
ASSESSING THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER RECHARGE POTENTIAL IN PALLADAN, ZARIA, KADUNA STATE, NIGERIA.

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ABSTRACT

Groundwater constitutes the primary source of potable water for communities in the Nigerian Basement Complex region, yet its sustainability is increasingly threatened by climate change-induced rainfall variability and anthropogenic land degradation. This study assessed groundwater recharge potential in Palladan, Zaria, Kaduna State, Nigeria, using a GIS-based Multi-Criteria Decision Analysis (MCDA) and Weighted Overlay Analysis (WOA) framework integrated with the Analytical Hierarchy Process (AHP) for criterion weight derivation. Seven thematic criteria — rainfall (CHIRPS v2.0, 1981-2024), soil type (FAO Nigeria dataset), slope (SRTM 30 m DEM), geology (FAO Nigeria dataset, geology attribute field), lineament density (terrain roughness proxy), drainage density (GRASS r.watershed), and land use/land cover (Landsat 8/9 OLI NDVI, November 2022) were acquired, pre-processed in QGIS 4.0.1, reclassified to a 1-5 ordinal scale, and combined using AHP-derived weights. The AHP pairwise comparison yielded a Consistency Ratio (CR) = 0.025 (< 0.10 threshold), confirming statistical reliability. Key results included mean annual rainfall of 966.21 mm/year, mean slope of 1.90 degrees, Clay Loam soil texture, Migmatite geology, and mean NDVI of 0.115. The resulting Groundwater Potential Index (GWPI) ranged from 2.31 to 4.56, with a mean of 3.57. Classification into four groundwater potential zones revealed that Palladan is predominantly characterized by High potential (Zone 4), which covers approximately 69% of the study area, driven by favourable rainfall and exceptionally flat terrain; Moderate potential (Zone 3) accounts for a further 29.5%, while Very Low and Low potential zones (Zones 1-2) together occupy less than 1.5% of the study area. The study concludes that while Palladan possesses substantial groundwater recharge potential, projected increases in rainfall variability and land degradation under climate change scenarios pose significant long-term threats to recharge sustainability.

Keywords: Groundwater; recharge potential; Climate change; GIS-based analysis; Palladan Zaria

1. INTRODUCTION

Groundwater is the primary source of freshwater for domestic, agricultural, and industrial use for approximately 2.5 billion people worldwide, and constitutes the dominant water supply source for rural and peri-urban communities across the Nigerian Basement Complex region (UNESCO, 2022; Adelana & MacDonald, 2008). In northern Nigeria, where seasonal rainfall is confined to a five-month wet season (April to October) and surface water availability is highly variable, sustainable groundwater management is a critical determinant of community water security.

The Palladan community in Zaria, Kaduna State, represents a rapidly growing peri-urban settlement located on the Precambrian Migmatite-Gneiss Basement Complex of North-Western Nigeria. Like many communities in the Guinea Savannah ecological zone, Palladan is heavily dependent on groundwater extracted from fractured basement aquifers for drinking water, domestic use, and small-scale agriculture. The sustainability of this groundwater resource is, however, subject to growing pressure from two converging threats: climate change-induced variability in rainfall patterns that reduces the predictability and volume of annual recharge, and anthropogenic land use degradation that diminishes the infiltration capacity of the land surface.

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) confirms that global mean temperatures have risen by approximately 1.1°C above pre-industrial levels,

with corresponding changes in the West African rainfall regime including increased inter-annual variability and shifts in seasonal rainfall distribution. For the Guinea Savannah zone of North-Western Nigeria, these changes translate directly into less predictable groundwater recharge, potential depletion of shallow basement aquifers during extended dry periods, and increased vulnerability of communities dependent on groundwater for year-round water supply. Long-term climate-groundwater interactions of this kind have been documented globally; for instance, Taylor et al. (2013) demonstrate that groundwater systems respond to climate variability on markedly longer timescales than surface water, with recharge signals often lagging rainfall anomalies by years to decades — underscoring the importance of establishing a robust present-day recharge-potential baseline, such as the one produced by this study, against which future climate-driven change can be measured.

Delineating groundwater potential zones — mapping where recharge is most likely to occur and be most productive — is a critical prerequisite for evidence-based groundwater management and borehole siting in data-scarce environments. GIS-based Multi-Criteria Decision Analysis (MCDA), integrated with the Analytical Hierarchy Process (AHP) and Weighted Overlay Analysis (WOA), has emerged as a widely validated and cost-effective methodology for this purpose in basement complex terrain across sub-Saharan Africa (Fashae et al., 2014; Jha et al., 2010; Osumaje et al., 2024).

This study applies GIS-based MCDA/WOA to assess groundwater recharge potential in Palladan, Zaria, using exclusively freely available open-access satellite datasets, thereby providing a replicable methodology for data-scarce communities across the Nigerian Basement Complex. The study frames this assessment within the context of climate change impacts on groundwater recharge, contributing to the growing body of literature on climate-groundwater interactions and assesses current land use and land cover conditions.

2. STUDY AREA

Palladan is a densely populated peri-urban community located within Sabon Gari Local Government Area, Zaria, Kaduna State, Nigeria (approximately 11.08°N, 7.69°E). The community lies adjacent to the Nigerian College of Aviation Technology (NCAT) and the Zaria Airport in the southern portion of Zaria metropolitan area. Palladan is situated within the Guinea Savannah ecological zone, characterized by a mean annual rainfall of approximately 966 mm/year (CHIRPS v2.0, 1981-2024) distributed across a five-month wet season (April to October) and a seven-month dry season dominated by the northeast trade winds (Harmattan).

The geology of the study area is dominated by Migmatite of the Precambrian Basement Complex, with associated gneisses and granite intrusions characteristic of the broader Zaria geological province. The dominant soil type is Clay Loam with moderate drainage and moderately deep profile, overlying the fractured Migmatite bedrock.

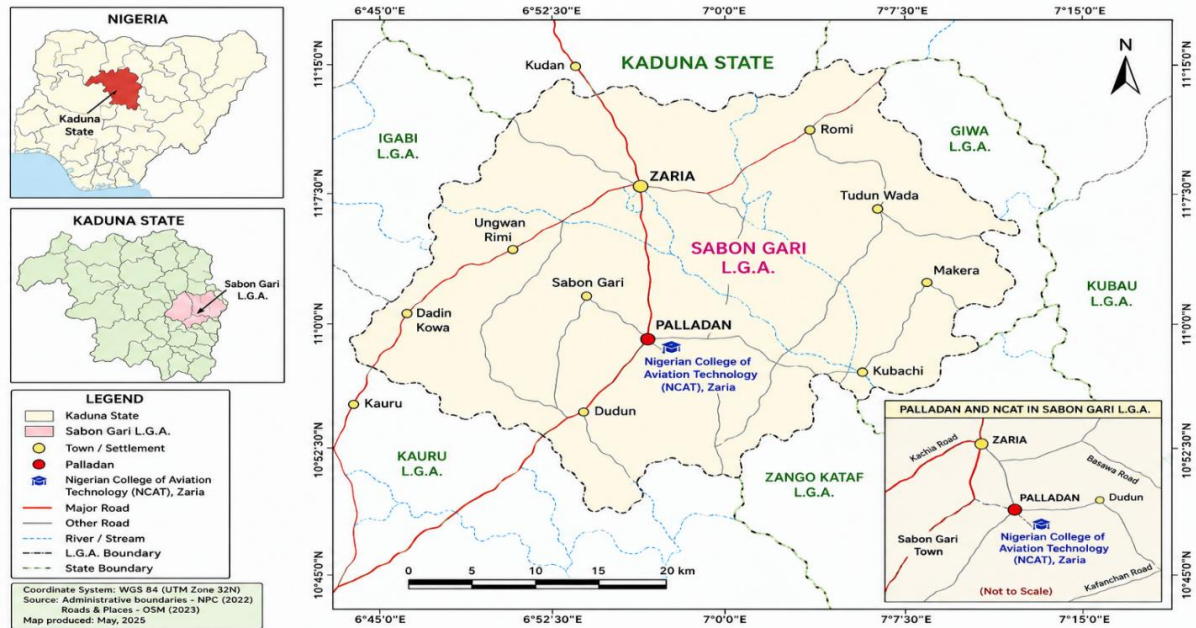


Figure 1: A map showing Palladan, the study area (boundary coordinates verified against the source GIS project: approx. 11.08°N, 7.69°E).

3. MATERIALS AND METHODS

3.1 Data Sources

Seven thematic datasets were acquired from open-access repositories. Table 1 summarizes the data sources, formats, and spatial resolutions used in this study. Soil texture and geology attributes were both derived from the same FAO World Soil Database for Nigeria: the soil layer draws on the SOIL_TEXTU and related soil attribute fields, while the geology layer draws on the GEOLOGY attribute field of the same clipped shapefile. They are therefore two attributes of a single source dataset rather than independently sourced layers; slope and elevation, by contrast, are derived separately from the SRTM 30 m DEM.

Table 1: Thematic datasets used in the study

Thematic Layer	Data Source	Format	Resolution / Period
Rainfall	CHIRPS v2.0	GeoTIFF	~5 km / 1981-2024
Soil (texture, drainage)	FAO World Soil Database — Nigeria (soil attribute fields)	Shapefile	1:5,000,000
Geology (lithology)	FAO World Soil Database — Nigeria (GEOLOGY attribute field, same shapefile as Soil)	Shapefile	1:5,000,000
Slope / Elevation	SRTM 1 Arc-Second Global (USGS, 2000) — Tile N11E007	GeoTIFF	30 m
Lineament density	Derived from SRTM DEM (Roughness tool, QGIS)	GeoTIFF	30 m
Drainage density	Derived from SRTM DEM (GRASS r.watershed)	GeoTIFF	30 m
LULC / NDVI	Landsat 8/9 OLI C2 L2 (USGS) — Path 189/Row 053	GeoTIFF	30 m / Nov 2022

3.2 Study Area Boundary Delineation

The Palladan study area boundary was manually digitized in QGIS (version 4.0.1) using Google Satellite imagery as the primary reference and OpenStreetMap as a supplementary base map for road and settlement boundary identification. In the absence of an officially gazetted community boundary for Palladan, the digitized polygon represents the spatial extent of the visible settlement. All spatial data were projected to WGS 84 / UTM Zone 32N (EPSG:32632) to ensure spatial consistency across all thematic layers.

3.3 Thematic Layer Processing

All datasets were pre-processed in QGIS and standardized to EPSG:32632 prior to analysis. The CHIRPS rainfall raster was reprojected using the GDAL Warp algorithm. The FAO soil shapefile was clipped to the Palladan boundary using the Vector Overlay Clip tool to extract soil type, drainage, and geology attributes. The SRTM DEM was reprojected, clipped, and processed through the QGIS Raster Terrain Analysis suite to derive slope and roughness layers; elevation itself is not one of the seven weighted criteria but is retained as an intermediate product of this processing chain, used solely to derive the slope layer. Drainage network extraction employed the GRASS r.watershed algorithm with a minimum basin size of 1,000 cells. NDVI was computed from Landsat 8/9 OLI Band 4 (Red) and Band 5 (Near Infrared) surface reflectance values using:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) = (\text{Band 5} - \text{Band 4}) / (\text{Band 5} + \text{Band 4}) \quad (1)$$

Mean values for each thematic layer within the Palladan boundary were extracted using the QGIS Zonal Statistics tool.

3.4 Reclassification

Each thematic layer was reclassified to a common ordinal scale of 1 to 5 to enable spatial combination, where higher scores indicate greater groundwater recharge potential. The complete reclassification scheme for each criterion, covering the full range of values encountered in the underlying dataset (not only the range observed within the Palladan boundary), is presented in Tables 2a-2g. The value applicable to Palladan is indicated in bold in each table.

Table 2a: Reclassification — Rainfall

Rainfall Range (mm/yr)	Score	Recharge Potential
< 400	1	Very Poor
400 – 600	2	Poor
600 – 800	3	Moderate
800 – 1,000	4	Favourable — Palladan (966.21 mm/yr)
> 1,000	5	Very Favourable

Table 2b: Reclassification — Slope

Slope Range (degrees)	Score	Recharge Implication
0 – 2	5	Very favourable — minimal runoff — Palladan mean 1.90°
2 – 5	4	Favourable
5 – 7.21	3	Moderate — Palladan maximum 7.21°

Table 2c: Reclassification — Soil Texture

Soil Texture	Score	Infiltration Characteristic
Gravel / Coarse Sand	5	Very rapid infiltration — excellent recharge
Sandy Loam	4	Rapid infiltration — good recharge
Clay Loam	3	Moderate infiltration — Palladan soil type
Silty Clay	2	Slow infiltration — limited recharge
Heavy Clay	1	Very slow / negligible infiltration

Table 2d: Reclassification — Geology

Rock / Geological Type	Score	Groundwater Potential Basis
Alluvium / River deposits	5	High primary porosity — excellent water storage
Sandstone / Limestone	4	Good natural porosity — reliable aquifer
Migmatite / Weathered basement	3	Secondary porosity through fractures — Palladan geology
Granite (fresh / unweathered)	2	Low porosity — poor aquifer
Quartzite	1	Near-impermeable — negligible groundwater potential

Table 2e: Reclassification — Lineament Density (Terrain Roughness Proxy)

Roughness Range	Score	Lineament Density Interpretation
0 – 2	1	Very low — Palladan mean roughness 2.855
2 – 4	2	Low to moderate
4 – 6	3	Moderate lineament density
6 – 8	4	High lineament density
8 – 10	5	Very high — intense fracturing or faulting (Palladan max = 9)

Table 2f: Reclassification — Drainage Density (Stream Order)

Stream Order	Score	Recharge Implication
Order 1 (lowest drainage)	5	Minimal channelled drainage — most rainfall infiltrates
Order 2	4	Low drainage — favourable for recharge
Order 3 (Palladan mean ~2.9)	3	Moderate drainage — balanced infiltration and runoff
Order 4	2	Higher drainage — reduced recharge opportunity
Order 5+ (major rivers)	1	Rapid runoff removal — minimal recharge

Table 2g: Reclassification — LULC / NDVI

NDVI Range	Land Cover Type	Score
< 0	Water bodies / dense cloud	—
0.00 – 0.10	Bare soil / impervious surfaces / rock outcrops	2
0.10 – 0.30	Sparse vegetation / degraded savannah — Palladan (0.115)	3
0.30 – 0.60	Moderate vegetation — shrubland, grassland	4
> 0.60	Dense vegetation — forest, thick farmland	5

3.5 Analytical Hierarchy Process (AHP) Weight Derivation

Criterion weights were derived using the AHP pairwise comparison method (Saaty, 1980). A 7x7 pairwise comparison matrix was constructed using Saaty's 1-9 importance scale, based on the established importance of each criterion for groundwater recharge in basement complex terrain; the full matrix is presented in Table 3a. Weights were derived through column normalization and row averaging of the pairwise matrix. The Consistency Ratio (CR) was calculated as:

$$CI = (\lambda_{\max} - n) / (n - 1) = (7.1973 - 7) / 6 = 0.0329 \dots \dots \dots (2)$$

$$CR = CI / RI = 0.0329 / 1.32 = 0.025 \dots \dots \dots (3)$$

The CR of 0.025 is well below Saaty's acceptable threshold of $CR < 0.10$, confirming the statistical consistency of the pairwise judgments. The derived weights are presented in Table 3b.

Table 3a: AHP pairwise comparison matrix

Criterion	Rainfall	Slope	Soil	Lineament	Geology	Drainage	LULC
Rainfall	1	2	3	4	5	6	7
Slope	1/2	1	2	3	4	5	6
Soil	1/3	1/2	1	2	3	4	5
Lineament	1/4	1/3	1/2	1	2	3	4
Geology	1/5	1/4	1/3	1/2	1	2	3
Drainage	1/6	1/5	1/4	1/3	1/2	1	2
LULC	1/7	1/6	1/5	1/4	1/3	1/2	1

Table 3b: AHP-derived criterion weights

Criterion	Weight	%	Rank
Rainfall	0.3504	35.04%	1
Slope	0.2375	23.75%	2
Soil	0.1590	15.90%	3
Lineament density	0.1056	10.56%	4
Geology	0.0696	6.96%	5
Drainage density	0.0462	4.62%	6
LULC / NDVI	0.0318	3.18%	7
CR = 0.025 (< 0.10 Consistent)	—	—	—

3.6 Weighted Overlay Analysis

The Groundwater Potential Index (GWPI) was computed using the GDAL Raster Calculator in QGIS by applying the expression:

$$\text{GWPI} = (0.3504 \times \text{Rainfall}) + (0.2375 \times \text{Slope}) + (0.1590 \times \text{Soil}) + (0.1056 \times \text{Lineament}) + (0.0696 \times \text{Geology}) + (0.0462 \times \text{Drainage}) + (0.0318 \times \text{LULC}) \dots (4)$$

The GWPI raster was subsequently classified into four groundwater potential zones using the Reclassify by Table tool: Very Low (GWPI 2.00 - 2.50), Low (2.50 - 3.00), Moderate (3.00 - 3.50), and High (3.50 - 4.56).

4. RESULTS

4.1 Thematic Layer Results

Table 4 presents a summary of the key thematic layer results derived from the spatial analysis. Elevation is listed for reference but, as noted in Section 3.3, is not one of the seven weighted criteria; it is an intermediate SRTM-derived layer used only to compute slope, which is why it carries no score or AHP weight.

Table 4: Summary of thematic layer results

Layer	Key Result	Score	AHP Weight
Rainfall (CHIRPS 1981-2024)	966.21 mm/year	4/5	35.04%
Soil (FAO)	Clay Loam / Dystric Cambisol	3/5	15.90%
Elevation (SRTM) — intermediate layer, not a scored criterion	Mean 663 m (range 644-678 m)	—	—
Slope (SRTM)	Mean 1.90 degrees (0-7.21 degrees)	3-5/5	23.75%
Geology (FAO)	Migmatite Basement Complex	3/5	6.96%
Lineament (roughness proxy)	Mean roughness 2.855 (0-9)	1-3/5	10.56%
Drainage (r.watershed)	Mean stream order 2.923 (2-4)	3/5	4.62%
LULC / NDVI (Landsat 8/9)	Mean NDVI 0.115	3/5	3.18%

4.2 Groundwater Potential Index (GWPI) and Zone Map

The Weighted Overlay Analysis produced a GWPI raster with values ranging from 2.31 to 4.56 across 3,270 valid pixels within the Palladan study area, with a mean of 3.57 (standard deviation 0.168). This mean falls within the High classification band (3.50-4.56), consistent with the spatial dominance of the High potential zone described below. Classification of the GWPI into four groundwater potential zones produced the map presented in Figure 2, while the zone distribution — including the percentage of the study area occupied by each zone, obtained from a unique-values area report on the classified zone raster — is summarized in Table 5.

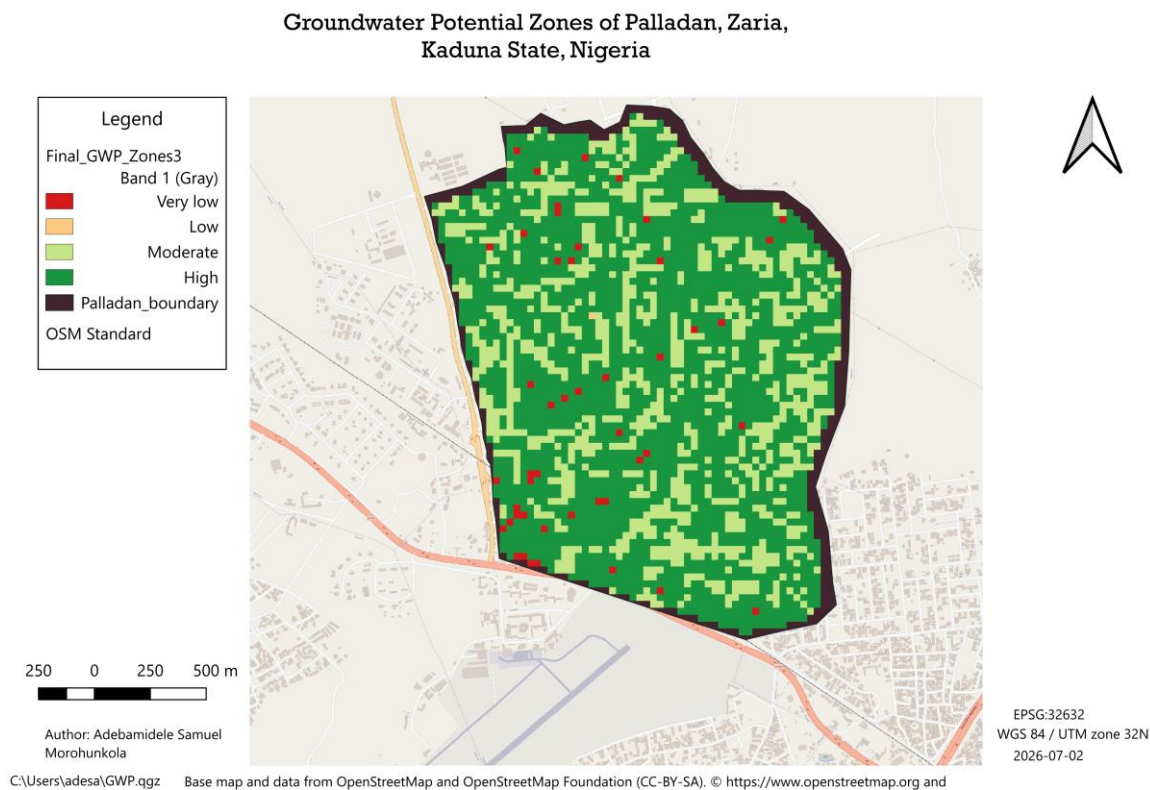


Figure 2: Groundwater Potential Zone Map of Palladan, Zaria, Kaduna State, Nigeria.

Table 5: Groundwater potential zone classification

Zone	GWPI Range	Classification	Pixel Count	Area (%)	Spatial Distribution
1	2.00-2.50	Very Low	47	1.44%	Isolated patches — boundary margins, areas of higher drainage density
2	2.50-3.00	Low	1	0.03%	Negligible — a single pixel within the study area
3	3.00-3.50	Moderate	965	29.51%	Patchy distribution — transitional areas
4	3.50-4.56	High	2,257	69.02%	Dominant — covers majority of Palladan (flat central and northern portions)

The High potential zone (Zone 4) dominates the spatial pattern of the GWPI map, covering approximately 69% of the Palladan study area, with the Moderate zone (Zone 3) accounting for a further 29.5%. Very Low and Low potential zones (Zones 1 and 2) together occupy less than 1.5% of the study area and are correctly described as isolated, near-negligible occurrences rather than a substantial minority class. This result is attributable to the combined effect of the two highest-weighted criteria: mean annual rainfall of 966.21 mm/year (score 4, weight 35.04%) and exceptionally flat terrain with mean slope of 1.90 degrees (score 5 for most pixels, weight 23.75%). Together, these two criteria contribute approximately 2.59 units to the GWPI of every flat-terrain pixel in Palladan, establishing a strong recharge potential foundation that is difficult to overcome even when other criteria score moderately.

It is worth noting that the GWPI distribution is not continuous but clusters around a small number of discrete value bands, as shown in the pixel-value histogram in Figure 3. This clustering arises

because most of the seven input layers are themselves discrete: rainfall, soil, and geology each take a single constant reclassified score across the entire Palladan raster (since each is derived from one CHIRPS value or one FAO polygon), while slope, lineament density, drainage density, and NDVI are each reclassified to a small set of integer scores (1-5) rather than varying continuously. Combining a limited number of discrete-scored layers through a fixed set of AHP weights necessarily produces a GWPI raster that can only take a limited number of possible values, which appear as distinct clusters separated by gaps rather than as a smooth continuous surface. This explains why the Very Low zone (2.00-2.50) contains a modest but real cluster of 47 pixels while the adjacent Low zone (2.50-3.00) captures only a single pixel: the fixed 0.50-wide zone boundaries used for classification happen to bisect a near-empty gap between two value clusters rather than reflecting any error in computation. This is a recognised characteristic of ordinal-reclassification-based MCDA/WOA models and does not affect the validity of the reported GWPI mean, zone-area percentages, or overall High-zone dominance.

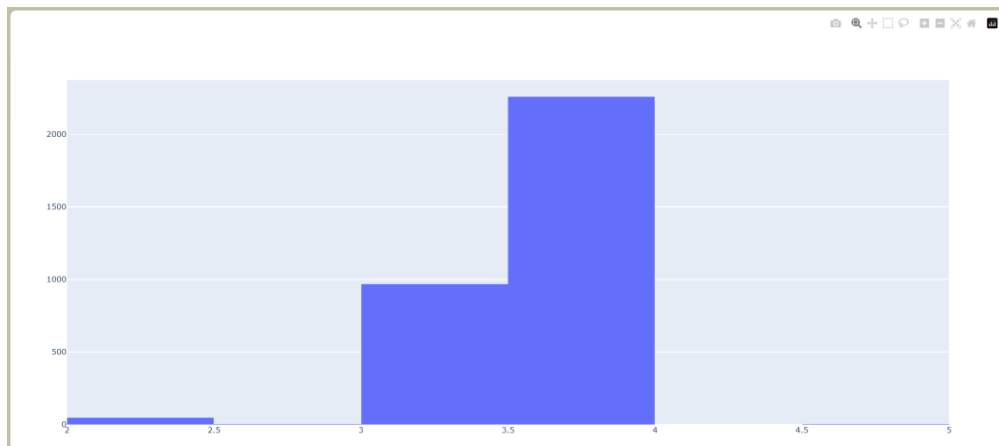


Figure 3: Histogram of GWPI pixel values (x-axis: GWPI, y-axis: pixel count), showing the discrete, clustered distribution underlying the zone classification in Table 5.

Very Low (Zone 1) and Low (Zone 2) potential zones occur as isolated, scattered patches within the study area, primarily in locations where terrain roughness is lower (indicating reduced fracture density) and drainage density is slightly higher (promoting faster runoff removal). The Moderate zone (Zone 3) is distributed as a substantial transitional band between the High and Very Low/Low zones, rather than as a minor category.

4.3 Validation

The groundwater potential zone map was validated against the independent geophysical investigation of Osumeje et al. (2024), who conducted an integrated remote sensing, aeromagnetic, and VES study across Palladan and Basawa in Sabon Gari LGA. Their study independently classified Palladan as exhibiting High groundwater potential, identified low-resistivity zones associated with NW/NE-trending fault systems as groundwater conduits, and reported fractured Migmatite basement aquifer thicknesses of 12-55 m.

This convergence is further supported by two additional independent geophysical investigations in and immediately around Palladan. Jegede et al. (2013) conducted a borehole-log and geophysical tomography investigation within Palladan itself, reporting a near-surface profile of approximately 10 m of loose, permeable laterite overlying degraded sand before the weathered Migmatite basement is reached — consistent with the moderately deep, moderately drained soil profile and fractured basement aquifer inferred from the FAO soil and geology layers used in this study. In the immediately adjacent ABU Samaru campus (approximately 2-3 km from Palladan, within the same basement complex terrain), Osumeje & Kudamnya (2014) used seismic refraction tomography across six profiles to

determine weathered-layer thickness and depth to fresh basement, reporting weathered thicknesses of 8-22 m and depths to fresh basement of 18-30 m, with four of the six profiles rated Good for groundwater potential and only one rated Poor. These independently derived depth and potential figures fall within a comparable range to the 12-55 m fractured aquifer thickness reported by Osumaje et al. (2024) for Palladan, reinforcing the overall picture of a productive, moderately thick weathered/fractured basement aquifer across the Palladan-Samaru area.

The convergence of results between the GIS-based MCDA/WOA model of this study and these three independent geophysical investigations — spanning Palladan itself and its immediately adjacent basement terrain — provides supporting qualitative cross-validation evidence for the reliability of the spatial model produced. This validation is, however, still qualitative in nature — based on agreement in overall classification and comparable depth ranges, rather than a formal quantitative accuracy metric such as percentage spatial overlap or statistical correlation with borehole yield data at specific coordinates. As acknowledged in the Limitations of the underlying dissertation this paper draws on, quantitative validation against primary borehole or pumping-test data referenced to the specific GWPI zones delineated in this study was not available and is recommended as a direction for future work; Fashae et al. (2014), for example, achieved a quantitative validation accuracy of 78% against borehole data in a comparable Basement Complex setting in South-Western Nigeria.

5. DISCUSSION

5.1 Groundwater Potential and Controlling Factors

The predominance of High groundwater potential zones in Palladan reflects a combination of hydrological and geomorphological conditions that are collectively favourable for groundwater recharge in basement complex terrain. The mean annual rainfall of 966.21 mm/year places Palladan within the upper portion of the favourable recharge rainfall bracket, providing a substantial annual water input that drives both diffuse and focused recharge mechanisms. The flat terrain, with the majority of the study area having slopes below 2 degrees, dramatically reduces surface runoff velocity and extends the residence time of rainfall on the land surface, maximizing infiltration opportunity through the Clay Loam soil profile into the underlying fractured Migmatite aquifer.

The moderate scores assigned to geology (Migmatite, score 3) and lineament density (roughness proxy, score 1-3) reflect the inherent limitations of crystalline basement terrain for groundwater storage compared to sedimentary formations. However, the aeromagnetic findings of Osumaje et al. (2024) confirmed NW/NE trending fault systems as productive groundwater conduits, suggesting that the terrain roughness proxy employed in this study underestimates true subsurface lineament density. This conservative treatment of lineament density implies that the GWPI values produced represent minimum estimates of Palladan's true groundwater potential; incorporating aeromagnetic-derived lineament density would likely yield higher GWPI values, potentially revealing very high potential zones in areas directly overlying the fault systems.

The degraded vegetation cover of Palladan (mean NDVI 0.115, Degraded Savannah Woodland) reflects decades of land use pressure from population growth, agricultural expansion, and fuelwood extraction. While this land cover condition scores 3 out of 5 for groundwater recharge potential, reflecting the moderate recharge implications of sparse vegetation, the progressive degradation of soil structure associated with reduced vegetation cover poses a long-term threat to infiltration capacity that is not captured by the static NDVI value used in this study.

5.2 Climate Change Implications

The 43-year CHIRPS rainfall record (1981-2024, Funk et al., 2015) used in this study captures a period of significant climate variability in the West African Guinea Savannah zone, encompassing the Sahel drought period of the 1970s-1980s and the subsequent partial rainfall recovery from the 1990s (Nicholson, 2013). The mean annual rainfall of 966.21 mm/year represents a long-term average that may mask important trends in seasonal rainfall distribution and inter-annual variability.

The IPCC (2021) projects increased rainfall variability for the Guinea Savannah zone under both moderate (SSP2-4.5) and high-emission (SSP5-8.5) climate scenarios, with potential increases in the frequency of extreme rainfall events offset by longer inter-event dry periods. For groundwater

recharge in Palladan, this has contrasting implications. On one hand, extended dry periods reduce cumulative infiltration and may fail to satisfy seasonal soil moisture deficits, reducing net recharge per rainfall event. On the other hand, the flat terrain of Palladan (mean slope 1.90 degrees) provides natural resilience to increased rainfall intensity by facilitating surface water ponding and focused recharge through ephemeral pools, partially compensating for reduced diffuse recharge during dry periods. This contrast is consistent with the broader finding of Taylor et al. (2013) that groundwater systems can act as a buffer against short-term climate variability even as they remain vulnerable to sustained, long-term reductions in recharge.

The degraded vegetation cover identified in this study (mean NDVI 0.115) amplifies climate change vulnerability. Reduced vegetation cover lowers evapotranspiration losses (potentially increasing available rainfall for recharge) but progressively reduces soil organic matter content, degrading soil structure and infiltration capacity over time. This long-term soil degradation pathway could gradually shift the dominant groundwater potential classification of Palladan from High toward Moderate under continued land degradation scenarios, even without any change in rainfall totals.

5.3 Comparison with Related Studies

The findings of this study are broadly consistent with related GIS-based groundwater potential assessments in the Nigerian Basement Complex. Fashae et al. (2014) applied AHP-WOA to delineate groundwater potential zones in the crystalline basement terrain of Oyo State, Nigeria, achieving 78% validation accuracy against existing borehole data, with rainfall and geology identified as the dominant controlling factors. Badamasi et al. (2016) mapped groundwater potential in Zaria, Kaduna State, using remote sensing and GIS, identifying the northern and northwestern areas of Zaria as highest potential zones — consistent with the location of Palladan in the northern Zaria metropolitan area. The present study builds directly on both these precedents by applying a validated MCDA/WOA methodology to a specific community-scale assessment, framed within a climate change impact context that is absent from the earlier studies.

The aeromagnetic findings of Osumaje et al. (2024) confirmed NW/NE trending fault systems as productive groundwater conduits, suggesting that the terrain roughness proxy employed in this study underestimates true subsurface lineament density. The present findings are also consistent with earlier geophysical work within and immediately around Palladan: Jegede et al. (2013) documented a permeable near-surface laterite-over-basement profile within Palladan itself, while Osumaje & Kudamnya (2014) reported comparable weathered-layer thicknesses and predominantly good groundwater potential ratings across the adjacent ABU Samaru campus, reinforcing the regional consistency of the High-potential classification produced by this study.

6. CONCLUSION

This study has demonstrated that Palladan, Zaria, Kaduna State, Nigeria, is a predominantly High groundwater recharge potential area, as determined through a GIS-based MCDA/WOA framework integrating seven thematic criteria from freely available open-access datasets. The High potential zone covers approximately 69% of Palladan, with a further 29.5% classified as Moderate potential; Very Low and Low potential zones together occupy less than 1.5% of the study area. This dominance is driven principally by favourable mean annual rainfall (966.21 mm/year) and exceptionally flat terrain (mean slope 1.90 degrees), which together account for approximately 59% of the total AHP weight and establish a strong natural foundation for groundwater recharge.

The Consistency Ratio of $CR = 0.025$ confirms the statistical reliability of the AHP weight assignment. Qualitative cross-validation against the independent VES-based investigation of Osumaje et al. (2024), which independently classified Palladan as a High groundwater potential area with productive fractured Migmatite aquifers (12-55 m thickness), provides supporting methodological validation for the spatial model produced, though quantitative validation against primary borehole data remains a recommended direction for future work.

Climate change poses a significant long-term threat to groundwater recharge sustainability in Palladan through projected increases in rainfall variability and continued land degradation. The flat terrain of Palladan confers natural resilience advantages through surface water ponding mechanisms, but active management interventions — including Managed Aquifer Recharge, vegetation restoration,

and groundwater monitoring — are essential to maintain groundwater availability under future climate scenarios. The replicable, cost-effective MCDA/WOA methodology demonstrated in this study is directly transferable to other data-scarce communities across the Nigerian Basement Complex facing similar groundwater management challenges under a changing climate.

7. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made for groundwater resource management in Palladan:

Groundwater Resource Management

i. Groundwater exploration and borehole siting should prioritize the High potential zones (Zone 4) in the flat central and northern portions of Palladan, where the combination of favourable rainfall, minimal slope, and moderate soil permeability creates the most productive recharge conditions consistent with fractured Migmatite aquifer depths of 12-55 m (Osumeje et al., 2024).

ii. Managed Aquifer Recharge (MAR) interventions including recharge pits, percolation tanks, and check dams across seasonal drainage channels should be implemented in High potential zones during the wet season (April to October) to enhance natural groundwater recharge. The flat terrain is ideal for MAR implementation.

iii. A groundwater level monitoring network should be established across the different potential zones of Palladan, including primary borehole yield or water-table measurements, to enable quantitative validation of the GWPI map, early detection of climate change-induced recharge decline, and evidence-based abstraction management.

Land Use and Environmental Management

i. A community vegetation restoration programme should be initiated to reverse the current degraded savannah condition (mean NDVI 0.115) through agroforestry, controlled grazing management, and native tree planting. Target NDVI values of 0.3-0.5 would substantially improve long-term soil infiltration capacity.

ii. Groundwater recharge protection should be incorporated into urban development planning for Palladan, with High potential zones designated as recharge protection areas where impervious surface coverage is minimized.

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