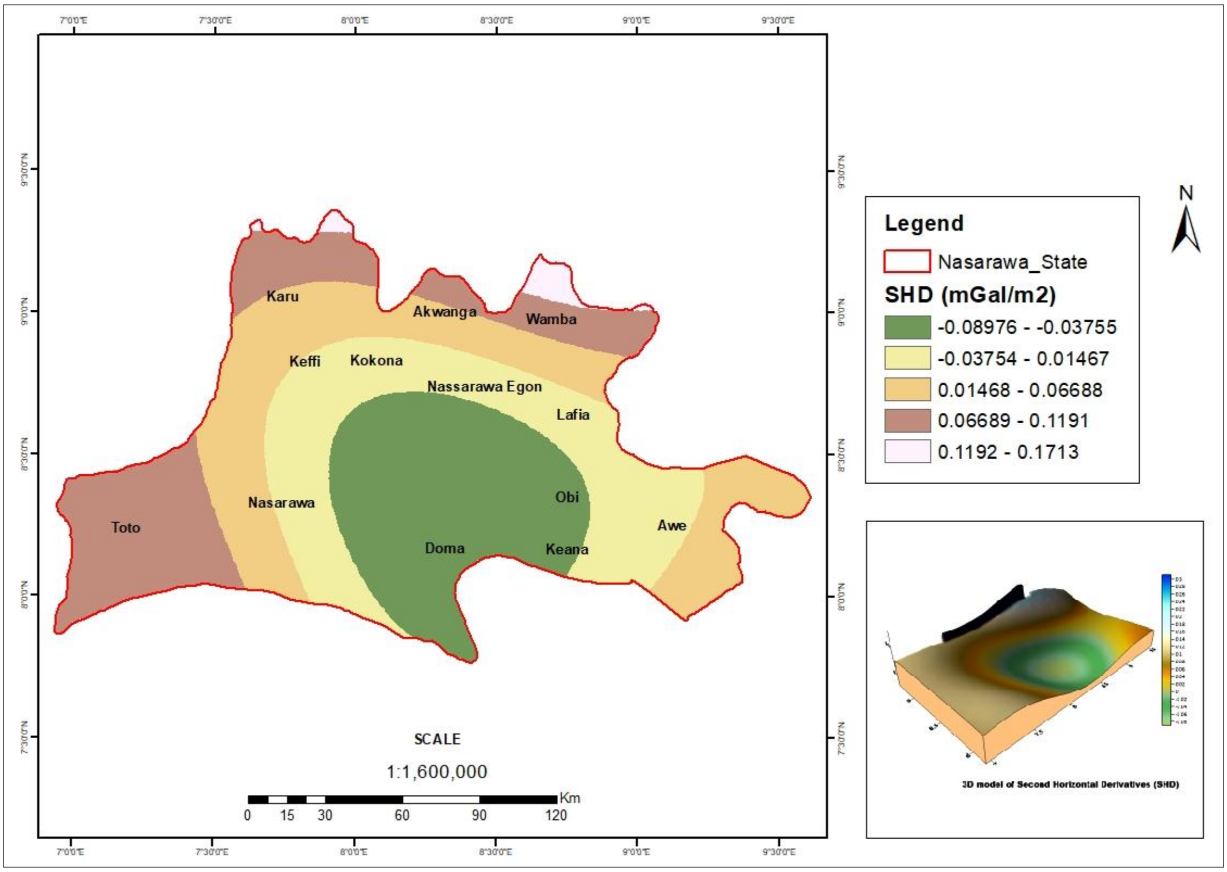

Figure 4. 7: Second Horizontal Derivative (SHD).

4.1.13 Basement Depth

The basement arches are important as a means of reconstructing the epirogenic movements that have taken place in the trough (Epuh and Joshua (2018). In hydrogeological investigations, the depth of the basement is a crucial component that affects the occurrence and transport of groundwater. A shallow depth of the basement can be a sign of unconsolidated sedimentary deposits that have the potential to become aquifers. Conversely, the existence of hard, impermeable rocks that restrict groundwater circulation may be indicated by a deeper basement. Figure 4.13 shows the basement depth of Nasarawa State.Satellite gravity data in Nassarawa state indicates that the basement's depth substantially impacts the groundwater potential. The greatest potential lies at depths ranging from 2.473 to 3.09 km, as these depths have thicker sedimentary layers that have a higher capacity to hold water. Depth ranges of 1.856 – 2.472km exhibit significant potential, whereas depths of 1.239 – 1.855km present a more moderate level of potentiality. The shallower depths, ranging from 0.6208 to 1.238 km and from 0.003538 to 0.6207 km, have the lowest contribution because thinner layers of sediment store a smaller amount of groundwater. This data aids in identifying the most favourable locations for groundwater exploration and the effective administration of groundwater resources.

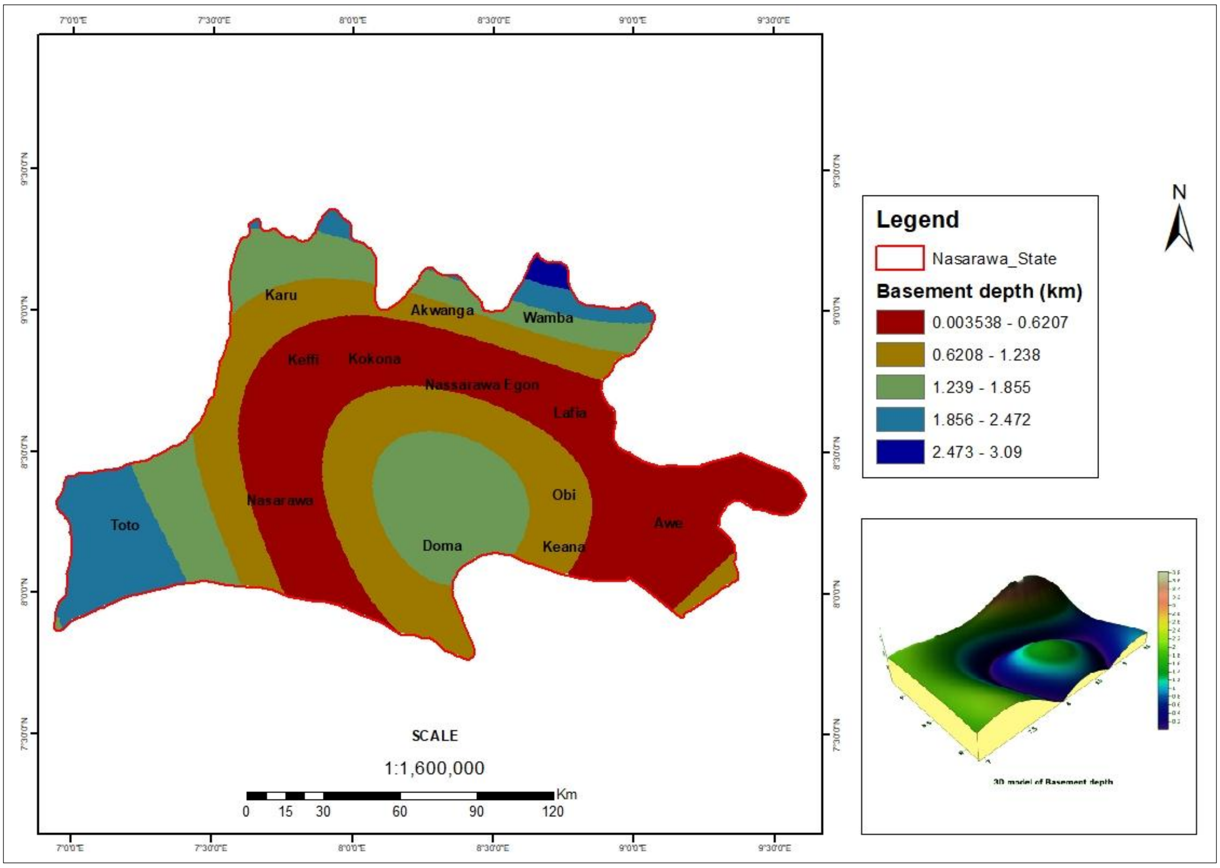

Figure 4. 13: Basement depth.

4.2 Generation of the groundwater potential maps

4.2.1 The Remote Sensing Groundwater potential map of Nasarawa State

The groundwater prospect zones were evaluated based on the integration of all groundwater influencing thematic layers: geology, lineament density, soil texture, drainage density, rainfall, slope, land cover. Figure 4.14 show the groundwater potential zones of Nasarawa State state as defined using the AHP methods. The results of the groundwater potential zones derived using the AHP model reveal that the majority of the area falls within the moderate potential zone, covering 19,577.23 km², which constitutes 75.23% of the total area (Karu, Keffi, Kokona, Toto, Akwanga, Wamba and obi local Government Area). The high potential zone accounts for 4,313.94 km² or 16.58%(Keana, Awe,some part of Doma and a significant part of Nasarawa local Government Area) while the low potential zone spans 2,131.24 km² or 8.19% (Nasarawa Egon, Northern Part of Wamba and Akwanga). The very low and very high potential zones are minimal, covering 0.92 km² (0.004%) and 0.7 km² (0.003%), respectively. These findings shown in figure 1.14 suggest that most of Nassarawa State has moderate to high groundwater potential, with negligible areas having very low or very high potential.

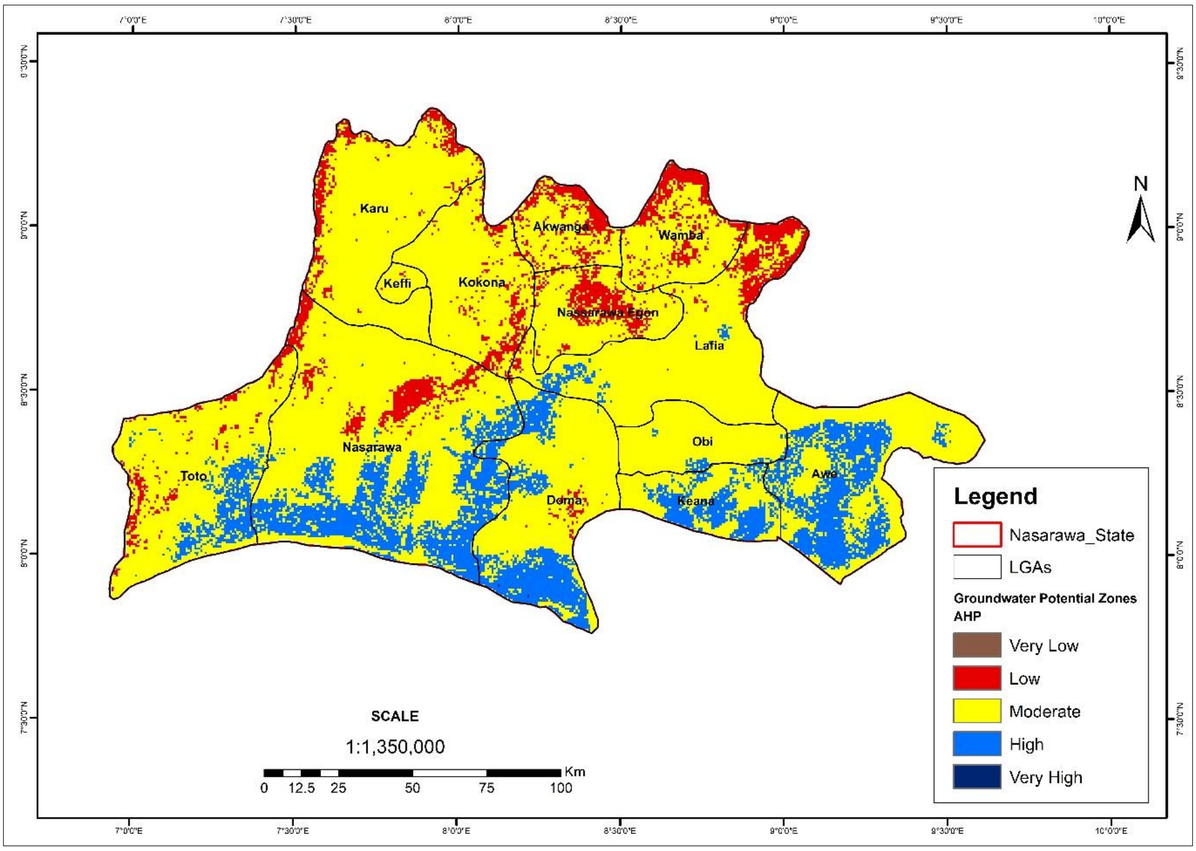

Figure 4. 14: Remote Sensing Groundwater Potential Zone.

Table 4. 1: Area and percentage distribution of the groundwater potential zones.

S/N	Zone	Area (Km^2)	Area (%)
1.	Very Low	0.92	0.004
2.	Low	2131.24	8.190
3.	Moderate	19577.23	75.228
4.	High	4313.94	16.577
5.	Very High	0.7	0.003
	TOTAL	**26024.03**	**100**

4.2.2 Groundwater Potential Zone Map Of Nasarawa State Using Integrated Remote Sensing And Gravity Thematic Maps

The results of the groundwater potential zones derived from integrating AHP and Satellite gravity as shown in figure 4.16 indicate that the majority of the area falls within the moderate potential zone, covering 12,423.79 km², which constitutes 47.74% of the total area. The high potential zone encompasses 7,407.09 km², accounting for 28.46%, while the low potential zone spans 3,333.73 km², or 12.81%. The very high potential zone covers 2,773.29 km² (10.66%), and the very low potential zone is minimal, covering 86.12 km² (0.33%). These findings suggest that most of Nassarawa State has moderate to high groundwater potential, with only small areas exhibiting very low potential.The result shows that places like Karu, Kokona, Toto and Lafia local Government Areas of the State falls in moderate categories.The low GWPZ can be significantly found in Keffi, Akwanga, Wamba and Nasarawa Egon Local Government Areas of the State.The high GWPZ can be largely found in Awe, Obi, and some part of Nasarawa local Government Areas of the State.The very high GWPZ can be found in some part of Doma and Kaena LGEA of the State.

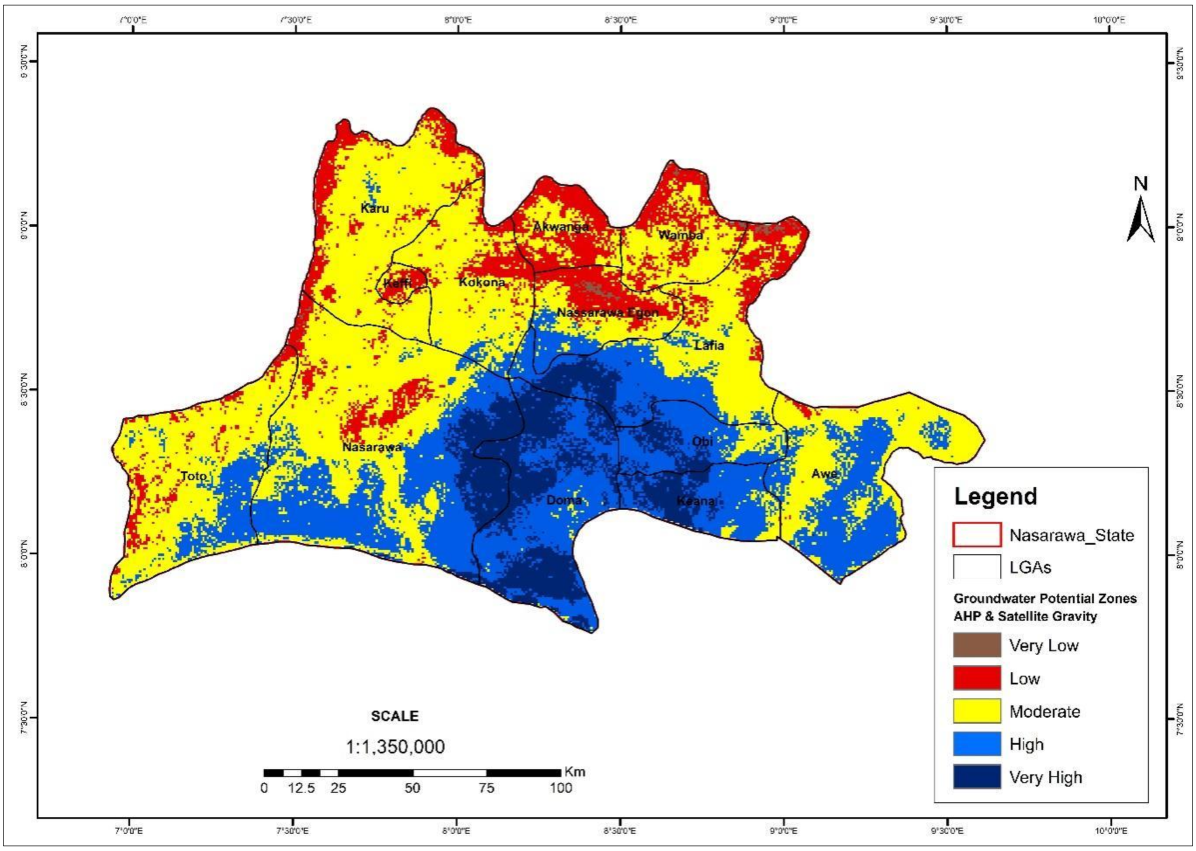

Figure 4.16: Groundwater Potential Zone (Remote sensing and Satellite Gravity).

Table 4. 2: Area and percentage distribution of the groundwater potential zones (Remote Sensing and Gravity).

S/N	Zone	Area (Km^2)	Area (%)
1.	Very Low	86.122	0.330933
2.	Low	3333.732	12.81021
3.	Moderate	12423.79	47.73969
4.	High	7407.092	28.46251
5.	Very High	2773.292	10.65666
	TOTAL	**26024.03**	**100**

4.3 Discussion

The results show that the groundwater potential zones of the study area were classified into five zones with the percentage for spatial distribution.The results of the groundwater potential zones derived from integrating AHP and Satellite gravity indicate that the majority of the area falls within the moderate potential zone, covering 12,423.79 km², which constitutes 47.74% of the total area. The high potential zone encompasses 7,407.09 km², accounting for 28.46%, while the low potential zone spans 3,333.73 km², or 12.81%. The very high potential zone covers 2,773.29 km² (10.66%), and the very low potential zone is minimal, covering 86.12 km² (0.33%). Alluvial, Sandstone and Shales found within the southern region of the state; occupied by high and very high groundwater potential zone. The latter is due to a favourable combination of hydrological, and hydrogeological factors, such as a low slope, low-moderate drainage density, high rainfall, permeable lithology and high lineament density (Abdullateef et al 2021).The undifferentiated basement complex and magnetite within the northwest and northeastern zones of Nasarawa State is occupied by the moderate and low groundwater potential zones. According to Abdullateef et al (2021), the basement setting (low-very low potential) can, however, be attributed to the generally undulating topography and medium-high slopes, moderate-low drainage density, high-moderate hydraulic head, and moderate-high lineament densities. Fashae et al. (2014), Tijani et al., (2016) and Abdullateef et al (2021) stated that the medium to low groundwater potential in the basement areas, is a reflection of the marginal aquifer productivity known to be associated with fracture-type aquifers in most basement terrain.The Bouguer anomaly map as shown in figure 4.9 is characterized by negative values (gravity lows) at the Southern part of Nasarawa State(Doma,Keana,Obi, Awe and Nasarawa local Govt Areas) and positive value at the northern part of the state(Wamba,Karu, Toto, Akwanga, and some part of Kokona,). This zone with high negative gravity value represents the sedimentary section of the Sate with the increase in gravity lows; synonymous with the presence of intrusive rocks and increase in sedimentary thickness towards the flanks. Positive Bouguer gravity anomaly in the northern area of the state marked the intrusion of dense rocks in this area.The mechanical stiffness map as shown in (Figure 4.12) shows the northern zone of the study area as zones of high rock mechanical stiffness indicating the dominant presence of igneous (crystalline) rocks with high density. The southern region of the state are zones of low mechanical rock stiffness indicating zones of low-density rock deposits. The southern region are zones of low mechanical rock stiffness indicating zones of low-density rock deposits.The southern zones are sedimentary zones and it corroborate with the findings from the remote sensing as a groundwater potential zone. According to (Pratsch, 1986, 1994 and Epuh *et al.*, (2011, 2017)) residual gravity anomaly maps indicates the direction of migration of a fluid in a basin. Figure 4.12 shows a residual gravity anormaly map with anormaly values decreasing towards the southern region of the state.This shows that the basin basement has a listric geometry which is inclined towards the flank (Southern region) and as such, groundwater within the basin, will naturally migrate towards the flank.

Figures 4.13 and 4.12 show linear features commonly representing lithological contacts which are interpreted as fault (sinistral strike-slip wrench) systems in the Lower Benue Trough contacts, faults, fractures and dyke swarms (Lee & Morris, 2013, Okiwelu *et al., 2015*). Lineament Basement rocks only acquire porosity and permeability when they fracture, that is, when stresses are applied to them and they break (Lachassagne et al, 2019)**.** The geologic structures like dykes, lineaments, and fractures act as both carriers as well as barriers for groundwater flow (Nilsen *et al.* 2003; Al-Taj 2008; Perrin *et al.* 2011 and Senthilkumar et al.; 2016).The basement depth map (figure 4.13) obtained shows a basement topography of between 0.003538km and 1.238km within the northern zones, and between 1.85km and 3.09km within the sedimentary zone (southern). This correspond with the works of Epuh *et al* (2011, 2017). Ejepu et al. (2017) affirmed that depth of basement is a very important in geophysics to evaluate potentiality of a location for groundwater exploration; the thicker the depth of basement, the more groundwater the area accumulates and the higher the viability of such location to yield groundwater.

4.4 Conclusion

The integration of Geographic Information Systems (GIS), Remote Sensing (RS), Satellite Gravity and Analytic Hierarchy Process (AHP) models has significantly transformed the process of mapping groundwater in Nassarawa State, Nigeria. The results of this study shows that the integration of remote sensing and satellite gravity thematic maps is an effective method of fusing the deep surface features and remote sensing features to produce an effective groundwater potential map.The findings in this study shows that the moderate potential zones dominate the state, followed by the high potential, the low potential zone, very high potential zone and very low potential zone respectively. The result further shows that the region with the high and very high groundwater have good geological formation the support groundwater infiltration and accumulation, such as shale and sand stones, large basement depth, high negative mechanical stiffness, negative bouguer anormaly values, which correspond with the remote sensing thematic maps groundwater contributing factors.This also indicate that the zone of high and very high potential have low elevation, low slope gradient, high lineament density, sandy loam soil, high agriculture and vegetation. While the region with moderate and low groundwater potential zones have geological formation such as undifferentiated basement complex and magnetite, which support little groundwater. The satellite gravity derivatives filter thematic maps equally indicate that this moderate and low zones have low basement depth, high bouguer and residual anomaly values and high mechanical stiffness values. The region is characterized with high elevation and slope, making water to flow downward.

The integration of remote sensing, GIS, and satellite gravity has proven to be an efficient, cost-effective, and time-saving approach for delineating groundwater potential zones. In the weighted overlay analysis, individual variables within each thematic map were assigned rankings and weights based on their influence. The study revealed significant spatial variability in groundwater potential across the study area, closely linked to variations in rainfall, geology, slope, soil, drainage density, lineament density, and land use. Additionally, the study demonstrated a positive correlation between groundwater potential and bedrock characteristic, as assessed using both GIS and remote sensing techniques, as well as the satellite gravity.

The utilization of geospatial and satellite gravity techniques is an easier and faster approach in prospecting and in preliminary survey in light of the fact that the cost of drilling boreholes in arbitrary manner is very expensive. However, the study suggests that Groundwater potential zones mapping ought to be completed for the whole nation to fill in as a guide for water asset organizations and artificial recharge points should be created especially in regions that has low and very low potential zones

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